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A REVIEW OF SOURCES FOR THE STUDY OF ARCHITECTURE IN WESTERN BELARUS, PUBLISHED IN THE PERIOD 1921–1939 IN THE SECOND POLISH REPUBLIC

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Abstract

The development of the professional architectural environment in the Second Polish Republic during the 1920 s – 1930 s took place in the context of active promotion of the latest achievements of the world and, subsequently, their own experience in architectural and urban planning theory and practice. This experience has been included in dozens of different publications that have become primary sources in the study of architecture and urban development in both the Second Polish Republic and Western Belarus. The article examines periodicals, reports of state-owned organizations, archival materials containing information about the studied objects on the territory of Western Belarus in 1921–1939. The most significant publications are described – the magazine «Architecture and Construction», reports of the Ministry of Public Works and the Military Housing Fund.

The key periodicals for the study are the journals «Architektura i budownictwo» and «Dom, Osiedle, Mieszkanie». A special place is occupied by reports on housing construction – «Budowa domów dla urzędników państwowych w województwach wschodnich», «Budowa pomieszczeń dla korpusu ochrony pogranicza i domów dla urzędników państwowych w województwach wschodnich», «Domy mieszkalne Funduszu Kwaterunku Wojskowego», «Sprawozdanie Funduszu Kwaterunku Wojskowego 1927–1937». A significant array of primary sources on the topic of research is located in the State Archives of the Brest Region. Most of the described sources are remotely accessible (digital libraries of universities, digitized archival materials) and are accessible through online resources indicated in the text of the article.

Keywords: history of architecture and urban planning, Western Belarus, review of sources, «Architecture and construction».

ОБЗОР ИСТОЧНИКОВ К ИЗУЧЕНИЮ АРХИТЕКТУРЫ ЗАПАДНОЙ БЕЛАРУСИ, ОПУБЛИКОВАННЫХ В ПЕРИОД 1921–1939 ГГ. ВО ВТОРОЙ ПОЛЬСКОЙ РЕСПУБЛИКЕ

С. В. Кивачук, Т. А. Панченко

Реферат

Развитие профессиональной архитектурной среды во Второй Польской республике в течение 1920–1930-х годов происходило в условиях активной пропаганды новейших достижений мирового и, впоследствии, собственного опыта архитектурно-градостроительной теории и практики. Этот опыт вошел в десятки различных изданий, ставших сегодня первоисточниками в изучении архитектуры и градостроительства как Второй Польской республики, так и Западной Беларуси. В статье рассматриваются периодические издания, отчеты государственных организаций, архивные материалы, содержащие информацию об исследуемых объекта на территории Западной Беларуси 1921–1939 гг.

Ключевыми для исследования периодическими изданиями выступают журналы «Architektura i budownictwo» и «Dom, Osiedle, Mieszkanie». Отдельное место занимают отчеты о строительстве жилья – «Budowa domów dla urzędników państwowych w województwach wschodnich», «Budowa pomieszczeń dla korpusu ochrony pogranicza i domów dla urzędników państwowych w województwach wschodnich», «Domy mieszkalne Funduszu Kwaterunku Wojskowego», «Sprawozdanie Funduszu Kwaterunku Wojskowego 1927–1937». Значительный массив первоисточников по теме исследования находится в Государственном архиве Брестской области. Большая часть из описанных источников находится в удаленном доступе (цифровые библиотеки университетов, оцифрованные архивные материалы) и доступна через онлайн-ресурсы, указанные в тексте статьи.

Ключевые слова: история архитектуры и градостроительства, Западная Беларусь, обзор источников, «Архитектура и строительство».

Introduction

Since the beginning of the 21st century, the interest of researchers around the world in the architectural heritage of the interwar period has increased significantly. Many objects of this period are taken under state protection, becoming part of the national cultural heritage [1, p. 72]. In Belarus, the architecture and urban planning of the Second Polish Republic have been practically unstudied. Nevertheless, modern approaches to architectural and urban planning activities that developed in the European culture of those years were implemented in many buildings in Western Belarus.

Materials and sources of the period chronologically coinciding with the time boundaries of the study play a huge role in the study of architectural issues from 1921 to 1939. These are various periodicals, archival materials, catalogues, collections and reports on construction, which contain an array of graphic and textual information about the objects under study.

Review of sources

Research by domestic (A. Shamruk and E. Morozov) and foreign (O. Mikhailishin, I. Vislotskaya, A. Olshevsky, P. Krakovsky, M. Pchelkovsky and others) authors on architecture and urban planning of the Second Polish Republic are based on information from primary sources, which are publications of the period 1921–1939. They reflected the latest architectural and urban planning concepts generated in the largest architectural centers of Poland – Warsaw and Lvov [2, p. 57]. The most important sources of information both in Polish professional circles and for architects of the western regions of Belarus were periodicals that reflected the entire range of architectural issues and covered the latest achievements of the industry [3, p. 48]. The range of issues raised in the pages of periodicals was closely linked to the socio-economic processes in the state and was aimed at solving pressing social problems: urban construction, development of housing stock and infrastructure facilities, and improvement of the urban environment.

The illustrated monthly «Architektura i budownictwo» (Architecture and Construction) is the most authoritative magazine of that time. The editorial board of the magazine included the best architects of the country (R. Gutt, J. Zhuravsky, T. Novakovsky, J. Lisetsky, T. Burshe, and others). The magazine was published from 1925 to 1939, the total volume is almost 7000 pages [4] (Figure 1). The authors' collective devoted monthly issues with a large number of illustrations (about 35–40 pages) to issues of architectural, urban planning and construction activities. The information posted in the magazine can be presented in the form of three blocks: 1) description of constructed objects in the country, 2) competitive projects for government orders, 3) review of foreign experience in design and construction. Some of the issues were thematic (No. 6, 1926 – Exhibition «Apartment and City»; Nos. 2–3, 1929 – On the Construction Activities of the Military Housing Fund; No. 4–5, 1930 – Construction of Bank Buildings; No. 4, 1933 – Housing Construction; No. 10–12, 1933 – Military Architecture; No. 8–10, 1936 – In Memory of Architect Czesław Przybylski, etc.). A number of articles related to the topic of the research were placed in the issues: No. 2, 1937 (military urban planning and urban planning techniques aimed at concealing objects from the enemy); No. 1, 1938 (general plans for various cities and towns), No. 6, 1939 (air and gas protection for buildings).

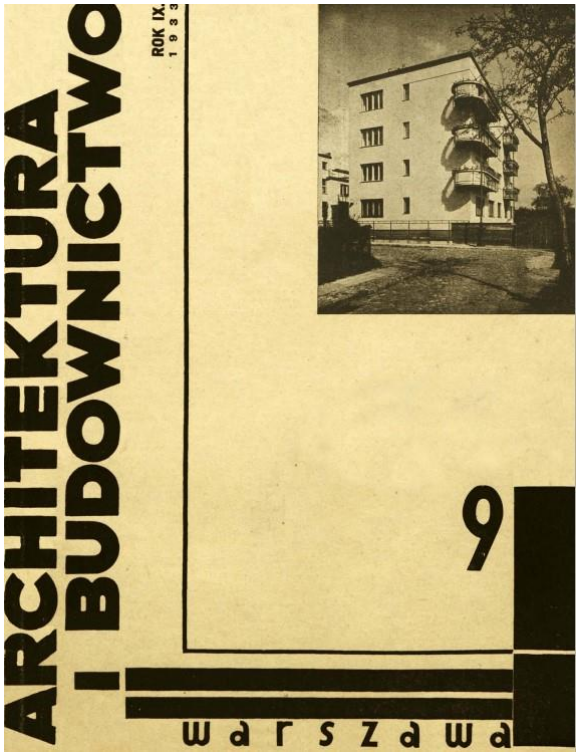

Figure 1 – Journal «Architecture and Construction»

The monthly's special feature is its materials, rich in illustrations, devoted to numerous national architectural competitions [10]. The pages of the magazine describe competition projects for the construction of large public buildings (No. 10, 1927 – Competitions for the buildings of the Ministry of Public Works and the Bank of National Economy; No. 7, 1930 – For the building of the Museum of Arts and Crafts). A special group consisted of competitions aimed at solving problems of urban planning of residential units (quarters, districts) of cities (in particular, Warsaw, Radom (No. 9, 1926), Poznan (No. 1, 1932)) and villages, which solved problems unprecedented in the urban planning practice of Poland.

The editorial board of the journal strove to inform the Polish architectural community as widely as possible about the latest world trends in the professional field. Thus, articles by A. Loos «Architecture» (No. 3, 1931), F. L. Wright «On the New Style» (No. 7, 1932), etc. were published in translation (in full or as abstracts) [5]. A number of issues included a review of the experience of European and American countries: No. 2 and No. 11–12, 1927 – Exhibition of the German Werkbund in Stuttgart (Weissenhof settlement); No. 7, 1930 – Architecture of Holland, works of arch. G. Rietveld; No. 1, 1931 – California School of Architecture, works of arch. R. Neutra; No. 3, 1931 – Housing construction in Germany, works by arch. O. Hessler.

The journal subscription is stored in the State Archives of the Brest Region (SABR), as well as in remote access on the website of the Digital Library of the Warsaw University of Technology and the Digital Library of the Lublin University of Technology [6, 7].

The second most important journal, «Dom, Osiedle, Mieszkanie», DOM (House, Estate, Apartment), was devoted to residential architecture (Figure 2). Issues No. 4–6 for 1937 contained a report on the construction of housing by the Workers' Settlement Association «Budownictwo mieszkaniowe Towarzystwa Osiedli Robotniczych» (TOR).

Figure 2 – Journal «House, Estate, Apartment»

Of no small importance for the study are some other periodicals containing information on the design and construction of the interwar period: «Album Młodej Architektury», «Architekt», «Komunikat SARP-u», etc. The peculiarities of regional development were covered by newspapers, including «Gazeta Poleska». An idea of the applied design solutions, materials and technologies for the construction of buildings is given by construction magazines «Przegląd Budowlany», «Beton», etc.

Thus, general information on the development of the industry, the latest achievements and major projects is reflected in periodicals (journals, newspapers, albums). Information on specific objects erected in the study area during the period 1921–1939, their number, authors, time of construction and other characteristics necessary for their attribution, is contained in reports and statistics of various government organizations (construction reports, collections, catalogues, anniversary editions).

Since 1921, the construction of housing projects in the western regions of Belarus has been carried out at the state level by the Ministry of Public Works. After 5 years of active work on the construction of new projects in the Eastern Voivodeships of the country, the Ministry published the collections «Budowa domów dla urzędników państwowych w województwach wschodnich», 1925 and «Budowa pomieszczeń dla korpusu ochrony pogranicza i domów dla urzędników państwowych w województwach wschodnich», 1925. They contain complete information on the projects built in the first half of the 1920s on the territory of Western Belarus (the period 1921–1925). The first collection is devoted to the con-

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struction of employee colonies in the Eastern Voivodeships of the country (Western Belarus, part of modern Ukraine and Lithuania). It provides data on the location of all construction projects (on cartograms), their main technical and economic indicators and estimated construction costs; indicates the firms performing construction work, the managers of the work on site; provides a list of types of houses and the authors of their projects; presents projects of individual buildings and employee colonies (in the form of master plan diagrams, visual illustrations (book graphics and photography), and building drawings). A significant part of the information in the collection is devoted to the construction of employee colonies in Brest.

The second collection (parts II and III) describes the construction of facilities for the Border Guard Corps and partially repeats the information on the construction of colonies for employees from the previous edition. The collection is also rich in various cartograms and illustrations. A significant portion of the information is devoted to the construction of a complex of Corps buildings in Kletsk and in the village of Ludvikovo in the Gantsevichi District of the Brest Region.

In the period from 1927 to 1939, the Military Quartering Fund (Funduszu Kwaterunku Wojskowego, FKW) of the Construction Department of the Ministry of Military Affairs was responsible for the construction of housing facilities in the western regions of Belarus at the state level. The Fund periodically published reports on the construction: «Domy mieszkalne Funduszu Kwaterunku Wojskowego. Sprawozdanie 1927–1930», 1930, «Domy mieszkalne Funduszu Kwa-terunku Wojskowego. "Sprawozdanie 1930–1933», 1934 (Figure 3), «Sprawozdanie Funduszu Kwaterunku Wojskowego 1927–1937», 1938. The reports contain complete information about the objects built from 1927 to 1937 on the territory of the Second Polish Republic. The report on the construction of objects after 1937 was probably not published due to the outbreak of World War II.

Figure 3 – FKW Report 1930-1933 (Volume II)

The first two reports (volumes) for a three-year period. The reports contain a «balance» by calendar periods (estimated cost), a list of real estate in the FKW account with its cost, the basics of FKW real estate management; a list of objects (in the form of a cartogram and tables), drawings of houses (fragments of plans and cross-sections) with a brief description and main technical and economic indicators; photographic documentation of completed buildings and their interiors. The reports reflect information on the construction of residential buildings for the garrison in Molodechno, and individual buildings in other cities of Belarus.

The report on the activities of the Fund for the next three years (1934–1937) is presented in the general report on the construction of houses, «Sprawozdanie Funduszu Kwaterunku Wojskowego 1927–1937», 1938. This report for a ten-year period also contains information from the previous reports in a more condensed form and is the main report on the activities of FKW for the entire period of its existence. The report includes: the rules and principles that the Fund follows in the design and construction of its projects; a «balance» by calendar periods (estimated cost); a list of real estate in the FKW account with their value; a complete list of all designers (engineers, architects) and student interns of the Fund; a list of construction and engineering firms implementing the projects; a cartogram of the location of objects throughout the country; an alphabetical list of all the Fund's houses in the form of a table; a graphic section in the form of photographs or perspective images of buildings, general plans, fragments of floor plans (apartment plans) and their brief descriptions; a detailed description of the main departmental facilities of the country, built by the Foundation.

The report presents information on the construction of the former settlement of Trauguttovo in Brest, a residential complex in Postavy, buildings of the Gelenovo garrison in Molodechno, a group of residential buildings in Slonim and individual buildings in other cities of Belarus.

Information on the activities of the Construction Department of the Ministry of Military Affairs for almost the entire interwar period is presented in the two-volume publication «Budownictwo wojskowe 1918–1935», 1936. The first volume is devoted to the history of construction and modern construction in individual areas of the national economy: barracks buildings, public buildings, health care, religious buildings, urban planning, housing construction. The second volume covers construction production technologies, features and rules for engineering equipment of buildings.

A separate place is occupied by catalogues with building projects recommended for repeated use and standard construction. The newly created Polish state faced problems in implementing the educational program in the first decade. One of them was the shortage of school buildings and the impossibility of adapting existing facilities to the needs of schools. In 1925, the Ministry of Religion and Education (Ministerstwo Wyznań Religijnych i Oświecenia Publicznego) published a catalogue of public school projects for repeated use (includes 48 projects) [8]. The catalogue presents schools of various capacities, for various construction areas, and also provides the minimum and optimal composition of school building premises, and provides the main regulatory requirements for the building and its site.

Since 1933, a significant portion of individual houses in the country, including in Western Belarus, were built according to projects developed by architects for the Bank of National Economy (Bank Gospodarstwa Krajowego, BGK); these projects were placed in the catalogue «Katalog typowych domów dla drobnego budownictwa mieszkalnego. Bank Gospodarstwa Krajowego», 1934. The catalogue contains 83 projects of individual residential buildings (one-, two-apartment and block), developed by architects on a competitive basis. In the catalogue, the projects are presented only in the form of sketches, allowing one to make a choice [9].

Following the Warsaw Housing Exhibition of 1935, the BGK published a catalogue of houses, the «Katalog Wystawy Budowlano-Mieszkaniowej Banku Gospodarstwa Krajowego w Warszawie na Kole 1935 maj–sierpień» and offered preferential loans for housing construction based on its own designs (Figure 4). Interested customers purchased initial designs from the Bank and erected houses on designated plots, often through the Workers' Settlement Association. Local authorities merely approved the placement of the building on the designated plot.

Thus, information on specific objects erected in the study area in the period 1921–1939, their quantity, authors, construction time and other characteristics is provided in the reports and statistics of state organizations (collections, catalogues, construction reports).

A significant array of primary sources on the topic of the study is presented in domestic and foreign archives and libraries. In the territory of the Republic of Belarus, this is, first of all, the State Archives of the Brest Region (SABR). Fund 1 of the SABR «Polesie Voivodeship Administration» contains information on the construction of housing in the territory of the Polesie Voivodeship [10, 11]; Fund 2 «Brest District Starostwo» – on construction in the territory of the Brest District and the city of Brest [12]; Fund 5 «Brest City Administration» – on the construction of both public

and private housing in the city, in particular – on the construction of buildings in the colonies of employees in Brest [13]; Fund 67 «Command of the Corps of District No. 9 in the City of Brest» stores information on departmental construction in the district [14, 15].

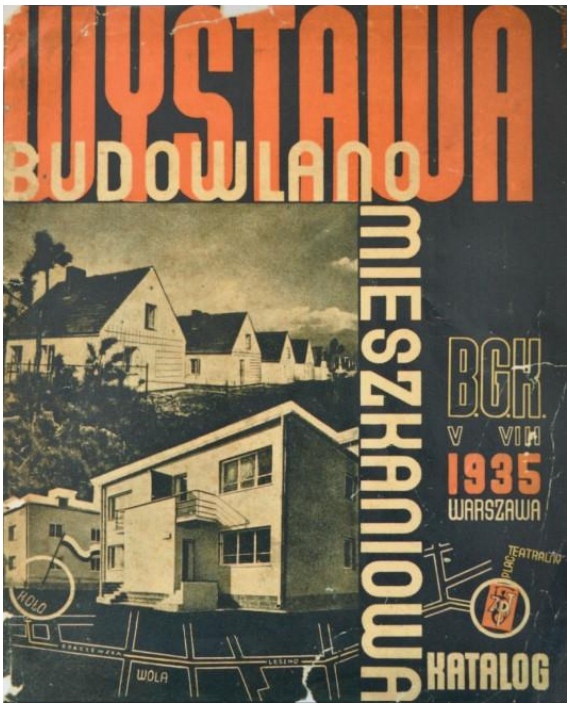

Figure 4 – BGK catalogue of the 1935 exhibition in Warsaw

A special place among the sources for studying the architecture and urban planning of the interwar period is occupied by remote access materials (digital libraries of universities, digitized archival materials), available through the following online resources:

1) National Digital Archives (NAC) [16]. The archive contains digitized graphic materials, primarily historical photographs of objects in Western Belarus from 1921 to 1939 (Brest, Baranovichi, Molodechno and other cities).

2) Digital Library of the Warsaw University of Technology [6]. The library stores digitized journals of the interwar period, including «Architektura i budownictwo», «Dom, Osiedle, Mieszkanie», «Album Młodej Architektury», «Architekt», «Przegląd Budowlany», «Komunikat SARP-u»; collections of the Ministry of Public Works from 1925 on the construction of housing for civil servants and the Border Guard Corps in the Eastern Voivodeships.

3) The Digital Library of the Lublin University of Technology [7] also contains journals from the interwar period, including «Architektura i budownictwo».

4) Archives of the Central Military Library named after Marshal Józef Piłsudski [17]. The library contains reports of the Military Housing Fund for 1927–1930, 1930–1933, 1927–1937.

5) Pomeranian Digital Library [18]. The library's website contains a two-volume report of the Construction Department of the Ministry of Military Affairs for 1918–1935.

6) Silesian Digital Library [19]. The library contains a digitized catalogue of the 1935 exhibition of the Bank of National Economy.

7) Lower Silesian Digital Library [20]. The library contains the publication «Słownik arkitektów i budowniczych Polaków oraz cudzoziemców w Polsce pracujących».

8) Electronic catalog of the US National Archives [21]. The National Archives at College Park, Maryland contains digitized cartographic materials (aerial photography) of the territories of modern Belarus, Poland, and Ukraine.

Conclusion

The above-described publications, such as «Architektura i budownictwo», «Dom, Osiedle, Mieszkanie», provide an opportunity to consider the architecture and urban planning of Western Belarus in the context of the development of the industry in the Second Polish Republic and Western Europe as a whole, to identify the main directions and trends in housing construction and urban planning practice.

The information collected in one-off publications (reports, collections, catalogues) allows us to evaluate the urban planning, architectural planning, construction, compositional, stylistic and other characteristic features of the studied objects of the period 1921–1939 on the territory of Western Belarus.

References

1. Morozov, E. V. Arhitekturnoe nasledie Belarusi 1920–1930-h gg. Problemy atribucii i sohraneniya / E. V. Morozov // Avangard i kul'tury: iskusstvo, dizajn, sreda: materialy Mezhdunarodnoj nauchnoj konferencii, Minsk, Belarus', 17–19 maya 2007 g. / [pod obshchej redakciej I. N. Duhana]. – Minsk, 2007. – S. 72–77.
2. Mykhaylyshyn, O. Architecture of avant-garde in Ukraine in 1921–1939: origins, ways of spreading, main features. Case study of Volyn / O. Mykhaylyshyn // Multiple Modernities in Ukraine: DOCOMOMO Journal, № 67, 12 december 2022. – Delphi : Delft University of Technology, 2022. – P. 56–64.
3. Morozov, E. V. Funkcionalizm kak fenomen evropejskoj arhitektury i ego rasprostranenie na belorusskih zemlyah v 1920–1930-h gg. / E. V. Morozov // Arhitektura: sbornik nauchnyh trudov. – Minsk, 2013. – Vyp. 6. – S. 44–49.
4. Architektura i Budownictwo: miesięcznik ilustrowany. – Warszawa, 1925–1939.
5. Mihajlishin, O. L. Chasopis «Arhitektura i budivnictvo» – dzherelo do istorii arhitekturi mizhvoєnnogo periodu / O. L. Mihajlishin // Budivnictvo ta arhitektura: XIV Mizhnarodna naukova internet-konferenciya Advanced technologies of science and education. – 2011. – URL: http://intkonf.org (data zvarotu: 04.11.2022).
6. Biblioteka Cyfrowa Politechniki Warszawskiej [strona internetowa]. – URL: https://bcpw.bg.pw.edu.pl (data dostępu: 08.01.2023).
7. Biblioteka Cyfrowa Politechniki Lubelskiej [strona internetowa]. – URL: http://bc.pollub.pl (data dostępu: 19.03.2023).
8. Projeкty budynków szkół powszechnych / Ministerstwo Wyznań Religijnych i Oświecenia Publicznego. – Warszawa, 1925. – 119 s.
9. Katalog typowych domów dla drobnego budownictwa mieszkalnego / Bank Gospodarstwa Krajowego. – Warszawa, 1934.
10. Gosudarstvennyj arhiv Brestskoj oblasti (GABO). – Fond 1. Op. 4. D. 1207, 1217, 1585.
11. GABO. – Fond 1. Op. 5. D. 604, 616.
12. GABO. – Fond 2. Op. 1. D. 193.
13. GABO. – Fond 5. Op. 1. D. 129, 383, 870, 1556, 2956.
14. GABO. – Fond 67. Op. 2. D. 1943, 1945–1948a, 1950, 1955, 1958.
15. GABO. Fond 67. Op. 4. D. 7, 8, 15, 18.
16. Narodowe Archiwum Cyfrowe [strona internetowa]. – URL: https://www.nac.gov.pl (data dostępu: 19.01.2023).
17. Centralna Biblioteka Wojskowa im. Marszałka Józefa Piłsudskiego [Zasób elektroniczny]. – URL: https://cbw.wp.mil.pl (data dostępu: 10.01.2023).
18. Pomorska Biblioteka Cyfrowa [strona internetowa]. – URL: https://pbc.gda.pl (data dostępu: 19.01.2022).
19. Śląska Biblioteka Cyfrowa [strona internetowa]. – URL: https://www.sbc.org.pl (data dostępu: 27.01.2023).
20. Dolnośląska Biblioteka Cyfrowa [strona internetowa]. – URL: https://www.dbc.wroc.pl (data dostępu: 19.04.2023).
21. National Archives Catalog. The National Archives at College Park, Maryland [site]. – URL: https://catalog.archives.gov (date of access: 29.04.2023).

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THE USAGE OF HEAT INSULATING MATERIAL FROM FLAX NOILS IN LOW-RISE RESIDENTIAL BUILDINGS

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Abstract

Based on complex experiments, an assessment was made of the use of flax noils as a fibrous structure-forming material for thermal insulation boards. The article presents information on the selection and ratio of thermal insulation components based on flax noils. The indices of sorption humidity at a relative air humidity of 40–97 % and the vapor permeability coefficients of insulation materials made of noils are determined. The issues of resistance of thermal insulation materials to fungus are considered. The results of full-scale tests of a wall enclosure with a ventilated insulation system, an external wall with a wooden frame system and an attic floor structure of residential buildings in operation, including insulation materials based on flax noils and fibres as thermal insulation, are presented. Based on the obtained data, the values of thermal transfer resistance of the enclosing structures under study are calculated. Based on the test results, it was determined that the wall enclosing structures containing flax noils thermal insulation boards provide a heat transfer resistance of 3,24−4,55 (m2·°C)/W at an air temperature of –22 °C and –23 °C. At an air temperature of –17 °C, the thermal resistance of the attic floor with insulation based on flax noils is 6,27 (m2·°C)/W. It was found that the heat transfer resistances of the experimental enclosing structures with flax noils thermal insulation materials exceed the indicators of the walls and attic floor structure, including flax fiber thermal insulation, by 11−16 %. Based on the tests conducted, the effectiveness of thermal insulation boards made from noils was confirmed in comparison with insulation materials based on various plant materials, including flax fibres.

As a result of the research, the rational use of flax noils as a structure-forming component of thermal insulation for low-rise residential buildings was substantiated.

Keywords: heat insulating material, flax noils, sorption humidity, vapor permeability coefficient, thermal transfer resistance.

УТЕПЛИТЕЛЬ ИЗ ЛЬНЯНЫХ ОЧЕСОВ ДЛЯ ТЕПЛОИЗОЛЯЦИИ ЖИЛЫХ МАЛОЭТАЖНЫХ ЗДАНИЙ

А. А. Бакатович, С. А. Романовский

Реферат

На основании комплексных экспериментов проведена оценка использования льняных очесов в качестве волокнистого структурообразующего материала теплоизоляционных плит. Приведены сведения о подборе и соотношении компонентов тепловой изоляции на основе очесов льна. Установлены показатели сорбционной влажности при относительной влажности воздуха 40–97 % и коэффициенты паропроницаемости утеплителей из очесов. Изучен вопрос стойкости теплоизоляционных материалов к появлению грибка. Представлены результаты натурных испытаний стенового ограждении с вентилируемой системой утепления, наружной стены с деревянной каркасной системой и конструкции чердачного перекрытия эксплуатируемых жилых домов, включающих в качестве тепловой изоляции утеплители на основе льняных очесов и волокон. Основываясь на полученных данных, рассчитаны значения сопротивления теплопередаче исследуемых ограждающих конструкций. По итогам испытаний определено, что стеновые ограждающие конструкции, содержащие теплоизоляционные плиты из очесов, при температуре воздуха –22 °С и –23 °С обеспечивают сопротивление теплопередачи 3,24−4,55 (м2·К)/Вт. При температуре воздуха –17 °С термическое сопротивление чердачного перекрытия с утеплителями на основе очесов льна составляет 6,27 (м2·К)/Вт. Установлено, что сопротивления теплопередаче экспериментальных ограждающих конструкций с теплоизоляционными материалами из льняных очесов превышают показатели стен и конструкции чердачного перекрытия, включающих тепловую изоляцию на основе волокон льна, на 11−16 %. На основании проведенных испытаний подтверждена эффективность теплоизоляционных плит из очесов относительно утеплителей на основе различного растительного сырья, включая льняные волокна.

В результате исследований обосновано рациональное применение льняных очесов в качестве структурообразующего компонента тепловой изоляции для жилых малоэтажных зданий.

Ключевые слова: утеплитель, очесы льна, сорбционная влажность, коэффициент паропроницаемости, термическое сопротивление теплопередаче.

Introduction

Growing energy consumption costs for heating residential and public buildings stimulate the development and use of new efficient thermal insulation materials that help increase the thermal resistance of enclosing structures. In addition to improving thermal performance, modern insulation materials also have environmental requirements. It should be noted that manufacturers and suppliers of thermal insulation both in Belarus and in other countries are not always ready to meet customer requirements for the environmental safety of thermal insulation. One of the most appropriate solutions for the production of environmentally friendly thermal insulation materials is the use of secondary fibrous plant materials of agricultural origin. The demand for this area is confirmed by scientific research conducted in many countries on the development of insulation using plant materials [1−5].

In Belarus and the Russian Federation, the most well-known application of flax fibers is as a structure-forming material for thermal insulation boards. Polyester fibers are used as a binder for insulation materials of the «Akoterm Flax» trademark [6], and starch is used for thermal insulation materials of the «Ecoteplin» brand [7]. Thermal insulation boards have a thermal conductivity coefficient of 0,038 to 0,04 W/(m·K) with an average density of 30−34 kg/m^3 and are used to insulate enclosing structures of low-rise buildings. The disadvantages of thermal insulation made

of flax fibers include high price and limited use due to the lack of rigidity of the material structure. It is also worth noting the low level of fire protection of «Akoterm Flax» thermal insulation boards, which belong to flammability group G4. To reduce the fire hazard of «Ecoteplin» thermal insulation materials, borax is added to the composition during the production of thermal insulation.

Research into the development of insulation materials based on industrial hemp and various binders such as polyester, polyalky fibers, and without a binder using a fire retardant is being conducted in various countries [8–10]. With a density of 35–90 kg/m^3, thermal insulation materials have a thermal conductivity coefficient of 0,037 to 0,04 W/(m·K). High cost and limitations in the area of application hinder the popularization of insulation materials based on hemp fibers.

Coconut fibers were used to produce thermal insulation boards based on secondary plant materials in Trinidad and Indonesia [11, 12]. The research results showed that the thermal insulation material has the following thermal engineering characteristics: average density of 30–115 kg/m^3 and thermal conductivity coefficient of 0,058–0,104 W/(m·K).

In Malaysia, the thermal insulation properties of thermal insulation made from oil palm bark fibers were studied [13, 14]. Samples of thermal insulation boards were made using only bark fiber. With an average density of 20 to 120 kg/m^3, the experimental compositions of thermal insulation boards provide a thermal conductivity coefficient in the range of 0,03–0,092 W/(m·K). Insulation materials based on a mixture of oil palm fibers and cellulose fibers were also obtained. Formaldehyde resin was used as a binder [15]. With the content of oil and cellulose fibers in a ratio of 1:1, the thermal conductivity coefficient of the thermal insulation boards at an average density of 250 kg/m^3 is 0,045 W/(m·K).

Cotton fibers were used as a structure-forming material for thermal insulation in a scientific paper [16]. The insulation is characterized by the following thermal performance indicators: average density of 150–450 kg/m^3 and thermal conductivity coefficient of 0,059–0,082 W/(m·K). Thermal insulation boards are intended for insulation of walls and attic floors.

Research by scientists from India is devoted to the production of thermal insulation materials from banana, pineapple and jute fibers [17]. Analysis of the obtained data allowed us to establish that the lowest values of the thermal conductivity coefficient were recorded with the following quantitative composition of the fiber components: banana – 60 %, pineapple – 32 % and jute 8 %. When banana fibers are used separately as a structure-forming material, the thermal conductivity coefficient of the insulation is 0,041–0,067 W/(m·K) with an average density varying from 20 to 120 kg/m^3 [18].

The search for alternative raw materials of agricultural origin for the production of thermal insulation boards is a relevant area for many countries around the world. With the correct selection of a binder, thermal insulation based on plant fibers should provide high thermal and operational properties. Comprehensive research on the production of thermal insulation boards based on plant fibers is carried out at the «Green Construction» laboratory at the Euphrosyne Polotskaya State University of Polotsk. Particular attention during testing is paid to the environmental safety of thermal insulation materials.

Methodology of experimental research

Samples of insulating materials made of flax noils or fibers were manufactured in accordance with a certain sequence of technological operations. The components were preliminarily dosed. To obtain a modified binder, lime was first added to the liquid sodium glass, and then gypsum was added. After each of the additive components was added, the binder was mixed. The mold was filled with fibrous structure-forming material uniformly and layer by layer throughout the entire volume. The binder was applied to each laid layer in turn, using a sprayer. Then, the samples of thermal insulation materials based on flax noils or fibers were kept in the mold for 6 hours at a temperature of 20±2 °C and stripped. Then the thermal insulation samples were dried for 4 hours at a temperature of 45–55 °C.

The average density of the samples was determined according to GOST 17177 «Building thermal insulation materials and products. Test methods» [19].

The thermal conductivity coefficient of the insulation materials was measured on sample slabs measuring 250×250×30 mm using the ITP-MG4 «250» device, in accordance with the requirements of Standards of the Republic of Belarus 1618 «Construction materials and products. Methods for determining thermal conductivity under steady-state thermal conditions» [20].

The determination of the water resistance of liquid glass modified with lime and gypsum was carried out according to the method given in the research paper [21].

The sorption moisture content of thermal insulation boards was determined according to Standards of the Republic of Belarus EN 12088 «Building thermal insulation products. Method for determining sorption moisture content» [22].

The vapor permeability of thermal insulation was studied in accordance with Standards of the Republic of Belarus EN 12086 «Building thermal insulation products. Method for determining vapor permeability» [23].

The thermophysical properties of thermal insulation boards under operating conditions were studied using the RTP-1-16T information and measuring complex. The ambient air temperature, on the surface and inside the materials under study were recorded using thermocouples, and heat flow indicators were measured using heat flow converters.

After full-scale tests, to study the humidity in thermal insulation materials, prism samples measuring 50×50 mm in cross-section were cut out along the thickness of the insulation. Then the prism sample was cut into fragments of the same thickness. Then each sample was weighed and placed in a drying cabinet. Upon reaching a constant mass, the fragments were weighed again. Humidity was determined by the change in the mass of the samples before and after drying.

Main points

Components of thermal insulation material. The initial stage of the research involved selecting a fibrous structure-forming material for producing thermal insulation boards based on secondary plant materials. Flax noils, flax fibers, jute, coconut, bamboo, nettle, cotton waste and oil palm bark fibers were considered as structure-forming materials. Liquid sodium glass was used as a binder. The thermal conductivity coefficient of the samples was determined at an average density of 50 kg/m^3 and the same component consumption. The tests showed that the samples based on flax noils and nettle fibers have the lowest thermal conductivity coefficient of 0,041 W/(m·K) among the samples studied. The thermal conductivity coefficient of the samples made of jute, bamboo and cotton waste fibers is 0,043 W/(m·K). The thermal conductivity of boards based on flax, oil palm bark and coconut fibers exceeds the thermal conductivity coefficient of materials made from noils and nettle fibers by 15–32 %.

At the next stage, polyvinyl acetate dispersion, starch and rosin were considered as alternative binders to liquid glass. The studies were conducted on Belarusian plant raw materials - flax noils, flax and nettle fibers. The results of the tests indicate that the thermal conductivity coefficient of the samples on liquid glass and rosin have almost identical values and are lower than that of the samples containing polyvinyl acetate dispersion and starch by an average of 10 %. It should be noted that there are difficulties in ensuring the required amount and uniform distribution of rosin in the structure of the material.

Liquid glass also has a disadvantage. When in contact with water, liquid glass dissolves. In the course of the conducted research on ensuring the durability of insulation materials when used in conditions of high humidity, the required amount of a two-component additive of lime and gypsum in a ratio of 1:1 was established to increase the water resistance of liquid glass. When introducing a modifying additive in an amount of 8–12 % of the binder mass, the water resistance of liquid glass is 93–97 %.

Due to the lack of agricultural crop areas and production lines for obtaining fibers from nettle stems in Belarus, as well as the existing significant difficulties with the distribution of rosin over the volume of thermal insulation, flax noils and modified liquid sodium glass were adopted as components of experimental compositions of thermal insulation boards.

Consumption of thermal insulation components. To determine the quantitative compositions of thermal insulation materials based on noils, providing a combination of the best thermal engineering characteristics, studies were carried out to establish the range of variation of the fibrous structure-forming material and modified binder. The lowest values of the thermal conductivity coefficient of 0,034–0,04 W/(m·K) were achieved with an average density of 60–100 kg/m^3. The consumption of thermal insulation board components is presented in Table 1.

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Table 1 – The consumption of thermal insulation board components from flax noils

The consumption of components per 1 m³, weight percentage		
structure-forming material	binding	modifying agent
0,86–0,92	0,08–0,14	0,08–0,12

Sorption moisture. Samples for determining sorption moisture were taken from thermal insulation based on flax noils with an average density of 70 kg/m³, providing a thermal conductivity coefficient of 0,035 W/(m·K). The quantitative composition of the insulation components per 1 m³ corresponded to the following values: flax noils – 60 kg/m³, liquid glass – 9 kg/m³, gypsum – 0,5 kg/m³ and lime – 0,5 kg/m³. Based on the data obtained, an isotherm of water vapor sorption of thermal insulation boards made of flax noils was constructed (Figure 1).

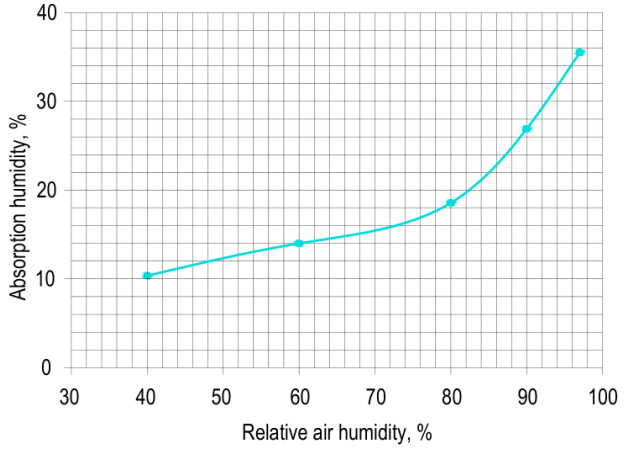


Figure 1 – Isotherm of water vapor sorption by flax noils

The conducted studies allowed us to establish that the sorption moisture content of the samples of thermal insulation materials based on flax noils at a relative air humidity of 40 % is 10,2 %. The value of the sorption moisture content of the samples at an air humidity of 60 % increases by 1,4 times. The maximum value of the sorption moisture content during storage of the samples at an air humidity of 80 % was recorded at 19,2 %. At a relative air humidity of 90 %, the sorption moisture content of the samples from flax noils reaches 26,5 %, and at an air humidity of 97 % it is 37,6 %.

For comparison, the sorption humidity values of the samples of flax fiber-based thermal insulation boards with identical quantitative composition with flax noils insulation were determined. The obtained experimental data indicate that at a relative air humidity of 40–90 %, the sorption humidity values of the samples of flax fiber-based thermal insulation practically coincide with those of noils materials. The sorption humidity value of the flax noils insulation at an air humidity of 97 % exceeds the value of flax fiber-based thermal insulation materials by 15 %. In comparison with liquid glass thermal insulation boards without a two-component additive, the introduction of lime and gypsum into the binder allows to reduce the sorption humidity values of the insulation by 20 % and 18 %, respectively, compared with samples made of noils or flax fibers.

In addition, an analysis of the sorption moisture values of the previously obtained and studied insulation materials based on plant raw materials and liquid glass was conducted. At a relative air humidity of 60–80 %, the sorption moisture of thermal insulation materials based on chopped straw, a mixture of straw and flax shives, eucalyptus fibers, coconut, jute, as well as a mixture of rice husks and straw is in the range from 8 to 24 % [24–27]. Based on these values, it can be concluded that the sorption moisture of thermal insulation based on flax noils has values close to those of insulation materials containing eucalyptus fibers, as well as a mixture of rice husks and straw. At the same time, the sorption moisture of thermal insulation materials made from noils is 24–42 % higher than the values of thermal insulation boards based on coconut and jute fibers, but 18–26 % lower than the values of thermal insulation made from a mixture of straw and flax shives, as well as chopped straw.

Simultaneously with the determination of the sorption humidity of the noils-based thermal insulation boards, the resistance of the samples to the appearance of fungal formations at a relative air humidity of 90–97 % was studied. Such conditions are as close as possible to the state of insulation soaking when the continuity of the protective coating of the roof or walls of the building is broken. After 200 days of keeping the samples in a desiccator at a relative air humidity of 90 %, there was no spot fungus on the surface of the materials. The formation of spot fungus on the surface of flax noils was recorded on the 135 th day when storing the samples in a desiccator with a relative air humidity of 97 %. It should be noted that when the samples are in a desiccator with an air humidity of 97 %, the time of the onset of spot fungus formation on the surface of noils coincides with the indicators of structure-forming materials made of flax fibers, straw, a mixture of straw and flax shives, and also significantly exceeds the value of thermal insulation based on a mixture of rice husks and straw. At a relative humidity of 90 % in the desiccator, the formation of spot fungus was not recorded on any samples.

Vapor permeability. The vapor permeability coefficient was determined on samples of flax noils measuring 110×110×50 mm. The quantitative composition, density and vapor permeability coefficient of the studied thermal insulation materials are presented in Table 2.

Table 2 – Composition, average density and vapor permeability coefficient of insulation materials made from flax noils

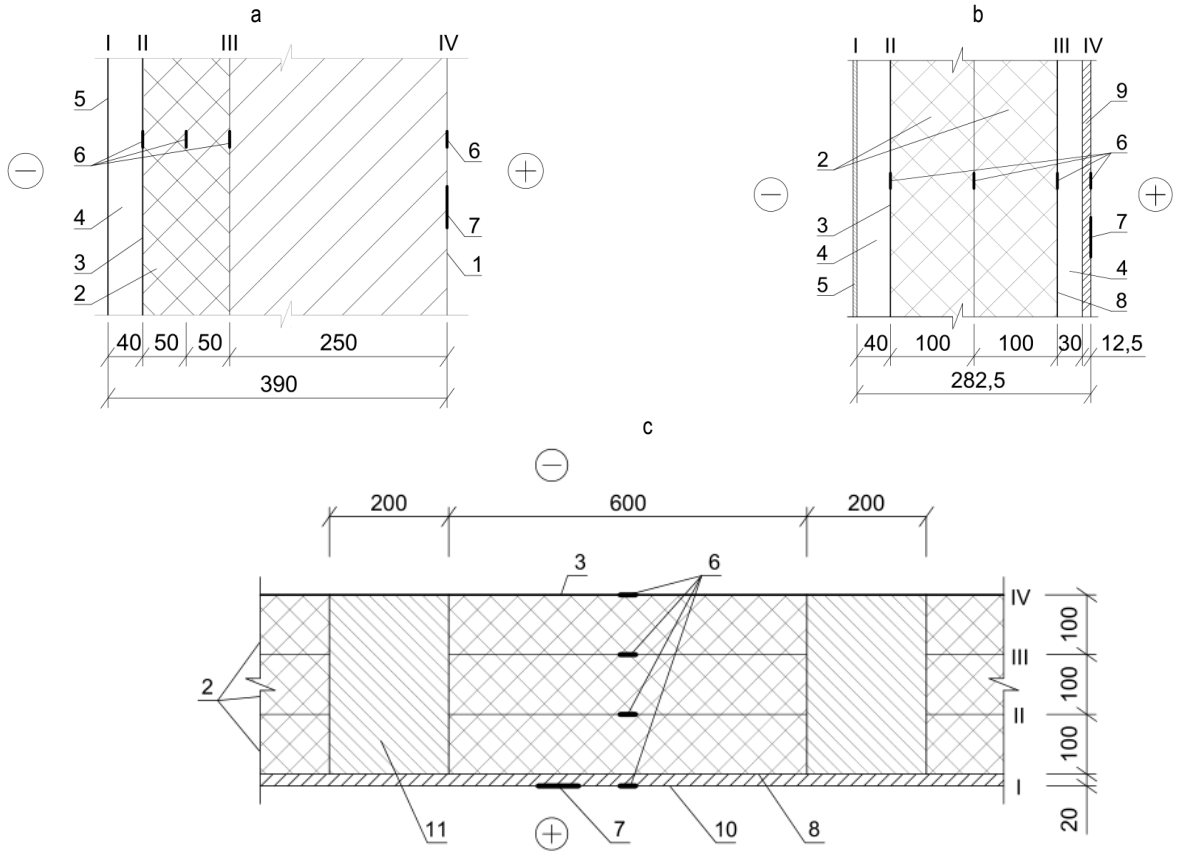
№ of sample	Consumption of components per 1 m³, kg				Average density, kg/m³	Vapor permeability coefficient, mg/(m·h·Pa)
	flax noils	liquid glass	lime	gypsum		
1	30	9	0,5	0,5	40	0,412
2	50	9	0,5	0,5	60	0,388
3	70	9	0,5	0,5	80	0,371
4	90	9	0,5	0,5	100	0,356
5	110	9	0,5	0,5	120	0,343

According to the data in Table 2, thermal insulation based on noils with an average density varying from 40 to 120 kg/m³ provides a vapor permeability coefficient within the range of 0,343–0,412 mg/(m·h·Pa). The established indicators of vapor permeability coefficients and sorption moisture of thermal insulation boards made of flax noils make it possible to calculate the humidity regime of enclosing structures of designed buildings.

A comparative analysis of the vapor permeability indices of samples based on plant waste has shown that the vapor permeability coefficients of thermal insulation materials containing flax noils are 5–10 % lower than the values of thermal insulation made from flax fibers and have values close to those of insulation materials based on chopped straw, as well as a mixture of straw and shives [24, 25]. The increase in the vapor permeability coefficients of thermal insulation boards made from mineral fibers relative to thermal insulation based on flax noils is 35–40 %.

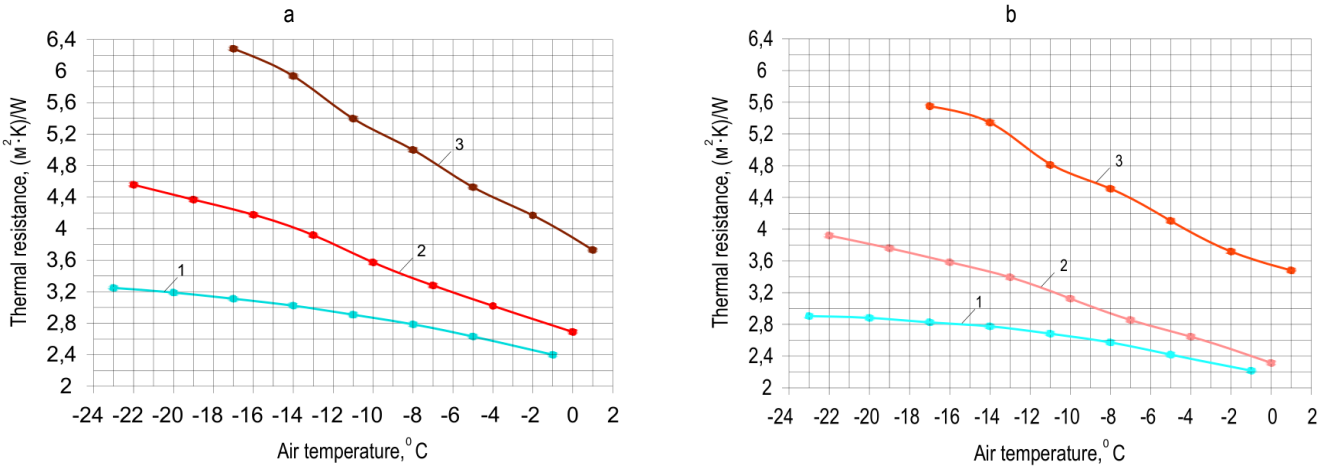
Full-scale tests of enclosing structures with insulation made of flax noils. In the autumn-spring periods of 2018–2024, full-scale tests of thermal insulation boards based on flax noils were carried out in enclosing structures of residential buildings in operation. Samples of insulation based on flax fibers were used for comparative tests. Observations of thermophysical processes occurring in enclosing structures containing insulation made of flax noils or fibers were carried out to confirm the effective operation of thermal insulation materials on plant raw materials. Samples based on flax noils or fibers were made in the form of slabs measuring 1200(1000)×500(600)×100 mm and used as thermal insulation in an external wall enclosure with a ventilated insulation system, an external wall with a wooden frame system and an attic floor of a one-story residential building. The average density of thermal insulation materials used for wall structures corresponded to 100 kg/m³, for an attic floor – 70 kg/m³. The schemes of the investigated enclosing structures with the location of thermocouples and heat flow sensors are shown in Figure 2.

Based on the obtained heat flow density values and temperature distribution across the thickness of the enclosing structures, the dependence of the thermal resistance of heat transfer of the studied wall structures and attic floor on the outside air temperature was determined (Figure 3). For the attic floor, the outside air temperature was taken to be the air temperature in the unheated attic. Full-scale tests for the specified structures were conducted in different time periods. For this reason, the thermal resistance values for each enclosing structure are specified for its own temperature range.



I, II, III, IV – boundaries of enclosure layers
1 – solid ceramic brick; 2 – insulation; 3 – water and wind protection membrane; 4 – air gap; 5 – facade metal cassette; 6 – thermocouple; 7 – heat flow sensor; 8 – vapor barrier; 9 – plasterboard; 10 – edged board of ceiling sheathing; 11 – wooden floor beam

Figure 2 – Layout of thermocouples and heat flow sensors by section:
a – external wall with ventilated insulation system; b – house walls with wooden frame system; c – attic floor structures



1 – external wall with ventilated insulation system; 2 – house wall with wooden frame system; 3 – attic floor structure

Figure 3 – Dependence of thermal resistance of enclosing structures with insulation made of flax noils (a) and fibers (b) on the temperature of the outside air (air in an unheated attic)

The dependencies presented in Figure 3 allowed us to establish that the wall enclosure with a ventilated insulation system containing flax noils insulation boards at an outside air temperature of –1 °C has a thermal resistance of heat transfer equal to 2,4 (m^2·K)/W, which is 9 % higher than the value of wall 1 with flax fiber-based materials. When the air temperature drops to –23 °C, the value of thermal resistance of enclosing structure 1 with flax noils insulation increases by 35 % to 3,24 (m^2·K)/W and is 11 % higher than the value of wall enclosure 1 with flax fiber-based insulation.

A similar dependence was established for the external enclosing structure of a house with a wooden frame system. The thermal resistance of wall 2 with flax noils insulation materials at an air temperature of 0 °C is 2,68 (m^2·K)/W, which is 16 % higher than the value of enclosing structure 2 with flax fiber-based insulation boards. The thermal resistance index of wall structure 2 containing noils insulation materials increases by 1,7 times to 4,55 (m^2·K)/W when the temperature drops to –22 °C, and is 17 % higher than the value of enclosing structure 2 including flax fiber-based insulation boards.

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The significant difference in the thermal resistance values of wall 1 and wall 2, containing slabs based on flax noils and fibers, is due to the increase in the thickness of the thermal insulation by 2 times from 100 mm (wall 1) to 200 mm (wall 2).

At the air temperature in the attic space of +1 °C, the thermal resistance to heat transfer of the attic floor with thermal insulation materials based on noils is 3.53 (m^2·K)/W, which is 8 % higher than the value of the attic floor with insulation made of flax fibers. A decrease in the temperature in the attic space to –17 °C leads to an increase in the thermal resistance of the attic floor with thermal insulation based on flax noils to 6.27 (m^2·K)/W, which is 13 % higher than the value of the insulated attic floor with flax fiber slabs.

The increase in the thermal resistance of heat transfer of experimental enclosing structures with slabs based on flax noils at low negative air temperatures is from 35 % to 78 %, which confirms the effective operation of thermal insulation made from flax noils in the winter period.

The increase in thermal resistance to heat transfer in the studied structures using heat-insulating boards based on noils compared to the use of insulation made of flax fibers is achieved due to the multidirectional arrangement of elementary fibers in the structure of the material, which prevents convective air transfer as a result of a decrease in the size of thin air layers of irregular shape and their partial localization in the form of individual closed microvoids.

After completion of the full-scale tests in the spring, the average values of the humidity of the thermal insulation materials were determined. Analysis of the obtained results allowed us to establish that the average humidity values of the flax noils-based thermal insulation boards after operation in the winter period are within the range of 12 % to 16 % and are 14–15 % lower than the humidity values of the flax fiber thermal insulation. The established humidity values of the insulation materials also determine the higher thermal performance of the flax noils-based insulation compared to the flax fiber thermal insulation boards obtained during full-scale tests.

Conclusion

According to the research results, it was established that the best values of thermal conductivity coefficients of 0,036−0,04 W/(m·K) can be achieved by using flax noils as a structure-forming material and an average density of insulating boards of 60−100 kg/m^3.

The analysis of the study of sorption humidity of insulation made of flax noils showed that at a relative air humidity of 60−80 %, the sorption humidity of thermal insulation based on tow is 14–19 %, which is a fairly low figure for thermal insulation based on plant materials. The formation of fungus on materials made of flax noils is possible only with long-term constant exposure to conditions with a relative air humidity of 97 %. However, such operating conditions are excluded with the correct maintenance of protective coatings of thermal insulation.

With an average density of 40 to 120 kg/m^3, the vapor permeability coefficient of insulation materials based on flax noils is within the range of 0,34−0,41 mg/(m·h·Pa). The obtained indicators of water vapor sorption and vapor permeability coefficients allow calculating the humidity regime of building enclosing structures using flax noils boards.

The use of flax noils thermal insulation during field tests in enclosing structures of residential buildings in operation made it possible to establish that the structures of a wall with a ventilated insulation system and a wall of a house with a wooden frame system that includes noils-based thermal insulation boards at an outside air temperature of –22°C and –23°C have a thermal resistance to heat transfer of 3,24 and 4,55 (m^2·K)/W, respectively, which exceeds the values of wall enclosures with flax fiber insulation by 11−16 %. The structure of an attic floor with noils-based thermal insulation boards at a minimum temperature in the attic space of –17 °C provides a thermal resistance to heat transfer of 6,27 (m^2·K)/W, which is 13 % higher than the value of a floor with flax fiber insulation. The obtained indicators indicate that the experimental slabs provide high thermal insulation properties in the winter period.

As a result of the tests, the efficiency of using noils insulation boards in enclosing structures of low-rise residential buildings in operation was confirmed.

References

1. Aliev, A. S. Ispol'zovanie lateksov dlya polucheniya voloknistyh plit / A. S. Aliev, A. YA. Vasil'kova // Molodye uchenye v reshenii aktual'nyh problem nauki : sbornik materialov Vserossijskoj nauch.-prakt. konf. studentov, aspirantov i molodyh uchenyh, Krasnoyarsk, 22–23 aprelya 2021 g. / Sibirskij gosudarstvennyj universitet nauki i tekhnologii imeni akademika M. F. Reshetneva. – Krasnoyarsk, 2021. − S. 299−300.
2. Development and performance evaluation of natural thermal-insulation materials composed of renewable resources / A. Korjenic, V. Petránek J. Zach, J. Hroudová // Energy and Buildings. – 2011. – № 43 (9). – P. 2518–2523. – DOI: 10.1016/j.enbuild.2011.06.012.
3. Vachnina, T. Results of determination of thermal conductivity coefficient for board materials from plant waste / T. N. Vachnina, I. V. Susoeva, A. A. Titunin // IOP Conference Series: Materials Science and Engineering 687. – 2019. – DOI: 10.1088/1757-899X/687/2/022005.
4. Kymalainen, H. R. Flax and hemp fibres as raw materials for thermal insulations / H. R. Kymalainen, A. M. Sjoberg // Building and Environment. – 2008. – № 43. – P. 1261–1269. – DOI: 10.1016/j.buildenv.2007.03.006.
5. Investigations on physical-mechanical properties of effective thermal insulation materials from fibrous hemp / A. Kremensas, A. Stapulione, S. Vaitkus, A. Kairyte // Procedia Engineering. – 2017. – № 172. – P. 586–594. – DOI: 10.1016/j.proeng.2017.02.069.
6. Plity teploizolyacionnye zvukopogloshchayushchie. Tekhnicheskie usloviya TU BY 391129716.001-2015. – Vved. 27.07.2015. – Orekhovsk, 2015. – 10 s.
7. Deryavkina, V. YU. Analiz rynka teploizolyacionnyh materialov / V. YU. Deryavkina, A. V. Erofeev // Aktual'nye innovacionnye issledovaniya: nauka i praktika. – 2015. – № 2. – S. 1.
8. YAkunina, E. A. Sovremennye teploizolyacionnye materialy, kak odna iz tendencij ekologicheskogo stroitel'stva / E. A. YAkunina // Sinergiya nauk. – 2018. – № 24. – S. 625–634.
9. Development and investigation of thermal insulation from hemp-polylatide fibres / R. stapulionienė, R. Tupčiauskas, S. Vaitkus, S. Vėjelis // Engineering structures and technologies. – 2016. – № 8 (1). – P. 23–30. – DOI: 10.3846/2029882X.2016.1158127.
10. Mezencev, I. S. Razrabotka stroitel'nogo uteplitelya na osnove volokon tekhnicheskoj konopli / I. S. Mezencev, I. V. Krasina, A. S. Parsanov // Tekhnologii i kachestvo. – 2022. – № 2 (56). – S. 40–45. – DOI: 10.34216/2587-6147-2022-2-56-40-45.
11. Manohar, K. Building Thermal Insulation – Biodegradable Sugarcane and Coconut Fiber / K. Manohar, David W. Yarbrough, G. S. Kochhar // Journal of Thermal Envelope and Building Science. – 2000. – № 23 (3). – P. 263–276. – DOI: 10.1177/174425910002300308.
12. Kimur, R. Development of Thermal Insulation Material Using Coconut Fiber to Reuse Agricultural Industrial Waste / R. Kimura, M. Ohsumi, L. Susanti // International Journal on Advanced Science Engineering and Information Technology. – 2018. – № 8 (3). – P. 805–810. – DOI: 10.18517/ijaseit.8.3.4610.
13. Hassan, S. Somparison study of thermal insulation characteristics from oil palm fibre / S. Hassan, A. Tesfamichael, M. Mohd Nor // MATEC Web of Conferences. ICPER 2014 - 4 th International Conference on Production, Energy and Reliability. – 2014. – Vol. 13. – DOI: 10.1051/matecconf/20141302016.
14. Manohar, K. Renewable Building Thermal Insulation – Oil Palm Fibre / K. Manohar // International Journal of Engineering and Technology. – 2012. – Vol. 2. – № 3. – P. 475–479.
15. Ibrahim, S. H. Thermal Performance of Oil Palm Fibre and Paper Pulp as the Insulation Materials / S. H. Ibrahim, W. K. Sia, A. Baharun // I UNIMAS e-Journal of Civil Engineering. – 2014. – № 5. – P. 22–28.
16. An environment-friendly thermal insulation material from cotton stalk fibers / X. Zhou [et al.] // Energy and Buildings. – 2010. – № 42. – P. 1070–1074. – DOI: 10.1016/j.enbuild.2010.01.020.

17. Muthukumar, K. Investigation of thermal conductivity and thermal resistance analysis on different combination of natural fiber composites of Banana, Pineapple and Jute / K. Muthukumar, R. V. Sabariraj, S. Dinesh Kumar [et al.] // Materials Today: Proceedings. − 2019. – DOI: 10.1016/j.matpr.2019.09.140.
18. Manohar, K. A Comparison of Banana Fiber Thermal Insulation with Conventional Building Thermal Insulation / K. Manohar, A. Adeyanju // British Journal of Applied Science & Technology. – 2016. – № 17 (3). – P. 1–9. – DOI: 10.9734/BJAST/2016/29070.
19. Materialy i izdeliya stroitel'nye teploizolyacionnye. Metody ispytanij : GOST 17177-94. – Vzamen GOST 17177-87. – Vved. 22.08.1995. – Minsk : Minstrojarhitektury, 1996. – 40 s.
20. Materialy i izdeliya stroitel'nye. Metody opredeleniya teploprovodnosti pri stacionarnom teplovom rezhime : STB 1618-2006. – Vved. 24.03.2006. – Minsk : Minstrojarhitektury, 2006. – 16 s.
21. Davydenko, N. V. Povyshenie vodostojkosti zhidkogo stekla, primenyaemogo v kachestve vyazhushchego pri proizvodstve teploizolyacionnyh kostrosolomennyh plit / N. V. Davydenko, A. A. Bakatovich // Vestnik Polockogo gosudarstvennogo universiteta. Seriya F, Stroitel'stvo. Prikladnye nauki. − 2015. – № 8. − S. 71−75.
22. Izdeliya stroitel'nye teploizolyacionnye. Metod opredeleniya sorbcionnogo uvlazhneniya : STB EN 12088-2016. – Vzamen STB EN 12088-2008. – Vved. 14.12.2016. – Minsk : Gosstandart, 2016. – 12 s.
23. Izdeliya stroitel'nye teploizolyacionnye. Metod opredeleniya paropronicaemosti : STB EN 12086−2016. – Vzamen STB EN 12086-2007. – Vved. 01.07.2017. – Minsk : Gosstandart, 2017. – 20 s.
24. Romanovskiy, S. A. Effect of Modified Liquid Glass on Absorption Humidity and Thermal Conductivity of Flax Fiber Slabs / S. A. Romanovskiy, A. A. Bakatovich // IOP Conf. Series: Materials Science and Engineering 660 (2019) 012072. – DOI: 10.1088/1757-899H/660/1/012072.
25. Davydenko, N. V. Teploizolyacionnye plity na osnove othodov rastenievodstva i neorganicheskogo vyazhushchego: avtoref. diss. kand. tekhn. nauk : 05.23.05 / Davydenko Nadezhda Vladimirovna. – Novopolock, 2016. – 28 s.
26. Bakatovich, A. A. Ocenka effektivnosti primeneniya volokon kory evkalipta kak strukturoobrazuyushchego materiala dlya teploizolyacii po pokazatelyu sorbcionnoj vlazhnosti / A. A. Bakatovich, R. L. Obrompal'skij // Arhitekturno-stroitel'nyj kompleks: problemy, perspektivy, innovacii : elektronnyj sbornik statej IV Mezhdunar. nauch. konf., Novopolock, 20–21 apr. 2022 g. / Poloc. gos. un-t im. Evfrosinii Polockoj; redkol.: D. N. Lazovskij (predsed.) [i dr.]. – Novopolock : Poloc. gos. un-t im. Evfrosinii Polockoj, 2022. – S. 78–83.
27. Bakatovich, A. A. Izolyacionnye kompozity na osnove smesi risovoj luzgi i solomy / A. A. Bakatovich, I. CHzhan, F. Gaspar // Vestnik Polockogo gosudarstvennogo universiteta. Seriya F, Stroitel'stvo. Prikladnye nauki. – 2022. – № 14. – S. 2–9. – DOI: 10.52928/2070-1683-2022-32-14-2-9.

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ANALYSIS ON THERMAL STRESS OF ULTRA-LONG BASEMENT BASED ON XFEM AND STRESS TRAJECTORY VISUALIZATION

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Abstract

Research is conducted on the cracking problem of the side walls of ultra-long seamless basement structures under high-temperature and sunny construction environments in summer. Long term temperature monitoring was conducted on a basement under construction in the Modern Service Industry Park of Honggutan District, Nanchang City. The temperature field was simulated using the commercial finite element software Abaqus, and the measured results were compared with the simulation results to verify the rationality of the theory of simulating the temperature field of sunlight. Based on the theory of simulating the temperature field of sunlight, numerical simulation experiments were conducted using the Extended Finite Element Method (XFEM) to analyze the temperature and stress fields of complete basement structures of different lengths in high-temperature sunlight environments. The differences in stress and critical cracking temperature difference of basement side walls of different lengths under the same temperature field were compared. Abaqus software was redeveloped using a principal stress trajectory visualization program written in Python, and a complete principal stress trajectory diagram of the basement structure was drawn. The analysis results show that under the same temperature gradient, the change in basement length has no significant effect on the magnitude of the principal stress on the side walls. The critical temperature difference between the upper and lower parts of the basement that caused the side wall to crack did not change significantly. Under the effect of uneven expansion, the crack shape of the basement side wall is in the shape of a "八". In high-temperature construction environments, the temperature rise of the basement ceiling should be carefully monitored to avoid excessive temperature differences between the upper and lower parts of the structure, which may cause the side walls to crack.

Keywords: reinforced concrete basement, sunshine temperature field, crack control, extended finite element method, principal stress trajectory, post-cast strip.

АНАЛИЗ ТЕРМИЧЕСКОГО НАПРЯЖЕНИЯ УЛЬТРАДЛИННОГО ПОДЗЕМНОГО СООРУЖЕНИЯ НА ОСНОВЕ XFEM И ВИЗУАЛИЗАЦИИ ТРАЕКТОРИИ НАПРЯЖЕНИЙ

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Реферат

Исследуется проблема растрескивания боковых стен ультрадлинных бесшовных подземных конструкций в условиях высокой температуры и солнечного освещения летом. Долгосрочный мониторинг температуры проводился на подземном сооружении, строящемся в Современном сервисном индустриальном парке района Хунгутан города Нанчанг. Температурное поле моделировалось с использованием коммерческого программного обеспечения конечных элементов Abaqus, а измеренные результаты сравнивались с результатами моделирования для проверки обоснованности теории моделирования температурного поля солнечного света. На основе теории моделирования температурного поля солнечного света были проведены численные симуляционные эксперименты с использованием Расширенного метода конечных элементов (XFEM) для анализа температурных и напряженных полей полноразмерных подземных конструкций различной длины в условиях высокой температуры солнечного света. Сравнивались различия в напряжении и критическая температура растрескивания боковых стен подземных сооружений различной длины при одном и том же температурном поле. Программное обеспечение Abaqus было дополнительно разработано с использованием программы визуализации траектории главных напряжений, написанной на Python, и был составлен полный диаграмма траектории главных напряжений подземного сооружения. Результаты анализа показывают, что при одинаковом температурном градиенте изменение длины подземного сооружения не оказывает значительного влияния на величину главного напряжения на боковых стенах. Критическая температура между верхней и нижней частями подземного сооружения, вызывающая растрескивание боковых стен, не изменялась значительно. Под действием неравномерного расширения форма трещины боковой стены подземного сооружения принимает вид «八». В условиях высокой температуры строительства необходимо тщательно контролировать повышение температуры потолка подземного сооружения, чтобы избежать чрезмерных температурных различий между верхней и нижней частями конструкции, что может вызвать растрескивание боковых стен.

Ключевые слова: железобетонное подземное сооружение, температурное поле солнечного света, контроль трещин, расширенный метод конечных элементов, траектория главного напряжения, постформировочная лента.

Introduction

Due to its excellent ability to utilize urban space, the structural form of "upper high-rise buildings + large area basements" has become the mainstream form of urban space development in China today. Especially the ultra-long seamless basement structure, due to its good overall integrity, ability to shorten construction period and improve engineering efficiency, is increasingly being applied in engineering [1]. Along with it comes the serious problem of crack control. Cracks on the exterior walls of the basement can cause problems such as water leakage, steel corrosion, and difficulty in repair, which in turn affect the durability and safety of the overall structure. In the past, the mainstream research on this topic both domestically and internationally was focused on the early hydration heat and temperature shrinkage of concrete [2–8]. In recent years, research on the temperature field of various concrete structures under sunlight has become increasingly common. Zhang Hanshuo et al. conducted long-term temperature field monitoring on the ultra-long concrete structure of the newly built station building at Xiamen North Railway Station. Their method of considering both the early hydration heat release of concrete and the influence of sunlight radiation in the thermal mechanical coupling finite element simulation provides a reference for related research [9]. The same numerical simulation theory of sunshine temperature field is also applicable to the analysis of structures such as concrete beam bridges, hydraulic concrete structures, and concrete basements [10, 11].

Long term engineering practice has shown that the cracking problem of basement structural side walls during summer construction is particularly severe in the vast southern regions of China. The basement structure constructed in a high-temperature sunlight environment can reach a surface temperature of over 60 degrees Celsius due to the long-term exposure of the roof to direct sunlight after demoulding and before backfilling the foundation pit. The bottom plate is located on the soil and is not affected by sunlight, resulting in a lower temperature. Under the influence of a large temperature gradient between the upper and lower parts of the structure, there will be significant differences in thermal expansion deformation. The upper part of the basement has a large amount of thermal expansion deformation, while the lower part has a small amount of thermal expansion, and the side walls are easily torn. This is the phenomenon of side wall cracking caused by the uneven expansion effect of the structure, and there is currently no relevant research on this aspect. Considering the differences between the problem of uneven expansion of concrete basements under temperature gradient and other temperature effects, there are two issues worth further discussion:

1. Will uneven expansion effect lead to cracking of side walls? There are many factors that affect the cracking of ultra-long basement structures, and the mechanism of uneven expansion effect induced cracking is not yet clear. There is still insufficient research on the differences in cracking morphology compared to other types of cracking.

2. The quantitative relationship between the magnitude of thermal stress generated by the temperature gradient between the upper and lower parts of the structure and the length of the basement is not yet clear.

In response to the above two issues, this article first conducts long-term temperature field monitoring of a basement project under construction in Nanchang City, Jiangxi Province, and uses concrete sunlight temperature field simulation theory to finely model and analyze the structure. The comparison between simulated data and measured results verified the rationality of the simulation theory. Then, based on this theory, the powerful function of the extended finite element method (XFEM) in simulating discontinuous problems such as interface development and crack growth is utilized for parameter analysis, and the crack morphology of the sidewall is predicted [12]. And the Abaqus software was further developed using a Python script editing program to draw the principal stress trajectory diagram of complete basement structure. Identify the cracking morphology and mechanism of basement side walls under the effect of uneven expansion. To investigate the quantitative relationship between the length of the basement and the critical temperature difference between the upper and lower parts that causes side wall cracking, in order to adopt different degrees of temperature control measures for basements of different lengths, and provide theoretical reference for similar crack control problems in practical engineering.

1 Simulation theory of concrete sunshine temperature field

There are three main ways of heat transfer in basement structures under sunlight conditions: heat conduction, heat convection, and heat radiation [13, 14, 15].

1.1 Heat conduction simulation

Heat conduction refers to the transfer of heat from the higher temperature parts of concrete to the lower temperature parts, and is the main way of heat transfer in solids, defined in the Abaqus material properties. According to Fourier's law $q_x'' = -k\frac{dT}{dx}$, under a constant temperature gradient, the heat transfer rate is proportional to the thermal conductivity of the material. Liu Xingfa et al. found that the range of thermal conductivity values for concrete materials is 1.16~3.5J/(m·s·K) [14]. The value obtained by Liu Cheng and others through thermal performance testing is 3.0J/(m·s·K) [16]. Article 4.1.8 of the "Code for Design of Concrete Structures" GB 50010-2010 states that when the temperature is within the range of 0 °C to 100 °C, the thermal conductivity of concrete can be set as 10.6kJ/(m·h·°C), which is 2.94J/(m·s·K) [17].

For the specific heat capacity of concrete, the range of values given in Appendix B.1 of the "Code for Thermal Design of Civil Building" GB 50176-2016 is 920~1050J/(kg·K) [18]. The recommended range of values given by Liu Xingfa and others after research is 879~1090J/(kg·K) [14].

1.2 Heat convection simulation

In the temperature field of concrete exposed to sunlight, convective heat transfer is the situation where the temperature of the concrete structure is driven by the increase in air temperature. Thermal convection simulation is defined in the Abaqus interaction module according to the "surface film condition". To define the thermal convection load conditions of concrete basement structures, it is necessary to measure or simulate the ambient temperature hourly. In the absence of hourly temperature monitoring data, the daily temperature model proposed by Liu Cheng et al. can be approximately used to simulate changes in external atmospheric temperature [16]. The specific calculation formula for environmental temperature $T_a(t)$ is shown in equation (1):

$$T_a(t)=\begin{cases}\dfrac{T_{\max}+T_{\min}}{2}-\dfrac{T_{\max}-T_{\min}}{2}\dfrac{t-t_{sr}+t_{night}}{t_{night}} & 0\le t\le t_{sr}\\ \dfrac{T_{\max}+T_{\min}}{2}-\dfrac{T_{\max}-T_{\min}}{2}\cos\left(\dfrac{3\pi}{2}\dfrac{t-t_{sr}}{t_{day}}\right) & t_{sr}\le t\le t_{ss}\\ T_{\max}-\dfrac{T_{\max}-T_{\min}}{2}\dfrac{t-t_{ss}+t_{night}}{t_{night}} & t_{ss}\le t\le 24\end{cases}. \quad (1)$$

In the formula: T_{max} is the highest daily temperature (°C); T_{min} is the daily minimum temperature (°C); t_{sr} is the sunrise time of the day (h); t_{ss} is the sunset time (h); t_{day} is the duration of daytime (h); t_{night} is the duration of nighttime (h).

1.3 Heat radiation simulation

The effect of solar radiation is one of the main factors causing the temperature rise of concrete structures. Solar radiation (shortwave radiation) can be divided into three categories: direct radiation, atmospheric scattering, and ground reflection, and its intensity is mainly affected by weather conditions such as atmospheric transparency.

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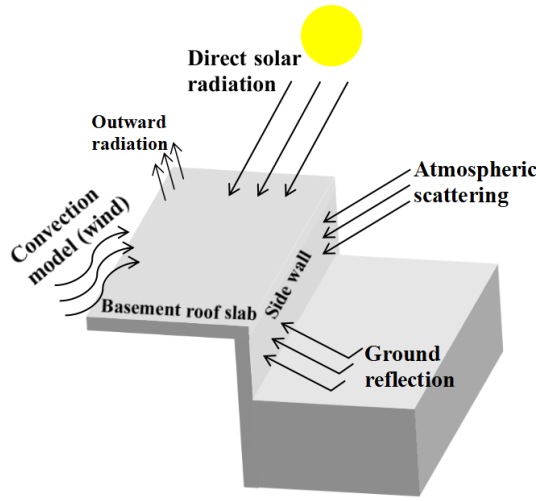


(a) Schematic diagram of sunlight radiation effect

(b) Cracks in the basement shear wall of Jinmei Hainan City project

Figure 1 – Schematic diagram of temperature field and high-temperature cracks in the basement (note: concrete was cast in June 2019, the highest daily temperature during the concrete curing period was 43 °C)

The direct radiation intensity on a plane perpendicular to the direction of solar radiation can be calculated using the following formula [10]

$$I_m = I_0 \frac{\sinh}{\sinh + \frac{1-P}{P}}. \quad (2)$$

In the formula: *h* is the solar altitude angle; *P* is the atmospheric transparency coefficient, which can be obtained by checking the meteorological parameters of the local meteorological station; I_0 is the solar constant. The formula for calculating the solar constant at the upper bound of the Earth's atmosphere on different dates of the year is: $I_0 = 1367\left[1 + 0.033\cos(\frac{360°N}{365})\right]$, *N* is the ordinal number of days in a year starting from January 1st [10]. The empirical estimation formula for scattering intensity on a horizontal plane is:

$$I_d = I_m(1 - 1.13K_T). \quad (3)$$

In the formula, K_T is the coefficient of clear sky, which can be taken as 0.3~0.8 for cities in the latitude range of 30°~40° in China, and 0.8~1.0 for other latitude regions. There is a linear relationship between the ratio of daily average scattering and average total radiation on the horizontal plane and the clear sky coefficient [10].

The calculation formula for the intensity of reflected radiation received by a receiving surface inclined to the ground is:

$$I_f = \rho^*(I_m + I_d)(1 - \cos\beta)/2. \quad (4)$$

In the formula, ρ^* is the ground reflection coefficient, which can be taken as 0.1 for general ground and 0.2 for water surface reflection [10]. Thermal radiation simulation is defined by surface heat flux in the Abaqus load module. By applying the above radiation loads and convective loads, combined with thermal performance parameters such as thermal conductivity and specific heat capacity, and reasonably setting the predefined temperature field of the model, the simulation of the temperature field of concrete structures under sunlight can be achieved.

2 Simulation and Monitoring of Temperature Field in the Basement of Nanchang Modern Service Industry Park

2.1 Overview of Concrete Basement Structure

This chapter establishes an Abaqus refined model based on the basement of Building 8 in Nanchang Modern Service Industry Park, and uses the sunlight temperature field simulation method described in the previous section to analyze the heat transfer of the basement model. Compare the results obtained from finite element method simulation with the measured temperature field data, analyze the basic characteristics of the sunshine temperature field, and verify the rationality of the sunshine temperature field simulation theory.

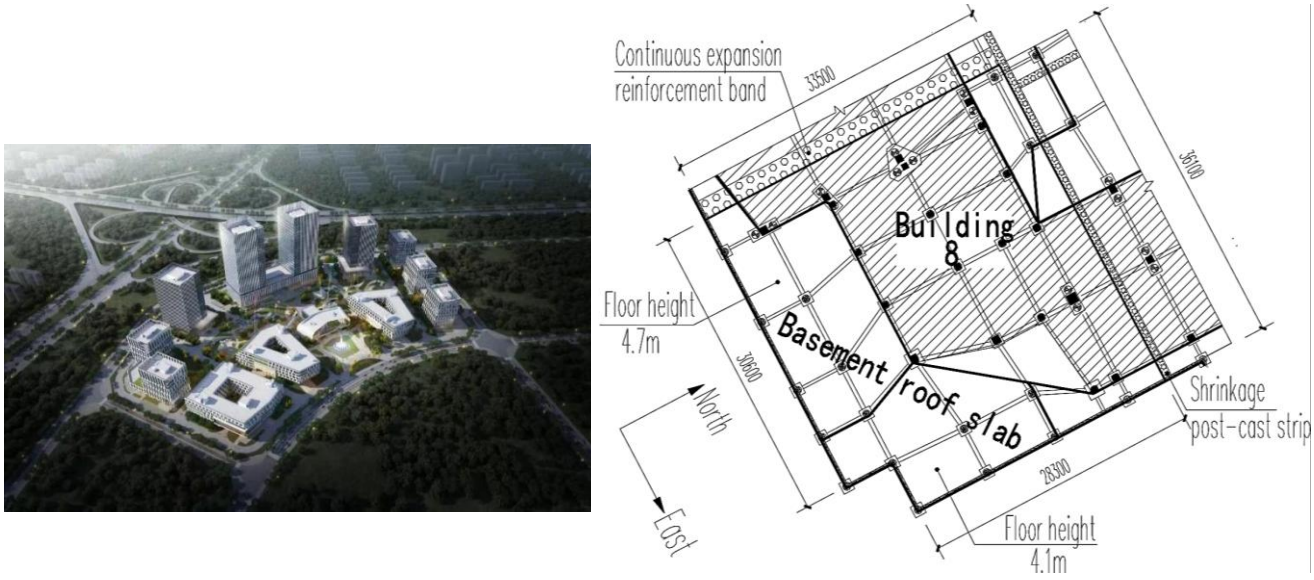
Nanchang Modern Service Industrial Park is located in Honggutan District, with a total construction area of approximately 330000 square meters. The basement below Building 8 is a reinforced concrete shear wall structure basement, and a section of the basement located between the continuous expansion strip and the shrinkage post-cast strip at the southeast corner of the basement was selected as the monitoring object. The selected section is 36.1 m long from east to west and 33.5 m wide from north to south. The basement roof on the west side has a higher floor height, with structural floor heights of 4.1 m and 4.7 m respectively. The concrete strength grade is C35. The basic overview of the industrial park and the monitoring locations in the basement are shown in Figure 2.

2.2 Overview of basement temperature field monitoring system

This experiment used the DH2002 online monitoring and analysis system to collect temperature data from the JCJ100TW temperature sensor, with a collection interval of 1 second, and conducted uninterrupted temperature field monitoring for a period of 2 months. To obtain the distribution pattern of temperature field in the underground structure, a total of 28 monitoring points were set up in the monitoring area of the basement, including 10 on the roof, 9 on the side walls 1 and 2 respectively, and temperature sensors on the outer, middle, and inner layers along the thickness direction of the concrete structure were installed at measuring points 4, 5, 6, 8, 12, 15, 18, 21, 24, and 27. The temperature sensors located on the outer and inner layers are 20 mm away from the outer and inner surfaces of the concrete structure, respectively. The temperature sensor located in the middle layer is placed at half the thickness of the concrete structure, while the sensors at other measuring points are arranged in the outer concrete. The layout of the measuring points is shown in Figure 3 (a), and the thermometer is fixed to the rebars at the measuring point position using zip ties as shown in Figure 3 (b).

2.3 Analysis of Finite Element Modeling and Temperature Field Simulation Results

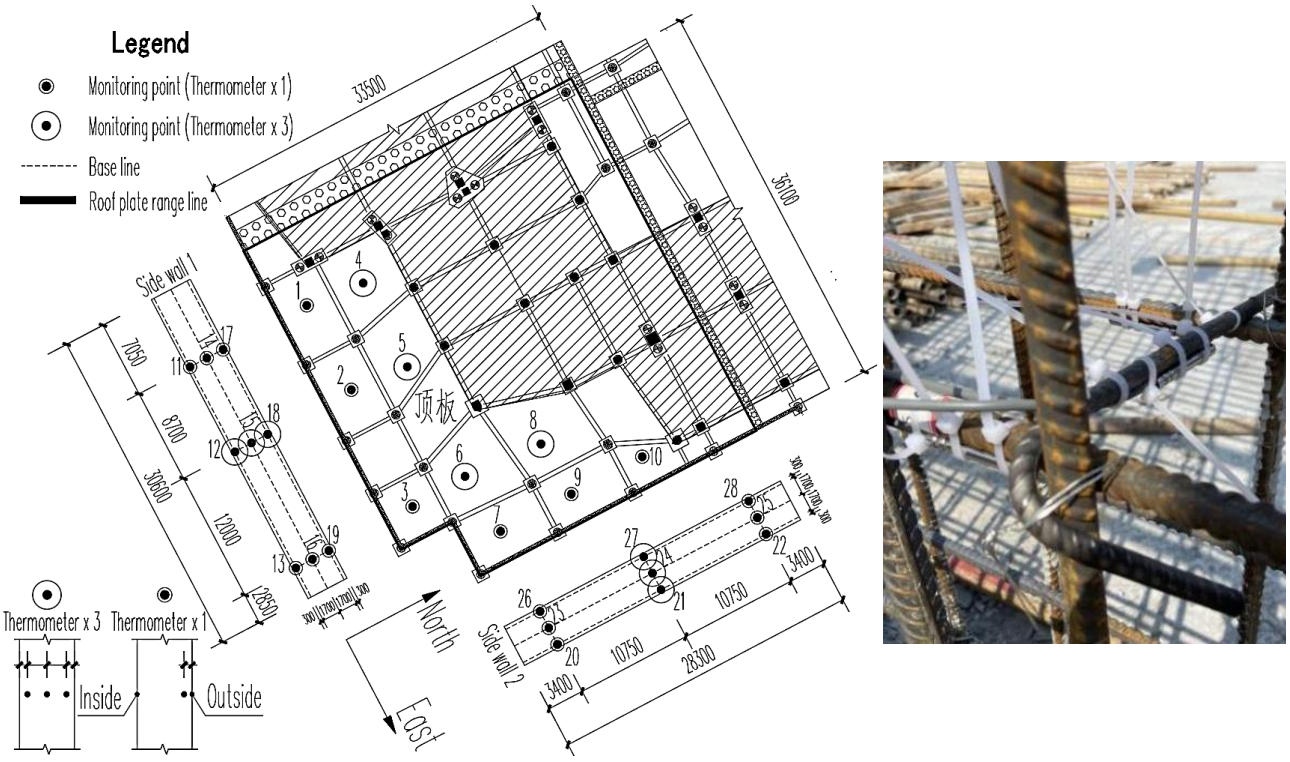
The basement structure of the monitoring area was poured on October 6, 2023. On October 23, partial soil backfilling was carried out on the outer side of the side walls. The east and south walls (at different heights of the basement structure) were exposed to the ground surface at a height of 1 m and 1.6 m, respectively. Select October 29 to October 31, 2023 as the temperature field simulation period, and establish an Abaqus refined finite element model as shown in Figure 4. The model is modeled using solid elements, and the material property parameters are shown in Table 1. The model mesh element type is C3D8RT eight node thermally coupled hexahedral structured element.



(a) Rendering of the completed park

(b) Layout plan of basement structure at monitoring location

Figure 2 – Project overview diagram



(a) Layout of basement temperature measurement points

(b) Temperature sensor binding method diagram

Figure 3 – Temperature Sensor Layout

Table 1 – Material Property Parameter Values

Property (unit: h)	Concrete grade	Density (kg/m³)	Thermal conductivity coefficient (J/h·m·°C)	Specific heat (J/kg·°C)	Thermal expansion coefficient (1/°C)	Young's modulus (GPa)	Poisson's ratio
	C35	2500	9180	930	0.00001	31.5	0.2

The atmospheric temperature data for 72 hours from October 29th to 31st, 2023 in Honggutan District, Nanchang City, obtained from the Xihe Energy Meteorological Big Data Platform, is shown in Figure 5 (a). Using the radiation load simulation theory described in the previous section, the radiation amount borne by the surface of the structure for three consecutive days was simulated, and the results are shown in Figure 5 (b) [19]. Apply heat convection and radiation load conditions to the model for heat transfer simulation analysis.

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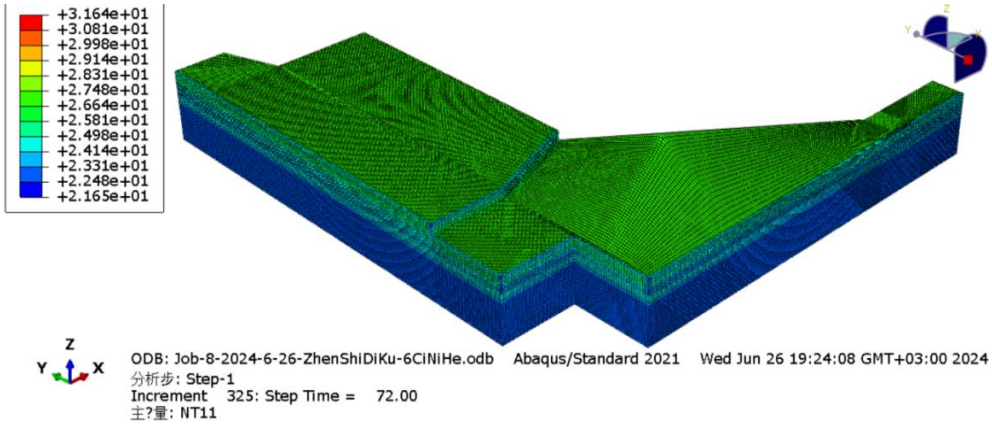
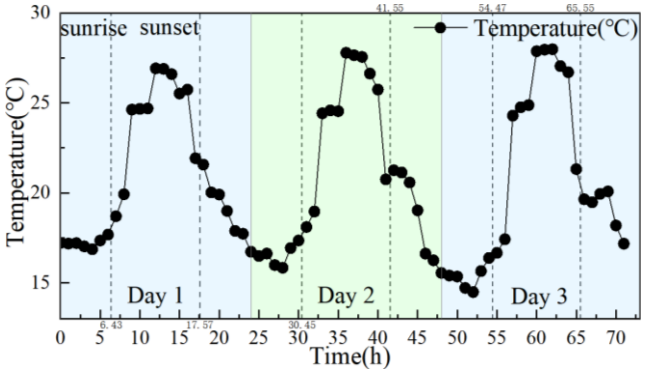
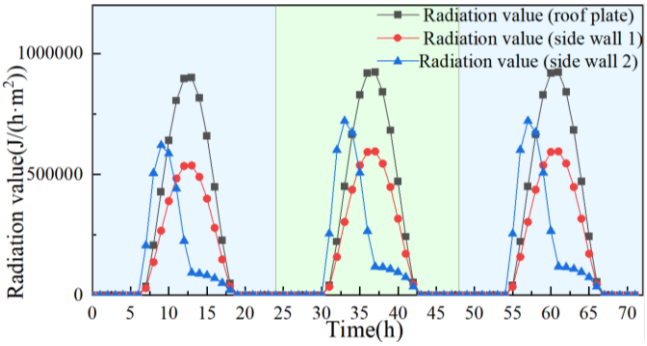


Figure 4 – Finite element model for basement heat transfer analysis (Grid size 0.15 m × 0.15 m × 0.15 m, with 65418 units; CPU: Intel (R) Core (TM) i7-8750H, 6 cores and 12 threads; System memory 8 GB, hard drive 1TB, computing time: 19 min 53 s)



(a) Atmospheric temperature variation curve



(b) Fitting curve of radiation exposure on top slab and side walls

Figure 5 – Temperature Load Simulation Data (Note: The temperature is taken from the instrument shelter located about 1.5–2 m above the ground)

Compare the temperature field simulation results with the measured data at measuring points 9, 18, 19, 28, and 4. The temperature curve comparison results are shown in Figure 6. As can be seen from the results, temperature undergoes tidal changes with sunrise and sunset. Along the thickness direction, there is a temperature gradient inside the component, and as the distance from the structure increases to the depth of the heated outer surface, the temperature change exhibits a more pronounced "hysteresis". Due to the rise and fall of the sun in the east and west, as well as the location of buildings, temperature peaks of components in different orientations alternate. The above three points are significant characteristics that distinguish the high-temperature sunlight temperature field from other temperature fields such as structural hydration heat temperature field and indoor heat source temperature field.

The temperature simulation results of the basement structure are basically consistent with the measured results. However, due to the presence of tall buildings under construction on the west side of the basement in real construction sites, as well as different levels of construction material accumulation on the basement roof, inconsistent radiation absorption intensity of various parts of concrete components, and many complex influencing factors, there are certain discrepancies between simulation results and actual measurement results. The most significant difference is that the temperature distribution of the same part (such as the outer surface) of the same component (such as the top plate) in real structures is uneven, while the finite element model results are uniform. This is due to the finite element model appropriately simplifying the model and influencing factors within a reasonable range. Overall, the error is within an acceptable range, and the temperature change trend of numerical simulation results is consistent with the measured results. The simulation theory of sunshine temperature field proposed earlier is reasonable and feasible.

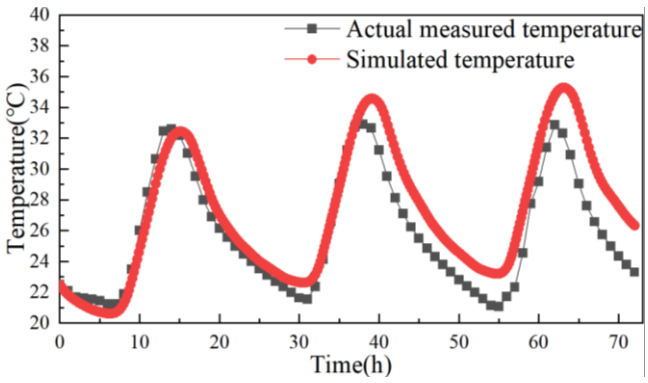
3 XFEM numerical simulation analysis

3.1 Extended Finite Element Theory

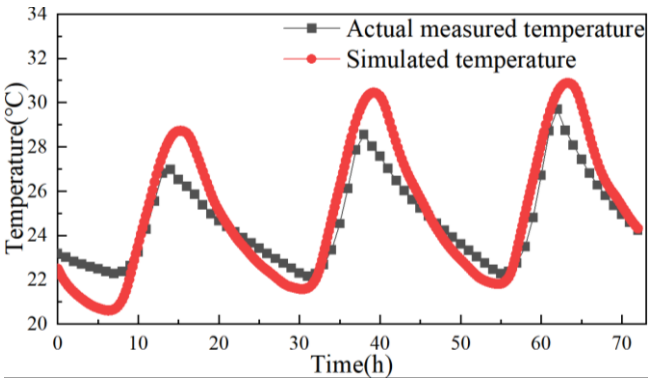
To study the quantitative relationship between the length of concrete structures and the critical temperature difference for side wall cracking, it is necessary to simulate crack growth in a refined finite element model. Considering the brittle characteristics of concrete materials, the XFEM method is based on the theory of linear elastic fracture mechanics and adopts the first strength theory (maximum principal stress criterion) as the criterion for identifying concrete damage (cracking). According to equation (5), pure compressive stress (with negative σ_{max}) will not cause cracking damage, and when f reaches 1, damage (cracking) begins to trigger. Where σ_{max} is the maximum principal stress value of concrete, $\sigma^0_{\max}$ is the maximum allowable stress, and " $\langle\,\rangle$ " is the Macaulay bracket [20].

$$f = \left\{ \frac{\langle \sigma_{\max} \rangle}{\sigma^0_{\max}} \right\}. \quad (5)$$

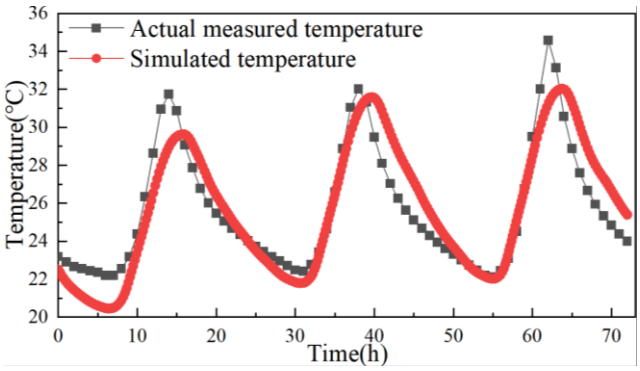
The extended finite element method determines whether the element is damaged by setting the parameters of the traction-separation law. Set the side wall as the crack propagation area, take the maximum allowable stress as its axial tensile strength characteristic value f_{tk} = 2.2 MPa [21, 22]. According to the fracture energy results of crushed stone concrete measured by Jia Yandong et al. using the wedge splitting method, the fracture energy of concrete is approximately 150~200N/m when the compressive strength value of the concrete cube at 28 days is f_{cu} = 35 MPa. In order to fully develop cracks and highlight the characteristics of crack morphology, the fracture energy of C 35 concrete is taken as 150 N/m [23]. The analysis only considers the propagation of side wall cracks under heating conditions, and does not study the situation after the crack interface closes during the cooling process. Abaqus calculates the stress (strain) state at the center of mass of the element in front of the crack and determines whether the damage initiation criterion has been reached, thereby determining the direction of crack propagation.



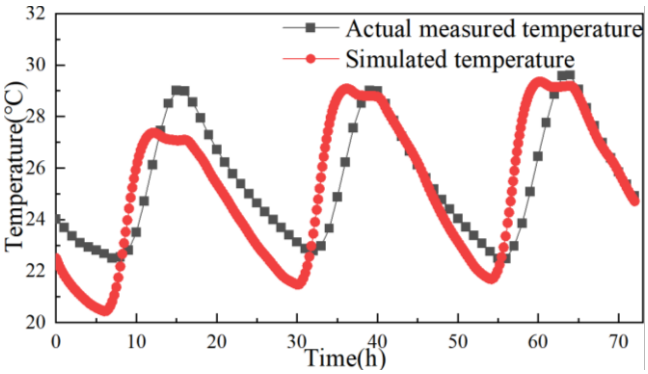
(a) Measurement point 9



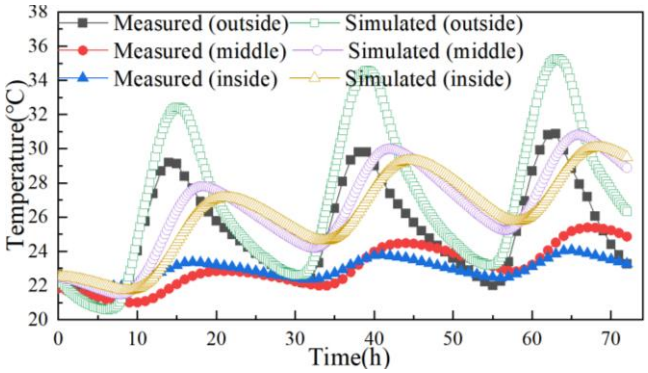
(b) Measurement point 18



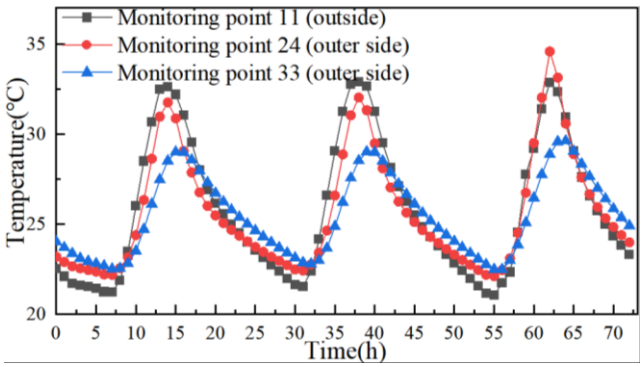
(c) Measurement point 19



(d) Measurement point 28

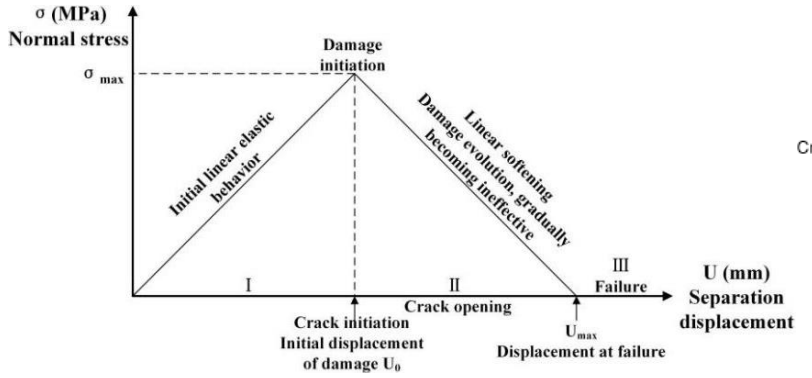


(e) Measurement point 4 (outer, middle, inner)

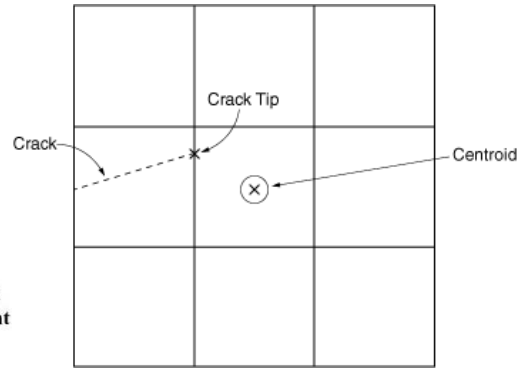


(f) Measurement points 9, 19, 18

Figure 6 – Comparison of Simulation Results of Temperature Field and Measurement Results



(a) Bilinear Traction-Separation Model



(b) Centroid and crack tip locations

Figure 7 – XFEM calculation principle

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3.2 Numerical simulation experiment

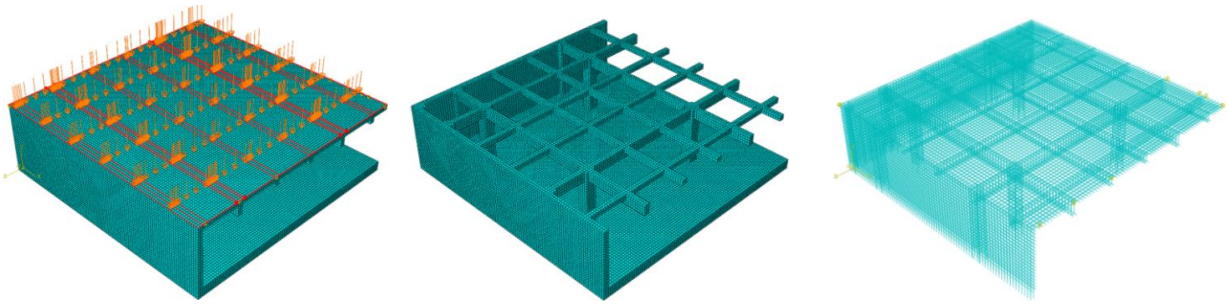
The model adopts a grillage beam floor system and an 8.1 m × 8.1 m large column grid system. The floor height is 3.9 m, the top plate is 30 cm thick, and the side walls are 30 cm thick. The bottom plate adopts a flat raft foundation with a thickness of 60 cm. Column section size: 600 mm × 600 mm, main beam section size: 900 mm × 300 mm, secondary beam section size: 600 mm × 300 mm. The rebars of the roof and side walls are arranged in an C20@200 form.

Ultra-long seamless structure refers to reinforced concrete structures where the spacing between expansion joints and post-cast strips exceeds the maximum spacing specified in the codes. According to Article 12.2.3 of the "Technical specification for concrete structures of tall building", a post construction pouring strip (joint), which connect the top plate, bottom (plate) and wall panels, can be installed every 30–40 meters in the basement of high-rise buildings [24]. Therefore, based on a 30 m basement, keeping the structural form unchanged and increasing the length of the basement, a numerical simulation experimental group was set up as shown in Table 2. To improve computational efficiency, the 1/4 modeling method is adopted for modeling. Taking the 30 m basement as an example, the refined structural model is shown in Figure 8.

Select the temperature and sunshine radiation curve of Nanchang City on August 4, 2023 as the model load, and the load curve is shown in Figure 9. To control variables, only consider the situation where the roof is affected by sunlight. Concrete and rebar modeling are respectively three-dimensional solid and solid line elements. Using a non coupled thermo-mechanical model, apply the temperature field obtained in the first step as a predefined field to the XFEM calculation file in the second step. Each experimental group's XFEM calculation file is calculated twice. The first time does not consider the cracking of the side wall and is used to calculate the stress distribution of the side wall. The second calculation simulates crack propagation to obtain the crack morphology of the side wall and the critical temperature difference between the upper and lower parts of the basement at the time of cracking.

Table 2 – Numerical Simulation Experiment Group Settings

Group.No	Model form	Length of basement (m)	Environmental temperature load
1	Plain concrete	30	Temperature and radiation curve on August 4, 2023
	With rebars		
2	Plain concrete	46.2	
	With rebars		
3	Plain concrete	62.4	
	With rebars		
4	Plain concrete	78.6	
	With rebars		
5	Plain concrete	94.8	
	With rebars		



(a) Concrete structure model (b) Structural beam column system (c) Rebars model

Figure 8 – Fine grained model of 30m basement (1/4 model, with 120056 units)

In the temperature field calculation steps, the concrete and steel mesh elements are respectively an eight node linear heat transfer element (DC3D8R) and a two node heat transfer connection element (DC1D2). In the XFEM thermal stress crack calculation steps, the concrete and steel mesh elements are respectively an eight node linear hexahedral element (C3D8R) and a two node linear three-dimensional truss element (T3D2).

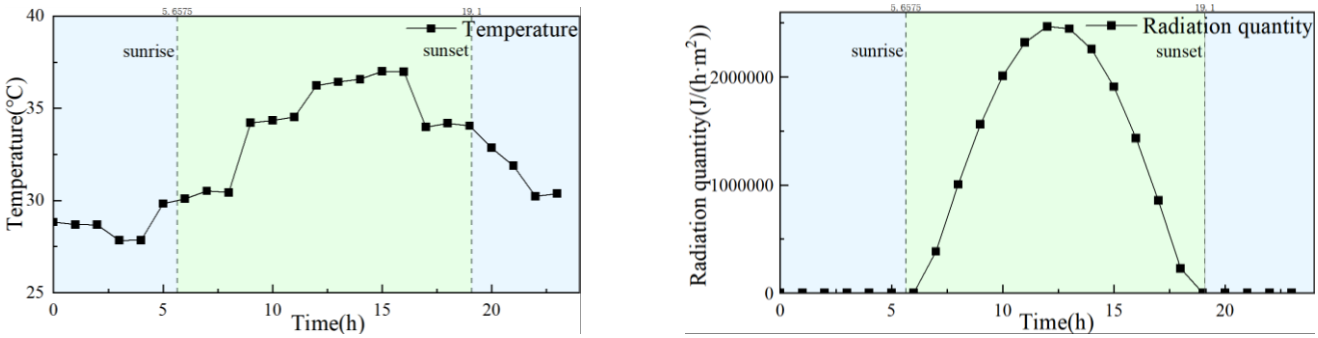


Figure 9 – Atmospheric temperature curve and sunshine radiation fitting curve in Nanchang City on August 4, 2023

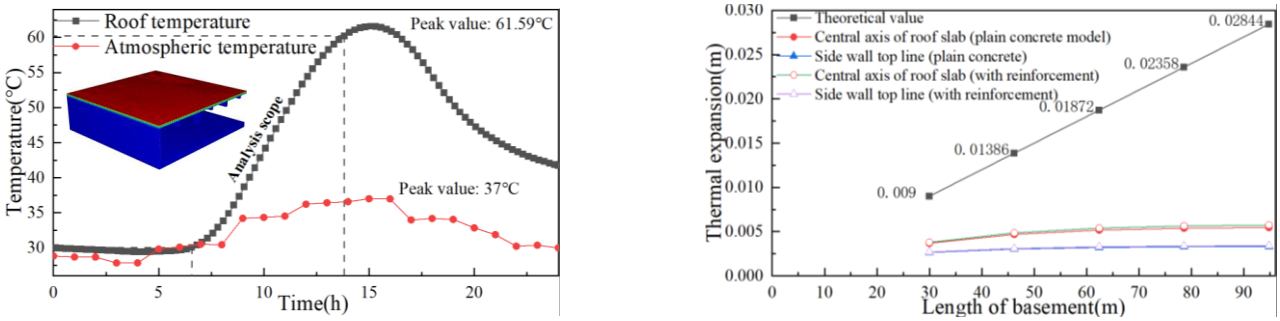
3.3 Simulation result analysis

The temperature load of each experimental group is consistent, and the 24-hour temperature change curve of the top plate surface under the action of temperature changes is shown in Figure 10 (a). Analysis shows that sunlight radiation is the main factor causing significant temperature rise in the roof. For each simulation experiment, select the temperature rise range of the top plate from 30 °C to 60 °C for displacement and stress analysis.

Extract the thermal expansion deformation values of the longitudinal axis of the top plate and the top line of the side walls for each experimental group model, and plot their relationship curves with the length of the basement as shown in Figure 10 (b). According to the one-dimensional linear expansion theory, with $\Delta L = \alpha L(T_1 - T_0)$, the thermal expansion value of the material is proportional to the length L of the material, assuming that the coefficient of thermal expansion α and temperature change (T_1–T_0) remain constant. As the length of the base-

ment increases, the deviation between the maximum thermal expansion values of the central axis of the roof and the top line of the side walls and the theoretical values becomes greater. The thermal expansion values of the central axis of the 30 m reinforced concrete basement roof and the top edge of the side walls are 3.79 mm and 2.69 mm, respectively, which are 42.1 % and 29.89 % of the theoretical values; The thermal expansion values of the central axis and side wall top edge of the 94.8 m reinforced concrete basement roof are 5.74 mm and 3.41 mm, respectively, which are 20.183 % and 11.99 % of the theoretical values.

As the length of the basement increases, the number of beam and column components also increases proportionally. The large number of beam column components greatly increases the constraints on the structure, resulting in thermal expansion values far below the estimated values. Therefore, one-dimensional linear expansion theory cannot be used to estimate the magnitude of thermal expansion of basement solid structures.



(a) Surface temperature curve on the top plate (b) Basement thermal expansion displacement curve

Figure 10 – Simulation result curve

Taking the 30 m reinforced concrete basement model as an example, as shown in Figure 11 (a), the basement roof expands in all directions with its geometric center as the expansion origin, with the maximum thermal expansion displacement at the corner of the roof. As shown in Figures 11 (b) and (c), under the effect of uneven expansion, the expansion of the basement roof is constrained by the surrounding side walls and beam column system, resulting in overall compression. The basement side walls are under overall tension, with high stress zones located at one-third on each side. The stress value is 2.2 MPa higher than the characteristic tensile strength value of C35 concrete, indicating the area where cracks develop. The reinforcing bars on the side walls are subjected to high tensile forces. As shown in Figure 11 (e), the crack propagation pattern of the side wall is an "八" – shaped diagonal crack.

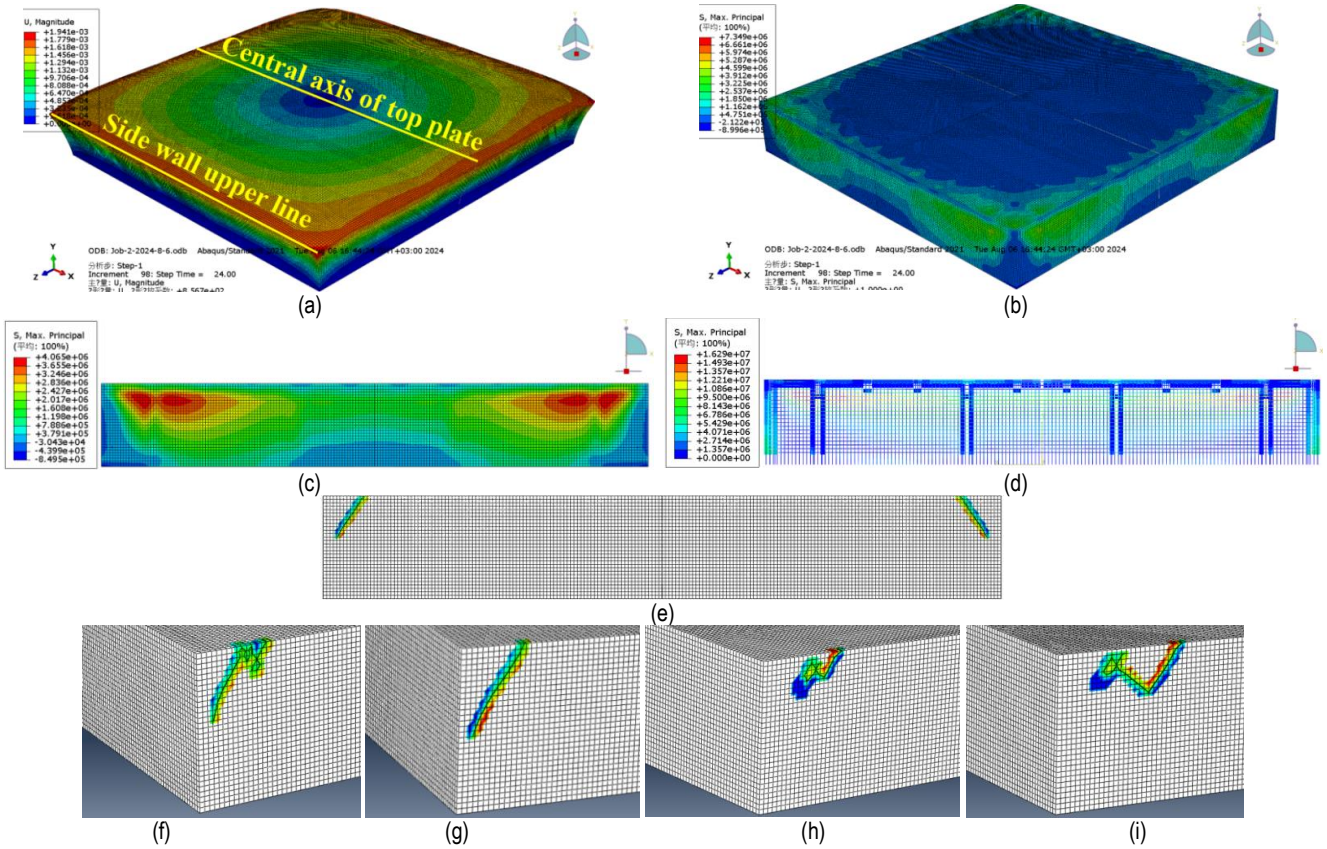


Figure 11 – Finite Element Simulation Results
(a – 30 m basement thermal expansion displacement cloud map; b – 30 m basement first principal stress cloud map; c – side wall concrete first principal stress cloud map; d – Cloud map of the first principal stress of the reinforcing steel bars on the side wall; e – Cracking result of 30 m basement side wall; f – Cracking result of 46.2 m basement side wall; g – Cracking result of 62.4 m basement side wall; h – Cracking result of 78.6 m basement side wall; i – Cracking result of 94.8 m basement side wall)

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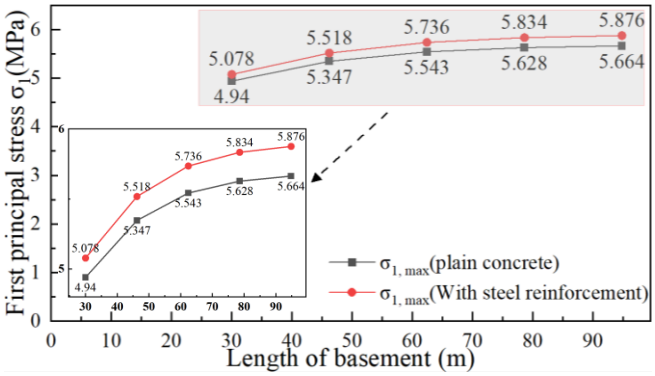
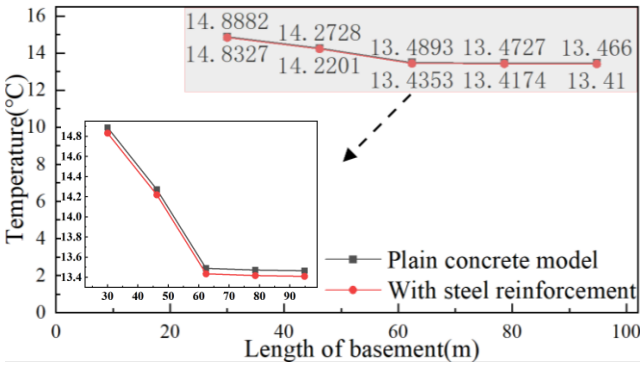
As shown in Figure 12 (a), when the top plate is uniformly heated from 30 °C to 60 °C, the basement model increases by 216 % from 30 m to 94.8 m, while the maximum principal stress of the side walls of the plain concrete model increases by 14.656 %. The maximum principal stress of the reinforced concrete model side wall increased by 15.715 %. The increase in the length of the basement did not cause a significant increase in the side wall σ_1, the length of the basement had little effect on the stress of the side wall. In other words, reducing the stress on the side walls by significantly shortening the length of the basement is of little significance. The maximum stress value of the side walls is not significantly related to the length, and the implementation of ultra-long seamless structures is feasible.

Meanwhile, the addition of steel bars in the model not only did not reduce the stress in the concrete, but also slightly increased the stress on the side walls. This is because the thermal expansion coefficient of steel bars is larger than that of concrete, and the thermal expansion effect of the top plate after reinforcement is more severe, resulting in an increase in the stress on the side walls.

As shown in Figure 12 (b), due to the slight increase in the principal stress σ_1 of the side wall with the length of the basement, the critical temperature difference for cracking of the side wall slightly decreases. The length of the basement increased by 216 %, and the critical temperature difference for cracking decreased by 9.553 % (plain concrete) and 9.592 % (reinforced concrete), indicating that under the same temperature rise conditions, the length of the basement has a relatively small impact on the critical temperature difference for side wall cracking. The curves of the plain concrete basement and the reinforced basement basically coincide, and the addition of steel bars has no significant effect on preventing side wall cracking.



(a) Basement length-side wall first principal stress curve



(b) Basement length-side wall cracking critical temperature difference curve

Figure 12 – Simulation result curve

4 Visualization of thermal stress trajectory in basement

The principal stress trajectory can display the load transfer path and reveal the potential direction of crack propagation. Most general finite element software currently cannot provide a complete structural stress trace diagram. Therefore, this article uses Python language to perform secondary development on Abaqus to obtain a complete principal stress trajectory diagram of the basement structure [25–28]. The idea is shown in the following Figure 13.

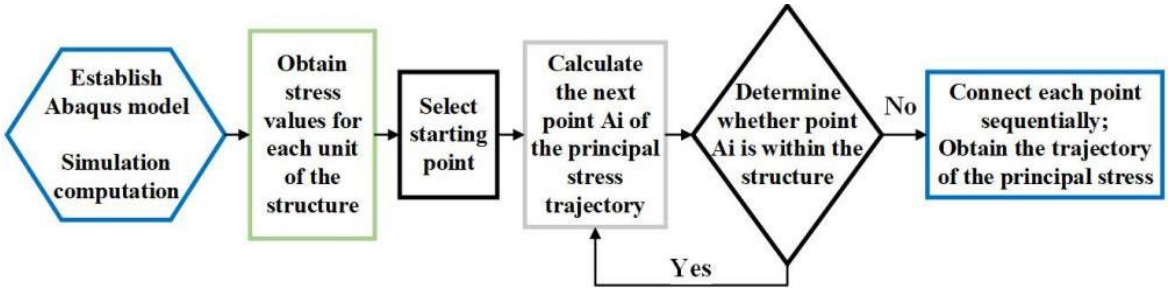


Figure 13 – Flow Chart for Automatic Drawing of Principal Stress Trajectory

The key point is to determine the direction cosine values l_i, m_i, n_i (I = 1, 2, 3) corresponding to the three principal stresses σ_i at any given point given the stress state σ_x, σ_y, σ_z, τ_{xy}, τ_{yz}, τ_{zx}. After knowing the cosine value of the direction of the point, the coordinates of the next point can be calculated based on a certain calculation step, and this process repeats itself. Solve equations (6) and (7) simultaneously. Using the cosine calculation formula of the principal stress direction provided by Wang Junbiao, the following equation is shown [29]:

$$\left.\begin{aligned}(\sigma_x-\sigma_i)l_i+\tau_{xy}m_i+\tau_{zx}n_i=0\\ \tau_{xy}l_i+(\sigma_y-\sigma_i)m_i+\tau_{yz}n_i=0\\ \tau_{zx}l_i+\tau_{yz}m_i+(\sigma_z-\sigma_i)n_i=0\end{aligned}\right\}. \quad (6)$$

$$l_i^2+m_i^2+n_i^2=1. \quad (7)$$

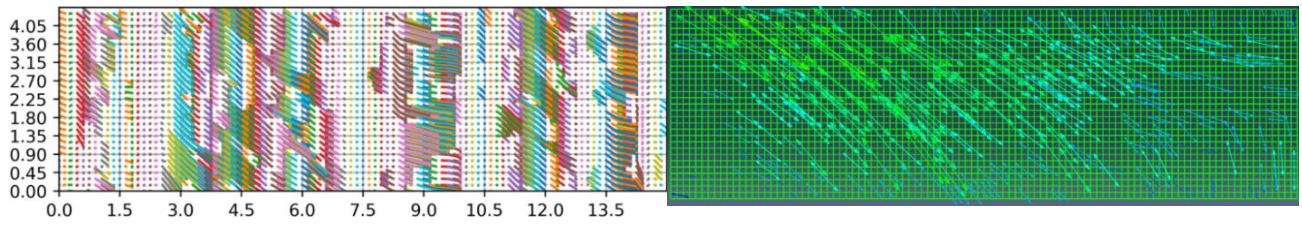
$$\left.\begin{aligned}l_i=\frac{A_i}{\sqrt{A_i^2+B_i^2+C_i^2}}\\ m_i=\frac{B_i}{\sqrt{A_i^2+B_i^2+C_i^2}}\\ n_i=\frac{C_i}{\sqrt{A_i^2+B_i^2+C_i^2}}\end{aligned}\right\}. \quad (8)$$

In the formula: $A_i=\tau_{xy}\tau_{yz}-(\sigma_y-\sigma_i)\tau_{zx}$;

$B_i=\tau_{xy}\tau_{zx}-(\sigma_x-\sigma_i)\tau_{yz}$;

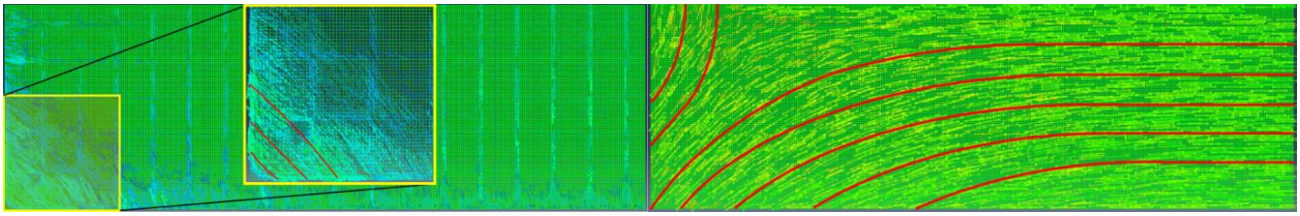
$C_i=(\sigma_x-\sigma_i)(\sigma_y-\sigma_i)-\tau_{xy}^2$.

When the surface temperature of the basement roof is 60 °C, the stress calculation results of the 30 m basement are extracted. Taking the side wall as an example, the first principal stress trajectory is drawn as shown in the following Figure 14.



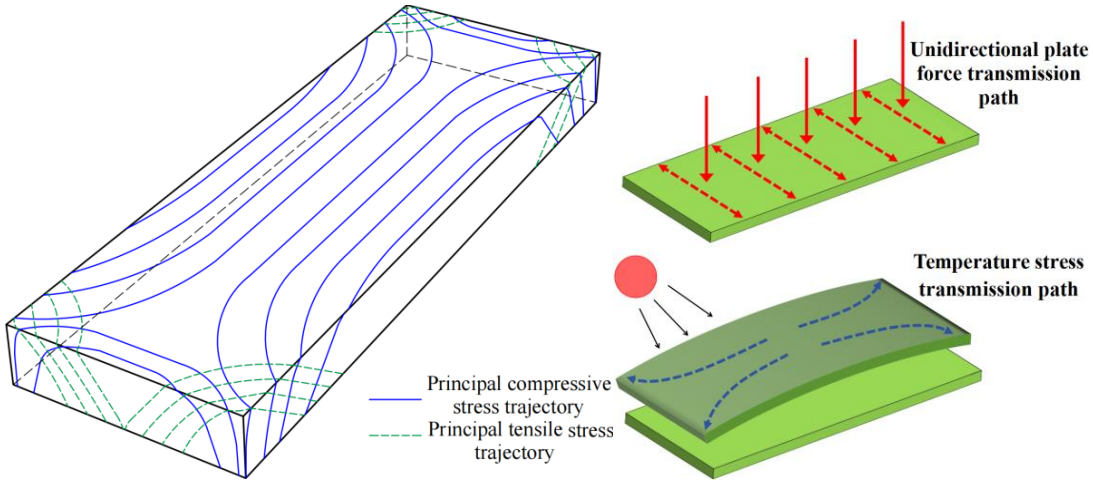
(a) Python script drawing results (b) Abaqus result principal stress vector diagram

Figure 14 – Trajectory diagram of the first principal stress on the 30 m basement side wall (1/2 side wall)



(a) First principal stress vector diagram (b) Third principal stress vector diagram

Figure 15 – Principal stress vector diagram of 94.6 m basement roof (1/4)



(a) Principal stress trajectory of concrete basement (b) Unidirectional plate force transmission path

Figure 16 – Schematic diagram of the transmission path of force

As can be seen from the figure, different from the general load action, temperature stress tends to propagate along the longest constrained path in the structure, that is, the "longest direction propagation" mechanism. The general load in the structure tends to be transmitted along the short direction (the path with higher stiffness), while minimizing the transmission through the path with lower stiffness as much as possible. The short stiffness of a unidirectional plate is much greater than its long stiffness, so the unidirectional plate transmits force along the short direction.

At the 1/3 positions on both ends of the longitudinal side wall, the main tensile stress traces are in the shape of "\" and "/" respectively, and this area is the high stress zone of the side wall. Therefore, cracks will develop in an "八" shape.

Conclusions

Based on the analysis of the response results of reinforced concrete basement structures with different lengths under high-temperature sunlight, the following basic conclusions can be drawn:

1. When the temperature gradient between the upper and lower parts of the basement structure is the same, increasing the length of the basement does not cause a significant increase in the principal stress values of the side walls. The ultra-long seamless structure is still reasonable and feasible under the uneven expansion effect caused by the high temperature of sunlight.

2. Under the uneven expansion effect caused by high temperature sunlight, the increase in basement length did not significantly reduce the critical cracking temperature difference value of the side walls. In engineering practice, under the same structural form, longer basement structures and shorter basement structures generally have the same temperature control range. Unlike the vertical cracks that usually appear on basement side walls, the uneven expansion effect causes the side wall cracks to form an "八" shape. This indicates that the common vertical cracks in basement side shear walls in engineering are unlikely to be caused by uneven expansion effects.

3. Unlike the stress propagation caused by general loads, the thermal stress generated by temperature action shows a trend of "longest direction propagation" in the structure, that is, temperature stress tends to propagate along the longest constrained path.

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References

1. Li Yang. Finite element simulation and temperature field analysis of super long concrete structure with expansion reinforcement [D] / Li Yang. – Hebei University of Engineering, 2021.
2. Analysis of effects on basement exterior wall cracks controlling measure [J] / Hou Juling, Peng Yunlin, Zhang Weiyang [et al.] // Construction Technology. – 2017. – Vol. 46(S2). – P. 1121–1123.
3. Treshchinostojkost' zhelezobetonnoj stenki v usloviyah stesnennoj osnovaniem temperaturnoj deformacii [J] / YU. G. Barabanshchikov, K. V. Semenov, S. S. Zimin [i dr.] // Stroitel'stvo unikal'nyh zdanij i sooruzhenij. – 2018. – № 8. – S. 51–62.
4. Wei Yinyin. Temperature effect analysis and crack control of super long concrete shear wall during construction period [D] / Wei Yinyin. – Chongqing University, 2019.
5. Zhou Ningbin. Study on early temperature stress of basement exterior wall and crack control [D] / Zhou Ningbin. – Chang'an University, 2020.
6. Yang Li. Finite element simulation and temperature field analysis of super long concrete structure with expansion reinforcement [D] / Yang Li. – Hebei University of Engineering, 2021.
7. Modelirovanie vliyaniya gradientov temperatur na raspredelenie napryazhenij na stadii gidratacii betonov / YU. A. Abzaev, A. I. Gnyrya, S. V. Korobkov [i dr.] // Vestnik Tomskogo gosudarstvennogo arhitekturno-stroitel'nogo universiteta. – 2016. – № 3 (56). – S. 129–138.
8. Chen Junyi. Analysis on temperature stress of super-long concrete structure and research on its control technology [D] / Chen Junyi. – Zhejiang University, 2006.
9. Temperature simulation and thermal effect research one extremely long-span concrete frame structure [J/OL] / Zhang Hanshuo, Bu Fanmin, Nie Jianguo [et al.] // Engineering Mechanics. – 2024. – Vol. 1–9.
10. Li Ziyi. Research on sunshine temperature field of curved concrete box girder bridge and its effects [D] / Li Ziyi. – Dalian University of Technology, 2022.
11. Xie Zhiqian. Solar Radiation Simulation Method for Hydraulic Concrete Structure [J] / Xie Zhiqiang, Fu Zhi, Lv Xingdong // Journal of Chongqing Jiaotong university(natural science). – 2019. – Vol. 38 (11). – P. 82–89.
12. Marzec, I. Quantitative assessment of the influence of tensile softening of concrete in beams under bending by numerical simulations with XFEM and cohesive cracks [J] / I. Marzec, J. Bobiński // Materials. – 2022. – Vol. 15(2). – P. 626.
13. Zhou Linren. Experimental investigation into effect of surface roughness on convective heat transfer of concrete [J] / Zhou Linren, Li Shaoji, Chen Lan // Journal of South China University of Technology (Natural Science Edition). – 2023. – Vol. 51(07). – P. 81–89.
14. Liu Xingfa. Temperature stress analysis of concrete structures [M] / Liu Xingfa. – People's Transportation Press, 1991.
15. Duffie, J. A. Solar engineering of thermal processes, photovoltaics and wind [M] / J. A. Duffie, W. A. Beckman, N. Blair. – John Wiley & Sons, 2020.
16. Liu Cheng. The temperature field and thermal effect of steel-concrete composite bridges [D] / Liu Cheng. – Tsinghua University, 2018.
17. GB 50010-2010, Code for Design of Concrete Structures (in Chinese) [S].
18. GB 50176-2016, Code for Thermal Design of Civil Buildings (in Chinese) [S].
19. Xihe Energy Meteorological Big Data Platform. Global Modeling and Assimilation Office (GMAO) (2015), MERRA-2 tavg1_2d_lnd_Nx, tavg1_2d_rad_Nx, tavg1_2d_slv_Nx: 2d,1-Hourly, Time-Averaged, Single-Level, Assimilation, Diagnostics V5.12.4 (M2T1NXSLV), Land Surface Diagnostics V5.12.4 (M2T1NXLND), Radiation Diagnostics V5.12.4 (M2T1NXRAD), Greenbelt, MD, USA, Goddard Earth Sciences Data and Information Services Center (GES DISC). – URL: https://www.xihe-energy.com (date of access: 14.09.2024).
20. Numerical Simulation of Fracture Performance of Concrete Three-Point Bending Beam Based on Extended Finite Element Method [J] / Zuo Yongmei, Guo Zhanglei, Zhu Lihua [et al.] // Journal of Hebei University of Engineering(Natural Science Edition). – 2022. – Vol. 39(04). – P. 26–32.
21. Roth, S. N. A combined XFEM–damage mechanics approach for concrete crack propagation [J] / S. N. Roth, P. Léger, A. Soulaïmani // Computer Methods in Applied Mechanics and Engineering. – 2015. – Vol. 283. – P. 923–955.
22. Liu Chun. Experimental investigation on fracture behavior of concrete under three point bending test and numerical simulation [D] / Liu Chun. – Guizhou university, 2017.
23. Jia Yandong. Research on the Fracture Performance and Experimental Methods of Concrete with Different Coarse Aggregates and Strength Grades [D] / Jia Yandong. – Dalian University of Technology, 2003.
24. JGJ 3-2010.Technical specification for concrete structures of tall building (in Chinese)[S].
25. 3D-TSV: The 3D trajectory-based stress visualizer / J. Wang, C. Neuhauser, J. Wu [et al.] // Advances in Engineering Software. – 2022. – Vol. 170. – P. 103144.
26. Yuan Yafei. Research of the method stress field's visualization based on principal stress trajectory [D] / Yuan Yafei. – Xi'an University of Science and Technology, 2019.
27. Zhang, H. Experimental Investigation on Stress Redistribution and Load-Transfer Paths of Shear Walls with Openings / H. Zhang, X. Liu, W. Yi // Journal of Structural Engineering. – 2018. – Vol. 144(9). – P. 296–311.
28. Kelly, D. W. An algorithm for defining load paths and a load bearing topology in finite element analysis / D. W. Kelly, C. A. Reidsema, M. C. W. Lee // Engineering Computations. – 2011. – Vol. 28(2). – P. 196–214.
29. Wang Junbiao. Formula for calculating the principal direction of stress[J] / Wang Junbiao // Mechanics in Engineering. – 1992. – Vol. 04. – P. 60.

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APPLICATION OF CONVOLUTIONAL NEURAL NETWORK IN STRESS CALCULATIONS OF REINFORCED CONCRETE SLABS OF ROAD PAVEMENTS

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Abstract

The design of rigid reinforced concrete slabs of foundations, slabs, road surfaces is based on calculation models, which are developed on a relatively limited number of experimental studies, in most cases requiring quite large material and time costs. The complex stress-strain state occurring in stiff reinforced concrete base and pavement slabs under load, especially under cyclic dynamic loading, can often lead to cracking and failure of the slabs. In this paper, reinforced concrete slabs of a container yard pavement were investigated for load bearing from the wheels of a reach stacker (container loading vehicle) travelling on the surface. Existing models for the design of such slabs typically consider the slab loaded by a single local load applied to an edge or corner of the slab from the wheels of a moving vehicle. In fact, there may be two wheels on the slab, resulting in more unfavorable conditions. The application of the finite element method in such problems is quite laborious as it requires highly skilled design engineers and considerable time, making the design routine and of limited use. This paper investigates an alternative approach based on the application of an artificial convolutional neural network (CNN) with U-Net architecture, which provides a reasonably accurate prediction of stresses in the slab much faster and simpler compared to the finite element method. The paper presents the architecture of the neural network with an indication of the features and stages of its training. Statistical analysis of the calculation results is performed, which allowed us to assess the reliability of the neural network model for determining stresses in reinforced concrete slabs on an elastic base.

Keywords: reinforced concrete slab, computational model, convolutional neural network, U-Net architecture.

ПРИМЕНЕНИЕ СВЁРТОЧНОЙ НЕЙРОННОЙ СЕТИ В РАСЧЁТАХ НАПРЯЖЕНИЙ ЖЕЛЕЗОБЕТОННЫХ ПЛИТ ДОРОЖНЫХ ПОКРЫТИЙ

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Реферат

В основу проектирования жёстких железобетонных плит фундаментов, перекрытий, дорожных покрытий положены расчётные модели, которые разработаны на относительно ограниченном количестве экспериментальных исследований, в большинстве случаев требующих достаточно больших материальных и временных затрат. Сложное напряжённо-деформированное состояние, возникающее в жёстких железобетонных плитах фундаментов и дорожных покрытий под нагрузкой, и в особенности под циклической динамической нагрузкой, часто может приводить к образованию трещин и разрушению плит. В работе исследовались железобетонные плиты покрытия контейнерной площадки, которые воспринимают нагрузку от колёс перемещающегося по поверхности ричстакера (транспортного средства для погрузки контейнеров). Существующие модели для проектирования таких плит рассматривают как правило плиту, загруженную одной локальной нагрузкой, приложенной на краю или в углу плиты, от колеса передвигающегося транспорта. Фактически на плите могут располагаться два колеса, что приводит к более неблагоприятному состоянию. Применение метода конечных элементов в таких задачах является достаточно трудоёмким, так как требует высокого уровня квалификации инженеров-проектировщиков и значительных временных и трудовых затрат, что делает проектирование рутинным и мало целесообразным. В данной работе исследован альтернативный подход, основанный на применении искусственной свёрточной нейронной сети (CNN) с архитектурой U-Net, позволяющий получить достаточно точное предсказание напряжений в плите значительно быстрее и проще в сравнении с методом конечных элементов. В работе приведена архитектура нейронной сети с указанием особенностей и этапов её обучения. Выполнен статистический анализ результатов расчёта, позволивший оценить достоверность нейросетевой модели определения напряжений в железобетонных плитах на упругом основании.

Ключевые слова: железобетонная плита, расчётная модель, свёрточная нейронная сеть, архитектура U-Net.

1 Introduction

Reinforced concrete pavement slabs have a non-linear behavior under load with a complex stress-strain condition due to the inhomogeneous anisotropic structure of the composite material. In the design of such slabs, simplified design models are used, which are based on a number of assumptions and simplifications, and are most often developed based on the results of experimental tests of reduced slab fragments.

Traditionally, the design of reinforced concrete slabs has been based on mathematical models, finite element methods (FEM) and experimental tests. Keeping a balance between safety and economic feasibility, over the last decades, researchers and engineers have proposed many calculation models [2–9] for reinforced concrete slabs, based on which various design standards have been developed and are used worldwide [1–6].

Mathematical models of the resistance of rigid reinforced concrete slabs do not allow taking into account a large number of variables simultaneously due to the complexity and labor-intensive nature of this approach [1]. As a rule, such models take into account the behavior of each individual element of the structure, which in general for a structural system leads to the calculation of several equations, especially when the influence of more than one parameter on the resistance is taken into account, and complicates the complexity and duration of the calculation [11].

The laboriousness and considerable duration of analytically solutions using mathematical models or the finite element method in the design of structures and the experimental determination of the behavior of structural elements under load indicate, according to the authors [11], the need for reliable alternative prediction.

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Due to the advances in computer science, many researchers have proposed to use soft computing methods to solve complex engineering problems in the last two decades [10–23]. The most popular of them are artificial neural networks, response surface methodology, fuzzy logic, particle swarm optimization and genetic algorithms [24].

In 1992, J. H. Garrett [25] reported that modelling with neural networks is much easier than with traditional mathematical models. Despite the fact that in neural networks the interconnections between its nodes (neurons) and minimization of the training error have a mathematical essence, mathematical formulas are not explicitly present in them. Artificial neural networks can be used to predict the strength of concrete and resistance of concrete structures with an error of less than 10 %.

It is also noted in [11] that neural networks can be used as an alternative to mathematical models or experimental tests at the initial design stage to obtain a quick prediction of the behavior of reinforced concrete slabs under load, determining the magnitude of resistance and deflections of resistance and deflections.

Neural networks are information processing systems whose architecture is based on the endeavor to replicate the structure of biological neural systems [26]. Unlike traditional computer programs, in which information is received and processed digitally in a sequential manner, neural networks store data in some way between individual neurons of the network by means of selected weighting coefficients. Neural networks do not contain any algorithms to process the data. They are 'trained' to find relationships, often not fully realized, that create a structure of causal interactions between input parameters and the result obtained.

Neural networks are able to model the behavior of systems with limited design costs and provide fast and reasonably accurate solutions in complex, uncertain and individual situations [27, 28]. Such prediction can be useful for a structural engineer in the preliminary design phase to determine the initial serviceability of a particular structure or to estimate the load carrying capacity of an in-service structure.

O. Moselhi in 2002 [28] highlighted the following characteristics of neural networks that make them useful for solving different types of engineering and scientific problems:

- neural networks are based on algorithms in which computational procedures are performed in parallel and decentralized rather than sequentially, as in conventional computer programs, resulting in fast data processing;
- they have a distributed memory represented by weight coefficients in the links distributed over all elements of the network;
- neural networks remain functional even after several network elements are damaged and fall out of network operation;
- they have the ability to learn from examples;
- allow predicting the behavior of systems with limited modelling capabilities;
- allow fast and reasonably accurate solutions to complex, uncertain and unusual situations.

Thus, it can be noted that the use of neural networks in engineering and scientific tasks allows to simplify and speed up the calculation procedure.

The main purpose of this work is:

- approbation of convolutional neural network in the problems of calculation of rigid reinforced concrete slabs of covering of container yards erected constructed on the ground base, determination of stresses in the design of such slabs caused by external influences from the loading vehicle (reach stacker) moving on the surface;
- to show the possibility of using 'soft computing' with the application of deep learning in tasks related to the design of building structures;
- to show the advantages of convolutional neural networks in comparison with other models in determining the stresses in reinforced concrete slabs on the base under different variants of concentrated loads from reach stacker wheels;
- evaluate the accuracy of stress values obtained using convolutional neural network.

2 Problem formulation and choice of neural network type

The design of reinforced concrete slab foundation on the soil base, for which the calculation was performed, consisted of two reinforced concrete slabs, of which the lower one modelled the reinforced concrete base slab of the container yard with a thickness of h = 100 mm, the upper one – the reinforced concrete cover slab of the container yard with a thickness of h = 250 mm.

In calculations for the base slab was taken concrete class $C^{12}/_{15}$ according to [29] with modulus of elasticity E = 19000 MPa, for the cover slab - concrete class $C^{32}/_{40}$ according to [29] with modulus of elasticity E = 38000 MPa. The Poisson's ratio for both slabs was assumed μ = 0.2.

The interaction of the upper and lower slabs with each other was modelled by means of elastic bonds of finite stiffness.

Calculation of the slabs for vertical loads from the wheels of a (reach stacker) travelling on the surface was initially performed by the LIRA PC.

The work of the elastic base was taken into account by means of the algorithm 'Soil Model' built into LIRA PC, which takes into account the elastic work of each layer of the soil base. Characteristics of soils in the layers were taken on the basis of engineering-geological surveys on the territory of the container site in the transshipment park of Brest-Northerly station in Brest.

The calculation was carried out for the action of constant load from the own weight of the base slabs and the container yard covering and short-term load on each front wheel from the reach stacker FERRARI F500-RS2. The area of load application from the reach stacker wheels, according to its technical specifications, was assumed to be A = 0,36 m^2. The value of the load from the reach stacker wheels was varied in the range from 150 to 900 kN to form a database for training the neural network.

The classification of neural networks developed to date is quite extensive. A perceptron with one hidden layer is a universal approximater, i.e. it is capable of approximating any continuous function with any degree of accuracy if a continuous, monotonically increasing, bounded function is used as the activation function of neural elements of the hidden layer [30]. Multilayer perceptron can be used for pattern classification, prediction and control tasks. Recurrent networks can be used for processing dynamic data, temporal patterns, solving prediction problems, system identification, speech recognition, natural language processing and control. Convolutional neural networks (CNN), which are a further development of multilayer perceptron, are widely used for image processing, and, unlike multilayer perceptron, they allow to take into account image topology and retain predictive properties in case of shifts, scaling and other distortions of the input image. Many other types of neural networks are also known.

Since the distribution of stresses, strains deformations or vertical displacements on the slab surface has similarity with the image, the authors of the paper decided to use convolutional neural network (CNN) to achieve the goal.

3 Data for neural network training

The dataset used in this study to train the CNN was obtained through parametric modelling in LIRA PC. A total of 125 numerical simulations (images) were performed with the inherent ability to vary at different levels three parameters: 1) the magnitude of the load from the wheels travelling on the surface of the container yard slab of the reach stacker with the container; 2) the location of the two front most loaded wheels on the surface of the slab; 3) the shape of the container yard cover slab in plan. The 125 numerical calculations were divided into two groups: 100 calculations were designed to train the CNN to predict the magnitude of stresses in the slab distributed over its surface; 25 calculations were designed to evaluate the accuracy of the developed CNN model.

The initial data intended for the formation of CNN feature maps characterizing the recognized image were generated using two different methods.

In the first case (model 1), the raw data were fed as four digital feature maps of dimensionality 56×56.

The first feature map, the shape feature, is designed to describe the shape of the slab by means of zeros and units. In this map, the body of the slab is described by units and the empty space by zeros.

The second feature map is the load map. The area to which the wheel load is applied is marked in the map with elements indicating the magnitude of the load applied to the corresponding area. The non-loaded area of the slab in the map is marked with zero elements.

The third and fourth feature maps describe the location of the reach stacker wheel load on the slab surface. In each of these maps, the center of the reach stacker wheel load area is described by a zero, and all other elements of the map represent the distance from this center to the corre-

sponding point on the slab surface. The third map describes the load position of the first wheel and the fourth map describes the load position of the second wheel.

In the second case (model 2), the input data were fed as a single digital feature map of dimension 56 × 56, which displayed the coordinates of the slab points in 0.1 m increments and the magnitude of the vertical concentrated load on the slab at each coordinate.

The output was to obtain the stresses in the slab distributed over its surface. The stresses obtained for CNN training in LIRA PC were formed into a stress map, in which each element represented the stresses in the corresponding point of the reinforced concrete slab.

4 Neural network architecture and algorithm

A convolutional neural network (CNN) with U-Net architecture was used to predict the stress distribution on the surface of a reinforced concrete slab. U-Net is considered one of the standard CNN architectures for image segmentation tasks, when it is necessary not only to define the whole image class, but also to segment its regions by class, to create a mask that will divide the image into several classes. [31]. There is a perception that a very large number of annotated training samples are required to successfully train deep neural networks. However, the study [31] presents a CNN with U-Net architecture that relies on the active use of additional data to make better use of the available annotated samples. The authors of [31] show that the network they developed can be trained on a very small number of images and outperforms the previous best method for a number of neuron segmentation tasks on electron microscopic tubes.

The architecture of the convolutional neural network used by the authors of this paper is shown in Figure 1. It consists of two parts – encoder («convolutional») and decoder («unfolding deconvolution»). Encoder converts the input image into a multidimensional feature representation. It performs the feature extraction function. Decoder creates a segmented image based on the features extracted from the convolutional part of the network.

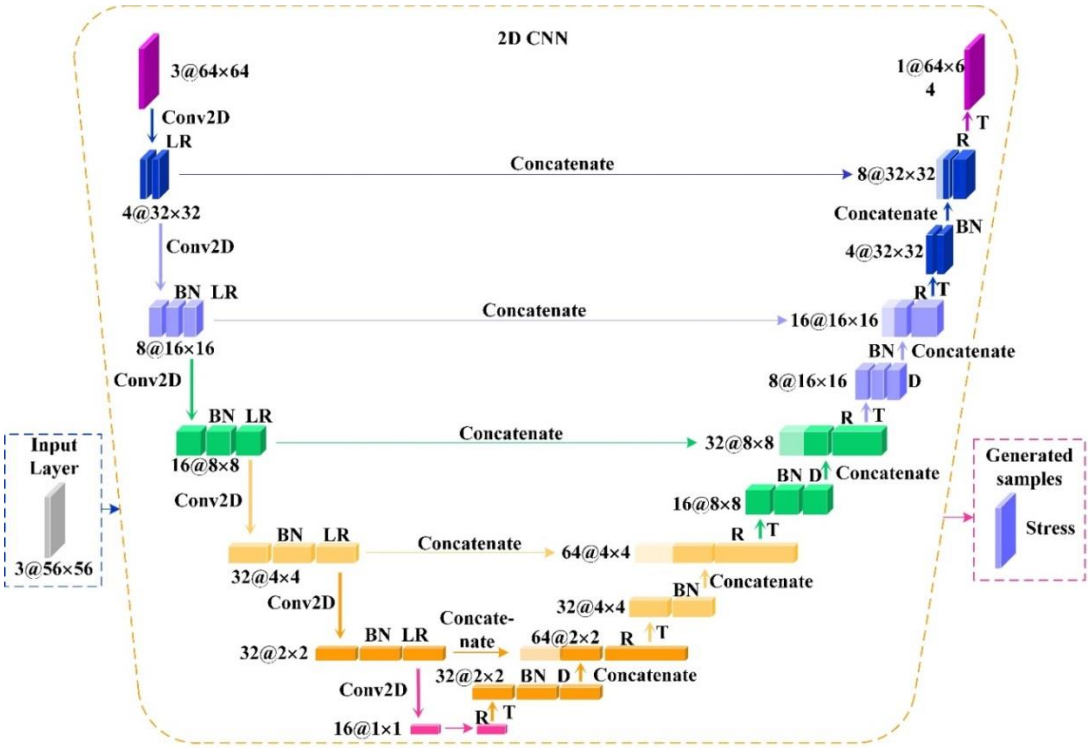

Figure 1 – Schematic of the applied CNN model with U-Net architecture with a single pixel at the lowest resolution. Each colored parallelepiped corresponds to a multi-channel feature map. The number of channels is indicated by the first digit (before @) in the map parameter signature. The map dimensions are indicated behind the @ sign in the map parameter caption. Transparent fields represent copied feature maps for the concatenate operation. The following parameters are labelled with letters: Conv 2D – Convolution 2D – 2D convolution; BN – Batch Normalization – Batch Normalization of data; LR – Leaky ReLU – activation function; R – ReLU – activation function; T – Conv2DTranspose – 2D transposed convolution layer; D – Dropout – regularization method designed to reduce network overfitting

The input was an image of an externally loaded slab with dimensions of 5,6 × 5,6 m, which were converted into three feature maps of dimensions 64 × 64. The feature map responsible for the shape of the slab was not considered at this stage of research as it was unchanged. The convolution represents a digital filter in which training was performed using the sliding window method [30] by means of weighted summation of values in the map cells (neurons) and weighting coefficients – coefficients of the convolution kernel. A sliding window is otherwise referred to as a local receptive field or filter kernel for the corresponding (usually one) neuron in the feature map (each receptive field in the input image space is mapped to a different neuron in each feature map). The total number of different synaptic connections in the convolutional layer is:

$$V(C_1) = M\left(p^2 + 1\right), \quad (1)$$

where C_1 is the convolutional layer designation and its number, p^2 is the total number of elements of the receptive field (kernels).

From expression (1) follows the peculiarity that the use of convolutional network reduces the total number of tunable customizable synaptic connections of a convolutional network in comparison with multilayer perceptron due to the use of identical neurons in each feature map [30].

The result of 'sliding' the kernel, in this paper sized 4 × 4 in steps of 2, across the entire image is written into a new image (a new feature map). At each layer, the coding block collapses the three-dimensional matrix, reducing the number of sampling points of the map by half and increasing the number of features (channels) responsible for the characteristic features (stress magnitude) of individual nodes of the network. To preserve the dimensions of the feature map output and capture extreme values, we added rows and columns to the right and left, as well as top and bottom, filled with zeros in the feature map (padding procedure).

If we represent the pixels of the input image in one-dimensional space, then the output value of the *ij*-th neuron for the *k*-th feature map in the convolutional layer is defined as [30]

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$$y_{ij}^k = F\left(S_{ij}^k\right), \quad (2)$$

$$S_{ij}^k = \sum_c \left| w_{cij}^k x_c - T_{ij}^k \right|, \quad (3)$$

where $c = \overline{1, p^2}$; F is the activation function; S_{ij}^k – weighted sum of the *ij*-th neuron in the *k*- th feature map; w_{cij}^k – weighting factor between the *c*-th neuron of the input layer and the *ij*-th neuron in the *k*-th feature map; T_{ij}^k – threshold value of the *ij*-th neuron in the *k*-th feature map.

Each feature map obtained by convolution reflects the same local features in all parts of the image. It represents a set of neurons, each of which has the higher value, the more the associated image fragment resembles a kernels.

At each stage of convolution, we performed batch normalization of the obtained data (Batch Normalization – BN in Figure 1), which allows to improve performance and stabilize the network, and rectification by a linear activation block Leaky ReLU (LR in Figure 1).

The second part of the network, «decoder» is a mirror image of the first. The image size needs to be restored to the original image size. To this end, up-sampling layers are used in combination with convolutional layers. Each layer in up-sampling represents the process of inverse convolution of the feature map, accompanied by doubling of its size and halving of the number of feature channels followed by batch normalization. The dropout layer following the batch normalization turns off at random (temporarily excludes from training) a certain percentage of neurons in the network at each training step, which helps to prevent overdependence of the model on specific paths and nodes in the network leading to overtraining [33]. The probability p with which each neuron will be excluded is typically between 0.2 and 0.5. The feature map obtained in this layer is concatenated with the corresponding trimmed feature map from the convolution layer and straightened by the linear activation unit ReLU. The last layer uses convolution 1 × 1 to map each 64-component feature vector to the correct number of classes.

5 Neural network training

It should be noted that in this study the number of trained parameters, which was 98673 in model 1 and 98545 in model 2, exceeds the number of images on which the model was trained, which, according to many researchers, is a drawback of the model.

When training in convolutional neural networks, the whole image or local regions (patches) around an image pixel can be provided as input data. The authors of [31] note that when optimizing computations by stochastic gradient descent, the method of convolution over the whole image is identical to training over local areas (patch). The authors of [31] did not find that patch training provides faster or better convergence for dense prediction, while whole-image training is, in their opinion, quite efficient and effective.

In [34], the authors are based on an elegant architecture, the so-called fully convolutional network proposed in [31]. They modify and extend this architecture so that it works with a small number of training images, by dividing images into local regions (patches), and performs more accurate image segmentation. The main idea of [31] is to supplement the usual convolutional network with sequential layers, in which the pooling operators are replaced by up-sampling operators (up-sampling or sampling operator). Thus, according to the authors, these layers increase the resolution of the output signal. For localization, the high-resolution features obtained during narrowing are combined with up-sampled output data (concatenate). As a result, the subsequent convolution layer receives more accurate input data.

An important change in the neural network architecture presented in [34], the authors note the presence of a large number of feature channels in the up-sampling procedure, which allow the network to transfer contextual information to layers with higher resolution. As a consequence, the expanding path (decoder) is more or less symmetric to the narrowing path (encoder) and yields a U-shaped architecture. The network does not have fully connected layers and uses only the valid part of each convolution, i.e., the segmentation map contains only those pixels for which full context is available in the input image. This strategy, according to the authors of [34], allows seamless segmentation of arbitrarily large images. To predict pixels in the boundary region of the image, the missing context is extrapolated by mirroring the input image. This procedure is important for applying the network to large images, since otherwise the resolution would be limited by the CPU memory.

The authors [34] emphasize that their U-Net CNN can recognize local area, has a much larger amount of training data in the form of local areas (patch) than the number of training images and has a high predictive ability.

Thus, it can be noted that the existing opinion that the training sample size should be equal to the size of the trained parameters in order to prevent overtraining of the network is currently debatable. The architecture of modern neural networks can be configured in such a way as to allow training on a small training sample size and achieve a sufficiently high predictive ability.

In this work, the authors used a two-dimensional convolutional neural network (CNN) with U-Net architecture to predict the stress distribution on the surface of a reinforced concrete slab using the stochastic gradient descent (SGD) method for training.

The training of the neural network, as mentioned above, is carried out using the Batch Normalization method by the error back propagation method according to the provisions given in [32]. In the batch normalization method, some layers of the neural network are fed with preprocessed data having zero mathematical expectation and unit variance.

The rectification function was used as neuron activation functions, by which neuron output values can be calculated as:

$$y_{ij}^k = F(S_{ij}^k) = \begin{cases} S_{ij}^k, S_{ij}^k > 0, \\ kS_{ij}^k, S_{ij}^k \le 0, \end{cases} \quad (4)$$

where S_{ij}^k – is the same as in formula (3); in convolution layers the coefficient k = 0.02 was taken, in unwrapped (deconvolution) layers – k = 0.

In both models (model 1 and model 2), 300 training epochs were assigned. To train the neural network, 100 samples were used with the ratio between training and validation samples being 97 % to 3 %. To test the prediction accuracy of the models, an additional test sample of 25 samples not used in the training of the network was used.

When testing the neural network, the mean absolute error with L1 norm [35, 36] was used, as this metric reflects well the accuracy of the prediction result. The loss function was defined as:

$$E = \frac{1}{n} \sum \left| Y_{target} - Y_{predicted} \right|, \quad (5)$$

where n – number of training images, Y_{target} – training data, $Y_{predicted}$ – predicted data.

All stages of CNN creation, training and validation were implemented using the Python programming language and the open-source machine learning software library developed by Google to solve the tasks of building and training the Tensorflow neural network [37].

6 Results of calculations and their analysis

As a result of this study, it was found that the input data layout in model 1 was better than in model 2. This is evidenced by the speed and quality of training of the neural network, as well as by the numerical statistical evaluation of the reliability of the coincidence between the training values obtained by finite element calculation and the stress values predicted by the neural network. A rather close coincidence of training and validation sampling errors in Model 1 is observed after 120 epochs of training and is maintained until the end of training (Figure 2a). The divergence of training and validation sampling errors is about 17 %. In model 2, the training and validation sampling errors are quite different. While the training sampling error decreases to 15 % during the training process, the validation sampling error fluctuates within 50 % almost during the whole training process (Figure 2b). In addition, the curve of variation of the training sampling error obtained by model 1 is smoother than by model 2, which indicates a greater stability of neural network training in the first case. The validation sampling error variation curve obtained by model 1 is also smoother.

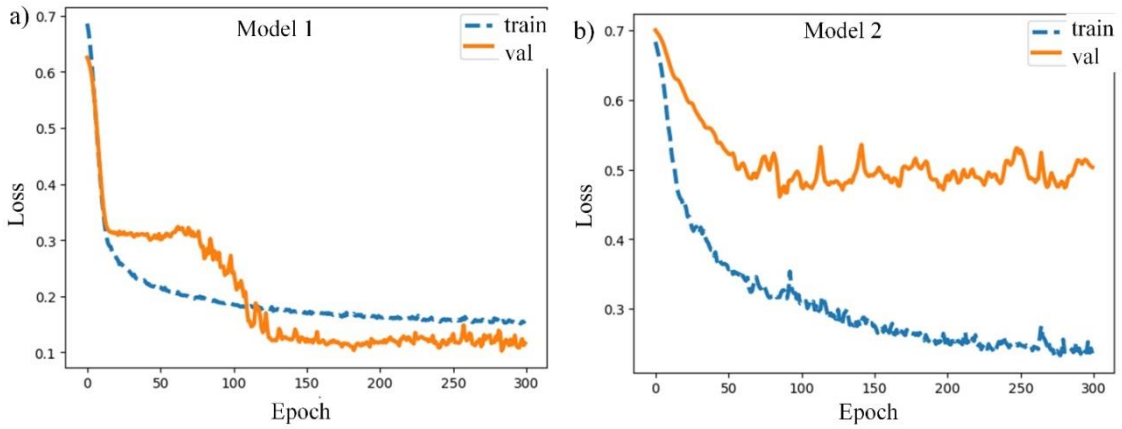

Figure 2 – Parameters of neural network training according to model 1 (a) and model 2 (b)

To evaluate the accuracy of stresses in reinforced concrete slabs predicted using neural network, we used well known mathematical statistics: mean absolute error (MAE), standard deviation (RMSE), Pearson correlation coefficient (r), coefficient of determination (R^2). In addition, we determined the value of correction factor b for the mean deviation of training and predicted stress values, the mean error value of models – Δ, obtained from the error vector δ, and the coefficient of variation V_δ (of the error vector δ), calculated according to the procedure given in Appendix D of CH 0.01.01 [38]. The specified statistical parameters are given in Table 1.

Table 1 – Statistical parameters characterizing the degree of accuracy of the developed neural network models

Model	*RMSE*	*MAE*	*r*	R^2	*b*	Δ	V_δ
Model 1	0,478	0,305	0,924	0,854	0,928	0,428	0,015
Model 2	0,637	0,424	0,862	0,733	0,853	0,658	0,146

The overall distribution of training and model 1 and model 2 predicted stresses in reinforced concrete slabs is shown in Figures 3 and 4, and the ratio of training and model 1 and model 2 predicted stresses in reinforced concrete slabs is shown in Figure 5.

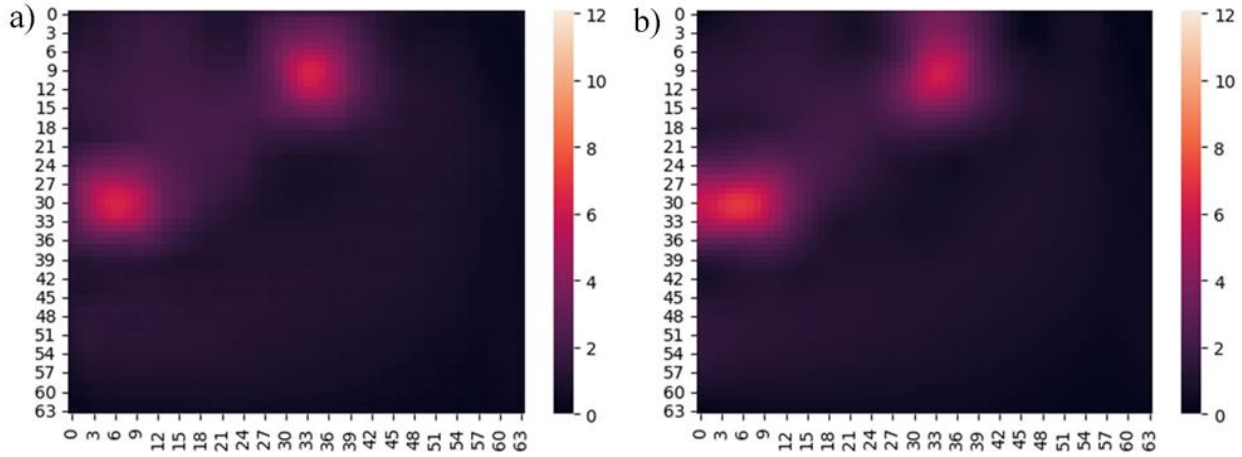

Figure 3 – Distribution of stresses predicted by model 1 (a) and training (b) in reinforced concrete slabs

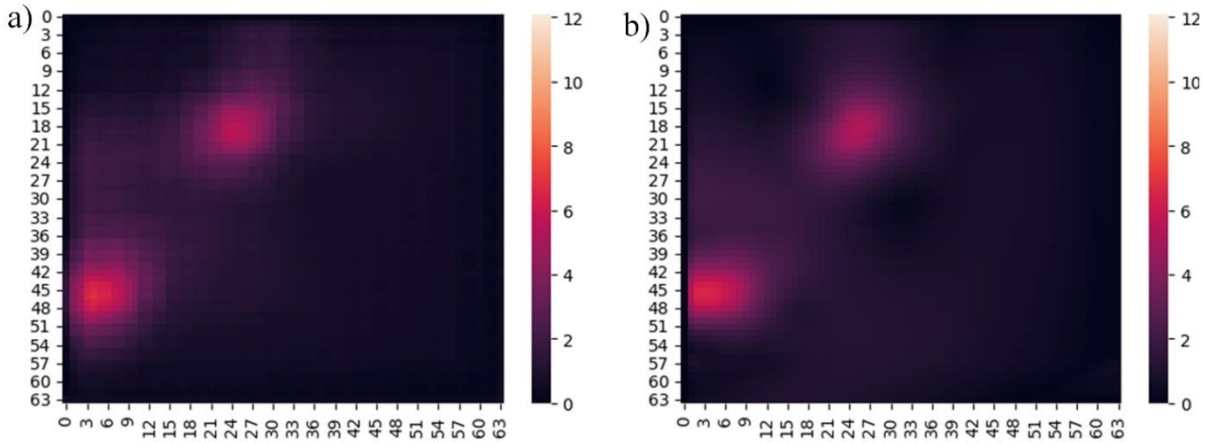

Figure 4 – Distribution of stresses predicted by model 2 (a) and training (b) in reinforced concrete slabs

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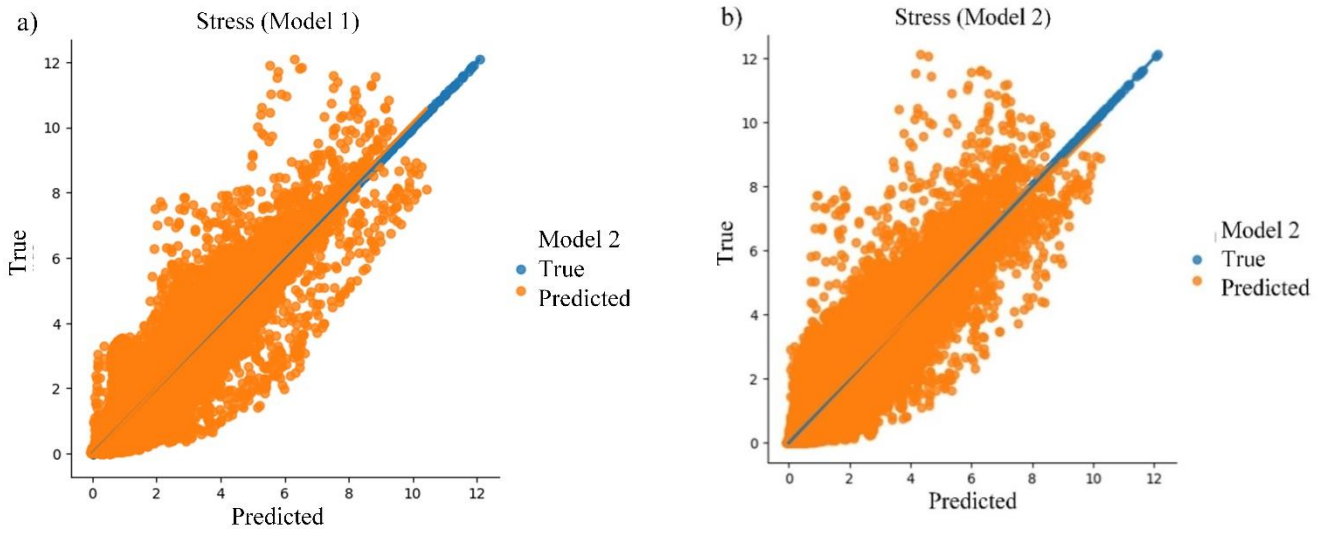

Figure 5 – Ratio of training and predicted stresses in reinforced concrete slabs using model 1 (a) and model 2 (b)

The predicted stresses in reinforced concrete slabs using the neural network have a relatively satisfactory coincidence with the training values in the whole range of values. On average, the predicted values of stresses exceed the training values by 7 % for model 1 and by 15 % for model 2, as evidenced by the value of the correction factor *b* (Figure 5, Table 1) for the mean deviation, determined by the expression:

$$b = \frac{\sum \sigma_a \sigma_p}{\sum \sigma_p^2}, \quad (5)$$

where σ_a, σ_p – are respectively the training (actual) and predicted stresses in the reinforced concrete slab [38].

Taking into account the small number of the training sample, this characterizes the predictive ability of the models as relatively high, but insufficiently safe. It is also impossible to speak about high density of distribution of predicted stress values along the line of training values. Most of the predicted values, which is about 85–90 %, deviate from it within 25 %. The maximum deviation, more typical for small stress values, is about 80 % (Figure 5).

The relatively low density of stress distribution is evidenced by the value of the mean absolute error, which for model 1 – *MAE* = 0,305, and for model 2 – *MAE* = 0,424. Relative to the mean value of stresses in reinforced concrete slabs, which is 0,938 MPa for the test sample, the mean absolute error (*MAE*) is 33 % and 45 %, respectively. The standard deviation for models 1 and 2 respectively are: *RMSE* = 0,478 and *RMSE* = 0,637.

It is accepted that computational models with a coefficient of determination above 0,8 and a correlation coefficient above 0,9 are considered good enough. When the coefficient of determination is equal to 1, there is a functional dependence between the compared values. In our study, when comparing training and predicted stresses, the values of correlation coefficient (for models 1 and 2 respectively: r = 0,924; 0,862) and coefficient of determination (for models 1 and 2 respectively: R^2 = 0,854; 0,733) meet the above criteria only for model 1 (Table 1).

The coefficient of variation of the error vector δ, equals to 0,015 and 0,146 for models 1 and 2, respectively, is less than the value of 0,33, which indicates a sufficiently high homogeneity of the studied data set [39].

Thus, it follows from the results of the statistical study that model 1 more accurately predicts the magnitude of stresses in the slab. The reason for this may lie in the input data for training, which in the first model are fed in the form of feature maps and form a common multilayer image of the object. Each feature map conveys the parameters of one layer of this image. All maps are united into a single image by the common geometric shape of the object. In the second model there is only one feature map, and the general geometry of the image is viewed only indirectly through the space coordinates, which are endowed with the necessary features.

7 Conclusions

Mathematical models of resistance of rigid reinforced concrete slabs do not allow to take into account a large number of variables simultaneously due to the complexity and labor-intensive nature of this approach. As a rule, such models take into account the behavior of each individual element of the structure, which in general for the structural system leads to the calculation of several equations, especially when taking into account the influence of more than one parameter on the resistance. This feature complicates the complexity and duration of the calculation and necessitates reliable alternative predictions.

As reported by many research papers, modelling the behavior of engineering structures using neural networks is much easier than using traditional mathematical models.

Neural networks can be used as an alternative to mathematical models or experimental tests at the initial design stage to obtain rapid prediction of the behavior of reinforced concrete slabs under load, determining the magnitude of resistance and deflections.

Neural networks are able to model the behavior of systems at limited design costs and provide fast and reasonably accurate solutions in complex, uncertain and individual situations.

Analyzing the results of the statistical study shows that model 1 is more accurate in predicting the magnitude of stresses in the slab due to a more efficient feedforward.

In general, despite the fact that most of the statistical parameters do not have the best values, the predictive ability of the models based on convolutional neural network with u-net architecture can be considered high enough.

The main reason for the error of the models is the small sample dataset size of training data, which requires replenishment of the sample, retraining of the neural network and subsequent assessment of its reliability.

References

1. Tully, S. H. A neural network approach for predicting the structural behavior of concrete slabs : a thesis submitted for the degree of master of engineering : 06.1997 / S. H. Tully. – Newfoundlan, 1997. – 126 p.
2. Betonnye i zhelezobetonnye konstrukcii = Betonnyya i zhalezabetonnyya kanstrukcyi : SP 5.03.01-2020. – Vved. 16.09.2020. – Minsk : RUP «Strojtekhnorm» : Ministerstvo arhitektury i stroitel'stva Respubliki Belarus', 2020. – 236 s.
3. Design of concrete structures – Part 1-1: General rules, rules for buildings, bridges and civil engineering structures : prEN 1992-1-1:2018 Eurocode 2. – Final draft of April 2018 by the Project Team SC2.T1 working on Phase 1 of the CEN/TC 250 work programme under Mandate M/515. – 293 p.
4. fib Model Code for Concrete Structures 2010. – Lausanne : International Federation for Structural Concrete (fib), Switzerland, 2013. – 432 p.

5. ACI. Building Code Requirements for Structural Concrete (ACI 318-08) and Commentary. In Aci-318-08; American Concrete Institute: Farmington Hills, MI, USA, 2008. – P. 1–471.
6. JSCE. Standard Specifications for Concrete Structures-2007. In JSCE Guideline for Concrete No. 15; JSCE: Tokyo, Japan, 2007. – P. 1–503.
7. CSA. Design of Concrete Structures. In A23.3-04; CSA: Mississauga, ON, Canada, 2004. – P. 1–232.
8. NZS. Concrete Structures Standard Part-1. In NZS 3101; New Zealand Standard. – Wellington, New Zealand, 2006. – Part 1. – P. 1–309.
9. KBCS. Korean Building Code-Structural (KBCS); Architectural Institute of Korea: Kimoondang, Korea, 2005.
10. Ahmad, A. Neural Network-Based Prediction: The Case of Reinforced Concrete Members under Simple and Complex Loading / A. Ahmad, N. D. Lagaros, D. M. Cotsovos // Applied Sciences. – 2021. – Vol. 11. – P. 4975. – DOI: 10.3390/app11114975.
11. Bamiyo, S. P. Prediction of Load deflection Behaviour of two way Rc Slab using Neural Network Approach / S. P. Bamiyo, O. A. Uche, M. Adamu // International journal of optimization in civil engineering. – 2017. – Vol. 7 (4). – P. 633–644.
12. Papadrakakis, M. Reliability-based structural optimization using neural networks and Monte Carlo simulation / M. Papadrakakis, N. D. Lagaros // Computer Methods in Applied Mechanics and Engineering. – 2002. – Vol. 191. – P. 3491–3507. – DOI: 10.1016/S0045-7825(02)00287-6.
13. Lagaros, N. D. Learning improvement of neural networks used in structural optimization / N. D. Lagaros, M. Papadrakakis // Advances in Engineering Software. – 2004. – Vol. 35, Iss. 1. – P. 9–25. – DOI: 10.1016/S0965-9978(03)00112-1.
14. Lagaros, N. D. An adaptive neural network strategy for improving the computational performance of evolutionary structural optimization / N. D. Lagaros, D. C. Charmpis, M. Papadrakakis // Computer Methods in Applied Mechanics and Engineering. – 2005. – Vol. 194, Iss. 33-33. – P. 3374–3393. – DOI: 10.1016/j.cma.2004.12.023.
15. Lagaros, N. D. Multi-objective design optimization using cascade evolutionary computations / N. D. Lagaros, V. Plevris, M. Papadrakakis // Computer Methods in Applied Mechanics and Engineering. – 2005. – Vol. 194. – P. 3496–3515.
16. Lagaros, N. D. Fragility assessment of steel frames using neural networks / N. D. Lagaros, M. Fragiadakis // Earthq. Spectra. – 2007. – Vol. 23. – P. 735–752. – DOI: 10.1193/1.2798241.
17. Ahmad, A. Prediction of Properties of FRP-Confined Concrete Cylinders Based on Artificial Neural Networks / A. Ahmad, V. Plevris, Q.-U.-Z. Khan // Crystals. – 2020. – Vol. 10. – 811 p. – DOI: 10.3390/cryst10090811.
18. Evaluating the Impacts of Pumping on Aquifer Depletion in Arid Regions Using MODFLOW, ANFIS and ANN / M. R. Almuhaylan, A. R. Ghumman, I. S. Al-Salamah [et al.] // Water. – 2020. – Vol. 12. – P. 2297. – DOI: 10.3390/w12082297.
19. Relating groundwater levels with meteorological parameters using ANN technique / M. Iqbal, U. A. Naeem, A. Ahmad [et al.] // Measurement. – 2020. – Vol. 166. – DOI: 10.1016/j.measurement.2020.108163.
20. Raza, A. Prediction of axial compressive strength for FRP-confined concrete compression members / A. Raza, Q. U. Z. Khan, A. Ahmad // KSCE Journal of Civil Engineering. – 2020. – Vol. 24. – P. 2099–2109. – DOI: 10.1007/s12205-020-1682-x.
21. The Role of Damage Extent in the Estimation of Direct Economic Losses of Existing RC Buildings / V. Manfredi, A. Masi, G. Nicodemo [et al.]. – Pisa, Italy : Pisa University Press, 2019. – P. 36–45.
22. Development of Integrated Techniques to Improve Seismic Performance and Energy Efficiency of Buildings: Preliminary Results of the Experimental Campaign on RC Portal Frames / D. Nigro, A. Digrisolo, G. Ventura [et al.]. – Pisa, Italy : Pisa University Press, 2019. – P. 128–137.
23. Structural health monitoring based on the hybrid ant colony algorithm by using Hooke–Jeeves pattern search / A. Shakya, M. Mishra, D. Maity, G. Santarsiero // SN Applied Sciences. – 2019. – Vol. 1. – P. 1–14. – DOI: 10.1007/s42452-019-0808-6.
24. Volna, E. Introduction to Soft Computing / E. Volna // 1st ed. ; Department of Computer Science. – Ostrava, Czechia : University of Ostrava, 2013. – P. 137.
25. Garrett, J. H. Neural Networks and their Applicability within Civil Engineering / J. H. Garrett // Proceedings, 8th Congress of Computing in Civil Engineering. ASCE. – New York, 1992.
26. Caudill, M. Naturally Intelligent Systems / M. Caudill, C. Butler. – Cambridge, Ma : MIT Press, 1990. – 314 p.
27. Moselhi, O. Neural networks for cost estimating of structural steel buildings / O. Moselhi, I. Siqueira // AACE Int. Transact. – 1998. – IT22.
28. Moselhi, O. Potential applications of neural networks in construction / O. Moselhi, T. Hegazy, P. Fazio // Canadian Journal of Civil Engineering. – 2002. – Vol. 19(3). – P. 521-529. – DOI: 10.1139/l92-061.
29. Betonnye i zhelezobetonnye konstrukcii = Betonnyya i zhalezabetonnyya kanstrukcyi : SP 5.03.01-2020. – Vved. 16.09.2020. – Minsk : RUP «Strojtekhnorm» : Min. arh. i str. Respubliki Belarus', 2020. – 244 s.
30. Golovko, V. A. Nejrosetevye tekhnologii obrabotki dannyh / V. A. Golovko, V. V. Krasnoproshin. – Minsk : Belorusskij gosudarstvennyj universitet, 2017. – 264 s.
31. Ronneberger, O. U-Net: Convolutional Networks for Biomedical Image Segmentation / O. Ronneberger, P. Fischer, T. Brox // University of Freiburg, Germany. – 2015. – arXiv: 1505.04597v1 [cs.CV]. – P. 8.
32. Ioffe, S. Batch Normalization: Accelerating Deep Network Training by Reducing Internal Covariate Shift / S. Ioffe, Ch. Szegedy // International Conference on Machine Learning, Lille, France. – 2015. – Vol. 37. – DOI: 10.48550/arXiv.1502.03167.
33. Dropout i Batch normalization. Blog kompanii M. Video-El'dorado. – URL: https://habr.com/ru/companies/mvideo/articles/782360 (data obrashcheniya: 22.05.2024).
34. Long, J. Fully Convolutional Networks for Semantic Segmentation / J. Long, E. Shelhamer, T. Darrell // IEEE Conference on Computer Vision and Pattern Recognition (CVPR). – 2015. – DOI: 10.1109/CVPR.2015.7298965.
35. Barrodale, I. L1 Approximation and the Analysis of Data / I. Barrodale // Journal of the Royal Statistical Society Series C: Applied Statistics. – 1968. – Vol. 17, Iss. 1. – P. 51–57. – DOI: 10.2307/2985267.
36. Mean absolute error with L1 norm. – URL: https://montjoile.medium.com/l0-norm-l1-norm-l2-norm-l-infinity-norm-7a7d18a4f40c (date of access: 20.12.2023).
37. Python programming language and the Tensorflow framework. – URL: https://www.tensorflow.org/about/bib (date of access: 22.10.2023).
38. Osnovy proektirovaniya stroitel'nyh konstrukcij = Asnovy praektavannya budaunichyh kanstrukcyj : SN 2.01.01. – Vved. 16.19.2019. – Minsk : RUP «Strojtekhnorm»: Ministerstvo arhitektury i stroitel'stva Respubliki Belarus', 2020. – 89 s.
39. Koefficient variacii (Variation coefficient). – URL: https://wiki.loginom.ru/articles/variation-coefficient.html (data obrashcheniya: 28.02.2024).

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EARLY-AGE EFFECTIVE ELASTIC PROPERTIES OF CEMENT-BASED COMPOSITES

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Abstract

The problem of the prediction the early age effective elastic properties of cement-based composites is one of the most important and at the same time complicated problems of concrete technology. Cement-based composites consist of a large number of randomly distributed phases with different geometric shapes and sizes at each structural level.

Currently, there are two common approaches to modeling the effective elastic properties of cement-based composites – analytical and numerical homogenization. Most of the researches of the effective properties of cement-based composites focused their attention on the effective medium theory as a part of analytical homogenization, in which all composite phases are considered as spherical inclusions leading to relatively simple computational models for prediction. This significant assumption affects the accuracy of predicting the effective properties, since it is a well-known fact that the real geometric shape of most phases of cement-based composites differs from spherical. One of the drawbacks of the effective medium theory is that solutions for non-spherical inclusions can only be received for a regular geometric shape representing an ellipsoid.

At the same time, one of the advantages of numerical homogenization based on finite element analysis is the possibility of calculating elastic properties for an arbitrary geometric shape of inclusions.

The purpose of the study is multiscale modelling the effective elastic properties of cement-based composites, using a combination of analytical and numerical homogenization, considering the geometric shape of the phases at each heterogeneous level, close to their real shape in the structure of composites.

Keywords: cement paste, concrete, analytical and numerical homogenization, multiscale structure, geometric shape.

ЭФФЕКТИВНЫЕ УПРУГИЕ СВОЙСТВА ЦЕМЕНТНЫХ КОМПОЗИТОВ В РАННЕМ ВОЗРАСТЕ

В. В. Кравченко

Реферат

Проблема оценки эффективных упругих свойств цементных композитов в раннем возрасте является одной из важнейших и в то же время сложных проблем технологии бетона. Цементные композиты состоят из большого количества случайно распределенных фаз различной геометрической формы и размеров на каждом из элементарных уровней строения их структуры.

В настоящее время существуют два распространенных подхода к моделированию эффективных упругих свойств цементных композитов – аналитическая и численная гомогенизация. Большинство проведенных исследований эффективных свойств цементных композитов основаны на положениях теории эффективной среды, относящейся к аналитической гомогенизации, в которых все фазы композита рассматривают как сферические включения, что позволяет получить относительно простые расчетные модели для их оценки. Это существенное допущение оказывает влияние на точность прогнозирования свойств, поскольку хорошо известно, что реальная геометрическая форма большинства фаз цементных композитов отличается от сферической. Одним из недостатков теории эффективной среды является то, что решения для несферических включений, могут быть получены только для правильной геометрической формы в виде эллипсоида.

В тоже время одним из преимуществ численной гомогенизации на основе конечно-элементного анализа является возможность определения упругих свойств для произвольной геометрической формы включений.

Данное исследование ориентировано на моделирование эффективных упругих свойств цементных композитов на основе многоуровневой схемы их структуры, используя для их оценки комбинацию аналитической и численной гомогенизации, рассматривая геометрическую форму фаз на каждом элементарном гетерогенном уровне, близкую к их реальной форме в структуре цементных композитов.

Ключевые слова: цементный камень, бетон, аналитическая и численная гомогенизация, многоуровневая структура, геометрическая форма.

Introduction

The elastic properties are crucial parameters, along with the compressive and tensile strengths, for describing the mechanical behavior of cement-based composites at an early age.

Modeling the elastic properties is the most complicated task in concrete technology. The reason is that, cement-based materials are three-phase composites consisting of a porous cement paste, the interfacial transition zone (ITZ), and aggregates [1]. In turn, cement paste itself is a composite with an extremely complex and heterogeneous structure formed during the hydration process.

It causes the fact, that modern approaches to modelling the elastic properties of cement-based composites involve a multiscale technique. This technique includes separate modelling the elastic properties at different scales depending on the microstructural morphology and sequential upscaling of properties from the underlying level to the upper one. A homogenization scheme is implemented at each level for predicting the effective elastic properties.

The key parameter of the homogenization is a representative element volume (REV), which is defined as the smallest volume element that has the same behaviour as the full-scale material [2]. Two scales can be well identified in the REV: the microscopic scale (or local scale) which represents the scale of inclusions, and the macroscopic scale (or overall scale) which represents the scale of the REV itself.

There are two principal ways for homogenization the elastic properties of composites:

1. Analytical homogenization (also called mean-field homogenization) based on the continuum mechanics, involving two class of effective theories: effective medium theory (EMT) and differential effective medium theory (DEMT) [3].
2. Numerical homogenization based on the finite element analysis (FEA)[1] [4].

[1] The numerical homogenization also involves the Fourier transform approach, which is not discussed here.

The analytical homogenization assumes that the microscopic strain fields are linked to the macroscopic ones throw the following linear dependency [5, 6]:

$$\boldsymbol{\varepsilon}_r = \mathbb{A}_r : \langle \boldsymbol{\varepsilon}_r \rangle_V; r = 1,2,\dots,n, \quad (1)$$

where $\boldsymbol{\varepsilon}_r$ – is the second-order strain tensor of the phase *r*;

$\mathbb{A}_r$ – is the fourth-order strain concentration tensor of the phase *r*;

$\langle \boldsymbol{\varepsilon}_r \rangle_V$ – is the second-order macroscopic strain tensor;

V – is the REV;

$\langle * \rangle_V$ – is the average of a field $\boldsymbol{f}$ over the REV, $\langle \boldsymbol{f} \rangle_V = \frac{1}{V}\int_V \boldsymbol{f}(\boldsymbol{x})dV$;

$\boldsymbol{x}$ – is the position of an arbitrary point in the REV;

n – is the number of phases;

«:» – is the double dot product.

The equation (1) describes the so-called localization problem in the homogenization theory.

Following the Hill-Mandel lemma, it leads to the macroscopic constitutive elastic law $\langle \boldsymbol{\sigma}_r \rangle_V = \mathbb{C}_{hom} : \langle \boldsymbol{\varepsilon}_r \rangle_V$, which along with the equation (1) brings out the next expression:

$$\langle \boldsymbol{\sigma}_r \rangle_V = \langle \mathbb{C}_r : \boldsymbol{\varepsilon}_r \rangle_V = \langle \mathbb{C}_r : \mathbb{A}_r : \langle \boldsymbol{\varepsilon}_r \rangle_V \rangle_V = \\ = \langle \mathbb{C}_r : \mathbb{A}_r \rangle_V : \langle \boldsymbol{\varepsilon}_r \rangle_V , \quad (2)$$

where $\langle \boldsymbol{\sigma}_r \rangle_V$ – is the second-order macroscopic stress tensor;

$\mathbb{C}_{hom}$ – is the fourth-order effective elasticity tensor;

$\mathbb{C}_r$ – is the fourth-order elasticity tensor of the phase *r*.

This in turn, yields the EMT homogenization model [5, 6]:

$$\mathbb{C}_{hom} = \sum_r f_r \, (\mathbb{C}_r : \mathbb{A}_r) , \quad (3)$$

where f_r – is the volume fraction of the phase *r*.

The most common solution of the localization problem, widely applied to cement-based composites, is the ellipsoidal inhomogeneity inclusion (also called the Eshelby's inclusion) embedded in a reference medium subjected to some uniform strain at infinity ($\boldsymbol{\varepsilon}_\infty$) [5]:

$$\boldsymbol{\varepsilon}_r = \mathbb{A}_r : \boldsymbol{\varepsilon}_\infty \quad (4)$$

$$\mathbb{A}_r = \left[\mathbb{I} + \mathbb{S}_r : \left(\mathbb{C}_0{}^{-1} : \mathbb{C}_r - \mathbb{I}\right)\right]^{-1}, \quad (5)$$

where $\mathbb{I}$ – is the fourth-order unit tensor;

$\mathbb{C}_0$ – is the fourth-order elasticity tensor of a reference medium;

$\mathbb{C}_r$ – is the fourth-order elasticity tensor of the phase *r*;

$\mathbb{S}_r$ – is the Eshelby tensor of the phase *r*, which depends on its geometric shape and elastic properties of a reference medium.

Taking the average of (4), we have:

$$\langle \boldsymbol{\varepsilon}_r \rangle_V = \langle \mathbb{A}_r : \boldsymbol{\varepsilon}_\infty \rangle_V = \langle \mathbb{A}_r \rangle_V : \boldsymbol{\varepsilon}_\infty = \left(\sum_r f_r \, \mathbb{A}_r\right) : \boldsymbol{\varepsilon}_\infty . \quad (6)$$

Finally, combining (3), (4), and (6) is given the following homogenization equation [3, 5]:

$$\mathbb{C}_{hom} = \sum_r f_r \, \mathbb{C}_r : [\mathbb{A}_r : (\textstyle\sum_r f_r \, \mathbb{A}_r)^{-1}]. \quad (7)$$

The elasticity tensor $\mathbb{C}_0$ should be chosen depending on specific morphology of the composite material. At the same time, there are several classical estimates for $\mathbb{C}_0$: the Mori-Tanaka (MT) scheme $\mathbb{C}_0 = \mathbb{C}_m$ ($\mathbb{C}_m$ – is the fourth-order elasticity tensor of a matrix phase), and the Self-Consistent (SC) scheme $\mathbb{C}_0 = \mathbb{C}_{hom}$ [5].

The DEMT deals with a two-phase composite characterized by matrix-inclusion morphology. Its homogenization model brings out from an iterative starting from a step where a dilute concentration of inclusions is randomly dispersed throughout a continuous matrix phase. At each step a differential volume element dV is replaced with the same volume of new inclusions randomly dispersed throughout the effective medium. Replacement inclusions are always an order of magnitude greater in size than those at the previous step. The effective elasticity tensor at each step is expressed by [3, 7]:

$$\mathbb{C}_{hom}(c + \Delta c) = \mathbb{C}_{hom}(c) + [(\mathbb{C}_{inc} - \mathbb{C}_{hom}) : \mathbb{A}_{inc}]\frac{dV}{V}, \quad (8)$$

where $\mathbb{C}_{inc}$ – is the fourth-order elasticity tensor of an inclusion;

$\mathbb{A}_{inc}$ – is the fourth-order strain concentration tensor of an inclusion;

c – is the volume fraction of an inclusion;

Δc – is the incremental volume concentration of an inclusion.

Which leads to the following generalized differential form [3, 7]:

$$\frac{d\boldsymbol{C}_{hom}}{dc} = \frac{1}{1-c}(\mathbb{C}_{inc} - \mathbb{C}_{hom}) : \mathbb{A}_{inc} , \quad (9)$$

with initial condition $\mathbb{C}_{hom} = \mathbb{C}_m$ at $c = 0$.

To sum up, analytical homogenization is most suitable for composites with spherical inclusions providing fairly simple models for calculating the effective elastic moduli. The considerable drawback is that analytical solutions to the Eshelby's inclusion are expressed for ellipsoidal inclusions, which restricts the geometric shape of composite inclusions to a sphere or spheroid.

The numerical homogenization assumes that the REV is subjected to a homogeneous strain field, where the equilibrium conditions for the microscopic stress field ($\boldsymbol{\sigma}(\boldsymbol{x})$) read as [4, 8]:

$$\nabla \cdot \boldsymbol{\sigma}(\boldsymbol{x}) = 0 \; \forall \boldsymbol{x} \in V \quad (10)$$

with the linear elastic constitutive law:

$$\boldsymbol{\sigma}(\boldsymbol{x}) = \mathbb{C}(\boldsymbol{x}) : \boldsymbol{\varepsilon}(\boldsymbol{x}) \; \forall \boldsymbol{x} \in V, \quad (11)$$

where $\mathbb{C}(\boldsymbol{x})$ – is the fourth-order elasticity tensor.

The microscopic strain field $\boldsymbol{\varepsilon}(\boldsymbol{x})$ can be split into the macroscopic strain $\bar{\boldsymbol{\varepsilon}}$ which would be the actual strain field in the REV if it were homogeneous, and the periodic fluctuation strain $\tilde{\boldsymbol{\varepsilon}}$ which accounts for the presence of heterogeneities [4, 8]:

$$\boldsymbol{\varepsilon}(\boldsymbol{x}) = \bar{\boldsymbol{\varepsilon}} + \tilde{\boldsymbol{\varepsilon}}\left(\tilde{\boldsymbol{u}}(\boldsymbol{x})\right), \quad (12)$$

where $\tilde{\boldsymbol{u}}(\boldsymbol{x})$ – is the periodic fluctuating displacement field.

Taking into consideration the condition $\langle \boldsymbol{\varepsilon} \rangle_V = \bar{\boldsymbol{\varepsilon}}$, it follows that $\langle \tilde{\boldsymbol{\varepsilon}} \rangle_V = 0$.

Generalizing (9), (10), and (11), the following variational formulation can be applied.

Find $\tilde{\boldsymbol{u}} \in V$ such that:

$$\int_V \left(\bar{\boldsymbol{\varepsilon}} + \tilde{\boldsymbol{\varepsilon}}(\tilde{\boldsymbol{u}})\right) : \mathbb{C}(\boldsymbol{x}) : \tilde{\boldsymbol{\varepsilon}}(\tilde{\boldsymbol{v}})dV = 0 \; \forall \tilde{\boldsymbol{v}} \in V, \quad (13)$$

$$\tilde{\boldsymbol{\varepsilon}}(\boldsymbol{u}) = \frac{1}{2}(\nabla \boldsymbol{u} + (\nabla \boldsymbol{u})^T) , \quad (14)$$

where $\tilde{\boldsymbol{v}}$ – is the test displacement function.

The above formulation is not well-posed due to the existence of the constraint $\langle \tilde{\boldsymbol{\varepsilon}} \rangle_V = 0$. One way to circumvent this is introducing a vectoral Lagrange multiplier $\boldsymbol{\lambda}$ as an additional unknown and reformulate the problem [9].

Find $(\tilde{\boldsymbol{u}}, \boldsymbol{\lambda}) \in V$ such that:

$$\int_V \left(\bar{\boldsymbol{\varepsilon}} + \tilde{\boldsymbol{\varepsilon}}(\tilde{\boldsymbol{u}})\right) : \mathbb{C}(\boldsymbol{x}) : \tilde{\boldsymbol{\varepsilon}}(\tilde{\boldsymbol{v}})dV + \int_V \boldsymbol{\lambda} \cdot \tilde{\boldsymbol{v}}dV + \int_V \boldsymbol{\theta} \cdot \tilde{\boldsymbol{u}} \, dV = \\ = 0 \; \forall (\tilde{\boldsymbol{v}}, \boldsymbol{\theta}) \in V , \quad (15)$$

where «·» – is the dot product.

The solution of above problem is performed for six elementary load cases consisting of uniaxial strain and pure shear solicitations by assigning unit values of the corresponding $\bar{\varepsilon}_{ij}$. The value $\bar{\varepsilon}_{ij}$ is usually taken to be 1 and 1/2 for uniaxial strain and shear, respectively. For example:

$$\bar{\varepsilon}_{11} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}; \bar{\varepsilon}_{12} = \begin{bmatrix} 0 & 1/2 & 0 \\ 1/2 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}. \quad (16)$$

For each load case, the average stress $\bar{\sigma}_{ij}$ is computed and then the components of the elasticity tensor $\boldsymbol{C}_{hom}$ are evaluated (see Figure 1).

Unlike the analytical homogenization, the numerical homogenization makes it possible to evaluate the effective elastic moduli of composites with inclusions of arbitrary geometrical shapes. The crucial disadvantages are significant difficulties related to generating a mesh for arbitrary geometry, and high computational complexity, which heavily depends on the mesh resolution and the finite elements used.

Cement-based composites consist of a large number of randomly distributed phases of different shapes and sizes, so to evaluate the effective elastic moduli it is most appropriate to use a combination of presented approaches, applying them primarily depending on the morphology of the phases at each elementary level. The geometric shape of phases plays important role in homogenization of effective properties along with their elastic properties and concentration, and is underestimated in the most existing models.

This paper presents the linear model of elastic properties of cement-based composites at early age based on the combination of these two approaches to provide a solution considering phase shapes close to the real ones, in contrast to existing approaches where they are mostly represented as spherical.

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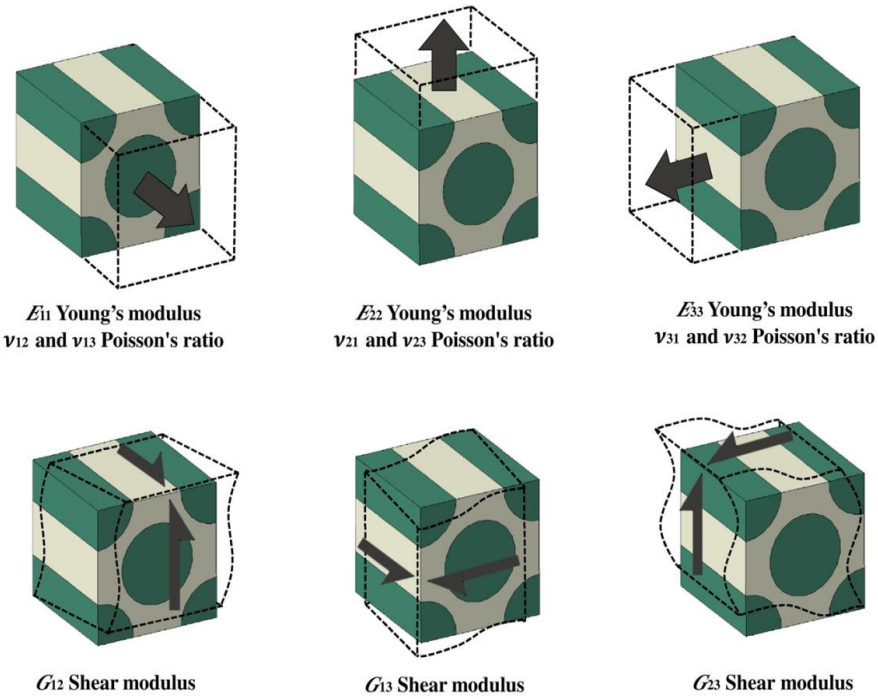

Figure 1 – Schematic representation of six elementary load cases required to estimate the effective elastic properties, according to [10]

Representation of multiscale microstructure

The microstructure of cement-based composites is divided into three elementary levels:

1. Level 1: Unhydrated cement consists of the C_3S[2], C_2S, C_3A, and C_4AF minerals, and hydration products consists of the CSH, CH, $C_6A\bar{S}_3H_{32}$, $C_4A\bar{S}H_{12}$, C_3AH_6, and FH_3 compounds;
2. Level 2: Cement paste consists of homogenous unhydrated cement, homogenous solid of hydration products, and porosity;
3. Level 3: Concrete consists of homogenous cement paste, the ITZ, and aggregates.

Microstructure development

One of the key features of modeling the effective elastic properties of cement-based composites is change over time in the volume fractions of the constitutive phases of cement paste.

The modeling of the microstructure development is a complex approach that includes two parts:

1) A hydration kinetics model for evaluating the hydration degree α at an arbitrary time step;

2) Predicting the volume fractions of cement paste phases corresponding hydration degree $f_r(\alpha)$ and associated with each hydration reaction.

The present model involves the kinetics model of Parrot and Killoh [11] and predicting the volume fractions using the stoichiometry of hydration reactions of clinker phases. To carry out the stoichiometry calculations, the sets of most well-known hydration reactions of Portland cement were taken from the model of Tennis and Jennings [12].

Another aspect of modeling is related to the fact that numerical homogenization requires spatial distribution cement paste phases over REV, which changes with time.

The most appropriate for these purposes is the discrete approach based on splitting up of REV into cubic cells with a certain edge length, typically 1 μm, called voxels. Each voxel represents part of a specific phase of REV at an arbitrary time step according to the stoichiometry of hydration reactions and the rules of handle individual voxels. The discrete approach can significantly simplify mesh generation.

One the well-known discrete models is CEMHYD3D [13]. However, the considered model uses a computationally simpler model presented in [14].

Multiscale homogenization

Level 1

The most suitable scheme at that level is the SC scheme, in which the reference medium coincides with the homogenized medium:

– for unhydrated cement: $\mathbb{C}_0 = \mathbb{C}_{uc}$;

– for hydration products: $\mathbb{C}_0 = \mathbb{C}_{hp}$;

where $\mathbb{C}_{uc}$ – is the fourth-order effective elasticity tensor of homogenous unhydrated cement;

$\mathbb{C}_{hp}$ – is the fourth-order effective elasticity tensor of homogenous solid of hydration products.

The SC scheme is classically used to homogenize a polycrystalline structure consists of an agglomeration of individual crystallites (grains), that accurately reflects both the structure of unhydrated cement and the solid of hydration products.

The main problem here is the choice of geometrical shape of phases. A spherical shape is a classical choice in most existing models. This is considerable assumption, since a lot of SEM analyses of the microstructure of cement paste identify that the shape of most hydration products is not spherical [15].

Meanwhile, as it has been noted, the analytical homogenization imposes restrictions that non-spherical inclusions can be approximated by one of the spheroidal shapes: oblate or prolate, i. e. homogenous solid of hydration products is represented by a set of spheroids, which differ in orientation. In this way, the problem is reduced to choosing the appropriate spheroid shape for each hydration product by determining its aspect ratio.

Assuming that spheroidal phases are isotropically oriented (i. e. in all directions) in the REV, the average strain concentration tensor is defined as [16, 17]:

$$\langle \mathbb{A}_r \rangle = \frac{1}{4\pi} \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi} \widetilde{\mathbb{A}}_r \, \sin\theta \, d\theta \, d\phi, \tag{17}$$

where $\widetilde{\mathbb{A}}_r$ – is the strain concentration tensor of the spheroidal phase *r* in the spherical coordinates, calculated as:

$$\widetilde{\mathbb{A}}_r = R_{im} R_{jn} R_{kp} R_{lq} A_{mnpq},$$

$$\text{and} = \begin{bmatrix} cos\theta & -sin\theta & 0 \\ sin\theta cos\phi & cos\theta cos\phi & -sin\phi \\ sin\theta sin\phi & cos\theta sin\phi & cos\phi \end{bmatrix}, \tag{18}$$

[2] The cement chemist notation is used.

where ϕ and θ – are the azimuthal and polar angle, respectively.

The average strain concentration tensor now should be taken for calculating the effective elasticity tensor in the homogenization equation (7), since the original tensor (5) assumes to axis-aligned orientation.

It is worth noting, that the above solution significantly increases computational costs, since the SC scheme is a system of nonlinear equations with respect to the components of the effective tensor, involving the above complex transformation of the fourth-order strain concentration tensor in solving it.

Regarding the morphology of Portland cement, it is not known with any certainty. Nevertheless, in this paper is assumed that it is close to spherical.

Level 2

The most frequent scheme at that level is the MT scheme, in which porosity is considered as spherical inclusions. However, pores cannot be completely characterized by a single geometric shape, the morphology of pores is complex and has a wide range of both pore shapes and sizes (from the nanometer to micrometer scale). In order to account the realistic pore characteristics, it is more suitable to use the FEA-based homogenization.

Besides, the pure MT scheme is not well-posed at that level since, the porosity of cement paste is partially saturated with water during the hydration process. Consequently, a combination of the MT scheme and poromechanics is required for predicting the effective moduli [18].

The FEA-based homogenization taken in conjunction with a discrete REV of cement paste provides more flexible solution not restricted by porosity shape, and can be effectively implemented without involving poromechanics.

The discrete REV represents the set of voxels each of which has stiffness depending on the phase it belongs to. And in addition, a voxel is cubic element that can be easily transformed into a hexahedral finite element.

The presented model uses a hexahedral mesh which is generated based on the discrete REV obtained from the microstructural model [14], and consists of the following finite elements:

– for strain field: a trilinear 8 nodes hexahedron with 3 degree-of-freedom (DOF) per node;

– for stress field: a trilinear 8 nodes hexahedron with 1 DOF per node.

The mesh has four subdomains related to the phases of unhydrated cement, hydration products, and porosity, represented by water and air subdomains. Each finite element has the same elasticity tensor within a subdomain.

The global stiffness matrix and nodal load vector are assembled by applying the variational formulation (15), where:

$$\mathbb{C}(\boldsymbol{x}) = \begin{cases} \mathbb{C}_{uc} \ \forall \boldsymbol{x} \in V_{uc} \\ \mathbb{C}_{hp} \ \forall \boldsymbol{x} \in V_{hp} \\ \mathbb{C}_{w} \ \forall \boldsymbol{x} \in V_{w} \\ \mathbb{C}_{air} \ \forall \boldsymbol{x} \in V_{air} \end{cases}, \tag{19}$$

where $\mathbb{C}_w$, $\mathbb{C}_{air}$ – is the fourth-order elasticity tensor of water and air, respectively;

V_{uc}, V_{hp}, V_w, V_{air} – are the subdomains of the REV referring to the phases of unhydrated cement, hydration products, water, and air, respectively.

One more important aspect of the FEA-based homogenization is boundary condition. Typical boundary condition for approximating a solution over a REV are periodic boundary conditions under which each node experiences the same periodic displacement as the opposite node.

This approach is characterized by high computational complexity associated with the assembly of the stiffness matrix and nodal load vector as well as solving the linear system, and the regeneration of the mesh at each time step.

Level 3

This level is characterized by fairly clear morphology: a cement matrix and aggregate particles of different sizes embedded into it. The ITZ around each aggregate particle separates them from a cement matrix. This area differs structurally and mechanically from both the cement matrix and aggregates.

One of possible approaches to modelling such a composite structure is reduce it to a two-phase morphology: a matrix with composite particles embedded into it, consisting of aggregate particles surrounded by an ITZ layer. It means, the original problem is divided into two subproblems:

1. Homogenization of a composite particle (also called effective particle mapping);
2. Homogenization of a concrete microstructure.

According to [19], the effective particle mapping for a spherical particle surrounded by a matrix shell, effectively can be done using the Generalized Self-Consistent (GSC) scheme:

$$\mathbb{C}_p = \mathbb{C}\left(\mathbb{C}_{ITZ}, \mathbb{C}_{agg}, \left(\frac{r_{agg}}{r_{agg}+\delta_{itz}}\right)^3\right), \tag{20}$$

where $\mathbb{C}_p$ – is the fourth-order effective elasticity tensor of a composite particle;

$\mathbb{C}_{ITZ}$ – is the fourth-order elasticity tensor of a matrix shell (in this case, it is the ITZ);

$\mathbb{C}_{agg}$ – is the fourth-order elasticity tensor of a representative aggregate particle;

r_{agg} – is the radius of a representative aggregate particle;

δ_{itz} – is the thickness of the ITZ around aggregate particles.

The presented scheme is certainly realizable for rounded fine aggregates and cubic coarse aggregates, since their shape can be approximated as spherical with relatively small error. On the contrary, the shape of flaky and elongated coarse aggregates is closer to a prolate spheroid, which reduces the accuracy of the scheme in relation to them.

In this way, for effective particle mapping of coarse aggregates preference is given to MT scheme:

$$\mathbb{C}_p = f_{agg}\left(\mathbb{C}_{agg} : \mathbb{A}_{agg}\right) + f_{ITZ}\mathbb{C}_{ITZ}, \tag{21}$$

where $\mathbb{A}_{agg}$ – is the strain concentration tensor of a representative aggregate particle, which is calculated according to (5);

f_{agg} – is the volume fraction of a representative aggregate particle inside a composite particle, which is calculated as:

$$f_{agg} = \frac{V_{agg}}{V_p}, \tag{22}$$

V_{agg} – is the volume of a representative aggregate particle;

V_p – is the volume of a composite particle;

f_{ITZ} – is the volume fraction of the ITZ in a composite particle, $f_{ITZ} = 1 - f_{agg}$.

The aggregates are a huge mass of particles of different sizes characterized by a particle size distribution. So, the following question arises, what a representative aggregate particle is in this case? The simplest answer to this is to take any type of averages, for instance, weighted average. However, it is obvious, simple averaging is not appropriate for estimating the entire population of aggregate particles.

Here, a more flexible iterative process is used, where at each step a composite consisting of a representative aggregate particle of the i-th fraction surrounded by a uniform matrix shell is considered. At each step, the thickness of a matrix shell remains constant. A number of steps is equal to a number of aggregate fractions.

The effective elasticity tensor calculated by (20) or (21) from the previous step is the matrix elasticity tensor for the current step. At the first step, the matrix elasticity tensor is $\mathbb{C}_{ITZ}$. Finaly, the effective elasticity tensor of a composite particle will be reached in the last step.

The analyzes of the concrete morphology indicates that the DEMT is probably the best choice for the homogenization its microstructure, since a well match is observed between a concept of the DEMT and the concrete microstructure. So, the effective elasticity tensor of concrete ($\mathbb{C}_c$) computes according to (9):

$$\frac{d\mathbb{C}_c}{dc} = \frac{1}{1-c}\left(\mathbb{C}_p - \mathbb{C}_c\right) : \langle \mathbb{A}_p \rangle, \tag{23}$$

with initial condition $\mathbb{C}_c = \mathbb{C}_{cp}$ at $c = 0$.

where : $\langle \mathbb{A}_p \rangle$ – is the average fourth-order strain concentration tensor of a composite particle, calculated using (17) for non-spherical particles, otherwise $\langle \mathbb{A}_p \rangle = \mathbb{A}_p$;

$\mathbb{C}_{cp}$ – is the fourth-order effective elasticity tensor of homogenous cement paste.

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Nevertheless, it is impossible to directly solve the above differential equation, since the composite contains composite particles of two types – fine and coarse. To get around this problem, one of the possible solutions is to use an iterative process similar to described one earlier: first the equation is solved for the fine composite particles, then this solution is the initial condition for the equation solving with respect to coarse composite particles.

Percolation threshold

Percolation threshold of the solid phase of cement paste plays key role from the point of view of its mechanical behavior. It describes a state of cement paste corresponding to the setting process during which the initial stiffness of the cement system is formed, i.e. below which elastic moduli can be neglected.

According to percolation theory any mechanical characteristic will be proportional to the volume of connected (percolated) clusters in the system. This means that it is necessary to determine the percolation clusters each time step in the discrete REV and the stiffness matrix and nodal vector must be assembled only from finite elements related to these clusters, that is a rather complex computational problem.

At the same time, the percolation theory provides a simple analytical solution represented by a power law in the following normalized form:

$$\mathbb{C}_{cp} = \mathbb{C}_{cp}^{FEA}\left(\frac{\alpha-\alpha_{per}}{1-\alpha_{per}}\right)^{\gamma}, \quad (24)$$

where $\mathbb{C}_{cp}^{FEA}$ – is the is the effective fourth-order elasticity tensor of cement paste according to the FEA-based homogenization;

α – is the hydration degree of cement;

α_{per} – is the hydration degree of cement corresponding to the percolation threshold of the solid phase;

γ – is the exponent.

Modelling results

Concrete with parameters reported in Table 1 was used for the simulation.

The parameters of the constitutive phases of cement paste report in Table 2. The elastic properties of the phases in Table 2 were taken according to [20].

The analyzed hydration period is 28 days.

The predicted phase composition of cement paste during hydration period is shown in Figure 2.

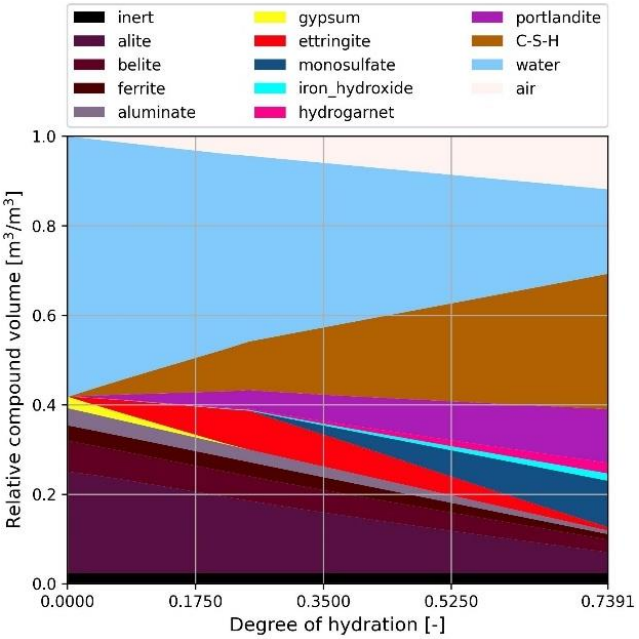

Figure 2 – The predicted phase composition of cement paste during hydration period

The REV resolution was considered in the range from 10 voxels/edge to 20 voxels/edge to reduce the computational cost (1 voxel = 1 μm³).

The Eshelby's tensor was computed according to [21].

Table 1 – Parameters of concrete

Mix proportions, kg/m³				Water to cement ratio	Density, kg/m³			Fineness of cement, m²/kg	Mineral composition of cement (mass %)
Portland Cement	Water	Aggregate			Portland Cement	Aggregate			
		fine	coarse			fine	coarse		
370	185	754	969	0,5	3150	2510	2640	345	C_3S: 54,5; C_2S: 17,3; C_3A: 8,9; C_4AF: 7,6; Gypsum: 5

Table 2 – Parameters of the constitutive phases of cement paste

Parameter	Phase										
	C_3S	C_2S	C_3A	C_4AF	CSH	CH	$C_6A\bar{S}_3H_{32}$	$C_4A\bar{S}H_{12}$	C_3AH_6	FH_3	Gypsum
Young's modulus, GPa	137,4	135,5	145,2	150,8	23,8	43,5	24,1	43,2	93,8	22,4	44,5
Poisson's ratio	0,299	0,297	0,278	0,318	0,24	0,294	0,321	0,292	0,32	0,25	0,33
Aspect ratio	1,0	1,0	1,0	1,0	0,01	0,1	100	10	1,0	1,0	1,0

The elastic properties of water: the bulk modulus is 2,2 GPa, the Poisson's ratio is 0,499. The elastic properties of air were taken to be close to zero.

The particle size distribution of aggregates is provided by Gates-Gaudin-Schuhman distribution. Characteristic particle diameter was taken for fine aggregate 8 mm, for coarse aggregate 31,5 mm. Particle size distribution exponent is equal to 1,5 for both cases.

The average particle size for each fraction of aggregates was determined as the volume-weighted mean diameter (also called De Brouckere mean diameter).

The parameters of aggregates report in Table 3.

The elastic properties of the ITZ were considered as 1/3 of the effective elastic properties of cement paste. The thickness of the ITZ is equal to 50 μm.

The exponent in the equation (24) is equal to 1.

The modeling results are presented in Figures 3, 4, and 5.

Table 3 – Parameters of aggregates

Parameter	Aggregate	
	fine	coarse
Young's modulus, GPa	59,5	63,5
Poisson's ratio	0,25	0,31
Aspect ratio	1,0	3,0
Sieve size, mm	0,5; 1; 2; 4; 8	4; 8; 16; 31,5

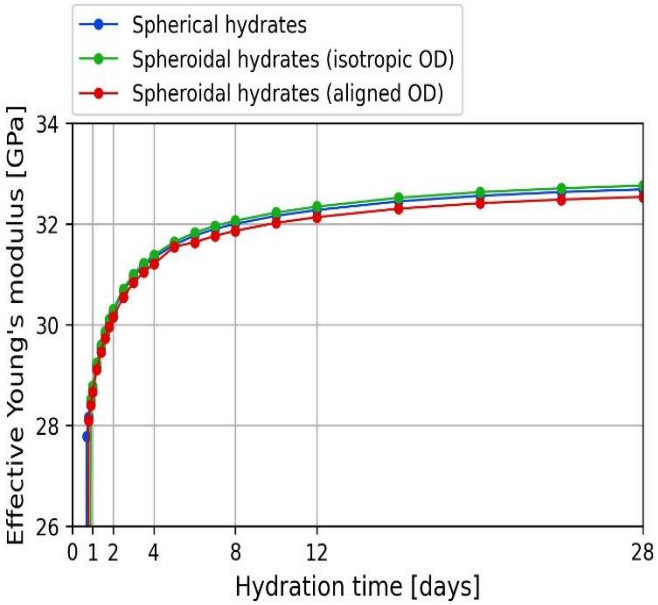

Figure 3 – Comparison of the effective Young's modulus of hydration products computed by using the SCS scheme, depending on their shape and orientation (OD – orientation distribution)

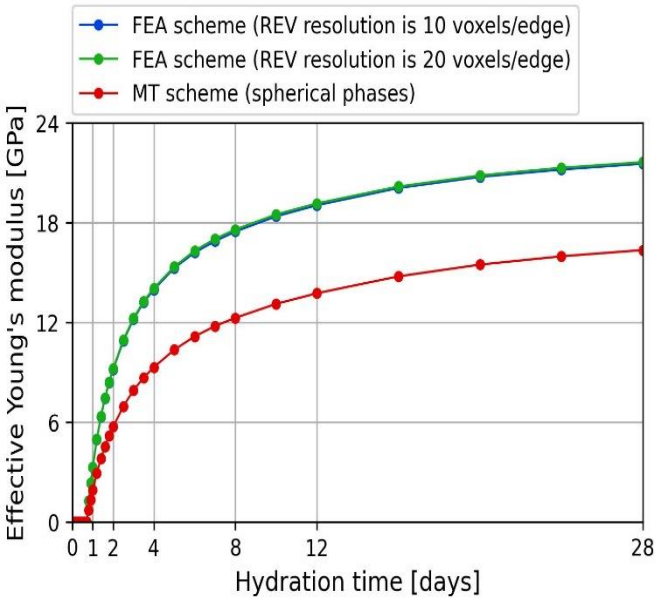

Figure 4 – Comparison of the effective Young's modulus of cement paste computed by using the FEA and MT schemes
(the effective Young's modulus of hydration products and clinker phases were computed by using the SC scheme)

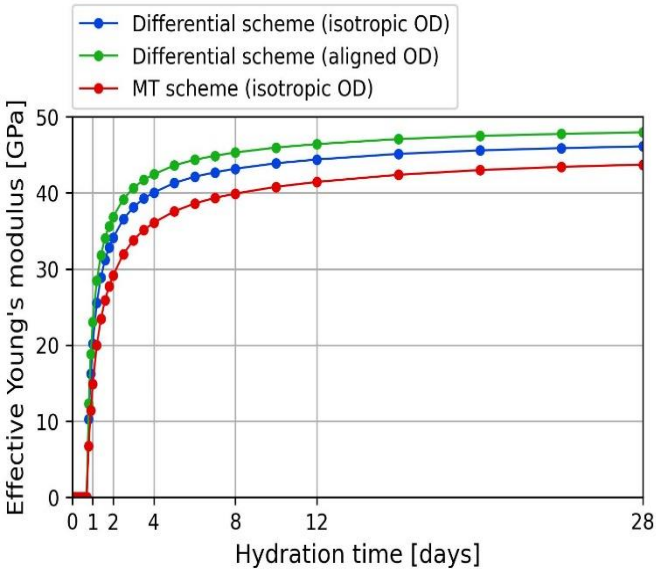

Figure 5 – Comparison of the effective Young's modulus of concrete computed by using the Differential and MT schemes
(the effective Young's modulus of hydration products and clinker phases were computed by using the SC scheme, the effective Young's modulus of cement paste using the FEA scheme at a REV resolution of 10 voxels/edge)

Conclusions

1. Cement-based composites consist of a large number of phases of different shapes and sizes, so an approach to predicting effective elastic properties considering all phases as spherical inclusions, is not an effective solution that may reduce the accuracy of predicting.
2. The structure of cement-based composites and morphology of phases differ significantly at each scale level preventing the use of only one specific way for homogenization elastic properties.
3. The most preferable approach is to use both analytical and numerical homogenization, which leads to achieving acceptable accuracy in predicting effective characteristics.
4. The limitation of as such approach is the high computational complexity.
5. Analysis of the microstructure of cement-based composites cement-based composites indicates that the SC scheme is the best possible way to predict the effective elastic properties of hydration products and clinker phases, for a cement paste – the FEA scheme, and for concrete – Differential scheme.

References

1. Nilsen, A. U. Concrete: A three phase material / A. U. Nilsen, P. J. M. Monteiro // Cement and Concrete Research. – 1993. – Vol. 23, Iss. 1. – P. 147–151. – DOI: 10.1016/0008-8846(94)90102-3.
2. Moumen, A. E. Numerical evaluation of the representative volume element for random composites / A. E. Moumen, T. Kanit, A. Imad // European Journal of Mechanics - A/Solids. – 2021. – Vol 86, article 104181. – P. 1–20. – DOI: 10.1016/j.euromechsol.2020.104181.
3. Dvorak, G. J. Micromechanics of Composite Materials / G. J. Dvorak. – New York : Springer Science & Business Media, 2012. – 460 p. – DOI: 10.1007/978-94-007-4101-0.
4. Yvonnet, J. Computational Homogenization of Heterogeneous Materials with Finite Elements / J. Yvonnet. – New York : Springer Cham, 2019. – 223 p. – DOI: 10.1007/978-3-030-18383-7.
5. Zaoui, A. Continuum micromechanics: survey / A. Zaoui // Journal of Engineering Mechanics. – 2002. – Vol 128, Iss. 8. – P. 808–816. – DOI: 10.1061/(ASCE)0733-9399(2002)128:8(808).
6. Segura, N. J. Concentration tensors preserving elastic symmetry of multiphase composites / N. J. Segura, B. L. A. Pichler, C. Hellmich // Mechanics of Materials. – 2023. – Vol. 178, article 104555. – P. 1–12. – DOI: 10.1016/j.mechmat.2023.104555.

7. Kim, M. Differential Scheme Effective Medium Theory for Hot-Mix Asphalt |E*| Prediction / M. Kim, W. G. Buttlar // Journal of Materials in Civil Engineering. – 2011. – Vol. 23, Iss. 1. – P. 69–78. – DOI: 10.1061/(ASCE)MT.1943-5533.000002.
8. Michel, J. C. Effective properties of composite materials with periodic microstructure: a computational approach / J. C. Michel, H. Moulinec, P. Suquet // Computer Methods in Applied Mechanics and Engineering. – 1999. – Vol 172, Iss. 1–4. – P. 109–143. – DOI: 10.1016/S0045-7825(98)00227-8.
9. Bleyer, J. Numerical Tours of Computational Mechanics with FEniCS / J. Bleyer. – Genève: Zenodo, 2018. – 100 p. – DOI: 10.5281/zenodo.1287832.
10. Omairey, S. L. Development of an ABAQUS plugin tool for periodic RVE homogenisation / S. L. Omairey, P. D. Dunning, S. Sriramula // Engineering with Computers. – 2019. – Vol 35. – P. 567–577. – DOI: 10.1007/s00366-018-0616-4.
11. Thermodynamic modelling of the effect of temperature on the hydration and porosity of Portland cement / B. Lothenbach, T. Matschei, G. Möschner, F. P. Glasser // Cement and Concrete Research. – 2008. – Vol. 38, Iss. 1. – P. 1–18. – DOI: 10.1016/j.cemconres.2007.08.017.
12. Tennis, P. D. A model for two types of calcium silicate hydrate in the microstructure of Portland cement pastes / P. D. Tennis, H. M. Jennings // Cement and Concrete Research. – 2000. – Vol. 30, Iss. 6. – P. 855–863. – DOI: 10.1016/S0008-8846(00)00257-X.
13. CEMHYD3D: A Three-Dimensional Cement Hydration and Microstructure Development Modelling Package: Version 3.0 : NIST Interagency Internal Report / National Institute of Standards and Technology ; ed. D. P. Bentz – Gaithersburg, 2005. – 227 p. – NISTIR 7232. – DOI: 10.6028/NIST.IR.7232.
14. Kravchenko, V. V. Modelling of the voxel-based microstructure of the cement paste / V. V. Kravchenko // Vestnik BSTU. – 2024. – Vol 1. – P. 14–18. – DOI: 10.36773/1818-1112-2024-133-1-14-18.
15. Stora, E. Influence of inclusion shapes on the effective linear elastic properties of hardened cement pastes / E. Stora, Q. C. He, B. Bary // Cement and Concrete Research. – 2006. – Vol. 36, Iss. 7. – P. 1330–1344. – DOI: 10.1016/j.cemconres.2006.02.007.
16. Sanahuja, J. Modelling elasticity of a hydrating cement paste / J. Sanahuja, L. Dormieux, G. Chanvillard // Cement and Concrete Research. – 2007. – Vol 37, Iss. 10. – P. 1427–1439. – DOI: 10.1016/j.cemconres.2007.07.003.
17. Sangryun, L. Theoretical study of the effective modulus of a composite considering the orientation distribution of the fillers and the interfacial damage / L. Sangryun, S. Ryu // European Journal of Mechanics - A/Solids. – 2018. – Vol 72. – P. 79–87. – DOI: 10.1016/j.euromechsol.2018.02.008.
18. Ulm, F. J. Is concrete a poromechanics materials? – A multiscale investigation of poroelastic properties / F. J. Ulm, G. Constantinides, F. H. Heukamp // Materials and Structures. – 2004. – Vol 37. – P. 43–58. – DOI: 10.1007/BF02481626.
19. Garboczi, E. J. Elastic moduli of a material containing composite inclusions: effective medium theory and finite element computations / E. J. Garboczi, J. G. Berryman // Mechanics of Materials. – 2001. – Vol. 33, Iss. 8. – P. 455–470. – DOI: 10.1016/S0167-6636(01)00067-9.
20. Rhardane, A. Development of a micro-mechanical model for the determination of damage properties of cement pastes / A. Rhardane, F. Grondin, S. Y. Alam // Construction and Building Materials. – 2020. – Vol. 261, article 120514. – P. 1–30. – DOI: 10.1016/j.conbuildmat.2020.120514.
21. Mura, T. Micromechanics of Defects in Solids / T. Mura. – Second edition. – Dordrecht : Springer, 1987. – 588 p. – DOI: 10.1007/978-94-009-3489-4.

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A HOMOGENIZATION METHOD FOR STIFFNESS CHARACTERISTICS OF CEMENT PASTE UNDER VISCOELASTIC BEHAVIOR

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Abstract

The microstructure of cement paste is extremely complex and heterogeneous, consists of randomly distributed phases with an arbitrary geometry, formed during the hydration process. The key phase of cement paste – calcium silicate hydrate exhibits distinct viscoelastic behavior causing creep in cement-based composites. These reasons make the problem of evaluating effective stiffness characteristics rather difficult, since stress-strain relationships under viscoelastic behavior are usually described using the principle of aging-time superposition, represented in the form of the Stiltes integral, which has not an analytical solution.

Existing approaches to solving this problem involve two principles: the Laplace–Carson transform and the effective medium theory. This makes possible to find a solution for the evaluate effective stiffness characteristics under viscoelastic behavior, but only for a limited geometric shape of inclusions in the form of an ellipsoid and its related shapes. However, such shapes are not fully matching the real geometric shape of most phases of cement paste, especially for capillary porosity.

The paper presents one more approach to solving the problem of effective stiffness characteristics of cement paste based on a FEA homogenization facilitates to evaluate effective stiffness properties for an arbitrary phase geometry, through introducing into the variational formulation the numerical inversion of the Stieltjes integral describing its viscoelastic behaviour. In addition, this approach best implements the solidification mechanism for the history of the aging stress-strain relation during the hydration process.

Keywords: cement paste, viscoelasticity, homogenization, solidification theory, FEA.

ПРИНЦИП ГОМОГЕНИЗАЦИИ ЖЕСТКОСТНЫХ ХАРАКТЕРИСТИК ЦЕМЕНТНОГО КАМНЯ ПРИ ВЯЗКОУПРУГОМ ПОВЕДЕНИИ

В. В. Кравченко

Реферат

Микроструктура цементного камня чрезвычайно сложна и неоднородна, состоит из хаотично распределенных фаз с произвольной геометрией, образуемых в процессе гидратации. При этом следует учитывать, что основная фаза цементного камня – гидросиликат кальция – проявляет ярко выраженное вязкоупругое поведение, обуславливая возникновение ползучести в цементных композитах. Эти причины делают задачу оценки его эффективных жесткостных характеристик достаточно сложной, поскольку напряженно-деформированное состояние в условиях вязкоупругого поведения принято рассматривать с позиций теории нелинейной наследственности, представляемой в виде интеграла Стилтьеса, не имеющего аналитического решения.

Существующие подходы к решению обозначенной проблемы сочетают два принципа: преобразование Лапласа – Карсона и положения теории эффективной среды, что позволяет находить решение задачи эффективных свойств композитов при вязкоупругом поведении. Однако поскольку получаемые решения в рамках такого подхода основаны на положениях теории эффективной среды, это приводит к достаточно существенному ограничению, накладываемому на геометрическую форму фаз композита, которые могут быть представлены только в виде эллипсоида и его производных форм, что не совсем соответствует реальной геометрической форме большинства фаз цементного камня, в особенности капиллярной пористости.

В статье представлен еще один подход к решению задачи эффективных жесткостных характеристик цементного камня при вязкоупругом поведении, основанный на положениях гомогенизации методом конечных элементов, позволяющей оценивать эффективные жесткостные характеристики композитов с произвольной геометрической формой фаз, в вариационную формулировку которого вводится численное обращение интеграла Стилтьеса, описывающего вязкоупругое поведение цементного камня. Кроме того, этот подход наилучшим образом реализует положения теории солидификации при формировании истории напряженно-деформированного состояния в период гидратации.

Ключевые слова: цементный камень, гомогенизация, вязкоупругость, теория солидификации, МКЭ.

Introduction

Cement paste[1] is a crucial phase of cement-based composites which in many respects determines their mechanical behavior at an early age. It is a composite consisting of a solid phase (hydration products and unhydrated cement), a liquid phase (water), and a gas phase (air) with a complex and heterogeneous structure formed during the hydration process.

One of the key features of cement paste is that the solid phase has the distinctly viscoelastic behavior which originates in the calcium silicate hydrates, and causes creep in cement-based composites [1].

There are many prediction models for evaluating the effective stiffness characteristics of cement paste based on the principles of multiscale modeling, and dealing with the following techniques of homogenization:

1. Analytical homogenization, including two class of effective theories: effective medium theory and differential effective medium theory [2].
2. Numerical homogenization based, including two methods based on: finite element analysis (FEA) [3] and the Fourier transform [4].

The obvious drawback of these models is that they consider cement paste through linear elastic behaviour. At the same, there are only a few models taking into consideration viscoelastic behavior of cement paste. The models [5, 6] use the Laplace–Carson transform which converts non-ageing linear viscoelastic behavior into linear elastic one, allowing to directly apply the analytical homogenization schemes. Then, the numerical inversion of the Laplace–Carson transform is used for the aging vis-

[1] Here the term «cement paste» refers to the hardened cement paste.

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coelastic solution. The model [7] uses a principle based on Volterra integral operators, allowing to directly apply the Mori-Tanaka scheme for the aging viscoelastic solution.

Despite the fact that these models allow for the possibility of linear viscoelastic behavior, they still have restrictions imposed by the analytical homogenization schemes related to the geometric shape of the inclusions, assuming to be spherical in most cases. This considerable assumption may decrease accuracy of predicting the effective stiffness characteristics, since it is a well-known fact that the shape of most hydration products is not spherical. This is especially so for capillary porosity with a complex morphology, including various geometric shapes with irregular spatial distribution.

This paper presents approach based on the FEA homogenization, which is not sensitive to a geometric shape of inclusions, through introducing into the variational formulation the numerical inversion of the following Stieltjes integral, expressing the principle of superposition [8]:

$$\boldsymbol{\varepsilon}(t) = \int_0^t \mathbb{J}(t,t')\ d\boldsymbol{\sigma}(t'), \quad (1)$$

where $\boldsymbol{\varepsilon}(t)$ – is the second-order microscopic strain tensor at time t representing the age of a cement-based composite;

$\mathbb{J}(t,t')$ – is the fourth-order compliance tensor representing the strain at time t caused by a stress that has been acting since time t';

$\boldsymbol{\sigma}(t')$ – is the second-order microscopic stress tensor at time t'.

The time-dependent compliance tensor contains a time-dependent elastic part and a time-dependent viscous part [8]:

$$\mathbb{J}(t,t') = \mathbb{C}(t')^{-1} + \mathbb{J}_v(t,t'), \quad (2)$$

where $\mathbb{C}$ – is the fourth-order elasticity tensor;

$\mathbb{J}_v$ – is the fourth-order viscoelastic compliance tensor.

The principle of superposition relates the stress and strain histories states that the response to a sum of two stress (or strain) histories is the sum of the responses to each of them taken separately [8]. For the microstructural development of cement paste caused by a hydration process, the stress and strain histories can be expressed throw the solidification theory that assumes that fictitious clusters of cement paste are gradually added to the existing ones. Cement paste is considered as a set of all formed clusters (see Figure 1). Since clusters are formed at different ages, history variables for different clusters are treated as mutually independent variables [9, 10].

The presented approach based on the FEA homogenization implements the principles of the solidification theory to express strain and stress history.

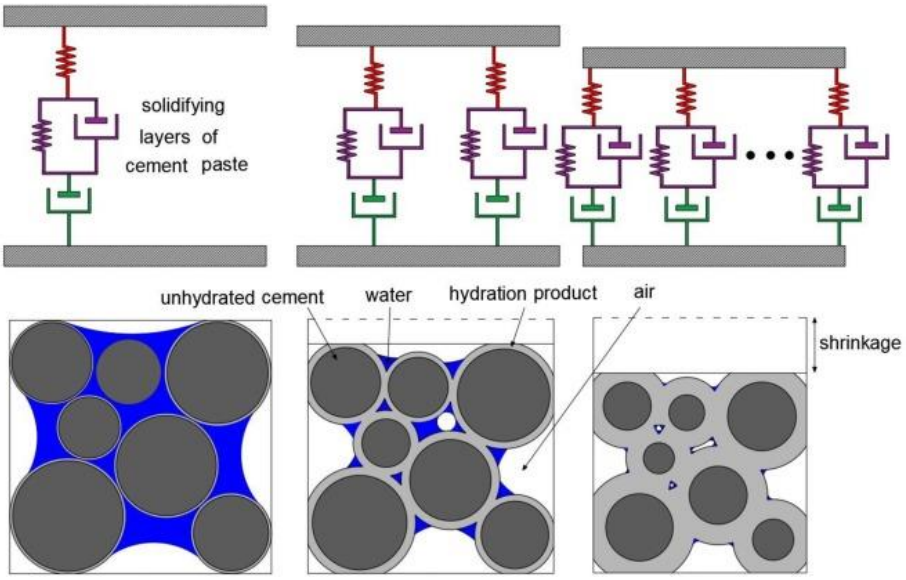

Figure 1 – Schematic representation of solidifying clusters of cement paste, according to [10]

Basic assumptions and principles

1. The microstructure of cement paste is considered at two scales:

– Level 1: Unhydrated cement consists of the C_3S[1], C_2S, C_3A, and C_4AF minerals, and hydration products consists of the CSH, CH, $C_6A\bar{S}_3H_{32}$, $C_4A\bar{S}H_{12}$, C_3AH_6, and FH_3 compounds.

– Level 2: Cement paste consists of homogenous unhydrated cement, a homogenous solid of hydration products, and porosity, including a liquid phase (water) and a gas phase (air).

2. The hydration-induced evolution of the volume fractions of clinker, hydrates, and pores is quantified based on the stoichiometry of hydration reactions of clinker phases. The hydration reactions of Portland cement were taken from the model of Tennis and Jennings [11].

3. Hydration of clinker phases is modeled through the kinetics model of Parrot and Killoh [12].

4. The morphology of cement particles is modeled as spherical, and the hydration products as prolate or oblate spheroidal that is isotropically oriented in the representative element volume (REV).

5. The effective elastic tensor of homogenous unhydrated cement ($\mathbb{C}_{uc}$) and a homogenous solid of hydration products ($\mathbb{C}_{hp}$) are estimated using the Self-Consistent scheme [2].

6. The REV of cement paste is a voxel-based grid considered no more 50×50×50 μm in size with a resolution of 1 μm^3/voxel.

7. The voxel-based microstructural model [13] is used for the spatial distribution the phases of cement paste over the REV during the hydration process.

8. Continuous hydration time is discretized into n time intervals $\Delta t_i = t_i - t_{i-1}, i = \overline{1,n}$.

9. A hexahedral mesh is generated based on the voxel-based REV, and consists of the following finite elements:

– for strain field: a trilinear 8 nodes hexahedron with 3 degree-of-freedom (DOF) per node;

– for stress field: a trilinear 8 nodes hexahedron with 1 DOF per node.

10. The hexahedral mesh is divided into four subdomains related to the phases of cement paste. Each finite element has the same elasticity tensor within a subdomain.

11. Periodic boundary conditions are implemented to approximate the REV as an infinite system with a structural periodicity.

[1] The cement chemist notation is used.

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12. Since, only the CSH phase has viscoelastic behavior, the modified model from [14] is used for the compliance tensor:

$$\mathbb{J}(t,t') = \mathbb{C}_{hp}(t')^{-1} + \mathbb{J}_{CSH}(t,t') = \\ = \mathbb{C}_{hp}(t')^{-1} + \mathbb{B}\frac{1}{C_v(1-\nu^2)} ln\left(1+\frac{t-t'}{\tau}\right), \quad (3)$$

where C_v – is the contact creep module calculated by [14];

$\mathbb{B}$ – is the fourth-order tensor for transformation into three-dimension stress-strain relationship, which depends on the elastic properties of the CSH phase [8];

ν – is the Poisson's ratio of the CSH phase;

τ – is the characteristic viscous time, 1,66 s [14].

13. The numerical inversion of the integral (1) is used according to the trapezoidal rule [8]:

$$\boldsymbol{\varepsilon}_i = \sum_{j=1}^{i}\left[\frac{1}{2}\left(\mathbb{J}(t_i,t_j) + \mathbb{J}(t_i,t_{j-1})\right) : \Delta\boldsymbol{\sigma}_j\right] = \sum_{j=1}^{i}\mathbb{J}(t_i,t_{j-1/2}) : \Delta\boldsymbol{\sigma}_j \text{ for } i \geq 1, \quad (4)$$

where $\boldsymbol{\varepsilon}_i$ – is the second-order stress tensor of i-th time interval;

t_i, t_j – is time related to the end of i-th and j-th time interval, respectively;

$t_{j-1/2}$ – is time related to the middle of j-th time interval;

$\Delta\boldsymbol{\sigma}_j$ – is the incremental of the second-order stress tensor of j-th time interval;

«:» – is the double dot product.

Then, the difference of the second-order stress tensor at i-th time interval ($\Delta\boldsymbol{\varepsilon}_i$) can be expressed by [8, 15]:

$$\Delta\boldsymbol{\varepsilon}_i = \mathbb{J}(t_i,t_{i-1/2}) : \Delta\boldsymbol{\sigma}_i + \sum_{j=1}^{i-1}\left[\left(\mathbb{J}(t_i,t_{j-1/2}) - \right.\right. \\ \left.\left. - \mathbb{J}(t_{i-1},t_{j-1/2})\right) : \Delta\boldsymbol{\sigma}_j\right] \text{ for } i > j. \quad (5)$$

Consequently, the stress tensor at i-th time interval is calculated by:

$$\boldsymbol{\sigma}_i = \boldsymbol{\sigma}_{i-1} + \Delta\boldsymbol{\sigma}_i\,. \quad (6)$$

14. The relation between the macroscopic stress and strain tensors is used is used to calculate the effective constitutive fourth-order tensor $\mathbb{C}_{eff}$ [11]:

$$\langle\boldsymbol{\sigma}\rangle_V = \mathbb{C}_{eff} : \langle\boldsymbol{\varepsilon}\rangle_V, \quad (7)$$

where $\langle * \rangle_V$ – is the average of a field $\boldsymbol{f}$ over the REV, $\langle\boldsymbol{f}\rangle_V = \frac{1}{V}\int_V \boldsymbol{f}(\boldsymbol{x})dV$.

Variational formulation

Following continuum micromechanics, the composite microstructure can be considered as a REV composed of homogeneous phases, and subjected to a macroscopic strain field ($\bar{\boldsymbol{\varepsilon}}$) prescribed at its boundaries. The local strain field of an arbitrary point in the REV $\boldsymbol{\varepsilon}(\boldsymbol{x})$ can be split into $\bar{\boldsymbol{\varepsilon}}$ and a periodic fluctuation strain $\tilde{\boldsymbol{\varepsilon}}(\tilde{\boldsymbol{u}}(\boldsymbol{x}))$, which accounts for the presence of heterogeneities [16].

Then, using the principle of virtual work and introducing an additional vectoral Lagrange multiplier as an additional unknown to make the average of $\tilde{\boldsymbol{\varepsilon}}$ over the REV is vanish, the following variational formulation gives [17]:

Find $(\tilde{\boldsymbol{u}}, \boldsymbol{\lambda}) \in V$ such that:

$$\int_V \boldsymbol{\sigma}(\tilde{\boldsymbol{u}}(\boldsymbol{x})) : \tilde{\boldsymbol{\varepsilon}}(\tilde{\boldsymbol{v}})dV + \int_V \boldsymbol{\lambda}\cdot\tilde{\boldsymbol{v}}dV + \int_V \boldsymbol{\theta}\cdot\tilde{\boldsymbol{u}}\,dV = \\ = 0\ \forall(\tilde{\boldsymbol{v}},\boldsymbol{\theta}) \in V, \quad (8)$$

where $\tilde{\boldsymbol{u}}$ – is the trial displacement function;

$\tilde{\boldsymbol{v}}$ – is the test displacement function;

$\boldsymbol{\lambda}$ – is the vectoral Lagrange multiplier;

$\boldsymbol{x}$ – is the position of an arbitrary point in the REV;

V – is the REV;

«·» – is the dot product.

And:

$$\boldsymbol{\sigma}(\tilde{\boldsymbol{u}}(\boldsymbol{x})) = \begin{cases} (\bar{\boldsymbol{\varepsilon}}_i + \tilde{\boldsymbol{\varepsilon}}(\tilde{\boldsymbol{u}}_i)) : \mathbb{C}_{uc}\ \forall\boldsymbol{x} \in V_{uc} \\ \boldsymbol{\sigma}_{i-1} + \Delta\boldsymbol{\sigma}_i\ \forall\boldsymbol{x} \in V_{hp} \\ (\bar{\boldsymbol{\varepsilon}}_i + \tilde{\boldsymbol{\varepsilon}}(\tilde{\boldsymbol{u}}_i)) : \mathbb{C}_w\ \forall\boldsymbol{x} \in V_w \\ (\bar{\boldsymbol{\varepsilon}}_i + \tilde{\boldsymbol{\varepsilon}}(\tilde{\boldsymbol{u}}_i)) : \mathbb{C}_{air}\ \forall\boldsymbol{x} \in V_{air} \end{cases}, \quad (9)$$

$$\tilde{\boldsymbol{\varepsilon}}(\boldsymbol{u}) = \frac{1}{2}(\nabla\boldsymbol{u} + (\nabla\boldsymbol{u})^T)\,, \quad (10)$$

where $\mathbb{C}_w$, $\mathbb{C}_{air}$ – is the fourth-order elasticity tensor of water and air, respectively;

V_{uc}, V_{hp}, V_w, V_{air} – are the subdomains of the REV referring to the phases of unhydrated cement, hydration products, water, and air, respectively.

The is the incremental of the stress tensor $\Delta\boldsymbol{\sigma}_i$ is expressed from (5), where $\Delta\boldsymbol{\varepsilon}_i = \Delta\bar{\boldsymbol{\varepsilon}}_i + \Delta\tilde{\boldsymbol{\varepsilon}}_i$.

Solidification of cement paste

According to the solidification theory, increment of stiffness of cement paste during a hydration process is given in relation to increment of a cluster thickness, which is represented by increment of the volume of hydration products (see Figure 1), and it is assumed that the properties of clusters do not vary with time [9]. The total number of fictitious clusters is equal to the number of time intervals.

The above principle can be easily applied to discrete REV, where a separate cluster is considered as a set of hydration product voxels that have been produced at i-th time interval. The use of the voxel-based microstructural model, for instance [9], allows creating a history of the formation of such clusters, as well as to keep the spatial position of the cluster voxels in the REV.

This also means that the finite elements within a mesh subdomain belonging to each cluster can be identified and explicitly associated with the stress-strain relation on the corresponding time interval unlike the classical approach where the fictitious clusters are assumed to be a dimensionless variable that is equal to the increment in degree of hydration.

Modelling results

The Portland cement paste with parameters reported in Table 1 was used for the simulation.

The parameters of the constitutive phases of cement paste report in Table 2. The elastic properties of the phases in Table 2 were taken according to [19].

Table 1 – Parameters of cement paste

Mix proportions, kg/m³		Water to cement ratio	Density of cement, kg/m³	Fineness of cement, m²/kg	Mineral composition of cement (mass %)
Portland Cement	Water				
370	185	0,5	3150	345	C_3S: 54,5; C_2S: 17,3; C_3A: 8,9; C_4AF: 7,6; Gypsum: 5

Table 2 – Parameters of the constitutive phases of cement paste

Parameter	Phase										
	C_3S	C_2S	C_3A	C_4AF	CSH	CH	$C_6A\bar{S}_3H_{32}$	$C_4A\bar{S}H_{12}$	C_3AH_6	FH_3	Gypsum
Young's modulus, GPa	137,4	135,5	145,2	150,8	23,8	43,5	24,1	43,2	93,8	22,4	44,5
Poisson's ratio	0,299	0,297	0,278	0,318	0,24	0,294	0,321	0,292	0,32	0,25	0,33
Aspect ratio	1,0	1,0	1,0	1,0	0,01	0,1	100	10	1,0	1,0	1,0

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The stiffness characteristics of water: the bulk modulus is 2,2 GPa, the Poisson's ratio is 0,499. The stiffness characteristics of air were taken to be close to zero.

The REV resolution of 10 voxels/edge was used in simulation to reduce the computational cost.

Six elementary load cases consisting of macroscopic uniaxial strain and shear solicitations were applied at each time step by assigning constant unit values $\bar{\varepsilon}_{ij}$: $\bar{\boldsymbol{\varepsilon}} = \boldsymbol{e}_i \otimes \boldsymbol{e}_i$ – for uniaxial strain, and

$$\bar{\boldsymbol{\varepsilon}} = \frac{1}{2}\left(\boldsymbol{e}_i \otimes \boldsymbol{e}_j + \boldsymbol{e}_j \otimes \boldsymbol{e}_i\right) \text{ – for shear strain} \quad (11)$$

where $\boldsymbol{e}_i$ – is the unitary bases;

«⊗» – is the tensor product.

Two additional creep compliance functions $J(t,t')$ were used for a comparative analysis of the effective properties:

1) adapted ACI model [20]:

$$J(t,t') = \frac{1+\varphi(t,t')}{E_{hp}(t')};\ (t,t') = 2{,}35 \cdot \frac{(t-t')^{0,6}}{10+(t-t')^{0,6}}, \quad (12)$$

where $E_{hp}(t')$ – is the effective elastic modulus of hydration products.

2) adapted CEB MC90 model [14]:

$$J(t,t') = \frac{1}{E_{hp}(t')} + \frac{\varphi(t,t')}{E_{hp,28}};\ \varphi(t,t') = \left[\frac{(t-t')}{500+(t-t')}\right]^{0,3}, \quad (13)$$

where $E_{hp,28}$ – is the effective elastic modulus of hydration products at 28 days, 33 GPa.

To evaluate the stiffness tensor considering the percolation of the solid phase of cement paste, a power law in the following normalized form was used:

$$\mathbb{C}_{eff} = \mathbb{C}_{eff}^{FEA}\left(\frac{\alpha-\alpha_{per}}{1-\alpha_{per}}\right)^{\gamma}, \quad (14)$$

where $\mathbb{C}_{eff}^{FEA}$ – is the effective fourth-order stiffness tensor of cement paste according to the FEA-based homogenization;

α – is the hydration degree of cement;

α_{per} – is the hydration degree of cement corresponding to the percolation threshold of the solid phase;

γ – is the exponent, 1.

The modeling results are presented in in Figures 2 and 3.

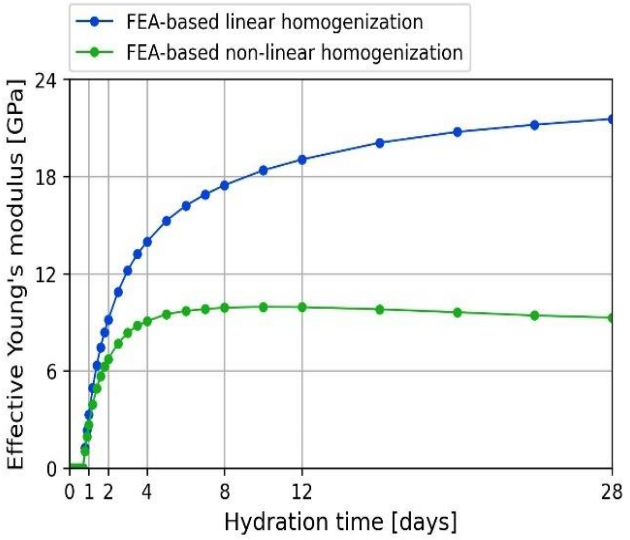

Figure 2 – Effective behavior of cement paste

Conclusions

1. Modelling the effective stiffness characteristics of cement paste is a rather difficult task, due to the combination of the facts that its structure consists of randomly distributed phases with an arbitrary geometry, and a solid phase has viscoelastic behaviour.

2. The article presents the approach to solving the problem of effective stiffness characteristics of cement paste given the above issues based on a FEA homogenization makes it possible to evaluate its effective properties for arbitrary phase geometry, throw introducing into the variational formulation the numerical inversion of the Stieltjes integral describing the constitutive model of viscoelastic of the solid phase of cement paste.

3. An important advantage of above approach is that the voxel REV used to generate the mesh can also implement solidification theory principles to express the strain and stress history associated not with fictitious but with each identified cluster formed during the hydration process.

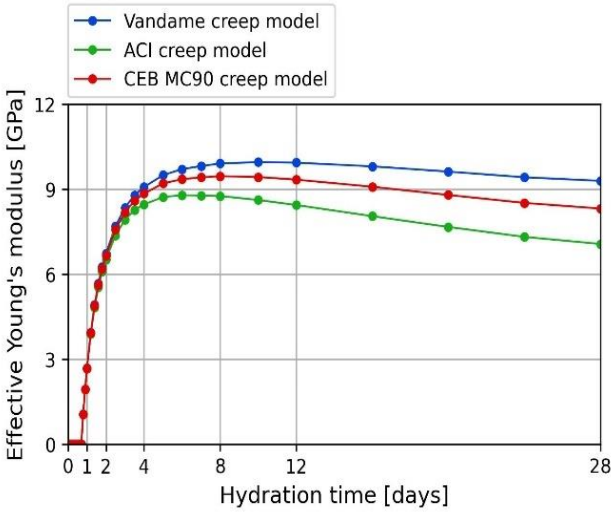

Figure 3 – Effective behavior of cement paste based on non-linear FEA-based homogenization using different creep models

References

1. Fundamental Research on Creep and Shrinkage of Concrete / ed. F. H. Wittman. – Dordrecht : Springer, 1982. – 528 p. – DOI: 10.1007/978-94-010-3716-7.
2. Dvorak, G. J. Micromechanics of Composite Materials / G. J. Dvorak. – New York: Springer Science & Business Media, 2012. – 460 p. – DOI: 10.1007/978-94-007-4101-0.
3. Yvonnet, J. Computational Homogenization of Heterogeneous Materials with Finite Elements / J. Yvonnet. – New York: Springer Cham, 2019. – 223 p. – DOI: 10.1007/978-3-030-18383-7.
4. Lucarini, S. FFT based approaches in micromechanics: fundamentals, methods and applications / S. Lucarini, M. V. Upadhyay, J. Segurado // Modelling and Simulation in Materials Science and Engineering. – 2022. – Vol 30, Iss. 22. – P. 1–97. – DOI: 10.1088/1361-651X/ac34e1.
5. Sanahuja, J. Creep of a C-S-H gel: a micromechanical approach / J. Sanahuja, L. Dormieux // Academia Brasileira de Ciências. – 2010. – Vol. 82, Iss. 1. – P. 25–41. – DOI: 10.1590/s0001-37652010000100004.
6. Downscaling Based Identification of Nonaging Power-Law Creep of Cement Hydrates / M. Königsberger, M. Irfan-ul-Hassan, B. Pichler, C. Hellmich // Journal of Engineering Mechanics. – 2018. – Vol. 142, Iss. 12. – P. 1–11. – DOI: 10.1061/(ASCE)EM.1943-7889.000116.
7. Honorio, T. Multiscale estimation of ageing viscoelastic properties of cement-based materials: A combined analytical and numerical approach to estimate the behaviour at early age / T. Honorio, B. Bary, F. Benboudjema // Cement and Concrete Research. – 2016. – Vol. 85. – P. 137–155. – DOI: 10.1016/j.cemconres.2016.03.010.
8. Majorana, C. E. Mathematical Modeling of Creep and Shrinkage of Concrete / C. E. Majorana ; Z. P. Bažant [et al.] ; ed.: Z. P. Bažant. – New York : John Wiley & Sons Ltd, 1989. – 484 p. – DOI: 10.1002/cnm.1630050609.
9. Maekawa, K. Multi-scale Modelling of Structural Concrete / K. Maekawa, T. Ishida, T. Kishi. – New York : Taylor & Francis Group, 2009. – 655 p. – DOI: 10.1201/9781482288599.

10. Numerical study of the autogenous shrinkage of cement pastes with supplementary cementitious materials based on solidification theory model / T. Lu, J. Ren, X. Deng, Z. Li // Construction and Building Materials. – 2023. – Vol. 392, article 131645. – P. 1–12. – DOI: 10.1016/j.conbuildmat.2023.131645.
11. Tennis, P. D. A model for two types of calcium silicate hydrate in the microstructure of Portland cement pastes / P. D. Tennis, H. M. Jennings // Cement and Concrete Research. – 2000. – Vol. 30, Iss. 6. – P. 855–863. – DOI: 10.1016/S0008-8846(00)00257-X.
12. Thermodynamic modelling of the effect of temperature on the hydration and porosity of Portland cement / B. Lothenbach, T. Matschei, G. Möschner, F. P. Glasser // Cement and Concrete Research. – 2008. – Vol. 38, Iss. 1. – P. 1–18. – DOI: 10.1016/j.cemconres.2007.08.017.
13. Kravchenko, V. V. Modelling of the voxel-based microstructure of the cement paste / V. V. Kravchenko // Vestnik BSTU. – 2024. – Vol 1. – P. 14–18. – DOI: 10.36773/1818-1112-2024-133-1-14-18.
14. Vandamme, M. The nanogranular origin of concrete creep: A nanoindentation investigation of microstructure and fundamental properties of calcium-silicate-hydrates : Ph.D. thesis / M. Vandamme. – Cambridge : Massachusetts Institute of Technology, 2008. – 366 p. – URL: http://hdl.handle.net/1721.1/43906 (date of access: 09.10.2024).
15. Early Age Deformation and Resultant Induced Stress in Expansive High Strength Concrete / H. Ito, I. Maruyama, M. Tanimura, R. Sato // Journal of Advanced Concrete Technology. – 2004. – Vol. 2, Iss. 2. – P. 155–174. – DOI: 10.3151/jact.2.155.
16. Torquato, S. Effective stiffness tensor of composite media—I. Exact series expansions / S. Torquato // Journal of the Mechanics and Physics of Solids. – 1997. – Vol. 45, Iss. 9. – P. 1421–1448. – DOI: 10.1016/S0022-5096(97)00019-7.
17. Michel, J. C. Effective properties of composite materials with periodic microstructure: a computational approach / J. C. Michel, H. Moulinec, P. Suquet // Computer Methods in Applied Mechanics and Engineering. – 1999. – Vol 172, Iss. 1–4. – P. 109–143.
18. Bleyer, J. Numerical Tours of Computational Mechanics with FEniCS / J. Bleyer. – Genève : Zenodo, 2018. – 100 p. – DOI: 10.5281/zenodo.1287832.
19. Rhardane, A. Development of a micro-mechanical model for the determination of damage properties of cement pastes / A. Rhardane, F. Grondin, S. Y. Alam // Construction and Building Materials. – 2020. – Vol. 261. – P. 1–30. – DOI: 10.1016/j.conbuildmat.2020.120514.
20. Guide for Modeling and Calculating Shrinkage and Creep in Hardened Concrete : ACI PRC-209.2-08 / ed.: C. C. Videla. – ACI : ACI Committee 209, 2008. – 45 p.

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INFLUENCE OF THE CONNECTION METHOD OF FLOOR-BY-FLOOR SUPPORTED MASONRY WALLS WITH THE SUPPORTING FLOOR ON THE CRACK RESISTANCE

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Abstract

The purpose of this article is to analyze the influence of deflections of supporting floors on the crack resistance of floor-by-floor supported masonry walls, depending on the method of their connec-tion with the reinforced concrete floor. This article shows that the deflection of the floor causes the appearance of main tensile stresses in the wall with the doorway, the maximum values of which are concentrated in the corner areas of the opening. To reduce the risk of cracks in the wall filling between the masonry and the supporting floor, it is recommended to install a separating layer of one or two layers of film material. In case of deflection of the supporting floor the separating layer allows to exclude the transfer of load to the walls, which may be caused by the adhesion of the leveling layer of mortar to the floor. It has been established that an increase of the coefficient of friction between the wall and the supporting floor leads to a decrease in the main tensile stresses in the corner area of the doorway. Therefore, when constructing a separating layer, it is not recommended to perform it at the end sections of the filling. Based on numerical studies, the dependence of the main tensile stresses in a partition with a doorway on the value of the coefficient of friction between the surfaces of the masonry and the supporting floor.

Keywords: masonry, floor-by-floor supported walls, deflection, supporting floor.

ВЛИЯНИЕ НА ТРЕЩИНОСТОЙКОСТЬ ПОЭТАЖНО ОПЕРТЫХ КАМЕННЫХ СТЕН СПОСОБА ИХ СОПРЯЖЕНИЯ С ПОДДЕРЖИВАЮЩИМ ПЕРЕКРЫТИЕМ

П. А. Новик, В. И. Юськович

Реферат

Целью данной статьи является анализ влияния прогибов поддерживающих перекрытий каменной кладки на трещиностойкость каменных стен поэтажно опертых стен в зависимости от способа их сопряжения с железобетонным перекрытием. В данной статье показано, что прогиб перекрытия вызывает в стене с дверным проемом появление главных растягивающих напряжений, максимальные значения которых концентрируются в угловых зонах проема. Для снижения риска возникновения трещин в стеновом заполнении между каменной кладкой и опорным перекрытием рекомендуется устраивать разделительный слой из одного-двух слоев пленочного материала. Разделительный слой позволяет при прогибе перекрытия исключить передачу на стены нагрузки, которая может быть обусловлена сцеплением выравнивающего слоя раствора с перекрытием. Установлено, что увеличение коэффициента трения между стеной и поддерживающим перекрытием приводит к снижению главных растягивающие напряжения в угловой зоне дверного проема. Поэтому при устройстве разделительного слоя его не рекомендуется выполнять на концевых участках заполнения. На основании численных исследований построена зависимость главных растягивающих напряжений в перегородке с дверным проемом от величины коэффициента трения между поверхностями каменной кладки и поддерживающим перекрытием.

Ключевые слова: каменная кладка, поэтажно опертые стены, прогиб, поддерживающее перекрытие.

Introduction

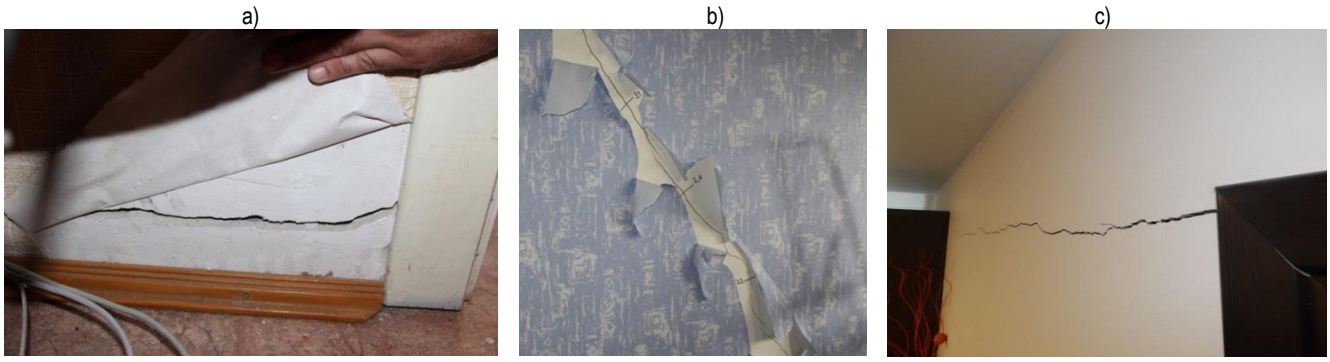
Modern frame buildings are erected in a short time. For this reason, floor-supported wall filling of frames in the form of internal and external walls is carried out in conditions where significant rheological deformations of reinforced concrete frame elements and uneven settlements of the foundations are possible. The wall filling of frames, as a rule, is erected on thin-layer mortar joints with a thickness of 0.5–3 mm. In terms of their homogeneity, masonry with thin-layer joints approaches monolithic unreinforced walls, which, from the point of view of crack formation, are very sensitive to uneven temperature and shrinkage deformations, local loads, uneven settlements of foundations, dynamic and other influences. As for floor-supported walls of frame buildings, practice shows that their cracking is predetermined by the deflections of the reinforced concrete floor. At the same time, technical solutions for connecting floor-by-floor supported walls with supporting floors have a significant impact on the stress-strain state of masonry and its crack resistance.

The nature of cracking in floor-by-floor supported walls during floor deflection

According to standard technical solutions [1–2], floor-by-floor supported walls and partitions should rest on the floors through a layer of M100 leveling cement mortar, and sometimes be fixed to them using tie elements in the form of reinforcing bars embedded in the masonry and supporting floor. This constructive solution for connecting the wall fence with the floor is incorrect, because it limits the deformation of the masonry in the plane of the wall caused by temperature and humidity influences, and leads to the transfer of a vertical load to the filling when the supporting floor deflects. It should be noted that there is a lack of special research concerning the nature of the load transfer from masonry walls to floors during their deflection, which led to incorrect decisions in typical albums of floor-by-floor supported walls [1–2].

After the erection of the wall filling, layers of acoustic insulation and finished floor screeds are laid on the floor, and the walls are finished. The increment of constant and variable load, after completing the specified works, will be approximately 20–25 % of its full value (80–75 % of the total value of constant and variable long-term load is the own weight of the floor and wall filling). Taking into account the creep of concrete, it can be assumed that the deflection of the floor after the erection of the walls will reach 40–50 % of the total deflection caused by the action of constant and variable long-term load, including the own weight of the floor. The increment of deflection of hollow floor slabs with a span of more than 6 m can be about 15 mm. For flat beamless slabs of frame buildings, the flexural rigidity of which is not great, this amount of deflection can be achieved with slab spans of 4.5–6 m.

When the floor deflects, the maximum values of the main tensile stresses “σ1” in masonry walls arise, as a rule, along the border of the contact zone of the masonry with the floor, and their trajectories are directed at an angle of ≈ 20º to the horizontal mortar joints [3–5]. This is explained by the fact that the flexural rigidity of the wall in its plane is significantly higher than the rigidity of the supporting floor and when the supporting floor deflects, a redistribution of contact pressure occurs between the wall and the floor, as a result, tangential and tensile stresses appear in the masonry, which can lead to the formation of cracks (Figure 1).



a) – longitudinal crack along the bottom of the wall; b) – an inclined crack along the body of the wall; c) − crack in the wall with a doorway

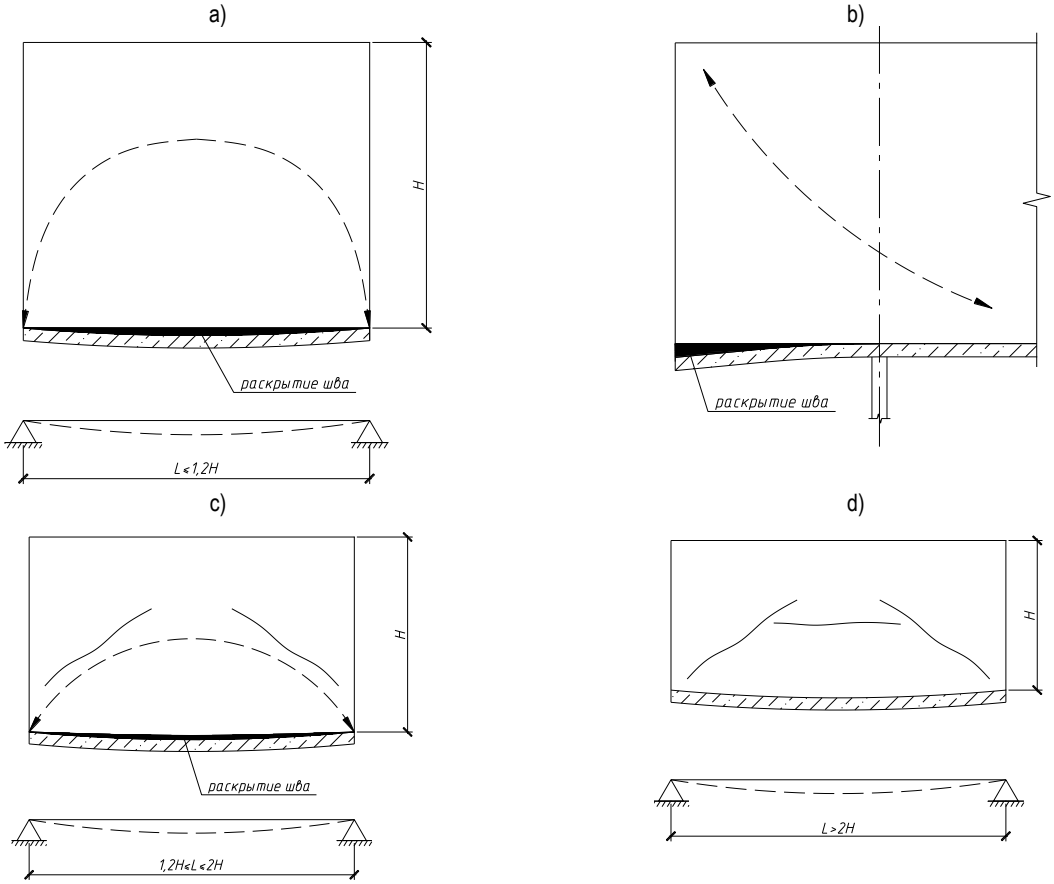
Figure 1 − The nature of the formation of cracks in the walls of a frame-monolithic building

The cracks shown in Figure 1 arose in the cellular concrete filling wall of the monolithic reinforced concrete frame of a residential building, six years after its commissioning.

Field examinations of wall filling and experimental and theoretical studies show that in case of deflection of the supporting floor various mechanisms for the formation of cracks in masonry walls can be realized [6–8].

For solid walls, the length L of which is commensurate with their height H (L/H ≤ 1.2), the opening of the joint between the wall and the supporting floor or the formation of a crack along the bottom of the wall, developing along the body of the masonry, is characteristic (Figures 2a, 2b). An analysis of the distribution of the main stresses along the plane of the wall indicates that in this case it works according to the arch principle.

As the length of the wall increases, the stresses that arise in it when the floor deflects increase. In this case, in the support zone of walls with 1.2 ≤ L/H ≤ 2.0, inclined cracks may appear, rising either directly along the masonry unit or along horizontal and vertical joints of the masonry (Figure 2c). After the occurrence of inclined cracks, the middle zone of the wall can still work according to the arched pattern. If L/H > 2.0, then in addition to inclined cracks, the formation of horizontal and vertical cracks in the middle zone of the wall is possible (Figure 2d).



a) at L/H ≤ 1.2; b) with cantilever slabs; c) at 1.2 ≤L/H≤ 2.0, d) at L/H>2.0

Figure 2 − Nature of crack formation in solid walls [7]

It should be noted that in addition to deflections of the floors, the appearance of main tensile stresses in the wall enclosure, the trajectories of which match with the direction of the horizontal mortar joints, is also caused by shrinkage of the masonry walls and partitions.

If there is a doorway or corridor in the middle zone of the wall, in case of deflection of the supporting floor, the wall is divided into two parts, the rotation of which leads to the appearance of cracks shown in Figures 3a, 3b. In walls with a doorway, the maximum principal tensile stresses are concentrated in the upper corners of the opening, and their trajectories are

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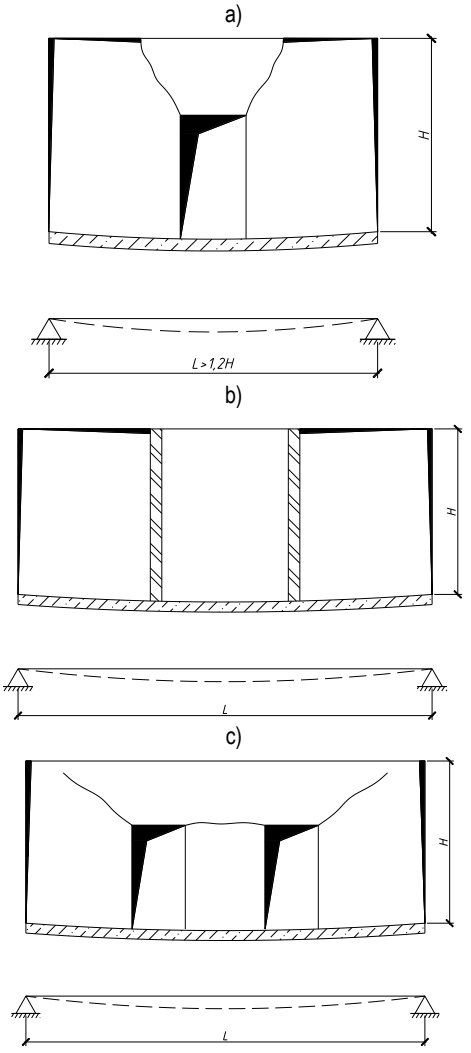
directed at an angle of approximately 45º to the horizontal mortar joints [9]. Calculation analysis shows that when the ratio of the length of the wall to its height is greater than 1,2 times, the main tensile stresses acting near the corners of the doorway exceed the tensile strength of the masonry in the corresponding direction [10]. This leads to the appearance of cracks in the corners of the opening, which subsequently develop along the trajectory of the main compressive stresses. The main tensile stresses near the corners of the doorway reach the tensile strength of the masonry almost immediately after breaking the contact between the wall and the floor, which is confirmed by the results of experimental studies [9, 11]. High values of the main tensile stresses in the direction of horizontal mortar joints arise in the lower zone of the above-opening section of the masonry. Tensile stresses also occur in the contact areas between the wall and the floor, but their values are significantly lower than in the corner areas of the openings. It should be noted that the presence of a doorway leads to a decrease in the main tensile stresses arising in the contact zones compared to a solid wall. The value of the maximum principal tensile stresses in the contact zone in the wall with the opening is about 5–6 % of the maximum value of contact compressive stresses.

In walls in which the opening is shifted to the edge, the maximum principal tensile stresses are localized near the corner adjacent to the long section of the wall. With two doorways, the highest values of the main tensile stresses occur in the corner zones formed by the sides of the middle pier and the horizontal edges of the openings. In such walls, cracks may appear in the middle wall between the openings, developing along the horizontal joints of the masonry (Figure 3c).



a) − with one doorway; b) − with an opening to the full height; c) − with two openings

Figure 3 − Nature of crack formation in walls with openings [7]

When designing, it is recommended to avoid placing doorways in the central zone of the walls. If this cannot be avoided, it is recommended to arrange openings for the entire height of the wall, followed by filling the above-opening belt with masonry in such a way that independent deformation of the wall masonry and the above-opening belt is ensured.

Conjugation of floor-by-floor supported walls with a supporting floor

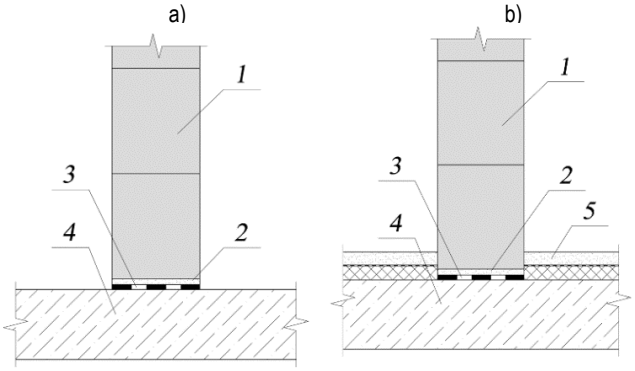
In foreign construction practice, a separating layer of film material is usually constructed between the floor and the filling [12–13]. The separating layer allows you to reduce the friction forces between the masonry and the floor (Table 1), and in case of deflection of the supporting floor, it eliminates the transfer of load to the filling, which may be caused by the adhesion of the leveling mortar layer to the floor.

Table 1 – Friction coefficient «*tga*» [14–15]

Value of «*tga*»	Contact between masonry and supporting structure
0,4–0,6	Two separating layers close to each other (for example, polyethylene film)
0,6–0,8	One separation layer
0,8–1,0	Without separating layer, masonry mortar

His technical solution reduces the tensile stresses that arise in the filling under temperature and humidity influences and deflections of the supporting floor, which has a beneficial effect on the crack resistance of masonry [16–17].

The first row of infill masonry is erected on a leveling layer of cement mortar 10–15 mm thick, laid along the separating layer. Due to the fact that the support of the filling on the supporting floor is carried out through the separating layer, the lower edge of the filling is considered as free supported in the vertical direction and having the ability to move in the horizontal direction, provided that there is no rigid floor screed on the supporting floor (Figure 4a). The floor screed, after gaining strength, limits horizontal movements and rotation of the lower edge of the filling out of the plane, creating conditions for its rigid pinching. This design solution is typical for internal filling, when the screed is adjacent to the masonry on both sides (Figure 4b).



1 – masonry filling, 2 – cement-sand mortar 1:3 (10 mm thick), 3 – separating layer of polyethylene film, 4 – reinforced concrete floor, 5 – cement-sand screed

Figure 4 − Example of pairing an internal wall with a monolithic supporting floor

In domestic construction practice, when constructing the walls of frame buildings, the installation of separating layers between the lower edge of the wall and the supporting floor is ignored. According to the requirements of SN 1.03.01 [18], the first row of masonry walls made of small blocks must be laid on a belt made of reinforced concrete lintels or ceramic bricks. This technical solution of connecting the walls with the supporting floor creates conditions for the formation of cracks in the masonry. Cracks not only worsen the aesthetic appearance of the walls, but also have a negative impact on their sound insulation and thermal characteristics, as well as fire resistance and durability [19–22].

To prevent the formation of cracks during the operation of a building for masonry walls with openings, you can also use local reinforcement of masonry with meshes made of composite materials in areas of expected crack-

ing (areas of masonry near the contact zone of the wall with the floor, corners of door and window openings). Reinforcing meshes should be placed so that their fiber guides, if possible, match with the trajectory of the main tensile stresses, which are established by calculation. In addition to composite meshes, steel meshes that comply with the STB EN 845-3 standard [23] can be used to reinforce walls with openings.

In addition to the reinforcement of masonry, additional measures should be taken that reduce the risk of cracks in the walls of the building:

– erection of masonry as late as possible after the construction of the building frame;

– proper storage conditions for masonry products before the erection of masonry (with protection from weathering by film materials);

– wetting masonry products before erecting masonry.

The influence of the separating layer on the stress-strain state of walls

Numerical studies show that the magnitude of the friction coefficient *tga* between the surfaces of the masonry and the floor significantly affects the magnitude of the main tensile stresses σ_1 arising in walls with a doorway. In this case, the maximum values of σ_1 are concentrated in the corner areas of the doorway.

Figure 5 shows the dependence «$\sigma_1/\sigma_{1(0)}$ – *tga*» at a constant value of the curvature of the axis of a single-span floor and the ratio of the dimensions of the brick partition L/H=2 ($\sigma_{1(0)}$ – the main tensile stresses in the corner zone of the doorway at *tga* = 0).

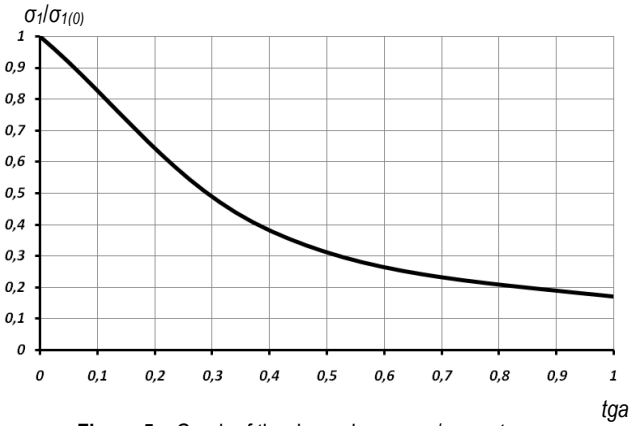


Figure 5 – Graph of the dependence «$\sigma_1/\sigma_{1(0)}$ – tga»

From Figure 5 it follows that an increase in the friction coefficient *tga* from 0 (frictionless contact) to ∞ (hard contact) leads to a decrease in the main tensile stresses σ_1 in the corner zone of the doorway. When *tga* changed from 0 to 1, the values of σ_1 decreased by approximately 6 times. At the same time, there was a drop in the main tensile stresses acting in the contact zone. Therefore, when constructing a separating layer, it is not recommended to perform it at the end sections of the filling.

Conclusion

Based on the above, we can draw the following conclusion:

1. The nature of cracking in floor-supported walls and partitions during deflection of supporting floors depends on the ratio of the overall dimensions of walls and partitions, the presence of openings, their location, conditions of contact with adjacent structures, strength and deformation characteristics of masonry. Walls with doorways made of autoclaved cellular concrete blocks are at greatest risk of cracks forming when in case of deflection of the supporting floor.

2. The building code SN 1.03.01 should include requirements regarding the installation of a separating layer of film material between floor-by-floor supported masonry walls with the supporting floor. The separating layer allows you to reduce the friction forces between the masonry and the floor, and in case of deflection of the supporting floor, to eliminate the transfer of load to the walls, which may be due to the adhesion of the leveling mortar layer to the floor.

References

1. Rekomendacii po proektirovaniyu poetazhno opertyh sten i peregorodok iz effektivnyh melkoshtuchnyh stenovyh materialov: R5.02.088.11 (s izm. № 1). – Vved. 29.09.11. – Minsk : RUP «Institut BelNIIS», 2011. – 51 s.
2. Uzly i detali poetazhno opertyh sten zhilyh i obshchestvennyh zdanij iz effektivnyh melkoshtuchnyh stenovyh materialov. Vypusk 1. Rabochie chertezhi: Seriya B 2.030-13.10. – Vved. 07.09.11. – Minsk : RUP «Institut BelNIIS», 2010. – 62 s.
3. Brameshuber W. Untersuchungen zur Vermeidung von Rißschäden bei nichttragenden Trennwänden / W. Brameshuber, I. Beer, Kang Bong-Gu // Mauerwerk. – 2007. – № 11. Heft 1. – P. 54–62.
4. Derkach, V. N. Issledovaniya napryazhenno-deformirovannogo sostoyaniya kamennyh peregorodok pri progibe perekrytiya / V. N. Derkach // Promyshlennoe i grazhdanskoe stroitel'stvo. – 2013. – № 6. – S. 62–66.
5. Derkach, V. N. Deformacionnye harakteristiki kamennoj kladki v usloviyah ploskogo napryazhennogo sostoyaniya / V. N. Derkach // Stroitel'stvo i rekonstrukciya. – Orel : OrelGTU, 2012. – № 2 (40). – S. 3–11.
6. Drobiec, L. Zapobieganie zarysowaniom scian murowych opartych na stropach zelbetowych / L. Drobiec, J. Kubica // Materialy budowlane. − 2006. − № 404. − S. 21–23.
7. Derkach, V. N. O morfologii treshchin, voznikayushchih vo vnutrennih peregorodkah sovremennyh zdanij / V. N. Derkach // Vestnik Brestskogo gosudarstvennogo tekhnicheskogo universiteta. – Stroitel'stvo i arhitektura. − 2010. − № 1. − S. 43–45.
8. Derkach, V. N. Problemy treshchinostojkosti stenovogo zapolneniya karkasnyh zdanij iz yacheistobetonnyh blokov / V. N. Derkach, A. S. Gorshkov, R. B. Orlovich // Stroitel'nye materialy. – 2019. – №3. – S. 52–56.
9. Derkach, V. N. Eksperimental'nye issledovaniya kamennyh peregorodok s dvernym proemom pri progibe perekrytiya / V. N. Derkach // Stroitel'stvo i rekonstrukciya. – Orel : OrelGTU, 2013. – № 4 (48). – S. 14–22.
10. Derkach, V. N. Povyshenie treshchinostojkosti vnutrennih peregorodok s proemami pri vozvedenii sovremennyh zdanij / V. N. Derkach, A. YA. Najchuk // Resursoekonomni materiali, konstrukcii, budivli ta sporudi: zbirnik naukovih prac'. – Ministerstvo osviti i nauki Ukraini, Akademiya budivnictva Ukraini, Nacional'nij universitet vodnogo gospodarstva ta prirodokoristovannya. – Rivne, 2009. – S. 276–283.
11. Tragwerkeaus Beton, Stallbeton und Spannbeton. Teil 1: Bemessung und Konstruktion: DIN 1045-1: 2001. – Berlin : Deutsches Institutfür Normung, 2001. – 67 p.
12. Derkach, V. N. Sopryazhenie kamennogo zapolneniya karkasnyh zdanij s konstrukciyami karkasa / V. N. Derkach // Arhitektura i stroitel'stvo. − № 1. − 2015.− S. 14–16.
13. Drobiec, L. Sposoby laczenia scian wypelniajacych z konstrukcja / L. Drobiec, R. Jasinski // Materialy budowlane. – 2014. – № 4.− S. 1–3.
14. Schubert, P. Vermiden von schadlichen Rissen in Mauerwerksbauten / P. Schubert // Mauerwerk-Kalender. – 1996. – № 21. – P. 621–651.
15. Schubert, P. Zur risfreien Wandlange von nichttragenden Mauerwerkwanden / P. Schubert // Mauerwerk-Kalender. – 1988. – № 13. – P. 473–488.
16. Rissfreie Wandlange von Porenbeton-Mauerwerk / W. Brameshuber Wolfgang, P. Schubert, U. Schmidt, J. Hannawald // Mauerwerk. – 2006. – No. 10, Heft 4. – P. 132–139.
17. Schubert, P. Vermeiden von schadlichen Rissen / P. Schubert // Mauerwerksbau-Praxis. – Bauwerk Verlag GmbH, 2007. – P. 213–237.
18. Vozvedenie stroitel'nyh konstrukcij, zdanij i sooruzhenij: SN 1.03.01-2019. − Vved. 29.11.2019. − Minsk : MAiS, 2021. − 123 s.
19. Derkach, V. N. Kamennye i armokamennye konstrukcii. Ocenka tekhnicheskogo sostoyaniya, remont i usilenie/ V. N. Derkach. − Minsk : StrojMediaProekt, 2021. − 256 s.
20. Drobiec L. Zapobieganie zarysowaniom scian murowych opartych na stropach zelbetowych / L. Drobiec, J. Kubica // Materialy budowlane. − 2006. − №404. − S. 21–23.
21. Göttlich, P. Begrenzung der Biegeschlankheit nach Eurocode 2 / P. Göttlich // Beton- und Stahlbetonbau. − 2012. − № 107, Heft 1. − S. 38–45.
22. Derkach, V. N. Treshchinostojkost' kamennyh peregorodok / V. N. Derkach, R. B. Orlovich // ZHilishchnoe stroitel'stvo. − 2012. − № 8. – S. 34–37.
23. Trebovaniya k vspomogatel'nym izdeliyam dlya kamennoj kladki. CHast' 3. Izdeliya dlya armirovaniya gorizontal'nyh shvov kamennoj kladki: STB EN 845-3-2012 (EN 845-3:2003, IDT). – Vved. 01.01.2013. – Minsk : RUP «Strojtekhnorm», 2013. – 26 s.

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CALCULATION OF STEEL-REINFORCED CONCRETE STRUCTURES OF THE BUILDING OF THE NATIONAL LIBRARY OF THE REPUBLIC OF BELARUS

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Abstract

The unique building of the National Library of the Republic of Belarus includes not only urban planning, architectural, technological modern solutions, but also structural ones. One of such modern structural solutions is the use of composite (steel-concrete) structural elements. The advantages of steel-reinforced concrete structures are manifested in the possibility of placing steel profiles of large cross-sectional area in their cross-section and protecting them from corrosion and high temperatures with concrete; the use of rigid reinforcement as load-bearing elements or formwork during their construction. The article presents the results of applying a nonlinear analysis to obtaining of the parameters of the stress-strain state (normal stresses, strains) at any stage of behavior under loading, including the construction stage, as well as the strength, deformability of complexly loaded composite elements under the condition of joint operation of rigid steel sections and reinforced concrete. The resolving system of equations of the nonlinear deformation model includes the conditions of equilibrium of internal forces in the cross-section, the condition of distribution of relative deformations along the height of the cross-section in accordance with the hypothesis of a flat section, as well as approximations of the deformation diagrams of concrete and rigid reinforcement in the form of rolled sections under tension-compression. A criterion for assessment the internal force corresponding to the resistance of a composite steel element, which does not require standardization of the ultimate compressibility of concrete and allows taking into account a high degree of redistribution of forces between the components in the cross section of the composite steel element is proposed. The advantages of the nonlinear design method are demonstrated with usage of the examples of calculating composite steel structures of the building of the National Library of the Republic of Belarus.

Keywords: steel-reinforced concrete structure, nonlinear deformation model, material deformation diagrams, plane section hypothesis, stress-strain state, concrete shrinkage, stages of work under load, failure criterion.

РАСЧЕТ СТАЛЕЖЕЛЕЗОБЕТОННЫХ КОНСТРУКЦИЙ ЗДАНИЯ НАЦИОНАЛЬНОЙ БИБЛИОТЕКИ РЕСПУБЛИКИ БЕЛАРУСЬ

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Реферат

Уникальное здание Национальной библиотеки Республики Беларусь включает в себя не только градостроительные, архитектурные, технологические современные решения, но и конструкционные. Одним из таких современных конструкционных решений является применение сталежелезобетонных конструкций. Преимущества сталежелезобетонных конструкций проявляются в возможности размещения в их поперечном сечении стальных профилей большой площади сечения и их защитой против коррозии и высоких температур бетоном, использовании при их возведении жесткой арматуры в качестве несущих элементов или опалубки. В статье представлены результаты применения нелинейного расчета для определения параметров напряженно-деформированного состояния (нормальных напряжений, относительных деформаций) на любой стадии работы под нагрузкой, включая стадию возведения, а также прочности, деформативности сложно нагруженных сталежелезобетонных элементов при условии совместной работы жестких стальных профилей и железобетона. Разрешающая система уравнений нелинейной деформационной модели включает в себя условия равновесия внутренних усилий в поперечном сечении, условие распределения относительных деформаций по высоте поперечного сечения в соответствии с гипотезой плоского сечения, а также аппроксимации диаграмм деформирования бетона и жесткой арматуры в виде прокатных профилей при растяжении-сжатии. Предложен критерий вычисления внутреннего усилия, соответствующего прочности сталежелезобетонного элемента, не требующий нормирования предельной сжимаемости бетона и позволяющий учитывать высокую степень перераспределения усилий между составляющими в поперечном сечении сталежелезобетонного элемента. Преимущества нелинейного метода расчета продемонстрированы на примерах расчета сталежелезобетонных конструкций здания Национальной библиотеки Республики Беларусь.

Ключевые слова: сталежелезобетонная конструкция, нелинейная деформационная модель, диаграммы деформирования материалов, гипотеза плоских сечений, напряженно-деформированное состояние, усадка бетона, стадии работы под нагрузкой, критерий разрушения.

Introduction

At the present stage of construction industry development, composite steel structures are widely used in the construction of frame buildings and structures with heavily loaded elements experiencing a complex stress-strain state under eccentric compression-tension and bending. The advantages of composite steel structures are manifested in the possibility of placing in their cross-section, in addition to steel bar flexible reinforcement, steel profiles (rigid reinforcement) with high physical and mechanical characteristics (compared to concrete) of a large cross-sectional area and their protection against corrosion and high temperatures by concrete; the use of rigid reinforcement as load-bearing elements or formwork during their construction [1–6].

The joint work of steel elements having a larger contact surface area with concrete than flexible reinforcement of a round cross-section, with concrete is ensured by the device of various transverse projections in the form of rigid anchor stops or flexible stud bolts, reinforcement rods welded at one end to the profile. This allows to exclude their mutual shift under load up to the ultimate stage of strength of steel-reinforced concrete elements [7–15].

Approaches to the design of steel-reinforced concrete elements as a composite structure have historically evolved from the method of allowable stresses for a reduced cross-section working elastically (steel structures) to the method of ultimate forces with plastic behaviour of concrete (rectangular block of normal stresses in concrete of the compressed zone) and limited plastic work of steel (reinforced concrete structures). Further development of the ultimate force method led to the method of ultimate states, which is used in regulatory and advisory documents on the calculation of steel-reinforced concrete elements to this day [7–15].

Advances in the development of computer –based design have made it possible to apply in practice the deformation approach to the calculation of cross-sections of steel-reinforced concrete elements, which allows obtaining the parameters of their stress-strain state (SSS) for a cross-section of any shape, with any distribution of rigid and flexible reinforcement across the cross-section, at any stage of their deformation under load [16–22], taking into account the actual nonlinearity of the work of materials in the cross-section, the phenomena of shrinkage and creep of concrete [23], and the monotonic stage-by-stage loading [24–26]. The proposed deformation approach to the design of composite elements is based on the usage of material stress-strain diagrams and the linear distribution of strains in the cross-section (the hypothesis of plain sections), which is valid for composite elements in the absence of slippage between rigid steel reinforcement and surrounding concrete [16].

One of the positive examples of the use of composite elements was the construction of the unique building of the National Library of the Republic of Belarus. The building of the National Library consists of two main volumes: a high-rise book depository building and a 2–4-story stylobate located around it, where the rooms provided for by the library technology are located. The height of the book depository building is 72.6 m, and the height of the stylobate is 17.5 m [27]. The book depository itself begins at the +12.6 m mark. The lobby and the central entrance are located in the building up to this mark. The round stylobate building has a diameter of 167.5 m [28, 29]. The stylobate is separated from the high-rise book depository by a fireproof monolithic reinforced concrete wall. The main, most interesting part of the design concept is the high-rise book depository. It is a volumetric "symmetrical crystal" with the geometric shape of a rhombicuboctahedron with maximum dimensions of 30 x 60 x 60 m. In the lower inclined part of the structure, additional rod elements of the external contour are provided, which significantly increased the rigidity and stability of the building. Increased requirements for the rigidity of the structural scheme of the book depository building, in addition to the standard ones, are explained by its continuous cladding with decorative glass.

Additional elements that increase the rigidity and stability of the book depository building frame are steel-reinforced concrete struts resting on the support ring and taking the load from the frame columns located between the reinforced concrete diaphragms. In this case, the vertical component of the forces in the inclined steel-reinforced concrete struts is transferred to additional reinforced concrete columns at the point of support of the struts along the perimeter of the ring. The use of composite elements simplified the technology of concreting in suspended formwork with their negative angle of inclination and the installation of supporting circles.

The aim of this study is to apply a nonlinear approach based on concrete stress-strain diagrams, rigid and flexible reinforcement, taking into account the loading stages of the steel and reinforced concrete parts of the element, to the calculation of composite elements of the book depository building of the National Library of the Republic of Belarus.

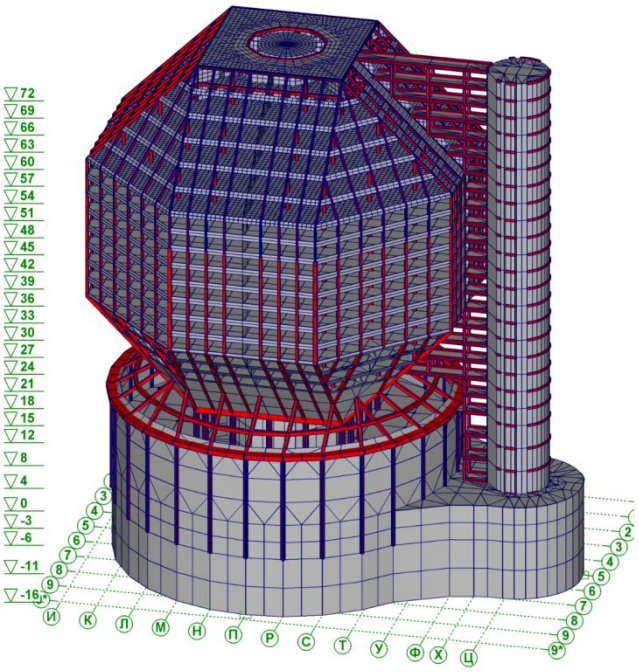

Figure 1 – Structural diagram of the building of the National Library of the Republic of Belarus

Nonlinear deformation model (NDM) for composite elements

According to the section method for NDM, the cross-section of a composite element consisting of concrete, rigid and flexible reinforcement is considered as a set of elementary areas with uniformly distributed compression-tensile stresses, the value of which depends on the strain in the center of gravity of the elementary area according to the material diagrams. The distribution of strain over the cross-section of the composite element obeys the Bernoulli hypothesis of a plain section.

The design stress-strain diagram of concrete under compression and tension, establishing the relationship between stresses and strains, is taken in the form of a parabolic curve with a descending branch, recommended by the European Concrete Committee (ECC-FIP) [30, 31], without limiting its length by deformations under compression in order to obtain a complete redistribution of forces between the components of the cross-section of the steel-reinforced concrete element.

The design stress-strain diagram of rigid and flexible reinforcement under compression and tension is taken to be bilinear (Prandtl diagram) with a limitation of strain of elongation at break. For flexible reinforcement of class S500, the stress-strain diagram according to [31] is taken with an inclined branch, the angle of inclination of which depends on the class of deformability (plasticity) of the reinforcement.

The system of NDM equations in the general case of loading for the composite cross-section of a element under the action of a longitudinal force N with eccentricities along the *x* and *y* axes relative to the center of gravity of the element section and bending moments M_x and M_y has the form:

$$\begin{cases} \sum \sigma_c(\varepsilon_c(x_c,y_c))A_c(x_c,y_c)(x_c-x_0)+\sum \sigma_s(\varepsilon_s(x_s,y_s))A_s(x_s,y_s)(x_s-x_0)-M_x-N\cdot e_{0,x}=0 \\ \sum \sigma_c(\varepsilon_c(x_c,y_c))A_c(x_c,y_c)(y_c-y_0)+\sum \sigma_s(\varepsilon_s(x_s,y_s))A_s(x_s,y_s)(y_s-y_0)-M_y-N\cdot e_{0,y}=0 \\ \sum \sigma_c(\varepsilon_c(x_c,y_c))A_c(x_c,y_c)+\sum \sigma_s(\varepsilon_s(x_s,y_s))A_s(x_s,y_s)-N=0 \\ \varepsilon_c(x_c,y_c)=\varepsilon_{c,II}+\varepsilon_z+1/r_x(x_c-x_0)+1/r_y(y_c-y_0) \\ \varepsilon_s(x_s,y_s)=\varepsilon_{s,II}+\varepsilon_z+1/r_x(x_s-x_0)+1/r_y(y_s-y_0) \end{cases}, \quad (1)$$

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where $\sigma(x, y)$, $\varepsilon(x, y)$ – normal stresses, strains in an elementary area of concrete, rigid or flexible reinforcement with coordinates (x, y);

$A_c(x_c, y_c)$, $A_s(x_s, y_s)$ – cross-sectional area of an elementary area of concrete, rigid or flexible reinforcement with coordinates (x, y);

(x_0, y_0) – coordinates of the center of gravity of the cross-section of the composite concrete element;

$1/r_x$, $1/r_y$ – curvature of the longitudinal axis of the composite concrete element in the plane of the x, y axes, respectively;

Strain ε_z at the center of gravity of the cross-section of the composite element is equal to:

$$\varepsilon_z = \frac{N}{\sum E_c A_c + \sum E_s A_s}. \quad (2)$$

The influence of longitudinal bending when calculating the parameters of the stress-strain state (SSS) of an eccentrically compressed composite element at any stage of its loading, including the ultimate strength, is produced by the coefficient η according to the formula [7, 30, 31]:

$$e_0 = \left(\sqrt{e_{0,x}^2 + e_{0,y}^2}\right) \cdot \eta, \quad (3)$$

where

$$\eta = \frac{1}{1 - N/N_{crit}}; \quad (4)$$

$$N_{crit} = \frac{\pi^2 \cdot (EI)}{l_0^2}; \quad (5)$$

l_0 – design effective length of the composite element; (EI) – the rigidity of the composite element at the calculated stage of its deformation.

$$EI = \frac{\sqrt{\left(N \cdot e_{0,x} + M_x\right)^2 + \left(N \cdot e_{0,y} + M_y\right)^2}}{\sqrt{\left(\frac{1}{r_x}\right)^2 + \left(\frac{1}{r_y}\right)^2}}. \quad (6)$$

The criterion for the formation of normal tensile cracks in a composite element is the achievement by concrete of the extreme tensile strain in relation to the neutral line of the elementary area. The failure criterion of the composite element is the maximum value of the internal force from external effects that the element perceives. The maximum value of the internal force $N(M)$, at which the process of successive approximations in the numerical solution of the system of equations (1) converges (the equilibrium conditions and the condition of strain compatibility are met), corresponds to the resistance of the composite concrete element. The advantage of the proposed failure criterion is the absence of the need to standardize the ultimate compressive strain of concrete and to take into account the high degree of redistribution of forces between the components in the cross section of the composite concrete element.

During the construction process, the rigid reinforcement of the composite elements is subject to the effects of its own weight and the weight of other precast elements supported by rigid sections, monolithic concrete and flexible reinforcement, and self-weight. This causes the appearance of an initial stress-strain state in the rigid reinforcement. The stage-by-stage construction process of composite elements [24–26] in the NDM is taken into account by summing the strains of each elementary area of the rigid reinforcement of the calculated cross-section with the strains $\varepsilon_{s,I}$, calculated at the first stage from the equations (7):

$$\begin{cases} \sum \sigma_s(\varepsilon_s(x_s, y_s)) A_s(x_s, y_s)(x_s - x_0) - M_{x,I} - N_I \cdot e_{0,x} = 0 \\ \sum \sigma_s(\varepsilon_s(x_s, y_s)) A_s(x_s, y_s)(y_s - y_0) - M_{y,I} - N_I \cdot e_{0,y} = 0 \\ \sum \sigma_s(\varepsilon_s(x_s, y_s)) A_s(x_s, y_s) - N_I = 0 \\ \varepsilon_{s,I}(x_s, y_s) = \varepsilon_{z,I} + 1/r_{x,I}(x_s - x_0) + 1/r_{y,I}(y_s - y_0) \end{cases}. \quad (7)$$

In addition, during concreting of composite structures and hardening of concrete, shrinkage strains appear, which are restrained by steel sections with a large contact surface and by the flexible reinforcement. For the given the high degree of deformation restraint composite elements, there is a risk of shrinkage cracking. Under the action of shrinkage deformations, compression deformations appear in rigid and flexible reinforcement, and tensile deformations in concrete.

In order to taking into account the shrinkage strain of concrete during its hardening at the second stage of design, the cross-section of the steel-reinforced concrete element is modeled without increasing the external load, compared to the first stage of the initial loading of rigid reinforcement. The value of the shrinkage strain of concrete $\varepsilon_{cs}(t, t_s)$ at time t, having an age of t_s at the time of the start of air-dry curing, is calculated using in accordance with [31]:

$$\varepsilon_{cs}(t, t_s) = \varepsilon_{cbs}(t) + \varepsilon_{cds}(t, t_s), \quad (8)$$

where $\varepsilon_{cbs}(t)$ – is the base shrinkage strain of concrete;

$\varepsilon_{cds}(t, t_s)$ – is the drying shrinkage strain of concrete.

The system of equations for calculating the stress-strain state parameters of the composite element at the second stage of the design is transformed to:

$$\begin{cases} \sum \sigma_{c,II}(\varepsilon_{c,II}(x_c, y_c)) A_c(x_c, y_c)(x_c - x_0) + \sum \sigma_{s,II}(\varepsilon_{s,II}(x_s, y_s)) A_s(x_s, y_s)(x_s - x_0) - M_{x,I} - N_I \cdot e_{0,x} = 0 \\ \sum \sigma_{c,II}(\varepsilon_{c,II}(x_c, y_c)) A_c(x_c, y_c)(y_c - y_0) + \sum \sigma_{s,II}(\varepsilon_{s,II}(x_s, y_s)) A_s(x_s, y_s)(y_s - y_0) - M_{y,I} - N_I \cdot e_{0,y} = 0 \\ \sum \sigma_{c,II}(\varepsilon_{c,II}(x_c, y_c)) A_c(x_c, y_c) + \sum \sigma_{s,II}(\varepsilon_{s,II}(x_s, y_s)) A_s(x_s, y_s) - N_I = 0 \\ \varepsilon_{c,II}(x_c, y_c) = \varepsilon_{z,I} + 1/r_x(x_c - x_0) + 1/r_y(y_c - y_0) + \varepsilon_{cs}(t, t_s) \\ \varepsilon_{s,II}(x_s, y_s) = \varepsilon_{s,I} + 1/r_x(x_s - x_0) + 1/r_y(y_s - y_0) + \varepsilon_{cs}(t, t_s) \end{cases}. \quad (9)$$

The strains distribution in the composite element sections obtained at the second stage of calculation will be the input ones at subsequent stages of its response under load (system of equations (1)).

Calculation of composite concrete elements according to NDM

The composite concrete elements of the book depository building of the National Library of the Republic of Belarus are: support ring (OK) with a radius of 27650 mm; inclined elements (НЭ1…НЭ3), supporting, cantilevering, bordering reinforced concrete floor beams, with a total length of 25400 mm and a calculated length (taking into account bracing along the length by floor beams) of l_0 = 4240 mm; braces (ПК), resting with one end on the composite concrete ring (OK), and the other on the inclined elements НЭ at the point of their connection with the bordering floor beams at the 18.600 m mark, with a length of 12100 mm (l_0 = 6050 mm) (Figure2). The steel-reinforced concrete element of the support ring experiences tension (+) with bending under the action of assembly forces, its own weight and internal forces from the acting loads, the other steel-reinforced concrete elements experience compression (–) with bending. The calculated forces in the composite elements under consideration at the time of their concreting (N_l, M_l) and from the calculated values of design effects of action (N, M) are given in Table 1.

Table 1 – Design values of the internal forces in composite elements

Element	N_l, kN	M_l, kN ·m	η_l	N, kN	M, kN ·m	η	N_u, kN	M_u kN ·m	η_u
ОК	+4250	168	–	+5285	280	–	+26823	1393	–
НЭ1	–43	26	1,000	–220	150	1,001	–2152	1498	1,027
НЭ2			1,000			1,001	–1743	1208	1,026
НЭ3			1,001			1,001	–1777	1226	1,018
ПК	–1364	18	1.000	–3560	21	1,001	–13587	461	2,679

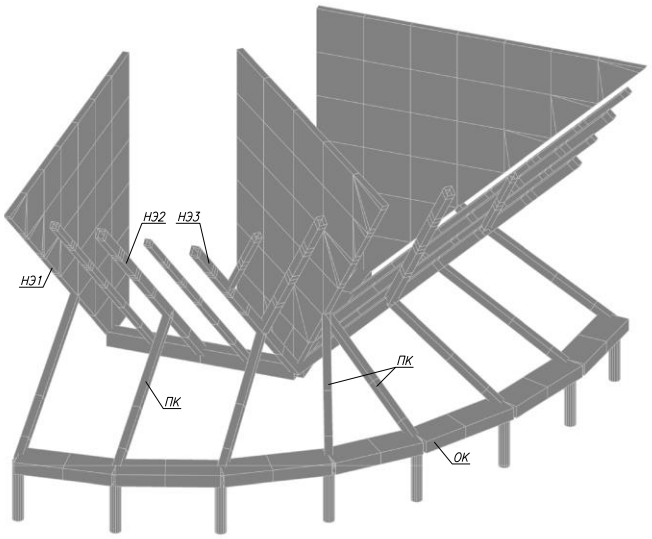


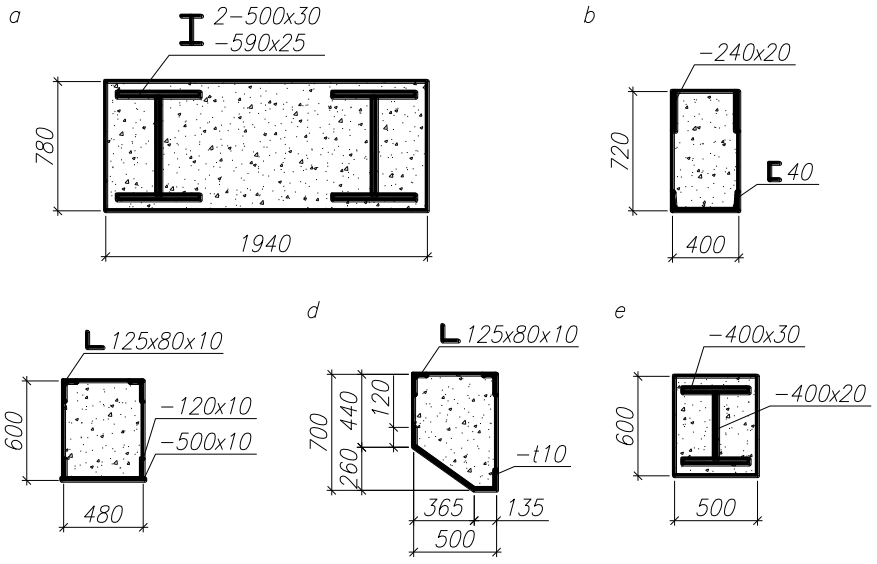
Figure 2 – Composite elements disposition in book depository building

The cross-sections of the considered composite elements with rigid reinforcement made of rolled and welded profiles are shown in Figure 3. All steel sections of the composite elements are made of steel C345, with the exception of inclined elements НЭ1…НЭ3, which are made of steel C245. Concrete class C25/30 is adopted for concreting all composite structural elements.

An example of calculating the parameters of the stress-strain state of the composite element using the proposed method for the support ring (OK) under the tensile force and bending moment is shown in Figure 4.

The analysis of the calculation results shown that the shrinkage strain of concrete $\varepsilon_{cs}(t,t_s)$ = 0.00025 caused the tensile stresses in concrete, and compressive stresses in rigid profile reinforcement, partially damping the tensile stresses from external effects. Under the design load, there are no flexural cracks in the concrete of the support ring. In the ultimate limit state, the support ring is loaded under tension with bending, but only rigid reinforcement, carry out effects of loading.

The strains and stresses distribution along the height of the cross-section of eccentrically compressed composite steel elements, taking into account their longitudinal bending, the initial stress-strain state at the time of concreting and the imposed shrinkage strain of the hardening concrete in the ultimate strength state, is shown in Figure 5. The results of calculating the ultimate forces (N_u, M_u) of the composite steel elements under consideration are given in Table 1.



a – support ring OK; b – inclined element NE1; c – inclined element NE2; d – inclined element NE3; e – struts PK

Figure 3 – Cross-sections of composite elements with rigid reinforcement

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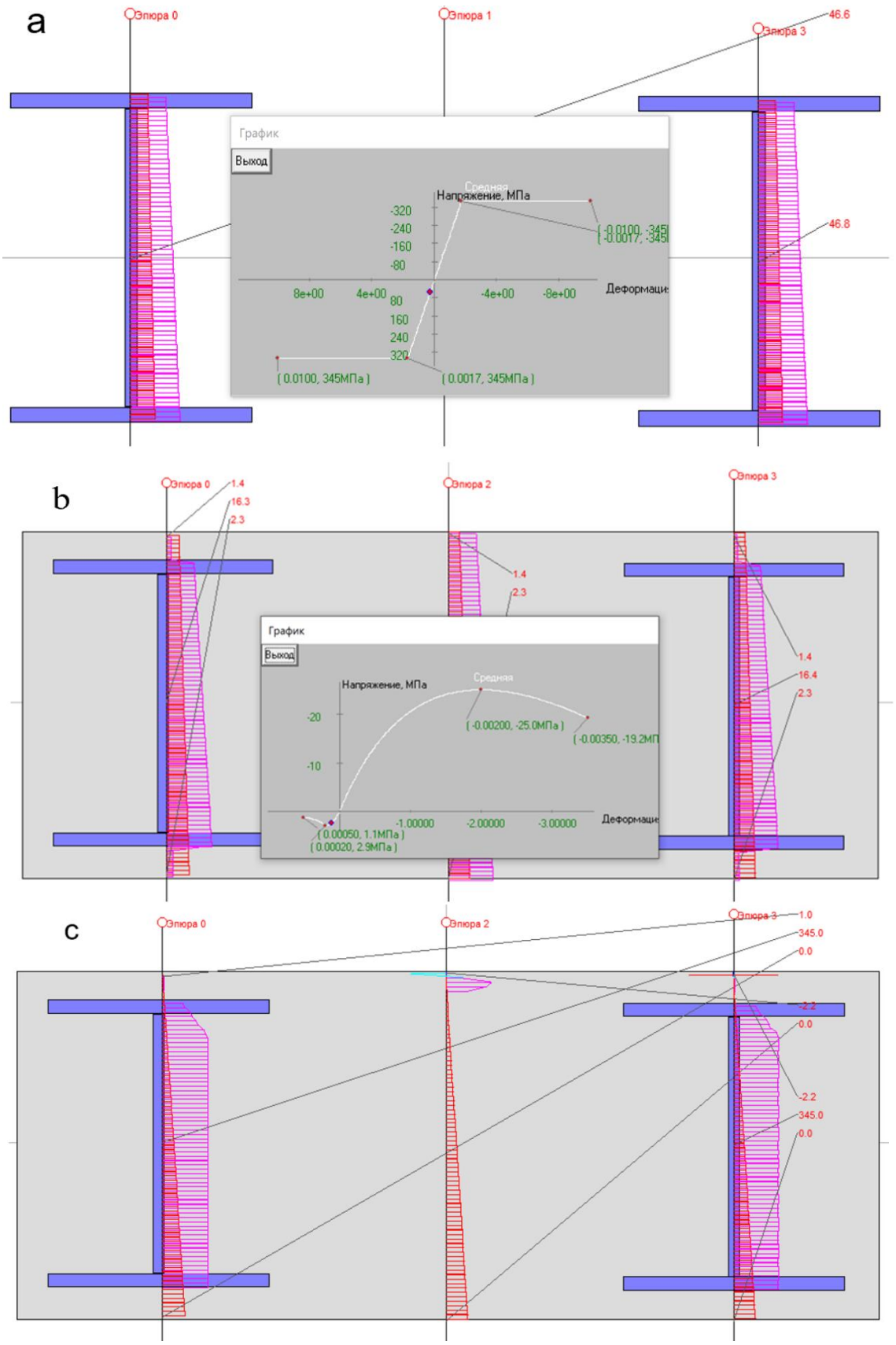
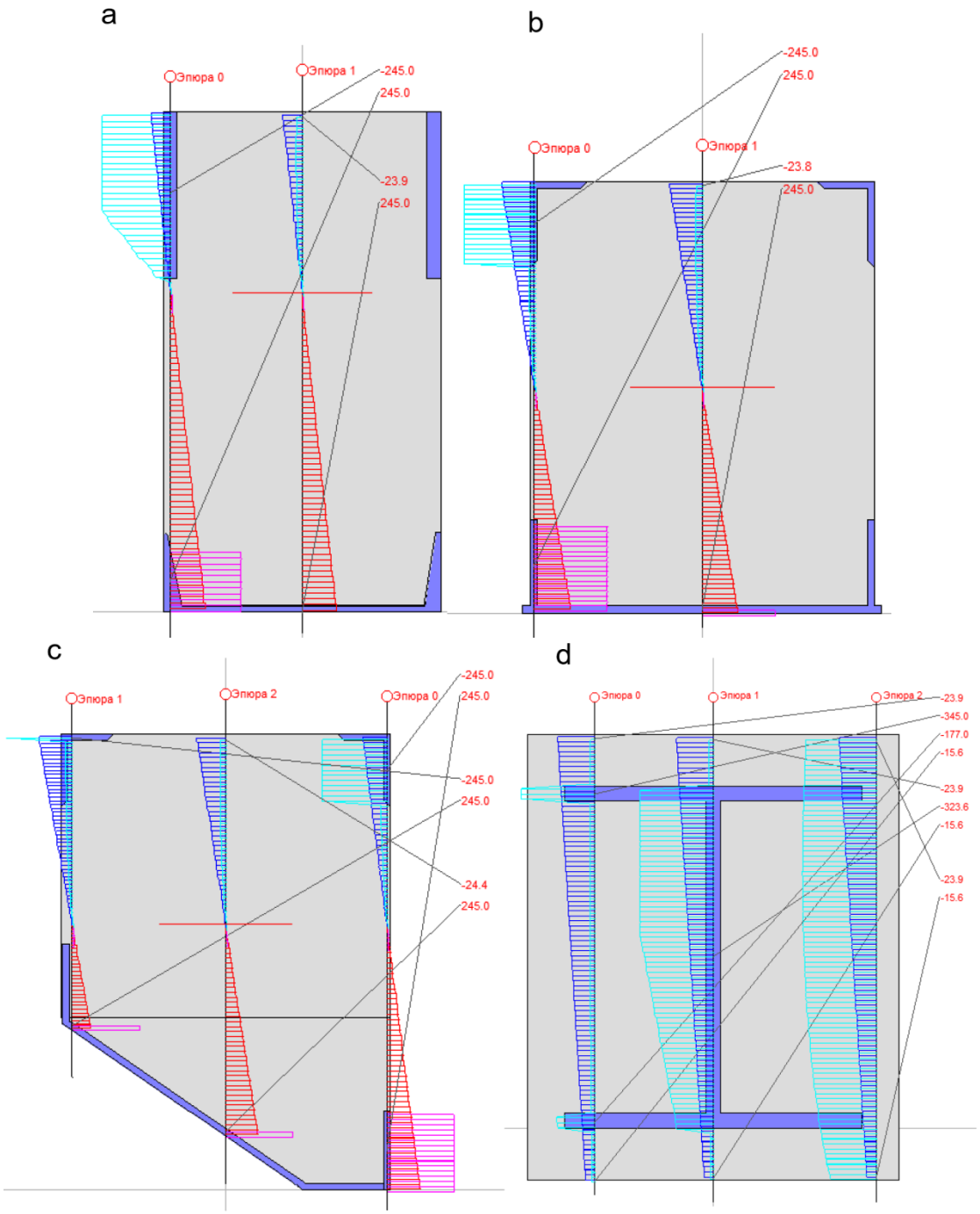


a – under the action of a tensile longitudinal force N_l = 4251 kN and a bending moment $M_{Sd,l}$ = 168 kN· m before concreting; b – the same, with the same internal forces and forces as a result of concrete shrinkage after its hardening; c – under the ultimate tensile longitudinal force N_u = 26823 kN and a bending moment Mu = 1393 kN·m (the numbers in red to the right of the cross-section are normal stresses in MPa)

Figure 4 – Results of calculating the distribution of strains and stresses across the cross-section of the composite element of the support ring OK



a – НЭ1; b – НЭ2; c – НЭ3; d – ПК (numbers in red to the right of the cross-section are normal stresses in MPa)

Figure 5 – Results of calculating the distribution of strains and stresses in the cross-section of compressed-bending composite elements in Ultimate Limit State (ULS)

The calculation of the maximum values of internal forces (effect of action) in the composite elements of the National Library of the Republic of Belarus shows a significant margin of safety when the resistance of the compressed concrete is taking into account.

Conclusion

Using the example of compressed (tensioned) with bending composite elements of the National Library of the Republic of Belarus, the applicability of a nonlinear deformation model for calculating their stress-strain state parameters at the stage of their construction is demonstrated, taking into account the effect of actions and imposed forces developed by concrete shrinkage during curing, when working under load, including the ultimate load.

Taking into account concrete shrinkage allows to increase the reliability of calculating the parameters of the stress-strain state of composite elements and to foresee the possibility of shrinkage cracks appearing at the stage of their concreting and curing.

The criterion for calculating internal forces corresponding to the resistance of element without the ultimate strain of concrete limiting and rigid reinforcement under compression makes it possible to take into account the redistribution of forces in the cross-section between rigid reinforcement and compressed concrete.

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References

1. Vasil'ev, A. P. ZHelezobeton s zhestkoj armaturoj / A. P. Vasil'ev ; Narodnyj komissariat po stroitel'stvu. Tekhn. upr. Central'nyj nauchno-issledovatel'skij institut promyshlennyh sooruzhenij – CNIPS. – Moskva ; Leningrad : Gosudarstvennoe izdatel'stvo stroitel'noj literatury, 1941. – 123 s.
2. Raschet stalezhelezobetonnoj kolonny vysotnogo doma na kosoe vnecentrennoe szhatie / A. M. Desyatkin, D. V. Konin, A. S. Martirosyan, V. I. Travush // ZHilishchnoe stroitel'stvo. – 2015. – S. 92–95.
3. Tamrazyan, A. G. Istoriya razvitiya teorii zhelezobetona: biograficheskij ocherk / A. G. Tamrazyan, A. F. Lolejt. – M. : MGSU, 2018. – 184 s.
4. Babalich, V. S. Stalezhelezobetonnye konstrukcii i perspektiva ih primeneniya v stroitel'noj praktike Rossii / V. S. Babalich, E. N. Androsov // Uspekhi sovremennoj nauki. – 2017. – T. 4, № 4. – S. 205–208.
5. Kibireva, YU. A. Primenenie konstrukcij iz stalezhelezobetona / YU. A. Kibireva, N. S. Astaf'eva // Ekologiya i stroitel'stvo. – 2018. – № 2. – S. 27–34. – DOI: 10.24411/2413-8452-2018-10004.
6. Vinogradova, N. A. Issledovaniya stalezhelezobetonnyh izgibaemyh konstrukcij (obzor) / N. A. Vinogradova, G. A. SHvec // Vestnik inzhenernoj shkoly DVFU. – 2020. – № 1(42). – S. 114–127.
7. Konstrukcii stalezhelezobetonnye. Pravila proektirovaniya : SP 266.1325800.2016. – M., 2017.
8. Konstrukcii stalezhelezobetonnye pokrytij i perekrytij. Pravila proektirovaniya : TKP 45-5.03-16-2005 (02250) / Ministerstvo arhitektury i stroitel'stva Respubliki Belarus'. –Minsk, 2006. – 71 s.
9. Metodicheskie rekomendacii po raschetu i proektirovaniyu stalezhelezobetonnyh perekrytij. – M. : Federal'nyj centr normirovaniya, standartizacii i ocenki sootvetstviya v stroitel'stve, 2018. – 62 s.
10. Metodicheskoe posobie po raschetu i proektirovaniyu stalezhelezobetonnyh konstrukcij s zhestkoj armaturoj. – M. : Federal'nyj centr normirovaniya, standartizacii i ocenki sootvetstviya v stroitel'stve, 2018. – 49 s.
11. Tonkih, G. P. Eksperimental'noe issledovanie sdvigovogo soedineniya monolitnyh stalezhelezobetonnyh perekrytij na ugolkovyh ankernyh uporah / G. P. Tonkih, D. A. CHesnokov // Vestnik MGSU. – 2021. – №2. – S. 144–152. – DOI: 10.22227/1997-0935.2021.2.144-152.
12. Semenov, V. A. Stalezhelezobetonnye konstrukcij. Oblast' primeneniya i osnovnye polozheniya SP 266.1325800.2016 «Konstrukcii stalezhelezobetonnye. Pravila proektirovaniya». Preimushchestva stalezhelezobetonnyh konstrukcij po sravneniyu s tradicionnymi resheniyami. Modelirovanie stalezhelezobetonnyh konstrukcij s pomoshch'yu sovremennogo inzhenernogo PO dlya proektirovshchikov / V. A. Semenov // Prezentaciya: Associaciya razvitiya stal'nogo stroitel'stva (ARSS). – URL: https://steel-fabrication.ru/mediatsentr/5_Vladimir%20Semenov_Tekhsoft.pdf (data obrashcheniya: 01.07.2024).
13. Rukovodstvo po proektirovaniyu zhelezobetonnyh konstrukcij s zhestkoj armaturoj. – M. : Strojizdat, 1978. – 57 s.
14. Proektirovanie stalezhelezobetonnyh konstrukcij : EN 1994-1-1:2005. Evrokod 4. – CH. 1. Obshchie pravila dlya zdanij i sooruzhenij. – M., 2011. – 123 s.
15. Proektirovanie stalezhelezobetonnyh konstrukcij : Rukovodstvo dlya proektirovshchikov k Evrokodu 4 EN 1994-1-1. – M., 2013. – 414 s.
16. Muhamediev, T. A. Raschet prochnosti stalezhelezobetonnyh kolonn s ispol'zovaniem deformacionnoj modeli / T. A. Muhamediev, O. I. Starchikova // Beton i zhelezobeton. – 2006. – № 4 (541). – S. 18–20.
17. Karpenko, N. I. K raschyotu prochnosti, zhyostkosti i treshchinostojkosti vnecentrenno szhatyh zhelezobetonnyh elementov s primeneniem nelinejnoj deformacionnoj modeli / N. I. Karpenko, B. S. Sokolov, O. V. Radajkin // Izvestiya Kazanskogo gosudarstvennogo arhitekturno-stroitel'nogo universiteta. – 2013. – № 4(26). – S. 113–120.
18. Kudinov, O. V. Novyj podhod k ocenke prochnosti stalezhelezobetonnyh perekrytij / O. V. Kudinov // Beton i zhelezobeton. – 2010. – № 2(563). – S. 14–16.
19. Arleninov, P. D. Sovremennoe sostoyanie nelinejnyh raschetov zhelezobetonnyh konstrukcij / P. D. Arleninov, S. B. Krylov // Sejsmostojkoe stroitel'stvo. Bezopasnost' sooruzhenij. – 2017. – № 3. – S. 50–53.
20. Gholamhoseini, A. Long-Term Behavior of Continuous Composite Concrete Slabs with Steel Decking / A. Gholamhoseini, R. I. Gilbert, M. Bradford // ACI Structural Journal. – 2018. – № 115. – P. 439–449.
21. Karpenko, N. I. Iskhodnye i transformirovannye diagrammy deformirovaniya betona i armatury / N. I. Karpenko, T. A. Muhamediev, A. N. Petrov // Napryazhenno-deformirovannoe sostoyanie betonnyh i zhelezobetonnyh konstrukcij. – M. : NIIZHB, 1988. – C. 7–25.
22. Bondarenko, V. M. Inzhenernye metody nelinejnoj teorii zhelezobetona / V. M. Bondarenko, S. V. Bondarenko. – M. : Strojizdat, 1982. – 287 s.
23. Uchet polzuchesti i usadki betona po SP 5.03.01-2020 pri raschete zhelezobetonnyh konstrukcij na osnove deformacionnoj raschetnoj modeli / D. N. Lazovskij, V. V. Tur, D. O. Gluhov, E. D. Lazovskij // Vestnik Brestskogo gosudarstvennogo tekhnicheskogo universiteta. – 2021. – № 2(125). – S. 7–12. – DOI: 10.36773/1818-1212-2021-125-2-7-12.
24. Lazovskij, D. N. Usilenie zhelezobetonnyh konstrukcij ekspluatiruemyh stroitel'nyh sooruzhenij / D. N. Lazovskij. – Novopolock : Polockij gosudarstvennyj universitet, 1998. – 240 s.
25. Nelinejnyj raschet izgibaemyh stalezhelezobetonnyh elementov / D. N. Lazovskij, D. O. Gluhov, A. M. Hatkevich [i dr.] // Vestnik Polockogo gosudarstvennogo universiteta. Seriya F. Stroitel'stvo. Prikladnye nauki. – 2024. – № 2(37). – S. 9-23. – DOI: 10.52928/2070-1683-2024-37-2-9-23.
26. Lazovskij, D. N. Deformacionnyj podhod k raschetu soprotivleniya szhatiyu stalezhelezobetonnyh elementov / D. N. Lazovskij, A. I. Gil', D. O. Gluhov // Vestnik MGSU. – 2024. – T. 19. Vyp. 9. – S. 1469–1483. – DOI: 10.22227/1997- 0935.2024.9.1469-1483.
27. Arhitekturno-konstruktivnye resheniya unikal'nogo zdaniya Nacional'noj biblioteki Belarusi / M. K. Vinogradov, V. V. Kramarenko, L. M. SHohina [i dr.] // Stroitel'naya nauka i tekhnika. – 2005. – № 1. – S. 8–13.
28. SHohina, L. M. Konstruktivnye resheniya novogo zdaniya biblioteki / L. M. SHohina // Arhitektura i stroitel'stvo. – 2003. – № 2. – S. 2–3.
29. Konstruktivnye resheniya vysotnogo zdaniya knigohranilishcha Nacional'noj biblioteki Belarusi / D. N. Lazovskij, A. V. Popravko, T. M. Pecol'd, L. M. SHohina // Vestnik Polockogo gosudarstvennogo universiteta. Seriya B: Prikladnye nauki. – 2006. – № 9. – S. 2–7.
30. Fib Model Code for Concrete Structures 2010. – Germany. – 402 p.
31. Betonnye i zhelezobetonnye konstrukcii : SP 5.03.01-2020 / RUP «Strojtekhnorm». – Minsk : Ministerstvo arhitektury i stroitel'stva Respubliki Belarus', 2020. – 236 s.

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ASSESSMENT OF THE PREDICTION METHODS OF RESTRAINED STRAINS AND SELF-STRESSES OF THE MEMBERS MADE OF EXPANSIVE CONCRETES

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Abstract

In various time periods, interest to RC structures made of expansive concretes was very different: from admiration after its successful utilization in the real practice of civil engineering works (for instance, jointless self-stressed and post-tensioned slab-on-ground with dimensions of 144 x 72 m^2) to great criticism and sarcasm when shrinkage cracking appeared after full self-stressing loosing or even self-damaging taking place in case, when «unbalanced» expansion and strength development were observed.

Nevertheless, the interest to the elements made of self-stressing concrete drastically increased in the last decades. By the way, it is necessary to mention that in its majority, there are elements with so-called composite reinforcement (bars). In such a bars, the reinforcing fibers are made of glass, aramid, carbon and etc. However, prediction methods of the restrained strains and self-stresses development are not always characterized by the accuracy in connection with the self-prestressing is a multifactorial process and, thus, these methods need for clarification and modification in future.

In this paper authors presented short historical review on expansive binders production for self-stressing and shrinkage-compensating concretes, discussed advantages and disadvantages of the known models for restrained strains and compressive stresses assessment as a result of self-prestrssing, as well as some own results of the behavior of self-stressed concrete structural elements, reinforced with both steel and glass fibers reinforced polymer (GFRP) bars on the both expansion (self-prestressing) stage and under the static loading.

Keywords: expansive concrete, self-stressed elements, restrained strains, conservation law of chemical energy, deformation approach.

ОЦЕНКА СУЩЕСТВУЮЩИХ МЕТОДИК РАСЧЁТА СОБСТВЕННЫХ ДЕФОРМАЦИЙ И САМОНАПРЯЖЕНИЙ ЭЛЕМЕНТОВ ИЗ НАПРЯГАЮЩИХ БЕТОНОВ

В. В. Тур, О. С. Семенюк, С. М. Семенюк, В. И. Юськович

Реферат

В различное время отношение к железобетонным конструкциям, выполненным из расширяющихся бетонов было различным: от признания перспективности материала после удачной реализации ряда объектов в реальной строительной практике (например, бесшовные самонапряжённые полы на упругом основании, выполненные с постнапряжением, размерами 144 × 72 $м^2$) до существенной критики и сарказма в отношении данного материала, когда в конструкциях наблюдали образование усадочных трещин после полной потери самонапряжения либо же констатировали саморазрушение элемента в случае несбалансированного развития динамики расширения бетона по отношению к динамике набора им прочности.

Тем не менее в последнее время возрос интерес к элементам из напрягающего бетона. В большей степени это элементы, выполненные с так называемым композитным армированием, где армирующим элементом является не арматурная сталь, волокна выполненные из стекла, арамида, карбона и т. д. Однако расчётные методики связанных деформаций и самонапряжений в таких элементах не всегда отличаются точностью в связи смногофакторностью процесса и требуют уточнения и доработки в дальнейшем.

В данной статье авторы представили короткий исторический обзор производства расширяющихся вяжущих для самонапрягающих бетонов и бетонов с компенсированной усадкой, обсудили преимущества и недостатки известных моделей для расчёта связанных деформаций и сжимающих напряжений в бетоне как результат самонапряжения, а также представили ряд собственных результатов исследования самонапряжённых бетонных элементов, армированными стальными и композитными стержнями как на стадии самонапряжения (расширения), так и на стадии статических испытаний.

Ключевые слова: расширяющийся бетон, самонапряжённые элементы, связанные деформации, закон сохранения химической энергии расширения, деформационные подходы.

Introduction. Historical review on expansive concretes and binders development

In the recent years a new wave of interest in the research and practical use of self-stressing concrete has been observed, now, specifically, in combination with various types of so-called non-traditional reinforcement. One of the widely used types of these reinforcements is FRP bars and long fibres (textile) (fibres made of glass, aramid carbon and etc.) [1]. The main problems of FRP reinforcement implementation as a structural reinforcement are related to the development of excessive deflections as well as crack opening under service loads. One of the most effective methods for concrete with FRP reinforcement performance enhancing is chemical prestressing with self-stressing (expansive) concretes.

Let's consider phenomena of concrete prestressing (chemical or mechanical) in general. Prestressing of concrete is a technique in which reinforcement is actively tensioned initially to later transfer, after reinforcement releasing, the stresses into hardened concrete (prestress). Such appeared compressive stresses in concrete counteracts the tensile stresses that occur at service stage and, hence, offset the risk of tensile cracking.

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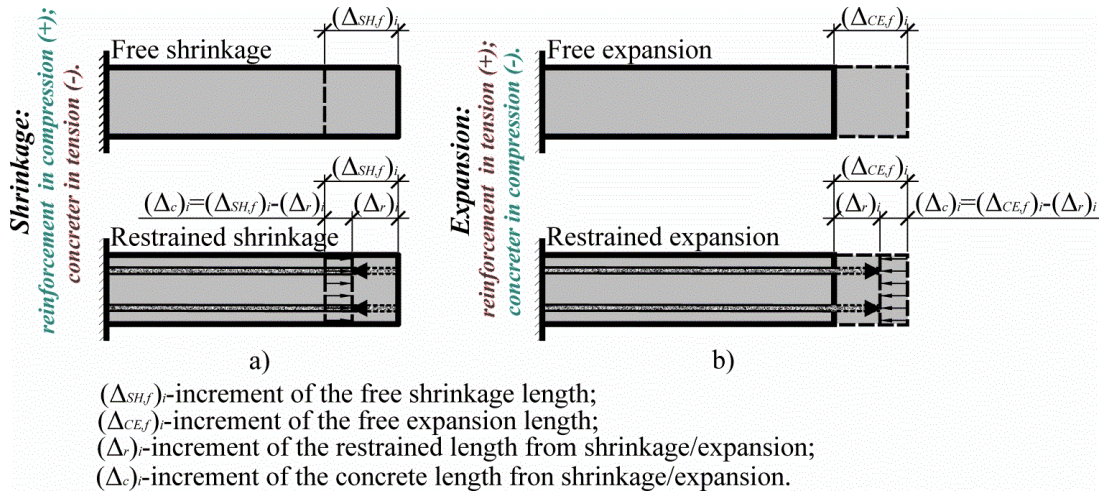
In the case of mechanical pre-tensioning of tendons, the following disadvantages exist: high needs for time and labor consumption, necessity of qualified personnel, usage of very expensive prestressing beds with loading jacks and anchorage systems. As well, traditional prestressing is feasible for one-directional prestress only. At the same time, the self-prestressing technology is becoming a viable alternative to traditional prestressing. Self-prestressing (see Figure 1) of concrete members is based solely on usage the restrained expansion capacity of self-stressing concrete during hardening to cause pretensioning of the reinforcement. Usage of self-stressing concrete for gradual prestressing allows to achieve the required levels of prestressing, as well as to save the major part of obtained prestress in time.



a) – plain concrete shrinkage; b) – self-stressing concrete expansion

Figure 1 – Schematic presentation of the shrinkage and expansion processes

Intensive development of the Portland cement concrete technology in the last decades allowed to obtain high-performance concrete (HPC) or even ultra-high performance concrete (UHPC) with a compressive strength above 120 MPa. Nevertheless, an inadequate ratio of such a concretes compressive to tensile strength allows to say, that concretes of the new generation still remain an artificial composite stone materials with a good performance under compression only in combination with inherent to concrete early-age and long-term effects (such as autogenous, plastic and drying shrinkage deformations, creep deformations, sensitivity to temperature differences). In its turn this situation unavoidable leads to decreasing of the serviceability parameters of concrete structures decreasing. For instance, restrained shrinkage and temperature deformations lead to the additional tensile stresses appearance in the concrete structure causing cracks (cracks of different sizes can be found almost in every reinforced concrete structures). Obviously, such cracking of concrete reduces structural durability in general. Based on the sustainable development strategy, presented at the *fib* Symposium 2020 in China defines concrete of the new generation as a high-durability concrete (HDC). To permit a more efficient utilization of structural concrete, the search for means of overcoming these weaknesses had led to mechanical prestressing of steel tendons. By keeping the concrete in compression, cracking is prevented. Considerable advantage can be derived from concrete expansion under the various types of restraint and in its turn to induce restrained strains and, respective to them, compressive pre-stressing of sufficient magnitude to compensate shrinkage effects (so-called shrinkage-compensating concrete) or to induce compressive stresses of a high enough magnitude, resulting in significant compression in the concrete after long-term and short-term processes have been realized in time and in such a way we obtain self-prestressing of concrete. The above-mentioned problem led to the idea of the physico-chemical (or sometimes called chemical) method of concrete structures volume prestressing. In 1953 **I. Giyon** wrote in his monograph: «*... In case we will reach a significant restrained expansion of the concrete, that could provide an adequate reinforcement pre-tensioning, without doubts, we will get a principally new method of the beams pre-stressing*».

The history of the development of expansive cement development and application (self-stressing and shrinkage-compensating concretes) counts about 90 years and it can be said, that it has originated from an investigation of ettringite in cement. Ettringite crystal (3CaO·Al2O3·3CaSO4·32H2O) represents by itself a phase, formed in different concrete phases during hydration of expansive cements, which are the source of the ability for expansion. It is comparable to the natural mineral of the same name. This high sulfate calcium sulfoaluminate is also formed by sulfate attack on mortar and concrete (so-called delayed ettringite) and was defined as «*cement bacillas*» in elder literature. **Candlot** reported in 1890s that this product resulted from reaction of ticalcium aluminate (C3A) with calcium sulfate (CaSO4). **Michaelis** in 1892 [2] suggested that ettringite was responsible for destructive expansion of Portland cement concretes in the presence of sulfates in ambient conditions.

One of the earliest investigators, recognized the potential of ettringite in the elimination of shrinkage and possibly of prestress inducing was **Lossier** [3]. His works continued more than 20 years, starting in the middle 1930s, and the cement he had developed was consisted of Portland cement, an expansive component (grinding gypsum, bauxites, chalk to slurry burning as the admixture to a clinker) and blast furnace slag.

Russian works, published by professor **Mikhajlov** in the field of expansive cements followed two different courses to obtain an expansive cements for the aims of repairing and/or waterproofing and self-prestressing. Expansive cement type-M either is a mixture of Portland cement, calcium aluminate cement and calcium sulfate or an interground product made with Portland cement clinker, calcium aluminate clinker and calcium sulfate. In monograph [4], we can find the first formulation of the solid-state or solid-phase expansion mechanism theory of the concrete matrix as a fundamental condition of concrete self-prestressing under restraint and the related to it requirements to the expansive cement compositions (for instance, the ratio Al_2O_3/SO_3 in both expansive additive and expansive concrete itself).

Studies performed by **Klein** [5] and his associates at the University of California are based on the formation of a stable anhydrous calcium sulfoaluminate compound by heat treating a mixture of bauxite, chalk, gypsum at about 2400F (≈1315 ºC). While the ingredients were quite similar to those were used by the Lossier in his cements, the material selection and clinkering conditions, probably, contributed to the formation of an anhydrous calcium sulfoaluminate, calcium sulfate and lime. As a result produced cement could be handled much in the same manner as a regular cement and adjusted to offset shrinkage and produce large net of expansion.

In recent years some new types of the expansive cement and expansive additives to OPC are proposed on the market of building materials, but all these materials based on the reacton of the ettringite formation (CSA-type of additives). It should be mentioned that besides the use of expansive potential generated by ettringite formation, another type of expansive admixtures takes use of hydroxide formation. As well, periclase has been employed in dam construction as the expanding agent in China.

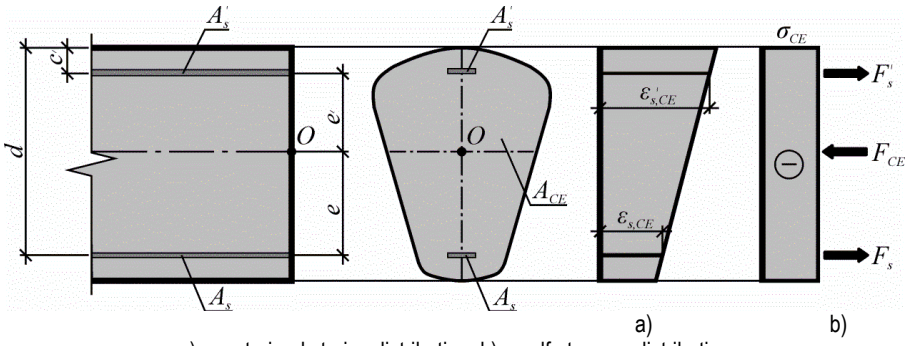
Models for assessment of the early-age stress-strain state in self-stressed concrete structures

In this paper, the attention is paid on the most controversial series of articles [6, 7] dedicated to textile-reinforced self-stressed concrete (TRSSC), mainly respectively the «*Theory of self-stressing distribution models*» and experimental results used for verification of these models. In recent decades, it was developed various types of reinforcing elements to replace conventional reinforcing steel (short fibres, various types of FRP bars). Firstly, let's pay attention on the replacement steel reinforcement by use of continuous fibres or grids that were made from continuous fibres began in the 1980s. Among experts, *this new, innovative composite building material* is known today as *textile-reinforced concrete* (TRC). In investigations *«self-stressing concrete (SSC) matrix was combined with textile to form a new composite material, namely, textile-reinforced self-stressing concrete (TRSSC). In this material, textile functions as expansion confinements to SSC to attain self-stress»*.

There is no doubts that to extend application of self-stressing concrete with any type of reinforcement in the practice of civil engineering the need for adequate models for assessment of stresses (strains) appeared in self-prestressed concrete structures is evident. In this paper the authors would like to show some most conservative and as well more complicated and prospective approaches used for stress-strain statement of self-prestressed structures prediction.

Models based on the conservation law of chemical energy

Finding out the origins of the models based on the conservation law of chemical energy brought us to the early 1970s. The fundamental for these models assumption was formulated by the V. Mikhailov and S. Litver in [4]: «… *it was established within numerous investigations that regardless of the reinforcement areas in the both zones* (*authors'note:* in tensile (A_{st}) and in compressive (A_{sc}) zones under the loading) *of the section* A_{sc} *and* A_{st}*, i.e. when* $A_{sc} \neq A_{st}$*, self-stressing concrete of the structure within expansion process accumulate* ***uniformly distributed through the section depth compressive stresses (self-stresses)***». It can be explained by the fact that tensile forces in reinforcement in the both of these zones perform the equal work on the obtained within expansion strains, and, as a result, strains and forces in the reinforcement of these zones are different, the cross-section of the structure loses its linearity and the concrete is precompressed uniformly». On the above-mentioned fundametal statement was based a number of standards [8] in accordance with the which it was reported, that: «*self-stresses in the concrete are accepted to be uniformly distributed through the cross-section depth:* ***resultant of the compressive stresses (self-stresses) is arranged in the cross-section gravity center***» (see Figure 2).



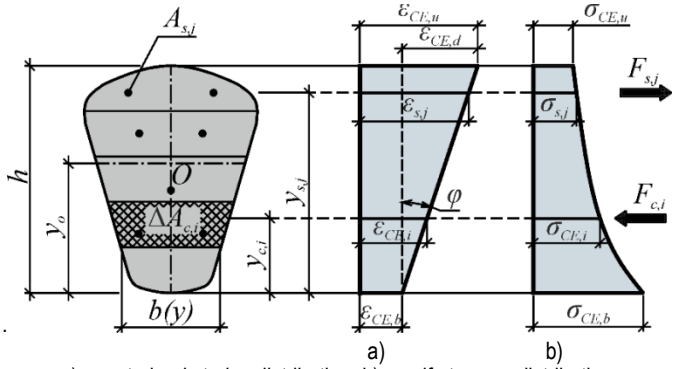
a) – restrained strains distribution; b) – self-stresses distribution

Figure 2 – Restrained strains and self-stresses distribution in the cross-section of the self-stressing concrete member in accordance with model [4, 8]

Evidently, that an accepted hypothesis essentially simplified assessment of the self-stresses value as far as for it became unnecessary to know the value of the concrete restrained strains. *It should be noted, that this circumstance led to the situation that for a long period of time resultant value of the free expansion strains to the expansion stabilization point was ignored as a necessary parameter for calculations*. As the main calculation parameters was accepted to consider $f_{CE,d}$ – reference self-stress of the concrete established in the standard restraint conditions to the concrete expansion stabilization, i.e. it is compressive stress in the self-stressing concrete prism under uniaxial symmetrical restraint with the stiffness equal to 1 % of the steel cross-sectional reinforcement ratio ($E_s = 200$ GPa).

Inspite of the evident simplicity of the models [4, 8], based on the *uniform self-stresses distribution through the section depth hypothesis*, it have to be mentioned that the hypothesis itself is not applicable at least for the case of the one-layer cross-sectional reinforcement arrangement: in such a case it is difficult to state that resultant force in the concrete in compression is in the concrete section gravity center (applied points mismatching of the resultant compressive force in concrete and resultant tensile force in the reinforcement causes appearance of the unbalanced moment in the cross-section to the concrete expansion stabilization). At the same time, an obtained value of the self-stress in concrete is a result of the elastic compressive strains amount accumulated in concrete to the expansion stabilization. Thus, in the self-stressed members in the same way like in the traditionally mechanically prestressed members, after the compression force transfer, cross-sectional equilibrium conditions have to be satisfied.

To the modified model based as well on the conservation law of chemical energy is referred model developed by Y. Tsuji [9] (see Figure 3).



a) – restrained strains distribution; b) – self-stresses distribution

Figure 3 – Restrained strains and self-stresses distribution in the cross-section of the self-stressing concrete member with multi-layer reinforcement arrangement in accordance with model [9]

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This model is more complex in comparison with the above-prescribed model [4, 8], as far as apart of the fundamental hyphothesis of conservation law of chemical energy it takes into account cross-section equilibrium conditions. The model is based on the following approaches: a) to the expansion stabilization restrained concrete strains are distributed linear throughout the cross-section depth (plain cross-section hypothesis is valid); b) the amount of work U_{CE}, that expansive concrete performs against restraint per unit volume, is a constant value regardless of the degree of restraint; c) self-stressing concrete and restraint compatibility of strains are respected throughout the expansion stage.

The same like in [9] $f_{CE,d}$ value is an «energetic» parameter that represents self-stress in concrete reached in standard restraint conditions, in [9] self-stressing concrete work amount U_{CE} (that is established in the same standard restraint conditions: centrally uniaxially arranged steel ($E_s = 200$ GPa) restraint in the concrete cross-section with reinforcement ratio $\rho_{l,s} = 1\%$) as well is an «energetic» parameter that is established in accordance with the following equation:

$$U_{CE} = \frac{\sigma_{CE} \cdot \varepsilon_{CE}}{2}, \quad (1)$$

where σ_{CE} and ε_{CE} – self-stress and respective to it concrete restrained strains respectively established in strandard restraint conditions ($E_s = 200$ GPa, $\rho_{l,s} = 1\%$) to the expansion stabilization.

In the article [10] disadvantages of the model [4, 8, 9] were found out on the basis of the numerical studies and described in details.

Summarizing all of the above-stated models based on the conservation law of chemical energy, it is possible to make following conclusions: any models based on predescribed hypothesis have a pretty tight diapason when they are applicable, in the other cases calculation results contradict the experimental values or, even, don't demonstrate a physical sense in general. Moreover, it is necessary to underline, that these models are valid only when as a free expansion strains restriction steel reinforcement is acting. It can be explained by the fact that reference energetic parameters in these models (such as $f_{CE,d}$ in [4, 8] and U_{CE} in [9]) are established in conditions when steel reinforcement is acting as a restraint. The models [4, 8, 9] are not applicable when, as a restraint, reinforcement with the different from steel elasticity modulus is utilized. It is connected with the fact, that these models don't take into account reinforcement properties itself such as stresses relaxation, development of which one is different for materials with not the same elasticity modulus.

Models based on the deformation approach

In the recent years a numerous of international publications [11] are devoted to the description of the self-stressing concrete expansion process with the deformation models. These models are universal as far as with it application it is possible to describe a physical side of the expansion process and to take into account a wide range of factors influenced on the kinetics of the self-stressing concrete expansion (the factors such as continuously changing at the self-stressing stage ratio between axial stiffness of the early-age concrete and of the restraint, as well as creep of early-age concrete), i.e. it allows to take into account continuous redistribution of the internal forces in the member cross-section as a result of non-elastic properties of the self-stressing concrete at early-age. Moreover, deformation models are able not only to describe expansion processes, but they can be easily extended on the following after expansion long-term processes (shrinkage, long-term creep) and its consideration allows to extract a number of self-stressing parameters (self-stresses, concrete restrained strains, accumulated in concrete elastic strains) to the any time-point of the expansion process (not only to the expansion stabilization).

In general case deformation models are based on the consideration of the following basic equation:

$$d\varepsilon_{CE,f} = d\varepsilon_r + d\varepsilon_{c,el} + d\varepsilon_{c,pl}, \quad (2)$$

where $d\varepsilon_{CE,f}$ – increment of the self-stressing concrete free expansion strains;

$d\varepsilon_r$ – increment of the self-stressing concrete restrained strains on the depth of the restraint;

$d\varepsilon_{c,el}$ and $d\varepsilon_{c,pl}$ – increment of the self-stressing concrete elastic and plastic strains respectively.

All of the known modifications of the deformation models are consisted in the consideration of the basic equation (2) on the elementary time-steps Δt_i, where the increment of the self-stressing concrete free expansion strains takes place on the background of the non-stopped development of the materials physico-mechanical properties at early-age, including creep. From the equation (2) it is possible to find out $d\varepsilon_r$ on the elementary time-step Δt_i. Detailed description of the deformation models are presented in [11].

It should be mentioned, that in contrast to the models based on the conservation law of chemical energy, where reference concrete characteristics ($f_{CE,d}$, U_{CE}) are established in the uniaxial standard restraint conditions, in deformation models self-stressing concrete free expansion (shrinkage) strains temporal progress (in such a models it is essential not only concrete free expansion (shrinkage) strains value to the expansion stabilization, but kinetics of its development) are considered as a basic concrete characteristic. To the input data for deformation models an appropriate early-age concrete creep function and function of the early-age concrete elasticity modulus development are referred as well.

Calculation results of the concrete restrained strained in accordance with the general concept of the deformation models demonstrate a good fit with experimental data [11]. It should be stated that that verification of the deformation models was performed, mostly, for concretes with free expansion strains to stabilization not higher than 0,05% and expansion stabilization was observed to the end of the first week of concrete age. Thus, such an expansive concrete can be referred to the shrinkage-compensating. Nevertheless, verification of the basic deformation model for the case of structural members made of self-stressing concrete (with high expansion energy capacity: concrete free expansion strains to the stabilization are higher than 0,2%, reference self-stress value to the expansion stabilization is about 3 MPa and expansion stabilization is observed on the 14 days or more of concrete age) doesn't demonstrate so good fit of the calculated and predicted by the model restrained strains value as for members made of shrinkage-compensating concretes. Increasing of the experimental and predicted values mismatching (predicted values become sufficiently higher those, established experimentally) increases with the concrete age increasing and with the increasing of the cross-section reinforcement ratio. In [12] one essential circumstance was noted: with the cross-section reinforcement ratio increasing, the higher part of the free expansion energy of concrete is spent on the elastic and early-age creep deforming of the composite itself. Besides, as it was suggested by the authors of this article [12], utilizing of the high expansion energy capacity concrete allows to deform restraint and the forces increment in the restraint reinforcement is acting as an additional restriction for the further reinforcement stretching and as well for further restrained concrete strains development. Thus, modification of the basic deformation model for the assessment of the accumulated restrained strains in the high expansion energy capacity self-stressing concrete members is necessary. Suggested by the authors modified strains development model (MSDM) was developed and verified for the uniaxially reinforced self-stressing concrete members with different reinforcement types (steel, FRP bars) and it is described in details in [12].

As well, it is necessary to point attention, that in the last years artificial neural network (ANN) and fuzzy inference system model (FIS) for predicting free expansion have been developed [13].

Discussion

All of the listed above models proposed for assessment early age restrained strains and/or self-stresses in the self-prestressed concrete elements are based on the following fundamental assumptions: (1) self-stressing is the specific type of the pre-stressing, in which the tensile force in the tendons and equal resultant compression force in concrete are induced gradually in time as a result of the work that self-stressing concrete performs against restraint; (2) expansive strains are linearly distributed in the direction of cross-sectional height (plain section hypothesis is valid). In the first approximation, the cases considered are those when misalignments are not produced at the respective boundaries between expansive concrete and reinforcing bars. Based on the assumption that self-stresses in concrete are considered as the product of the elastic strains and modulus of elasticity $E_{cm}(t)$, at the state of stabilization of the expansion stresses are distributed linearly too.

On the other hand, the distribution of the stresses in the cross-section can be calculated as well as for the mechanically pre-stressed structure. Here, the resultant force in restraint is considered as a pre-stressing force.

Anyway, in some articles [6, 7] we can read following statement: *"Self-stress is distributed along the fiber bundle in the textile and exhibits similar effect to that of mechanical pre-stress."* This statement complies with assumptions adopted in the models listed above and considered TRSSC element as the pre-stressed element, but the following model assumptions about stresses distributions look strange and speculative and require comments.

According to [6, 7] *analysis of cracking load is based on the following three assumptions:*

a. The beam is in elastic stage and conforms to the assumption of small deformation before cracking.

b. The relative displacement between matrix and the woven fabric is ignored.

c. ***The self-stress value was distributed identically within range of 5mm above and below the textile*** *(see Figure 4).*

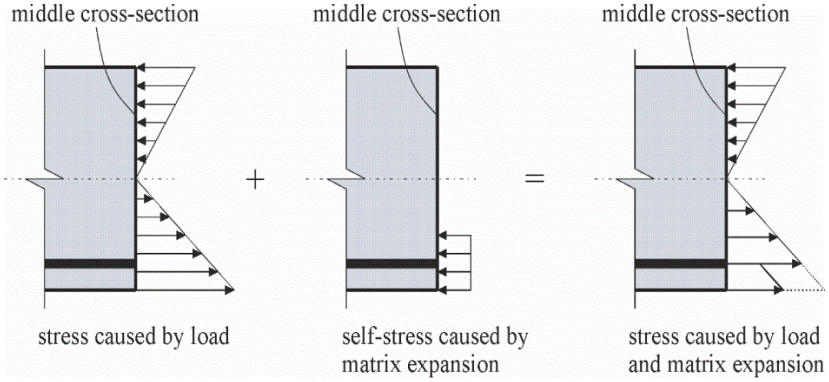


Figure 4 – Stress distribution in TRSSC beam section according to [6, 7]

Analysis of presented assumptions (mainly assumption c) and Figure 4 initiates following questions:

(1) Why self-stresses are distributed uniformly at the local area limited within the range of 5 mm above and below the textile? (Why is it not 5,5 mm; 7 mm; 5,6 mm...? What is the influence of bundle area? What is the scientific background of this range?);

(2) Does for a such new composites plain section law at the stage of expansion is not valid and does it mean, that authors observed in test deplanation of the section?

(3) If self-stresses concentrate within a limited range above and below textile reinforcement, could we say, that the rest part of section is free from self-stressing?

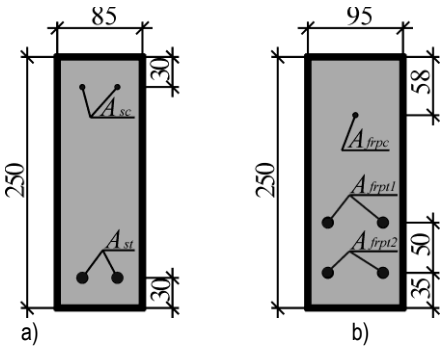
Experimental studies of self-stressed element reinforced with FRP

Let's consider the results of the research work [14], in which we used self-stressing concrete for beam elements reinforced with FRP bars. In [14], the possibility of applying self-stressing concrete to increase FRP reinforcement's effectiveness, mainly increasing crack resistance and flexural stiffness (satisfying the serviceability limit state requirements) was studied. We adopted the following work hypothesis: expanding of self-stressing concrete in restraint conditions developed by FRP bars induces tensile force in restraint and compression forces (self-stresses) in concrete. The relatively low axial stiffness of FRP bars allows sufficient restrained strains that cannot fully be compensated for shrinkage development.

Experimental studies [14] were carried out on two series of self-stressed concrete beams with different type of reinforcing bars. Experimental beams cross-section geometry with reinforcement areas and arrangement are shown in Figure 5.

Expansive cement composition was consisted of 3 components in the following proportions (by weight): Ordinary Portland cement (CEMI-42,5N) – 71 %; metakaolin – 14 %; gypsum ($CaSO_4 \cdot 2H_2O$) – 15 %. The main mechanical characteristics of the hardened expansive cement are presented in Table 1.

Self-stressed beams of the both series were made of self-stressing concrete with characteristics presented in Table 2.



a) – self-stressed beams of the series I (I-BECS-(1…4): A_{sc} = 25,1 mm² (2Ø4); A_{st} = 157,0 mm² (2Ø10)); b) – self-stressed beams of the series II (II-BECF-(1,2): A_{frpc} = 13,7 mm² (1Ø4); A_{frpt1} = 143,5 mm² (2Ø10); A_{frpt2} = 143,5 mm² (2Ø10); II-BECF-(3): A_{frpc} = 13,7 mm² (1Ø4); A_{frpt1} = 143,5 mm² (2Ø10); A_{frpt2} = 330,5 mm² (2Ø14))

Figure 5 – Experimental beams cross-section geometry with reinforcement areas and arrangement [14]

Table 1 – Expansive cement characteristics

Expansion		Strength	
free expansion strain ε_f, %	reference self-stress $f_{CE,d}$, MPa	flexural f_{flex}, MPa	compressive f_{cm}, MPa
1,21	5,9	5,5	50,8

Notes: *1. Expansion and strength characteristics were established at the 28 days age of the mortar bars hardened in the unrestrained conditions.*
2. Reference self-stress, $f_{CE,d}$, was established in standard restraint conditions:
ρ_l = 1 % and E_s = 200 GPa.

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Table 2 – Average values of the self-stressing concrete characteristics

Series	Expansion characteristics at the concrete expansion stabilization		Mechanical characteristics	
	free expansion strain $\varepsilon_{CE,f}$, %	reference self-stress $f_{CE,d}$, MPa	compressive strength $f_{cm,28}$, MPa	modulus of elasticity $E_{cm,28}$, GPa
I	0,47	2,4	33,2	25,3
II	0,55	2,8	37,8	25,7

Notes: *1. Free expansion strain, $\varepsilon_{CE,f}$, was established on the unrestrained specimens;*
2. Reference self-stress, $f_{CE,d}$, was established in the standard restraint conditions:
ρ_l = 1 % and E_s = 200 GPa;
3. Modulus of elasticity was established on the cylindrical specimens (Ø = 150 mm, h = 300 mm).

Steel and FRP reinforcing bars characteristics are listed in Table 3 and Table 4.

Table 3 – Average values of the mechanical characteristics of steel reinforcing bars (experimental values)

Nominal diameter, mm	Yield stress f_{ym}, MPa	Modulus of elasticity E_{sm}, GPa
4	573,2	200,0
10	625,7	

Table 4 – Average values of the mechanical characteristics of FRP reinforcing bars (experimental values)

Nominal diameter, mm	Type of fibers	Modulus of elasticity E_{frpm}, GPa	Tensile strength f_{frpm}, MPa	Ultimate tensile strain ε_{frpm}, %
5	Basalt	51,5	1262	2,45
10	Glass	45,2	1027	2,27
14	Glass			

Experimental values of the restrained strains and self-stresses in concrete on the depth of the cross-section gravity center immediately before static loading are listed in the Table 5.

Table 5 – Experimental values of restrained strains and self-stresses immediately before static loading

Unit code	Restrained strains, [%]			Self-stress σ_{CE}, [MPa]
	$\Sigma(\Delta\varepsilon_{CE,t})_i$	$\Sigma(\Delta\varepsilon_{CE,m})_i$	$\Sigma(\Delta\varepsilon_{CE,b})_i$	
I-BECS-(1)	0,342	–	0,128	2,69
I-BECS-(2)	0,372	–	0,144	2,95
I-BECS-(3)	0,443	–	0,144	3,00
I-BECS-(4)	0,499	–	0,154	3,46
II-BECF-(1)	0,481	0,330	0,269	1,78
II-BECF-(2)	0,556	0,365	0,276	1,92
II-BECF-(3)	0,429	0,267	0,197	2,10

As shown in Table 5, in all the tested beams, the initial value of self-stresses was got in the range from 1,8 to 3,5 MPa depending on the reinforcing bars' type, area, and arrangement. Reached pre-tensioning in reinforcing bars were at average 46 % from yield strain and 14 % from ultimate tensile strain for steel and FRP reinforcing bars respectively. It should be pointed that for the members pre-stressed with FRP reinforcing bars in accordance with [15], initial values of the pre-stress should be limited by the 24 % from the ultimate tensile strength.

Beams initial restrained expansion curvature values obtained on the basis of measured restrained strains and measures deflections varied in the diapason $(1{,}16–1{,}82)\cdot10^{-5}$ mm^{-1} and (3,7–4,1) mm respectively. These values of the initial restrained expansion curvature of the beams got at the self-stressing stage should be considered because two developed in time superposed basic processes: (1) on the one hand–self-stressing concrete expansion in asymmetrical restraint conditions and (2) on the other hand–concrete elastic compressive strains accumulating under monotonically increasing in time restraint reaction. It should be pointed that plane section hypothesis was valid for all tested beams. The so-called beam initial «elastic» curvature (that is determined from the accumulated concrete elastic compressive strains distribution) only have an influence on the self-stressed member behaviour under the applied static load in terms of traditional decompression. In contrast with traditional pre-stressed members, in the self-stressed members the values of the beam initial «elastic» curvature is not possible to establish based on the direct strains measurement, but it can be obtained under the proposed MSDM concept [12].

After the self-stressing concrete expansion stabilization was reached, self-stressed beams were tested with monotonically increasing load by means of two concentrated forces applied at the 1/3 and 2/3 points of the 1200 mm span. The main aim of the static loading consisted in the investigation of the influence of the achieved initial stress-strain state obtained to the self-stressing concrete expansion stabilization on the behavior of the tested beams under the load.

The moment-curvature and moment-deflection curves for specimens of series I and series II are shown in Figure 6.

Test results obtained within loading of the self-stressed beams are listed in Table 6 and Table 7.

Table 6 – Failure modes and experimental value of cracking and ultimate loads obtained within self-stressed beams testing

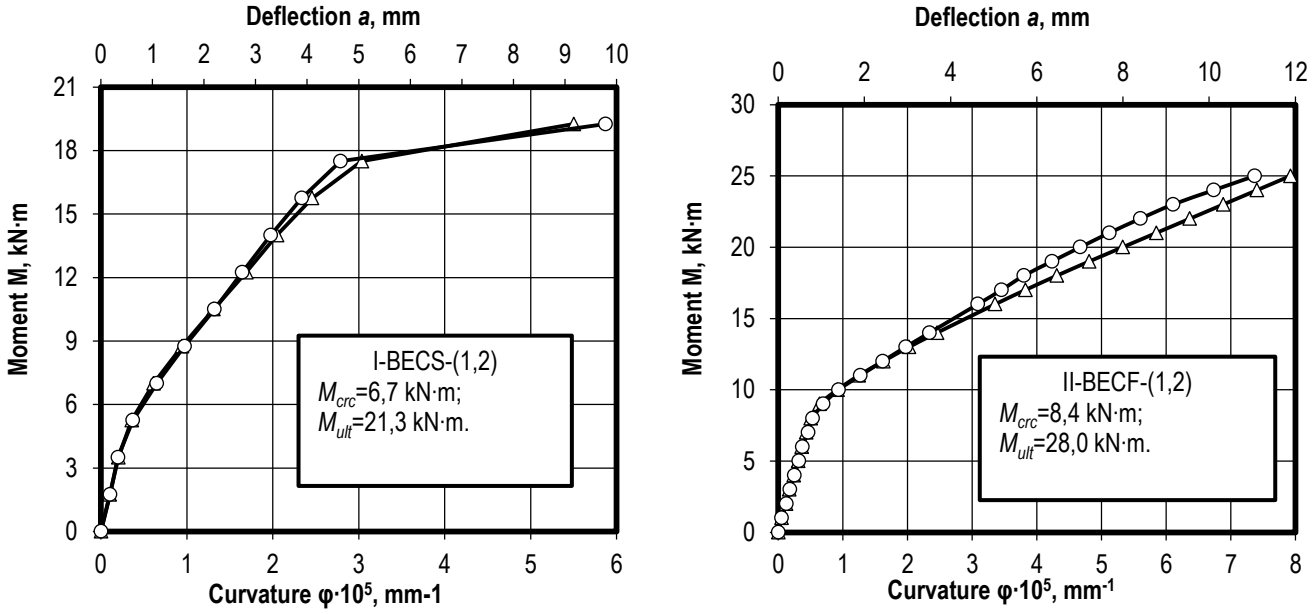
Unit code	Cracking load (force) P_{crc}, kN (M_{crc}, kN·m)	Ultimate load (force) P_{ult}, kN (M_{ult}, kN·m)	Failure mode
I-BECS-(1)	34 (6,8)	108 (21,6)	«B»
I-BECS-(2)	37,3 (6,5)	120 (21,0)	
I-BECS-(3)	39,5 (6,9)	120 (21,0)	
I-BECS-(4)	46,6 (8,2)	125,4 (22,0)	
II-BECF-(1)	40,5 (8,1)	150 (30,0)	«Sh»
II-BECF-(2)	43,5 (8,7)	130 (26,0)	
II-BECF-(3)	39,0 (7,8)	150 (30,0)	

Note *– «B» – flexural failure mode; «Sh» – shear failure mode.*

Table 7 – Experimental values of the deflection and crack width obtained within self-stressed beams testing

Unit code	Deflection *a*, mm	Crack width (w_{max}/w_m), mm
I-BECS-(1)	2,3	0,1/0,1
I-BECS-(2)	2,7	0,15/0,07
I-BECS-(3)	2,9	0,1/0,09
I-BECS-(4)	3,2	0,1/0,1
II-BECF-(1)	4,9	0,7/0,59
II-BECF-(2)	4,6	0,6/0,38
II-BECF-(3)	4,6	0,6/0,47

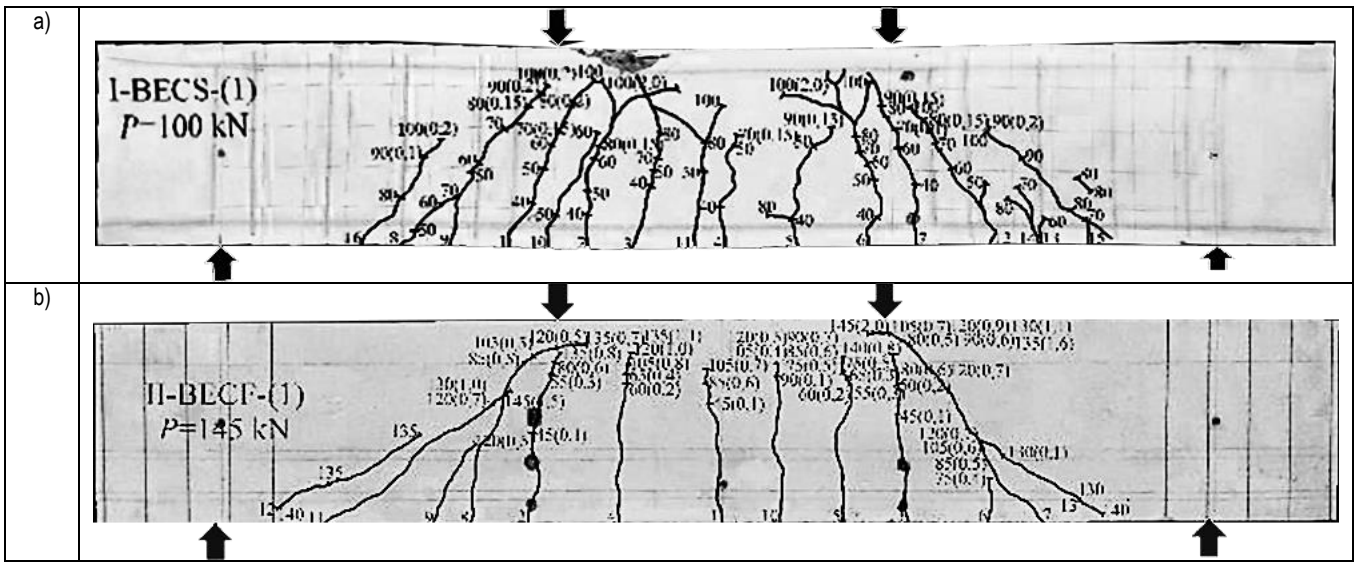
Note *– In the table values of deflections, maximum and average crack width correspond to the loading rate of ≈$0{,}6\cdot P_{ult}$, where P_{ult} – ultimate load.*



a) – self-stressed beams of the series I; b) – self-stressed beams of the series II
Figure 6 – Relations «*M-φ*» and «*M-a*» obtained on the static loading stage

For beams of series I and series II, the first cracks occurred in the pure bending region at the load of 44 kN (7,1 kN·m) and 41 kN (8,2 kN·m) on average, respectively. After that in case of FRP reinforced beams, the slope of moment-curvature (moment-deflection) curves showed considerable drop and it was kept almost constant up to failure, as it is shown in Figure 3. In case of steel reinforced beams, three characteristic branch sections with different slopes was observed: the first branch section – up to cracking; the second branch section – from cracking and up to reinforcing steel yielding; the third branch section – from reinforcing steel yielding and up to the failure (see Figure 3). With increasing of the bending moment up to 24 kN·m, in the FRP reinforced beams, multiple inclined flexural shear cracks occurred outside the pure bending region and extended to a distance approximately 20 mm from the top surface of the beam. When applied load reached 143,3 kN (28,7 kN·m) at average, diagonal tension flexural shear failure mode was reached, but to this time FRP reinforcing bars didn't reach its ultimate tensile strains (in accordance with test results: $\varepsilon_{rt,frp}$ = 0,933 %). Taking into account that FRP reinforced self-stressed beams reinforcement ratio was equal to 1,6 % and 2,1 % for II-BECF-(1,2) and II-BECF-(3) respectively, that is considerably higher of the both balanced reinforcement ratio (ρ_{bal} = 0,3 %) and recommended reinforcement ratio 1,4· ρ_{bal} = 0,42 %. For the real reinforcement ratio of the tested beams, expected failure mode is due to crushing of the concrete in compression, but an observed failure mode had changed on the flexural shear without crushing of the concrete in compression. Moreover, registered within testing value of the ultimate moment was at average in 2 times higher than predicted value of the ultimate moment in accordance with [16] and based on the mean and established in tests values of the materials characteristics. In opposite to the FRP reinforced beams, failure mode and value of the ultimate load for steel reinforced self-stressed beams of series I was the same as it was predicted in accordance with [16] (ratio between predicted and established within loading ultimate bending moments was equal to 0,90).

Characteristic modes of failure and crack patterns for beams of the both series I and series II are shown in the Figure 7.



a) – self-stressed beams of the series I; b) – self-stressed beams of the series II
Figure 7 – General view of the beam crack patterns after test

Based on the analysis of the obtained experimental results, it can be stated, that initial early age stress-strain state obtained on the expansion stage influenced on the beams behavior during loading. It was observed that for the both series I and series II self-stressed beams cracking load was near 30 % from the ultimate load (see Table 6). Flexural cracks development through the concrete cross-section depth was following: arised flexural cracks extended on the average depth about 180 mm and 195 mm (≈75 % from cross-section depth) for series I and series II beams respectively and saved this position almost up to the failure on the background of the gradually increasing cracks number and its opening. This effect is explained that in the self-stressed structures initial compressive stresses are saved in concrete under the crack. An observed cracks patterns in the member tensile zone (see Figure 7) with an average distance between cracks 60±15 mm indicated about practically uniform distribution of the stresses longwise reinforcing bars in tension, that is inherent for pre-stressed structures.

To analyze results obtained within static loading of the self-stressed beams with non-symmetric both FRP and steel reinforcement arrangement the «*M*-$\varepsilon_{rt,x}$» diagram was proposed (where *M* is a bending moment; $\varepsilon_{rt,x}$ is a longitudinal tensile strain from the loading on depth of gravity center of the reinforcement in tension). The general view of the diagram is presented in the Figure 8.

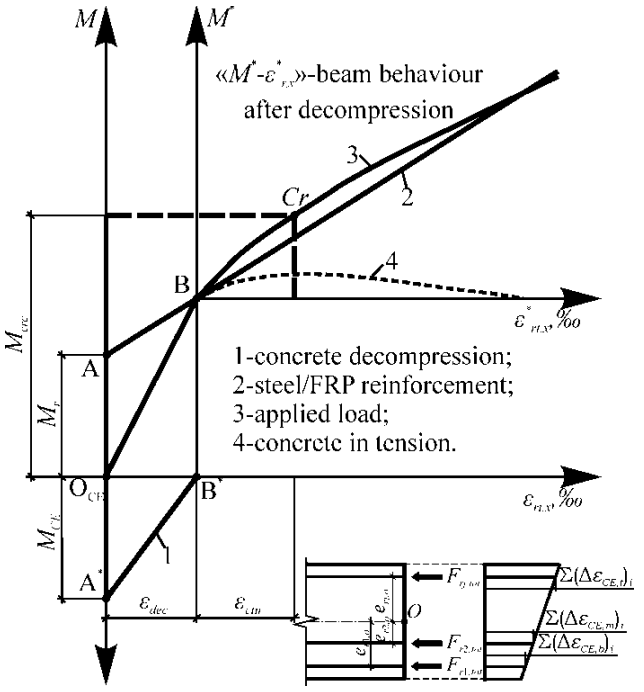


Figure 8 – Diagram for analysis of the initial stress-strain state influence on the behaviour under the loading of the non-symmetrically reinforced beams

Before load applying, in the beam cross-section balanced internal forces, obtained within self-stressing concrete expansion, are acting (see Figure 8: $O_{CE}A=O_{CE}A^*$, $M_{CE}=M_r$). Moments from the internal forces, accumulated to the end of the self-stressing stage, respectively concrete cross-section gravity center can be determined with respect to the value of the fixed restrained strains in reinforcement:

$$M_{CE}=M_r=\sum_{j=1}^{n}F_{rj,tot}\cdot e_{rj,o}, \tag{3}$$

where M_{CE} and M_r are the balanced moments from self-stressing;

$e_{rj,o}$ – eccentricity of the force in the *j*-th restraint reinforcement line respectively concrete cross-section gravity center;

$F_{rj,tot}$ – force in the *j*-th restraint reinforcement line, accumulated on the self-stressing stage to the concrete expansion stabilization, that is determined as follows:

$$F_{rj,tot}=\varepsilon_{rj}\left(t_{tot}\right)\cdot E_r\cdot A_r, \tag{4}$$

where $\varepsilon_{rj}\left(t_{tot}\right)$ – strain in the *j*-th restraint reinforcement line, accumulated on the self-stressing stage to the concrete expansion stabilization, calculated in accordance with MSDM model [12];

E_r, A_r – modulus of elasticity and area of the restraint reinforcement respectively.

After applying and further monotonically increasing of the load, reducing of the initial concrete cross-section pre-compression, obtained on the self-stressing stage, was observed. Besides, up to decompression point B* (see diagram in the Figure 8), cross-sectional tensile force is sustained by the reinforcement only (like it is in the traditional pre-stressed structures, line AB). Increment of the strains in reinforcement and increment of the bending moment, sustained by the reinforcement, before concrete decompression point B* is characterized by the AB line on the diagram in the Figure 6. At the same time, reducing of the concrete initial compressive stresses corresponds to the internal moment changing along the A*B* line. At the point B* (see Figure 8) concrete initial elastic compressive strains on the depth of gravity center of the reinforcement in tension reduces to 0 (so-called decompression stage). At the point B, line AB has the common point with the line O_{CE}B, characterized changing of the bending moment from the externally applied load. Within further loading after decompression point B*, behavior of the self-stressed member is the same like behavior of the conventional RC-beam without any initial pre-stressing (part of the diagram in the «$M^*-\varepsilon^*_{rt,x}$» axises). At this loading stage, a tensile force in concrete cross-section is sustained together by the concrete in tension and reinforcement right up to the flexural cracks appearing. Flexural cracks appear when tensile strains in concrete exceeds its ultimate values ε_{ctu} (see diagram in «$M^*-\varepsilon^*_{rt,x}$» axises in the Figure 8).

Thus, to the flexural cracks formation, the total strains respect to cracking $\varepsilon_{rt,crc}$ on the depth of reinforcement gravity center, is considered as a sum of decompression starins ε_{dec} and ultimate concrete tensile strains ε_{ctu}.

Resultant value of the cumulative concrete elastic strains $\varepsilon_{CE,el}\left(t_{sl}\right)$, that corresponds to the decompression strains ε_{dec} at the static loading should be calculated as follows:

$$\varepsilon_{dec}=\varepsilon_{CE,el}\left(t_{sl}\right)=\frac{\varepsilon_{CE,eltot}\left(t_i\right)\cdot E_{c,aw}\left(t_i\right)}{E_{cm,sl}}, \tag{5}$$

where $\varepsilon_{CE,eltot}\left(t_i\right)$ – concrete elastic strains accumulated to the end of the expansion stage and saved in structural memeber immediately before loading. It have to be calculated in accordance with proposed MSDM model [12];

$E_{c,aw}\left(t_i\right)$ – «average-weighted» expansive concrete modulus of elasticity, calculation procedure of it is presented in detail in [12];

$E_{cm,sl}$ – concrete modulus of elasticity to the static loading time;

t_i – age of concrete immediately before static loading.

Considering that decompression strains are a parameter that allows assessing the effectiveness of the initial self-stressing and to predict its further influence on the crack behaviour of the beams, this parameter (ε_{dec}) was got from experimental results analysis with diagram «M-$\varepsilon_{rt,x}$» using and compared with the total tensile strains immediately before cracking measured on the depth of the reinforcement gravity centre

$\varepsilon_{rt,crc}$. This analysis of the self-stressing effectiveness was based on the assessment of the ratio between decompression strains ($\varepsilon_{dec,exp}$) and total tensile strains ($\varepsilon_{rt,crc}$), that is presented in Table 8.

Table 8 – Experimental values of the concrete tensile strains on the depth of the reinforcement gravity center

Unit code	$\varepsilon_{dec,exp}$, ‰	$\varepsilon_{rt,crc}$, ‰	(2)/(3)
(1)	(2)	(3)	(4)
I-BECS-(1)	0,189	0,528	0,36
I-BECS-(2)	0,241	0,542	0,44
I-BECS-(3)	0,229	0,533	0,43
I-BECS-(4)	0,312	0,658	0,47
II-BECF-(1)	0,091	0,494	0,18
II-BECF-(2)	0,095	0,480	0,20
II-BECF-(3)	0,101	0,490	0,21

As it is shown in Table 8, from experimental research [14] this ratio was at average 0,43 and 0,20 for self-stressed beams of the series I and series II respectively.

For effectiveness of the FRP reinforcing bars application in the pre-stressed (self-stressed) structures, «M–$\varepsilon_{rt,x}$» diagram was utilized (see Figure 8). It was assessed from the experimental results, that before loading in the beams of Series I and Series II almost equal values of the moments created by the pre-compression forces was obtained (was at average 3 kN·m). Therefore decompression strains in case of FRP bars using were less approximately in two times in comparison with decompression strains registered in self-stressed beams with steel reinforcement (see Table 8). It was stated, that up to decompression point, resultant force in tensile zone of the cross-section is sustained by the reinforcing bars only (at this stage concrete is under the initial compressive stresses). Taking into account that steel and FRP bars are characterized by the different values of modulus of elasticity (FRP bars modulus of elasticity E_{frpm} = 45,2 GPa, that was close to the concrete modulus of elasticity E_{cm} = 25,7 GPa), a different values of the moment increment was observed for the same levels of the longitudinal tensile strains in reinforcement (in case of FRP reinforcement, such increments were sufficiently less). To obtain equal values of the moment increments in case of FRP and steel bars utilizing, required area of FRP reinforcement have to be increased considerably and can be found based on the optimization procedure (it consists in the assessment of the FRP reinforcement axial stiffness, that is necessary to provide desired values of the moment increments within decompression stage as well as initial self-stresses at the expansion stage).

Nevertheless, it should be pointed that obtained self-stressing parameters in the members reinforced with FRP bars not only lead to the cracking moment increasing, but change series II self-stressed beams post-cracking behavior. A number of cracks, comparable with cracks number in series I self-stressed beams with steel reinforcing bars was observed (N = 9 and N = 12 at average respectively), and maximum flexural crack width was not exceed 0,6 mm under the loading rate near $0{,}6 \cdot P_{ult}$.

Conclusions

1. A self-stressed structure is a prestressed structure, in which we create the tension of the reinforcement by the work that self-stressing concrete performed against restraint at the expansion stage [17]. Resultant pre-stressing force transfers from tendons to expanding concrete by the bond or anchorage and depends on the degree of restraint. The cases considered are those when misalignments are not produced at the respective contact surface between expansive concrete and reinforcing bars [18].

2. Independently from the type of restraint (steel bars or FRP bars) transferring of the chemical pre-stressing force to self-stressing concrete is realized like for traditional pre-stressed structure [19]. At all stages of the self-stressing expansive strains are linearly distributed in the direction of the cross-sectional height [20]. Considering that self-stresses distribution is related to the restrained strain distribution It is difficult to imagine why such local stress distribution was adopted by some authors as a basic assumption in the «theory of self-stressing distribution model» [7] and repeated in a more controversial form as an assumption to «calculation model of cracking load and deflection of textile reinforced self-stressing concrete» [6].

3. Self-stressing is related to the elastic part of deformations only. All rules applied to the design of the pre-stressed structures (for checking of the serviceability limit states) are valid for self-stressed structures reinforced with FRP [21]. In such a case, why do we have to apply the finite difference method for the calculation of cracking load and deflection of TRSSC beams? According to the modern crack resistance theory cracking load depends mainly on the ultimate tensile strain of concrete (no tensile strength). Based on the obtained test results by the authors, it is possible to make a conclusion, that *«the comparison of calculated and test values indicates an error of less than 30%, which is consistent with each other, thus verifying the applicability of calculation method*». It is a very optimistic statement!

The following conclusion is optimistic too: *«self-stress can significantly improve the cracking resistance of TRSSC beams. Although the tensile strength of the matrix of TRSSC is 26% lower than that TCR, the cracking loads of the TRSSC beam are increased by 33% and 30%».* In first, in the experiment self-stressing cement grade 4,0 (self-stress in standard condition is equal to $f_{ct,m}$ = 4,0 MPa) was used. Matrix specimens were cured before tensile testing in non-restrained conditions. In such conditions unbalanced expansion of the active self-stressing cement matrix, leads to self-damaging of the own material structure and decreasing of the tensile (and compressive) strength. Testing these specimens after curing in the restrained conditions (like it was in tested prisms) will get higher values of the tensile strength. Now it is difficult to assess what is the value of tensile strength we have to account for when we want to verify the proposed crack resistance model. Moreover, experimental results presented in [6, 7] are very unclear and non-representative (for instance, the same mix proportions for matrix type NC and SSC; dimensions of the reinforced TRSSC beams (prisms 100 × 100 × 400 mm for testing so sensitive parameter as crack resistance); measurement (with unknown error) of the longitudinal deformations with the usage of the laser rangefinder only at the level of the layer of textile; curing under standard conditions, etc.)

Influence of the initial self-stressing on the concrete member behavior under the monotonically increasing loading was studied with the proposed diagram method. Obtained within self-stressing concrete expansion stress-strain state in the both steel and FRP reinforced self-stressed beams positively influenced on these member behavior under the applied load. Nevertheless, considerable difference in the behavior of the self-stressed beams with steel and FRP reinforcement was observed, especially up to decompression point. For FRP reinforcement effective utilizing, optimization procedure based on the joint consideration of the proposed both MSDM [12] and diagram method have to be applied for certain design case.

References

1. Yan, Z. Concrete column shape modification with FRP shells and expansive cement concrete / Z. Yan, C. P. Pantelides // Construction and Building Materials. – 2011. – Vol. 25, Iss. 1. – P. 396–405.
2. Michaelis, W. Tonindustrie-Zeitung (Goslar) / W. Michaelis. – 1892. – Vol. 16. – P. 105.
3. Lossier, H. Expanding Cements and Their Application – Self-stressed concrete / H. Lossier, A. Gagout // Le Genie Civil (Paris). – 1944. – Vol. 121, Iss. 8. – P. 61–65.
4. Mihajlov, V. V. Rasshiryayushchijsya i napryagayushchij cementy i samonapryazhennye zhelezobetonnye konstrukcii / V. V. Mihajlov, S. L. Litver. – M. : Strojizdat, 1974. – 312 s.
5. Klein, A. Studies of Calcium Sulfoaluminate Admixtures for Expansive Cement / A. Klein, A. Troxell // ASTM. – 1958. – Vol. 58. – P. 968–1008.
6. Calculation methos of cracking load and deflection of textile reinforced self-stressing concrete / Boxin Wang, Ke Yuan, Xinyu Lu, Jianyu Zhao // Construction and Building Materials. – 2021. – Vol. 304. – P. 122–136. – DOI: 10.1016/j.conbuildmat.2021.124622.

7. Wang, B. Distributed models of self-stresses value in textile reinforced self-stressing concrete / B. Wang, J. Zhao, Q. Wang // Construction and Building Materials. – 2016. – Vol. 126. – P. 286–296. – DOI: 10.1016/j.conbuildmat.2016.06.149.
8. Betony napryagayushchie : tekhnicheskie usloviya : STB 2101-2010. – Vved. 01.01.2011. – Minsk : Gosstandart, 2011. – 20 s.
9. Tsuji, Y. Methods of estimating chemical prestress and expansion distribution in expansive concrete subjected to uniaxial restraint / Y. Tsuji // Concrete Library of JSCE. – 1984. – No. 3. – P. 131–143.
10. Early-age strain and self-stresses of expansive concrete members under uniaxial restraint conditions / V. Semianiuk, V. Tur, M. F. Herrador, M. P. González // Construction and Building Materials. – 2017. – Vol. 131. – P. 39–49. – DOI: 10.1016/j.conbuildmat.2016.11.008.
11. Early age deformation and resultant induced stress in expansive high strength concrete / H. Ito, I. Maruyama, M. Tanimura, R. Sato // Journal of Advanced Concrete Technology. – 2004. – № 2 (2). – P. 155–174. – DOI: 10.3151/jact.2.155.
12. Tur, V. Self-stressed concrete members reinforced with FRP bars / V. Tur, M. F. Herrador, V. Semianiuk // Proceedings of the *fib* Symposium. – 2017. – P. 431–438.
13. Wang, V. Prediction of expansion behavior of self-stressing concrete by artificial neural networks and fuzzy inference systems / V. Wang, T. Han, H. Jin // Construction and Building Materials. – 2015. – Vol. 84. – P. 184–191. – DOI: 10.1016/j.conbuildmat.2015.03.059.
14. Semianiuk, V. Crack resistance of self-stressed members reinforced with FRP / V. Semianiuk, V. Tur // Solid state phenomena. – 2018. – Vol. 272. – P. 244–249. – DOI:10.4028/www.scientific.net/SSP.272.244.
15. CNR-DT 203/2006. Guide for the Design and Construction of Concrete Structures Reinforced with Fiber-Reinforced Polymer Bars. – Rome, Italy, 2007. – 39 p.
16. EN 1992-1 Eurocode 2: Design of concrete structures – Part 1–1: General rules and rules for buildings. – URL: https://www.phd.eng.br/wp-content/uploads/2015/12/en.1992.1.1.2004.pdf (date of access: 19.09.2024).
17. Guttman, P. V. Expansive cement in USA / P. V. Guttman // ASCE Journal. – 1967. – Vol. 37. – P. 135–139.
18. Ishikava, Y. Initial stress analysis of expansive concrete material under restrictions based on chemical conservation law / Y. Ishikava, K. Shitaba, T. Tanabe // Creep, shrinkage and durability mechanics of concrete and concrete structures. – 2009. – P. 437–443.
19. Mather, B. Expansive cement / B. Mather // Miscellaneous paper C-7-21, National Technical Information Service. – 1970.
20. Instrukciya po proektirovaniyu samonapryazhennyh zhelezobetonnyh konstrukcij : SN 511-78. – 32 s.
21. Zdanowicz, K. Chemical prestress on concrete with carbon textile reinforcement: Theoretical and analytical approaches / K. Zdanowicz, S. Marx // Proceedings of the *fib* Symposium. – Krakow, Poland, 2019. – P. 259–265.

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TO THE ISSUE OF INCREASING THE RELIABILITY OF DETERMINING THE MECHANICAL CHARACTERISTICS OF SOILS

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Abstract

The problem of determining reliable characteristics of soils necessary for the design of foundations of buildings and structures is important and urgent. The main parameters determining the mechanical properties of soils are their strength and deformation characteristics, obtained, as a rule, by the results of static probing. Investigations of the process of probe immersion into the soil have allowed to identify a zone of fracture, within which shear deformations take place; a zone of elastic-plastic shear deformations and a zone of elastic deformations. This obviously leads to a change in the determined soil parameters around the probe. Comparing the interaction of the pile and the surrounding soil with the processes occurring during the probe immersion, the values of the obtained characteristics of sandy soils during probing are revealed with their values for the sands of natural composition, which allows to obtain more reliable values for the design of bases and foundations. The article examines the features of the interaction of the surrounding soil with piles and a probe during their immersion, associated with a change in the porosity coefficient.

Keywords: porosity coefficient, static soil probing, soil compaction, mechanical characteristics, soil compaction area.

К ВОПРОСУ ПОВЫШЕНИЯ ДОСТОВЕРНОСТИ ОПРЕДЕЛЕНИЯ МЕХАНИЧЕСКИХ ХАРАКТЕРИСТИК ГРУНТОВ

П. С. Пойта, Н. Н. Шалобыта, Т. П. Шалобыта

Реферат

Проблема определения достоверных характеристик грунтов, необходимых для проектирования фундаментов зданий и сооружений, является важной и актуальной. Основные параметры, определяющие механические свойства грунтов – это их прочностные и деформационные характеристики, получаемые, как правило, по результатам статического зондирования. Исследования процесса погружения зонда в грунт позволили выявить зону разрушения, в пределах которой имеют место деформации сдвига, зону упругопластических деформаций сдвига и зону упругих деформаций. Это, очевидно, приводит к изменению определяемых параметров грунта вокруг зонда. Сопоставляя взаимодействие погружаемой сваи и окружающего ее грунта с процессами, происходящими при погружении зонда, выявлены значения получаемых характеристик песчаных грунтов при зондировании с их значениями для песков природного сложения, что позволяет получить более достоверные их значения для проектирования оснований и фундаментов. В статье рассмотрены особенности взаимодействия окружающего грунта со сваями и зондом при их погружении, связанные с изменением коэффициента пористости.

Ключевые слова: коэффициент пористости, статическое зондирование грунта, уплотнение грунтов, механические характеристики, область уплотнения грунта.

Introduction

The most important reserve for improving the quality of designing foundations and bases is the reliability of determining the physical and mechanical characteristics of soils. The main parameters of the mechanical properties of soils that determine the foundation bearing capacity and deformability of foundations are the valuesof strength and deformation characteristics: the internal friction angle, specific adhesion, deformation modulus. These parameters, with the same type of granulometric composition, plasticity number, vary in significant ranges depending on porosity coefficient values, fluidity index, etc. [1, 2, 3]. Therefore, obtaining objective reliable information on the soil properties located in the active zone of the foundation of the designed buildings and structures is a very important task of engineering and geological surveys which determine the feasibility and effectiveness of the decisions taken on the foundation type and design [15, 18–20].

In accordance with [2], when conducting engineering and geological surveys with the aim of determining soil strength and deformation characteristics for the design and construction of buildings and structures of II and III levels of responsibility, it is allowed to use statistical probing data.

Soil testing by probing is used in conjunction with other types of engineering and geological surveys or separately [11].

Theoretical analysis of the reliability of determining the mechanical characteristics of soils

Determinating the physical and mechanical characteristics of soils is carried out according to tables [2]. In this case, the porosity coefficient e of sandy soils should be taken from the table or from the correlation dependence

$$e = 0.815 - 0.104 \ln q_s,$$

where q_s – specific soil resistance under the probe tip.

The value of e, in addition to q_s, is not affected by the genesis of sands, their granulometric composition, or humidity.

This statement is incorrect, since “Without studying the genesis and diagenesis of rocks, it is impossible to correctly estimate their physical and mechanical properties in space and depth, the nature and intensity of change under the influence of various factor, properties of a given rock in relation to the designed structure [13]”.

Thus, the value of the porosity coefficient is affected only by the specific resistance of the soil under the probe tip. Consequently, the obtained value of e should correspond to the soil natural density. However, the density values which are obtained in this way are of a purely preliminary, forecasting, nature [4, 5, 19].

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Driving the probe into the soil results in its displacement into the area surrounding the probe.

The trajectory of the soil particle movement, its resistance when a conical tip is driven into it from the action of a static load, can be considered as the interaction of the surrounding soil and the pile driven into the soil "in the area" of its tip. When driving a pile, a so-called internal uplift appears under the tip of the pile, which forms a plastic zone around the pile. Further on, in the volume adjacent to this zone, the soil passes into an elastic state (Figure 1). The size of the elastic-plastic area, within which the soil is in a compacted state versus its natural state, depends on the strength characteristics. This is confirmed by natural and model studies of pile driving into various soils [6, 8, 9].

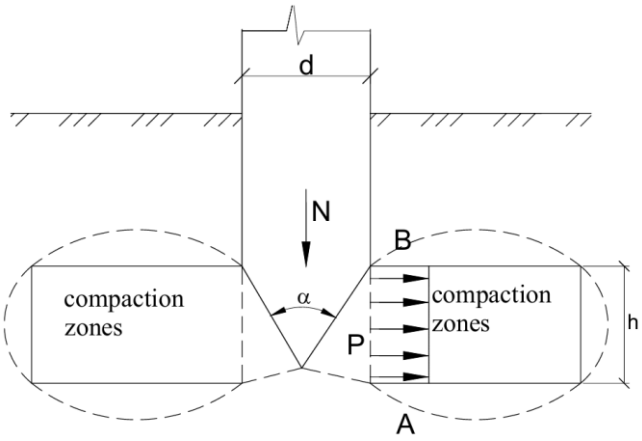


Figure 1 – Diagram of soil compaction when immersing a probe

Field studies by the Krasnodar PromstroyNIIproekt showed that when driving piles into clay soil, the compaction zones around the pile have the shape of a cylinder with a diameter of about (7–8)d (d – the diameter of the pile) [6].

The annular sand zones displaced by the pile around its shaft d = 10,7 cm have an average width of 1,9 cm along the entire height. The area of this annular zone in the horizontal section is 1,84 times greater than the cross-sectional area of the pile. Thus, all the soil in the volume of the pile was squeezed out to the sides with its simultaneous compaction. The decrease in the initial soil porosity in this zone is 16 %.

A compacted soil core is also formed under the lower end of the probe during its immersion, which has a great influence on the nature of the formation of the surrounding massif [8, 9].

A number of studies of the interaction of the driven pile and the surrounding soil confirm the formation of areas of horizontal displacement of soil particles and its compaction around the ring piles in a radius of 2 to 10,0d [6, 7, 8]. Some of the latest studies of the process of continuous immersion of the probe into the soil [14, 16, 17] made it possible to identify the following zones of its deformation as it moves away from the probe:

– destruction zone, in which the soil shear deformations reached and exceeded the ultimate strength values;

– zone of elastic-plastic shear deformations that did not reach the ultimate value;

– zone of minor elastic shear deformations, soil compression.

The sizes of these zones change proportionally to the initial soil density.

Thus, the experimental studies conducted with various soils on the models allowed us to establish compaction zones below the tip (compacted core) and deformation zones, mainly in the horizontal direction.

The elastic part of the compacted core causes the formation of a compaction zone. When the soil is displaced in the radial direction, compression pressure P occurs on the probe contour, causing the movement of soil particles in the plastic area, i.e. causing its compaction (Figure 2). This means that when the probe is driven in, the soil natural density changes: loose soil is compressed, and dense soil is loosened. Besides, a similarity in the nature of the deformation of the base during the immersion of the probe and pile models into the soil was revealed, which makes it possible to mutually extrapolate the analytical and numerical solutions obtained for both problems.

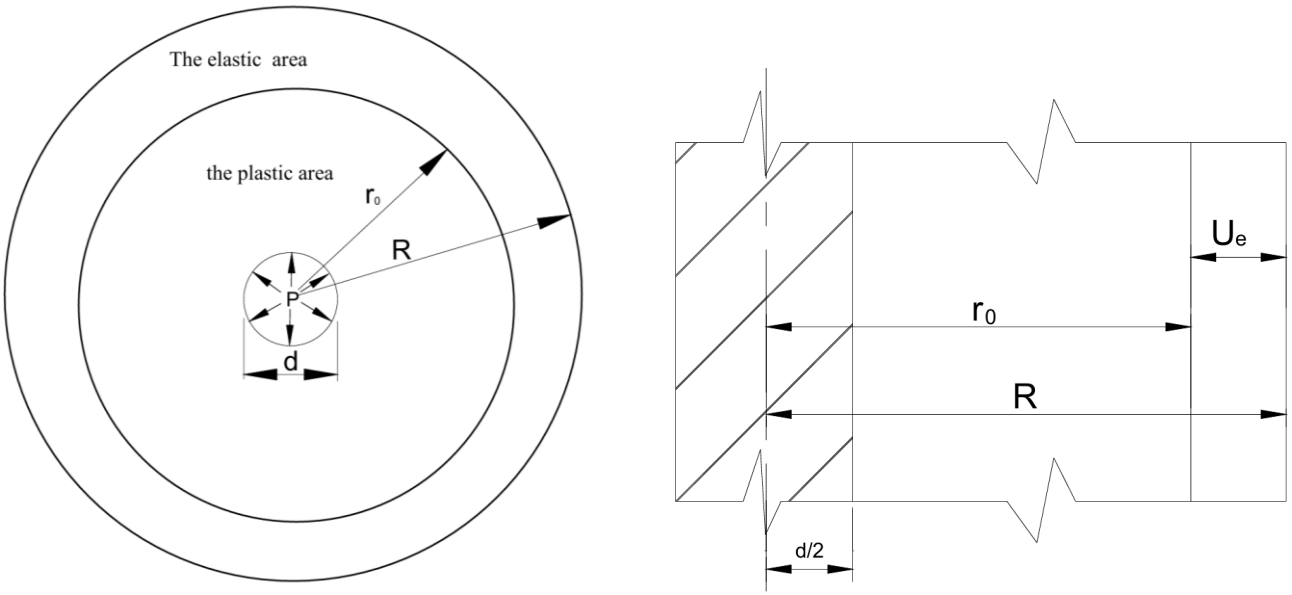


Figure 2 – Calculation scheme

The identified peculiarities of the interaction of the surrounding soil with the piles and the probe during their immersion are connected with a change in the porosity coefficient compared to its natural value.

The porosity coefficient for sandy soils is one of the main classification indicators, according to which sands are divided into varieties by density. The value of this indicator is affected by the dispersion of the sandy soil and its natural composition density, humidity, which determines the value of mechanical characteristics.

Consequently, the issues of the reliability of determining the natural density and mechanical characteristics of soil are very important.

Let us designate the porosity coefficient of natural soil as e, and the porosity coefficient of compacted soil as e_c. Taking into account that soil compaction occurs mainly within the plastic area (Figure 2), since the value of U_e is usually insignificant compared to the plastic area, then e_c is characteristic as the average coefficient of soil porosity in this area. Supposing that all solid particles in the probe volrme are displaced into the soil volume limited by the radius r_o, the equation will look

$$e_c = e - \frac{d^2}{4r_o^2}(1+e).$$

Hence

$$e = \frac{r_o^2(1+e_c)}{r_o^2 - 0{,}25d^2} - 1.$$

In accordance with [9], the radius of the soil maximum state zone in the plane passing through the tip of the cone is determined by the formula

$$r_0 = \frac{d}{2}\left[1 + \frac{\sqrt{2}\cdot e\left(\frac{\pi}{2} - \frac{\varphi}{2}\right)tg\varphi}{sin\left(\frac{\pi}{2} + \frac{\varphi}{2}\right)}\right].$$

Denoting the expression in square brackets D, we obtain

$$r_0 = D\cdot\frac{d}{2}.$$

Then

$$e = \frac{D^2(1+e_c)}{D^2 - 1} - 1.$$

Obviously, in the plastic area and when the cone is immersed, the change in the porosity coefficient of the compacted soil depends on the distance from the probe edge, where the density will be maximum and as it moves away from the probe, it will decrease to the natural one.

The change in the porosity coefficient e_r within the compacted area is accepted, taking into account the logarithmic nature of the development of shear deformations [10], according to the formula

$$e_r = e\cdot e_н^{-\frac{r}{a}},$$

where $e_н$ is the base of the natural logarithm.

r is the distance from the compaction boundary to the point under consideration,

a is a certain coefficient.

Analysis of the change in the porosity coefficient in the direction from the probe to the boundary of the plastic area shows that at the probe surface e has the lowest value and when approaching the edge of the plastic area e increases. The difference in soil density between these characteristic points is about 14 %.

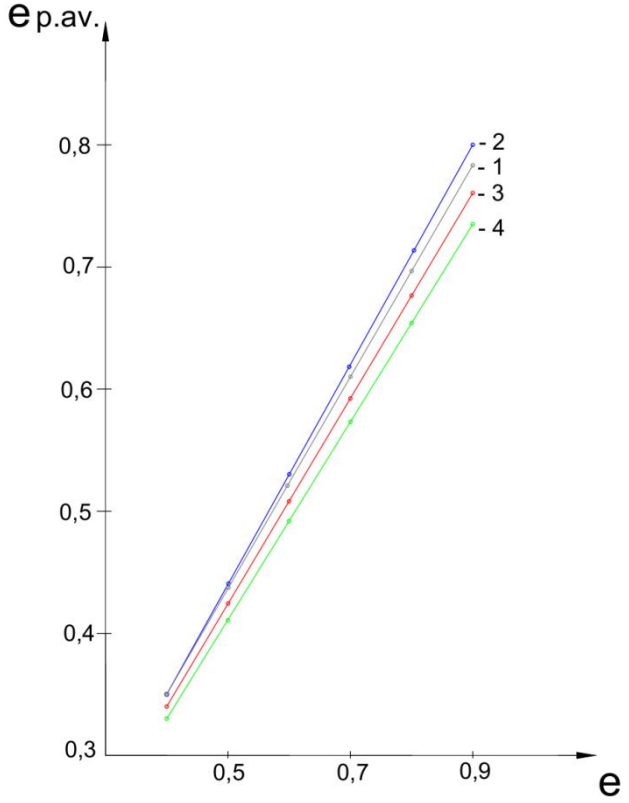
At $r = 0$; $e_r = e$; if $r = r_0 - \frac{d}{2}$; $e_r = e_p$ is the porosity coefficient of the soil at the probe surface.

The most intense change in the porosity coefficient is observed in the section from the probe surface to $0{,}25d$. It is obvious that the maximum soil density during probing tests will be in the area adjacent to the probe surface. Taking into account the results of testing models of piles driven into sandy soils, and also guided by the need to determine the most reliable characteristics of the soils, we will determine the value of $e_{p.av}$ within the range of $0{,}30d$. Then the value of $e_{p.av}$ will be equal to

$$e_{p.av} = e\cdot e_н^{\frac{-(r_o - 0{,}3d)}{a}}.$$

Calculations show that within the $0{,}2d$ area, the change in the porosity coefficient does not exceed 10 %. Figure 3 shows the change in the porosity coefficient of natural soil composition in the $0{,}3d$ area depending on the average porosity coefficient when the probe is immersed. There is a clear linear relationship between $e_{p.av}$ and e for sandy soils of different coarseness. The angle of inclination of the line to the abscissa axis depends on the angle of internal friction of the soil. The greater the value of φ, the smaller the angle of inclination α. This indicates that for the same value of $e_{p.av}$, the value of e for different soils is different in density: with a larger sand coarseness of the determining fraction, the natural density of the soil is higher.

Conversely, for the same natural density of the soil, the average value of $e_{p.av}$ is higher for fine and dusty sands than for coarse and gravelly sands; the higher is the value of e, the greater is this difference.



1 – $e_{p.av}$ within $0{,}3d$; 2 – $e_{p.av}$ at $\varphi = 24°$; 3 – $e_{p.av}$ at $\varphi = 36°$; 4 – $e_{p.av}$ at $\varphi = 42°$.

Figure 3 – Change in $e_{p.av}$ for sandy soils of different densities

Figure 4 shows the graphs of the change in the specific soil resistance under the probe tip q_s depending on e. The graphs show that for any given value q_s, the actual value of e is less than the determined by [2].

And this, as is obvious, affects the value of mechanical characteristics determined according to [11–13]. The comparison of the deformation modulus for coarse sands according to the proposed procedure and in compliance with [11–13] shows this difference of up to 17 %.

Conclusions

1. When the cone is immersed into the soil, the soil is displaced in the radial direction, which causes its additional compaction.

2. The determination of the soil porosity coefficient, its strength and deformation characteristics should be carried out taking into account the presence of a zone of additional soil compaction “in the area” of the immersed probe.

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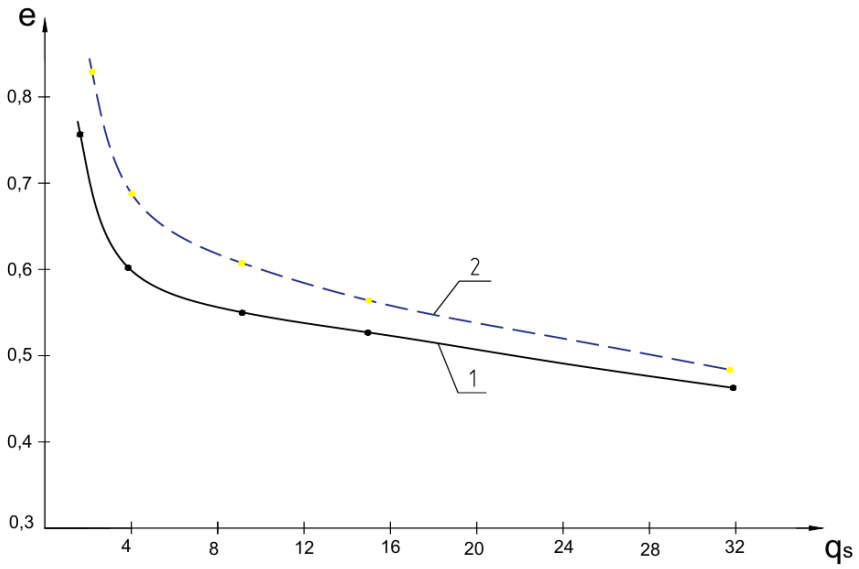

1 – according to [2]; 2 – by formula (1).
Figure 4 – Change in q_s depending on e

References

1. Grunty. Klassifikaciya : GOST 25100-2020. – Vzamen GOST 25100-2011 ; vved. 01.01.2021. – Moskva : Standartinform, 2020. – 38 s.
2. Prochnostnye i deformacionnye harakteristiki gruntov po dannym staticheskogo zondirovaniya i penetracionnogo karotazha. Pravila opredeleniya = Tryvalasnyya i defarmacyjnyya haraktarystyki gruntoý pa dannyh statychnaga zandziravannya i penetracyjnaga karatazhu. Pravily vyznachennya: TKP 45-5.01-15-2005 (02250). – Vved. 01.07.2006. – Minsk : Minstrojarhitektury Respubliki Belarus': Minsktipproekt, 2006. – III, 21 s.
3. Inzhenernye izyskanie dlya stroitel'stva = Inzhynernyya vyshukanni dlya budaýnictva : SN 1.02.01-2019. – Vved. 26.12.2019. – Minsk : Minstrojarhitektury, 2020. – 109 s.
4. Kurilovich, A. E. K voprosu ob opredelenii fizicheskih svojstv peschanyh gruntov po dannym staticheskogo zondirovaniya / A. E. Kurilovich // Vestnik VGU. Seriya Geologiya. – 2013. – № 2. – S. 184–187.
5. Inzhenerno-geologicheskie izyskaniya dlya stroitel'stva. CHast' 1. Obshchie pravila proizvodstva rabot : SP 11-102-97. – Vved. 15.08.1997. – M. : Gosstroj RF, 1977. – 37 s.
6. CHernov, V. K. O deformaciyah glinistyh gruntov vokrug zabivnyh svaj / V. K. CHernov, V. V. Znamenskij, YU. P. YUrko // Stroitel'stvo v rajonah Vostochnoj Sibiri i Krajnego Severa. – Krasnoyarsk, 1971. – Vyp. 17. – S. 59–66.
7. Cooke, R. W. Strains and displacements around friction piles / R. W. Cooke, G. Price // Proceedings of the eighth international conference on Soil Mech and Found engineering. – Moscow, 1973. – Vol. 2, p. 1. – P. 53–60.
8. Lapshin, F. K. Raschet svaj po predel'nym sostoyaniyam / F. K. Lapshin. – Saratov : Izd-vo Sarat. un-ta, 1979. – 151 s.
9. Berezancev, V. G. Raschet prochnosti osnovanij sooruzhenij / V. G. Berezancev. – M. : Gosstrojizdat, 1960. – 138 s.
10. Solov'ev, YU. I. Variacionnyj metod opredeleniya nesushchej sposobnosti osnovanij i sooruzhenij / YU. I. Solov'ev // Izvestiya vuzov. Stroitel'stvo i arhitektura. – 1970. – № 7.
11. Grunty. Metody polevyh ispytanij staticheskim i dinamicheskim zondirovaniem. GOST 19912-2012. – Vzamen GOST 19912-2001, vved. 01.11.2013. – M. : Standartinform, 2013. – 23 s.
12. Pojta, P. S. O vzaimosvyazi opredelennyh v laboratornyh usloviyah parametrov gruntov s dannymi ih staticheskogo zondirovaniya / P. S. Pojta, T. P. SHalobyta // Vestnik Brestskogo gosudarstvennogo tekhnicheskogo universiteta. Seriya: Stroitel'stvo i arhitektura. – 2005. – № 2 (32). – S. 83–85.
13. Spravochnik geotekhnika. Osnovaniya, fundamenty i podzemnye sooruzheniya / pod obshch. red. V. A. Il'icheva, R. A. Mangusheva. – M. : Izd-vo ASV, 2014. – 728 s.
14. Mel'nikov, A. V. Eksperimental'no-teoreticheskie issledovaniya metoda statisticheskogo zondirovaniya gruntov : avtoref. dis. … kand. tekhn. nauk : 05.23.02 / Mel'nikov Aleksej Vladimirovich ; Mosk. gos. stroit. un-t. – Moskva, 2015. – 20 s.
15. Poyta, P. S. Nekotorye problemy proektirovaniya i stroitel'stva fundamentov zdanij i sooruzhenij / P. S. Poyta, N. N. Shalobyta, T. P. Shalobyta // Perspektivnye napravleniya innovacionnogo razvitiya i podgotovki kadrov : Mezhdunarodnaya nauchno-prakticheskaya konferenciya, Brest, 31 oktyabrya – 2 noyabrya 2024 g. – Brest, 2024. – S. 280–287.
16. Mel'nikov, A. V. Issledovanie haraktera deformirovaniya peska v processe staticheskogo zondirovaniya / A. V. Mel'nikov, G. G. Boldyrev // Osnovaniya, fundamenty i mekhanika gruntov. – 2014. – № 6. – S. 14–18.
17. Mel'nikov, A. V. Issledovanie deformirovannogo sostoyaniya peschanogo osnovaniya pri vypolnenii staticheskogo zondirovaniya / A. V. Mel'nikov // Voprosy planirovki i zastrojki gorodov : trudy XX Mezhdunarodnoj nauchno-tekhnicheskoj konferencii. – Penza : PGUAS, 2013. – S. 132–135.
18. Sanglera, G. Issledovanie gruntov metodom zondirovaniya (s primeneniem penetrometrov) / G. Sanglera ; per. s fr. N. P. Belyakovoj ; pod obshch. red. N. I. Maslova. – Moskva : Strojizdat, 1971. – 232 s.
19. Busel, I. A. Prognozirovanie stroitel'nyh svojstv gruntov / I. A. Busel. – Minsk : Nauka i tekhnika, 1989. – 246 s.
20. Ziangirov R. S. Staticheskoe zondirovanie v inzhenerno-geologicheskih izyskaniyah / R. S. Ziangirov, V. I. Kashirskij // Inzhenernaya geologiya. – 2006. – № 11. – S. 13–20.

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INFLUENCE OF ENVIRONMENTAL PARAMETERS ON THE PROCESSES OF OCCURRENCE AND DEVELOPMENT OF DEFECTS IN BRIDGE STRUCTURES

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Abstract

Environment influence in the form of precipitation, temperature variations, seasonal freeze-thaw cycles and human activity lead to the appearance of damages (defects) on the surface of reinforced concrete structures of buildings. As studies show, untimely performance of works on maintenance of objects and subsequent elimination of defects during operation increases the probability of premature destruction of the structure many times.

The article analyzes and classifies the main defects and damages of elements and structures of transport infrastructure structures depending on the place of formation on the structures, the nature of distribution, the impact on the main technical and economic indicators and parameters. The reasons of their appearance and subsequent influence on durability, traffic safety and load-carrying capacity of the structure are revealed. Based on the results of the inspection of the technical condition of the building structures of individual bridge structures, laboratory tests were performed to determine the physical condition of concrete by taking samples from the elements at the locations of identified damages and defects. The content of calcium ions, chlorides, pH, as well as the degree of carbonization were determined in the concrete samples under investigation, and the results were compared within the bridge structures under consideration and with the data of normative and technical literature. To obtain an objective picture, laboratory tests of water samples from the bridges crossing obstacles (rivers) were carried out. The influence of the geographical location of the structures on the condition of materials of building structures, the degree of their damage and operating conditions was assessed. The existing approaches to predicting the durability of transport infrastructure structures were analyzed separately – the reliability of the results obtained taking into account the technical condition of structures (damage and defects of materials), the quality of work performed during the construction of the structure and others.

Keywords: structural damage and defects, bridge structures, chloride content, calcium ions, water extracts, durability prediction.

ВЛИЯНИЕ ПАРАМЕТРОВ ОКРУЖАЮЩЕЙ СРЕДЫ НА ПРОЦЕССЫ ВОЗНИКНОВЕНИЯ И РАЗВИТИЯ ДЕФЕКТОВ МОСТОВЫХ СООРУЖЕНИЙ

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Реферат

Влияние окружающей среды в виде атмосферных осадков, перепадов температуры, сезонных циклов замораживания-оттаивания и деятельности человека приводят к появлению повреждений (дефектов) на поверхности железобетонных конструкций сооружений. Как показывают исследования, несвоевременное выполнение работ по содержанию объектов и последующее устранение дефектов при эксплуатации в разы увеличивает вероятность преждевременного разрушения сооружения.

В статье выполнен анализ и классификация основных дефектов и повреждений элементов и конструкций сооружений транспортной инфраструктуры в зависимости от места образования на конструкциях, характера распространения, влияния на основные технико-экономические показатели и параметры. Выявлены причины их появления и последующее влияние на долговечность, безопасность движения и грузоподъёмность сооружения. По результатам обследования технического состояния строительных конструкций отдельных мостовых сооружений выполнялись лабораторные исследования по определению физического состояния бетона путем отбора проб образцов из элементов в местах выявленных повреждений и дефектов. В пробах исследуемых образцов бетона определялось содержание ионов кальция, хлоридов, pH, а также выборочно оценивалась степень карбонизации и выполнялся сопоставительный анализ результатов в пределах рассматриваемых мостовых сооружениях и с данными нормативно-технической литературы. Для получения объективной картины осуществлялись лабораторные исследования проб воды пересекаемых препятствий (рек) мостами. Оценивалось влияние географического расположения сооружений на состояние материалов строительных конструкций, степень их повреждений и условия эксплуатации. Отдельно проанализированы существующие подходы прогнозирования долговечности сооружений транспортной инфраструктуры – достоверность получаемых результатов с учетом технического состояния конструкций (повреждений и дефектов материалов), качество выполняемых работ при возведении сооружения и другие.

Ключевые слова: повреждения и дефекты конструкций, мостовые сооружения, содержание хлоридов, ионы кальция, водные вытяжки, прогнозирование долговечности.

Introduction

External effects associated with temperature fluctuations with simultaneous frequent precipitation contribute to the acceleration of corrosion processes of building materials of engineering structures, formation of defects and damages in the concrete of structures. At the same time, the increase of carbon dioxide content in humid air leads to the acceleration of carbonization processes in the pore space of concrete of bridge and hydraulic structures, overpasses [1].

Influence of environmental parameters on the processes of occurrence and development of defects in bridge structures

According to [2], depending on the degree of influence, defects are divided into maintenance defects, which are the result of violation of the terms of routine maintenance of the structure; safety defects, which prevent the free and safe movement of vehicles and pedestrians on the structure and under it (if necessary) and load capacity defects, leading to a decrease in the load-carrying capacity of spans and supports.

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Durability defects [3, 4], which do not directly affect the operational performance of the structure, but if not eliminated in time, may lead to a decrease in load capacity and deterioration of safety performance in the future, can also be singled out as a separate category. The most common defects identified by the results of bridge structures inspection for each category are shown in Table 1 and Figure 1.

Table 1 – Defects of bridge structures

Defects of bridge structures		
influencing the durability of the structure	influencing traffic safety	influencing the load capacity of the structure
– destruction of the bridge deck waterproofing structure; – soaking, caking, efflorescence on concrete; – thawing (frost degradation) of concrete, including bare reinforcement (Figure 1a); – insufficient protective layer of concrete, corrosion of structural reinforcement; – corrosion cracks (corrosion of working reinforcement) (Figure 1b); – water filtration along the joint, leaching, suede, efflorescence, stalactites; – failure of concrete of span girder joints; – spalling of concrete without bareness with bareness of reinforcement; – destruction of expansion joints, their unsealing; – defrosting of beam ends, corrosion of anchor washers; – corrosion and destruction of support parts; – destruction of drainage pipes, their insufficient length; – cone subsidence under the nozzles of the end supports and transition plates (Figure 1d); – erosion of cones and embankment slopes	– cracks in the pavement of the bridge deck and approaches; – patching of the pavement and approaches (Figure 1c); – contamination of the bridge deck and sidewalks; – elements of barrier fencing or their fastening on the bridge and approaches do not meet regulatory requirements (no reflective inserts, corrosion of metal elements); – railings are wobbly; – cone subsidence under the end piers and transition plates; – erosion of cones and embankment slopes; – organized conjugation of sidewalks with approaches is destroyed; – through destruction of sidewalks; – sidewalks are not covered; – drainage pipes have no grids; – stairs on the approaches are destroyed or missing	– corrosion of working reinforcement; – thawing (frost degradation) of concrete, including bare reinforcement; – increased thickness of the roadbed; – corrosion of anchor washers; – destruction of supporting parts

a) thawing (frost destruction) of concrete with bare and corroded reinforcement; b) corrosion cracks (corrosion of principal reinforcement); c) patching in the bridge deck covering; d) cone subsidence under the end piers nozzles

Figure 1 – Defects of bridge structures

When diagnosing and inspecting the technical condition of bridge structures, defects are identified on the basis of visual inspection, and its assignment to one or another category largely depends on the qualifications, experience and subjective opinion of the specialist conducting the inspection. At the same time, a number of defects and damages can be established visually – the presence of corrosion or force cracks, concrete thawing, non-compliance of some structural elements with the normative requirements [5]. Other defects cannot be detected without the use of modern highly specialized devices or laboratory tests, such as hidden corrosion of reinforcement, carbonization and chloride saturation of concrete, but can lead to rapid deterioration of the technical condition of structures [6, 7].

In the process of long-term operation of bridge structures their elements are exposed to the action of water ions chemically active in relation to cement stone, such as chlorides, nitrates, sulfates, which contribute to the destruction of concrete and reinforcement. One of the main factors determining the deterioration of technical building structures is the rate of diffusion and the rate of chemical reactions with hydration products of cement minerals.

The quality of natural water in water bodies where engineering structures are operated depends largely on the content of dissolved salts of mineral origin. The main salt content is due to calcium and magnesium compounds, which characterize water hardness. The content of chlorine anions, sulfate anions, carbonates and hydrocarbonates, iron cations and other ions determine the mineralization of natural water bodies. For each of the salt ions the normative value of MPC is established (Table 2).

Table 2 – Main indicators of maximum permissible concentrations of components that create water mineralization

Cations and anions of salts	MPC (maximum permissible concentration)
Calcium Ca^{2+}	200 mg/l
Magnesium Mg^{2+}	100 mg/l
Sulfate SO^{2-}	500 mg/l
Chloride Cl^{-}	350 mg/l
Total iron Fe^{2+}, Fe^{3+}	0,3 mg/l

The main indicator of water quality of a natural water body includes the hydrogen indicator – pH. The normative pH value for water bodies ranges from 6.5 to 8.5. Deviation of pH value in natural water from the established norm causes air pollution by acidic impurities, which fall into the water body with atmospheric precipitation. Change of pH can cause insufficiently treated and untreated wastewater from industrial enterprises, creating an aggressive environment in relation to hydraulic and bridge structures.

For this purpose, the study determined some water quality indicators in samples from water bodies.

To assess the impact of water bodies on bridge structures in the places of their operation, samples were taken from the Usa, Karpilovka and Poplavka rivers [8]. Water hardness, chloride content, and hydrogen index were determined in the samples. The results of the studies are summarized in Table 3.

Table 3 – Water quality indicators in samples of natural water bodies

Name of the river	pH	Hardness mgeq/l Ca^{2+}/ Mg^{2+}	Chlorides mg/l	Sulfates mg/l
Usa	8,06	5,5	45,67	57,2
Karpilovka	7,42	4,4	101, 18	48,8
Poplavka	7,86	4,3	49,70	58,7

It is known that when water hardness decreases, i. e. the content of ions Ca^{2+}, Mg^{2+} and the value of hydrogen index pH increases, the probability of free CO_2 in water increases, which accelerates the processes of corrosion of reinforcement and carbonization of concrete of bridge and hydraulic structures.

Analyzing the results of water samples in the rivers, it can be concluded that the studied indicators do not exceed the established standards of water quality in natural water bodies. It has been established that the natural content of sulfates in surface and ground waters is caused by weathering of rocks and biochemical processes occurring in aquifers. The maximum content of sulfate ions in water from centralized water supply sources should not exceed 500 mg/l, but, as a rule, in river water the concentration of sulfates is 100–150 mg/l. Increased concentration of sulfates may indicate pollution of a water body by industrial wastewater.

Chlorides are a constituent of most natural waters. However, in river water the concentration of chlorides is low – usually it does not exceed 10–30 mg/l, so the increased amount of chloride ions (Table 3) indicates pollution of the water body by wastewater. According to water quality standards for natural water bodies, chloride concentration should not exceed 350 mg/l. At certain ratios of sulfate and chloride, water becomes aggressive towards different types of concrete [9].

The rate of penetration of active components into the depth of concrete depends on both the nature of the medium and the structure of concrete [10]. It is necessary to take into account the hygroscopic property of nitrate, sulfate and chloride salts, which attract water and moisture from the atmosphere, i. e. as the salt content in the material increases, the water content also increases.

The practice of operation of concrete and reinforced concrete structures shows that waters containing aggressive carbon dioxide in the amount of more than 300 mg/l are highly aggressive. The process of carbonization of building materials proceeds in several stages. The first stage is the penetration of carbon dioxide by diffusion into the surface capillaries of the building material. In this case, the formation of carbonic acid takes place inside the capillary system of the material. This is followed by a neutralization reaction of carbonic acid by the alkaline components of cement mortars, bricks, natural and artificial stone.

$$H_2O + CO_2 \rightarrow H_2CO_3 \quad (1)$$

$$Ca(OH)_2+CO_2+H_2O \rightarrow CaCO_3+2H_2O \quad (2)$$

$$CaCO_3 + H_2O + CO_2 \rightarrow Ca(HCO_3)_2 \quad (3)$$

Thus, the mechanism of carbon dioxide corrosion of concrete cement stone is determined by two interrelated processes: formation of calcium carbonate (2) and its dissolution by reaction (3):

Reaction (3) is reversible and depends on the humidity and temperature of the environment, the porosity of the material, and the concentration of carbon dioxide in the atmospheric air. The dissolution and recrystallization processes of calcium carbonate depend on the same factors, as an increase in temperature promotes crystallization and the presence of moisture leads to the migration of hydrocarbonate to other areas of the material.

Corrosion of cement stone, in an environment containing corrosive carbon dioxide, proceeds with the decomposition of all Portland cement clinker minerals and their hydrate compounds in concrete.

The reversible reaction must be distinguished from the carbon dioxide bound in $Ca(HCO3)_2$ hydrogen carbonate. The appearance of a "super-equilibrium" amount of carbonic acid in solution causes the dissolution of more and more portions of $CaCO_3$. This excess acid is called corrosive acid. Carbonic acid corrosion acts on concrete the weaker, the more in the aqueous solution of calcium and magnesium hydrocarbonates.

Thus, the process of carbonic acid corrosion of concrete can be investigated by the change in the concentration of Ca^{2+}, $CO3^{2-}$, $HCO3^{-}$, pH in aqueous extracts from different layers of concrete specimens.

Carbon dioxide can be present in solution as three forms [9, 11]:

1) free carbon dioxide, which is formed by the interaction of CO_2 and H_2O;

2) carbon dioxide in the form of $HCO3^{-}$;

3) carbon dioxide in the form of $CO3^{2-}$.

All three forms can change from one to another depending on the pH of the medium.

The content of calcium and magnesium ions in the samples (Table 3) showed that the water in the rivers belongs to the category of water of medium hardness.

Concrete samples are taken from the main load-bearing structures to predict changes in the condition of the bridge structure in operation. The content of chlorides, calcium ions and pH in bridge elements (Table 4) was assessed and the influence of river water quality on their value was analyzed.

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The chemical process of carbonization, as a result of calcium carbonate formation in the porous structure of concrete, leads to a decrease in the pH value and to an increase a chlorine ion content [12]. As a result of the decrease in protective properties, salts accumulate in the material, causing deterioration and the formation of cracks. This leads to further penetration of aggressive medium, moisture and gases into the concrete, which in turn causes corrosion of reinforcement and propagation of structural defects. Therefore, the study of the properties of the material from which bridge structures are made is an important task in the development of sectors of the national economy. The chemical process of carbonization, as a result of calcium carbonate formation in the porous structure of concrete, leads to a decrease in the pH value. As a result of the decrease in protective properties, salts accumulate in the material, causing deterioration and the formation of cracks. This leads to further penetration of aggressive medium, moisture and gases into the concrete, which in turn causes corrosion of reinforcement and propagation of structural defects. Therefore, the study of the properties of the material from which bridge structures are made is an important task in the development of sectors of the national economy.

Table 4 – Results of determination of chemical parameters in aqueous extracts of concrete samples

Elements of bridge structures	Chemical parameters			
	pH	content Ca^{2+}(mg/l)	content Cl^- mg eq / 100g	content Cl^- in %
Ptich River Bridge				
Support 5	9,08	55	2,14	0,075
Head beam 4	9,26	16	2,34	0,082
Beam B1	9,13	37	5,99	0,209
Beam B3	9,43	56	3,99	0,138
Usa River Bridge				
Support 2	10,54	32	1,54	0,054
Head beam 2	9,74	24	0,48	0,017
Beam B2	9,63	14	0,75	0,026
Karpilovka River Bridge				
Support 2	8,94	13	0,25	0,009
Plate 3	8,95	11	1,45	0,051
Poplavka River Bridge				
Head beam 3	10,56	30	1.16	0,02
Head beam 4	8,49	30	1,68	0,059
Head beam 5	9,11	40	1,68	0,059
Strut 3	9	34	1,67	0,059
Beam 1	9,79	26	0,76	0,03

The chemical process of carbonization, as a result of calcium carbonate formation in the porous structure of concrete, leads to a decrease in the pH value. As a result of the decrease in protective properties, salts accumulate in the material, causing deterioration and the formation of cracks. This leads to further penetration of aggressive medium, moisture and gases into the concrete, which in turn causes corrosion of reinforcement and propagation of structural defects. Therefore, the study of the properties of the material from which bridge structures are made is an important task in the development of sectors of the national economy.

As it is known, the moisture content of the building material always depends on the air humidity. Since calcium carbonate is a hygroscopic salt, its formation in the pores of the material increases the moisture level even at temperatures below the dew point. Moreover, the thinner the pores, the more intensive is condensation on the pore surface, disturbing the equilibrium humidity of the building material (2). The equilibrium shifts towards soluble calcium hydrocarbonate.

The soluble calcium salt is subsequently washed out of the material by groundwater, seepage or rainwater, or penetrates deep into the material. This causes damage to the structure of the material.

Samples of bridge elements located in the vertical plane, such as piers and supports, have a higher calcium ion content, which corresponds to a higher pH value.

At the same time, the content of chloride ions in extracts of these elements is predominantly lower than in samples of elements located in the horizontal plane, i. e. in slabs, superstructures and girders.

When analyzing the research results, it is necessary to take into account the service life of bridge structures**.** The bridge over the Ptich River has been in operation for more than 40 years. The higher content of calcium ions in the vertical structures of this bridge indicates the transition of calcium into soluble compounds, which are washed out of the concrete by seeping water or precipitation. The high chloride content in the extreme girder of the bridge (more than 0,2 %) may indicate the long-term use of salt during winter operation of the structure.

In this work, along with the study on chloride and calcium content, the degree of carbonization of concrete of engineering structures of road infrastructure such as overpasses, bridges and reclamation structures and structures was determined.

The concentration of carbon dioxide in atmospheric air noticeably affects the carbonization process, the rate of which increases with increasing carbon dioxide content and increasing temperature. It should be noted that the diffusion of carbon dioxide in moist air is about 10000 times faster than in water moistening the protective layer of concrete.

In concrete that has been operated in an aggressive atmosphere containing acid gases, three main layers are usually distinguished [9]:

- external, neutralized by a gas forming a stronger acid than carbonic acid;
- middle, carbonized;
- internal, not exposed to acid gases.

After carbonization of the protective layer of concrete to its entire depth, corrosion of steel reinforcement is intensified, which is the main cause of failure of reinforced concrete structures.

In the work we determined the degree of carbonization for a bridge structure over the Usa River. The degree of carbonization of concrete is characterized by carbon dioxide chemically bound to the cement stone, which is determined as a percentage of the mass of cement in accordance with STB 1481-2011. The results of the research are given in Table 5.

Table 5 – Degree of carbonization of samples of elements of the bridge over the Usa River

Element name	Degree of carbonization (%)
Support 2	7,62
Head beam 2	8,36
Beam 2	5,87

However, the issue of criteria for assessing the state of concrete and its protective properties in relation to steel reinforcement is currently problematic [13]. According to the research of V. I. Babushkin [14] concrete loses its protective properties in relation to reinforcement at pH < 11.8, but this does not mean that the degree of carbonization at such an indicator will be maximum. The decrease in the values of the hydrogen index may be a consequence of internal physicochemical processes of salt recrystallization.

Decrease in pH value in concrete extracts is not a criterion for evaluating the carbon dioxide content in the pore structure of concrete. It is obvious that the content of carbon dioxide and other acidic gases in the surface layers of concrete will be higher and the pH value will be lower, but what is the depth of penetration of carbon dioxide into the depth of concrete in this case remains unknown.

Consequently, during the comprehensive inspection of objects of various infrastructure there is a need to determine the content of carbon dioxide in samples of materials at different depths from the surface of the sample.

An important stage in determining the technical condition of the structure is the prediction of the bridge durability [15] (Table 6). According to [16], it is recommended to perform the prediction based on the data from the results of previous surveys extrapolating the reduction of the load-carrying capacity class according to the elliptical dependence. Under

unfavorable operating conditions (systematic freezing, exposure to chemically active de-icing agents) it is necessary to take into account the reduction of strength and deformative properties of concrete as a result of degradation processes in accordance with Appendix B [16]. Corrosion of reinforcement also affects the reduction of span load carrying capacity; therefore, the method developed in the Russian Federation [17] provides not only for prediction of concrete carbonization but also for corrosion of reinforcement.

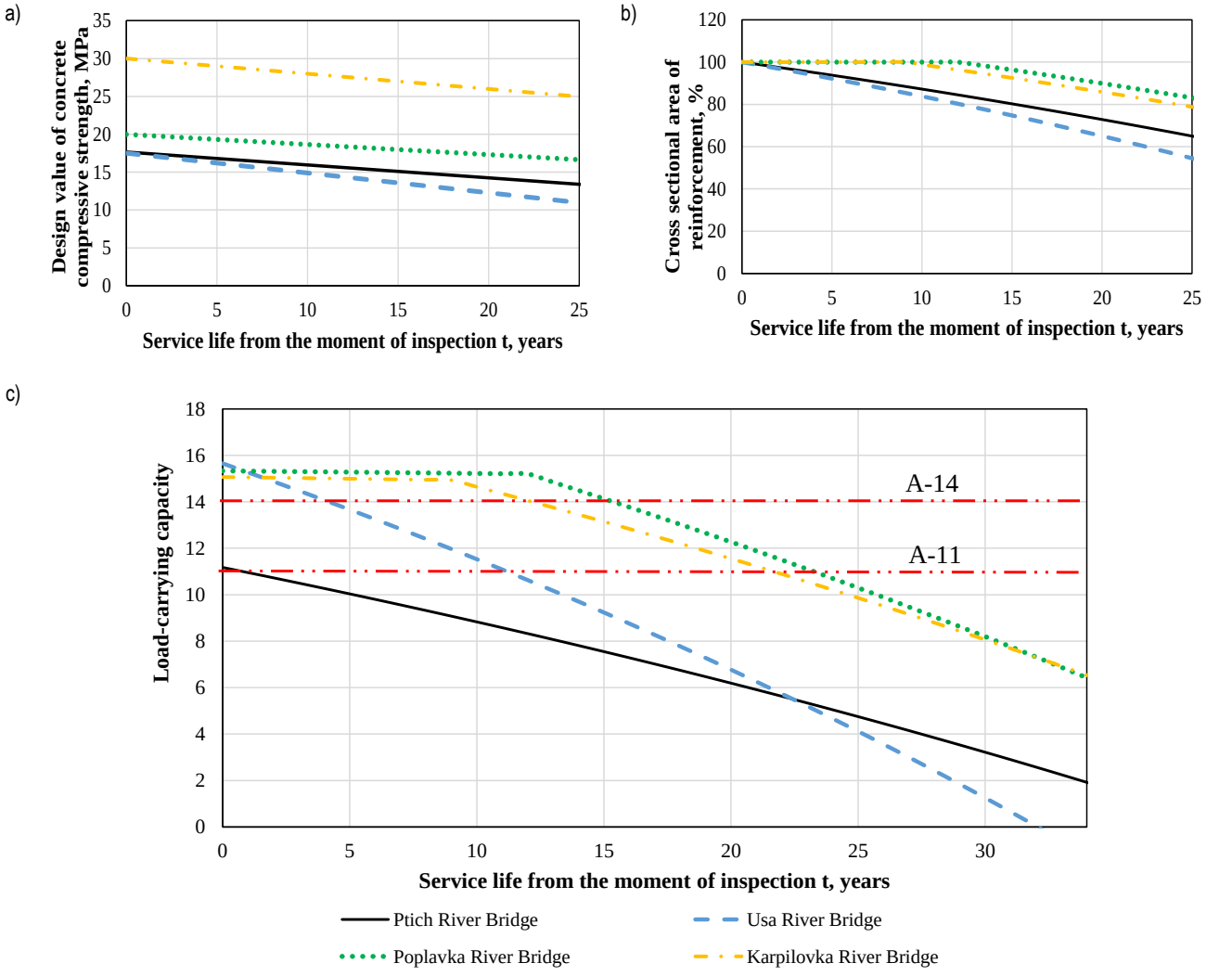
The methods given in normative documents [16, 17] do not always allow us to reliably obtain data on the predicted service life of structures, since the rate of development of concrete carbonization and reinforcement corrosion depends largely on the initial quality of materials, as well as on the operating conditions of the structure, which can be very different even within the same structure: end and middle beams of the span, structures located at the expansion joint, etc. [18]. It is obvious that in order to perform reasonable calculations of the predicted durability of bridge elements, it is necessary to have accurate and detailed information on the processes of concrete carbonization and reinforcement corrosion occurring in the structure at the inspection stage [19, 20].

In order to fully assess the technical condition and predict the residual life of structures, the specialist performing the inspection should have data on the condition of the structure, the degree of concrete carbonization, and the corrosion processes occurring in the reinforcement during the entire period of operation, which is not always possible.

Table 6 – Normative (forecast) indicators of durability of structures

Bridge name	Year of construction / last major repair (reconstruction)	Design service life of structures, years		Remaining service life of structures [16], years	
		Spans	Supports	Spans	Supports
Ptich River Bridge	1972	75	100	24	49
Usa River Bridge	1972 / –			24	49
Karpilovka River Bridge	1987 / 2012			63	63 / 88
Poplavka River Bridge	2012 / –			63	88

On the basis of actual data on the technical condition of structures (physical deterioration) and laboratory studies of their materials, the calculation of predicting the durability of the structure was performed by determining the load capacity of the structures of spans and supports (Figure 2).



a) degradation of design value of concrete compressive strength; b) decreasing of cross sectional area of reinforcement; c) decreasing load-carrying capacity

Figure 2 – Prediction of the bridge durability

Prediction of the decrease in the design compressive strength of concrete during the operation period was made using coefficients that take into account the operating conditions of the structure, which were established during the inspection of the structure. The time variation of the working reinforcement corrosion degree was taken into account by decreasing the effective diameter of the reinforcing bar during t_i years of the bridge structure operation, taking into account the data obtained as a result of the survey. The actual degree of concrete carbonization and, consequently, the residual concrete protective layer determined in the present study were taken into account. The function of reinforcement cross-sectional reduction (reinforcement wear) in accordance with [17], can be described using the reliability theory failure function and transformed into the dependence of the effective cross-sectional area of the working reinforcement of the slab on the service life of the span. The results of numerical modeling are presented in Table 7.

Table 7 – Results of numerical modeling of durability of structures

Bridge name	Bridge load capacity category	Number of years until the expiration of the reliability requirements for the calculated load capacity
Ptich River Bridge	A-11	0,8
Usa River Bridge	A-11	11,2
Karpilovka River Bridge	A-14	12,2
Poplavka River Bridge	A-14	15,4

Conclusions

1. Diagnostics of defects in bridge structures can be carried out based on the results of visual inspection and appropriate measurements. The most promising methods are the methods of chemical analysis, which allow to obtain information about the condition of the structure and identify hidden defects.

2 The main indicators controlled by chemical analysis of concrete condition are chloride content, degree of carbonization and pH, which depend on the initial quality of materials, as well as the operating conditions of the structure, which can vary greatly even within the same structure.

3. The question of criteria for assessing on the basis of chemical analysis the condition of concrete, its protective properties in relation to steel reinforcement remains unresolved, because, as the experience of the performed surveys shows, a decrease in the pH of concrete does not always lead to an increase in the degree of carbonization and, consequently, more rapid development of defects.

4. Prediction of the bridge durability based on the data on its load carrying capacity, determined by the results of previous surveys, allows taking into account the development of degradation processes in concrete and corrosion of reinforcement. To perform appropriate calculations it is necessary to have information on the degree of concrete carbonization, corrosion processes in reinforcement during the whole operation period. Analysis of the obtained durability indicators (Figure 2, Table 7) of the bridge structures considered in the article indicates the necessity of systematic monitoring of their technical condition and performance of repair and rehabilitation works for some of them. In this connection it is urgent to create a database of bridge structures containing data not only on their structural design and main defects, but also on changes in chloride content, degree of carbonization and pH during different periods of operation.

References

1. Ekolu, S. O. A review on effects of curing, sheltering, and CO2 concentration upon natural carbonation of concrete / S. O. Ekolu // Construction and Building Materials. – 2016. – Vol. 127. – P. 306–320. – DOI: 10.1016/j.conbuildmat.2016.09.056.
2. Mosty avtodorozhnye. Pravila vypolneniya diagnostiki : TKP 227-2018 / Minstrojarhitektury Respubliki Belarus'. – Minsk, 2017. – 118 s.
3. Krivickij, P. V. Defekty mostovyh sooruzhenij i metody ih diagnostiki / P. V. Krivickij, N. V. Matveenko // Teoriya i praktika issledovanij, proektirovaniya i SAPR v stroitel'stve : sbornik statej VI Mezhdunarodnoj nauchno-tekhnicheskoj konferencii, 23 noyabrya 2023 g. / Brestskij gosudarstvennyj tekhnicheskij universitet ; redkol.: N. N. SHalobyta [i dr.]. – Brest, 2023. – S. 23–30. – URL: https://rep.bstu.by/handle/data/42534 (data obrashcheniya: 13.10.2024).
4. Kamiński, T. Defects and Failures Influencing the Mechanical Performance of Bridge Structures / T. Kamiński // Procedia Engineering. – 2016. – Vol. 161. – P. 1260–1267. – DOI: 10.1016/j.proeng.2016.08.565.
5. Obsledovanie mostovyh sooruzhenij s pomoshch'yu sovremennogo oborudovaniya / A. V. Makarov, E. V. Kroshneva, A. F. Fajzaliev [i dr.] // Inzhenernyj vestnik Dona. – 2021. – № 7 (79). – URL: https://cyberleninka.ru/article/n/obsledovanie-mostovyh-sooruzheniy-s-pomoschyu-sovremennogo-oborudovaniya (data obrashcheniya: 11.10.2024).
6. Causes and statistical characteristics of bridge failures: A review / G. Zhang, Y. Liu, J. Liu [etc.] // Journal of Traffic and Transportation Engineering (English Edition). – 2022. – Vol. 9, iss. 3. – P. 388–406. – DOI: 10.1016/j.jtte.2021.12.003.
7. Smith, Dw. Bridge failures / Dw. Smith // Proceedings of the Institution of Civil Engineers. – 1976. – Vol. 60, iss. 3. – P. 367–382. – DOI: 10.1680/iicep.1976.3389.
8. Levchuk, N. V. Eksperimental'no-teoreticheskie issledovaniya obrazcov betona mostovyh sooruzhenij po nekotorym himicheskim pokazatelyam / N. V. Levchuk, K. A. Olekhnovich // Vestnik Brestskogo gosudarstvennogo tekhnicheskogo universiteta. – 2023. – № 2 (131). – S. 44–47. – DOI: 10.36773/1818-1112-2023-131-2-44-47.
9. Linnik, L. I. Himiya vody i mikrobiologiya : konspekt lekcij dlya studentov special'nosti 1-70 04 03 «Vodosnabzhenie, vodootvedenie i ohrana vodnyh resursov»; specializaciya 1-70 04 03 02 «Tekhnicheskaya ekspluataciya i rekonstrukciya sistem vodosnabzheniya i vodootvedeniya» / L. I. Linnik. – Novopolock : PGU, 2015. – 228 s.
10. Fressel', F. Remont vlazhnostnyh i povrezhdennyh solyami stroitel'nyh sooruzhenij / F. Fressel'. – M. : OOO «Pejnt-Media», 2006. – 320 s.
11. Voronov, YU. V. Vodootvedenie i ochistka stochnyh vod : uchebnik dlya vuzov / YU. V. Voronov, S. V. YAkovlev. – M. : Izdatel'stvo Associacii stroitel'nyh vuzov, 2006. – 704 s.
12. Zhang, D. Effect of early carbonation curing on chloride penetration and weathering carbonation in concrete / D. Zhang, Y. Shao // Construction and Building Materials. – 2016. – Vol. 123. – P. 516–526. – DOI: 10.1016/j.conbuildmat.2016.07.041.
13. Vasil'ev, A. A. Ocenka i prognozirovanie stepeni karbonizacii betona / A. A. Vasil'ev // Innovacionnoe razvitie: potencial nauki i sovremennogo obrazovaniya : monografiya / A. A. Vasil'ev. – Penza, 2018. – Gl. 13. – S. 148–158.
14. Babushkin, V. I. Fiziko-himicheskie processy korrozii betona i zhelezobetona / V. I. Babushkin. – M.: Strojizdat, 1968. – 187 s.
15. Rekunov, S. S. Ob ocenke nadyozhnosti i vosstanovlenii ekspluatacionnyh kachestv mostovyh sooruzhenij / S. S. Rekunov // Transportnye sooruzheniya. – 2016. – T. 3, № 2. – URL: https://t-s.today/PDF/07TS216.pdf (data obrashcheniya: 28.09.2024).
16. Pravila opredeleniya gruzopod"emnosti zhelezobetonnyh i stalezhelezobetonnyh balochnyh proletnyh stroenij avtodorozhnyh : TKP 479-2019 / Mintrasporta i kommunikacij RB. – Mn., 2019. – 248 s.
17. SHesterikov, V. I. Metodika raschetnogo prognozirovaniya sroka sluzhby zhelezobetonnyh proletnyh stroenij avtodorozhnyh mostov / V. I. SHesterikov, L. I. Iosilevskij, E. A. Andropova. – M. : Rosavtodor, 2002. – 140 s.
18. Impact of the Structural Defects on Risk Assessment of Concrete Bridges According to the Italian Guidelines 2020 / A. Miano, A. Mele, I. Della Ragione [etc.] // Infrastructures. – 2023. – Vol. 8, iss. 135. – DOI: 10.3390/infrastructures8090135.
19. Ho, D. W. S. Carbonation of concrete and its prediction / D. W. S. Ho, R. K. Lewis // Cement and Concrete Research. – 1987. – Vol. 17, iss. 3. – P. 489–504. – DOI: 10.1016/0008-8846(87)90012-3.
20. Ganiev, I. G. Opredelenie iznosa v elementah proletnyh stroenij s uchetom karbonizacii betona v konstrukciyah mostov / I. G. Ganiev // Transport Rossijskoj Federacii. ZHurnal o nauke, praktike, ekonomike. – 2008. – № 5 (18). – URL: https://cyberleninka.ru/article/n/opredelenie-iznosa-v-elementah-proletnyh-stroeniy-s-uchetom-karbonizatsii-betona-v-konstruktsiyah-mostov (data obrashcheniya: 29.10.2024).

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THE USE OF POWDER MATERIALS OF HIGHLY HARD COMPOUNDS FOR THE FORMATION OF ELECTRIC SPARK COATINGS FOR VARIOUS FUNCTIONAL PURPOSES

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Abstract

Electric spark alloying of solid surfaces is a promising direction for increasing the performance properties of materials. Formation of superhard material coatings on a substrate allows to significantly increase hardness, wear resistance, resistance to high temperatures and pressure, and improve the performance characteristics of products by 1.5–5 times. This is due to the formation of various multicomponent structures in electric spark coatings that have increased strength and tribotechnical characteristics. The aim of the work was to study the structure and physical and mechanical properties of electric spark coatings obtained from powder materials. Various powder charge compositions and electric spark discharge parameters were used to form the coatings. The coatings were formed under standard climatic conditions by combining powder materials based on titanium carbide (TiC), aluminum (Al), carbon (technical graphite), titanium nitride (TiN), aluminum nitride (AlN) using the developed technology. The strength and adhesion properties of coatings obtained by the electric spark alloying method were studied. The studies to determine the adhesion characteristics using scratch analysis and Rockwell methods showed that coatings based on TiN+Al compounds have high adhesion strength. It was found that in TiN+Al coatings, electric spark alloying can lead to the formation of MAX phases and high-entropy compounds, which has a positive effect on the physical and mechanical properties of the formed coatings. The microhardness of the studied coatings is increased by 2–4 times compared to the original titanium substrates. The dependence of the coating microhardness on the indenter penetration depth was studied. The dependence of the strength characteristics on the indenter penetration depth of the TiC+Al electric spark coating (0.9 J) formed on the VT1 titanium alloy is nonlinear with an extremum in the region of a coating thickness of 9–10 μm. The strength characteristics of electrospark coatings formed by a contactless method from refractory metals were investigated. The possibility of forming coatings from silicate ceramics with increased values of microhardness and adhesive strength was established.

Keywords: electric spark alloying, hardness, nanocomposites, titanium carbides and nitrides.

ИСПОЛЬЗОВАНИЕ ПОРОШКОВЫХ МАТЕРИАЛОВ ВЫСОКОТВЕРДЫХ СОЕДИНЕНИЙ ДЛЯ ФОРМИРОВАНИЯ ЭЛЕКТРОИСКРОВЫХ ПОКРЫТИЙ РАЗЛИЧНОГО ФУНКЦИОНАЛЬНОГО НАЗНАЧЕНИЯ

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Реферат

Электроискровое легирование поверхностей твердых тел является перспективным направлением увеличения эксплуатационных свойств материалов. Формирование покрытий сверхтвердых материалов на субстрате позволяет существенно увеличить твердость, износостойкость, стойкость к воздействию высоких температур и давления, повысить эксплуатационные характеристики изделий в 1,5–5 раз. Это обусловлено образованием в электроискровых покрытиях различных многокомпонентных структур, обладающих повышенными прочностными и триботехническими характеристиками. Целью работы являлось изучение структуры и физико-механических свойств электроискровых покрытий, получаемых из порошковых материалов. Для формирования покрытий использовались различные составы порошковой шихты и параметры электроискрового разряда. Покрытия формировались в стандартных климатических условиях путем совмещения порошковых материалов на основе карбида титана (TiC), алюминия (Al), углерода (технического графита), нитрида титана (TiN), нитрида алюминия (AlN) по разработанной технологии. Проведены исследования прочностных и адгезионных свойств покрытий, полученных методом электроискрового легирования. Проведенные исследования по определению адгезионных характеристик методами скретч-анализа и

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Роквелла показали, что покрытия на основе соединений TiN+Al обладают высокой адгезионной прочностью. Установлено, что в покрытиях TiN+Al электроискровое легирование может приводить к образованию MAX-фаз и высокоэнтропийных соединений, что положительно сказывается на физико-механических свойствах формируемых покрытий. Микротвердость исследуемых покрытий повышена в 2–4 раза по сравнению с исходными титановыми подложками. Исследована зависимость микротвердости покрытия от глубины внедрения индентора. Зависимость прочностных характеристик от глубины внедрения индентора электроискрового покрытия TiC+Al (0,9 Дж), сформированного на титановом сплаве ВТ1, носит нелинейный характер с экстремумом в области толщины покрытия 9–10 мкм. Исследованы прочностные характеристики электроискровых покрытий, сформированных бесконтактным способом из тугоплавких металлов. Установлена возможность формирования покрытий из силикатной керамики, обладающих повышенными значениями микротвердости и адгезионной прочности.

Ключевые слова: электроискровое легирование, твердость, нанокомпозиты, карбиды и нитриды титана.

Introduction

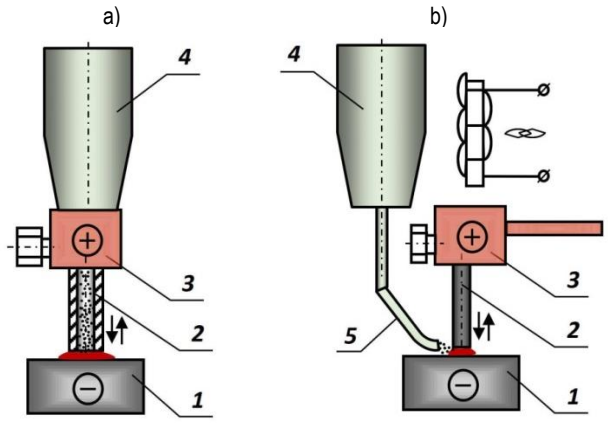
The electric spark alloying (ESA) method using powder materials is a promising technology for creating new-generation metallic materials and coatings with improved physical and mechanical properties. ESA of solid conductive surfaces involves the passage of electrode material between the electrodes, resulting in a directed ejection of the electrode material. The anode is predominantly destroyed during the electric spark discharge. Since ESA is carried out in a gaseous environment, this leads to the fact that under specified conditions, the anode material, which is mainly in the gas or liquid phase, is applied to the cathode. As a result of the interaction of the applied material with the cathode material and the environment, a layer with certain physical and mechanical properties is formed on the cathode. This layer has a complex chemical composition and structure and usually contains not only the anode material, but also solid solutions, chemical compounds, various alloys and pseudo-alloys. The formation of electric spark coatings leads to a significant change in the mechanical, electrical, thermal, magnetic, and thermionic properties of the modified surface layers of solids. The advantages of electric spark alloying are: high adhesive strength of the coating to the substrate; the possibility of obtaining coatings from refractory materials without heating the base material; the surfaces on which ESA coatings are formed do not require any preliminary preparation; simplicity, reliability and transportability of the process equipment [1–23].

Currently, there is insufficient information and knowledge about the main reasons for the limited life of tools and parts, factors that contribute to increased wear resistance, and a lack of understanding of the features of the electric spark process. In addition, there is insufficient practical experience in working with ESA installations using powder materials to form coatings. Also, for the successful use of this technological method of electric spark hardening, there is currently no necessary technological support for its application. With the high versatility of the electric spark method of applying metal nanocomposite coatings from powder materials, a system is required to simplify the methodology of their development to create effective hardening technologies. In this regard, the subject matter of the presented project is relevant. The main scientific idea is the use of powder materials of refractory metals and graphite with a certain percentage of ligands, which allow obtaining nanocomposite coatings of the appropriate composition and physical and mechanical properties during the process of electric spark alloying [6–9].

The aim of this work is to study the structure and physical and mechanical properties of electric spark coatings formed from powder materials of high-hardness compounds.

Experimental technique

Composite electric spark coatings based on nitrides, carbides, silicides of titanium and aluminum were applied by the method of electric spark alloying on a specialized installation (Figure 1), allowing the powder materials to enter the zone of electric spark discharge. Alloy VT1-0 was used as a substrate for the formation of coatings. The coatings were applied both to the metal in the delivery condition, which was ground to 9–10 purity class. Figure 1 shows the process flow chart for the formation of ESA coatings using this technology. To determine the optimal mode, in which the maximum amount of powder could get into the discharge zone, the vibration frequency of the processing electrode was slowly varied from 100 to 30 Hz. The ESA process was carried out in the range of discharge energy valuesfrom 0.3 to 10.0 J. Various powder charge compositions and electric spark discharge parameters were used to form the coatings (Table 1).



1 – workpiece (cathode); 2 – electrode (anode); 3 – applicator; 4 – hopper; 5 – powder feed tube into the working area; a – powder is introduced into the gap through a tubular electrode; b – powder is introduced from the side of the processing electrode

Figure 1 – Powder alloying methods

Table 1 – Coating compositions and modes of formation of electrospark coatings

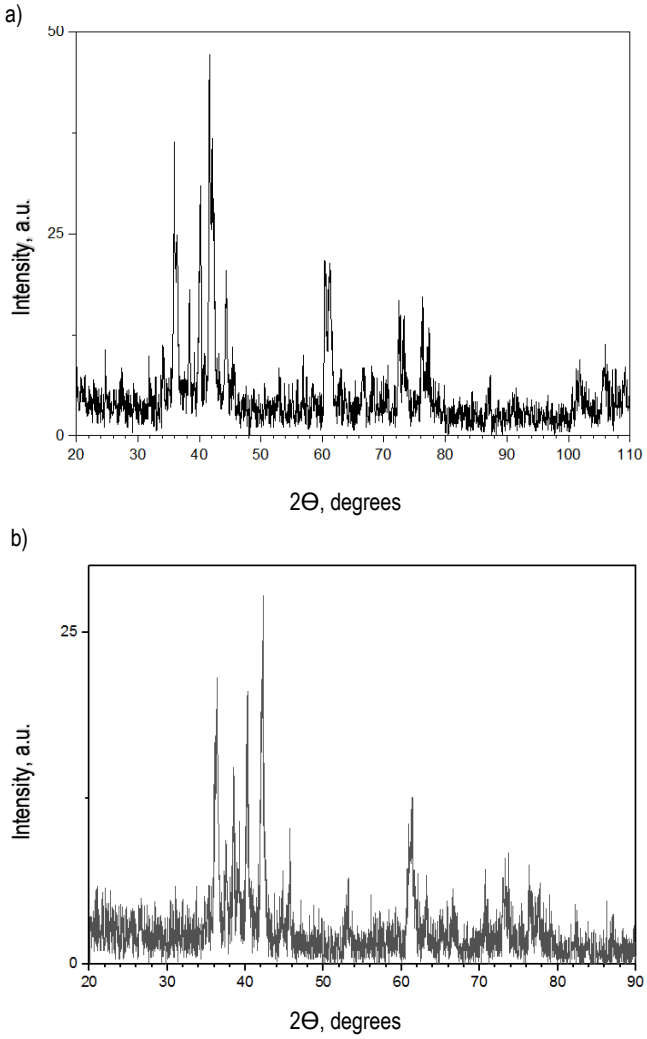
№	Composition of the powder mixture	Coating formation mode, J
1	–	–
2	TiC+Al	0.3
3	SiO_2	0.3
4	TiN	0.3
5	TiC+Al	0.9
6	Al+C	0.3
7	TiN+Al	0.3
8	Al+C	0.9
9	Ti+Al (heat treatment)	0.3
10	Ti (heat treatment)	0.3

The analysis of the structural features of metal coatings and their subjected to various types of processing was carried out on a universal metallographic complex manufactured by ZAO Spectroscopic Systems.

The features of the boundary layer structure in functional composite materials were studied using modern methods: scanning electron microscopy, atomic force microscopy, X-ray diffraction analysis (DRON-3.0) using standard techniques. X-ray diffraction analysis was used to determine the structure of thin-layer vacuum coatings. X-ray patterns were obtained on a general-purpose X-ray diffractometer DRON-3.0 using a standard technique, using the radiation of the Kα line from a tube with a copper anticathode, filtered at a wavelength of λ = 1.54051 Å. To measure the microhardness of coatings formed on metals, a hardness tester "Mikrosize uvicky" was used. The operating principle of the device is based on changing the linear value of the diagonal of the imprint c, obtained by pressing a diamond pyramid into the material under study under a certain load. A tetrahedral diamond pyramid with an angle of 136° between opposite faces was used for the studies, the load on the pyramid was 0.5 N. The thickness of the formed coatings was within ~ 60 μm.

Research results

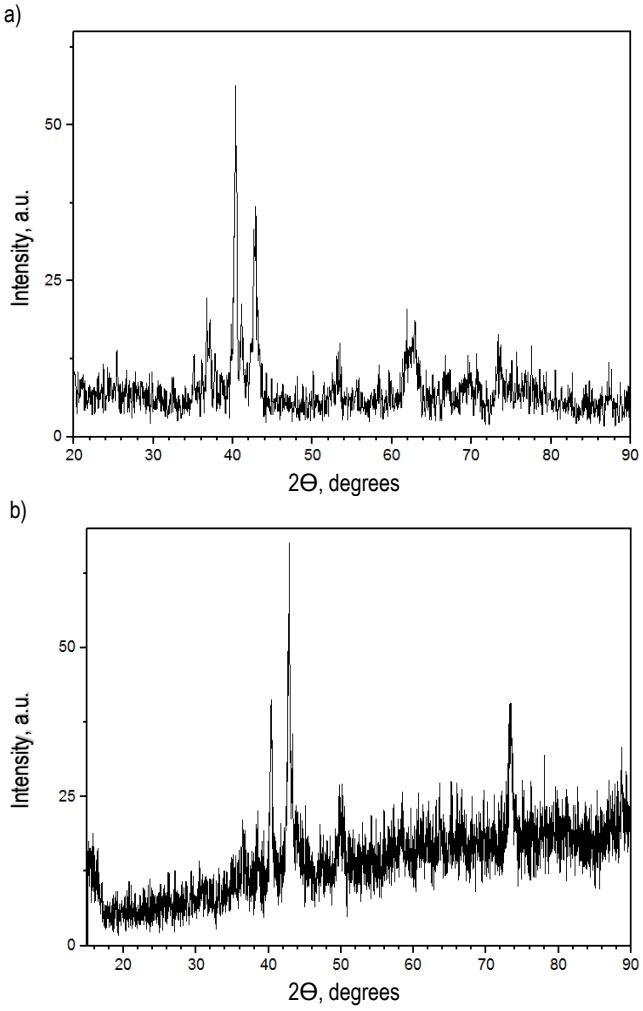
According to the X-ray phase analysis data, low-dimensional objects and MAX phases (Figures 2, 3) are possible in the electric spark coatings obtained by the contactless formation technology, which is confirmed by the presence of diffraction maxima in the areas of 2Θ~38°, 53°, 61° (Figure 2a) and 2Θ~43°, 73° (Figure 3b). The coatings were formed under standard environmental conditions by combining powder materials based on titanium carbide (TiC), aluminum (Al), carbon (technical graphite), titanium nitride (TiN), aluminum nitride (AlN) according to the technology shown in Figure 1.



a – TiC+Al coating, b – Al+C

Figure 2 – X-ray diffraction patterns of ESA coatings formed using a contactless method

In works [9–11] a qualitative method of determination of adhesive interaction between a solid substrate and a metal, ceramic coating obtained by various technological methods is proposed. The essence of the method lies in pressing an indenter in the form of a cone with an angle of 120° and a radius of curvature of the pin of 0.2 mm under a load of 150 kgf. Standard testing equipment is used for carrying out measurements, in particular, a Rockwell hardness tester. The holding time of the indenter in the coating under study is 6 s. After removing the load and extracting the indenter, the resulting imprint is studied using a metallographic optical microscope. The degree of adhesion of the coating is determined by studying the shape of the imprint. A variational series of images of the test results is constructed from good samples with a small number of cracks to samples in which complete peeling of the coating from the substrate is observed (Figure 4).



a – TiN coating, b – Ti+AlN

Figure 3 – X-ray diffraction patterns of ESA coatings formed using a contactless method

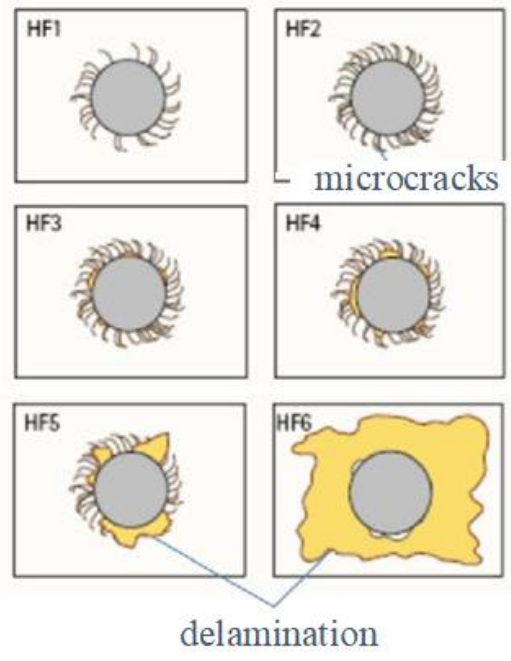


Figure 4 – Types of standardized coating failure prints according to DIN 4856:2018-02 and VDI 3198

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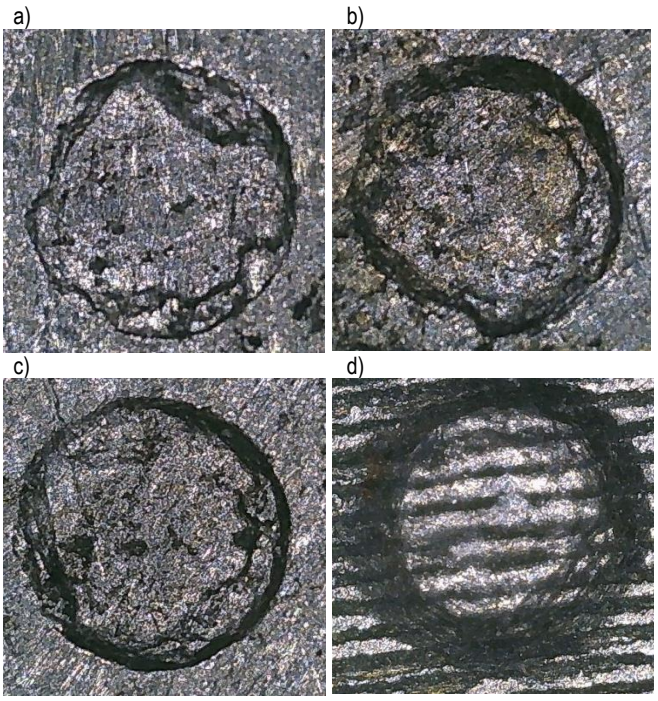
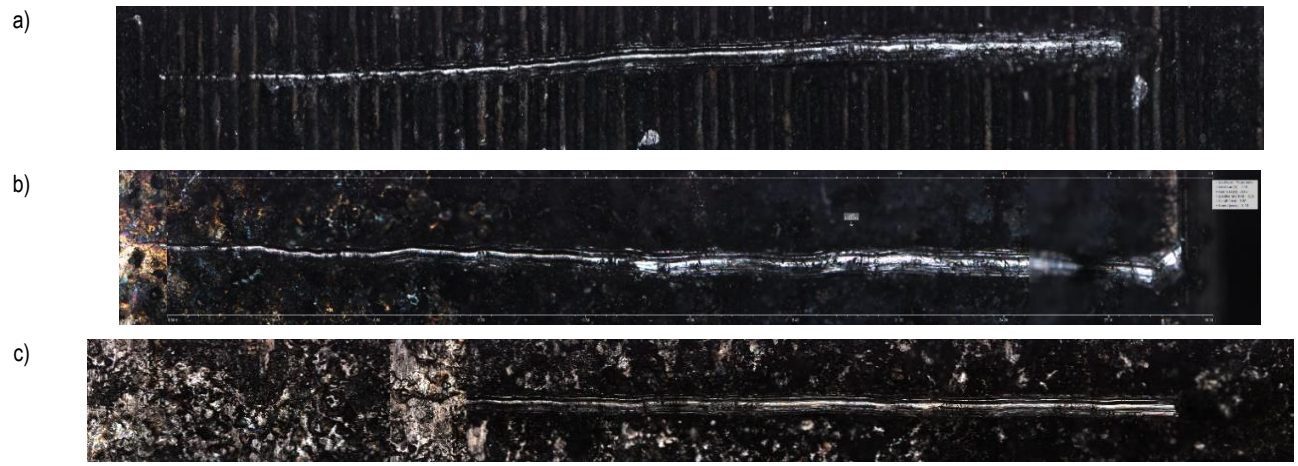
The results of the tests carried out according to DIN 4856:2018-02 and VDI 3198 are shown in Figure 5. According to the obtained data, the TiC+Al and SiO_2 electrospark coatings can be classified as HF5, the SiO_2 coating as HF4, and the TiN+Al coating as HF1 [12]. The high adhesive strength of coatings based on the TiN+Al system is most likely due to the fact that the use of aluminum allows increasing the plasticity of the coating while maintaining high strength characteristics. It is also possible to form compounds of the MAX phase type or high-entropy phases, since the substrate and coating contain the required amount of chemical elements to form these compounds, and the deposition process modes create the necessary physicochemical conditions for reactions that contribute to the formation of highly hard, plastic compounds. The scratch analysis method was used to determine the values of the adhesive interaction of the studied coatings sprayed by a contactless electrospark method onto metal substrates. The optimum mode, in which the highest values of adhesive interaction can be achieved, was determined with the following process parameters: the vibration frequency of the processing electrode was slowly varied from 100 to 30 Hz. Both industrial and experimental installations were used as sources of pulse discharges. The ESA process was carried out in the range of discharge energy values from 0.3 to 10.0 J. The results of the studies are presented in Figure 6.

The conducted studies to determine the microhardness values of electrospark coatings formed using contactless technology allowed us to establish an increase in the strength characteristics of modified titanium substrates by 1.3–5 times. The conducted studies to study the strength characteristics of electrospark coatings, in particular using the dynamic indentation method, showed an increase in the hardness values of titanium substrates after the formation of electrospark coatings obtained using contactless technology (Figure 8). To form the coatings, various powder charge compositions and electrospark discharge parameters were used (Table 1).



a – TiC+Al; b – SiO_2; c – TiN; d – TiN+Al

Figure 5 – Surface morphology of spark-ignition coatings after testing for adhesion strength according to DIN 4856:2018-02



a) Al+C; b)TiC+Al; c) Ti+AlN

Figure 6 – Morphology of the indentation surface during scratch analysis of the coating obtained by non-contact electric spark alloying

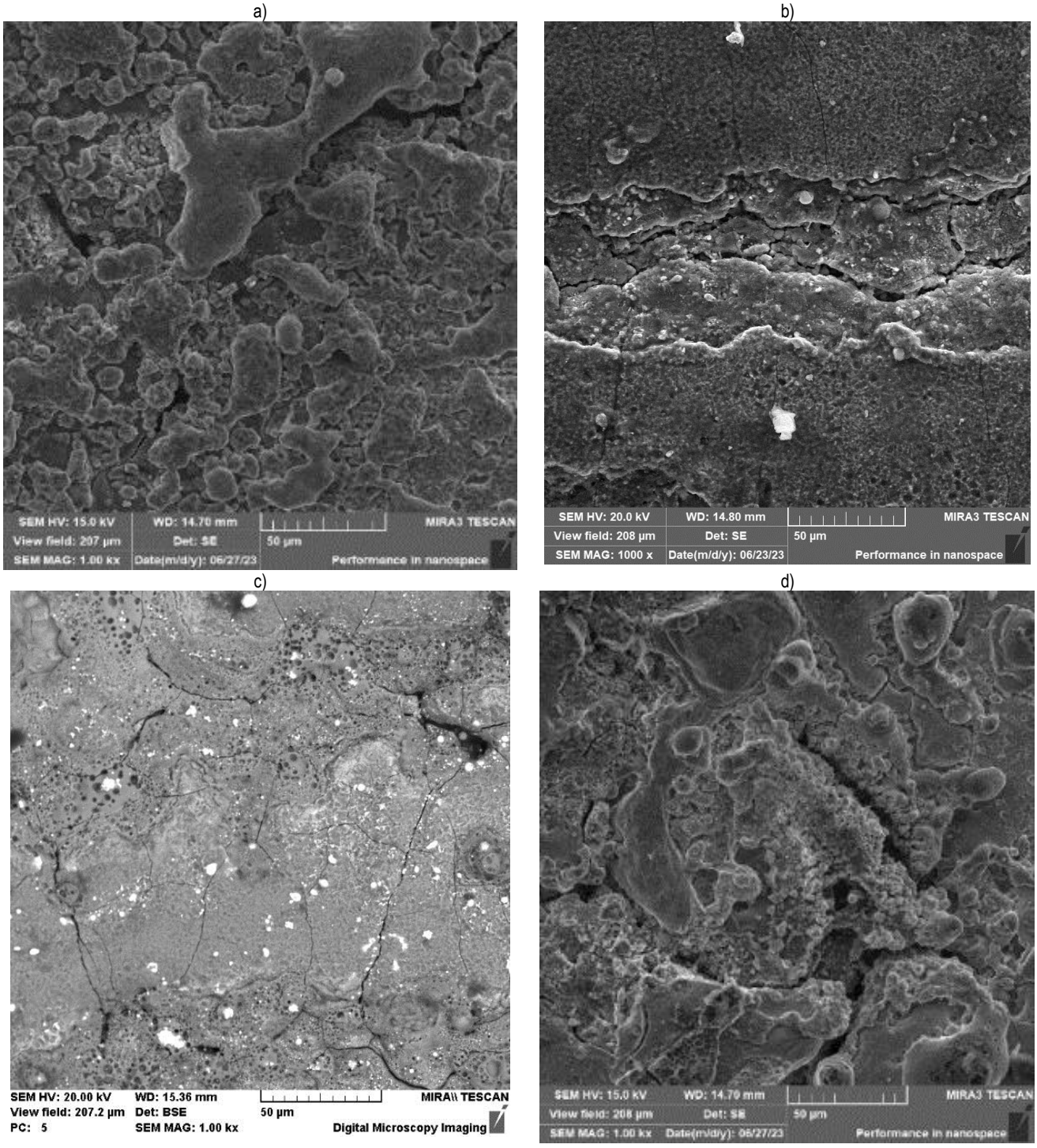
According to the data presented in Figures 4–6, it is evident that the highest adhesive strength is possessed by Ti+AlN coatings formed by the contactless method of electrospark alloying. Actual partial peeling of the coating is observed at normal load values in the region above 20 N. Whereas for Al+C, TiC+Al coatings, the onset of loss of adhesive strength begins at values of 10–15 N. Sufficiently high values of adhesive strength for Ti+AlN-based coatings are due to the application of a thermodynamically compatible titanium sublayer to the VT1 alloy by the electrospark method, which ensures good diffusion of the sublayer into the metal base.

Further deposition of the AlN-based coating, which is actually a ceramic and dielectric material, leads to the formation of surface layers with high physical and mechanical properties. High adhesive strength of the AlN layer to the metallic titanium sublayer is ensured by the fact that the entire process of forming this composite electrospark coating takes place in a single technological cycle. The results of determining the values of the adhesion work of the coatings to the titanium substrate correlate well with the scratch analysis data. The morphology of the electrospark coatings is quite developed. On the surface of the formed layers of refractory metals, a certain number of microroughnesses and voids are observed, which can be identified as closed pores and protrusions, as well as cracks (Figure 7).

The interest in the use of dynamic indentation to determine the hardness of materials is due to the fact that this approach allows us to determine the hardness under dynamic effects that constantly occur when using products in real operating conditions. While the methods of hardness testing (it is possible to consider as a special case of strength) according to Brinell, Rockwell, Vickers determine hardness statically, which in some cases does not provide complete information on the strength characteristics of materials used in structures that are operated under dynamic conditions. Determination of hardness values by the Leib method (dynamic indentation) is carried out according to the formula:

$$HL = 1000(v_b/v_a), \quad (1)$$

where v_a is the speed of the spherical indenter falling before interacting with the surface of the measured material, v_b is the speed of the spherical indenter rebound after interacting with the surface of the studied material.



a – TiC+Al, b – Al+C, c – TiN, d – TiN+Al
Figure 7 – Morphology of ESA coatings

Based on the conducted studies, it is evident that the Leyd hardness values increased from 6 to 22 % compared to the original titanium material. Taking into account that the method of electric spark alloying is a surface hardening technology with a hardening zone thickness of approximately 40–60 µm, and the method of dynamic indentation leaves an imprint from the indenter with a depth of about 100 µm or more, the obtained hardness values indicate a significant modification of the surface layers of metal substrates when applying superhard coatings by the method of contactless electric spark alloying. The conducted studies of hardness by the Vickers microindentation method confirm the results obtained by the dynamic indentation method. Studies were conducted to study the microhardness of the titanium substrate depending on the depth of indenter (Figure 9). According to the obtained results, the microhardness of the surface layers of the original titanium (VT1 alloy) is not a constant value and changes depending on the depth of indenter penetration into the material under study. This dependence of the strength characteristics on the thickness of the surface layer coincides well with the theoretical and practical results associated with the structure of the surface layers of a solid.

The conducted studies on the microhardness of electric spark coatings formed on a titanium substrate made of VT1 alloy show an increase in the microhardness values for all types of formed ESA coatings (Figures 10, 11).

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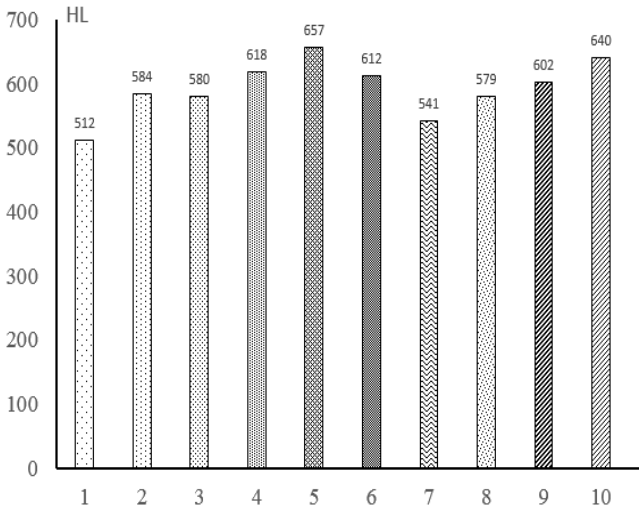


1 – original substrate; 2 – coating No. 2; 3 – coating No. 3; 4 – coating No. 4; 5 – coating No. 5; 6 – coating No. 6; 7 – coating No. 7; 8 – coating No. 8; 9 – coating No. 9; 10 – coating No. 10 (Table 1)

Figure 8 – Hardness values of electrospark coatings formed using contactless technology on titanium substrates

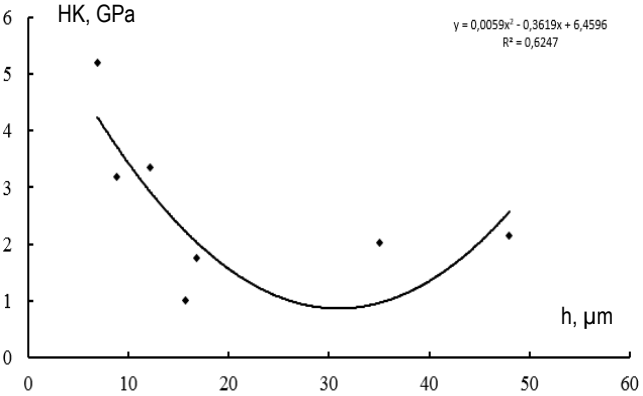
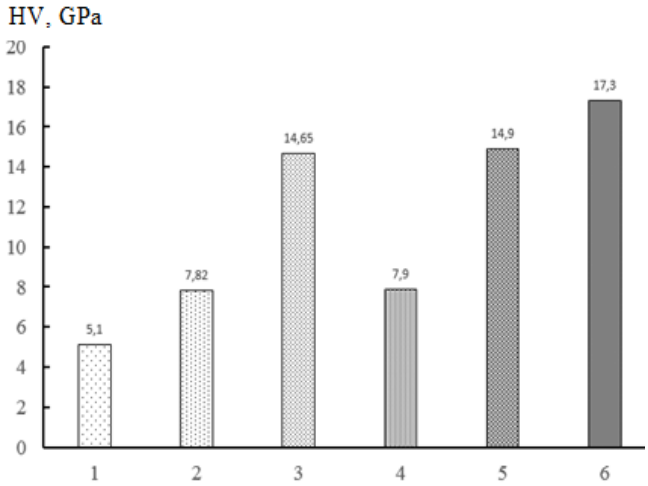


Figure 9 – Dependence of the microhardness of the titanium alloy VT1 on the depth of indenter penetration



1 – VT 1 (original sample); 2 – TiC+Al (0.3 J); 3 – SiO_2 (0.3 J); 4 – Al+C (0.3 J); 5 – Al+C (0.9 J); 6 – Al+C (1.2 J)

Figure 10 – Microhardness values of electrospark coatings formed by contactless technology on titanium substrates

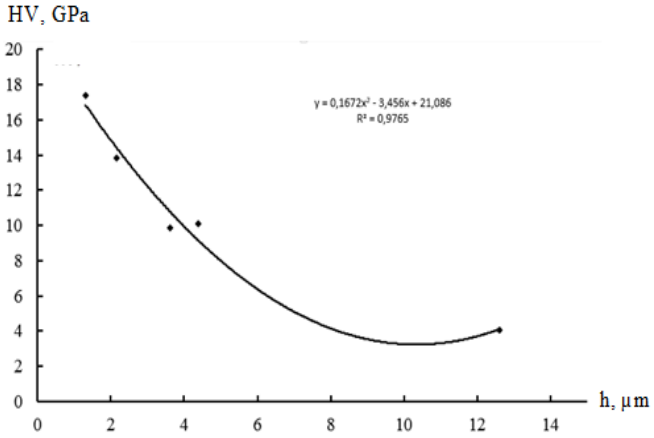


Figure 11 – Dependence of the microhardness of the TiC+Al (0.9 J) electric spark coating formed on the VT1 titanium alloy on the depth of indenter penetration

The dependence of the strength characteristics on the indenter penetration depth, as well as in the case of the control sample, is nonlinear. An extreme point is observed in the region of a coating thickness of 9–10 µm. The strength characteristics of electrospark coatings formed by a contactless method from refractory metals were studied.

Conclusion

The conducted studies have shown that the coatings formed by the ESA method have increased strength and adhesive properties. This effect is due to high values of the physical and mechanical properties of the deposited metals and alloys. The conducted studies to determine the adhesion characteristics using scratch analysis and Rockwell methods have shown that coatings based on TiN+Al compounds are characterized by high values of adhesive strength. This effect is explained by the thermodynamic compatibility of the applied spark coating and the titanium substrate, which ensures good diffusion of the sublayer into the metal base. In TiN+Al coatings, spark deposition can form MAX-phases and high-entropy compounds, which has a positive effect on the physical and mechanical properties of the formed coatings. It is shown that the microhardness values of the studied coatings exceed the values of the original titanium substrates by 2–4 times. The microhardness values depend on the composition of the applied powder materials, as well as the energy of the electric discharge in the area of obtaining the superhard coating.

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References

1. Lazarenko, B. R. Elektroiskrovaya obrabotka tokoprovodyashchih materialov / B. R. Lazarenko, N. I. Lazarenko. – M. : Izd. AN SSSR, 1958. – 184 c.
2. Struktura i adgezionnye harakteristiki elektroiskrovyh pokrytij, poluchaemyh po beskontaktnoj tekhnologii / V. V. Mihajlov [i dr.] // Sovremennye metody i tekhnologii sozdaniya i obrabotki materialov : v 3 kn. : sb. nauch. tr. – Minsk : FTI NAN Belarusi, 2023. – Kn. 1. Materialovedenie. – S. 206–213. – URL: https://elib.grsu.by/doc/104749 (data obrashcheniya: 19.09.2024).
3. Ivanov, G. P. Tekhnologiya elektroiskrovogo uprochneniya instrumentov i detalej mashin / G. P. Ivanov. – Moskva : Mashgiz, 1957. – 188 s.
4. Ovchinnikov, E. V. Tekhnologiya sinteza nanostruktur pri elektroiskrovom legirovanii / E. V. Ovchinnikov, V. V. Mihajlov, N. M. CHekan // Aktual'nye problemy prochnosti: monografiya / pod red. V. V. Rubanika. – Molodechno, 2020. – S. 345–358.
5. Improving Abrasive Wear Resistance for Steel Hardox 400 by Electro-Spark Deposition / E. Katinas, V. Jankauskas, N. Kazak, V. Mikhailov // Journal of Friction and Wear. – 2019. – Vol. 40. – P. 100–106. – DOI: 10.3103/S1068366619010070.

6. Synthesis of Multicomponent Coatings by Electrospark Alloying with Powder Materials / V. Mihailov, N. Kazak, S. Ivashcu [et al.] // Coatings. – 2023. – Vol. 13(3), No. 651. – URL: https://elib.grsu.by/doc/102735 (data obrashcheniya: 01.10.2024).
7. Ovchinnikov, E. V. Elektroiskrovye pokrytiya: struktura, svojstva, tekhnologiya formirovaniya: monografiya / E. V. Ovchinnikov. – Grodno : GrGU im. YAnki Kupaly, 2022. – 254 s. – URL: https://elib.grsu.by/doc/92711 (data obrashcheniya: 04.10.2024).
8. Fiziko-mekhanicheskie harakteristiki additivnyh pokrytij / E. V. Ovchinnikov, A. I. Veremejchik, V. M. Hvisevich [i dr.] // Vestnik Brestskogo gosudarstvennogo tekhnicheskogo universiteta. – 2022. – № 2 (128). – S. 95–99. – DOI: 10.36773/1818-1112-2022-128-2-95-99.
9. Enhancing fatigue life of additive manufactured parts with electrospark deposition post-processing / P. D. Enrique, A. Keshavarzkermani, R. Esmaeilizadeh [et al.] // Additive Manufacturing. – 2020. – Vol. 36. – P. 1–13. – DOI: 10.1016/j.addma.2020.101526.
10. Verhoturov, A. D. Tekhnologiya elektroiskrovogo legirovaniya metallicheskih poverhnostej / A. D. Verhoturov, I. M. Muha – Kiev : Tekhnika. 1982. – 184 s.
11. Rockwell adhesion test – Approach to standard modernization / D. Hatic, X. Cheng, T. Weibel [et al.] // The Gap between Visualization Research and Visualization Software. – 2020. – P. 29–31. – DOI: 10.2312/eurp.20201121.
12. Use of machine learning for automatic Rockwell adhesion test classification based on descriptive and quantitative features. / D. Hatic, X. Cheng, T. Stephani [et al.] // Surface and Coatings Technology. – 2021. – Vol. 427(3), 127762. – DOI: 10.1016/j.surfcoat.2021.127762.
13. Korrozionnaya stojkost' i prochnostnye harakteristiki nanostrukturirovannyh pokrytij, poluchennyh metodom elektroiskrovogo legirovaniya / N. N. Kazak, V. V. Mihajlov, N. M. CHekan [i dr.] // Aktual'nye problemy prochnosti : materialy mezhdunarodnoj nauchnoj konferencii, Vitebsk, 25–29 maya 2020 g. / pod red. V. V. Rubanika. – Molodechno : Tipografiya "Pobeda", 2020. – S. 320–322.
14. Struktura elektroiskrovyh nanokompozicionnyh pokrytij na metallicheskoj matrice / E. V. Ovchinnikov, N. M. CHekan, V. M. Hvisevich [i dr.] // Vestnik Brestskogo gosudarstvennogo tekhnicheskogo universiteta. – 2021. – № 1 (124). – S. 49–53. – DOI: 10.36773/1818-1212-2021-124-1-49-53.
15. Morfologiya pokrytij, formiruemyh beskontaktnym metodom elektroiskrovogo razryada iz tugoplavkih poroshkovyh materialov / G. A. Kostyukovich, V. M. Hvisevich, E. V. Ovchinnikov [i dr.] // Novye tekhnologii i materialy, avtomatizaciya proizvodstva : sbornik statej mezhdunarodnoj nauchno-prakticheskoj konferencii, Brest, 16–17 noyabrya 2023 g. / Brestskij gosudarstvennyj tekhnicheskij universitet ; redkol.: S. R. Onys'ko [i dr.]. – Brest : BrGTU, 2023. – S. 158–162. – URL: https://rep.bstu.by/handle/data/41724 (data obrashcheniya: 04.10.2024).
16. Elektroiskrovye tekhnologii vosstanovleniya i uprochneniya detalej mashin i instrumentov (teoriya i praktika) / F. H. Burumkulov [i dr.]. – Saransk : tipografiya Krasnyj Oktyabr', 2003. – 504 s.
17. Burkov, A. A. Formation and Study of Electrospark Coatings Based on Titanium Aluminides / A. A. Burkov // Journal of Surface Investigation. X-ray, Synchrotron and Neutron Techniques, – 2013.– Vol. 7, № 3. – P. 515–522. – DOI: 10.1134/S1027451013030336.
18. Kuznecov, I. S. Elektroiskrovye pokrytiya iz amorfnogo i nanokristallicheskogo splavov na osnove zheleza / I. S. Kuznecov // Izvestiya vuzov: poroshkovaya metallurgiya i funkcional'nye pokrytiya. – 2016. – № 2. – S. 63–70. – DOI: 10.17073/1997-308X-2016-2-63-70.
19. Vliyanie izotermicheskogo nagreva na sostav i svojstva TI-Al-B-C elektroiskrovyh pokrytij / S. A. Pyachin, A. A. Burkov, B. YA. Mokrickij, N. M. Vlasova // Spravochnik. Inzhenernyj zhurnal s prilozheniem. – 2019. – № 1 (262). – S. 3–8. – DOI: 10.14489/hb.2019.01.pp.003-008.
20. Burkov, A. A. Tribotekhnicheskaya i korrozionnaya harakteristika elektroiskrovyh Fe–Al alyuminidnyh pokrytij na nerzhaveyushchej stali AISI 304 / A. A. Burkov // Trenie i iznos. – 2022. – T. 43, № 4. – S. 361–369. – DOI: 10.32864/0202-4977-2022-43-4-361-369.
21. Vidakis, N. The VDI 3198 indentation test evaluation of a reliable qualitative control for layered compounds / N. Vidakis, A. Antoniadis, N. Bilalis // Journal of Materials Processing Technology. – 2003. – Vol. 143–144 (1). – P. 481–485. – DOI: 10.1016/S0924-0136(03)00300-5.
22. Use of the electrospark alloying method to increase the corrosion resistance of a titanium surface / L. P. Kornienko, G. P. Chernova, V. V. Mihailov [et al.] // Surface Engineering and Applied Electrochemistry. – 2011. – Vol. 47(1). – P. 9−17. – DOI: 10.3103/S106837551101011X.
23. Karimov, R. R. Osobennosti formirovaniya elektroiskrovyh pokrytij iz elektrodnogo materiala STIM 2/40NZH na stali 20H13 / R. R. Karimov, A. E. Kudryashov // Sovremennye problemy gorno-metallurgicheskogo kompleksa. Nauka i proizvodstvo: materialy XVII Vserossijskoj nauchno-prakticheskoj konferencii. – Staryj Oskol : Staroskol'skij tekhnologicheskij institu, 2021. – S. 218–225.

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MICROSTRUCTURE OF RAPIDLY SOLIDIFIED ALLOY Al-1.5 WT.% Pb

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Abstract

Ultra-rapid quenching from the melt makes it possible to obtain a significant refinement of the structural components of alloys, a significant increase in the mutual solubility of components during the formation of solid solutions, and the release of metastable phases. When using the ultrafast quenching method, the cooling rate of the liquid reaches 105 K/s and higher. Aluminum alloys doped with bismuth and lead can be used to generate hydrogen by their interaction with water. During ultra-fast quenching from the melt, a microcrystalline structure is formed containing dispersed precipitates of the second component. Foils of the Al-1.5 wt. % Pb alloy are obtained from a melt droplet weighing approximately 0.3 g, injected onto the inner polished surface of a rapidly rotating copper cylinder, where it spreads and solidifies into a foil. The estimated cooling rate of the melt reached 106 K/s. A cellular structure is formed in the Al-1.5 wt. % Pb foil layer adjacent to the free surface. Dispersed lead particles are located at the cell boundaries and in the cell volume. The shape of the lead particles is close to spherical, which is due to the minimum value of the surface energy of the alloy. Isothermal annealing of rapidly solidified foils of the alloy under study at 295 °C did not have a significant effect on the average diameter of lead particle cross-sections, while annealing at 400 °C caused their monotonous growth. With an increase in the annealing temperature above 400 °C, a stronger growth of lead particles located at the grain boundaries is observed than in the volume of their cells. In rapidly solidified foils of the alloy under study, a (111) texture is formed. This is explained by the fact that in the direction of heat removal, predominantly those grains grow whose {111} planes coincide with the interphase boundary and are parallel to the crystallizer surface.

Keywords: ultra-rapid quenching from melt, rapidly solidified foils of monotectic alloy Al-1.5 wt.% Pb, cellular structure, dispersed lead particles.

МИКРОСТРУКТУРА БЫСТРОЗАТВЕРДЕВШЕГО СПЛАВА Al-1.5 МАСС. % Pb

В. И. Гладковский, Т. Л. Кушнер, Ю. В. Максимов, А. И. Пинчук, В. Г. Шепелевич

Реферат

Сверхбыстрая закалка из расплава позволяет получить существенное измельчение структурных составляющих сплавов, значительное увеличение взаимной растворимости компонентов при образовании твердых растворов, выделение метастабильных фаз. При использовании метода сверхбыстрой закалки скорость охлаждения жидкости достигает 105 К/с и выше. Сплавы алюминия, легированные висмутом и свинцом, могут использоваться для генерирования водорода при их взаимодействии с водой. При сверхбыстрой закалке из расплава происходит формирование микрокристаллической структуры, содержащей дисперсные выделения второго компонента. Фольги сплава Al-1,5 масс. % Pb получены из капли расплава массой примерно 0.3 г, инжектируемой на внутреннюю полированную поверхность быстро вращающегося медного цилиндра, где она растекается и затвердевает в виде фольги. Расчетная скорость охлаждения расплава достигала 106 К/с. В слое фольги Al-1,5 масс. % Pb, примыкающей к свободной поверхности, формируется ячеистая структура. На границах ячеек и в объеме ячеек располагались дисперсные частицы свинца. Форма частиц свинца близка к шарообразной, что обусловлено минимальным значением поверхностной энергии сплава. Изотермический отжиг быстрозатвердевших фольг исследуемого сплава при 295 °С не оказал существенного влияния на средний диаметр сечений частиц свинца, а отжиг при 400 °С вызывает их монотонный рост. С увеличением температуры отжига выше 400 °С наблюдается более сильный рост частиц свинца, находящихся на границах зерен, чем в объеме их ячеек. В быстрозатвердевших фольгах исследуемого сплава образуется текстура (111). Это объясняется тем, что в направлении теплоотвода растут преимущественно те зерна, у которых плоскости {111} совпадают с межфазной границей и параллельны поверхности кристаллизатора.

Ключевые слова: сверхбыстрая закалка из расплава, быстрозатвердевшие фольги монотектического сплава Al-1.5 масс.% Pb, ячеистая структура, дисперсные частицы свинца.

Introduction

Technological processes in metallurgy make it possible to give metals and alloys the required mechanical properties and structure, and to change their physical and chemical properties to achieve the necessary performance characteristics of modern structures and products.

In recent decades, innovative approaches to the development and production of new materials have been actively developing. One of these new scientific directions is the production of metals and alloys from the liquid phase by the method of ultrafast quenching from melt, at which the liquid cooling rate reaches 10^5 K/s and higher. The term "ultra-fast melt quenching" refers to a process operation involving the rapid cooling of the melt.

The use of such a cooling rate leads to the formation of one or another metastable state. The value of this rate depends on both the type of alloy and the nature of metastability. High-speed solidification of materials allows obtaining various states: amorphous, quasi-crystalline and microcrystalline. This type of hardening causes a significant grinding of structural components, a significant increase in the mutual solubility of components during the formation of solid solutions, and the release of metastable phases. To achieve the required cooling rates (10^7 – 10^{10} K/s), technological solutions are required that differ significantly from traditional casting methods. The main method for ultra-fast melt quenching is to cool the melt by removing heat through a solid substrate through thermal conduction.

The main condition for ultra-fast cooling in this case is that the thickness of the melt in the direction of heat transfer should be as small as possible. For effective heat removal, good contact of the melt with the coolant, high thermal conductivity of the coolant, and an increase in the heat transfer coefficient at its boundary with the heat-conducting substrate are also important.

According to the type of cooling, there are three methods of ultra-fast melt quenching: single-sided, double-sided and multi-sided cooling. Single-sided cooling methods involve the injection of droplets or a melt jet on a well-dissipated heat removal substrate. The increase in the contact area is achieved by spreading the drop upon impact with the substrate.

The formation of a thin layer of liquid that is in good thermal contact with the heat receiver is based on the use of contact between the thin liquid belt and the moving cooling substrate. In the spinning method, a drop of molten metal hits the polished surface of a fast-rotating copper cylinder and solidifies in the form of foil.

The structure of rapidly solidified foils differs significantly from the structure of massive samples obtained at low and medium cooling rates, and also has features compared to the structure of rapidly solidified metals with a higher melting point. Micro- and nanocrystalline materials obtained by ultra-fast quenching from the melt have characteristics almost equal to those of amorphous metals and have greater thermal stability. This has generated interest in rapidly cooled alloys with a low melting point. Aluminum-based alloys are quite dependent on the rate and history of cooling and are well modified by annealing, cold working, and other methods of external action.

Alloys of the aluminum-lead system, in which monotectic transformation takes place at 659 °C and eutectic transformation at 327 °C, are used in mechanical engineering as antifriction and damped materials [1, 2, 3]. In alloys of the Al-Pb, Al-Bi, Al-In and other systems, stratification into two liquids occurs, one of which is enriched with aluminum, and the other with an alloying element [3]. There have been reports of the use of aluminum alloys doped with bismuth and lead to generate hydrogen when interacting with water [4, 5]. Studies have been carried out on the interaction of aluminum with water at high pressures and temperatures in order to produce hydrogen [6–10]. In recent decades, research has been actively carried out on materials synthesized under highly non-equilibrium conditions, for example, during ultrafast melt quenching, when the cooling rate reaches 10^6 K/s [11–13]. Studies of the influence of external energy influences, in particular, a weak magnetic field, on the physical and mechanical properties of non-magnetic metals are also being actively investigated [14, 15]. In case of ultra-rapid quenching, a microcrystalline structure is formed, containing dispersed precipitates of the second component. It has been established that rapidly solidified alloys of the Al-Bi system interact with water at room temperature and normal atmospheric pressure, forming aluminum oxides and generating hydrogen [15, 16], which can be used immediately after its release. In this regard, the study of the structure and properties of rapidly solidified foils of the monotectic alloy Al-1.5 wt.% Pb, as well as their stability, is relevant and has scientific and practical significance.

Experimental methods

Monotectic alloy Al-1.5 wt. % Pb is made by fusing the components in a quartz ampoule. The purity of the components used is 99.99. The foils are obtained from a drop of melt weighing ≈ 0.3 g, injected onto the inner polished surface of a rapidly rotating copper cylinder, where it spreads and solidifies into a foil [17]. In the study of the structure, fast-hardened foils with a thickness of 40–70 μm were used. The estimated cooling rate of the melt reached 10^6 K/s. The study of the structure of the foils was carried out on a LEO 1455VP scanning electron microscope with a special "HKL CHANNEL 5" attachment. X-ray spectral microanalysis of rapidly solidified alloy foils was carried out using a Rontec detector. X-ray structural studies were performed on the Ultima 1V diffractometer using copper radiation. The pole densities of the diffraction lines of the inverse polar figures were calculated using the Harris method [18]. The parameters of the microstructure (grain size and specific surface energy of grain boundaries) were determined by the method of random secant cross-sections of grains [19]; the measurement error was 5–8 %. The microhardness of the foils was measured using a microhardness tester using a load of 3 g.

Results and discussion

To study the structure and properties, rapidly solidified foils were used, the length and width of which reached 10 and 1 cm, respectively. Micron-sized cavities were observed on the mirror surface (A) of the foil in contact with the crystallizer. Due to the decrease in heat transfer in this area of the foil, the cooling rate of the melt decreased, which led to the appearance of lead particle precipitation on the surface of the cavities. The opposite surface of the rapidly solidified foil (B) had a bumpy structure. A cellular structure was observed on it (Figure 1); the size of the cell cross-sections varied in the interval from 2 to 8 μm. Dispersed lead particles were located at the cell boundaries and in the cell volume.

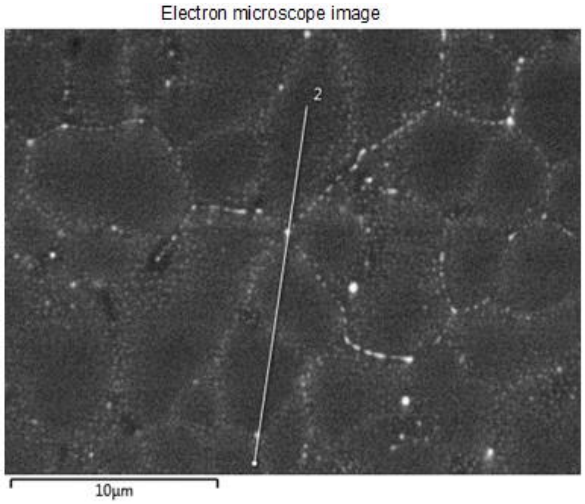
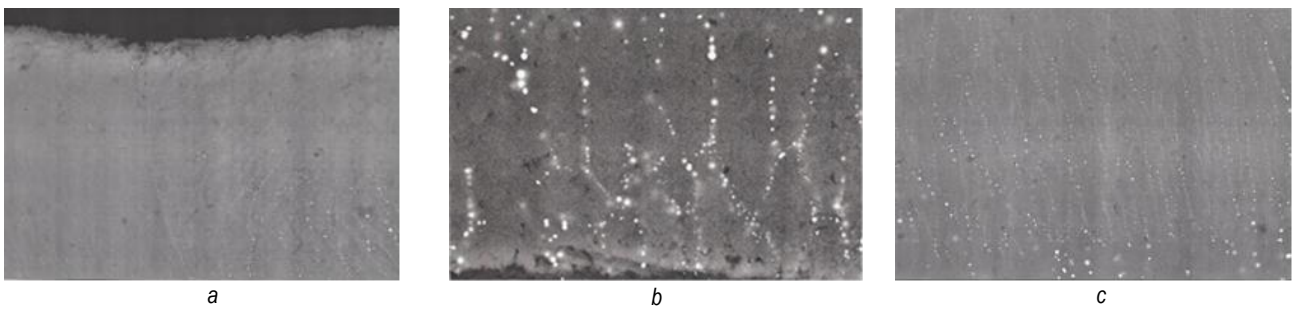


Figure 1 – Cellular structure of surface B of rapidly solidified Al-1.5 wt.% Pb alloy foil

The cross-sectional image of the rapidly solidified Al-1.5 wt.% Pb alloy foil is shown in Figure 2. Layers *a* and *b* are adjacent to the foil surfaces A and B, respectively, and layer *c* is located in the middle part of the foil. Layer *a* has more dispersed lead particles than layers *b* and *c*. As the crystallization front moves from surface A to B, enlargement of lead particles is observed, which is associated with a decrease in supercooling of the liquid phase. The shape of lead particles is close to spherical, which is due to the minimum value of the surface energy of the alloy [20].



a *b* *c*

Figure 2 – Cross-sectional microstructure of Al-1.5 wt.% Pb alloy foil. (*a*, *b* are the foil layers adjacent to its surfaces A and B, respectively, *c* is the middle part of the foil)

https://doi.org/10.36773/1818-1112-2024-135-3-81-84

Distributions of cross-section diameters of lead particles of the Al-1.5 wt.% Pb alloy by size groups in layers *a*, *b* and *c* are characterized by the presence of a maximum. The average size of lead precipitates in the foil increases as the crystallization front moves. The structure of foils and massive samples was compared. In massive samples obtained at cooling rates of 10^{-2} and 10^{2} K/s, the average size of lead particles is 15 and 1.2 μm, respectively, and in layers *a*, *b*, and *c* of rapidly solidified foils, 0.11, 0.13, and 0.15 μm, respectively.

Isothermal annealing of quickly solidified foils of the alloy under study was performed for eight hours at temperatures below and above the melting point of lead. Annealing at 295 °C did not have a significant effect on the average diameter of lead particle cross-sections, while annealing at 400 °C caused their monotonous growth.

During high-speed solidification, due to significant supercooling of the melt, lead atoms are "captured" by aluminum precipitates. According to the data of work [21], devoted to the study of the effect of supercooling on the decomposition of a supersaturated aluminum-lead solution, it was found that when the melt is supercooled by more than 20 °C, lead nanoclusters are formed in it. During high-speed cooling of the melt [12], supercooling in the layer adjacent to the crystallizer surface reaches 200 °C, which promotes the formation of dispersed lead deposits. When the crystallization front moves from surface A to surface B, due to the release of heat during crystallization, the value of supercooling of the liquid phase decreases, which causes an increase in lead deposits and the formation of a cellular structure.

When the alloy is cooled below the eutectic temperature, the remaining lead-rich liquid undergoes a eutectic transformation, which produces lead and aluminum precipitates. The aluminum precipitates are adjacent to the previously solidified aluminum. Lead deposits are located at the grain boundaries of the main component; they are larger compared to previously formed lead particles and localized at the cell boundaries and inside them. This difference is 2–4 times.

Rapidly solidified foils of the monotectic Al-1.5 wt.% Pb alloy have a microcrystalline structure. Figure 3 shows images of the grain structure on the A side of the foil.

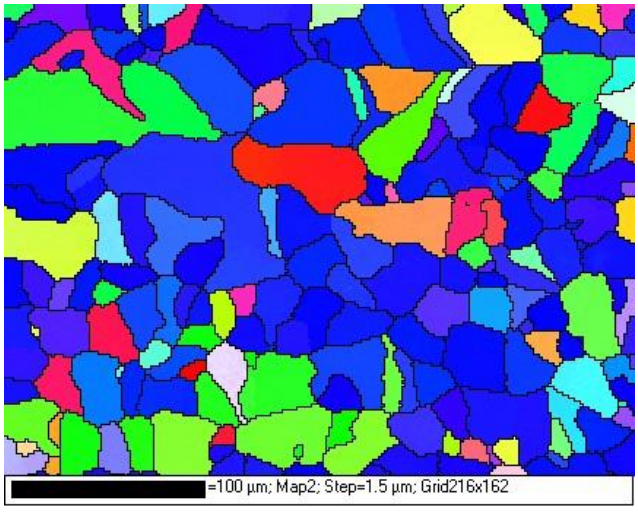


Figure 3 – Grain structure of rapidly solidified Al-1.5 wt.% Pb alloy foil on surface A.

The random intercept method was used to determine the distribution of chords on grain cross-sections by size groups and presented as histograms in Figure 4. The maximum proportion of chords falls on the size group from 20 to 40 μm. The parameters of the grain structure were determined. The average values of the chord lengths on grain cross-sections on surfaces A and B are 31 and 30 μm, respectively. The average value of the grain size is 52 and 50 μm, respectively. The specific surface area of the grain boundaries is 120 μm^{-1}.

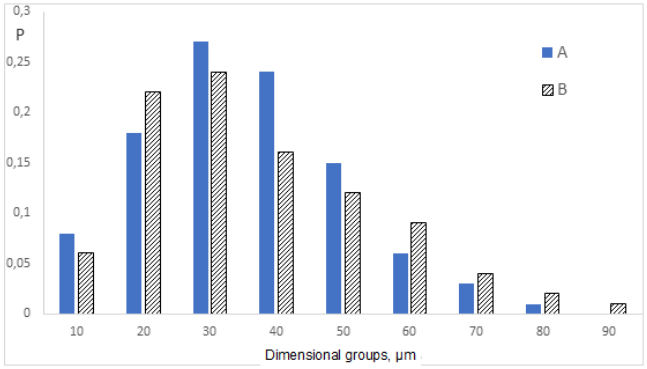


Figure 4 – Histogram of the distribution of chords of random secants on the sections of grains of rapidly solidified foils of the Al-1.5 wt.% Pb alloy in the initial state on the surface A (a) B (b)

In rapidly solidified foils of the alloy under study, a preferred grain orientation is formed. Figure 5 shows the pole figures of the {111} planes of aluminum on the surface of foil A. Gnomostereographic projections of the {111} planes of aluminum are located predominantly in the center of the projection circle or at a small distance from it, which indicates the formation of the {111} texture. A weaker similar texture is formed in the foil layer adjacent to the free surface, i. e. the texture of the rapidly solidified foil {111} is retained as the crystallization front moves.

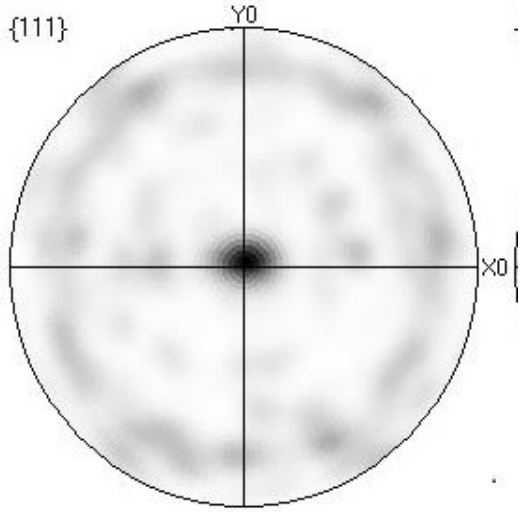


Figure 5 – Pole figure of the gnostereometric projections of the {111} planes of the aluminum foil of the Al-1.5 wt.% Pb alloy on the surface A

The formation of aluminum texture (111) in rapidly hardened foils is confirmed by the calculation of the inverse pole densities of aluminum diffraction lines presented in Table 1. Pole densities were calculated using the Harris method. Texture formation (111) has been observed previously in fast-hardened foils of other aluminum alloys with other elements [22, 23].

Table 1 – Pole densities of diffraction lines of rapidly solidified foils of Al-1.5 wt.% Pb alloy

Diffration reflections	Annealing temperature, °C				
	20 °C	180 °C	350 °C	470 °C	600 °C
200	0,2	0,2	0,3	0,2	0,2
220	0,5	0,4	0,4	0,4	0,4
311	0,3	0,4	0,3	0,3	0,3
222	4,7	4,7	4,6	4,7	4,7
331	0,2	0,2	0,2	0,2	0,2
429	0,1	0,1	0,2	0,2	0,2

The rationale for the formation of the (111) texture in aluminum is given in [24, 25], which presents the results of calculating the energy barrier during the movement of the crystal-liquid interphase boundary for various crystallographic planes. It has been established that its value takes a minimum value for the interphase boundary coinciding with the {111} planes. Therefore, in the direction of heat removal, predominantly those grains grow whose {111} planes coincide with the interphase boundary, i. e. are parallel to the crystallizer surface, thereby forming the (111) texture.

A study was conducted on the effect of annealing on the texture of the foils of the alloy under study. It was found that in the annealing temperature range from 20 to 600 °C, the pole densities of diffraction reflections change by no more than 0.1, i. e. the texture of rapidly solidified foils is preserved, which may be due to the presence of liquid dispersed lead deposits at the grain boundaries.

Rapidly solidified foils of the investigated Al-1.5 wt.% Pb alloy are in an unstable state. Thus, holding rapid solidified foils at room temperature for 2 hours leads to an increase in microhardness by 20 %, which is explained by the decomposition of the supersaturated solid solution based on aluminum, causing the release of strengthening dispersed lead particles.

A subsequent increase in the exposure of foils at room temperature does not change their microhardness. However, with an increase in the annealing temperature above 400 °C, there is a stronger growth of lead particles located at the grain boundaries than in their cell volume (Figure 6). Most likely, this is due to the fact that the diffusion processes that cause the movement of lead atoms in the area of grain boundaries proceed more intensively than in their volume at the same annealing temperature.

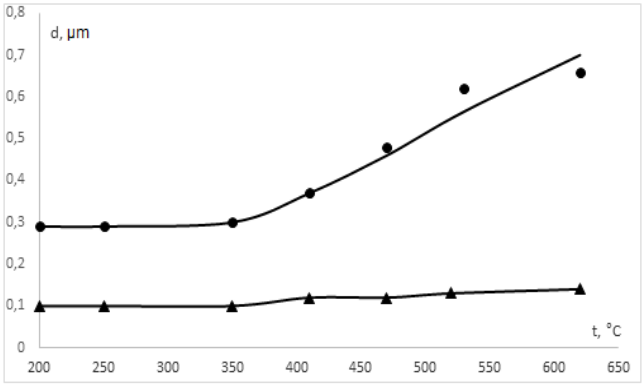


Figure 6 – Dependence of the average diameter of lead particles of the Al-1.5 wt.% Pb alloy located at grain boundaries (1) and in the bulk of cells (2) on the annealing temperature

Conclusions

Thus, a cellular structure is formed in the Al-1.5 wt. % Pb foil layer adjacent to the free surface. The size of the cell sections varied in the range from 2 to 8 μm. The diameter of the lead particle cross-sections increases monotonically with the movement of the crystallization front from 0.1 to 0.3 μm. The average grain size in the foils is 51 μm, and the specific surface area of the grain boundaries is 120 μm^{-1}. In rapidly solidified foils of the alloy, a (111) texture is formed. Annealing the foils above 400°C causes a decrease in the density of lead particles and an increase in the diameter of their cross-sections. The texture of the foils of the 1.5 mass. % Pb alloy is retained upon annealing up to 600 °C.

References

1. Troickij, O. A. Fizicheskie osnovy i tekhnologii obrabotki sovremennyh materialov : v 2 t. / O. A. Troickij, YU. A. Baranov, YU. D. Avraamov. – Moskva–Izhevsk, 2004. – T. 1. – 468 s.
2. Avraamov, YU. S. Splavy na osnove sistem s ogranichennoj rastvorimost'yu v zhidkom sostoyanii (teoriya, tekhnologiya, struktura, svojstva) / YU. S. Avraamov, A. D. SHlyapin. – M. : Interkontakt nauki, 2002. – 371 s.
3. Lyakishev, N. P. Diagrammy sostoyaniya dvojnyh metallicheskih system : spravochnik / pod obshchej red. N. P. Lyakisheva. – M. : Mashinostroenie, 1996. – T. 1. – 992 s.
4. Patent US 20080063597 : Power Generation from Solid Aluminum / M. J. Woodall, T. Z. Jeffrey, R. A. Charles. – 2008.
5. Patent RU 2356830C2, MPK C01B 3/08 (2006.01). Sposob polucheniya vodoroda : № 2007123715/15 : zayavleno 26.06.2007 : opubl. 27.05.2009 / K. N. Koshkin, V. V. Semenov, G. V. Seropyan, K. H. Urusov. – 2009. – 5 s.
6. Patent RU 2606449, MPK 2 606 449(13)C2. Sposob aktivacii alyuminiya dlya polucheniya vodoroda : № 2014143582 : zayavleno 29.10.2014 : opubl. 10.01.2017 / E. I. SHkol'nikov, I. N. Atmanyuk, A. V. Dolzhenko, I. V. YAkilkin. – 2017. – 1 s.
7. Liquid Phase-enabled Reaction of Al-Ga and Al-In-Sn Alloys with Water / J. T. Ziebarth, M. J. Woodall, R. A. Kramer, Go Choi // International Journal of Hydrogen Energy. – 2011. – No. 36(9). – P. 5271–5279. – DOI: 10.1016/j.ijhydene.2011.01.127.
8. Kinetika i mehanizm corozionnogo rastreskivanija aluminija / L. F. Kozin, S. V. Volkov, S. G. Goncharenko [i dr.] // Ukrainiskii chemicheskii Zhurnal. – 2009. – Vol. 75, No. 11. – S. 3–11.
9. Kinetika i mehanizm vzaimodejstvija s vodoj aluminija i magnija / L. F. Kozin [et al.] // Physicahemija poverhnosti i zashchita materialov. – 2011. – Vol. 47, No. 2. – S. 144–153.
10. Kudryasheva, O. B. Opredelenie optimal'nyh parametrov reakcij polucheniya vody na osnove okisleniya nanoporoshka alyuminiya / O. B. Kudryasheva // YUzhno-Sibirskij nauchnyj zhurnal. – 2017. – № 4 (20). – S. 43–47.
11. Salli, I. V. Kristallizaciya pri sverhvysokih skorostyah ohlazhdeniya / I. V. Salli. – Kiev : Navukova dumka,1972. – 136 s.
12. Miroshnichenko, I. S. Zakalka iz zhidkogo sostoyaniya / I. S. Miroshnichenko. – M. : Metallurgiya, 1982. – 168 s.
13. Dobatkin, V. I. Bystrozakristallizovannye alyuminievye splavy / V. I. Dobatkin, V. I. Elagin, V. M. Fedorov. – M. : VILS, 1995. – 341 s.
14. Pinchuk, A. I. Plastifikaciya monokristallov vismuta pri odnovremennom nalozhenii elektricheskogo i magnitnogo polya / A. I. Pinchuk, V. S. Savenko, S. D. SHavrej // Izvestiya Akademii Nauk. Seriya fizicheskaya. – 1997. – T. 61, № 5. – S. 932–936.
15. Shavrei, S. D. A decrease in the mobility and multiplication of twinning dislocations in bismuth crystals exposed to constant magnetic field / S. D. Shavrei, A. I. Pinchook // Technical Physics Letters. – 2003. – Vol. 29, No 8. – P. 632–633. – DOI: 10.1134/1.1606770.
16. Shepelevich, V. G. Structure of rapidly solidified Al – (0,25 – 2,0) wt. % Bi alloys / V. G. Shepelevich // Inorganic Materials. Applied Research. – 2023. – Vol. 3. – P. 720–723.
17. SHepelevich, V. G. Poluchenie vodoroda pri vzaimodejstvii bystrozatverdevshih fol'g splava iz alyuminievogo loma i vismuta s vodoj / V. G. SHepelevich // Fizika i himiya obrabotki materialov. – 2024. – № 3. – S. 49–55.
18. SHepelevich, V. G. Bystrozatverdevshie legkoplavkie splavy / V. G. SHepelevich. – Minsk : BGU, 2015. – 192 s.
19. Vasserman, G. Tekstury metallicheskih materialov / G. Vasserman, I. Greven. – M. : Metallurgiya, 1969. – 655 s.
20. Salticov, S. A. Stereometricheskaja metallografija / S. A. Salticov. – M. : Metallrgija, 1976. – 272 s.
21. Sheng, H. W. Melting and freezing behaviors of Pb nanoparticles embedded in an Al matrix / H. W. Sheng, Z. Q. Hu, K. Lu // Nanostructured Mater. – 1997. – Vol. 9, Is. 1–8. – P. 661–664. – DOI: 10.1016/S0965-9773(97)00145-1.
22. Gabrisch, Heika. Equilibrium shape and interface roughening of small liquid Pb inclusion in solid Al / Heika Gabrisch, L. Kjeldgard, E. Johnson, Ulrich Dahman // Acta Materialia. – 2001. – Vol. 49(20). – P. 4259–4264. – DOI:10.1016/S1359-6454(01)00307-X.
23. Neumerzhickaya, E. YU. Struktura, svojstva i termicheskaya stabil'nost' bystrozatverdevshih fol'g splavov alyuminiya s hromom, nikelem i margancem / E. YU. Neumerzhickaya, V. G. SHepelevich // Perspektivnye materialy. – 2005. – № 4. – S. 69–73.
24. Sivcova, P. A. Bystrozatverdevshie splavy alyuminiya s perekhodnymi metallami / P. A. Sivcova, V. G. SHepelevich. – Minsk : RIVSH, 2013. – 176 s.
25. Li, D. Y. A possible rule for surface packing density in the formation of (111) texture in solidified FCC metals / D. Y. Li, I. A. Szpunur // Journal of Materials Science Letters. – 1994. – Vol. 13, No 21. – P. 1521–1523. – DOI: 10.1007/bf00626496.

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MODELLING PHOTOSYNTHETICALLY ACTIVE RADIATION IN BELARUS

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Abstract

This research considers indirect methods for modelling values of photosynthetically active radiation (PAR) from shortwave radiation data in the Republic of Belarus. The authors performed calculation and modelling in three models. Model 1 (the Ross and Tooming formula) is a universal one and does not take into account the area latitude. The PAR coefficient (qf) here is 52 % of the shortwave radiation. Models 2 and 3 were proposed by the Meteorological Observatory of Moscow State University and applied to the territory of Belarus. One of them was adjusted for Belarus area particularly. The results of calculation by model 2 show that the PAR coefficient (qf) for Belarus is 46–47 % of the shortwave radiation at different times of the year. Thus, PAR ranges from 1500 MJ/m^2 to 1600 MJ/m^2 around Belarus in the vegetation period. The PAR values calculated in the third model range from 1540 MJ/m^2 in Vitebsk and Braslav to 1630 MJ/m^2 in the area of the Polesskaya station. In central Belarus, PAR is 1560–1580 MJ/m^2. The comparison analysis of the modelling results with each other and the results of similar research in the neighboring countries shows advantages and drawbacks of the models under consideration. The calculation results are visualized on the maps created by the authors to show the distribution of photosynthetically active radiation over the territory of Belarus. The spatial distribution of PAR across the territory of Belarus goes in the direction from northwest to southeast.

Keywords: photosynthetically active radiation, shortwave radiation, modelling, spatial distribution of PAR, Belarus.

МОДЕЛИРОВАНИЕ ФОТОСИНТЕТИЧЕСКИ АКТИВНОЙ РАДИАЦИИ В УСЛОВИЯХ РЕСПУБЛИКИ БЕЛАРУСЬ

О. П. Мешик, М. В. Борушко

Реферат

В работе рассматриваются косвенные методики моделирования значений суммарной фотосинтетически активной радиации (ФАР) на основе данных о суммарной коротковолновой радиации в Республике Беларусь. Выполнены расчеты и моделирование по трем моделям. Универсальная модель 1 (формула Росса-Тооминга) не учитывает широту местности. Коэффициент ФАР (q_f) по формуле Росса-Тооминга составляет 52 % от коротковолновой радиации. Модели 2 и 3 предложены специалистами Метеорологической обсерватории Московского государственного университета и применены к территории Республики Беларуси. Одна из них адаптирована авторами именно для территории Беларуси. Результаты расчета по модели 3 показывают, что коэффициент ФАР (q_f) для Беларуси составляет 46–47 % от коротковолновой радиации в разное время года. Таким образом, ФАР колеблется от 1500 МДж/м^2 до 1600 МДж/м^2 по территории Беларуси в течение вегетационного периода. Величины ФАР, рассчитанные по третьей модели, варьируются от 1540 МДж/м^2 в Витебске и Браславе до 1630 МДж/м^2 в районе станции Полесская. В центральной части Беларуси ФАР составляет 1560–1580 МДж/м^2. Сравнительный анализ полученных результатов между собой и с подобными исследованиями в соседних регионах выявил преимущества и недостатки исследуемых моделей. Полученные результаты вычислений визуализированы на картах, построенных авторами с целью наглядной демонстрации распределения суммарной фотосинтетически активной радиации на территории Республики Беларусь. Пространственное распределение фотосинтетически активной радиации по территории Беларуси идет в направлении с северо-запада на юго-восток.

Ключевые слова: фотосинтетически активная радиация, коротковолновая радиация, моделирование, пространственное распределение ФАР, Беларусь.

Introduction

Most biochemical processes in living nature, including photosynthesis, occur thanks to solar radiation. Chlorophyll molecules in plants are activated by quanta not of the entire spectrum of sunlight but only of the blue-violet and orange-red parts which are called photosynthetically active radiation (PAR). Its wavelength ranges from 400 to 700 nm (Figure 1).

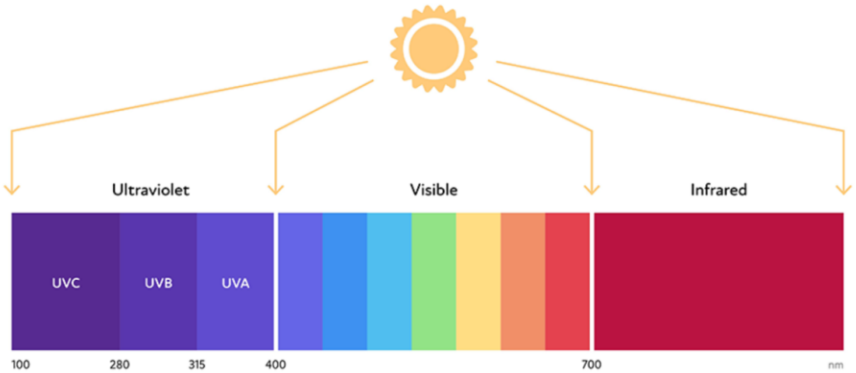

Figure 1 – Sunlight spectrum, PAR

Data on PAR are sought after in agricultural engineering, plant growing, forestry and other industries. It is necessary to know PAR values to study the productivity of vegetation, and therefore to forecast and possibly increase crop yields in different areas by using different agricultural techniques. Organic substances generated during photosynthesis make up 90–95 % of dry plant biomass. Therefore, the main way to increase crop yields is to increase the photosynthetic productivity of plants and the PAR utilization coefficient, for instance, by supplementary lighting of plants in agricultural seedling production [1] or creating optimum conditions for growing plants in greenhouses [2, 3]. Data on direct, diffuse and total radiation are used not only in agriculture, agrometeorology and hydrometeorology but also in industries such as construction, utilities, solar engineering, healthcare, fisheries, peat extraction and refrigeration.

Researchers worldwide are developing empirical PAR models that can satisfactorily predict PAR at different locations [4]. The models are different for different climates. The authors propose to use easily observable meteorological parameters [5–8].

Knowing the inflow of PAR in a certain area allows calculating the value of the potential biomass of plants in the area. A. A. Nichiporovich [9] developed a method to calculate a potential yield. It includes the inflow of PAR and a coefficient of its utilization. His approach has become widespread. The potential yield of absolutely dry mass is determined by the formula

$$y = \frac{\sum Q_p * K}{10^5 * g}, \quad (1)$$

where Y is a biological yield of absolutely dry plant mass, t/ha; $\sum Q_p$ is the amount of PAR during the vegetation period of a crop in a certain area, billion kcal/ha; K is a designed utilization coefficient of PAR, %; g is the amount of energy released when 1 kg dry plant biomass is burnt, kcal/ha; 10^5 is conversion of kg to tons.

Although there are attempts to learn how to measure PAR by instrumental methods [10], for practical purposes it makes sense to model the PAR values in a certain area (farm) based on the data on shortwave solar radiation observed at the nearest actinometric station. In the Republic of Belarus, solar radiation observations are carried out only at three meteorological stations: Minsk, Vasilevichi, and Polesskaya. The database with their actinometric observations is stored in the Republican Hydrometeorological Centre.

Modelling PAR

The sums of shortwave radiation registered at weather stations can be converted into the sum of PAR ($\sum Q_{PAR}$) using the Ross and Tooming formula developed in the 1960s by Estonian scientists with theoretical calculations of the energy in the solar radiation spectrum [11]:

$$\sum Q_{PAR} = 0{,}4225 \sum S + 0{,}582 \sum D, \quad (2)$$

where $\sum S$ is the sum of direct solar radiation, $\sum D$ is the sum of diffuse solar radiation.

Later it became clear that it is more expedient to use a single coefficient q_f to estimate the total PAR instead of two individual ones for direct and diffuse radiation. Moreover, there are difficulties in accessing data on direct and diffuse radiation therefore the method of modelling Q_{PAR} by the total shortwave radiation Q has become widespread [11]:

$$\sum Q_{PAR} = 0{,}52 \sum Q. \quad (3)$$

Since actinometric observation over shortwave radiation in Belarus is performed only at a few meteorological stations and these measurements are not enough to receive better differentiated values of PAR for the rest of the country, it becomes necessary to calculate the values of total Q for the entire territory of the republic [12]. There are various empirical models for calculating solar radiation values based on more easily accessible meteorological parameters, such as cloudiness, sunshine duration, and ambient temperature. In this study, we used the method described in [13] to model monthly amounts of total shortwave radiation in Belarus. Table 1 presents the results of the calculation performed. Figure 2 shows a spatial distribution of yearly sums of total shortwave radiation in Belarus [14].

Table 1 – Total shortwave radiation in Belarus (Q), MJ/m^2

	January	February	March	April	May	June	July	August	September	October	November	December	Year
Brest Region													
Brest	73	143	291	431	576	618	610	500	341	206	94	51	3933
Polesskaya	61	133	281	422	567	607	596	483	323	188	79	39	3909
Pruzhany	60	129	277	419	566	609	560	487	326	190	81	38	3782
Vitebsk Region													
Vitebsk	46	116	266	416	573	622	609	487	318	177	67	25	3719
Verhnedvinsk	54	125	277	427	585	633	621	498	328	187	75	32	3840
Lepel	55	125	277	425	580	628	617	496	328	187	76	34	3828
Gomel Region													
Gomel	71	140	288	429	575	618	610	499	389	203	92	49	3912
Vasilevichi	72	141	290	430	574	614	606	497	339	204	93	51	3910
Bragin	76	145	294	432	576	617	610	501	343	208	97	54	3953
Grodno Region													
Grodno	59	129	278	422	573	619	610	494	330	191	80	37	3822
Oshmyany	56	145	277	423	577	623	612	493	327	188	77	35	3833
Lida	57	127	276	421	573	619	610	493	328	189	78	36	3808
Mogilev Region													
Mogilev	57	127	277	422	574	619	609	492	327	188	78	35	3805
Gorki	56	127	278	423	576	622	611	493	327	188	77	35	3814
Minsk Region													
Minsk	58	127	276	420	571	615	607	494	329	190	80	37	3804
Soligorsk	60	129	276	419	566	608	599	487	326	190	81	39	3778
Borisov	57	127	277	423	576	622	611	493	327	188	77	35	3812

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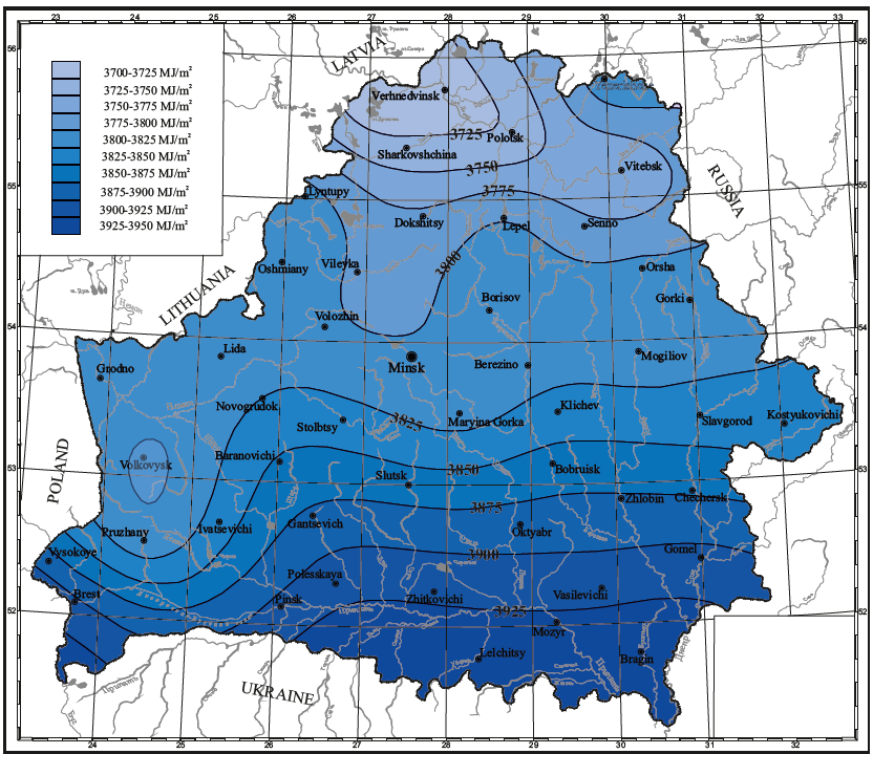

Figure 2 – Total shortwave radiation in Belarus (Q), MJ/m²

Comparison of the calculated values of total shortwave radiation with those measured at the Minsk and Vasilevichi stations shows a sufficiently high convergence in the results [13], which allows us to apply the theoretical model for calculating integral radiation *Q* at any geographic point in Belarus with errors that do not exceed instrumental measurements. A discrepancy of 20–40 MJ/m² per month is observed in the summer months [15, 16]. We consider such a discrepancy in *Q* values to be insignificant for the warm season. The results of modelling the *Q* values are presented in Figure 3 as a map of spatial distribution of the total annual shortwave radiation in the territory of the Republic of Belarus. The modelling considers the total shortwave radiation for the vegetation period with the average daily air temperature of over 5°C, i. e. from April to October.

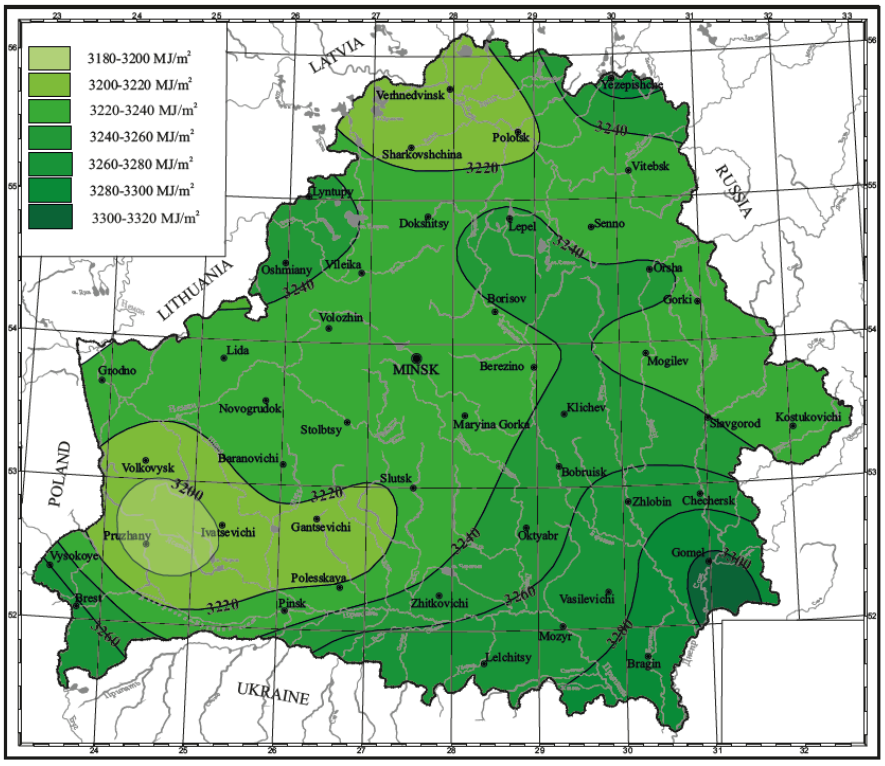

Figure 3 – Total shortwave radiation in April-October, MJ/m²

Figures 2 and 3 show that the isolines of the total shortwave radiation do not have a strict latitude direction. The radiation grows from the northwest to the southeast. Thus, the values of the total shortwave radiation in the warm season range from 3200 MJ/m^2 in Pruzhany and Verkhnedvinsk to 3320 MJ/m^2 in Gomel.

In this study, calculation of total PAR (Q_{PAR}) was performed with the use of 3 models. All of them are based on total shortwave radiation data. The calculation results of all the three models are presented selectively in Table 2.

Table 2 – PAR values calculated in the models under study, MJ/m^2

	Model 1	Model 2	Model 3
Brest	1706	1551	1589
Vitebsk	1664	1512	1545
Gomel	1702	1547	1584
Grodno	1684	1530	1566
Minsk	1678	1525	1560
Mogilev	1680	1527	1562

The 1st theoretical model ($Q_{PAR} = 0,52Q$) is mentioned above [11]. The modelling results are depictured in Figure 4.

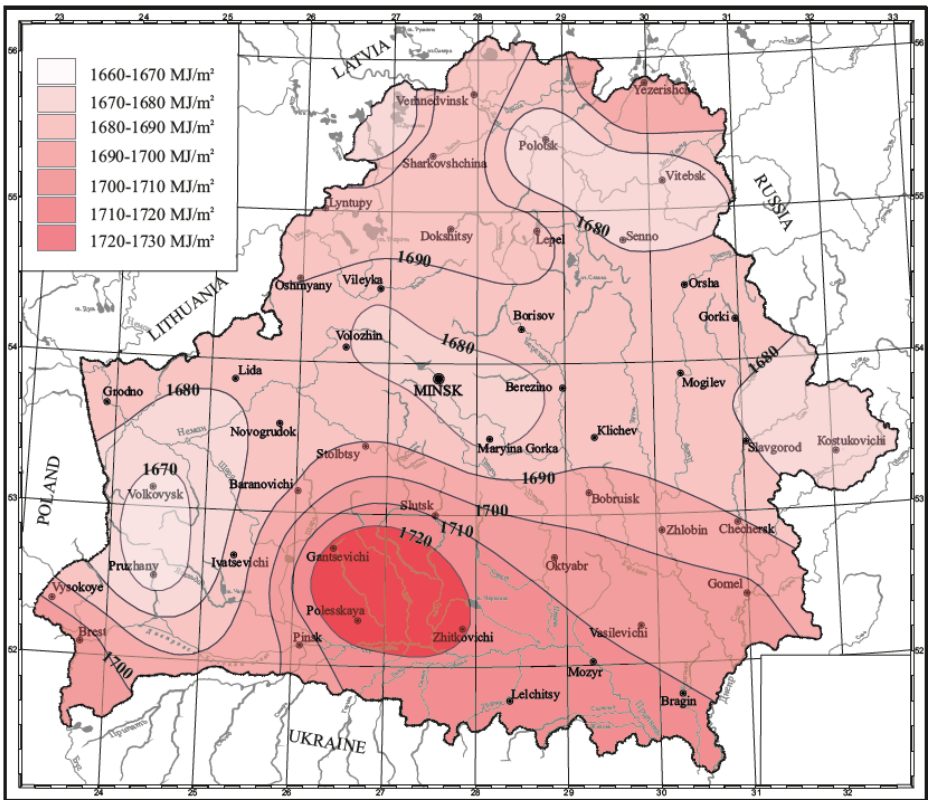

Figure 4 – Total PAR calculated in model 1 (April-October), MJ/m^2

The other two models were developed by the Meteorological Observatory of Moscow State University based on data on total integral radiation [17]. In order to get more accurate values of PAR using the model $Q_{PAR} = q_f Q_{ir}$, the authors propose calculating a more accurate transition coefficient of PAR (q_f) for specific geographic points using the formula [17]:

$$q_f = 0,451 - 0,0217(\sin h)^2 + 0,0449\sin h, \quad (4)$$

where h is the sun elevation at noon.

According to formular 4, the PAR coefficient (q_f) for Belarus is 46–47 % of the shortwave radiation at different times of the year. Thus, PAR ranges from 1500 MJ/m^2 in Volkovysk to 1600 MJ/m^2 at Polesskaya station in the vegetation period (Figure 5). As we can see, the PAR values calculated by the formula $Q_{PAR} = q_f Q_{ir}$ with the transition coefficient $q_f = 0.46\text{-}0.47$ adjusted for the territory of Belarus are naturally lower than those calculated by the traditional formula $Q_{PAR} = 0.52Q$. The spatial distribution of the total PAR, modelled by the formula $Q_{PAR} = q_f Q_{ir}$, MJ/m^2, is shown in Figure 5.

The third model applied in this study was also developed by the researchers at the Moscow State University Meteorological Observatory. They propose modelling the total PAR for the warm season of the year using the formula [17]:

$$Q_{PAR} = 0,4424\exp(0,1148\sin h) Q_{ir}, \quad (5)$$

where h is the sun elevation at noon, Q_{ir} is the sum of integral irradiance per day.

The authors claim that the calculation error is 6–8 %, which is even less than the error in measuring PAR instrumentally.

Modelling of PAR with model 3 is presented in Figure 6. The spatial distribution of PAR across the territory of Belarus goes in the same direction from northwest to southeast, which is not surprising, since all the three models (Figures 4–6) are based on the values of total shortwave radiation and correlate with its spatial distribution (Figure 2 and 3). However, the PAR values here are somewhat higher than in model 2 ($Q_{PAR} = q_f Q_{ir}$) where $q_f = 0.46–0.47$ for the territory of Belarus.

The PAR values calculated in the third model (formular 5) range from 1540 MJ/m^2 in Vitebsk and Braslav to 1630 MJ/m^2 in the area of the Polesskaya station. In central Belarus, PAR is 1560–1580 MJ/m^2.

Comparison of the modelling results shows that the PAR values in the first model (formular 3) are somewhat overestimated. The calculation results in models 2 and 3 are more accurate since they take into account the sun elevation, i. e. the latitude of the area. Moreover, comparing the modelling results with similar studies in neighbouring regions [18–20], namely Ukraine, shows that the results of models 2 and 3 are consistent with the data of the study [18–19] where Q_{PAR} in the north of Ukraine (Kovel, Boryspil) on the border with Belarus is 1650–1670 MJ/m^2.

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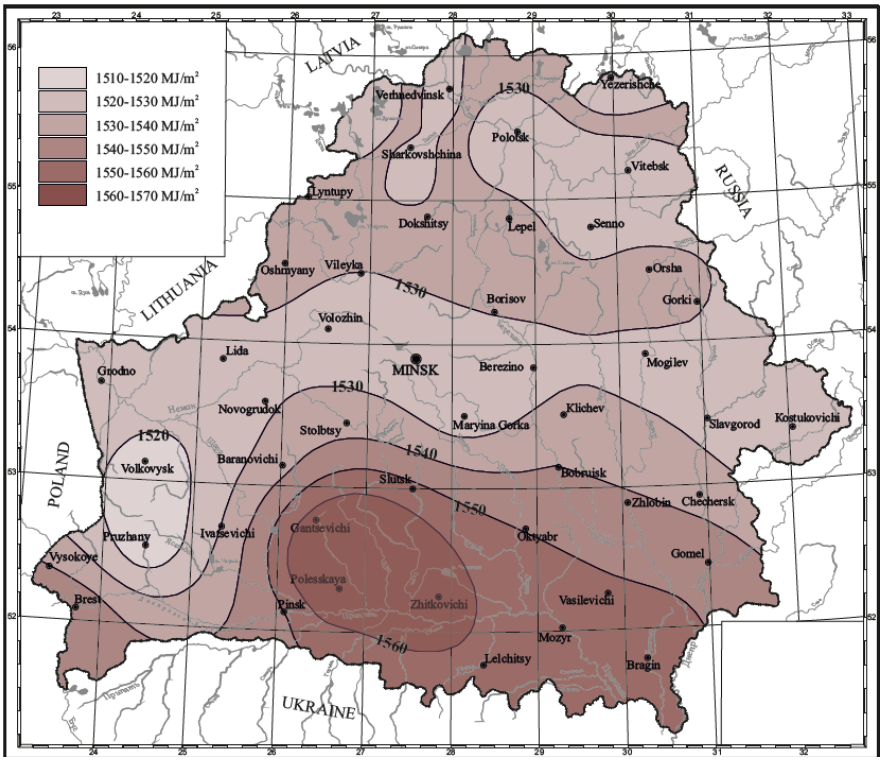

Figure 5 – Total PAR calculated in model 2 (April-October), MJ/m^2

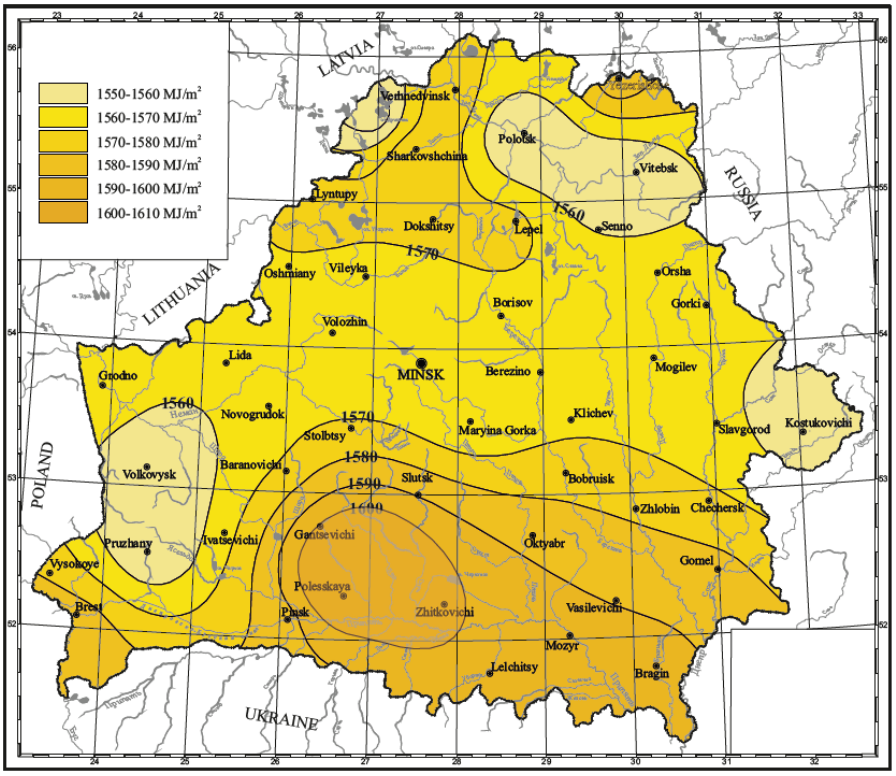

Figure 6 – Total PAR calculated with model 3 (April-October), MJ/m^2

Conclusion

There is a need for agrometeorologists to get PAR data to help solve problems in the long-term effective planning of agricultural development of regions. The use of indirect methods for PAR assessment in areas where there are no regular instrumental measurements can be a good alternative to complex instrumental measurements of PAR. Modelling of PAR values based on total shortwave radiation data revealed differences in the calculation results. Comparison of the calculation results with each other and with the research done in the neighbouring regions showed that the PAR values in model 1 are somewhat overestimated while the calculation results in the 2nd and 3rd models are more accurate. The calculation of the total PAR from shortwave radiation data in Belarus in models 2 and 3 is consistent with similar results in other regions of the temperate zone.

References

1. Egorov, M. YU. Analiz sushchestvuyushchih ustrojstv i tekhnologij dlya dopolnitel'nogo osveshcheniya rassady / M. YU. Egorov, G. S. Kornilova // Vestnik NGIEI. – 2021. – № 11 (126). – S. 17–27. – DOI: 10.24412/2227-9407-2021-11-17-27.
2. Vyazov, E. V. Aktivnost' fotosinteticheskogo apparata i zashchitnaya sistema rastenij ogurca (Cucumis sativus L.) pri uzkopolosnom osveshchenii razlichnogo spektral'nogo sostava / E. V. Vyazov, N. V. SHalygo // Ves. Nac. akad. navuk Belarusi. Ser. biyal. navuk. – 2016. – № 4. – S. 19–26.
3. Vliyanie spektral'nogo sostava sveta na morfogenez kul'tiviruemoj v oranzheree epifitnoj orhidei Cattleya labiata Lindl. / N. V. Getko, N. A. Burchik, M. I. Barkun, V. V. Titok // Ves. Nac. akad. navuk Belarusi. Ser. biyal. navuk. – 2022. – T. 67, № 1. – S. 16–23. – DOI: 10.29235/1029-8940-2022-67-1-16-23.
4. Modeling photosynthetically active radiation: A review / M. M. A. Noriega Gardea, L. F. Corral Martínez, M. Anguiano Morales [et al.] // Atmósfera. – 2021. – № 34(3). – P. 357–370. – DOI: 10.20937/atm.52737.
5. Warner, D. D. Predictions of the interacting boson approximation in a consistent Q framework / D. D. Warner, R. F. Casten // Physical Review C. – 1983. – № 28(4). – P. 1798–1806. – DOI: 10.1103/physrevc.28.1798.
6. Angstrom, A. "Solar and terrestrial radiation. Report to the international commission for solar research on actinometric investigations of solar and atmospheric radiation," Quarterly Journal of the Royal Meteorological Society. – 1924. – Vol. 50, Iss. 210. – P. 121–126.
7. Prescott, J. A. Evaporation from a water surface in relation to solar radiation / J. A. Prescott // Transactions of the Royal Society of South Australia. – 1940. – Vol. 46. – P. 114–118.
8. Bristow, K. L. On the Relationship between Incoming Solar Radiation and Daily Maximum and Minimum Temperature / K. L. Bristow, G. S. Campbell // Agricultural and Forest Meteorology. – 1984. – № 31. – P. 159–166. – DOI: 10.1016/0168-1923(84)90017-0.
9. Tooming, H. M. Metodika izmereniya fotosinteticheski aktivnoj radiacii / H. M. Tooming, B. I. Gulyaev. – M. : Nauka, 1967. – 144 p.
10. McCree, KJ. A solarimeter for measuring photosynthetically active radiation / KJ. McCree // Agricultural Meteorology. – 1966. – № 3. – P. 353–366. – DOI: 10.1016/0002-1571(66)90017-3.
11. Geograficheskoe raspredelenie fotosinteticheski aktivnoj radiacii na territorii evropejskoj chasti SSSR. / H. Moldau, YU. Ross, H. Tooming, N. Undla // Fotosintez i voprosy produktivnosti rastenij / pod red. A. A. Nichiporovicha. – M. : Izd-vo AN SSSR, 1963. – P. 145–158.
12. Meshik, O. P. Sovremennye ocenki harakteristik solnechnoj radiacii territorii Respubliki Belarus'. / O. P. Meshik, M. V. Borushko, V. A. Morozova // Vestnik BrGTU. – 2023. – № 2. – P. 115–122. – DOI: 10.36773/1818-1112-2023-131-2-115-122.
13. Metodika rascheta summarnoj solnechnoj radiacii i prodolzhitel'nosti solnechnogo siyaniya na territorii Respubliki Belarus' / O. P. Meshik, M. V. Borushko, V. A. Morozova, K. O Meshik // Aktual'nye nauchno-tekhnicheskie i ekologicheskie problemy sohraneniya sredy obitaniya : sb. trudov V Mezhdunar. nauch.-prakt. konf., posvyashch. 50-letiyu kafedry prirodoobustrojstva, Brest, 26–28 oktyabrya 2022 g. / Brest. gos. tekh. un-t ; redkol.: A. A. Volchek [i dr.] ; nauch. red. A. A. Volchek, O. P. Meshik. – Brest : BrGTU, 2022. – CH. 1. – P. 123–129.
14. Climate Resource Potential to Develop Solar Power in Belarus / A. Meshyk, M. Barushka, V. Marozava [et al.] // E3S Web Conf., 212 (2020) 01012. – DOI: 10.1051/e3sconf/202021201012.
15. Meshik, O. P. Ocenka gelioenergeticheskih resursov klimata Belarusi / O. P. Meshik, M. V. Borushko, V. A. Morozova // Vestnik BrGTU. – 2020. – № 2: Vodohozyajstvennoe stroitel'stvo, teploenergetika i geoekologiya. – P. 93–99. – DOI: 10.36773/1818-1212-2020-120-2.1-93-99.
16. Prodolzhitel'nost' solnechnogo siyaniya kak osnovnoj faktor, formiruyushchij gelioenergeticheskie resursy klimata Belarusi / O. P. Meshik, M. V. Borushko, M. M. Mirzoev [i dr.] // Peasant. – 2022. – № 3 (96). – S. 127–133.
17. SHilovceva, O. A. Kosvennye metody rascheta summarnoj fotosinteticheski aktivnoj radiacii po dannym aktinometricheskih i meteorologicheskih nablyudenij / O. A. SHilovceva, K. N. D'yakonov, E. A. Baldina // Meteorologiya i gidrologiya. – 2005. – № 1. – S. 37–47.
18. Dynamics of photosynthetic solar active radiation in Ukraine over 1986–2015 / L. S. Rybchenko, S. V. Savchuk, V. E. Timofeev [i dr.] // Ukrainian hydrometeorological journal. – 2022. – № 30. – P. 12–23. – DOI: 10.31481/uhmj.30.2022.02.
19. Rybchenko, L. S. Monitoring the solar energy resources of Ukraine / L. S. Rybchenko, S. V. Savchuk // Ukrainian hydrometeorological journal. – 2017. – № 19. – P. 65–71.
20. D'yakonov, K. N. Raspredelenie fotosinteticheski aktivnoj radiacii na territorii Vostochno-evropejskoj ravniny / K. N. D'yakonov, O. A. SHilovceva, E. A. Baldina // Vestnik Moskovskogo universiteta. Seriya 5: Geografiya, Izd-vo Mosk. un-ta (M.). – 2004. – № 1. – P. 38–38.

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COMPREHENSIVE ASSESSMENT OF THE ECOLOGICAL STATE OF RESERVOIRS IN THE URBANIZED TERRITORIES OF THE SOUTH-WEST OF BELARUS

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Abstract

The current state of reservoirs in urban areas is one of the characteristics of the ecology of the urban system and its social attractiveness. Therefore, the development of criteria for a comprehensive assessment of reservoirs in urbanized areas in order to develop recommendations for rehabilitation and maintenance in a good ecological condition is a rather urgent task.

The purpose of the work is to develop criteria for assessing the comprehensive index of the ecological state of reservoirs in urbanized territories, taking into account the recreational and aesthetic load on the example of water bodies in the south-west of Belarus. The objects of the study are typical reservoirs of urban areas in the southwest of the Belarus.

Based on the analysis of the results of our own expeditionary and laboratory studies and existing information on reservoirs in the urbanized territories of the south-west of Belarus, the choice of criteria was substantiated and for the first time a point scale for assessing the complex index of the ecological state of urban reservoirs was developed, taking into account the current conditions of anthropogenic influence. The criteria for the scoring of the complex index are based on hydrobiological, hydrochemical, and hydromorphological indicators of the ecological state of reservoirs, their recreational significance, anthropogenic transformation, trophic state, and environmental degradation.

The results of the developed point assessment of the complexindex of the ecological state of reservoirs in the urbanized territories of the south-west of Belarus for 2020 are presented. It has been established that the overwhelming majority of urban water bodies in the south-west of Belarus (3/5 of the total) are characterized by a satisfactory ecological status, 1/5 of the studied reservoirs are in poor condition, and 1/5 of the total are in good condition. The research results can be used to develop recommendations for measures to improve and rehabilitate reservoirs in satisfactory and poor ecological condition.

Keywords: urban reservoirs, comprehensive index of ecological state, recreational potential, environmental degradation.

КОМПЛЕКСНАЯ ОЦЕНКА ЭКОЛОГИЧЕСКОГО СОСТОЯНИЯ ВОДОЕМОВ УРБАНИЗИРОВАННЫХ ТЕРРИТОРИЙ ЮГО-ЗАПАДА БЕЛАРУСИ

Л. А. Кириченко, А. А. Волчек

Реферат

Современное состояние водных объектов городских территорий является одной из характеристик экологии урбосистемы и её социальной привлекательности. Поэтому разработка критериев комплексной оценки водных объектов урбанизированных территорий с целью разработки рекомендаций по реабилитации и поддержанию в хорошем экологическом состоянии представляет собой достаточно актуальную задачу.

Цель исследования – разработка критериев комплексной бальной оценки общего состояния водоемов урбанизированных территорий на примере водоемов юго-запада Беларуси. Объекты исследования – типичные водоемы городских территорий юго-запада Беларуси.

На основании анализа результатов собственных экспедиционных и лабораторных исследований и существующей информации по водоемам урбанизированных территорий юго-запада Беларуси обоснован выбор критериев и впервые разработана бальная шкала оценки комплексного индекса экологического состояния городских водоемов с учетом сложившихся условий антропогенного влияния. В основу критериев бальной оценки комплексного индекса положены гидробиологические, гидрохимические, гидроморфологические показатели экологического состояния водоемов, их рекреационная значимость, антропогенная трансформация, трофическое состояние и экологическая деградация.

Приводятся результаты разработанной бальной оценки комплексного индекса экологического состояния водоемов урбанизированных территорий юго-запада Беларуси за 2020 г. Установлено, что для подавляющего большинства городских водоемов юго-запада Беларуси (3/5 части) характерен удовлетворительный экологический статус, в плохом состоянии находится 1/5 часть из исследуемых водоемов, в хорошем – 1/5 часть. Результаты исследований могут быть использованы для разработки рекомендаций мероприятий по улучшению и реабилитации водных объектов, находящихся в удовлетворительном и плохом экологическом состоянии.

Ключевые слова: городские водоёмы, комплексный индекс экологического состояния, рекреационный потенциал, экологическая деградация.

Introduction

Most of the reservoirs of the city are the least studied water resources in Belarus due to their shallow depth and small water area, since they are not included in the NEMS. Water bodies of urbanized areas are subject to the influence of many factors, both abiotic and anthropogenic. This affects the ecological state of such reservoirs in such a way that water protection measures alone are sufficient, environmental measures in the form of a water protection zone are not quite effective. The self-cleaning ability of most of these reservoirs deteriorates due to the inflow of various pollutants into the water from the catchment area, with groundwater, precipitation, etc. In this case, there is a need to apply measures to improve the ecological condition and recreational opportunities of urbanized reservoirs.

The use of only a technical approach in solving these problems most often turns out to be impossible, inexpedient or ineffective. Therefore, an integrated approach is needed to solve technical and environmental problems to maintain a good ecological condition of urbanized reservoirs or restore (rehabilitate) them to a good condition.

It follows from this that the assessment of the ecological state of urban reservoirs should include a variety of criteria, not only hydrochemical, hydrobiological and hydromorphological, but also cultural, historical, social, recreational, etc.

For this purpose, we have developed a point assessment of the criteria for determining the ecological state and recreational opportunities of urban reservoirs.

Thus, the purpose of the work is to develop criteria for assessing the comprehensive index of the ecological state of reservoirs in urbanized territories, taking into account the recreational and aesthetic load on the example of water bodies in the south-west of Belarus.

Materials and methods

The objects of the study are typical representative water bodies of the urbanized territories of the south-west of Belarus, characterized by different recreational load and different degrees of anthropogenic impact (Figure 1).

To determine the criteria for assessing the comprehensive index of the ecological state (CIES) of urban reservoirs, the indicators of the ecological state (hydromorphological, hydrochemical, hydrobiological), as well as recreational and aesthetic potential, anthropogenic transformation, etc., are used.

To determine the estimated state of reservoirs in urbanized areas subject to various anthropogenic impacts, a system of criteria (levels) is proposed.

The ecological state of urban reservoirs was assessed on the basis of hydrochemical and hydrobiological indicators by known methods. The ecological state of urbanized reservoirs in terms of hydrochemical indicators was determined based on the multiplicity of exceeding the MPC by comparing the studied indicators with the lowest (most stringent) indicators of permissible concentrations of chemical indicators from the combined lists of information documents of the Republic of Belarus on the quality of surface waters: within the boundaries of settlements, recreational areas, MPC of pollutants of fishery water bodies and MPC of drinking water [1–4]. The ecological state according to hydrobiological indicators was assessed by the indicator of the saprobity index of reservoirs by macrophytes [5, 6].

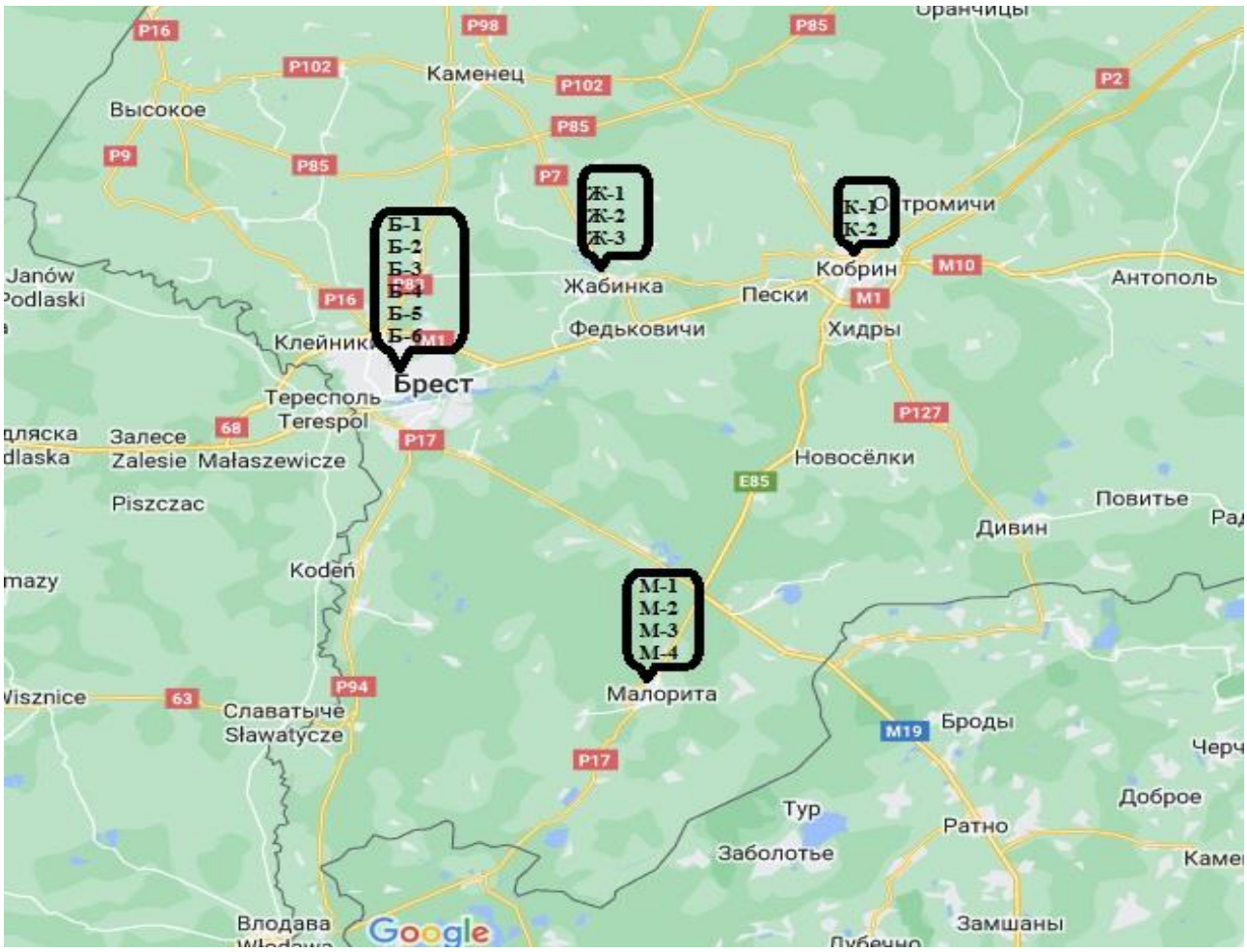

Figure 1 – Sampling sites: Kobryn – K-1 park pond, K-2 pond w/n on Polesskaya Street; Zhabinka – Zh-1 park pond, Zh-2 pond "Mukhina Yama", Zh-3 pond "Vdkhr Vizzhar"; Malorita – M-1 park pond, M-2 pond w/n on Dzerzhinskaya Street, M-3 pond "Voennoye Ozero", M-4 pond "Torfboloto"; Brest – B-1 pond "Vychulki", B-2 pond "Zodchikh", B-3 park pond "Nizhny", B-4 pond "Gershonsky", B-5 pond w/n on Kirpichnaya Street, B-6 pond "Zerkalka"

The assessment of the recreational potential and anthropogenic impact on urban reservoirs is considered using the indicators introduced by us: the level of recreational significance, the level of anthropogenic transformation (Tables 1, 2) [4, 7–10].

The level of environmental degradation of water bodies in urbanized areas was assessed based on their trophic state according to the indicators of the trophic state index TSI, the nitrification index I_{nitr} and the modified aggregation index $I_{m\text{-}agr}$ according to the methods [11–17].

Results and discussion

On the basis of the ecological state according to hydrochemical, hydrobiological and hydromorphological indicators, as well as with the help of such indicators of recreational potential and the magnitude of anthropogenic impact on water bodies as the level of recreational significance, the level of anthropogenic transformation and the level of environmental degradation, we propose a point assessment of the integrated index of the ecological state of reservoirs of the CIES of urbanized territories, specified in the Table 3.

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Table 1 – Indicators of the level of recreational significance of reservoirs in urbanized areas [7]

Level of recreational significance, score	Characteristics of the level of recreational significance
High	*Recreational-safe* water bodies are reservoirs that are in good and satisfactory ecological and sanitary-hygienic condition, used by the population in various types of recreation, and have recreational, cultural and historical potential
Average	*Recreationally significant* – reservoirs that are in a satisfactory ecological and sanitary-hygienic condition, have a high aesthetic load and are used by the population in contact types of recreation
Low	*Recreational-insignificant* – reservoirs that are in a satisfactory ecological condition, the banks of which are used for non-contact types of recreation and have an insignificant recreational potential (or in a poor ecological condition with a significant recreational potential), which cannot be used for the organization of active recreation zones, but for them it is possible to develop projects to increase the recreational potential or environmental protection or rehabilitation to a satisfactory environmental condition
"Zero"	*Recreationally insignificant* – reservoirs that are in a poor ecological condition (or in a state of degradation) and do not have a recreational potential (or with an insignificant recreational potential), which are not used by the population for recreational purposes, for which rehabilitation to a satisfactory ecological condition is impossible or inexpedient

Table 2 – Indicators of the level of anthropogenic transformation of reservoirs [7]

Level of anthropogenic transformation	Characteristics of anthropogenic transformation
"Zero" transformation	A favorable indicator of safety for recreation, characterized by insignificant anthropogenic interference (up to 5 %), as well as in the case when the reservoir has retained its original appearance
Minor Transformation	A favorable or relatively favorable indicator of safety for recreation, characterized by the engineering arrangement of a part of the coastline or a change in the lithological composition of the bottom of the reservoir by up to 30 %
Partial Transformation	A relatively favorable indicator of safety for recreation, characterized by a complete (or partial) change of the coastline, transformation from 30 to 60 %
Significant transformation	An unfavorable indicator of safety for recreation characterizes reservoirs, part of the area of which (more than 60 %) has been lost (filled up or drained)
Complete Transformation	An unfavorable indicator of safety for recreation characterizes completely lost reservoirs, or transformed into underground water bodies, or technological water bodies

The ecological state of reservoirs is assessed by comparing the results of research on hydrochemical and hydrobiological indicators. If the status of the water body of the reservoirs of urbanized territories in terms of hydrobiological indicators is higher than in terms of hydrochemical indicators, then the ecological state in terms of hydrochemical indicators is considered a priority. In our opinion, such a priority determination of the ecological state by hydrochemical indicators is associated with the effect of anthropogenic factors on the reservoirs: water pollution with chemicals has already occurred, and living organisms have not yet had time to adapt to the changed conditions of existence.

Table 3 – Score assessment of the Complex Index of the Ecological State of reservoirs of urbanized territories

No p/n	Criteria for the CIES of the reservoir	Point
Ecological state		
Hydrochemical indicators		
1	Excellent condition / low contamination water (no indicators of exceeding the MPC)	1
2	Good (favorable) / low (MPC multiplicity 1–2)	2
3	Satisfactory (relatively favorable) / medium (MPC multiplicity 2–10)	3
4	Bad (unfavorable) / high (MPC multiplicity 10–50)	4
5	Very poor ecological condition (degradation) / extremely high (MPC multiplicity >50)	5
Hydrobiological indicators		
1	Excellent environmental condition	1
2	Good (favorable) environmental condition	2
3	Satisfactory (relatively favorable) environmental condition	3
4	Poor (unfavorable) environmental condition	4
5	Very poor environmental condition	5
Recreational potential		
Level of recreational significance		
1	High	1
2	Average	2
3	Low	3
4	"Zero"	4
5	Missing	5
Level of anthropogenic transformation		
1	"Zero" transformation	1
2	Minor Transformation	2
3	Partial Transformation	3
4	Significant transformation	4
5	Complete Transformation	5
Degradation of a water body		
Level of environmental degradation		
1	A reservoir with a natural ecosystem	1
2	A reservoirs in an anthropogenically stressed trophic state	2
3	A reservoirs in a crisis trophic state	3
4	A reservoirs in a catastrophic trophic state	4
5	The reservoir is completely lost	5

When assessing the CIES of an urbanized reservoirs, a higher score of the ecological state indicator in terms of hydrochemical and hydrobiological indicators is taken into account, taking into account the predominance of the hydrochemical indicator.

The points of recreational potential and environmental degradation are summed up.

The CIES, like existing methods, classifies the ecological status of water bodies as *excellent*, *good*, *satisfactory*, *bad and very bad*. It is calculated according to the following formula

$$\text{CIES} = \sum {}^{UES}/_{n},$$

where UES is the level (criterion) of the status of a reservoirs, *n* is the number of criteria.

The values of the CIES are characterized by the following:
Excellent condition – 1–1.49 points;
Good condition – 1.5–2.5 points;
Satisfactory condition – 2.51–3.0 points;
Poor condition – 3.01–4.0 points;
Very poor condition – 4.01–5 points.

Thus, when calculating the CIES of water bodies, all factors affecting the reservoirs of urbanized areas are taken into account. At the same time, the following trend can be traced – the higher the score for a particular indicator, the worse the general condition of the reservoirs.

However, if:

– the general condition of reservoirs in urbanized areas is excellent, but isolated cases of water blooms have been recorded, then their condition is assessed as good;

– the general condition of the water body of the reservoirs of urbanized areas is good, but the cases of water blooming are frequent, the condition is assessed as satisfactory;

– the general condition of the reservoirs of urbanized areas is satisfactory, but the cases of water blooms are annual and its condition is assessed as poor.

According to the developed point assessment, the ecological state of urbanized reservoirs in the south-west of Belarus was studied, the results of the research are shown in Table 4.

Based on the results obtained, it was established that most of the water bodies in the south-west of Belarus are in good and satisfactory condition, except for the pond "Vychulki" of the pond "Voennoye Ozero" and the "Nizhny" park pond, for which a poor ecological condition has been established (Table 4) [18–20].

Thus, the results of the CIES show the true ecological state of reservoirs in urbanized areas, taking into account the recreational potential and the level of environmental degradation.

Conclusion

Almost all urban reservoirs are natural-anthropogenic or anthropogenic water bodies, the intensity of self-purification processes in which is slowed down. Therefore, a more accurate determination of the ecological state of reservoirs in urbanized areas requires an integrated approach based on the ranking of mutually related biotic, abiotic and anthropogenic factors.

Table 4 – The state of urbanized reservoirs in the south-west of Belarus in the summer period of 2020

Indicators/ Basin	Hydrochemical	Hydrobiological	Level of recreational significance	Level of environmental degradation	Level of anthropogenic transformation	CIES	Condition
K-1	4	4	2	2	3	2,75	Satisfactory
K-2	5	5	4	3	2	3,5	Bad
Zh-1	3	2	2	1	2	2	Good
Zh-2	2	3	3	1	1	1,75	Good
Zh-3	4	4	2	2	3	2,75	Satisfactory
M-1	3	2	2	1	3	9	Good
M-2	4	4	3	2	2	2,75	Satisfactory
M-3	4	5	3	4	2	3,25	Bad
M-4	3	4	3	2	1	2,75	Satisfactory
B-1	5	5	3	3	3	3,5	Bad
B-2	4	4	2	2	2	2,5	Satisfactory
B-3	5	5	2	4	3	3,5	Bad
B-4	2	2	2	1	1	1,5	Good
B-5	3	3	3	2	1	2,25	Satisfactory
B-6	4	4	2	1	2	2,25	Satisfactory

* the underlining indicates the score of the ecological state for the assessment of the CIES of the reservoirs of urbanized areas

The proposed system for assessing the comprehensive index of the ecological state of urbanized reservoirs, taking into account the ecological state in terms of hydrochemical, hydrobiological and hydromorphological indicators, environmental degradation, social and recreational attractiveness of urban reservoirs, quite objectively reflects the changes occurring with them in the current conditions of external influences.

A comprehensive assessment of the ecological state of water bodies in urbanized areas showed that the vast majority of urban reservoirs in the southwest of Belarus (3/5) are characterized by a satisfactory ecological status, 1/5 of the studied reservoirs are in poor condition, and 1/5 are in good condition. For these water bodies, it is necessary to develop measures to improve and (or) rehabilitate the ecological state.

It has been tested in the development of measures to maintain a good ecological condition of water bodies and (or) the need to rehabilitate reservoirs in the urbanized territories of the south-west of Belarus, as well as in the development of measures for restoration and reclamation and restoration of the hydraulic system of the park of the State Institution of Culture "Historical and Memorial Museum "Nemtsevich Estate".

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References

1. Ob utverzhdenii Sanitarnyh norm i pravil «Trebovaniya k soderzhaniyu poverhnostnyh vodnyh ob"ektov pri ih rekreacionnom ispol'zovanii» : postanovlenie Ministerstva zdravoohraneniya Respubliki Belarus' ot 5 dekabrya 2016 g. № 122 // Nacional'nyj pravovoj Internet-portal Respubliki Belarus'. – URL: https://pravo.by/document/?guid=12551&p0=W21631536p (data obrashcheniya: 23.10.2024).
2. Ohrana okruzhayushchej sredy i prirodopol'zovanie. Gidrosfera. Kompleksnaya ocenka ekologicheskogo riska i raschet normativov dopustimyh rekreacionnyh nagruzok na vodnye ob"ekty v rekreacionnyh zonah Belarusi : TKP 17.06-17-2018 (33140), BY. – Vveden 01.06.19. – Minsk : Minprirody, 2019. – III, 19 s.
3. Pit'evaya voda. Gigienicheskie trebovaniya k kachestvu vody centralizovannyh sistem pit'evogo vodosnabzheniya. Kontrol' kachestva. Sanitarnye pravila i normy : SanPiN 10-124 RB 99. – Minsk : Minzdrav, 2000. – 48 s.
4. Ohrana okruzhayushchej sredy i prirodopol'zovanie. Gidrosfera. Trebovaniya k soderzhaniyu poverhnostnyh vodnyh ob"ektov v nadlezhashchem sostoyanii i ih blagoustrojstvu: EkoNiP 17.06.08-003-2022. – Vveden 15.05.2022. – Minsk : Minprirody, 2022. – 28 s.

https://doi.org/10.36773/1818-1112-2024-135-3-91-95

5. Volkova, I. V. Ocenka kachestva vody vodoemov rybohozyajstvennogo naznacheniya : uchebnoe posobie dlya vuzov / I. V. Volkova, T. S. Ershova, S. V. SHipulin. – 2-e izd., ispr. i dop. – Moskva : Izdatel'stvo YUrajt, 2018. – 353 s.
6. Vysshaya rastitel'nost' ozera Nozhnicy / L. M. Merzhvinskij, V. P. Martynenko, YU. I. Vysockij, YU. L. Stanovaya // Vesnik Vicebskaga dzyarzhaŭnaga ŭniversiteta. – 2013. – № 2 (74). – S. 60–66.
7. Ocenka rekreacionnoj privlekatel'nosti vodoemov urbanizirovannyh territorij yugo-zapada Belarusi po gidromorfologicheskim pokazatelyam / L. A. Kirichenko, A. A. Volchek // Prirodopol'zovanie : sbornik nauchnyh trudov. – 2024. – № 1. – S. 54–67.
8. Ovcharova, E. P. Geoekologicheskie kriterii dlya celej reabilitacii vodnyh ob"ektov na urbanizirovannyh territoriyah / E. P. Ovcharova, O. V. Kadackaya // Prirodopol'zovanie : sbornik nauchnyh trudov / Nacional'naya akademiya nauk Belarusi, Gosudarstvennoe nauchnoe uchrezhdenie "Institut prirodopol'zovaniya". – Minsk, 1996. – S. 25–30.
9. Kirichenko, L. A. Issledovanie ekologo-rekreacionnoj znachimosti nekotoryh vodoemov g. Bresta / L. A. Kirichenko // Perspektivnye metody ochistki prirodnyh i stochnyh vod : sbornik statej regional'noj nauchno-tekhnicheskoj konferencii, Brest, 26 sentyabrya 2019 g. / Ministerstvo obrazovaniya Respubliki Belarus', Brestskij gosudarstvennyj tekhnicheskij universitet, Kafedra vodosnabzheniya, vodootvedeniya i ohrany vodnyh resursov ; redkol.: S. G. Belov [i dr.]. – Brest : BrGTU, 2019. – S. 68–71.
10. Tomash, M. S. Rekreacionnyj potencial limnosistem g. Gomelya / M. S. Tomash // Vesnik Bresckaga ŭniversiteta. Seryya 5. Himiya. Biyalogiya. Navuki ab zyamli. – 2020. – № 2. – S. 148–156.
11. Zlyvko, A. S. Antropogennaya transformaciya i samoochishchayushchaya sposobnost' maloj reki / A. S. Zlyvko, S. M. CHesnokova, I. A. Borodina // Teoreticheskaya i prikladnaya ekologiya. – 2012. – № 3 – S. 44–49.
12. Neverova-Dziopak, E. Ocenka troficheskogo sostoyaniya poverhnostnyh vod : monografiya / E. Neverova-Dziopak, L. I. Cvetkova ; SPbGASU. – SPb., 2020. – 176 s.
13. Kirichenko, L. A. Troficheskoe sostoyanie i sposobnost' k samoochishcheniyu vodoemov urbanizirovannyh territorij YUgo-Zapada Belarusi v 2020 g. / L. A. Kirichenko, A. A. Volchek // Vesnik Grodzenskaga dzyarzhaŭnaga ŭniversiteta imya YAnki Kupaly : navukovy chasopis. – 2024. – T. 14, № 1. – S. 177–186.
14. Hrisanov, N. I. Upravlenie evtrofirovaniem vodoemov / N. I. Hrisanov, G. V. Osipov. – SPb., 1993. – 279 s.
15. Bulgakov, N. G. Biogennye elementy v srede i fitoplankton: sootnoshenie azota i fosfora kak samostoyatel'nyj faktor regulirovaniya struktury al'gocenoza / N. G. Bulgakov, A. P. Levich // Uspekhi sovremennoj biologii. – 1995. – T. 115. № 1. – S. 13.
16. Kratzer, C. R. A Carlson-type trophic state index for nitrogen in Florida Lakes / C. R. Kratzer, P. L. Brezonik // Water Resources Bulletin. – 1981. – Vol. 17. – P. 713–715.
17. Dunalska, J. Total organic carbon as a new index for monitoring trophic states in lakes / J. Dunalska // Oceanography and Hydrobiology. – 2011. – Vol. 20. – P. 112–115.
18. Kirichenko, L. A. Ekologicheskoe sostoyanie gorodskih vodoemov yugo-zapada Belarusi v vesennij period 2020 g. / L. A. Kirichenko, A. A. Volchek // Pryrodnae asyaroddze Palessya: asablivasci i perspektyvy razviccya : zbornik navukovyh prac / Nacyyanal'naya akademiya navuk Belarusi, Paleski agrarna-ekalagichny instytut, redkal. M. V. Mihal'chuk (gal. red.) [i insh.]. – Minsk : Belaruskaya navuka, 2022. – Vyp. 13. – S. 117–120.
19. Ekologo-gidrohimicheskoe sostoyanie vodoemov urboterritorij yugo-zapada Belarusi v zimnij period / L. A. Kirichenko [i dr.] // Vestnik Brestskogo gosudarstvennogo tekhnicheskogo universiteta. Seriya: Vodohozyajstvennoe stroitel'stvo, teploenergetika i geoekologiya. – 2020. – № 2. – S. 80–82.
20. Kirichenko, L. Ecological condition of water bodies of the south-west of Belarus in spring 2020 / L. Kirichenko, A. Volchak, A. Golovach // 2020 International Conference on Building Energy Conservation, Thermal Safety and Environmental Pollution Control (ICBTE 2020). – 2020. – Volume 212. – 11 p. – DOI: 10.1051/e3sconf/202021201007.

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MODELING OF EROSION AND DESIGN OF STRUCTURES FOR STRENGTHENING THE WESTERN BUG RIVER BANKS

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Abstract

The Western Bug River is a transboundary river in Eastern Europe. The average long-term water discharge in the studied section is 80.2 m^3/s, and the spring flood with 1% probability is 818 m^3/s. Retrospective analyses of aerial photography data for the period from 2004 to 2022 allowed us to establish the average annual bank movement rate, which was 0.85 m/year. A digital relief model of the catchment area was created and a detailed channel model was constructed, which is based on the use of low-water and Navier-Stokes equations. The calculations were carried out using the server computing equipment of BrSTU and allowed us to build a picture of the spatial and temporal patterns of the free surface levels of the flow, as well as the velocity field. The total spatial and temporal resolution of the model is 371,000 cells with 100–200 time intervals at 10–20 vertical grid layers. To implement the program, a programming language was selected that ensures efficient calculations and convenient interaction with the existing MIKE 3 environment. As a result, Python/C++ was chosen, providing flexibility and high performance. The river sections exposed to the risk of erosion are identified, namely the coastal and coastal zone along the right bank in the area of the bend, both before and after it. The second section belongs to the floodplain zone, the flooding of which occurs during the spring flood corresponding to the maximum convergence of the meanders of the channel. The velocities obtained as a result of modeling do not exceed 2 m/s in the channel part. Areas at risk of erosion are highlighted. In the channel part, bank stabilization is recommended in the form of rock fill or stone paving. For the floodplain part near two meanders, it is necessary to provide for stabilization in the form of rock fill with a connecting structure for the passage of flood waters.

Keywords: river, runoff, modeling, erosion, meandering, fastening.

МОДЕЛИРОВАНИЕ РАЗМЫВА И ПРОЕКТИРОВАНИЕ СООРУЖЕНИЙ ДЛЯ УКРЕПЛЕНИЯ БЕРЕГОВ РЕКИ ЗАПАДНЫЙ БУГ

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Реферат

Река Западный Буг – трансграничная река в Восточной Европе. Средний многолетний расход воды в исследуемом створе составляет 80,2 $м^3/с$, а весеннего половодья 1 % обеспеченности – 818 $м^3/с$. Ретроспективный анализ данных аэрофотосъемки за период с 2004 по 2022 гг. позволил установить среднегодовую скорость перемещения береговой линии, которая составила 0,85 м/год. Создана цифровая модель рельефа местности водосбора и построена детальная модель русла, которая основана на использовании уравнений малой воды и Навье-Стокса. Расчеты проводились с применением серверного вычислительного оборудования БрГТУ и позволили построить картину пространственного временных закономерностей уровней свободной поверхности потока, а также поля скоростей. Общее пространственно-временное разрешение модели 371000 ячеек с 100–200 временными интервалами при 10–20 слоях вертикальной сетки. Для реализации программы выбран язык программирования, обеспечивающий эффективные вычисления и удобное взаимодействие с существующей средой MIKE 3. В результате выбора был сделан в пользу Python/C++, обеспечивающего гибкость и высокую производительность. Выделены участки реки, подверженные риску размыва, а именно прибрежная и береговая зона по правому берегу в районе излучины как перед ней, так и после нее. Второй участок относится к пойменной зоне, затопление которой происходит в период весеннего половодья соответствующий максимальному сближению меандр русла. Полученные в результате моделирования скорости не превышают 2 м/с в русловой части. Выделены участки подверженные риску размыва. В русловой части крепление берегов рекомендуется в виде каменной наброски или каменного мощения. Для пойменной части вблизи двух меандр необходимо предусмотреть крепление в виде каменной наброски с устройством сопрягающего сооружения для пропуска паводковых вод.

Ключевые слова: река, сток, моделирование, размыв, меандрирование, крепление.

Introduction

The Western Bug River is a transboundary river in Eastern Europe, flowing through the territory of Ukraine, Belarus and Poland. It originates in the Podolsk Upland and flows through Ukraine, then along the border of Belarus and Poland and flows into the Zegrze Reservoir, and then into the Vistula River. The total length of the river is 772 km, on the territory of Belarus – 154 km. In the upper and lower reaches, the river valley is clearly defined and does not exceed 2–3 km in width, the floodplain is intermittent, with numerous oxbow lakes. In the middle section, the valley of the Western Bug widens to 3–4 km and has a wide, low, swampy floodplain. The river bed is winding throughout its entire length. It gradually widens from 10–20 m in the upper reaches to 50–75 m in the lower reaches, sometimes up to 200–300 m. The banks are mostly flat and swampy, covered with forest in some areas [1, 2].

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Currently, a hydrological gauging station operates on the Western Bug River in the village of Novoselki, as well as on the tributaries of the Mukhavets and Lesnaya Rivers. Observations have been conducted since 1975. The Western Bug River is characterized by mixed feeding with a predominance of groundwater, which is caused by the low thickness of the snow cover and the predominance of easily permeable soils. The average annual water flow on the border of Ukraine and Belarus is 50 m^3/s, when leaving Belarus – 100 m^3/s [3, 4].

Study of hydromorphological parameters associated with changes in the river bank. The study of the Western Bug River was carried out within the framework of the State Scientific and Technical Program "Nature Management and Environmental Risks" on the assignment "To assess changes in hydromorphological, hydrological and hydrochemical indicators of the Western Bug River and to develop measures to reduce their negative consequences". During which it was established that significant changes in the coastline occur from the right (Belarusian) bank due to the nature of the river flow from south to north and the direction of the Coriolis force vector [5, 6].

The Western Bug River is a water body with a high risk of flooding due to spring floods and rain floods, which can result in significant flooding of coastal areas, including border infrastructure, agricultural lands and objects, residential and other buildings.

The main factors that lead to the shift of the fairway of the Western Bug River are: abrasion (erosion) of the banks, breakthrough of meanders, multi-branching (formation of shoals and islands). The maximum established displacement was 470 m. As a result of previous studies, 36 sections of the Western Bug River with a significant (more than 100 m) displacement of the river fairway over a 35-year period (1981–2016) were identified. 198 sections with multiple branches and 93 sections with right bank abrasion were identified. The amount of right bank abrasion at 255 sections was 3.665 km^2. Natural hydromorphological changes in the Western Bug River led to both right bank abrasion (channel displacement to the right) and right bank accumulation (channel displacement to the left). The amount of right bank accumulation at 252 sections was 4.137 km^2. Despite the fact that the overall balance of right bank abrasion and accumulation is positive for Belarus along the entire transboundary section of the Western Bug River (+47.2 ha), it should be noted the intense prevailing abrasion of the right bank on the "upper section" of the river.

Western Bug from the state border "Belarus – Ukraine" to the settlement Domachevo, as well as a number of individual sections with intense abrasion of the right bank (more than 3 ha) on the "middle section" from the settlement Domachevo to the city of Brest and the "lower section" from the city of Brest to the settlement Krynki [7, 8].

The purpose of the work was to provide a hydrological justification for the implementation of channel-regulating and bank protection measures in connection with the ongoing coastal erosion processes on the border sections of the Western Bug River.

Materials and methods

Estimated hydrological parameters

The observation period for the maximum water levels of the spring flood on the Western Bug River at the Novoselki section and on the Lesnaya River at the Tyukhinichi section is 35 years from 1988 to 2022. To identify the features of fluctuations in the maximum water levels of the spring flood on the Western Bug and Lesnaya Rivers, difference integral curves were constructed for 1988–2022, which show that the period under study includes intervals of decrease and increase in the maximum water levels of the spring flood, and since the beginning of the 20th century it has been in a positive phase – an upward trend, and only in recent years have the maximum water levels begun to decrease.

The results of calculations to determine the maximum water levels of the spring flood with a probability of 1, 3, 5 and 10 % along the Western Bug River at the Novoselki section are presented in Table 1, which were performed using the Hydrolog-2 software package [9–12].

Table 1 – Maximum water levels of spring floods with 1, 3, 5 and 10 % probability of the river Western Bug – Novoselki

Parameter	Water level, cm	Absolute level of BS, m
H_P = 1 %	556	124.56
H_P = 3 %	504	124.04
H_P = 5 %	479	123.79
H_P = 10 %	442	123.42

In classical approaches to hydrology, the provided values of levels are determined on the basis of data from hydrometric gauging stations located above and below the section under study. However, in this case, the Western Bug River, being a border river, does not have hydrometric gauging stations upstream and downstream of the study area. Transfer of levels of different probability is possible only on the basis of observation data from two observation points, both of which are located downstream, namely, a gauging station on the Lesnaya River in the settlement of Tyukhinichi and a gauging station on the studied Western Bug River in the settlement of Novoselki. In this case, we have, on the one hand, a gauging station on the studied river at a considerable distance, and on the other hand, a gauging station on a river of a lower order much closer downstream, but at the same time having different hydraulic conditions for the formation of levels and discharges. In conditions of limited observation data, observation data from both gauging stations were used simultaneously. Three approaches were used to calculate the calculated slopes: average annual level, level in the calculated month and level on the date of measurements. The level on the date of measurements should be discussed separately. Based on the data of one-time hydrometric studies, the actual levels in the section of the object on the Western Bug River were determined. One-time data allowed us to calculate the slopes during the period of work, which provided the possibility of verifying the results.

The transfer of levels was made on the basis of the calculated values of hydraulic slopes corresponding to the high-water period, taking into account the assumption of similar hydraulic conditions for the rivers Western Bug and Lesnaya in the high-water period. The averaged results for two calculation points are presented in Table 2.

Table 2 – Maximum water levels of spring floods with 1, 3, 5 and 10 % probability of the Western Bug River – the section under study

Parameter	Absolute level of BS, m
H_P = 1 %	130.87
H_P = 3 %	130.52
H_P = 5 %	130.34
H_P = 10 %	130.08

To transfer the average levels, we used data from natural (one-time measurements) and data from observations of the water level at the Novoselki station, assuming that on the date of measurements the levels in the studied section corresponded to the long-term level (126.40). The calculated levels in the studied section are presented in Table 3.

Table 3 – Average annual water levels of the river. Western Bug – Novoselki

Parameter	Absolute level of BS, m
H_P = 25 %	126.78
H_P = 50 %	126.58
H_P = 75 %	126.44

Due to the lack of hydrological observation data on water flow along the Western Bug River in the studied section, we used various alternative methods for determining the main hydrological parameters and obtained the following values of average annual water flow (Table 4).

Table 4 – Average annual water flow of the Western Bug River in the studied section

Parameter	Q, m^3/s
Q_P = 5 %	154
Q_P = 10 %	133
Q_P = 25 %	106
Q_P = 50 %	80.2
Q_P = 75 %	58.6
Q_P = 90 %	45.9
Q_P = 95 %	35.6

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Analysis of the Western Bug riverbed transformation

Geoinformation systems are widely used in modern science. For the retrospective analysis of the spatial displacement of the studied section of the Western Bug river bed, remote sensing data in the form of visible range images from 2004 to 2022 were used. The collected raster data were spatially referenced in the flat coordinate system Pulkovo_1942_CS63_Zone_C1. A database of the spatial position of the right bank of the river was formed in the form of linear vector objects (Figure 1) [13].

Using the methodology developed by the authors and described in detail in [14, 15], the shift in the position of the channel and the transformation of sinuosity were analyzed. In addition, the developed spatial model of the channel was used as a basis for the research. The results of digital information processing are presented in Figure 2–4.

Figure 1 – Vector object "bed edge"

Figure 2 – Analysis of displacements of the coastline of a section of the river bed (2004–2022)

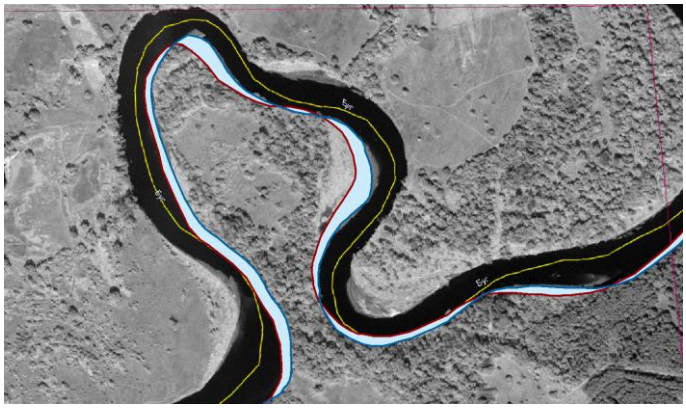

Figure 3 – Analysis of displacements of the coastline of a section of the river bed (2004–2022)

Figure 4 – Analysis of the displacement of the coastline of the river bed section (2012–2022)

Thus, the conducted analysis allowed us to record the change in the coastline over time in the studied area, which indicates the advisability of carrying out bank protection works in order to prevent the erosion of the coast by the current and, as a consequence, the formation of a new channel [16].

To process the remote sensing data, the indicator of the speed of the coastline movement process was used, which is the ratio of the right/left areas formed by the intersection of the vector object of the coastline at the initial and final moment of time, to the length of the studied section of the river and the time of these processes. Thus, the following results were obtained, presented in Table 5.

Table 5 – Calculation of the transformation rate of the Western Bug River bank

Time period, years	Sum of right areas, m^2	Sum of left areas, m^2	Section length, m	Velocity of transformation in the form of blur, m/year	Velocity of transformation in the form of deposits, m/year
2004–2012	17372.16	12611.67	2400	0.90	0.66
2012–2022	20951.33	7166.72	2485	0.84	0.29
2004–2022	36723.95	18178.84	2400	0.85	0.42

As can be seen from this table, the rate of these processes for individual time intervals differs slightly; primarily this concerns the rate of formation of a new coastline due to deposits. However, the erosion process, which is comparable for both time intervals, is of considerable interest from the point of view of predicting the occurrence of negative consequences. In further studies, the rate of spatial deformation of the coastline was adopted as 0.85 m/year.

Digital models of the river section relief development

GIS support ArcGis and its ArcToolbox toolkit, as well as tools of the MIKE 3 hydraulic modeling environment [17–19].

The following raster layers of various scales were used as cartographic bases:

– raster topographic maps;
– raster map of the Open street maps web service;

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– raster images of remote sensing of the earth (maps.googleapis.com; Bing.map, etc.);
– data of geodetic surveys provided by the customer;
– data of echo sounding surveys of the river depth within the study area provided by the customer.

The data from the usgs.gov portal were used as the initial digital relief map for calculating the river catchment area in the calculation section. Within the study area, 30 raster data on the elevation marks of the terrain are available, with a resolution of one arc minute [20]. The resolution of the digital elevation model was 30 m by 38 m. Using the algorithms of the ArcGIS application, the catchment area of the Western Bug River in the studied section was calculated, which was 24865501221 m^2.

An irregular grid with a customizable cell size was used as the basis for the channel model. Thus, for the channel zone within the echolocation survey data, the maximum grid size was no more than 50 m^2, for the channel zone – 70 m^2, for the floodplain part – 400 m^2. To form the general boundaries of the model area, arcs with specified arc parameters were drawn.

General description of the water mass movement hydrodynamic model

Low water equations are a system of hydrodynamic equations adapted for modeling water flows in shallow water conditions. In the context of this work, low water equations play a key role in providing accurate and efficient modeling of water mass motion in river systems and coastal zones. The Navier-Stokes equations are the complete hydrodynamic equations describing fluid motion. In the context of hydrodynamic modeling for aquatic systems, they are written as [21, 22, 23]:

$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u} \cdot \nabla)\boldsymbol{u} = -\frac{1}{\rho}\nabla \boldsymbol{p} + \boldsymbol{g} + \nu \nabla^2 \boldsymbol{u}\,; \quad (1)$$

$$\nabla \cdot \boldsymbol{u} = \boldsymbol{0}\,, \quad (2)$$

where $\boldsymbol{h}$ – the velocity vector, $\boldsymbol{u}$ – the velocity vector, $\boldsymbol{\rho}$ – the fluid density, $\boldsymbol{p}$ – the pressure, $\boldsymbol{g}$ – the acceleration of gravity, $\boldsymbol{v}$ – the kinematic viscosity.

Low water equations are a simplified version of the Navier-Stokes equations used in shallow waters. The main difference is that low water equations take into account the vertical pressure distribution, making them more suitable for modeling river and coastal flows.

In low water equations:

$$\frac{\partial \mathrm{h}}{\partial t} + \frac{\partial (\boldsymbol{hu})}{\partial x} + \frac{\partial (\boldsymbol{h}\mathrm{v})}{\partial y} = \boldsymbol{P} - \boldsymbol{E} - \boldsymbol{R}\,; \quad (3)$$

$$\frac{\partial (\boldsymbol{hu})}{\partial t} + \frac{\partial (\boldsymbol{hu}\mathrm{v})}{\partial y} + \frac{\partial (\boldsymbol{hu}^2 + \frac{1}{2}g\boldsymbol{h}^2)}{\partial x} = -\frac{\partial \boldsymbol{p}}{\partial x} + \boldsymbol{Tbx}\,; \quad (4)$$

$$\frac{\partial (\boldsymbol{h}\mathrm{v})}{\partial t} + \frac{\partial (\boldsymbol{hu}\mathrm{v})}{\partial x} + \frac{\partial (\boldsymbol{h}\mathrm{v}^2 + \frac{1}{2}g\boldsymbol{h}^2)}{\partial y} = -\frac{\partial \boldsymbol{p}}{\partial y} + \boldsymbol{Tby}\,, \quad (5)$$

where $\boldsymbol{h}$ – the water depth, $\boldsymbol{u}$ and $\boldsymbol{v}$ – the horizontal and vertical velocity components, respectively, $\boldsymbol{P}$ – the moisture input, $\boldsymbol{E}$ – the evaporation, $\boldsymbol{R}$ – the runoff, $\boldsymbol{g}$ – the acceleration due to gravity, $\boldsymbol{Tbx}$ and $\boldsymbol{Tby}$ – the horizontal and vertical components of the frictional moment.

The choice of low-water equations is justified by the need to take into account the features of hydrodynamic processes in river systems and coastal zones. Low-water equations provide an adequate description of water movement at shallow depths, which is often encountered in these conditions [24]. A comparative analysis of the equations allows us to highlight their applicability in various modeling scenarios, and low-water equations become the preferred choice for this work, providing a balance between accuracy and computational efficiency in conditions of limited depths.

Development Methodology

The first stage of the program development was the definition of goals and objectives. This included defining the scope of the program, end users and expected results. The goal was to create a tool capable of simulating the movement of water masses in river systems with high accuracy.

After defining the goals, an analysis of available technologies and tools for program development was carried out.

The design of the program architecture included defining the data structure, choosing numerical analysis methods, and integration with the MIKE 3 interface. The program architecture ensured the efficient execution of numerical calculations and ease of implementation in the existing MIKE 3 environment [17, 18].

At the stage of implementing the mathematical model, algorithms based on low-water equations were written. The numerical methods used to solve differential equations ensure stability and accuracy of calculations. The integration of the program with MIKE 3 required interaction with the API and technical specifications of MIKE 3. This included the correct transfer of data between the program and the MIKE 3 platform, as well as ensuring compliance with MIKE 3 standards and requirements.

The program was tested on various test scenarios, including various hydrodynamic conditions and geographical features. Debugging included fixing identified errors and optimizing performance.

After completion of the development, the program was validated and calibrated. This stage included comparing the simulation results with real data and adjusting the model parameters to achieve optimal compliance with real conditions.

The entire development process is documented, including a description of the architecture, solution methods, and technical documentation on integration with MIKE 3. This ensured understanding and support of the program.

Implementation of the program

To implement the program, a programming language was selected that ensures efficient calculations and convenient interaction with the existing MIKE 3 environment. As a result, Python/C++ was chosen, providing flexibility and high performance [20].

To speed up development and ensure program stability, appropriate libraries and frameworks were used. This included libraries for numerical calculations, data processing and interaction with the MIKE 3 interface.

The program was developed taking into account a modular architecture that allows for easy support and further expansion. The modules included the main computing units, an interface for interaction with MIKE and components for processing input and output data.

The solution of the system of low-water equations was implemented using numerical methods. Suitable methods were selected for numerical integration and solving differential equations, ensuring stability and accuracy of calculations.

To successfully integrate the program with MIKE, interaction with the API was carried out. This included the transfer of hydrodynamic model data between the program and MIKE, as well as the management of modeling processes via the MIKE interface.

The program provides means for visualizing modeling results. This includes graphical display of water mass trajectories, changes in water depth, and other parameters, allowing users to visually evaluate the results.

The entire development process was accompanied by documentation, including technical documentation on the MIKE 3 API, user manuals, and installation instructions. This ensures transparency in using the program and facilitates the implementation process.

After successful completion of all testing and troubleshooting stages, the program is ready for the final stage of implementation.

Model parameters

The model parameters were adjusted based on calibration data in the form of the maximum spring flood flow of 50 % of the estimated probability.

The adjustment was carried out in the absence of the influence of the planned construction of protective dams.

The adjustment was carried out with the following parameters: the average annual flow of the Western Bug River in the studied section is 80.2 m^3/s, the mark in the inlet section is 126.58 m BS, the hydraulic slope is 0.122 ‰. Using these model parameters, the natural roughness of the river bed was adjusted.

The model took into account the effect of Coriolis acceleration, as well as the unevenness of the model grid.

Results and discussion

Analysis of research results

The calculations were carried out using the server computing equipment of BrSTU and allowed us to build a picture of the spatial and temporal patterns of the free surface levels of the flow, as well as the velocity field. The total spatial and temporal resolution of the model is 371,000 cells with 100–200 time intervals at 10–20 layers of the vertical grid. Thus, the maximum number of calculation cells is 1484 million and, accordingly, the same number of equations in the system. The adjustment was carried out by adjusting the parameters of the channel roughness, as well as the structure and parameters of the calculation grid. The number of time intervals was adjusted in order to achieve a steady state, as can be seen in Figure 5, as a rule, stabilization was observed at the 80–90 time step.

The overall simulation results for four design flow rates and levels are shown in Figures 6–8.

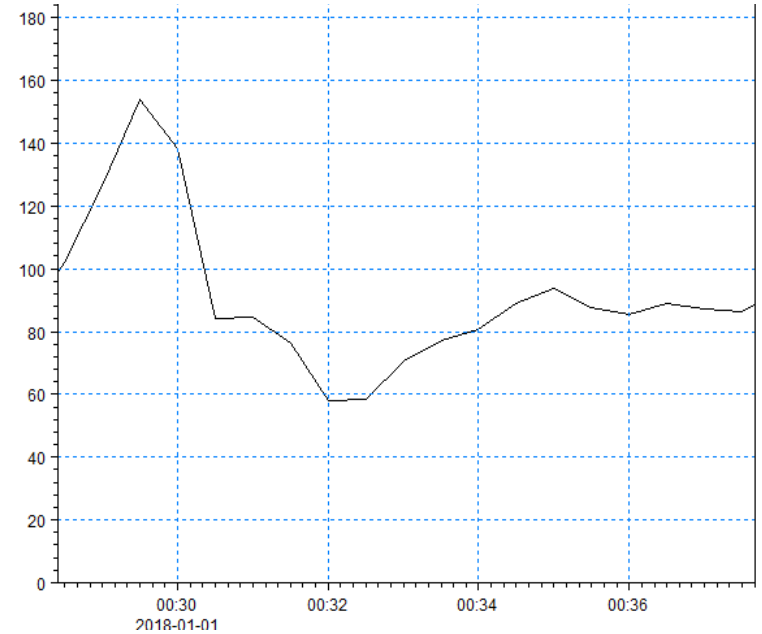

Figure 5 – Variability of flow rate in the design section over time

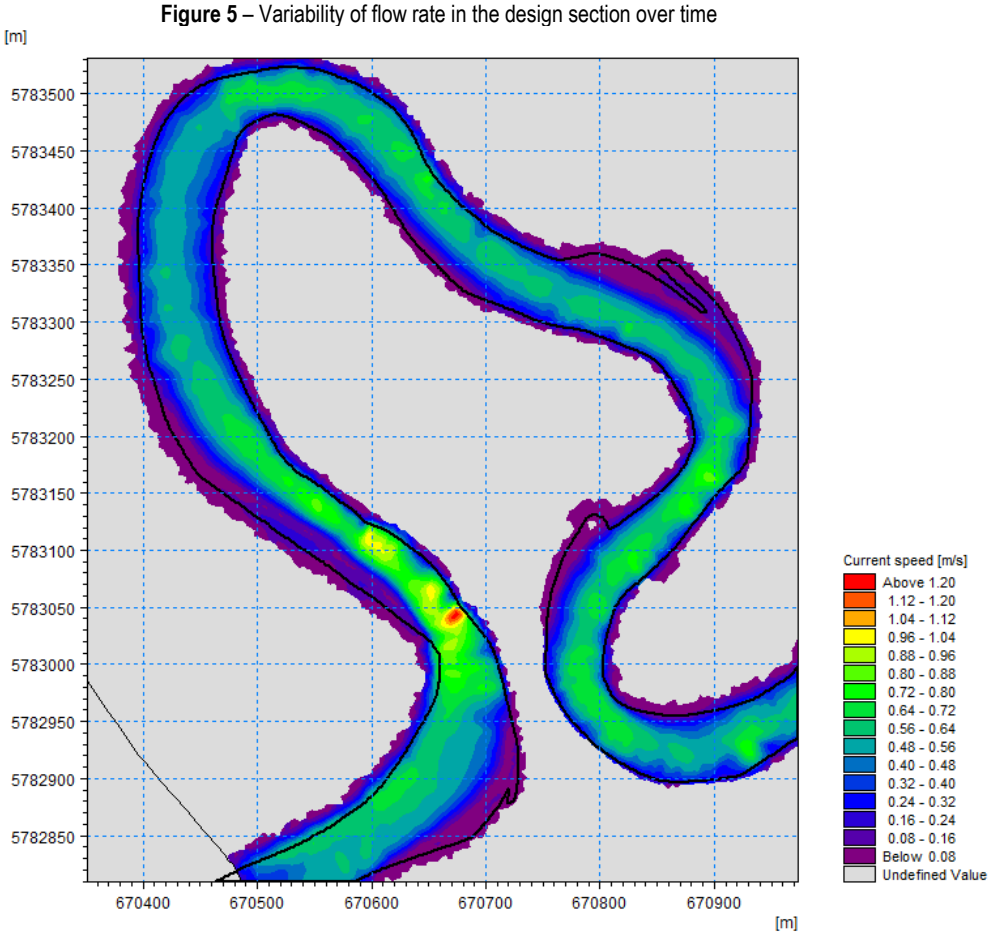

Figure 6 – Velocity field at an average annual flow rate of 25 % probability

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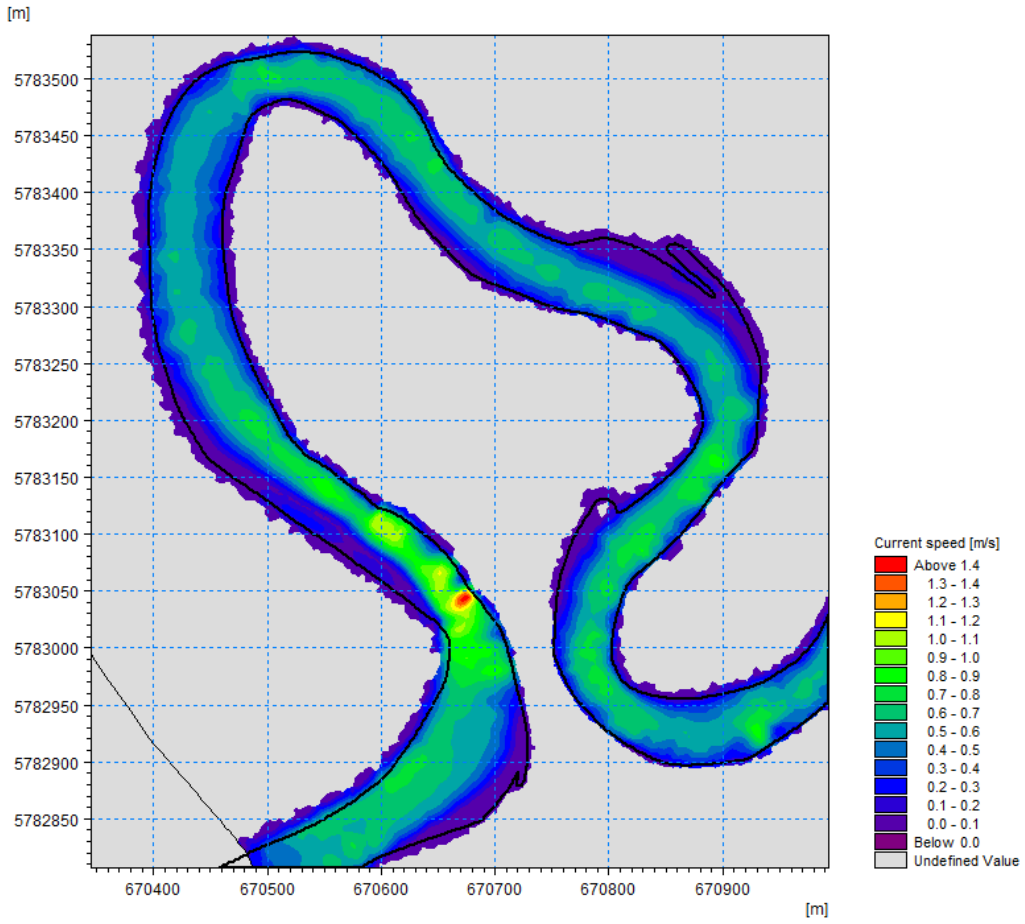

Figure 7 – Velocity field at an average annual flow rate of 50 % probability

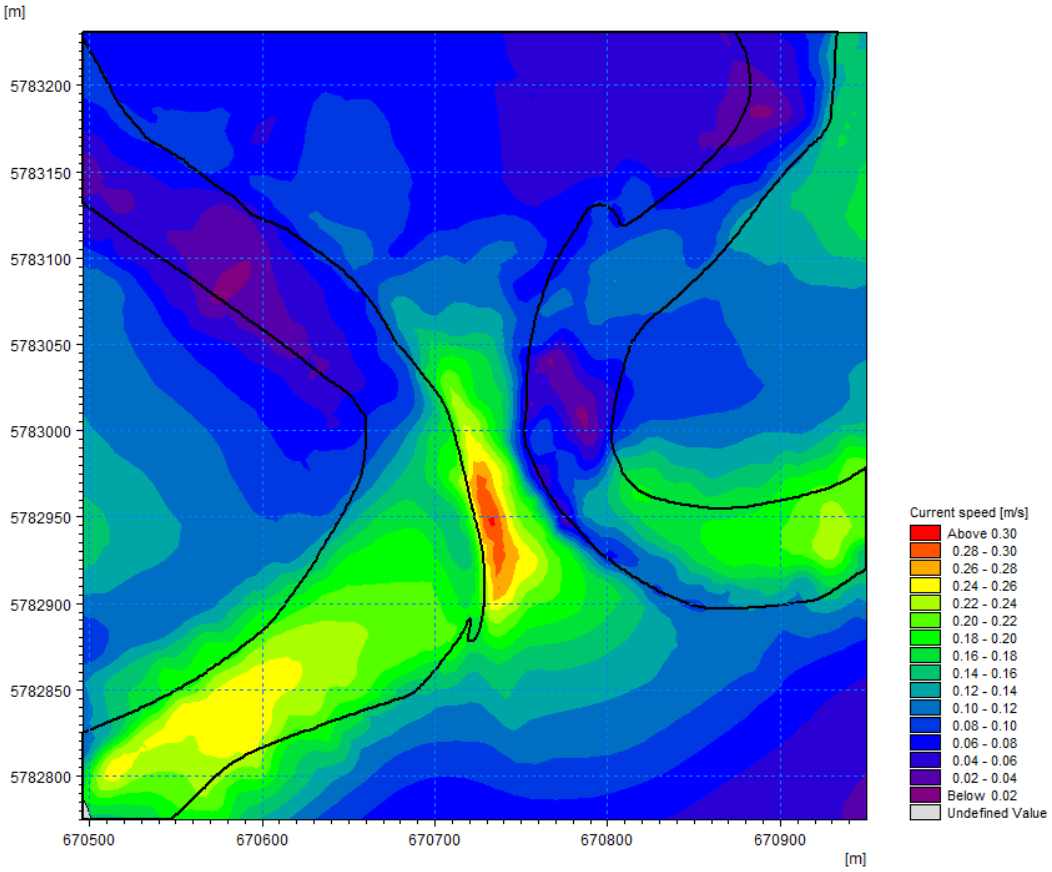

Figure 8 – Velocity field at spring flood flow rate of 10 % probability

Analyzing the obtained results, it is possible to identify areas at risk of erosion, namely the coastal/shore zone along the right bank in the area of the bend, both before and after it. The second section refers to the floodplain zone, the flooding of which occurs during the spring flood corresponding to the maximum convergence of the meanders of the channel. The velocities obtained as a result of modeling do not exceed 2 m/s in the channel part. The recommended method of support is rock fill or stone paving. For the floodplain part near two meanders, it is also necessary to provide for support in the form of rock fill with the device of a connecting structure for the passage of flood waters. The dimensions of the structure and the parameters of the support are determined by the project based on the actual geological conditions, resistance to erosion and the availability of applicable materials.

Coastal fortifications

The choice of the type of bank reinforcement is made subject to the conditions of technical feasibility and economic advantage; it is recommended to use building material available at the work site or in the immediate area. Technical feasibility consists in the fact that the strength of the bank reinforcement structure corresponds to the forces it must withstand. Engineer Fargues, famous for his works in France, established a direct relationship between the curvature of the bank and the depth of the river near it, i.e. the degree of its erosion by the current. It should also be taken into account that the lower part of the bank slope in height from the base to the horizon of medium-low low water is constantly under water and is subject to the continuous eroding action of the river flow. The part of the slope from the horizon of medium-low low water to the horizon of the highest water is subject to the periodic eroding action of the flow, the destructive action of ice moving near the banks, the influence of atmospheric and ground water, in winter - the action of frost and, finally, is partially destroyed by trampling by animals and people. Above the horizon of the highest waters, the coast is exposed only to atmospheric waters and frost, and to trampling by animals and people. Particular attention should be paid to protecting the lower part of the slope from its base to the horizon of medium-low low waters, since the destruction of this part of the slope causes the collapse of the entire part located above. Part of the coastal slope from the last horizon to the horizon of the highest waters is first cut off and planned for a certain slope – from one and a half to three times, depending on the nature of the soil of which the coast consists. For weaker soils, a gentler slope is adopted. One or another type of coating is arranged along the planned slope, depending mainly on the magnitude of the spring flow speeds and the power of spring ice drift.

A distinction is made between active and passive coastal fortifications. The former significantly affect the structure of the flow in the coastal area, and the latter only protect the coastal slope from erosion. Coastal coverings can be continuous, securing the entire coastal slope from erosion, and strip covering separate parts of the river slope along the length from erosion.

Calculations of coastal coverings include the following sections [25, 26]:

– assessment of the stability of the covering under the influence of the current;

– determination of the length and width of the covering;

– calculation of the size of the stone and the thickness of the concrete slabs in the above-water part of the structure;

– determination of the thickness of the stone ballast in the underwater part of the slope.

Coastal slopes and fortifications on them, first of all, need to be checked for resistance to the impact of the current velocity in the area of the fortified bank. To determine the current velocity in the alongshore stream, natural or calculated plans of the flow on the river section are constructed at the average low-water and average flood water flow. If the river floodplain on the section is flooded during the flood, then the level of the floodplain (low-water) edges is taken as the calculated high water level. Based on the data on the granulometric composition of the soil making up the coastal slope and on regulatory materials, permissible (non-erosive) current velocities at the calculated water levels are established. Depending on the composition of the soils making up the slope, in accordance with regulatory requirements, the permissible laying of the coastal slope during its fortification is also established. Comparison of actual current velocities with permissible ones allows us to estimate the stability of the coastal slope under the impact of the water flow on it, and, if necessary, select the appropriate coastal fortification. The length of the coastal slope reinforcement zone is established on the basis of compared and combined plans of the site for a long-term period and plans of the flow at characteristic water levels.

To determine the width of the reinforcement, the coastal slope is divided into four zones: I – above-water slope zone; II – wave run-up and wind surge zone; III – variable level zone; IV – underwater slope zone (below low water levels).

The width of the reinforcement in each zone and the size of the stone for reinforcing the above-water slope are determined by calculation. The lower boundary of the protected area, as a rule, is located in the zone of intersection of the plane of the slopes and slopes with their base. If maximum bottom velocities exceed permissible values of non-eroding bottom velocities, an anti-erosion apron in the form of a flexible mattress, rock fill, etc. must be provided in the design of the bank protection structure. The erosion depth must be established based on in-kind observations or determined on the basis of calculations.

In order to select the most effective type of bank protection structure for a specific section and correctly assign its parameters, it is necessary to carry out detailed hydrological studies of the river regime, the results of which must contain the following data:

– the length and sources of supply of the river, the area of its catchment basin;

– the width and depth of the channel flow, its slope;

– the nature of the banks and the type of channel process in the studied section of the river, an assessment of the nature of deep and planned deformations of the channel and floodplain;

– current velocities, discharge and river level marks during low water and floods, their recurrence and probability;

– characteristics of floods, their intensity and duration, the boundaries of flooding of the area;

– data on the height, length, period and occurrence of wind waves;

– duration of ice drifts, as well as data on the thickness and density of the ice cover.

Comparison and selection of optimal designs should be accompanied by appropriate technical and economic justifications, the development of which should take into account the degree of feasibility and effectiveness of design and construction solutions for various options. Technical and technological solutions for a specific option should contain assessments of the economic, social and environmental effects of its implementation.

Conclusion

Retrospective analysis of aerial photography data for the period from 2004 to 2022 based on the dynamics of spatial deformation of the river bed made it possible to establish the average annual rate of coastline displacement, which amounted to 0.85 m/year. Provided that the general cross-section of the channel and the established predicted displacement rate are preserved, the value of channel erosion in the vertical plane was determined (0.41 m/year).

Based on the results of in-kind studies and remote sensing, a digital model of the terrain of the Western Bug River catchment area in the studied section was created, and based on the data of geodetic surveys and echo sounding, a detailed model of the channel of the studied area was constructed. The average long-term water flow in the studied section of the Western Bug River was 80.2 m^3/s, and the spring flood of 1 % probability was 818 m^3/s. The determination of the calculated levels was carried out on the basis of the natural hydraulic slope.

The developed hydraulic model of the studied section of the channel is based on the use of two dependencies: the low-water equation and the Navier-Stokes equation. The method was selected based on the convergence data when calculating the coefficient matrix of the system of equations. The model included from 10 to 20 layers of the computational grid vertically. Sections at risk of erosion were identified, namely the coastal/shore zone along the right bank in the area of the bend, both before and after it. The second section refers to the floodplain zone corresponding to the maximum convergence of the meanders of the channel, the flooding of which occurs during the spring flood.

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In the channel part, bank stabilization is recommended in the form of rock fill or stone paving, since the flow rates do not exceed 2 m/s. For the floodplain part near two meanders, it is necessary to provide for stabilization in the form of rock fill with a connecting structure for passing flood waters.

References

1. Volchek, A. A. Vodnye resursy Brestskoj oblasti / A. A. Volchek, M. Ju. Kalinin. – Minsk : Izdatel'skij centr BGU, 2002. – 436 s.
2. Loginov, V. F. Vodnyj balans rechnyh vodosborov Belarusi / V. F. Loginov, A. A. Volchek. – Minsk : Tonpik, 2006. – 160 s.
3. Proekt Plana upravlenija bassejnom r. Zapadnyj Bug. – Minsk, 2016. – 54 s.
4. Ocenka izmenenija gidromorfologicheskih, gidrologicheskih i gidrohimicheskih pokazatelej reki Zapadnyj Bug i meroprijatija po snizheniju ih negativnyh posledstvij / V. N. Korneev, E. E. Petlickij, K. S. Titov, I. A. Bulak // Vestnik Brestskogo gosudarstvennogo tehnicheskogo universiteta. – 2021. – № 1 (124). – S. 90–95. – DOI: 10.36773/1818-1212-2021-124-1-90-95.
5. Pen'kovskaja, A. M. Vlijanie gidromorfologicheskih izmenenij v rechnoj seti na jeko-logicheskij status vodnyh ob'ektov bassejna reki Zapadnyj Bug / A. M. Pen'kovskaja, E. N. Popova, I. A. Bulak // Vestnik Brestskogo gosudar-stvennogo tehnicheskogo universiteta. Serija: Vodohozjajstvennoe stroitel'stvo, teplojenergetika i geojekologija. – 2016. – № 2. – S. 24–29.
6. Pen'kovskaja, A. M. Jekologicheskoe sostojanie poverhnostnyh vodnyh ob#ektov, vodoho-zjajstvennye problemy i meroprijatija, napravlennye na ih reshenie v bassejne reki Zapadnyj Bug / A. M. Pen'kovskaja, E. N. Popova. – Minsk : CNIIKIVR, 2015. – S. 226–228.
7. Mihnevich, Je. I. Ustojchivost' beregov vodohranilishh pri formirovanii profilja dinamicheskogo ravnovesija v nesvjaznyh gruntah / Je. I. Mihnevich, V. E. Levkevich // Melioracija. – 2016. – № 4 (78). – S. 18–23.
8. Volchek, An. A. Zatoplenija na territorii Belarusi / An. A. Volchek // Vestnik Brestskogo gosudarstvennogo tehnicheskogo universiteta. Serija: Vodohozjajstvennoe stroitel'stvo, teplojenergetika i geojekologija. – 2017. – № 2. – S. 39–53.
9. Volchek, A. A. Paket prikladnykh programm dlya opredeleniya raschetnykh kharak-teristik rechnogo stoka / A. A. Volchek, S. I. Parfomuk // Vesnik Paleskaga dzhzyarzhaýnaga universiteta. Seryya pryrodaznaýchykh navuk. – 2009. – №1. – S. 22–30.
10. Volchek, A. A. Gidrologicheskie raschety : ucheb.-metod. posobie // A. A. Volchek, P. S. Lopuh, An.A. Volchek. – Minsk : BGU, 2019. – 316 s.
11. Zheljaznjakov, G. V. Tochnost' gidrologicheskih izmerenij i raschetov / G. V. Zheljaznjakov, B. B. Danilevich. – L. : Gidrometeorologicheskoe izd-vo, 1966. – 240 s.
12. Raschetnye gidrologicheskie harakteristiki. Porjadok opredelenija. Tehnicheskij kodeks ustanovivshejsja praktiki : TKP 45-3.04-168-2009(02250). – Minsk : RUP «Strojtehnorm», 2010. – 55 s.
13. Volchek, A. A. Geoinformacionnaja sistema gidrograficheskoj seti vodosbora r. Zapadnyj Bug / A. A. Volchek, V. Sobolevski, N. N. Sheshko // Vestnik Brestskogo gosudarstvennogo tehnicheskogo universiteta. Serija: Vodohozjajstvennoe stroitel'stvo i teplojenergetika. – 2009. – № 2. – S. 2–8.
14. Volchek, A. A. Transformacija gidrograficheskoj seti malyh rek vodosbora r. Pripjat' v predelah prirodno-territorial'nogo kompleksa nacional'nogo parka «Pripjatskij» / A. A. Volchek, O. P. Meshik, N. N. Sheshko // Pyrodnae asjaroddze Palessja: zb. navuk. prac / Paleski agrarna-jekalagichny instytut NAN Belarusi; rjedkal. M. V. Mihal'chuk (gal. rjed.) [i insh.]. – Brjest; Al'ternativa, 2014. – Vyp. 7. – S. 11–14.
15. Volchek, A. A. Uchet razovyh gidrometricheskih izmerenij pri opredelenii osnovnyh gidrologicheskih harakteristik i parametrov rusla / A. A. Volchek, N. N. Sheshko // Saharovskie chtenija 2011 goda: jekologicheskie problemy XXI veka : materialy 11-j mezhdunar. nauch. konf., 19–20 maja 2011 g., g. Minsk, Respublika Belarus' / pod red. S. P. Kundasa, S. S. Poznjaka. – Minsk : MGJeU im. A. D. Saharova, 2011. – S. 237–238.
16. Makarevich, A. A. Rechnoj stok i ruslovye processy : posobie / A. A. Makarevich, A. E. Jarotov. – Minsk : BGU, 2019 – 115 s.
17. Flow Model FM – Hydrodynamic Module Scientific Documentation // DHI. MIKE 3. – URL: https://www.mikepoweredbydhi.com/products (date of access: 30.07.2024).
18. Sediment Transport Module ST – Scientific Documentation // DHI. MIKE 3. – URL: https://www.mikepoweredbydhi.com (date of access: 01.07.2024).
19. Kurushin, A. A. Reshenie mul'tifizicheskih SVCh zadach s pomoshh'ju SAPR COMSOL / Kurushin. – M. : «One-Book», 2016. – 376 s.
20. Kosicin, D. Ju. Jazyk programmirovanija Python: ucheb.-metod. posobie / D. Ju. Kosicin. – Minsk : BGU, 2019. – 136 s.
21. Aleksandrov, D. V. Vvedenie v gidrodinamiku: ucheb. posobie / D. V. Aleksandrov, A. Ju. Zubarev, L. Ju. Iskakova. – Ekaterinburg : Izd-vo Ural. un-ta, 2012. – 112 s.
22. Komp'juternoe modelirovanie processov perenosa i deformacij v sploshnyh sredah: Uchebnoe posobie / V. E. Ankudinov, D. D. Afljatunova, M. D. Krivilev, G. A. Gordeev. – 1-e izdanie. – Izhevsk : Izd-vo «Udmurtskij universitet», 2014. – 108 s.
23. Kolesnichenko, V. I. Vvedenie v mehaniku neszhimaemoj zhidkosti: ucheb. posobie / V. I. Kolesnichenko, A. N. Sharifulin. – Perm' : Izd-vo Perm. nac. issled. politehn. un-ta, 2019. – 127 s.
24. Kalugin, A. S. Matematicheskoe modelirovanie dvizhenija pavodochnoj volny pri ispol'zovanii ishodnoj informacii razlichnoj detal'nosti / A. S. Kalugin, I. N. Krylenko // Vodnoe hozjajstvo Rossii. – 2014. – №3. – S. 138–145.
25. Melezh, T. A. Inzhenerno–geologicheskaja ocenka jekzodinamicheskih rezhimov doliny reki Pripjat' i prilegajushhih territorij / T. A. Melezh, A. I. Pavlovskij // Vestnik VGU. Serija: Geologija. – 2015. – № 3 – S. 122–124.
26. Mihnevich, Je. I. Propusknaja sposobnost' rusel reguliruemyh rek i vodootvodjashhih kanalov / Je. I. Mihnevich // Prirodnaja sreda Poles'ja: osobennosti i perspektivy razvitija: sb. nauch. tr. Vyp. 1: v 2 t. – Brest : Al'ternativa, 2008. – T. 2. Vodnye resursy Poles'ja. – S. 38–41.

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EXTRACTION OF NITROGEN AND PHOSPHORUS FROM THE WASTEWATER OF MUNICIPAL TREATMENT FACILITIES

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Abstract

The article presents a new solution to reduce the load of phosphorus and nitrogen on urban wastewater treatment plants, based on the use of semi-burnt dolomite to extract these elements from sludge waters. The efficiency of the proposed method is compared with existing purification technologies using the example of the Minsk wastewater treatment plant. The methods for determining the concentrations of phosphate phosphorus and ammonium nitrogen in model and real wastewater samples are described in detail. The analysis of model data simulating various pollution scenarios made it possible to evaluate the efficiency of phosphorus and nitrogen extraction using various reagents. The study takes into account all key return flows of wastewater treatment plants, including silt ponds, water after compaction of activated sludge and fugate after sludge dewatering. Daily material balances for total nitrogen and total phosphorus have been developed for a comprehensive assessment. Experimental studies with fugate obtained after dehydration of sediment with pretreatment with polyelectrolyte have confirmed the effectiveness of semi-burnt dolomite for the extraction of phosphorus and nitrogen, which opens up prospects for obtaining phosphorus-containing fertilizers. The dependence of the degree of extraction of phosphates and ammonium nitrogen on factors such as pH and the initial ratio of concentrations of these elements in the return streams was revealed. The results obtained indicate the high efficiency of using semi-burnt dolomite to reduce the load on wastewater treatment plants and create conditions for the production of environmentally friendly fertilizers. This scientific research is of high practical importance and contributes to the development of resource-saving and environmentally friendly wastewater treatment technologies.

Keywords: extraction, ammonium nitrogen, phosphate phosphorus, wastewater treatment plants, liquid fraction from mechanical sludge dewatering, return flows, semi-burnt dolomite.

ИЗВЛЕЧЕНИЕ АЗОТА И ФОСФОРА ИЗ ИЛОВЫХ ВОД КОММУНАЛЬНЫХ ОЧИСТНЫХ СООРУЖЕНИЙ

Н. Г. Бунина, В. Н. Марцуль, А. И. Чухольский

Реферат

В статье представлено новое решение для снижения нагрузки фосфора и азота на городские очистные сооружения, основанное на применении полуобожженного доломита для извлечения этих элементов из иловых вод. Проведено сравнение эффективности предлагаемого метода с существующими технологиями очистки на примере Минской очистной станции. Подробно описаны методики определения концентраций фосфора фосфатного и азота аммонийного в модельных и реальных пробах сточных вод. Анализ модельных данных, имитирующих различные сценарии загрязнения, позволил оценить эффективность извлечения фосфора и азота при использовании различных реагентов. В исследовании учтены все ключевые возвратные потоки очистных сооружений, включая иловые пруды, воду после уплотнения активного ила и фугат после обезвоживания осадка. Для комплексной оценки разработаны суточные материальные балансы по общему азоту и общему фосфору. Экспериментальные исследования с фугатом, полученным после обезвоживания осадка с предварительной обработкой полиэлектролитом, подтвердили эффективность полуобожженного доломита для извлечения фосфора и азота, что открывает перспективы получения фосфорсодержащего удобрения. Выявлена зависимость степени извлечения фосфатов и аммонийного азота от факторов, таких как pH и исходное соотношение концентраций этих элементов в возвратных потоках. Полученные результаты свидетельствуют о высокой эффективности применения полуобожженного доломита для уменьшения нагрузки на очистные сооружения и создания условий для производства экологически чистого удобрения. Данное научное исследование имеет высокое практическое значение и вносит вклад в разработку ресурсосберегающих и экологически безопасных технологий очистки сточных вод.

Ключевые слова: извлечение, азот аммонийный, фосфор фосфатный, очистные сооружения, фугат, возвратные потоки, полуобожженный доломит.

Introduction

Currently, nitrogen and phosphorus are indispensable elements for plant growth and form the basis of mineral fertilizers, the demand for which is constantly increasing under conditions of intensive agriculture. The sole source of phosphorus for fertilizer production is non-renewable phosphate and apatite ores, which will lead to its future scarcity [1].

Municipal wastewater treatment plants (WWTPs) play a crucial role in ensuring the environmental safety of water bodies. A key indicator of their efficiency is the degree of reduction in the content of nitrogen and phosphorus compounds in wastewater. The excessive influx of these elements into water bodies leads to eutrophication, disrupting the ecological balance and deteriorating water quality [2].

Traditional methods of wastewater treatment for biogenic elements do not always provide sufficient efficiency. In particular, sludge water generated during the thickening and mechanical dewatering of sewage sludge (filtrate) contains significant concentrations of nitrogen and phosphorus [3]. Returning to the inlet chamber, it increases the load on the wastewater treatment plant and reduces the quality of treatment.

Therefore, the development of effective methods for extracting biogenic elements in a usable form from sludge water is a pressing task. This will not only reduce environmental pollution but also create an opportunity for the production of valuable fertilizers.

1 Principal methods for phosphorus removal from wastewater

The elevated phosphorus concentration in municipal wastewater, significantly exceeding that found in natural water bodies, is a primary driver of eutrophication and consequent water quality degradation. Municipal wastewater exhibits approximately 250 times higher phosphorus levels

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compared to natural environments. Phosphorus enters WWTPs via the sewerage system. Principal sources of phosphorus in municipal wastewater include human waste products and phosphate-based detergents [4].

Various methods exist for phosphorus removal from wastewater, broadly categorized into three groups: chemical, physico-chemical, and biological [5]. Chemical methods rely on the application of chemical reagents to bind phosphorus and render it insoluble. Physico-chemical methods encompass processes such as precipitation, coagulation, flotation, and adsorption, all aimed at phosphorus removal through insolubilization. Biological methods utilize microorganisms to absorb phosphorus from wastewater and incorporate it into their biomass [6].

Currently, a widely employed method involves the extraction of phosphorus from sludge water as a complex ammonium, magnesium, and orthophosphoric acid salt – the sparingly soluble compound $MgNH_4PO_4$ (struvite) – which can subsequently be utilized as a fertilizer [7]. This method facilitates the simultaneous removal of nitrogen and phosphorus, enhancing its ecological and economic viability.

Research into struvite recovery from wastewater and its application as fertilizer is ongoing globally. Technological schemes for struvite extraction have been developed for various sources, including municipal wastewater, steel mills, tanneries, coking processes, landfill leachate, livestock and dairy farms, and blackwater from decentralized treatment systems. Research into struvite's application as a fertilizer has spanned nearly two decades [8, 9].

In global wastewater treatment practices, various technologies are employed for the removal of nitrogen and phosphorus compounds. These include:

1. The University of Cape Town process. This process design minimizes nitrate inflow to the anaerobic treatment zone, thereby enhancing the efficiency of biological phosphorus removal.

2. The A2/O process. This represents a modification of the A/O process, incorporating a dedicated denitrification zone. Effective phosphorus removal using this configuration is limited to wastewaters exhibiting high concentrations of organic compounds.

3. The Bardenpho process. This five-stage process includes an additional denitrification/nitrification step compared to the A2/O process, mitigating the adverse effects of nitrate within the anaerobic zone under conditions of incomplete denitrification [10].

Separate technologies are employed for the treatment of sludge water, targeting either nitrogen or phosphorus extraction. Phosphorus recovery technologies include Phostrip, Ostara PEARL, and PRISA, while nitrogen removal is achieved using BABE, CANON, and DEMON processes. Phosphorus removal efficiencies may reach 85 %, while nitrogen removal rarely exceeds 30 % [11–13].

The application of semi-burnt dolomite (calcined at 600–750°C) represents a promising approach for phosphorus adsorption. Prior research has demonstrated its high effectiveness in removing phosphate phosphorus from wastewater treatment plant return streams [14].

The present investigation aims to assess the efficiency of nitrogen and phosphorus extraction from sludge water under operational wastewater treatment plant conditions using a range of reagents. The following objectives will be pursued:

1. Conduct a compositional analysis of return flows from the Minsk wastewater treatment plant and establish a mass balance for nitrogen and phosphorus.
2. Determine the extraction efficiency of nitrogen and phosphorus from sludge water at the operational wastewater treatment plant using various reagents.
3. Quantify the yield of phosphorus-containing products resulting from phosphorus extraction from sludge water at the treatment plant.

2 Materials and methods

Model waters containing phosphate phosphorus and ammonium nitrogen and silt waters formed at the Minsk treatment plant during compaction and mechanical dewatering of sediment (fugate) were used as research objects.

Model wastewater containing ammonium and phosphate ions at specified concentrations was obtained by mixing solutions of K_2HPO_4 and NH_4Cl in terms of phosphate and ammonium ion in certain ratios. The concentrations of ammonium nitrogen and phosphate phosphorus were assumed to be similar to their content in the streams that have developed and are predicted in the streams of wastewater treatment plants.

To determine the composition of the return flows of the Minsk treatment plant with determination of the concentration of ammonium nitrogen (NH_4^+) and phosphate phosphorus (PO_4^{3-}), samples of fugate, silt waters from ponds and after silt compactors were used, which were selected on 04/24/2024.

$MGSO_4 \cdot 7H_2O$, semi-burnt dolomite (firing temperature – 700–750 °C), CaO were used as reagents for the extraction of phosphate phosphorus and ammonium nitrogen.

Magnesium sulfate is a water-soluble fine powder of white or light gray color. It is obtained by the interaction of magnesite with sulfuric acid, followed by filtration, crystallization and drying of the product in a drying drum. Magnesium sulfate 7-aqueous is used in agriculture as a fertilizer and in the production of synthetic detergents, as a technological raw material in the chemical, metallurgical, pulp and paper, textile industries, in the production of building materials and other industries [15].

The concentration of phosphate phosphorus was determined by photometric method with ammonium molybdate, and ammonium nitrogen was determined by photometric method using Nessler reagent [16, 17].

3 Nitrogen and Phosphorus Extraction from Wastewater Sludge Using Semi-burnt Dolomite

To establish the established distribution of nitrogen and phosphorus throughout the wastewater treatment plant's material flows, in addition to the routinely monitored concentrations in the influent and effluent wastewater streams, the concentrations of ammonium nitrogen (NH_4^+) and phosphate phosphorus (PO_4^{3-}) were determined in the return flows. These return flows included the return from sludge ponds, sludge water after thickening of excess activated sludge (EAS), and the fugate after cake dewatering.

The concentrations of ammonium nitrogen and phosphate phosphorus in the return flows from the Minsk wastewater treatment plant are presented in Table 1.

Table 1 – Ammonium nitrogen and phosphate phosphorus concentrations in return flows from the Minsk wastewater treatment plant

Return flow	Concentration, mg/dm^3			
	ammonium nitrogen		phosphorus phosphate	
	minimum value	maximum value	minimum value	maximum value
From sludge ponds	10,5	535	14,1	143
After sealing the EAS	2,6	29,1	7,0	131
Fugate	26,8	73,2	63,3	191

Analysis of Table 1 reveals a substantial variation and wide range in ammonium nitrogen and phosphate phosphorus concentrations within the return flows of the Minsk wastewater treatment plant. The highest concentrations of both nutrients are observed in the return flow from sludge ponds, indicating a significant load on the treatment plant due to the transfer of these nutrients from the sludge deposited in the ponds into the sludge water.

Based on the data obtained during the analysis of the composition of return flows and wastewater at the entrance and exit from the treatment facilities, the material balances of total phosphorus and nitrogen for the Minsk treatment plant per day were compiled.

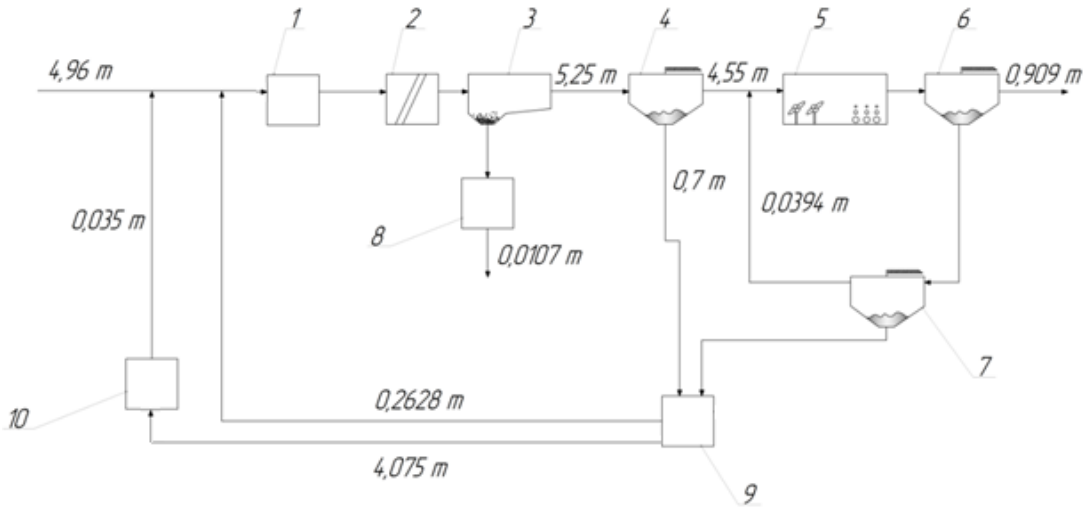
The daily material balance for total phosphorus is shown in Figure 1.

Figure 2 illustrates the daily mass balance for total nitrogen.

The analysis of material balances shows that the nitrogen and phosphorus content in the return streams has a significant effect on the composition of wastewater entering the aeration tank. Given that sediments placed on silt ponds are not used, it is possible to estimate how much nitrogen and phosphorus are annually withdrawn from circulation at wastewater treatment plants.

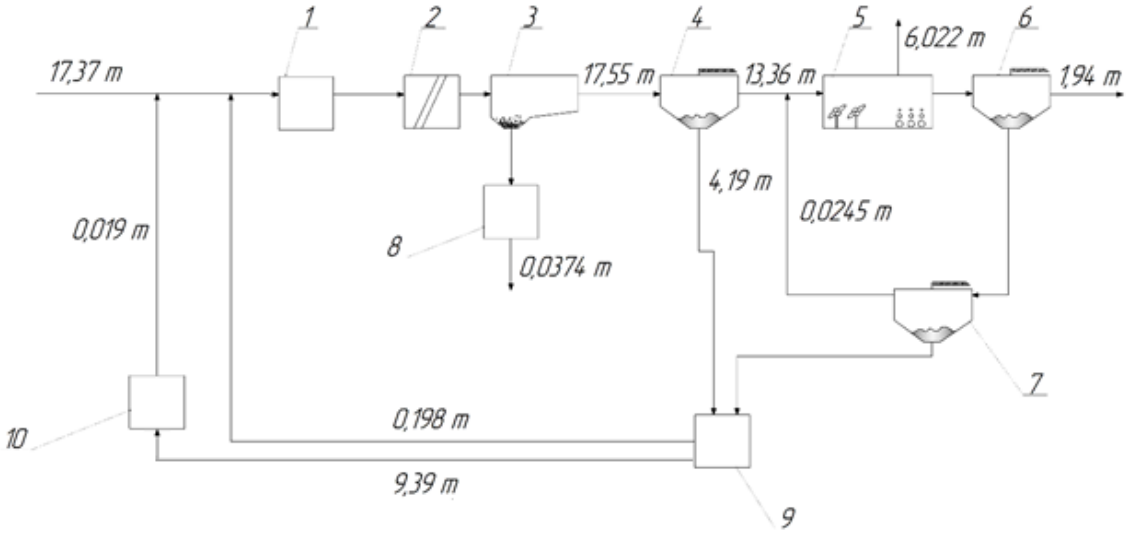
For effective biological treatment, a BOD (biological oxygen demand):N:P ratio of 100:5:1 is required [18]. Significant deviations from this ratio will reduce the overall efficiency of water treatment.

It is important to note that the nitrogen and phosphorus concentrations in the return flows significantly exceed those in the influent wastewater, substantially increasing the load on the treatment plant. The use of a biogas complex for sludge stabilization will further increase the load on the aeration tank with respect to these compounds.



1 – influent chamber; 2 – screens; 3 – grit chambers; 4 – primary clarifiers; 5 – aeration tanks; 6 – secondary clarifiers; 7 – sludge thickeners; 8 – grit storage areas; 9 – sludge treatment facility; 10 – sludge ponds

Figure 1 – Daily mass balance of total phosphorus in return flows at the Minsk wastewater treatment plant



1 – influent chamber; 2 – screens; 3 – grit chambers; 4 – primary settling tanks; 5 – aeration tank; 6 – secondary settling tanks; 7 – sludge thickeners; 8 – grit storage areas; 9 – sludge treatment facility; 10 – sludge ponds

Figure 2 – Daily mass balance of total nitrogen in return flows at the Minsk wastewater treatment plant

To study the efficiency of extraction of ammonium and phosphate ions from sludge waters, studies have been conducted on model wastewater. The model wastewater contained ammonium and phosphate ions in concentrations corresponding to their content in the streams of the Minsk treatment plant. Published data were used to account for the concentrations of these elements in sludge waters after the introduction of the biogas complex [19].

This study investigated three options for ammonium and phosphate ion removal, differing in the type of reagents used: $MgSO_4 \cdot 7H_2O$, partially semi-burnt dolomite, and CaO.

The results of the studies are presented in Table 2.

Analysis of the results presented in Table 2 shows that the use of semi-burnt dolomite (700 °C) provides the most effective phosphorus removal (over 90 %) from the model wastewater. Ammonium nitrogen removal efficiency is also quite high (70–80 %) with this method. The use of $MgSO_4 \cdot 7H_2O$ results in lower ammonium removal (around 60 %), but higher phosphorus removal (around 85 %). The addition of CaO provides the lowest removal efficiency for both phosphorus and ammonium.

It is important to note that when the ratio of ammonium and phosphate ions in the model wastewater is changed (samples 4–6), a decrease in phosphorus removal efficiency is observed when using $MgSO_4 \cdot 7H_2O$ and CaO. Meanwhile, the use of semi-burnt dolomite (700 °C) maintains a high degree of phosphorus removal.

Samples 1–3 of the model wastewater contained ammonium nitrogen and phosphate phosphorus in ratios similar to those found at the Minsk Wastewater Treatment Plant. Samples 4–6 reflected the concentrations of these substances in the digestate after anaerobic digestion.

The results from the model wastewater studies were used to select the optimal conditions for removing nitrogen and phosphorus from the digestate produced at the Minsk wastewater treatment plant. This digestate is the byproduct of sludge dewatering with a prior polymer conditioning. The initial concentrations of ammonium nitrogen and phosphate phosphorus in the digestate were 45 mg/dm³ and 131 mg/dm³, respectively.

Depending on the type and concentration of reagents, the removal efficiency of ammonium nitrogen varied from 37.7 % to 96.6 %, and phosphate phosphorus from 57.1 % to 99.5 %. Increasing the nitrogen removal efficiency was achieved by adding phosphate to concentrations stoichiometrically appropriate for the formation of magnesium ammonium phosphate. Nitrogen and phosphorus were removed as a part of the sludge, separated from the sludge water by settling for 30 minutes after reagent addition and mixing.

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Currently, a reconstruction project is underway at the Minsk Wastewater Treatment Plant. This project aims to increase the depth of dephosphorization/denitrification and construct an anaerobic digestion sludge treatment block. The project will be implemented in stages over 5–6 years [20].

Given this, a crucial task for the Minsk Wastewater Treatment Plant is now ensuring nitrogen and phosphorus removal from the sludge water. This will not only improve the overall treatment efficiency for these compounds but also create a valuable fertilizer.

Table 2 – Results of studies on model wastewater

Model water No.	Reagents	Ammonium ion concentration (mg/dm³)		Removal efficiency (%)	Phosphate phosphorus concentration (mg/dm³)		Removal efficiency (%)	pH	
		before	after		before	after		before	after
1	$MgSO_4 \cdot 7H_2O$	40	16,4	59	150	21,8	85,5	9,4	9,4
	semi-burnt dolomite (700 °C)		4,27	89,3		1,61	98,9	7,2	9,6
	CaO		28,2	29,5		11,9	92,1	7,2	8,5
2	$MgSO_4 \cdot 7H_2O$	50	5,78	89,4	200	40,2	79,9	10,4	9,9
	semi-burnt dolomite (750 °C)		8,47	78,1		7,68	91,2	7,2	9,3
								9,3	9,8
	CaO		41,2	17,6		50,9	74,6	7,2	8
3	$MgSO_4 \cdot 7H_2O$	60	16,2	73	250	47,4	81,0	9,76	9,5
	semi-burnt dolomite (700 °C)		18,3	64,5		24,3	85,3	7,1	8,2
								8,2	8,6
	CaO		43,1	28,2		38,8	84,8	7,1	8,0
4	$MgSO_4 \cdot 7H_2O$	640	255	60,2	370	6,2	98,3	9,7	9,5
	semi-burnt dolomite (700 °C)		351	40,2		1,04	94,7	6,3	8,5
								8,5	8,96
	CaO		568	11,3		139	62,5	6,3	7,7
5	$MgSO_4 \cdot 7H_2O$	540	221	59,1	320	19,9	93,8	9,54	9,54
	semi-burnt dolomite (700 °C)		125	71,8		3	94,1	6,96	9,5
								9,5	9,86
	CaO		521	3,5		101	68,5	6,93	7,9
6	$MgSO_4 \cdot 7H_2O$	740	289	61	420	7,32	98,3	9,45	9,4
	semi-burnt dolomite (700 °C)		2,6	95,6		3,41	95,2	6,84	10,2
								10,2	11,8
	CaO		517	30,1		122	71	6,75	7,8

Conclusion

This study confirmed the effectiveness of removing nitrogen and phosphorus compounds from wastewater treatment plant sludge water using semi-burnt dolomite and $MgSO_4 \cdot 7H_2O$.

The efficiency of ammonium nitrogen and phosphate phosphorus removal depends on several factors, including pH, the initial nitrogen-to-phosphorus ratio in the water, and the type of reagents used. The best results for simultaneous nitrogen and phosphorus removal from the Minsk Wastewater Treatment Plant digestate were achieved using an additional phosphate source (NaH_2PO_4).

Using this nitrogen and phosphorus removal process from the Minsk Wastewater Treatment Plant digestate, up to 0.26 tons of total phosphorus and up to 0.19 tons of total nitrogen per day can be recovered as a phosphorus- and nitrogen-containing fertilizer (up to 2 tons total).

When removing nitrogen and phosphorus from the digestate of digested sludge, up to 1.672 tons of total phosphorus and up to 2 tons of total nitrogen per day can be recovered as a phosphorus- and nitrogen-containing fertilizer (up to 13 tons total).

References

1. Izmenenie obespechennosti fosforom pahotnyh i lugovyh pochv Belarusi / I. M. Bogdevich, YU. V. Putyatin, I. S. Stanilevich, O. L. Lomonos // Pochvovedenie i agrohimiya. – 2019. – № 2 (63). – S. 68–78.
2. Varnikova, S. A. Rol' mineral'nyh udobrenij v evtrofirovanii vodoemov / S. A. Varnikova // Teoriya i praktika sovremennoj nauki. – 2016. – № 12–1 (18). – S. 214–216.
3. Biologicheskoe udalenie iz stochnyh vod azota i fosfora v aerotenkah Minskoj ochistnoj stancii aeracii / R. M. Markevich, M. V. Rymovskaya, O. I. Lazovskaya, N. V. Holodinskaya // Trudy Belorusskogo gosudarstvennogo tekhnologicheskogo universiteta. Seriya 4. Himiya i tekhnologiya organicheskih veshchestv, 2009. – S. 242–246.
4. Zalyotova, N. A. Osobennosti himicheskogo udaleniya fosfora pri biologicheskoj ochistke stochnyh vod / N. A. Zalyotova // Vodosnabzhenie i sanitarnaya tekhnika. – 2011. – № 11. – S. 1.
5. Novikova, O. K. Ochistka stochnyh vod ot biogennyh elementov : ucheb.-metod. posobie / O. K. Novikova. – Gomel' : BelGUT, 2019. – 55 s.
6. Teplyh, S. YU. Issledovanie sposobov udaleniya fosfatov iz bytovyh stochnyh vod / S. YU. Teplyh, D. S. Bochkov, A. O. Bazarova // Gradostroitel'stvo i arhitektura / Samarskij gosudarstvennyj tekhnicheskij universitet. – 2020. – № 4. – Tom 10: Vodosnabzhenie, kanalizaciya, stroitel'nye sistemy ohrany vodnyh resursov. – S. 69–77.
7. Yakovleva, A. A. Sposoby polucheniya struvita iz stochnyh vod / A. A. Yakovleva, N. I. Yakusheva, O. A. Fedotova // Permskij nacional'nyj issledovatel'skij politekhnicheskij universitet. – 2019. – № 4. – S. 11.
8. Kofman, V. Ya. Izvlechenie azota i fosfora v vide struvita iz stochnyh vod s vysokim soderzhaniem biogenov / V. Ya. Kofman // Vodosnabzhenie i sanitarnaya tekhnika. – 2017. – № 3. – S. 1.
9. Patent RU 2756807C1. Sposob regeneracii azota i fosfora iz stochnyh vod osazhdeniem ih ionov v forme struvita : zayavleno 2020.12.01 : opubl. 05.10.2021 / YU. V. Kuznecova, V. V. Vol'hin, I. A. Permyakova, I. A. CHernyh, G. V. Leont'eva, L. I. Ismagzamova. – URL: https://yandex.ru/patents/doc/RU2756807C1_20211005 (data obrashcheniya: 07.10.2024).
10. Dolina, L. F. Ochistka stochnyh vod ot biogennyh elementov / L. F. Dolina. – URL: https://studylib.ru/doc/2270194/ochistka-stochnyh-vod-ot-biogennyh-e-lementov (data obrashcheniya: 01.11.2024).
11. Obrabotka osadkov stochnyh vod: poleznyj opyt i prakticheskie sovety. – URL: https://studylib.ru/doc/2045183/obrabotka-osadka-stochnyh-vod--poleznyj-opyt-i (data obrashcheniya: 01.11.2024).
12. The DEMON deamonification process. – URL: https://clck.ru/3B7ya9 (date of access: 08.10.2024).

13. Wastewater Technology Fact Sheet Side Stream Nutrient Removal / United States Environmental Protection Agency. – September 2007. – URL: https://clck.ru/3B7xEQ (date of access: 08.10.2024).
14. Sapon, E. G. Ochistka vozvratnyh potokov ochistnyh sooruzhenij ot fosfatov obozhzhennym dolomitom / E. G. Sapon, V. N. Marcul' // Trudy BGTU. Seriya 2. – 2017. – № 1. – S. 106–113.
15. Magnesium sulfate 7-aqueous // AstraHim. – URL: https://astrahim.by/catalog/reaktivy/Magniy_sernokislyy_7_vodnyy (data obrashcheniya: 10.11.2024).
16. Kachestvo vody. Opredelenie fosfora. Spektrometricheskij metod s molibdatom ammoniya : STB ISO 6878-2005. – Vveden vpervye. – Minsk : Gosstandart, 2024. – 19 s. – URL: https://meganorm.ru/Data2/1/4293739/4293739297.pdf (data obrashcheniya: 11.11.2024).
17. Voda. Metody opredeleniya azotsoderzhashchih veshchestv : GOST 33045-2014. – Vzamen GOST 4192-82, GOST 18826-73 ; Vved. 01.01.2016. – M. : Standartinform, 2019. – 31 s. – URL: https://meganorm.ru/Data/588/58829.pdf (data obrashcheniya: 11.11.2024).
18. Kombinirovanie himicheskih i biologicheskih sposobov ochistki kaprolaktamsoderzhashchih stokov / A. B. Sokolov, M. G. Pechatnikov, A. S. Krizhanovskij, G. G. Petrov // Rossijskij himicheskij zhurnal. – 2006. – № 3. – S. 48–53.
19. Sapon, E. G. Pereraspredelenie fosfora mezhdu fazami suspenzii izbytochnogo aktivnogo ila pri aerobnoj i anaerobnoj stabilizacii / E. G. Sapon, V. N. Marcul' // Trudy BGTU. – 2015. – № 4. – S. 288–294.
20. UP «Minskvodokanal». Dopolnitel'naya ocenka vozdejstviya na okruzhayushchuyu sredu i social'nuyu sferu. Otchet. – URL: https://clck.ru/3EjvU8 (data obrashcheniya: 12.11.2024).

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PROBLEMS OF RISK MANAGEMENT IN THE RADIATION SAFETY IN THE REPUBLIC OF BELARUS IN DIFFERENT SITUATIONS

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Abstract

The article presents an analysis of the main sources of radioecological risks and disasters in the world and the Republic of Belarus. It is shown that the consequences of radioecological disasters are aggravated by natural phenomena and disasters (hydrometeorological, seismological, etc.). For the Republic of Belarus, the most significant sources are nuclear heritage sites, potential nuclear and radiation disasters, transportation of nuclear materials and transboundary transfer. The main problems of radioecological risk management in Belarus before 1986 are identified and methods for solving them are proposed, taking into account the implementation of a preventive approach. The need for control and management of organizational risks in the radiation safety is shown. The importance of improving the efficiency of the radiation monitoring and radiation situation forecast system, as well as early warning systems and threat and risk mapping, was noted, taking into account known current and potential threats.

Keywords: radioecological disasters and radiation safety, radioecological risk management mechanisms, risk rank, monitoring and forecasting of the radiation situation, exposure situations, radiation safety management (RSM), ionizing radiation (IR), Sendai Framework for Disaster Risk Reduction 2015–2030.

ПРОБЛЕМЫ УПРАВЛЕНИЯ РИСКАМИ В СФЕРЕ РАДИАЦИОННОЙ БЕЗОПАСНОСТИ В РЕСПУБЛИКЕ БЕЛАРУСЬ В РАЗЛИЧНЫХ СИТУАЦИЯХ

М. Г. Герменчук

Реферат

В статье представлен анализ основных источников радиоэкологических рисков и бедствий в мире и Республике Беларусь. Показано, что последствия радиоэкологических бедствий усугубляются явлениями и бедствиями природного характера (гидрометеорологическими, сейсмологическими и др.). Для Республики Беларусь наиболее значимыми источниками являются объекты ядерного наследия, потенциальные ядерные и радиационные катастрофы, транспортирование ядерных материалов и трансграничный перенос. Выделены основные проблемы управления радиоэкологическими рисками в Беларуси до 1986 и предложены методы их решения с учетом реализации превентивного подхода. Показана необходимость контроля и управления организационными рисками в сфере ОРБ. Отмечена важность повышения эффективности системы радиационного мониторинга и прогноза радиационной обстановки, а также систем раннего оповещения и картирования угроз и рисков, учитывая известные действующие и потенциальные угрозы.

Ключевые слова: радиоэкологические бедствия и радиационная безопасность, механизмы управления радиоэкологическими рисками, степень риска, мониторинг и прогноз радиационной обстановки, ситуации облучения, обеспечение радиационной безопасности (ОРБ), ионизирующее излучение (ИИ), Сендайская рамочная программа по снижению риска бедствий на 2015–2030 гг.

Introduction

The results of the analysis of disaster management activities, including in the field of radiation safety, lead to the conclusion that the most effective method is the systematic implementation of a preventive approach. This means increasing the role of disaster risk prediction for planning protective measures and subsequent resilience building in terms of establishing and maintaining risk management mechanisms, as envisioned by the Sendai Framework for Disaster Risk Reduction 2015–2030 (hereinafter referred to as the SDRR).

It is important to note that the SDRR provides middle-income countries that face specific challenges with additional support through international cooperation to provide them with means of implementation in line with their national priorities.

The Republic of Belarus, which faces specific difficulties in the form of radiological and radioecological consequences of the Chernobyl catastrophe, has had scientific, technical and humanitarian support for a long period of time in the framework of international conventions and bi- and multilateral treaties.

The SDRR currently consists of seven global targets, two of which directly affect radiation protection and safety:

Strengthening critical infrastructure and disaster resilience;

implementation of multi-hazard early warning systems, and improving access to information and assessments of disaster risk for information stakeholders, primarily the public.

Materials and methods of research

The object of the study is radiation safety and sources of radioecological risks and disasters. The subject of the study is the methods of radioecological risk management. As a general scientific, methodological and practical base the current strategies of disaster risk reduction of natural and anthropogenic character, proposed by the PSA, adapted to radioecological risks important for the Republic of Belarus are used [1]. Based on this approach, a critical analysis of the main problems of radiation safety in the Republic of Belarus before and after the Chernobyl NPP disaster is presented [2, 3, 4, 5].

The logical-historical approach and system analysis, risk theory, expert and other methods were used in the analysis.

Sources of radioecological risks and disasters in the world in the Republic of Belarus

The worldwide practice of disaster management in the field of radiation safety identifies six main categories that cover a wide range of man-made events and that generate different types of exposure situations:

I. Nuclear and radiation accidents and disasters, including nuclear and reactor accidents, industrial accidents, accidents with orphaned IR source, accidents with spacecraft and satellites, accidental discharges into the world's oceans, and others.

II. Nuclear explosions for peaceful purposes.

III. Mining of naturally occurring radioactive materials.

IV. Dumping of radioactive materials into the world's oceans for disposal.
V. Transportation of radioactive materials.
VI. Nuclear Legacy.

It should be noted that analysis of the data presented in available sources shows that all categories, except III and V, consider only those events that are a fait accompli of an accident or disaster. Potential sources of disasters are not identified, e.g. planned for construction nuclear power facilities (hereinafter – NPF) are not systematically analyzed and categorized, which does not allow assessing the whole range of radiation safety threats and risks.

Note that global radioactive contamination due to the testing and use of nuclear weapons as a source of radioecological disasters is also not singled out as a separate category, but can be considered in Category I as the event itself, and in Category VI "Nuclear Legacy" as radioecological consequences for the environment. It should be noted that as of January 1, 1990, no less than 1806 nuclear explosions had been carried out in the world in natural mediums: in space, in the atmosphere, under water and underground. Of these, 922 (51 %) were carried out by the USA and 644 (36 %) by the former USSR, while the remaining countries accounted for 240 (13 %) [6].

In general, it can be stated that six known Category I events caused radioecological disasters of different levels and scales: from 5 to 7 on the INES scale, including the Chernobyl and Fukushima NPP catastrophes (Table).

Table – The most significant nuclear and radiation accidents and disasters at nuclear and reactor facilities

№	Name of the object/location of the source radioecological risk, contaminated environmental objects	Causes of accident, catastrophe / INES level	Time	Main radionuclides in the release / discharge, other parameters of the radiation situation
1.	Mayak Production Enterprise / former USSR, Russia, Southern Urals / Techa River, East Ural trace / atmosphere, soil / hydrosphere, flora, fauna	Violations of radiation safety requirements / Level 6	1949–1956	Strontium-89,90, cesium-137, ruthenium-103,106, zirconium-95, niobium-95, cerium-141,144, yttrium-91, barium-140
2.	Sellafield nuclear complex, Windscale site / United Kingdom, Cumbria, / atmosphere, soil	Violations of nuclear and radiation safety requirements / Level 5	1957	Iodine-131, cesium-137, ruthenium-106, xenon-133, polonium-210
3	Mayak Production Enterprise / former USSR, Russia, South Urals, Kyshtym / Lake Karachay, Karachay trace / soil, bottom sediments	Violations of radiation safety requirements in combination with natural hazards / Level 6	1967	Strontium-89, 90, cesium-137, cerium-144
4	Three Mile Island Nuclear Power Plant / USA, Pennsylvania / Atmosphere	Violations of nuclear and radiation safety requirements / Level 5	1979	Iodine-131, cesium-137, xenon-133
5	Chernobyl NPP / former USSR, Ukraine, Chernobyl, atmosphere, soil, hydrosphere, flora and fauna	Violations of nuclear and radiation safety requirements, the consequences of which were multiplied by the transfer of radioactive materials in the biosphere and the negative impact of IR on biota and humans / Level 7	1986	Radioisotopes of iodine and tellurium, including iodine-131, tellurium-132, cesium-134,136,137, ruthenium-103,106, IRBs, including xenon-133, strontium-89,90, zirconium-95, niobium-95, cerium-141,144, barium-140, plutonium-238,239,240 and others
6	Fukushima NPP / Japan, Fukushima Prefecture / atmosphere, soil, hydrosphere, flora and fauna	Natural processes (tsunamis) that resulted in nuclear and radiation safety violations, the consequences of which were multiplied by the transport of radioactive materials in the biosphere and the consequences of the negative impact of IR on biota and humans / Level 7	2011	Radioisotopes of iodine and tellurium, including iodine-131, tellurium-132, cesium-134,137

At present radiological and radioecological consequences of these accidents and disasters are studied quite well and are used in the scientific process as a reliable base of empirical and theoretical knowledge, but attention should be paid to an important identified property of such events – aggravation of negative consequences for humans and the biosphere in the interaction of man-made disasters, in our case - radioecological, with natural conditions/disasters of hydrometeorological, seismic and other nature.

Thus, as an example of such a negative interaction effect, we can consider the events (radioecological disasters) associated with Mayak Production Enterprise (Lake Karachay and Karachay trace, 1967), as well as the disasters at the Chernobyl NPP (1986) and Fukushima NPP (2011).

Radioactive contamination of Lake Karachay (water and bottom sediments) was caused by the fact that, starting from 1951, liquid radioactive waste of Mayak Production Enterprise through the hydrographic network was redirected into Lake Karachay [7].

As a result of natural sedimentation processes in the bottom sediments of the lake, significant amounts of radioactive substances were accumulated from the suspended sediment and, partially, from the soluble fraction, which were artificially removed into the hydrographic network.

In 1967, due to dangerous hydrometeorological phenomena (drought and lowering of the lake level), radioactive contamination of the territories adjacent to Lake Karachay occurred, when about 5 hectares of the lake bed dried up, exposing radioactive bottom sediments. Then, under the action of meteorological phenomena (dust wind uplift and strong wind), radioactive material from the lake bottom got into the surface layer of the atmosphere and in the form of finely dispersed particles and aerosols atmospheric transport was activated, as a result, radioactive contamina-

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tion with a total activity of about 22 TBq (strontium-90, cesium-137, cerium-144) was formed in the area of more than 2700 square kilometers adjacent to the lake [8].

Thus, we can say that for Lake Karachay and Karachay trace the process of radioactive contamination consisted of three parts: artificial release of radioactive substances into the environment (discharges of liquid RAW by the enterprise "Mayak" into the river Techa and Lake Karachay) → natural processes of redistribution of radioactive substances in the lake ecosystems → natural processes in the environment (drought, wind uplift, strong wind), which led to further redistribution of radioactive substances in the surface layer of the atmosphere, in soil, biotic and abiotic objects and formed the "Karachay trace".

The process of radioactive contamination of the biosphere as a result of the Chernobyl NPP catastrophe consisted of two parts: artificial release of radioactive substances into the environment as a result of the release from the accident reactor → natural processes of redistribution of accidental radioactive substances in the environment (near and far atmospheric transport, wind uplift, surface and underground watercourses, washing off from catchments, biogeochemical processes in soils, subsoils and biotic objects) → radioactive contamination of the atmosphere, soils and hydrosphere.

As a result, radioactive substances of "Chernobyl" origin were recorded on the territory of the Northern Hemisphere of the Earth, which were further included in the global processes of substance transfer in nature [9].

Let us analyze the process of radioactive contamination of the environment as a result of the Fukushima NPP catastrophe in 2011, which looks as follows: natural processes (tsunami) led to the disruption of safe operation of the NPP (including disruption of emergency power supply) → artificial release of radioactive substances into the environment as a result of releases from 3 emergency reactors → natural processes of redistribution of emergency radioactive substances in the environment (near and far atmospheric transport, wind uplift, surface and airborne radioactive contamination of the environment) [10, 11]. As is known, the scale of radioactive contamination of the Fukushima catastrophe is so significant for the Northern Hemisphere of the Earth that traces of iodine-131, cesium-134,137 of "Fukushima" origin were detected on the radiation monitoring network even in Belarus at a distance of more than 11 thousand kilometers [12].

Analysis of the sources of disasters in the field of radiation safety listed above, as applied to the Republic of Belarus, shows that out of the six categories identified, the following are relevant for Belarus:

nuclear and radiation accidents and disasters, in terms of accidents at nuclear and reactor facilities, industrial accidents, accidents with orphaned IR sources;

extraction of natural radioactive materials – mining of potash ores and production of potash fertilizers on the territory of Minsk and Gomel oblasts of Belarus, as well as the presence of natural radionuclides in the waste of phosphate fertilizers production (Gomel oblast);

nuclear legacy – consequences of global nuclear weapons tests and the Chernobyl NPP catastrophe, storage and disposal sites for nuclear materials and RW, as well as disposal sites for decontamination waste;

transportation of nuclear and radioactive materials, including transboundary transportation;

use of nuclear materials for medical, energy and other purposes.

It should be noted that accidents with spacecraft and satellites, accidental discharges into the world ocean, nuclear explosions for peaceful purposes are of no practical importance for ensuring radiation protection and safety of the population and the environment in the Republic of Belarus.

An important task of radiation safety in Belarus is to study the threats and risks of Category V related to the management of RW received from previous activities and, which is a specific country feature, with decontamination wastes, which were formed in the process of ensuring radiation protection of facilities in settlements and other territories and (or) industries (forestry, agriculture, municipal, etc.) after the Chernobyl NPP catastrophe.

In the Republic of Belarus, by decision of the Department of Nuclear and Radiation Safety of the Ministry of Emergency Situations, the "Register of radioactive waste and nuclear heritage storage (disposal) facilities" (hereinafter – the Register), which includes 101 objects, has been created [13].

As of 2024, the most numerous group of objects included in the Register is 86 objects of decontamination waste disposal, 10 objects of RAW storage and disposal at UE "Ecores". Belarusian NPP is responsible for 2 RAW storage facilities (solid RAW storage facilities at Units 1 and 2). The Scientific Institution of NAS of Belarus "United Institute of Nuclear Research – Sosny" ensures nuclear and radiation safety of the complex of buildings and structures decommissioned after years of scientific research using nuclear energy. The Gomel-30 radioactive waste disposal facility is included in the Register as a separate facility.

In addition, the Polessky State Radioecological Reserve is included in the Register as a nuclear legacy site. The PGRES includes the Belarusian sector of the Chernobyl NPP Exclusion Zone and adjacent territories, where the highest levels of radioactive contamination of atmospheric air, soil, surface water, flora and fauna have been recorded, with the forecast indicating that the radiation situation will not change significantly over the next centuries due to transuranic elements [14, 15].

In the Republic of Belarus, according to the annual Reviews of the state of nuclear and radiation safety in the Republic of Belarus submitted by the Department of Nuclear and Radiation Safety of the Ministry of Emergency Situations of the Republic of Belarus, 4 cases related to the discovery of lost radioactive sources and other radiation incidents were registered in 2022, in 2021 – 2, in 2020 – 5, in 2019 – 10, in 2018 – 5 [4, 5].

There are industries (Category III) in the world, which include thousands of facilities related to the extraction of natural radioactive materials (uranium mining) or in which radioactive materials are a by-product of production (metallurgical, phosphate, coal and other fuel, oil and gas industries, etc.). In the case of the Republic of Belarus, attention should be paid to the phosphate, potash and fuel industries.

In Belarus, over the decades of operation of the Gomel Chemical Plant, which is engaged in the production of complex phosphorus-containing fertilizers, powerful dumps have formed, which consist mainly of phosphogypsum, their mass to date exceeding 20 million tons, the highest dumps reaching 95 m [16]. At present, phosphogypsum dumps of the Gomel Chemical Plant as a monitoring object in the NSMOS of the Republic of Belarus are not included in the radiation monitoring programs, which is associated with low activities of natural radionuclides of the uranium-thorium series in the production waste; however, the existing dumps can be considered as a potential source of negative impact of IR on the environment and humans.

It should be noted that it is also necessary to refer to assessments of radioecological risks in potash fertilizer production, which can potentially be the subject of management in the field of radiation protection and radiation safety for the Republic of Belarus, which, along with Canada, Russia, Germany, Brazil, USA, Israel and Jordan, is the leader in potassium salt reserves with total reserves of more than 7.6 billion tons. The content of potassium chloride in sylvinite of the second horizon at the deposits of the Republic of Belarus is 25–33 %, at the same time, the content of radioactive potassium-40 in the natural mixture of potassium-39,40,41 is known to be 0.012 %.

Analysis of the world practice shows that the activity on transportation of radioactive materials, including transboundary transportation, is the most active. Every year many thousands of cargo/packages with radioactive materials are transported by road, rail, sea and air. Many thousands of radioactive material packages are routinely transported annually both within and between countries by road, rail, sea and air. In Europe alone there are over 1 million shipments a year [17]. It should be noted that in 2023, the Department of Nuclear and Radiation Safety issued 213 permits for the import/export of radioactive materials to the Republic of Belarus.

In conditions of "Chernobyl" radioactive contamination of the territory of the Republic of Belarus the use of local fuel resources, mainly wood and peat, has formed local problems due to increase of caesium-137 radionuclide concentration in ash waste, and it is possible to obtain ash with activity corresponding to the category of radioactive waste (more than 10 000 Bq/kg). According to the radiation safety requirements established in the Republic of Belarus, specific activity of cesium-137 in wood fuel should not exceed 740 Bq/kg ("Republican permissible levels of cesium-137 content in wood, wood and wood products and other non-food forestry products (RPL-2001)".

Main problems of radioecological risks management on the example of the Republic of Belarus and methods of their resolution

At the present stage, a general algorithm of radiation safety risk management, which includes eight blocks/subsystems, has been created and is used for analysis [18].

Retrospective analysis of the practice of radiation safety management in the Republic of Belarus in the period from 1960 to April 1986 and in the first period of the Chernobyl NPP catastrophe from the point of view of the modern system of radioecological risk management shows that the lack of long-term system planning in case of an accident has led to the following consequences: scientific, methodological, organizational, technical and informational problems were formed in each subsystem.

Subsystem I "Radiation Safety Threat Assessment" (scientific, methodological and information problem)

In practice, sources of threats in the sphere of radiation safety have not been identified, quantified and ranked, with the exception of a "nuclear" strike during military operations, while global radioactive contamination, existing and potential scientific and industrial nuclear facilities, including power plants (Chernobyl, Ignalina, Rovno, Smolensk NPPs), other sources of radiation impact on the population and territories as a threat to radiation safety have not been considered [18, 19].

Subsystem II "Vulnerability Assessment" (problem (scientific, methodological and informational)

Only "present and future generations" in the context of radiological risks were considered as the main object of radiation protection, which is the most vulnerable from the point of view of negative impact of IR; due to the lack of assessments of threats in the sphere of radiation safety, the vulnerability of other objects, including natural ones, was not assessed, which should have been differentiated: at the territorial level (settlement, district, city, region), at the level of ecosystems, at the social level (economy, health care, etc.).

Subsystem III "Assessment of existing and planned activities" (scientific, methodological and information problem)

Before the Chernobyl disaster, large nuclear facilities, such as the four nuclear power plants around the country's borders, as well as planned activities, such as the design of the Belarusian nuclear thermal power plant, were not considered as sources of radioecological risks and threats due to the lack of scientifically based requirements for assessing radiation safety threats and vulnerability.

Subsystem IV "Analysis and Identification of Radiation Safety Risks" (scientific, methodological and information problem)

Due to the erroneous statement about "absolute safety of NPPs" for the population and the environment, risks from nuclear power facilities in the energy sector were not analyzed, and the radiation control system included, as a rule, only the 30-km zone around the nuclear power plant. Nevertheless, the rank of risk, for example, from radioactive contamination of the environment with radioactive iodine on the territory of Belarus in April-August 1986 was characterized as "high" and "extremely high". At the same time, the scientific community, the public and the mass media did not have access to reliable information important for radiation protection and safety until 1987 [21].

Subsystem V "Analysis of possible options for risk reduction" (scientific, methodological, organizational, technical and information problem)

Based on the documents on civil defense of the population for "wartime" in force in 1986, it was assumed that the following options for limiting exposure in the short term were possible: special protective suits, sheltering in a specialized protective facility, limitation of food consumption, limitation of stay in the open air, taking iodine preparations and, finally, evacuation.

Decisions to ensure the radiation safety of the public and the environment based on a choice among these options in the first phase of the accident in 1986 were ineffective because they should have been based on a preliminary vulnerability and risk assessment, which were not performed. At the same time, in 1986, decisions were made in an extremely short time frame in the absence of necessary information in a situation of uncertainty. Protective measures of medium- and long-term nature were not planned, as well as measures aimed at minimizing environmental pollution and its consequences.

Subsystem VI "Complex of operational and long-term measures to prevent and neutralize radiation safety threats and risks" (scientific, methodological, organizational, technical and information problem)

Lack of forces and means maintained in constant readiness on the basis of organizational, personnel, financial, material, technical, informational and other resource support did not allow taking all necessary measures to ensure radiation safety of the population and territories. Combined with the policy of "closedness" of information about the Chernobyl NPP radiation catastrophe and its consequences, and in the absence of an effective system of radiation monitoring of the environment, the situation only worsened.

As is well known, the so-called "iodine prophylaxis" of the population was not carried out in time to block radioactive iodine intake into the body "spontaneous" amateur iodine prophylaxis of the population was late and, of course, ineffective. It was not possible to promptly assess the scale of radioactive contamination of the territory of Belarus, for example, samples of atmospheric air and soil were not taken in time for determination of short-lived iodine-131 on the whole territory of Belarus, and systematic study of radioactive contamination of soil in the Mogilev region was started only in June 1986.

Subsystem VII "Implementation of the complex of measures" (scientific, methodological, organizational and informational problem)

The absence in the first years after the Chernobyl NPP catastrophe of a normative legal framework for the implementation of a set of measures in the form of laws of the Republic of Belarus, resolutions of the Council of Ministers, other normative and normative technical acts, as well as state and regional programs to eliminate and minimize the consequences of the Chernobyl catastrophe, including radiation monitoring, had a negative impact on the level of radiation safety.

Subsystem VIII "Evaluation of results and adjustment of the set of measures, including on the basis of program monitoring" (scientific, methodological, organizational and information problem)

Fulfillment of the requirements of this subsystem is currently implemented through improvement of the regulatory legal framework in the field of radiation safety, in the form of state programs to eliminate and minimize the consequences of the Chernobyl catastrophe, including in terms of radiation monitoring, including using the "feedback method".

Based on the results of logical-historical analysis, we note that Belarus had sufficient material, human and financial resources for the purposes of radiation safety in the conditions of global bomb contamination.

However, in the conditions of the Chernobyl NPP catastrophe, the problems of lack of resources for protection from the known, but not previously assessed threat immediately arose, including the lack of specialized laboratories equipped with the appropriate equipment (except for some institutes of the Academy of Sciences, BSU, regional design and survey stations of agricultural chemicalization of the Ministry of Agriculture and Food), the lack of a sufficient number of qualified specialists, as well as the lack of planned allocations for the purchase of equipment, consumables and other materials.

It should be noted that in 1986 the equipment in common use had an insufficient sensitivity threshold because it was designed to detect very high levels of contamination due to a possible nuclear strike. For example, the DP-5 dosimeter, which were mostly used at civil defense posts, had a lower range of dose rate measurement (hereinafter referred to as DPM) of 0 – 50 μR/h, while the DPM from natural background radiation in the Republic of Belarus was estimated as 4 – 20 μR/h, and the widely used at that time field scintillation radiometer (type SRP-6801), originally designed for geological exploration works, due to its design features had a significant overestimation error in the lower range of measurements. As a rule, the equipment was not calibrated and certified, calibration sources and batteries were often missing, and there was no system of test quality control.

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Unfortunately, it should be recognized that by this time there was also no real assessment of the needs of different information groups, so the information that could be obtained could not fully satisfy the state administration bodies, radioecologists, radiobiologists and radiation hygienists, as well as the public [18].

Let us analyze the problems of radioecological risk management when decisions in the field of radiation safety are made in situations of risk and uncertainty, assuming that these situations need to be reduced to a situation of certainty.

The situation of risk is applicable to the situation of existing exposure, for example, in the conditions of known radioactive contamination of the environment after the Chernobyl catastrophe in the long term, when risks are identified, ranked, for example, by RR, and programs for their minimization are in place.

On the one hand, assessments of the radiation situation, based on data from environmental radiation monitoring and radiation monitoring of foodstuffs, make it possible to control radioecological and radiological risks and to maintain radiation safety at a socially acceptable level.

On the other hand, the existence of a number of variants (scenarios) of radiation situation development and the presence of organizational risks in the course of implementation of activities in the field of radiation protection do not always allow to turn the situation of risk into a situation of certainty. It should be noted that in this case such function of the system of radiation monitoring of the environment as "assessment and forecast of changes in the environment under the influence of natural and anthropogenic factors" becomes decisive for assessment of consequences of realization of this or that variant (scenario) of changes in the radiation situation.

Besides the problems related to forecasting, in the situation of risk in the system of ensuring radiation safety there arises a methodical problem of "radioactive contamination control". At present, the regulatory documents of the Republic of Belarus determine that radioactive contamination control is subject to objects for which permissible levels of controlled parameters are established [22].

For example, in accordance with the Law of the Republic of Belarus "On the legal regime of the territories affected after the Chernobyl NPP catastrophe" the territories, settlements are referred to the zones of radioactive contamination when the control value of excess of radiation dose over natural 1 mSv per year or "density of soil contamination with cesium-137, strontium-90, plutonium - 238, 239, 240 is more than 1, 0.15 and 0.01 Ci/sq.km, respectively" [23], and rationing of radiation doses was carried out through radioactive contamination of foodstuffs in accordance with the current hygienic standards or other standards of maximum permissible exposure to ionizing radiation [23].

Norming of radiation doses was carried out through rationing of radioactive contamination of foodstuffs in accordance with the current hygienic standards or other standards of maximum permissible exposure to ionizing radiation.

At the same time, it should be realized that the problem of "control of radioactive contamination" carries hidden additional risks. These risks may be related, for example, to changes in the rationing systems. It should be noted that food products in the post-Chernobyl period were consistently rationed by a number of normative technical acts: from temporarily permissible levels (TPL) during the accident, republican permissible levels – 1992, 2000, 2012 to the regulations of the Customs Union.

This state of affairs causes another type of risks - organizational risks, and can lead to a significant loss of information quality, since radiation monitoring is carried out at the input and output of the technological process of production of certain types of products at the enterprise to assess its compliance with hygienic standards and does not meet the quality requirements for spatial and temporal parameters mandatory for the monitoring network [18].

At the same time, the equipment massively used for product monitoring, which is relatively inexpensive and, as a rule, has a low threshold of ispulse measurement, does not allow obtaining representative results in a range much smaller than the specified control levels. However, it is this range that is of interest in terms of the timely detection of trends in radiation parameters, e. g. radioactive contamination of local foodstuffs of plant and animal origin. On the contrary, the monitoring system uses expensive measuring equipment with high sensitivity thresholds designed to measure very low activities in samples, allowing to detect additional contamination above the background contamination.

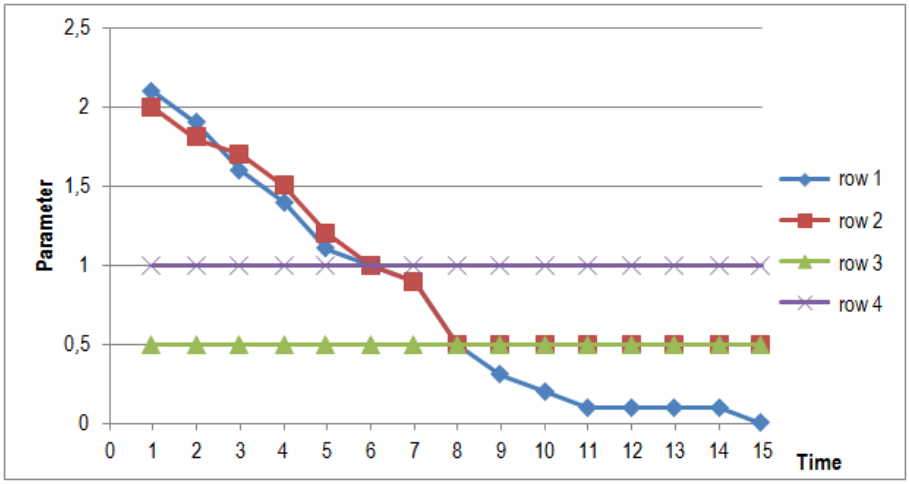

Figure 1 – Positive scenario (row 1 – monitoring results, row 2 – control results, row 3 – lower detection limit of massively used equipment, row 4 – norm)

The diagrams shown in Figure 1 and Figure 2 illustrate the above. Let's analyze the results of measurements of some environmental object in the "control" mode and in the "monitoring" mode for some specified time.

So, if we take the conditional standard equal to 1 (row 4), and the lower limit of detection of massively used equipment is conditionally taken equal to 0.5 (row 3), it is obvious that the results in the "control" mode (row 2), presented in Figure 1 indicate that the situation in the entire time period 1 – 15 is positive: in the first period 1 – 8 there was a sharp decrease in contamination of the object under study, then in the time period 8 – 15 results "reached the plateau" of the lower detection limit and the curve of results actually merged with it (rows 2 and 3). At the same time it should be noted that the main task of control in terms of radiation safety – detection and withdrawal from circulation of environmental objects that do not meet the requirements of safety standards, for example, foodstuffs, is completely fulfilled.

However, the results of the "control" mode do not give an idea of how the situation develops in the range below the detection limit [0 – 0.5]. Nevertheless, from the point of view of radiation safety, two scenarios are possible here: positive and negative, and it is clear that organizational risks are present in both cases.

Let us consider the positive scenario further, when in the time period 8 – 15 the real measured contamination levels continue to decrease and finally gradually tend to trace amounts, which is clearly demonstrated by the results of monitoring using highly sensitive equipment (row 1).

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It is obvious that mass radiation monitoring, which requires a significant amount of financial, material and labor resources, is irrational at this stage, i. e. there are organizational risks. To resolve this situation, it is sufficient to organize random inspections and ensure monitoring at production nodal points, which, in the end, allows optimizing the functioning of the control system and reducing the risks associated with a negative outcome, as will be shown below, as well as eliminating the inefficient use of available resources.

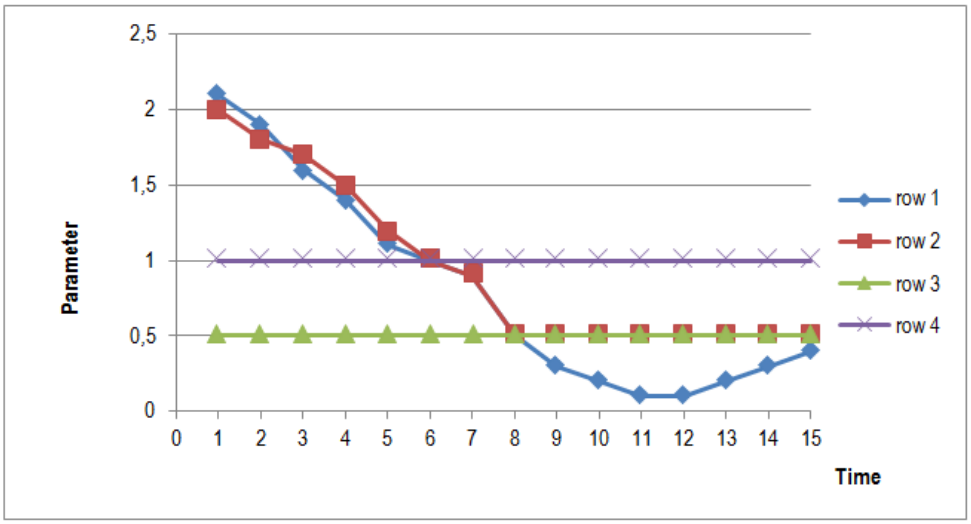

Figure 2 – Negative scenario (row 1 – monitoring results, row 2 – control results, row 3 – lower detection limit of massively used equipment, row 4 – norm)

Let us consider a negative scenario (Figure 2), when in the time period 8 – 11 real contamination levels continue to decrease, but in the period 12 – 15 a negative trend appears – radioactive contamination of the object increases (row 1), but radiation control data do not show this (row 2). This is due to the fact that the "control" system, unlike the "monitoring" system, does not react to changes in the trend from positive to negative, if these changes are in the range significantly below the control level and the lower measurement threshold.

Thus prerequisites are created for occurrence of organizational risks on timely detection and reduction of risks of achievement and exceeding of normative values of radioactive contamination of controlled objects. It is likely that already in the period 12 – 13, when the negative trend has formed and become stable, there is an opportunity to take timely measures to identify and eliminate its causes.

As a result, it is shown that the range of parameter values closed in the "control" mode contains important information about the trends of their changes in both positive and negative contexts.

The situation of uncertainty is the most difficult from the point of view of radiation safety, since it is associated with a large number of possible outcomes, and their probabilities are unknown.

From the point of view of radiation safety, a situation of uncertainty arises in the case of emergency exposure and/or emergency planning. In this case it is very important that the source of uncertainty can be incomplete and (or) unreliable information from the system of radiation monitoring of the environment or from other systems, e.g. monitoring of emergency situations, for example, about the facts of threat realization. In general, the requirements to information quality can be formulated as five basic requirements to information quality: timeliness, reliability, completeness, accessibility, sources of uncertainty and their assessment [18].

Of course, the ideal risk management strategy is to eliminate risks and threats, i. e. to directly affect their source, which is practically impossible due to the objective nature of risks and threats in the field of radiation safety. In this case, the most effective way to minimize risks in the situation of uncertainty is the method of modeling and forecasting of radiation situation and characteristics of the radiation monitoring system of the environment. An obligatory condition for modeling is the ranking of current or potential risks and threats for subsequent emergency planning. It should be noted that this is the approach proposed by the SDRR.

In order to improve early warning systems in the field of radiation safety, automatic systems for early detection and warning of radioactive contamination of the environment in 100 km zones of Chernobyl, Ignalina, Rovno and Smolensk NPPs, as well as in the surveillance zone of Belarusian NPPs, are currently established and successfully functioning in the Republic of Belarus; information is generally available on-line using modern communicative IT-technologies [24, 25].

The SDRR proposes four main priority areas of risk management activities.

Priority 1. Understanding disaster risk: to effectively counteract disasters, it is necessary to ensure that radiation safety hazards and risks are assessed on a continuous basis, assessing the vulnerability of protection facilities before events occur and preventing disasters or mitigating their consequences through the development and implementation of appropriate measures.

The development and implementation of such an approach in the Republic of Belarus will ensure a socially acceptable level of DRR in different conditions/types of exposure situations in the medium and long term.

Priority 2. Improving the organizational and legal framework for disaster risk management: The organizational and legal framework for disaster risk reduction at the national, regional and global levels is of great importance for effective and efficient risk management in the sphere of radiation safety [26].

In the Republic of Belarus, the necessary strategies for counteracting risks at the national level have been developed and are in place, including specific plans and activities, for example, the External Emergency for the Belarusian NPP or the "Strategy for Radioactive Waste Management in the Republic of Belarus" [27], defining the competencies of individual state administration bodies in the field of ORB and their coordination at the level of individual sectors of the economy and between sectors, as well as the participation of relevant stakeholders – subjects of the economy.

Priority 3: Investments in disaster risk reduction measures to strengthen resilience: public investments in prevention and risk reduction in the form of:

scientific activities in the field of nuclear energy utilization and counteracting the risks accompanying these activities;

formation of necessary emergency response forces and means.

It is important that investing in the introduction of modern IT and AI-technologies allows improving early warning systems within the framework of radiation monitoring and radioactive contamination mapping, which, along with a preventive approach, is one of the most important priorities in countering radioecological disasters.

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Priority 4: Enhancing disaster preparedness for effective response and implementing the principle of "doing better than before" in recovery, rehabilitation and reconstruction activities: practical activities on the example of the Republic of Belarus on minimizing the consequences of the radioecological disaster – the Chernobyl NPP catastrophe – demonstrate that the recovery, rehabilitation and reconstruction stage is crucial for implementing the principle of "doing better than before", including by combining measures Such an example is the State programs that envisage advanced socio-economic development of the territories affected by the Chernobyl disaster, construction of centralized water supply systems and gasification of rural settlements, expansion of the network of qualified medical services, measures to increase productivity in agriculture, which are designed to ensure an acceptable level of radiation protection and safety and, on the other hand, solve social and domestic problems.

Wide use of nuclear energy for scientific and economic progress, improvement of human life quality, solution of other social or military tasks, creates new sources of risks, threats and disasters of anthropogenic nature (radioecological disasters), the consequences of which may be aggravated by natural phenomena and disasters (hydrometeorological, seismological, other).

In addition to radioecological risks for radiation safety purposes it is important to identify and assess for subsequent management other risks – organizational risks.

Analysis of available information on the sources of radiological and radioecological risks allows us to conclude that the number of realized events important for radiation safety can be estimated in the range from six most significant nuclear and radiation disasters to 1,806 (categories I and II – nuclear and radiation accidents, testing and use of nuclear weapons). The number of potentially dangerous events from other sources of radioecological risks, e. g. transportation of radioactive materials (category V), can reach several millions.

For the Republic of Belarus, the most significant sources of radioecological risks and disasters are nuclear legacy sites, potential nuclear and radiation accidents, transportation of nuclear materials and transboundary transfer.

In the period before 1986, information on current and potential sources of radiation safety threats and risks was clearly insufficient and, due to underestimation of its importance, was not a valid factor of radiation safety.

Belarus had sufficient material, human and financial resources for radiation safety in the conditions of global bomb contamination before 1986, but the Chernobyl NPP catastrophe showed that the system of radiation monitoring of the environment was ineffective in the conditions of emergency exposure.

Retrospective analysis of the practice of the Republic of Belarus in the period from 1960 to April 1986 and in the first period of the Chernobyl NPP catastrophe shows that the lack of long-term systematic planning in case of an accident led to the emergence of scientific, methodological, organizational, technical and informational problems that required resolution at a high scientific level.

In order to successfully solve these problems with respect to the Republic of Belarus, a critical analysis of the sources of disasters and methods of risk management in the field of radiation safety for effective counteraction to radioecological disasters is necessary to act in the long and medium term.

In the long term, radiological/radioecological risk management mechanisms should be maintained on an ongoing basis:

(A) monitor radiological and radioecological risks with subsequent risk assessment and ranking;

(B) ensure effective functioning of the radiation monitoring system (observations, assessment and forecast of radiation situation, mapping), including the use of IT and IA technologies;

(C) ensure the functioning of the early warning system on radioecological threats, risks and disasters, including with the use of IT- and IA-technologies;

(D) provide scientific and information support for risk management and radiation safety activities.

In the medium term:

(A) assess radioecological and radiological risks in the potash industry and phosphate fertilizer production in the situation of planned irradiation (for the Republic of Belarus) in order to make a subsequent decision on the inclusion of additional observation points in the National Environmental Monitoring Program;

(B) to pay special attention to specific difficulties of the Republic of Belarus: long-term radioactive contamination of the environment due to the Chernobyl NPP catastrophe, presence of a large object of "nuclear legacy" – the territory of Polessky State Radioecological Reserve.

To achieve these goals it is necessary to further improve and increase the efficiency of the system of radiation monitoring and forecasting of radiation situation, as well as early warning systems, taking into account all known current and potential threats.

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References

1. Sendajskaya ramochnaya programma po snizheniyu riska bedstvij na 2015–2030 gg. – URL: https://www.unisdr.org/files/43291_russiansendaiframeworkfordisasterri.pdf (data obrashcheniya: 10.12.2024).
2. Krupnye radiacionnye avarii: posledstviya i zashchitnye mery / R. M. Aleksahin, L. A. Buldakov, V. A. Gubanov [i dr.] ; pod obshch. red. L. A. Il'ina, V. A. Gubanova. – M. : IzdAT, 2001. – 752 s.
3. Avdot'in, V. P. Ocenka ushcherba ot chrezvychajnyh situacij prirodnogo i tekhnogennogo haraktera : monografiya / V. P. Avdot'in, M. M. Dzybov, K. P. Samsonov ; MCHS Rossii. – M. : FGBU VNII GOCHS (FC), 2012. – 468 s.
4. Obzor sostoyaniya yadernoj i radiacionnoj bezopasnosti v Respublike Belarus' za 2022 god / Departament po yadernoj i radiacionnoj bezopasnosti Ministerstva po chrezvychajnym situaciyam Respubliki Belarus'. – URL: https://gosatomnadzor.mchs.gov.by/upload/iblock/ff6/dfjims13b2tgwl9jjkrc2j1bw61tuosq/OBZOR_final.pdf (data obrashcheniya: 27.05.2024).
5. Obzor sostoyaniya radiacionnoj bezopasnosti v Respublike Belarus' za 2023 god / Departament po yadernoj i radiacionnoj bezopasnosti Ministerstva po chrezvychajnym situaciyam Respubliki Belarus'. – Minsk : Kovcheg, 2024. – 110 s.
6. SHipko, YU. E. Severnyj poligon / YU. E. SHipko, N. P. Filonov // Informacionnyj byulleten' Mezhvedomstvennogo soveta po informacii i svyazyam s obshchestvennost'yu v oblasti atomnoj energii. – M., 1990. – S. 6–18.
7. Akleyev, A. V. Radioecological consequences of radioactive releases due to weaponsgrade plutonium production at the 'Mayak' facility in the Russian Federation / A. V. Akleyev, M.O. Degteva // Journal of Radiological Protection. – 2021. – Vol. 41(2). – DOI: 10.1088/1361-6498/abdfbb.
8. Atlas Vostochno-Ural'skogo i Karachaevskogo radioaktivnyh sledov, vklyuchaya prognoz do 2047 goda / pod red. YU. A. Izraelya. – M. : IGKE Rosgidrometa i RAN, Fond «Infosfera» – NIA-Priroda, 2013. – 140 s.
9. Atlas zagryazneniya Evropy ceziem posle CHernobyl'skoj avarii: sbornik kart / M. De Kort, G. Dyubua, SH. D. Fridman [i dr.] ; pod obshch. red. YU. A. Izraelya. – Lyuksemburg : Lyuksemburgskoe byuro dlya oficial'nyh izdanij evropejskih soobshchestv, 1998. – 65 s.
10. Long-term dynamics of the Chernobyl-derived radionuclides in rivers and lakes / A. Konoplev, V. Kanivets, G. Laptev [et al.] // Behavior of Radionuclides in Environment II: Chernobyl. / editor: A. Konoplev, K. Kato, S. Kalmykov. – Tokyo : SPRINGER, 2020. – P. 323–348. – DOI: 10.1007/978-981-15-3568-0_7.

11. Sistemnyj analiz prichin i posledstvij avarii na AES Fukusima-1 / R. V. Arutyan, L. A. Bol'shov, A. A. Borovoj [i dr.]. – M. : IBRAE RAN, 2018. – 408 s.
12. Avarii na AES «Fukusima» i vzaimodejstvie radiometricheskih sluzhb Rossii, Belorussii i Ukrainy / V. G. Bulgakov, S. M. Vakulovskij, N. K. Valetova [i dr.] // 50 let obshchegosudartsvennoj radiometricheskoj sluzhbe : materialy nauch.-prakt. konf., Obninsk, 31 maya 2011 g. – Obninsk : NPO «Tajfun», 2011. – S. 20–21.
13. Reestr ob"ektov hraneniya (zahoroneniya) radioaktivnyh othodov, yadernogo naslediya god / Departament po yadernoj i radiacionnoj bezopasnosti Ministerstva po chrezvychajnym situaciyam Respubliki Belarus'. – URL: https://gosatomnadzor.mchs.gov.by/upload/iblock/b70/9q7jadz81g1z8w91xqh05zg8id02ejj5/Reestr-obektov-khraneniya-_zakhoroneniya_-radioaktivnykh-otkhodov_-yadernogo-naslediya.pdf (data obrashcheniya: 10.12.2024).
14. Germenchuk, M. G. Retrospektivnaya ocenka i modelirovanie radioaktivnogo zagryazneniya territorii Respubliki Belarus' v rezul'tate katastrofy na CHernobyl'skoj AES / M. G. Germenchuk, V. V. ZHuravkov // ZHurnal Belorusskogo gosudarstvennogo universiteta. Ekologiya. – 2022. – № 1. – P. 56–67. – URL: https://journals.bsu.by/index.php/ecology/article/view/4792 (data obrashcheniya: 10.12.2024).
15. Atlas sovremennyh i prognoznyh aspektov posledstvij avarii CHernobyl'skoj AES na postradavshih territoriyah Rossii i Belarusi (ASPA Rossiya – Belarus') / pod red. YU. A. Izraelya, I. M. Bogdevicha. – M. : Fond «Infosfera» – NIA-Priroda ; Minsk : Belkartografiya, 2009. – 140 s.
16. SHershnev, O. V. Ocenka vozdejstviya othodov fosfogipsa na komponenty okruzhayushchej sredy / O. V. SHershnev // Ekologicheskij vestnik. – 2016. – № 2 (36). – S. 97–103.
17. Information paper: Radiation Dose Assessment for Transport of Nuclear Fuel Cycle Materials. Revised Edition: (W. Wilkinson, ed.) World Nuclear Transport Institute, London, 2006. – URL: https://www.wnti.co.uk/resource/information-paper-radiation-dose-assessment-for-the-transport-of-nuclear-fuel-cycle-materials (date of access: 09.12.2024).
18. Germenchuk, M. G. Osnovnye mekhanizmy upravleniya riskami v sfere radiacionnoj bezopasnosti i monitoring okruzhayushchej sredy / M. G. Germenchuk, N. N. Cybul'ko // Vestnik Brestskogo gosudarstvennogo tekhnicheskogo universiteta. – 2024. – No. 1(133). – S. 160–168. – DOI: 10.36773/1818-1112-2024-133-1-160-168.
19. Mahon'ko, K. P. Kontrol' za radioaktivnym zagryazneniem prirodnoj sredy v okrestnostyah AES / K. P. Mahon'ko, A. N. Silant'ev, I. G. SHkuratova. – L. : Gidrometeoizdat, 1985. – 136 s.
20. Mahon'ko, K. P. Rukovodstvo po organizacii kontrolya sostoyaniya prirodnoj sredy v rajone raspolozheniya AES / K. P. Mahon'ko. – L. : Gidrometeoizdat, 1990. – 342 s.
21. Izrael, Yu. A. Severs. Modeling of the radioactive fallout in the neighboring to the accident on Chernobyl NPP zone / Yu. A. Izrael, V. N. Petrov // Meteorology and Hydrology. – 1987. – Vol. 7. – P. 5–12.
22. O kontrole radioaktivnogo zagryazneniya : postanovlenie Soveta Ministrov Respubliki Belarus' ot 20.02.2020 № 102. – URL: https://pravo.by/document/?guid=12551&p0=C22000102 (data obrashcheniya: 10.12.2024).
23. O pravovom rezhime territorij, podvergshihsya radioaktivnomu zagryazneniyu v rezul'tate katastrofy na CHernobyl'skoj AES : Zakon Respubliki Belarus' ot 26 maya 2012 g. № 385-Z. – URL: https://etalonline.by/document/?regnum=h11200385 (data obrashcheniya: 10.12.2024).
24. Germenchuk, M. G. Radiacionnyj monitoring okruzhayushchej sredy: uchebnoe posobie / M. G. Germenchuk. – Minsk : Vyshejshaya shkola, 2021. – 278 s.
25. Dinamika sostava radiacionnoj obstanovki i ranzhirovanie radioekologicheskih riskov v Respublike Belarus' / M. G. Germenchuk, N. N. Cybul'ko, P. K. SHal'kevich, T. V. Dashkevich // Vestnik Brestskogo gosudarstvennogo tekhnicheskogo universiteta. – 2024. – No. 2 (134). – S. 136–145. – DOI: 10.36773/1818-1112-2024-134-2-136-145.
26. O radiacionnoj bezopasnosti : Zakon Respubliki Belarus' ot 18.06.2019 N 198-Z, ot 26.06.2019 № 2/2636 // Nacional'nyj pravovoj Internet-portal Respubliki Belarus'. – URL: https://pravo.by/upload/docs/op/H11900198_1561496400.pdf (data obrashcheniya: 05.12.2024).
27. Ob utverzhdenii plana zashchitnyh meropriyatij pri radiacionnoj avarii na Belorusskoj atomnoj elektrostancii (vneshnego avarijnogo plana) : postanovlenie Soveta Ministrov Respubliki Belarus' ot 22 marta 2018 g. № 211. – URL: https://pda.government.by/upload/docs/filecba86a77834f904a.PDF (data obrashcheniya: 10.12.2024).

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ECONOMICS

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ASSESSMENT OF DEMAND AND SUPPLY OF SCIENTIFIC AND TECHNICAL INFORMATION IN THE CONTEXT OF FORECASTING TECHNOLOGICAL TRENDS

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Abstract

Each year, an increasing number of countries base their innovation development strategies on forecasts of scientific and technological development. There are numerous methods for forecasting technological trends, with the STI proposal being a key indicator. This article presents an improved methodology for forecasting technological trends, which includes an analysis of not only the supply of STI but also the demand for it.

In particular, it is proposed to supplement the method based on the analysis of the STI proposal with statistics on the volume of STI user requests on the Internet and in scientific and technical libraries for the necessary keywords related to the object under study.

By comparing the dynamics of STI data in Belarus with current global trends, it is possible to assess the interests of the domestic scientific community in various areas of research and identify the most significant of them. Studying the dynamics, structure and territoriality of demand for STI and comparing these data with the STI supply makes it possible to assess the degree of satisfaction of needs in STI. Based on the STI supply, specialists can draw conclusions about the possible emergence of new technologies and product groups in a certain forecast period.

The results of such analysis can be used to more accurately predict technological trends.

Keywords: methodology, forecasting technology trends, state system of scientific and technical information, scientific and technical information.

ОЦЕНКА СПРОСА И ПРЕДЛОЖЕНИЯ НАУЧНО-ТЕХНИЧЕСКОЙ ИНФОРМАЦИИ В КОНТЕКСТЕ ПРОГНОЗИРОВАНИЯ ТЕХНОЛОГИЧЕСКИХ ТРЕНДОВ

С. В. Макаревич

Реферат

Ежегодно все большее число стран, основываясь на прогнозах научно-технологического развития, выстраивают свою стратегию инновационного развития. Существует множество методов прогнозирования технологических тенденций, основным показателем которых выступают предложения НТИ. В статье представлена усовершенствованная методика прогнозирования технологических тенденций, включающая анализ не только предложения НТИ, но и спроса на нее.

В частности, предлагается дополнить метод, основанный на анализе предложения НТИ, статистикой объемов запросов НТИ пользователей в Интернете и в научно-технические библиотеки по необходимым ключевым словам, относящимся к исследуемому объекту.

Сопоставляя динамику данных по НТИ в Беларуси с актуальными мировыми тенденциями, можно оценить интересы отечественного научного сообщества к различным направлениям исследований, выделить наиболее значимые из них. Изучение динамики, структуры и территориальности спроса на НТИ и сопоставление этих данных с предложением НТИ дают возможность оценивать степень удовлетворенности потребностей в НТИ. Исходя из предложения НТИ, специалисты могут делать выводы о возможном появлении в определенном прогнозном периоде новых технологий и товарных групп.

Результаты такого анализа могут быть использованы для более обоснованного прогнозирования технологических тенденций.

Ключевые слова: методология, прогнозирование технологических тенденций, государственная система научно-технической информации, научно-техническая информация.

Introduction

Due to the increasing role of innovations in the development of national economies [1, 2, 3], the demand for forecasts of innovative and scientific-technological development as a tool of strategic management is growing [4]. Such forecasts allow identifying trends in the development of technologies, assessing the prospects for the emergence of new markets, and also exploring production and personnel capabilities and challenges. The obtained forecasting results help to determine priority areas of technological development, develop scenarios for economic growth and optimize investment risks [5].

As world practice shows, developing and especially developed countries regularly design forecasts of scientific and technological development. In the Russian Federation, since 2013, forecasts of scientific and technological development have also been developed on a regular basis, the latest of which was the Forecast of Scientific and Technological Development of the Russian Federation until 2030. In the Republic of Belarus, a Comprehensive Forecast of Scientific and Technological Progress of Belarus for 2026–2030 and for the period until 2045 (hereinafter – CF STP 2045) has been developed.

One of the common methods used to forecast technological trends is based on studying the dynamics and structure of scientific publications and registered patents, i.e. on the analysis of the STI proposal both on a global scale and by comparing this data for individual countries [6, 7, 8]. By comparing the dynamics of data in Belarus with the corresponding global trends, it is possible to assess the interest of the domestic scientific community in various areas of research and identify the most relevant ones. Based on the STI proposal, specialists can draw conclusions about the possible emergence of new technologies and product groups in a certain forecast period.

The purpose of this study is to improve the methodology for forecasting technological trends by including not only an analysis of the supply of STI, but also an analysis of the demand for STI.

1. Analysis of the dynamics of the STI proposal in the CF STP 2045

The method of forecasting technological trends based on the STI proposal (hereinafter referred to as the STI proposal method) was used along with other methods in the development of the Comprehensive Forecast of Scientific and Technological Progress of the Republic of Belarus for 2026–2030 and for the period until 2045 [9].

The CF STP 2045 presents a list of forecasting objects, which are understood as innovative goods, product groups and technologies.

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For each forecasting object, the values of parameter groups were determined: global trends in publications and patents; world market capacity; the state of the infrastructure of the Republic of Belarus. The first two groups of parameters characterized the demand for the forecasting object in the forecast period, the third group of parameters – the feasibility of the forecasting object in the forecast period.

Global trends in publications and patents for each forecast object were assessed based on an analysis of scientific publications in foreign sources and patents in foreign patent databases. For this purpose, the number of foreign publications and international patents for the previous 5 years was determined for each forecast object.

The group of parameters characterizing the feasibility of the object also included such parameters as the domestic scientific publications and patents in bibliographic and patent registers, databases and other STI resources.

As an example, Figures 1–4 shows data on the forecasting object "System for assessing transport flow parameters based on processing navigation data on vehicle movement" (hereinafter referred to as the "Assessment system...") from the CF STP 2025, which was implemented in 2018 [10], the methodology of which will make it possible to determine the capacity of the road network, the efficiency of using the existing network, the volume and structure of transport demand.

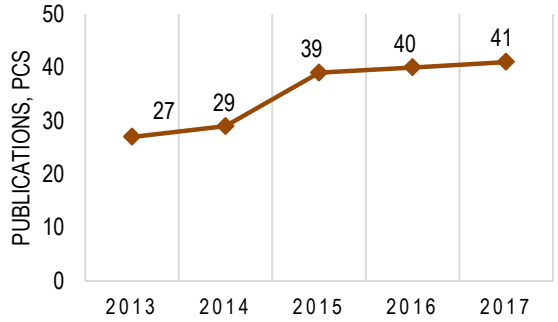

Figure 1 – Dynamics of international publications on the forecast object "Assessment system…"

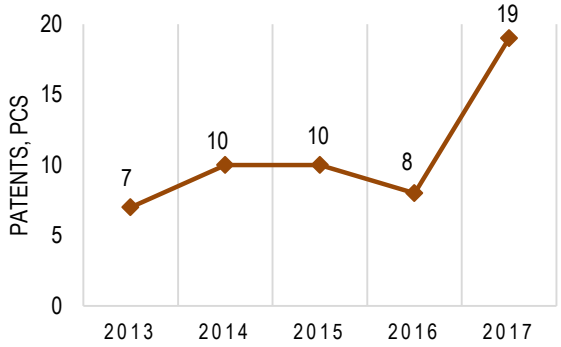

Figure 2 – Dynamics of international patenting for the forecast object "Assessment system…"

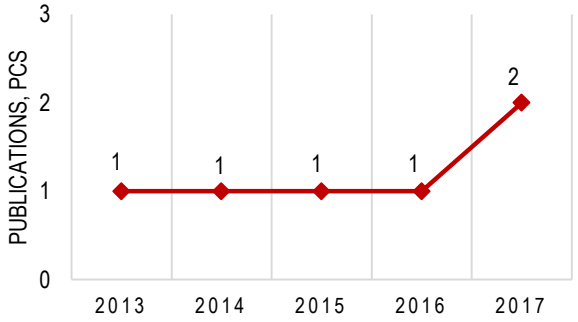

Figure 3 – Dynamics of publications in the Republic of Belarus for the forecast object "Assessment system…"

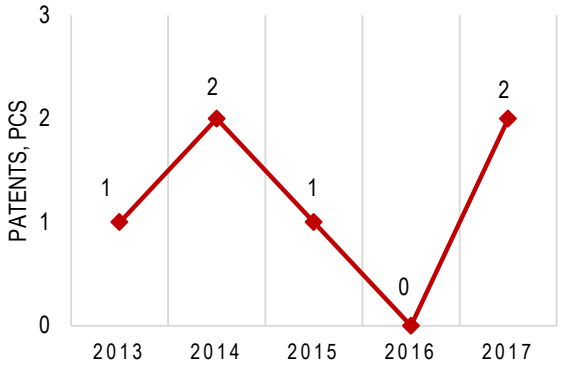

Figure 4 – Dynamics of patenhting in te Republic of Belarus for the forecast object "Assessment system…"

Figures 1–2 show that the activity in international publications and patents increases annually in relation to the forecasting object under consideration. In turn, Figures 3–4 show low activity in the field of publications and patents in the Republic of Belarus. It can be concluded that there is high interest in the forecasting object in the international scientific community and that this object has great prospects as an innovative product. From the graphs in Figures 3–4 it follows that the reserve in the country is low, and taking into account global prospects, it is worth assessing the possibility and feasibility of research in this direction.

2. Analysis of the dynamics of demand for STI

It is necessary to distinguish between the demand for STI and the supply of STI. As already stated above, the supply of STI is understood as published scientific works and registered patents both in paper and electronic form. The demand for STI is understood as a set of search queries aimed at finding scientific and technical information (search among STI offers). Accordingly, the demand for STI can serve as an indicator of the demand for certain areas of STI.

In the forecasting method described above, based on studying the STI supply, the basis for further forecasting is the already created and publicly available STI (STI supply). However, modern information technologies allow not only to analyze the STI already available in the public domain (i.e., the STI supply), but also to study the volumes of search queries for STI in various categories, made both in global and local networks (i.e., the demand for STI). Studying the dynamics, structure, and territoriality of STI demand and comparing this data with the STI supply makes it possible to assess the degree of satisfaction of STI needs. The results of such an analysis can be used for more substantiated forecasting of technological trends.

Demand for STI can be tracked in various ways and by various organizations or individuals (individually). To perform a semantic search for data on the number of requests, it is necessary to define the keywords of the area of interest. Data on the number of queries is searched for on the internet using various specialized program that show user query activity: *Google trends, Google Analytics, Google Ads, Keyword Tool, Key Collector, Wordstat* and etc.

These software resources allow you to see the demand of Internet users for STI by specified keywords. They display statistics: on the dynamics, structure and territoriality of demand. It is necessary to mention a particular feature of these systems: they do not include information on the dynamics of queries made before 2004.

The methodology outlined above should also be supplemented with statistics on user queries to scientific and technical libraries for the necessary keywords related to the studied STI object.

As an example, Figure 5 provides data on the STI object "Artificial Intelligence" (hereinafter referred to as AI). The given figure shows the dynamics of publications of scientific articles and registration of patents as a percentage of the base year 2004 for the period 2004–2022. It also shows the dynamics of Internet user requests for this STI object as a percentage of the base year 2004.

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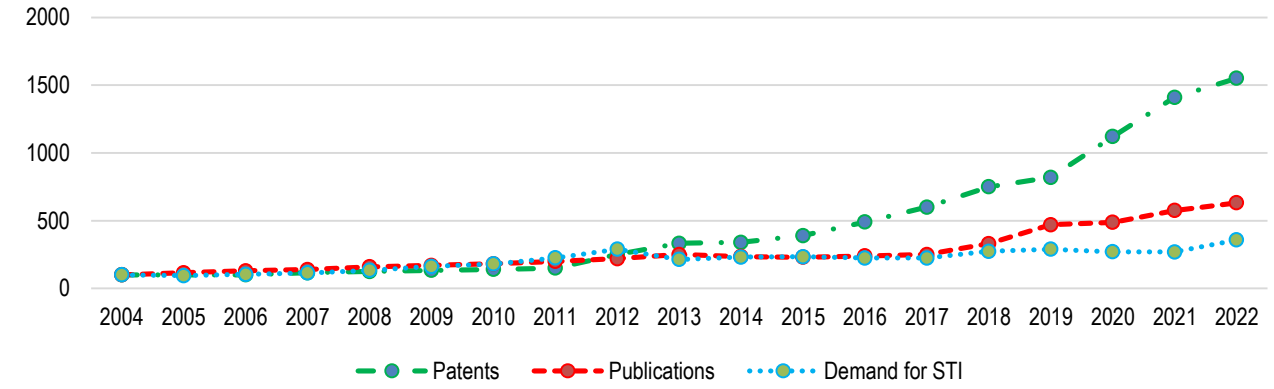
а) In the period 2004–2022.



б) In the period 2009–2014.

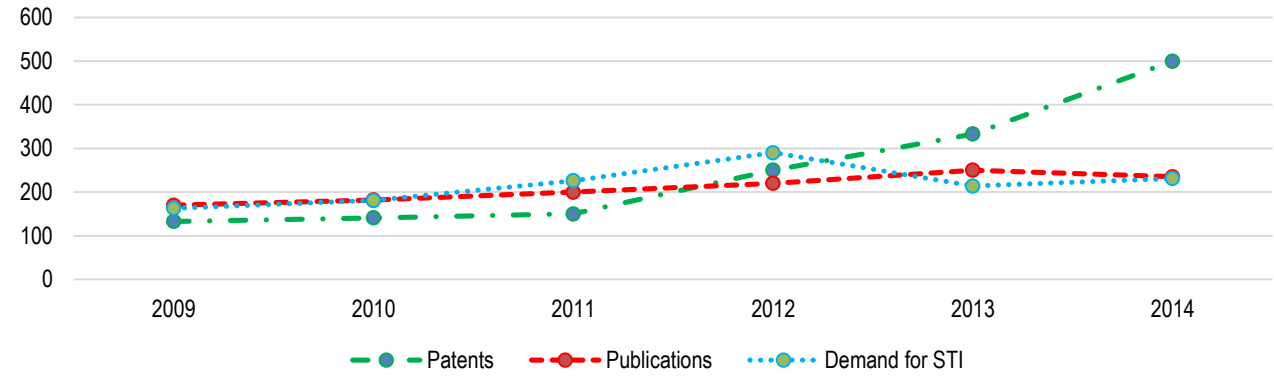


Figure 5 – Dynamics of STI demand for the STI object "*Artificial Intelligence*" [11]

From Figure 5 it is evident that the growth rate of demand for STI and the supply of STI for the STI object under consideration practically repeat each other's dynamics with a supply lag of an average of 1 year.

This situation can be explained as follows: To research a given topic or develop a new project, a scientific team needs to explore a specific area, which consequently leads to an increase in demand for STI. The next stage involves preparing a scientific paper and submitting it for publication (or preparing a patent application). Occasionally, there may be a surge in demand for STI, which is driven by a new discovery or a change in approach within the research area. Figure 6 shows a surge in user queries related to the STI object "Artificial Intelligence."

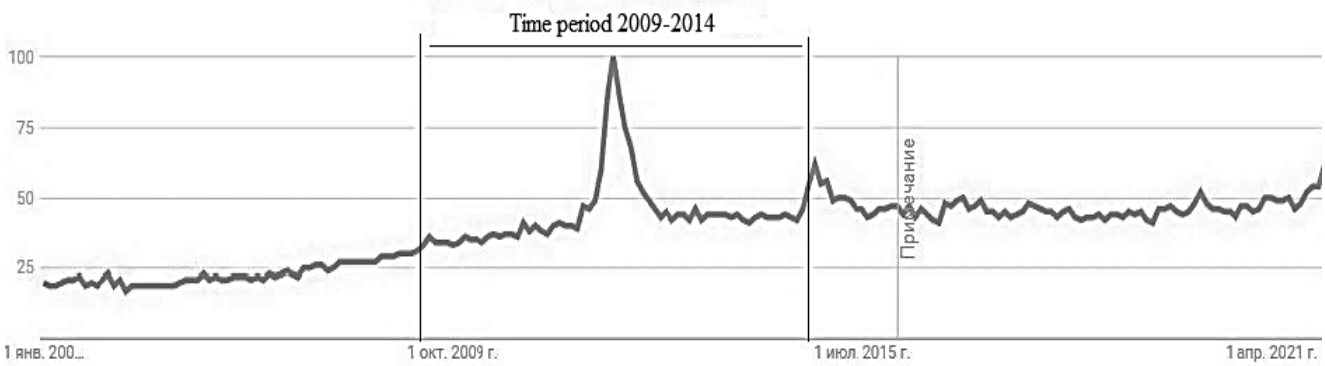


Figure 6 – Activity graph for the STI object "*Artificial Intelligence*" in the period 2004–2021, displayed in the *Google trends* [12]

A surge in STI queries is noted starting in 2010. This increase is linked to the growth in computer processing power, which enabled the combination of Big Data with Deep Learning methods based on artificial neural networks. Subsequently, this led to the successful application of artificial intelligence in many fields (such as speech and image recognition, natural language understanding, autonomous vehicles, etc.), which, in turn, marked a resurgence of AI [13].

Similarly, we can consider the demand for STI in the area of Big Data.

Figure 7 shows the growth of activity in the mentioned object since 2011, which is caused by the trend related to the analysis of big data by scientific universities within the framework of scientific and statistical research. By early 2012, the volume of data had grown to massive scales, creating a need for its systematization and practical application.

From 2014 onwards, leading global universities specializing in applied engineering and IT disciplines began to focus on Big Data. Subsequently, IT corporations such as Microsoft, IBM, Oracle, and EMC, followed by Google, Apple, Facebook, and Amazon, became involved in data collection and analysis. Today, large industry companies and government agencies utilize Big Data.

The demand for the STI object "Big Data" can be examined not only on a global scale but also within individual countries.

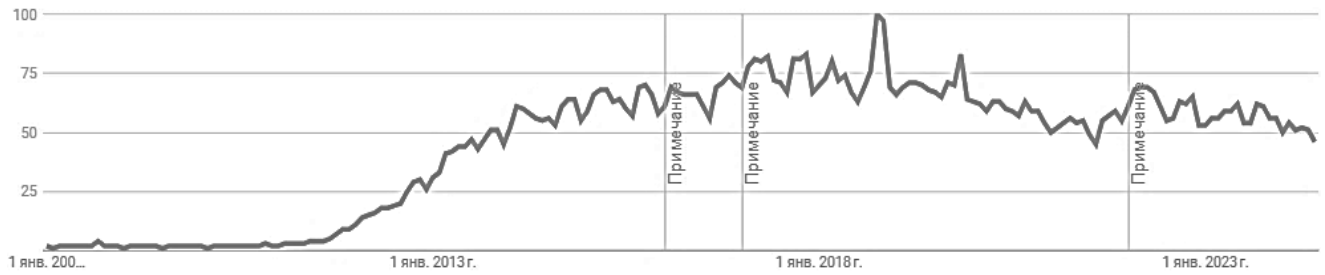


Figure 7 – Activity graph for the STI object "Big Data" in the period 2008–2024, displayed in the *Google trends* [12]

The dynamics of STI queries in the Russian Federation clearly show a surge in interest in the research object (Figure 8). This is evident, as in 2019, 68 % of organizations tested the implementation of Big Data analysis tools, which is recognized as the most frequently adopted technology in Russian companies [14].

It is also useful to compare the demand for STI across different countries and then rank them, which involves identifying potentially developed countries and those developing in various research areas.

When comparing the demand for STI related to Big Data in South Korea (Figure 9) and the Russian Federation (Figure 8), it is noticeable that the surge in South Korea occurred in 2017, while in Russia, it was at the end of 2019. The difference in the timing of the demand surge for the research object allows us to infer which country is potentially developed and which is developing in this direction.

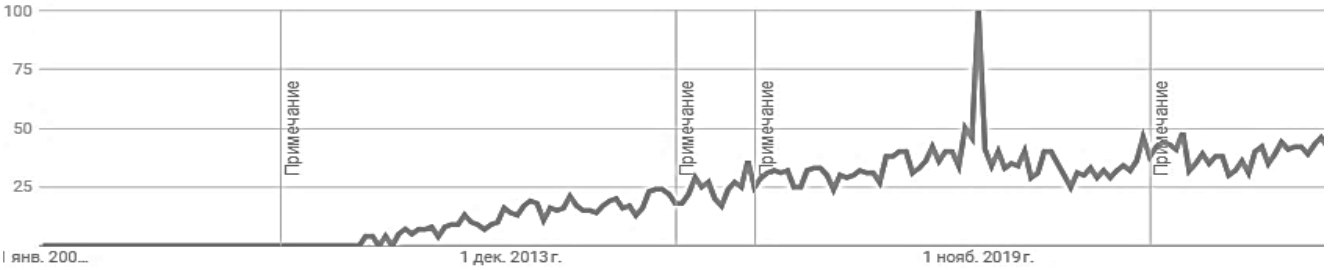


Figure 8 – Graph of activity in the Russian Federation for the STI object *"Big Data"* in the period 2008–2024, displayed in the *Google trends* program [12]

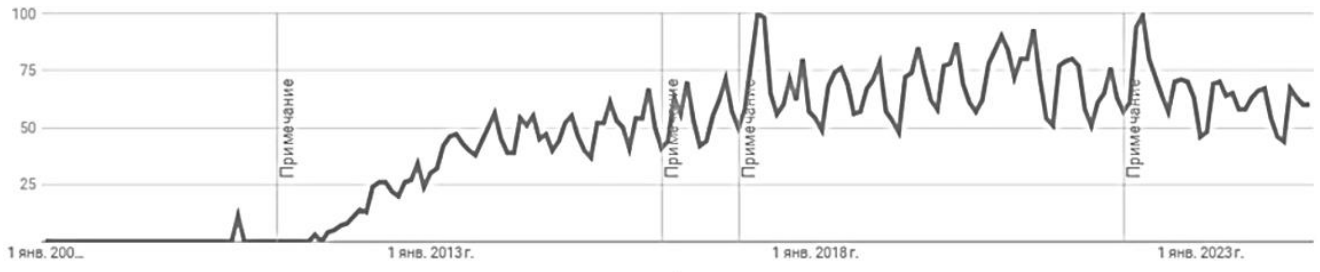


Figure 9 – Graph of activity in the Republic of Korea for the STI object "*Big Data*" in the period 2008–2024, displayed in the *Google trends* program [12]

3. Collection and analysis of data on supply and demand of STI in the State System of Scientific and Technical Information of the Republic of Belarus

As is well known, the vast amount of scientific and technical documentation generates enormous information flows, which are increasing annually. Consequently, there is a growing need for the development of effective STI monitoring systems. For example, a large amount of new digital information is created globally each year [15]: in 2018 alone, approximately 33 zettabytes (10^{21} bytes) were generated, and between 2020 and 2021, humanity produced more information than in all of previous history. Furthermore, the volume of generated information is expected to continue increasing each year. According to forecasts, by 2025, the annual global volume of generated information may reach 175 zettabytes (Figure 10) [15].

The above information indicates colossal information flows that require study. For these purposes, specialized systems have been created and are successfully operating in a number of technologically advanced countries. The Republic of Belarus is no exception.

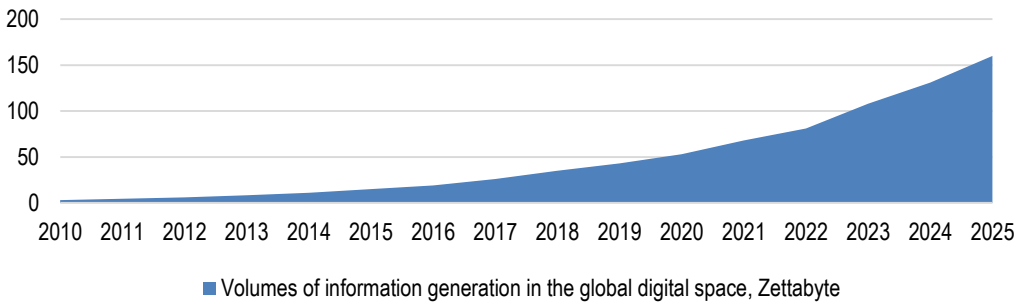


Figure 10 – Dynamics of generation of new information in the global digital space (2010–2025)

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Currently, Belarus has a functioning State System of Scientific and Technical Information (SSTI), which includes: republican information centers; library infrastructure; industry-specific STI centers and services; regional STI centers; a system for publishing and distributing scientific and technical literature; and an information and telecommunication infrastructure. The primary tasks of these components are the collection, storage, and dissemination of STI [16, 17, 18, 19].

Empowering the SSTI of the Republic of Belarus with the capability to analyze the dynamics and structure of the demand for and supply of scientific and technical information will allow to use this data in forecasting scientific and technological progress. Analyzing STI demand will enable the comparison of STI demand with its supply and facilitate the early identification of emerging technological trends.

It would also be beneficial to develop an information system that automatically tracks surges in demand for STI to identify new technological trends at their formative stage. This would allow for the anticipation of technological trends approximately one year earlier compared to the analysis of STI supply alone.

The obtained data can also be utilized by research organizations when forming prospective research and development plans, where labor savings can be achieved by reducing research work on less promising areas [20, 21].

Conclusion

Each year, an increasing number of countries conduct forecasts of scientific and technological development to determine priority areas for national economic development scenarios and to optimize and reduce investment risks. The Republic of Belarus is no exception.

In our country, forecasting methods based on the analysis of the STI supply are used. This method was used in the Comprehensive Forecast of Scientific and Technological Progress of Belarus for 2026–2030 and up to 2045. It is based on studying the dynamics and structure of scientific publications and registered patents both globally and by comparing this data across countries, which allows to identify global development trends. The domestic scientific publications and patents is another important parameter used in this method to assess the feasibility of a forecasting object**.**

The method based on STI supply analysis can be supplemented with statistics on STI query volumes from users on the internet and in scientific and technical libraries using relevant keywords related to the research object. Studying the dynamics, structure, and territorial distribution of STI demand and comparing this data with the STI supply makes it possible to assess the extent to which STI needs are being met. The results of such analysis can be used for more substantiated forecasting of technological trends.

Given the functions and tasks, as well as the departmental structure, it is advisable to assign the responsibilities for monitoring and analysing STI demand to the State System of Scientific and Technical Information (SSTI).

This innovation will improve the efficiency and accuracy of forecasts of scientific and technological progress conducted in the Republic of Belarus.

References

1. Gurskij, V. L. Formirovanie edinogo nauchno-tekhnologicheskogo prostranstva Soyuznogo gosudarstva: potencial uchastnikov, mekhanizmy, perspektivy / V. L. Gurskij, E. V. Presnyakova, M. B. Petrov // Ekonomicheskaya nauka segodnya : sb. nauch. st. / Belorus. nac. tekhn. un-t. – Minsk, 2022. – Vyp. 16. – S. 141–152.
2. Guc, YU. V. Sfera nauki v kontekste formirovaniya intellektual'nogo kapitala / YU. V. Guc, A. V. Bondar' // Nauch. tr. / Belorus. gos. ekon. un-t. – Minsk, 2021. – Vyp. 14. – S. 115–122.
3. ZHukovskaya, O. YU. Sushchnost', formirovanie i osobennosti ocenki nacional'nyh innovacionnyh ekosistem / O. YU. ZHukovskaya // Nauka i innovacii. – 2022. – № 8. – S. 51–56.
4. SHumilin, A. G. O perspektivah nauchno-tekhnicheskogo i innovacionnogo razvitiya Respubliki Belarus' (sostoyanie, problemy, puti resheniya) / A. G. SHumilin // Sistema «nauka – tekhnologii – innovacii»: metodologiya, opyt, perspektivy : materialy Mezhdunar. nauch.-prakt. konf., Minsk, 1 dek. 2016 g. / Centr sistem. analiza i strateg. issled. NAN Belarusi ; redkol.: V. V. Goncharov (otv. red.) [i dr.]. – Minsk, 2016. – S. 4–12.
5. Solodovnikov, S. YU. Modernizaciya belorusskoj ekonomiki i ekonomika riskov: aktual'nye problemy i perspektivy / S. YU. Solodovnikov, T. V. Sergievich, YU. V. Meleshko. – Minsk : Belorus. nac. tekhn. un-t, 2019. – 491 s.
6. Zianchuk, M. Foresighting technological and innovative development of Belarus / M. Zianchuk, I. Saltanova // MEST Journal. – 2020. – № 2 (8). – P. 192–199. – DOI: 10.12709/mest.08.08.02.22.
7. Zianchuk, M. Uneven development of production innovations and consumer innovations and its conse-quences for economic growth / M. Zianchuk // Vestnik of Brest State Technical University. – 2023. – No. 3(132). – P. 99–102.
8. SHlychkov, S. V. Metodologicheskie osnovy razrabotki Kompleksnogo prognoza nauchno-tekhnicheskogo progressa Respubliki Belarus' / S. V. SHlychkov, N. F. Zen'chuk, I. V. Saltanova // Novosti nauki i tekhnologij. – 2018. – № 4 (47). – S. 10–18.
9. Gosudarstvennoe uchrezhdeniya Belorusskiy institut sistemnogo analiza i informatsionnogo obespecheniya nauchno-tekhnicheskoy sfery. – URL: http://www.belisa.org.by/ru/KPNTP (data obrashcheniya: 25.07.2024).
10. Kompleksnyj prognoz nauchno-tekhnicheskogo progressa Respubliki Belarus' na 2021–2025 gg. i na period do 2040 g. / pod red. A. G. SHumilina. – Minsk : GU «BelISA», 2019. – 750 s.
11. Elsevier. – URL: https://www.elsevier.com/?a=823654 (data obrashcheniya: 15.09.2022).
12. Trends.google. – URL: https://trends.google.ru/trends/explore?date=all&q=AI (data obrashcheniya: 15.09.2023).
13. United Nations Educational, Scientific and Cultural Organization. – URL: https://ru.unesco.org/courier/2018-3/iskusstvennyy-intellekt-mezhdu-mifom-i-realnostyu (data obrashcheniya: 15.09.2023).
14. DELOVOY PROFIL [site]. – URL: https://delprof.ru (data obrashcheniya: 08.07. 2024).
15. Reinsel, D. The digitization of the world from edge to core: an IDC white paper – #US44413318 / D. Reinsel, J. Gantz, J. Rydning // Seagate. – URL: https://www.seagate.com/files/www-content/our-story/trends/files/idc-seagate-dataage-whitepaper.pdf (data obrashcheniya: 14.12.2023).
16. Makarevich, S. V. Improving SSTI for innovative economic development: experience of Belarus / S. V. Makarevich // Management, Economics, Education, Science & Society Technologies. – № 2020. – № 2 (8). – P. 130–136.
17. Kosovskij, A. A. Razvitie gosudarstvennoj sistemy nauchno-tekhnicheskoj informacii Respubliki Belarus' / A. A. Kosovskij // Razvitie informatizacii i gosudarstvennoj sistemy nauchno-tekhnicheskoj informacii : RINTI – 2018 : XVII Mezhdunar. konf., Minsk, 20 sent. 2018 g. : doklady / Ob"ed. in-t problem informatiki NAN Belarusi ; nauch. red.: A. V. Tuzikov, R. B. Grigyanec, V. N. Vengerov. – Minsk, 2018. – S. 6–9.
18. Makarevich, S. Rol' gosudarstvennyh resursov nauchno-tekhnicheskoj informacii v usloviyah formirovaniya innovacionnoj ekonomiki / S. V. Makarevich // Sistema «Nauka – tekhnologii – innovacii» : metodologiya, opyt, perspektivy» : materialy Mezhdunar. nauch.-prakt. konf., Minsk, 23–24 sent. 2021 g. / Centr sistemnogo analiza i strategicheskih issledovanij NAN Belarusi. – Minsk, 2021.– S. 299–302.
19. Ugrinovich, E. V. Preodolenie negativnyh trendov, ugroz i riskov v processe formirovaniya mezhdunarodnoj informacionnoj infrastruktury nauki i obrazovaniya / E. V. Ugrinovich, D. V. Mun, D. V. Popeta // Sistema «nauka – tekhnologii – innovacii»: metodologiya, opyt, perspektivy : materialy Mezhdunar. nauch.-prakt. konf., Minsk, 26–27 okt. 2017 g. / Centr sistem. analiza i strateg. issled. NAN Belarusi ; redkol.: V. V. Goncharov (otv. red.) [i dr.]. – Minsk, 2017. – S. 54–64.
20. Bajnev, V. F. Poleznostnyj metod analiza nauchno-tekhnicheskoj deyatel'nosti / V. F. Bajnev, S. V. Makarevich // Ekonomicheskaya nauka segodnya : sb. nauch. st. / Belorus. nac. tekhn. un-t. – Minsk, 2023. – Vyp. 17. – S. 41–50.
21. Bajnev, V. F. Resursno-poleznostnyj podhod k obespecheniyu tekhnologicheskoj bezopasnosti Respubliki Belarus' / V. F. Bajnev, S. V. Makarevich // Nauka i innovacii. – 2023. – № 5. – S. 27–32.

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MECHANISM FOR THE DEVELOPMENT OF DIGITAL TRANSFORMATION OF TRANSPORT AND LOGISTICS ACTIVITIES

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Abstract

In modern economic conditions, the management of transport and logistics flows is associated with the universal penetration of digital technologies. Digitalization allows for the optimization of the entire supply chain, including transportation and warehousing operations. Digital technologies provide opportunities to increase the economic efficiency of business processes in logistics, improve the safety and quality of transport and logistics flow management, and enhance the competitiveness of entities in transport and logistics systems.

This article presents the research results of the mechanism for the digital transformation development of transport and logistics activities. The developed mechanism includes the process of automation and informatization of business processes; the process of combining various information technologies; the process of creating a model reflecting data online; the process of deciphering the received data; the process of compiling forecast data, as well as the process of editing the system without human intervention. The ultimate goals of developing this mechanism may be the creation of a digital product development system, the formation of a digital platform for integration into a flexible network, the creation of a digital transformation ecosystem, the implementation of flexible and integrated supply chain management, the development of a KPI system and evaluation of the effectiveness of transport and logistics activities, the selection and hiring of qualified personnel, the creation of an integrated information system and cloud data storage; as well as the implementation of electronic document management and a digital modeling and forecasting system.

The comprehensive development and transformation of transport and logistics systems through their digitalization will ensure such potential results as the transition to new business models for the functioning of systems, flexible communication channels in the process of performing transport operations, as well as to products and business processes that are based on fundamentally new approaches to information management using digital technologies, and, as a result, to a significant increase in the efficiency of transport and logistics systems and their long-term sustainability.

Keywords: transport and logistics activities, development, digital transformation, mechanism.

МЕХАНИЗМ РАЗВИТИЯ ЦИФРОВОЙ ТРАНСФОРМАЦИИ ТРАНСПОРТНО-ЛОГИСТИЧЕСКОЙ ДЕЯТЕЛЬНОСТИ

П. И. Лапковская, Е. А. Семашко

Реферат

В современных экономических условиях управление транспортно-логистическими потоками связано со всеобщим проникновением цифровых технологий. Цифровизация позволяет осуществлять оптимизацию всей цепи поставок, включая перевозку и складские операции. Цифровые технологии обеспечивают возможности повышения экономической эффективности бизнес-процессов в логистике, повышают безопасность и качество управления транспортно-логистическими потоками, усиливают конкурентоспособность субъектов транспортно-логистических систем.

В данной статье представлены результаты исследования по разработке механизма развития цифровой трансформации транспортно-логистической деятельности. Разработанный механизм включает процесс автоматизации и информатизации бизнес-процессов; процесс объединения различных информационных технологий; процесс создания модели, отражающей данные в режиме online; процесс расшифровки полученных данных; процесс составления прогнозных данных, а также процесс редактирования системы без участия человека. Конечными целями разработки данного механизма могут быть создание цифровой системы разработки продукции, формирование цифровой платформы для интеграции в гибкую сеть, создание экосистемы цифровой трансформации, внедрение гибкого и интегрированного управления цепями поставок, разработка системы KPI и оценки эффективности транспортно-логистической деятельности, осуществление подбора и найма квалифицированного персонала, создание интегрированной информационной системы и облачных хранилищ данных; а также внедрение электронного документооборота и системы цифрового моделирования и прогнозирования.

Комплексное развитие и преобразование транспортно-логистических систем путем их цифровизации обеспечат такие потенциальные результаты как переход к новым бизнес-моделям функционирования систем, гибким каналам коммуникаций в процессе выполнения транспортных операций, а также к продуктам и бизнес-процессам, которые базируются на принципиально новых подходах к управлению информацией с использованием цифровых технологий, и как следствие, к значительному повышению эффективности транспортно-логистических систем и их долгосрочной устойчивости.

Ключевые слова: транспортно-логистическая деятельность, развитие, цифровая трансформация, механизм.

Introduction

In the 21st century, rational management of transport and logistics flows is an important task for the development of the logistics system of any state, the solution of which cannot be imagined without the use of modern information technologies. In the process of research, the emerging set of various information technologies gives rise to such terms as informatization, digitalization and digital transformation.

A full description of the presented concepts is described in the Law of the Republic of Belarus "On Information, Informatization and Information Protection" dated November 10, 2008 No. 455-Z and STB 1693-2009 "Informatization. Terms and Definitions". Thus, informatization is an organizational, socio-economic and scientific-technical process that provides conditions for the formation and use of information resources and the implementation of information relations [1, 2]. Digitalization is a new stage of automation and informatization of economic activity and public administration, the process of transition to digital technologies, which is based not only on the use of information and communication technologies to solve production or management problems, but also on the accumulation and analysis of big data with their help in order to forecast the situation, optimize processes and costs, attract new contractors, etc. [3]. Digital transformation is a manifestation of qualitative, revolutionary changes, consisting not only in individual digital transformations, but in a fundamental change in the structure of the economy, in the transfer of centers for creating added value to the sphere of building digital resources and end-to-end digital processes. As a

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result of digital transformation, a transition to a new technological and economic structure is carried out, and new sectors of the economy are created [3]. Digitalization can be considered in three dimensions: 1) the use of digital technologies in the business sphere, associated with the formation, optimization and transformation of business processes, the transformation of digital data into useful knowledge; 2) use in a specific environment, for example, in the creation of a "digital workplace"; 3) the introduction of digital technologies in all areas of social and humanitarian activities [4]. To assess the effectiveness and level of digital transformation of transport and logistics, various approaches can be used [5, 6, 7, 8].

Development of organizational and economic foundations for the mechanism for developing digital transformation of transport and logistics activities

Today, it is generally recognized that the future development of the economy, and subsequently of all mankind, is associated with the digital economy. In this regard, the attention of researchers is increasingly attracted by theoretical and practical problems of digitalization. The continuous process of digitalization development is associated with the endless growth of information flows. The constant growth of volumes of heterogeneous information, which can come in numerous directions, has recently accompanied both large and fairly small transport and logistics organizations. All information flow entering the organization is subject to certain storage, evaluation, structuring, analysis and accounting. Without the use of specialized information systems, it is difficult and almost impossible to solve the above problem, and even with a huge amount of information. And since today the most important factor is the speed of response to incoming requests in doing business, organizations that want to work effectively need to radically improve the processing of incoming and outgoing information flows. Digital technologies make it possible to accumulate huge amounts of information that companies not only can, but must use to make management decisions. The vast majority of areas of human activity, including logistics, are subject to global automation. In other words, thanks to the development of digitalization, new opportunities have emerged for the creation and development of end-to-end management systems for material and related flows in the economy, which has contributed to the development of logistics as an activity for managing these flows based on pre-developed, controlled indicators. A marketing study of the business services market by the consulting company Deloitte showed that only a third of all surveyed representatives of the largest companies are confident that they will be able to adapt to the conditions that the digitalization era will set for them. In addition, J. Chambers' forecast is as follows: in the next decade, of all the companies studied to date, only slightly more than half (about 60 %) will remain operating in the economy, which is due to the unpreparedness of companies for the total digitalization of business [9].

Today, there are already many examples of brands that used to have a large market share, but today their customer base has become invisible (Kodak, MySpace, Motorola, Blackberry, etc.). Having studied the other side of this phenomenon, it is necessary to note those corporations that, on the contrary, used this situation to improve their position in the market (Google, Apple, Microsoft, Amazon, etc.) [10]. McKinsey&Company experts claim that "in today's reality, innovations are needed by businesses not only to accelerate the pace of development, strengthen leadership and break away from competitors, but also for timely protection against damage to the industry in the event of the introduction of radical innovations that make entire areas of business economically inexpedient" [11]. When managing transport and logistics flows, various factors arise that significantly affect the process under consideration. Such factors, according to K. V. Kholopov are divided into external and internal [12]. External factors impose greater uncertainty on the process of managing transport and logistics flows. Based on this, their study should be approached with a greater degree of responsibility and analysis should be carried out with a large number of experimental samples (examples) [12].

In the conditions of the economic development that modern society dictates to us, the management of transport and logistics systems and flows, as noted earlier, is associated with the universal penetration of digital technologies.

Digitalization allows you to optimize the transport and logistics process. Digital technologies guarantee increased economic efficiency of business processes in logistics, improve the safety and quality of transport and logistics services, and provide a significant competitive advantage. At the same time, according to some authors, at the current stage of digital transformation in international road transport, there is a fragmentary use of modern digital technologies, which is due to their disunity [13]. But with the digitalization of the transport industry, due to a certain unification of cargo and commercial information, it is possible to introduce an "electronic transportation passport" [14].

It should be noted that digital traceability of the movement of products, goods, services and digital assets is one of the six top priorities for the implementation of the digital agenda of the Eurasian Economic Union (EAEU) until 2025 [15], which is confirmed by the introduction of electronic document management systems by the customs authorities of the EAEU [16]. In addition, Resolution No. 66 of the Council of Ministers of the Republic of Belarus dated February 2, 2021 approved the State Program "Digital Development of Belarus" for 2021–2025, which determined the creation of an integration platform for the national electronic logistics system [17].

Today, there are already some models that systematize the process of digital transformation of an organization.

The first model is presented by the Center for Digital Business at the Massachusetts Institute of Technology. The essence of this model is that all its blocks and elements are interdependent. The first block is a block consisting of elements characteristic of working with clients, i.e. the relationship with the external environment. The second block characterizes the production process itself. The third block is the model itself, which must be achieved using the developments of the first and second blocks. The third block is the goal to be achieved [18].

The second model is the digital maturity model (DMF) of Deloitte. This model assesses the level of digital transformation using the following indicators:

- client;
- production process;
- organization strategy;
- production technology;
- structure;
- organization culture.

At the initial stage, the organization's strategy is studied. Based on the results of its study, further directions of the organization's development in the field of digital transformation are visible [19].

Such a task as digital transformation of any process, or business in general, and in this case flow management, is in service with the vast majority of organizations among various types of economic activity. Being a fairly new direction that has replaced partial computerization and informatization of business processes, digitalization creates conditions for the growth of the number of companies that need to develop and implement their own digital software products. Thus, there is an increase in the innovative component of business, which in turn contributes to the effective development of the economy and logistics. It is important to note the opinion of T. G. Shulzhenko, which says that digitalization of transport and logistics flow management contributes to the emergence and further development of innovative production, growth of competitiveness in conditions in which the role of individualization of consumer requirements for goods and services increases [20]. However, based on the above, logistics at the current stage of development is somewhat behind such types of economic activity as banking services, trade, telecommunications and communications, etc. In the vast majority of transport and logistics organizations, when organizing the work process, there are many manual operations, the organization's assets are not used fully effectively, which slows down the process of digital transformation of business. It is important to note that today many scientific papers have been written on digitalization, which define its conceptual apparatus, scope of application, technological component of digital transformation, etc., but it is difficult to find any recommendations that need to be followed by transport and logistics organizations implementing digitalization tools, which is due to the complexity of their perception at the moment.

Thus, the study of the main and auxiliary business processes of the organizations contributes to the creation of a special mechanism for the development of digital transformation of transport and logistics activities, which would be standard for any logistics organization.

Obviously, the digitalization of an organization is a rather long and complex process that requires a certain level of attention. In addition, the digital transformation of business at its various stages should have a positive effect on the company's performance indicators. To develop a mechanism for the development of digital transformation of transport and logistics activities, it is necessary to solve the following problems:

- define the goals and objectives of the mechanism;
- define the subjects and objects of the mechanism;
- develop the principle of operation of the mechanism.

The purpose of the developed mechanism is to structure the sequence of actions for organizations moving to digital transformation of their activities.

To achieve this goal, it is necessary to solve the following problems:

– develop a sequence of stages for the mechanism of digital transformation of transport and logistics activities;

– provide for a list of activities required at one or another stage of the developed mechanism;

– ensure the interconnection between all stages of the digital transformation mechanism of transport and logistics activities.

The objects of the mechanism for developing digital transformation of transport and logistics activities are the transport and logistics flows of the organization in the context of digital transformation, as well as the transport and logistics system of the country as a whole. The subjects of the mechanism are various organizations that carry out any transport and logistics activities. When developing specific stages of digitalization, it is necessary to take into account that each stage should be based on the previous one and include a description and a set of tools necessary for its implementation. The mechanism for developing digital transformation of transport and logistics activities developed by the authors includes a set of stages and activities characteristic of digitalization.

Stage 1. The process of automation and informatization of business processes. At this stage, you can consider the use of specialized systems for managing transport and logistics flows in the organization. For example, to informatize the process of transporting goods, you can provide for the introduction of a satellite tracking system that will allow you to control the order fulfillment time. If we consider an enterprise that has an established warehousing system, then at the first stage we can consider connecting a WMS system (Warehouse Management System) to manage the flow of goods that pass through the warehouse.

This stage is the basis of this mechanism. Its peculiarity consists in partial automation and informatization, that is, the information technologies present in the organization at this stage are used without connection into a single whole.

Stage 2. The process of combining various information technologies. At the second stage, the information technologies used by the organization are combined, which are necessary for solving issues that arise in the process of doing business, namely flow management. Such products include TMS (Transportation Management System), WMS, automated inventory management systems and others, which can be combined, for example, in the ERP (Enterprise Resource Planning) system.

However, it should be noted that despite the use of various information and communication technologies that are capable of mutual connection and exchange of information data, total integration in this area has not been formed at the present stage.

Stage 3. The process of creating a model that reflects data online. Providing data in real time is possible by installing RFID tags. These tags have the ability to record events and the state of objects online throughout the entire process of information flow through the organization's logistics system. Such information will contribute to making more effective decisions due to the constantly available up-to-date information.

Stage 4. The process of deciphering the received data. In order to use and present the received data correctly, it is necessary to process and analyze them correctly. Thus, generalization, understanding the nature and role of the received information and analysis of large amounts of data leads to making adequate management decisions in a relatively short time. Since at this stage it is necessary to process and analyze huge amounts of data, then for such cases it is advisable to use digital platforms like Big Data technology.

Stage 5. The process of compiling forecast data. At this stage, the expected development options for a particular logistics business process of the organization are modeled based on the information obtained after processing by Big Data. If any problematic situations were identified during the modeling process, then using digital technologies such as artificial intelligence, it is possible to develop response and protective measures. As a result, the management of the organization's transport and logistics flows becomes quite predictable and predictable, which makes it possible to quickly respond to any changes without significant time and material costs.

Stage 6. The process of editing the system without human participation. The formed flexibility of the organization and its predictability make it possible to transfer the process of making optimal decisions for the company using artificial intelligence (AI) technologies. If, with the help of AI, some proposals were made for options for solving the problems that arose, and they turned out to be the most effective and were implemented in the shortest possible time, while human participation was not envisaged, then this is direct evidence of the success of this solution.

The developed mechanism for the development of digital transformation of the organization's transport and logistics activities is shown in Figure 1.

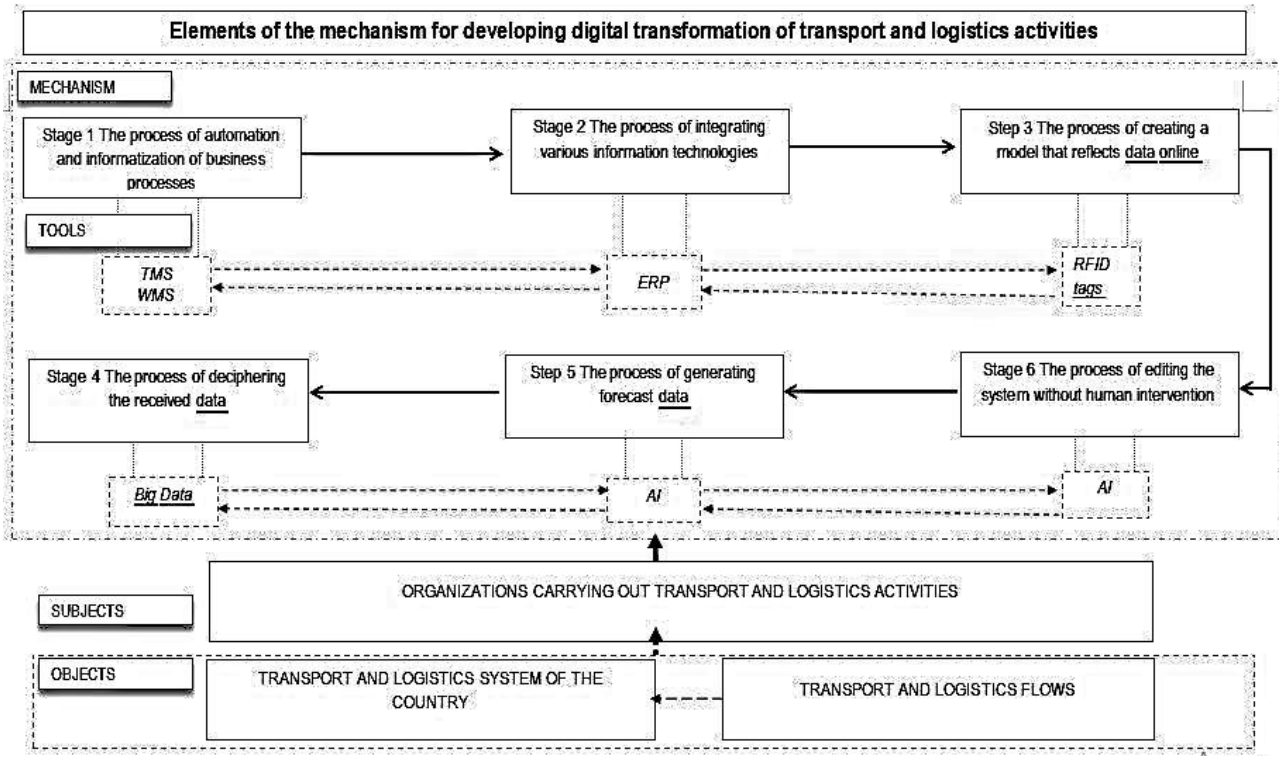

Figure 1 – Mechanism for digital transformation developing of transport and logistics activities

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Today, the agenda of many transport and logistics organizations includes the issue of creating a suitable information base or infrastructure that will allow companies to move to the second stage of digital transformation of the logistics business as a whole. Since it is necessary to understand that partial digitalization of individual business processes slows down the formation of unified digital platforms that would unite the entire supply chain.

The transition from the first to the second stage is the beginning, without which the transition to digital transformation of a transport and logistics organization is impossible.

Conclusion

The purpose of this mechanism is to select the target stage of digitalization that the organization wants to achieve during the digital transformation of its activities.

Thus, the developed mechanism can become a kind of tool for a transport and logistics organization to determine its current position in the process of achieving business digitalization. In addition, this mechanism will help the organization develop a list of activities necessary to achieve the target stage of digital transformation.

References

1. Ob informacii, informatizacii i zashchite informacii : zakon Resp. Belarus', 10 noyabrya 2008 g., № 455-Z / Nacional'nyj pravovoj Internet-portal Respubliki Belarus'. – URL: https://pravo.by/document/?guid=3871&p0=h10800455 (data obrashcheniya: 20.08.2024).
2. Informatizaciya. Terminy i opredeleniya : STB 1693-2009. – Vzamen STB P 1693-2006; vved. 2010 g. – Minsk : Belorusskij gosudarstvennyj institut standartizacii i sertifikacii (BelGISS), 2009. – 12 s.
3. Pervaya redakciya STB «Cifrovaya transformaciya. Terminy i opredeleniya». – URL: https://stb.by/Stb/ProjectFileDownload.php?UrlId=9032 (data obrashcheniya: 28.08.2024).
4. Krishtanosov, V. B. Cifrovaya ekonomika: sovremennye napravleniya, dinamika razvitiya, vyzovy / V. B. Krishtanosov // Trudy BGTU. Ser. 5, Ekonomika i upr. – 2020. – № 1. – S. 13–30.
5. Ivut', R. B. Organizacionno-ekonomicheskie osnovy cifrovoj transformacii transporta: konceptual'nye podhody i napravleniya razvitiya / R. B. Ivut', A. A. Horoshevich. – Minsk : BNTU, 2024. – 224 s. – URL: https://rep.bntu.by/handle/data/142758 (data obrashcheniya: 12.09.2024).
6. Horoshevich, A. A. Metodika ocenki urovnya cifrovoj transformacii transportnoj otrasli / A. A. Horoshevich // Vestnik Belorusskogo gosudarstvennogo ekonomicheskogo universiteta. – 2023. – № 5. – S. 14–22. – URL: http://edoc.bseu.by:8080/handle/edoc/100058 (data obrashcheniya: 12.09.2024).
7. Cifrovaya ekonomika – shans dlya Belarusi : monogr. / M. M. Kovalev, G. G. Golovenchik. – Minsk : Izd. centr BGU, 2018. – 327 s.
8. Ekonomicheskij mekhanizm razvitiya transportno-logisticheskoj deyatel'nosti na predpriyatiyah: monografiya / R. B. Ivut' [i dr.]. – Minsk : BNTU, 2022. – 240 s. – URL: https://rep.bntu.by/handle/data/118578 (data obrashcheniya: 20.09.2024).
9. Eks-SEO Cisco: 45% startapov ischeznut v blizhajshie dva goda – Inc. Russia. – URL: https://incrussia.ru/news/eks-ceo-cisco (data obrashcheniya: 26.09.2024).
10. Bloomberg. com. – URL: https://www.bloomberg.com/europe (data obrashcheniya: 28.09.2024).
11. Global'nyj upravlencheskij konsalting. – URL: https://www.mckinsey.com (data obrashcheniya: 28.09.2024).
12. Holopov, K. V. Sovremennoe soderzhanie i formy eksporta transportnyh uslug / K. V. Holopov, O. V. Sokolova // Rossijskij vneshneekonomicheskij vestnik, 2018. – № 2. – S. 25–32.
13. Krasnova, I. I. Transformaciya transportnoj logistiki v Respublike Belarus' na sovremennom etape / I. I. Krasnova, YU. A. Osipova. – URL: https://elib.bsu.by/bitstream/123456789/250661/1/71-75.pdf (data obrashcheniya: 26.09.2024).
14. Ismagilova, O. Cifrovaya proslezhivaemost' tovarov v EAES / O. Ismagilova. – URL: https://www.vavt-imef.ru/wp-content/uploads/2024/09/Monitoring_12.02.pdf (data obrashcheniya: 20.09.2024).
15. Prioritetnye napravleniya formirovaniya cifrovoj ekonomiki v Respublike Belarus': Vystuplenie Ministra svyazi i informatizacii Popkova S.P. na Respublikanskom seminare po cifrovoj ekonomike. – URL: https://www.mpt.gov.by/sites/default/files/doklad-ministra.pdf (data obrashcheniya: 19.08.2024).
16. Agreement on the labeling of goods by means of identification in the Eurasian Economic Union // Evrazijskij ekonomicheskij soyuz: [sajt]. – 2020. – 6 fevr. – URL: http://www.eaeunion.org (data obrashcheniya: 19.08.2024).
17. O Gosudarstvennoj programme «Cifrovoe razvitie Belarusi» na 2021–2025 gody : postanovlenie Soveta Ministrov Resp. Belarus', 2 fevr. 2021 g., № 66 // Nacional'nyj pravovoj Internet-portal Respubliki Belarus'. – URL: https://pravo.by/upload/docs/op/C22100066_1612472400.pdf (data obrashcheniya: 20.08.2024).
18. Otchet Massachusetskogo tekhnologicheskogo instituta: Digital Transformation: A Roadmap For Billion-Dollar Organizations. – 2011.
19. Digital Maturity Model [site]. – URL: http://www2.deloitte.com (data obrashcheniya: 14.10.2024).
20. SHul'zhenko, T. G. Metody delovogo administrirovaniya v usloviyah cifrovizacii upravleniya logisticheskoj deyatel'nost'yu / T. G. SHul'zhenko // Vestnik fakul'teta upravleniya SPbGEU. – 2018. – № 3. – S. 321–326.

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TOPICAL ISSUES OF ARTIFICIAL INTELLIGENCE IN THE EDUCATION SYSTEM

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Abstract

The active implementation of artificial intelligence technologies in various spheres of global public life contributes to the actualization of questions about the role of the education system in the technical and technological development of the nation. The goal of the higher education system in the modern conditions of a dynamic and high-tech rhythm is the training of qualified specialists, who are capable to implement their professional activities in conditions of working with highly intelligent technologies. To determine what and how to teach future specialists who will be in demand in the sectors of the economy focused on the use of artificial intelligence, it is necessary to understand the essence and functional role of artificial intelligence, as well as to systematize the idea of using artificial intelligence in education.

The study of the historical dialectic of artificial intelligence technologies shows that artificial intelligence has been improving progressively. In the early stages of its development, it depended on the technical and technological level of development of economic systems. Understanding the essence and the term "artificial intelligence" also occurred gradually. Artificial intelligence was often called ordinary information and information management systems. A modern understanding of the essence of artificial intelligence, based on previous and current achievements in computer science, allows us to highlight the main features that characterize artificial intelligence. These are computer networks, artificial neural networks, databases (BIG DATA), the ability of an intelligent system to self-learn. The inevitability of the introduction of artificial intelligence into the national economy and social life of society leads to the natural need to transform the learning process at universities, the essence of which is the introduction of the use of artificial intelligence into the learning process. The higher education system should include educational technologies that provide future specialists with competencies not only within the framework of professional training, but also skills, abilities and the need for continuous self-development, considering the tools of artificial intelligence and trends in the development of the global educational space.

Keywords: artificial intelligence, higher education system, neural networks, self-learning, intelligent technologies in education.

АКТУАЛЬНЫЕ ВОПРОСЫ ИСПОЛЬЗОВАНИЯ ИСКУССТВЕННОГО ИНТЕЛЛЕКТА В СИСТЕМЕ ОБРАЗОВАНИЯ

Т. В. Пильгун, Е. В. Пильгун

Реферат

Активное внедрение искусственного интеллекта в различных сферах общественной жизни способствует актуализации вопросов о роли системы образования в техническом и технологическом развитии нации. Цель системы высшего образования в современных условиях динамичного и высокотехнологического ритма – подготовка квалифицированных специалистов, способных и имеющих потребность реализовывать профессиональную деятельность в условиях работы с высокоинтеллектуальными технологиями. Для того чтобы определить, чему и как учить будущих специалистов, которые будут востребованными в отраслях экономики, ориентированных на использование искусственного интеллекта, необходимо понять какова сущность и функциональная роль искусственного интеллекта, а также систематизировать представление об использовании искусственного интеллекта в образовательном процессе.

Исследование исторической диалектики технологий искусственного интеллекта показывает, что искусственный интеллект совершенствовался поступательно, на ранних этапах своего развития зависел от технического и технологического уровня развития экономических систем. Понимание сущности и термина «искусственный интеллект» также происходило постепенно. Искусственным интеллектом часто называли обычные информационные и информационно-управляющие системы. Современное понимание сущности искусственного интеллекта, основанное на предыдущих и настоящих достижениях компьютерных наук, позволяет выделить основные признаки, характеризующие искусственный интеллект. Это – компьютерные сети, искусственные нейронные сети, базы данных (BIG DATA), способность интеллектуальной системы самообучаться.

Неизбежность внедрения искусственного интеллекта в национальную экономику и социальную жизнь общества приводит к закономерной необходимости трансформации процесса обучения в университетах, суть которой внедрение использования искусственного интеллекта в процесс обучения. Система высшего образования должна включать образовательные технологии, обеспечивающие будущим специалистам компетенции не только в рамках профессиональной подготовки, но и умения, навыки и потребность постоянного саморазвития с учетом инструментов искусственного интеллекта и тенденций развития мирового образовательного пространства.

Ключевые слова: искусственный интеллект, система высшего образования, нейронные сети, самообучение, интеллектуальные технологии в образовании.

Introduction

The creation of artificial intelligence technologies (hereinafter referred to as AI) is a high-tech breakthrough, comparable in significance to the advent of computers and the Internet. AI, as a developing paradigm, is gradually penetrating many areas of human and social life, becoming an integral part of the optimization of production systems and the improvement of the social life of society. The introduction of AI technologies, as well as the digitalization of processes in general, contributes to the efficient functioning of the economic system, the expansion of investment opportunities, an increase in the level of social security, the efficiency of public administration, etc. In general, digitalization processes are widely supported by the state, therefore, conditions are created at the regulatory level to ensure activities related, among other things, to the use of AI technologies. Programs, concepts, and other strategic documents are being developed to implement the objectives of the digital agenda. In Belarus, issues of digitalization of the economy and society, including the use of AI technologies, are included in the programs for the period 2021–2025: "State Program for Innovative Development of the Republic of Belarus"; State Program "Digital Development of Belarus"; "State Program for the Socio-Economic Development of the Republic of Belarus".

The digital agenda has also affected the education system, and the issues of using AI in the educational process are both a stage in its optimization and a stumbling block in the interaction between teachers and students. According to the UNESCO report [1], in the context of the fourth industrial revolu-

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tion, the economic and social development of a nation is closely linked to its technological progress. In this light, the technical and technological progress of society directly depends on the tasks of higher education. The higher education system makes a significant contribution to innovative and economic development through three missions: teaching and learning, scientific research and interaction with production, organizational management.

The tasks of the educational process are formed based on the social demand of society, in accordance with the needs of the economy and national interests. According to state policy, the training of personnel in higher education institutions involves academic fundamentality and a practice-oriented approach [2]. The result of the universities' activities soon should be the training and provision of such personnel potential that will be able to work in the conditions of a dynamic high-tech rhythm, namely, to use intelligent systems and AI in their professional activities. If not today, then tomorrow in the real sector of the Belarusian economy the need for graduates-specialists capable of solving production problems in interaction with AI will increase. On the one hand, AI encourages the idea of automating teacher tasks [3, 4] on the other hand, it allows to expand human knowledge in learning [5, 6], increase students' motivation, provide them with knowledge and skills that will allow them to work hard [7, p. 19], encourages socialization, namely provides tools for participation in certain social, cultural interactions [7, p. 20], and does not neglect the individualization of the learning process, i.e., to become more autonomous and independent in thinking and acting [7, p. 21]. The higher education system should provide competencies that correspond to the current processes and trends of digitalization of the Belarusian society, as well as consider the main trends in the development of the global educational space, use educational technologies, including the capabilities of AI. Nevertheless, at present the idea of using AI elements in education is not complete and requires proper systematization. Several questions arise, including what the essence and functional role of AI in the training of specialists is; what and how to teach in order to increase the demand for graduates in the context of digitalization and the development of AI in the country's economic systems, etc.

Main part. Problems and prospects of AI in the system of higher education

Part 1. Evolution of understanding and modern perception of AI

People often attribute specialized computer programs to AI that allow to get rid of routine work or, even more, allow to make control decisions. But such an interpretation does not provide an understanding of what functionality AI carries and where the boundary between information technology and artificial intelligence lies. Research of literary sources [8, 9,10, 11, 12, 13] has shown that a generally accepted definition of the concept of "artificial intelligence" has not yet been fully formed. At the same time, the modern perception of the essence of AI is dynamic. The stages of development of understanding of the essence of AI are proposed in the Table.

Table – Characteristics of the stages of development of perception of the essence of AI by year

Stages by year	AI related activities
1935–1960	In 1935, Alan Turing formulated the idea of an abstract computing machine consisting of an infinite memory and a scanner that moves forward and backward through the memory. (Alan Turing, work "Computing Machinery and Intelligence"). The founder of the term AI is John McCarthy – an American scientist who in 1956 with his colleagues (Marvin Minksy, Nathaniel Rochester and Claude Shannon) suggested that "Every aspect of learning or any other characteristic of intelligence can in principle be so precisely described that a machine can be designed to imitate it" [14].
1960–1979	Development of the theoretical and philosophical concept of AI, the main essence of which is self-learning of an intelligent system. Self-learning requires powerful computer support. As a result – the development of computing equipment and computing technologies (storage of large amounts of information, increasing the speed of information processing), the beginning of research by scientists of methods and algorithms of machine learning. Creation of agencies and funds for research in the field of AI, mainly in the USA.
1980–1990	Development of algorithmic tools in the field of AI, expansion of research in the field of machine learning. David Rumelhart and John Hopfield published the results of research on deep learning methods.
1990–early 2000 s	Achieving many goals and objectives in the field of AI, due to the development of significant capacities of software and computing systems. In different countries, research in the field of AI was actively disseminated, experience in using AI was increasing, intelligent systems acquired the ability to self-learn, while collecting, systematizing, analyzing data, making decisions, which was only possible for a person. Such well-known AI applications as Google Search, YouTube, Amazone, Netfix, Google Assistant, Apple Intelligence, ChatGPT, etc. appeared.
2000 s – present	AI "assistants", intelligent technologies and AI elements are becoming an integral part of production and public-social systems. The development and implementation of AI in production is provided for by state and regional strategic programs.

An analysis of the development of events and processes preceding the current understanding of AI allows to identify the enlarged technological periods of the formation of the concept of AI:

The first period (1935–1970) can be called theoretical, when people understood the need and value of accumulated information in electronic form about business, the market, clients, in order to use it more effectively to achieve their goals. The following technical solutions were aimed at achieving this goal: obtaining, processing information, forming and storing data arrays. It is hardly possible to classify the technologies of this period as AI. These were technological operations and processes based on software and computer complexes for the formation of scientific reference information (SRI), which began to be called information systems. According to [15]: "An information system (IS) is a set of data banks, information technologies and software and hardware complexes." Any information system that solves an intellectual problem or uses artificial intelligence methods is classified as intelligent [16].

In the next period (1970 s – 2000 s), with the increasing complexity of NSI arrays (increasing volumes, their heterogeneity), there is a need to automate analytical processes, generate and forecast heterogeneous sets of information, draw conclusions, adapt to emerging failures, and even offer management solutions. All this freed from routine tasks, was useful in production processes, and strengthened the confidence of managers in decision-making. In production and technological systems based on increasingly sophisticated software and computer tools, they sought to move from information systems to information and management systems.

In recent decades, due to several technical innovations, AI has developed rapidly. AI technologies allow an intelligent system to receive and process big data in real time, promptly adjust design decisions, control operations, and draw practical conclusions that contribute to confident decision-making [17].

The study of the history of AI technology development shows that AI has improved and depended on the level of technical support for intelligent systems and their technological development, and, accordingly, different understandings of the essence of AI have arisen. Throughout each period of development of understanding of AI, scientists and researchers have attempted to formulate the definition and essence of AI.

Thus, at the stages of early understanding (before the 90s), in the definitions of AI, researchers emphasize the machine, mechanical, and functional components of artificial intelligence. As a typical example, we will cite the definition given by one of the founders of AI, Marvin Minsky: "The science of how machines do things that would require intelligence as if humans did them" [17]. A similar idea can be seen in the understanding of the essence of AI by other early researchers: John McCarthy, Alan Turing and others.

Starting from the 90 s – 2000 s, the presentation of the essence of AI has acquired a more expanded form. A distinctive feature of the interpretation of AI in recent decades was that AI necessarily works based on the use of neural networks.

Most clearly and accurately, in the authors' opinion, the essence of AI is reflected in the characterization of this term by the English scientist Russell Stewart Jonathan: "Artificial intelligence in the broadest sense is the intelligence demonstrated by machines, in particular computer systems. It is an area of research in computer science that develops and studies methods and software that allow machines to perceive the environment and use learning and intelligence to perform actions that maximize their chances of achieving their goals. Such machines can be called artificial intelligence" [18].

Thus, understanding the essence of AI has its own dialectic of development, which ultimately comes down to the ability of an intelligent system to self-learn and use the acquired knowledge to solve problems, including making decisions, as a person would do. The ability to self-learn can be called one of the main features of AI. Other features of AI are: computer networks (computer and network equipment, software); artificial neural networks (programs or algorithms that use computing systems), databases (BIG DATA).

Currently, AI technologies are being implemented in many sectors of the economy. Many examples of AI use are noted in healthcare, military affairs, financial management systems and banking, online trading, transport and logistics systems, and others. In communication and telecommunications systems, the use of automated online assistants is becoming the norm. The most famous AI systems in the world are: ChatGPT (from the English Generative Pre-trained Transformer), capable of working in a dialog mode, supporting requests in different languages. The system can answer questions, generate texts in various subject areas; Deep Blue is a chess supercomputer; MYCIN is one of the early intelligent systems, was designed for diagnostic tasks in medicine. There are many computer games using AI technologies, the direction is called "gaming artificial intelligence". The largest research centres in the field of artificial intelligence are in the USA, Germany, Japan, Russia, India, China. The Chinese AI industry is developing rapidly. This is confirmed by the fact that the growth rate of the number of patents in this area in the PRC is on average 1.4 times higher than the global average. In China, AI has become one of the key areas of the country's digital economy.

The above facts are a small part of what characterizes the long-term potential of AI, which is actively being introduced into various spheres of public life. It seems that the requirements for AI will only increase over time, since in essence this system must be able to cope with cognitive tasks inherent in humans. At the same time, according to the assessment given in [19]: "Artificial intelligence is algorithms, neural networks of various types, which are laid down by humans. AI will never be smarter than all people, because it is a product of human thinking. AI will not develop until humans develop. And this is the main thing today for understanding the essence of artificial intelligence and the directions in which this all-knowing assistant should be developed." Therefore, the development of AI potential depends on highly qualified specialists, who already today need to be taught to understand AI and work with it, thereby developing themselves and AI itself.

Part 2. Potential and tasks of AI in higher education

Considering the essence of AI, which we adhere to in this article, a qualified specialist must be ready to perceive any innovative solution, able to constantly develop his mental activity in the field of his profession. The main qualification quality of a graduate of our time who has a higher education is not just to have knowledge and skills base, abilities within the framework of his profession, but to understand the main modern and promising trends, considering which to have the ability to implement his activities in the conditions of working with intelligent technologies. This means that a university graduate must acquire the skill of continuous self-development considering AI tools.

Many scientists and practitioners note that despite the gradual improvement of legislation in the field of digital technologies, insufficient attention is paid to the issues of using AI technologies in the university education system. The question: "In what format should AI be used in the higher education system" is discussed at many seminars, forums, and platforms. At the Russian forum on AI in higher education (June 28–30, 2024 in Tyumen), it was noted that "On the one hand, we are witnessing the rapid development of technologies, when literally every month AI solutions appear that seemed impossible to implement six months ago. On the other hand, the university system is inherently inertial and introduces innovations more slowly than businesses. As a result, the gap between university pedagogical formats, educational models and organizational structure, on the one hand, and the opportunities that AI opens, on the other, is steadily growing" [20]. The conclusion that should be drawn from this and other similar publications is that in the era of AI implementation, a fundamental change in approaches to the educational process in universities will be required. The existing system of education (let's call it traditional) in the university today is characterized for most specialties as a passive acquisition of knowledge.

Of course, at present the possibilities for conducting lectures are wider and more visual than a couple of decades ago: interactive systems are used, in their absence – project presentation systems, visual information is provided.

A positive element of modernity is the availability of electronic educational and methodological complexes, electronic methodological manuals for conducting practical and laboratory classes, available to the student at any time, thanks to modern devices.

On the other hand, the availability of electronic sources weakens the systematicity and progressiveness in the acquisition of knowledge by students, instils the hope of "I'll read it later".

The presence of mobile phones in students distracts from listening and deep understanding of the topic, answers to questions are found on the Internet without hesitation. In addition, the use of electronic mini tools used by students when passing the exam, and the presence of which is difficult for the teacher to detect, allows you to mislead the teacher regarding the assessment of knowledge.

All the innovative possibilities and achievements of modern gadgets are useful and deserve approval, but with the traditional way of organizing the learning process, they contribute to a decrease in the effectiveness of learning, students do not learn to think, remember and, accordingly, make independent decisions. Of course, the main role in presenting information in organizing the lecture process belongs to the teacher, but even the most wonderful speaker with interesting presentation materials significantly reduces the effectiveness of the acquired competencies in relation to the level of modern competence requirements in the context of digitalization and AI.

The memorandum adopted following the Forum "AI in Higher Education: Pedagogical Challenges and Prospects of Russian Universities", which took place on June 28–30, 2024 in Tyumen, noted that "the tasks of training highly qualified specialists are becoming more complex in our time: there should be not subordinating of a student to AI, but moving him to the position of a subject of cognition and activity, capable of creatively using and developing AI as a working tool" [20].

The inevitability of the promising use of AI technologies in the educational system already today requires a constant search for effective system tools and experimentation with various innovative educational techniques. It also does not seem possible to quickly and widely implement the idea of using AI in the educational process for all universities. This also depends on specialties and disciplines. Specialized universities or divisions of universities that train specialists related to computer science (engineering, digital technologies, programming) are in an advantageous position. These educational institutions have the appropriate material and technical base and qualified faculty in the field of digital infrastructure and AI.

Some technical specialties (in the fields of mechanical engineering, energy, instrument making and others) also have trends close to interaction with AI, for which classes are conducted using equipment and specialized technologies that are elements of AI. For example, additive technologies in manufacturing. But in addition to specialties related to computer science, many specialists are graduated from other industries that are very necessary for the country's economy. For many specialties, the potential of AI is not used at all or is used chaotically and insignificantly. There is a problem of having an appropriate material and technical base, as well as the selection and acquisition of educational software tools.

What AI content systems for training are available today on the global network. The most famous generative technologies are ChatGPT, Gemini, Llama, developed and supported by large technological giants OpenAL, GOOGLE, Facebook. Perhaps in the future, there will be many smaller, more accessible specialized models in the world. It is no secret that some students turn to ChatGPT to complete their term papers, theses, and projects. This is a text generative application. But the system generates the information that is in the database. Is the process of com-

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pleting work with the involvement of AI and the resulting product useful for students? If the student does not participate in the generation, then it is not useful. A competent teacher will immediately determine that the work was not completed by the student. This chat will be useful if the student interacts with the generator. Asks questions, thereby clarifying and adjusting the requirements. At the same time, the chat replenishes its database on a specific issue and learns to formulate an answer in accordance with the questions, that is, it self-learns. There is also a benefit for the student, since questions must be formulated. Without knowledge, you cannot formulate a question. So, after all, the student needs to acquire competencies. Thus, interest in learning appears through gamification (increasing interest in learning through play).

It is also useful for a teacher to use these generators to search for information, create interesting lectures, visual materials, presentations, projects and research, etc. In higher education, it is necessary to develop a system that provides for increasingly independent mastering of educational material by students under the supervision of a teacher. This increases the efficiency of knowledge acquisition and teaches independent thinking. An important aspect is the manageability of the educational process with the involvement of AI for the preparation of modern qualified specialists for all sectors of the economy, which should begin at the state level. It is advisable to have a consolidating body that will be engaged in the development of methodological approaches to the educational process with the involvement of AI technologies in universities in future.

Conclusion

Based on the conducted study of the essence of the modern understanding of AI and the identification of the main features characterizing AI, the author's definition of the concept is proposed: "Artificial intelligence is an area of computer science that explores methods and technologies based on the principles of operation of artificial neural networks, allowing computer systems, taking into account large amounts of information (BIG DATA), to perform tasks comparable to human cognitive abilities."

The inevitability of the introduction of AI into the national economy and social life of society leads to a natural need to transform the learning process at universities, the essence of which is the introduction of AI in the process of higher education.

Benefits of transforming the learning process in terms of involving AI:

the attractiveness of learning through gamification increases;

student interest increases due to increased conversion from learning. By setting tasks for the generator, the student becomes interested in the result. To ask a question, you need to know something yourself;

it becomes possible to create educational content based on curriculum standards and student levels;

improving the training strategy due to the need to analyze the interaction of AI with students;

ensuring the training of specialists who meet the requirements of a high-tech developing economy, who are capable of self-study and have the need to implement their activities in conditions of work with highly intelligent technologies.

There are also problems in connection with the upcoming transformation, which can be called tasks, since they need to be solved:

financial investments are required for the development of products, their implementation and training of teachers, development of the material and technical base;

systemic methodological and effective educational solutions aimed at the use of AI tools in education will be required at the state level;

overcoming the inertia, and sometimes outright skepticism of most of the teaching community regarding AI in relation to the higher education system.

References

1. Galán-Muros, V. Higher education contribution to national technological development / V. Galán-Muros, A. Blancas, B. L. Liu ; Gruppa podgotovki Vsemirnogo doklada po monitoringu obrazovaniya, Mezhdunarodnyj institut YUNESKO po vysshemu obrazovaniyu v Latinskoj Amerike i Karibskom bassejne // Unesko. – 2023. – DOI: 10.54676/PZAH9105.
2. Vysshee obrazovanie v Respublike Belarus' // Ministerstvo obrazovaniya Respubliki Belarus'. – URL: https://edu.gov.by/urovni-obrazovaniya/vysshee-obrazovanie/studentam (data obrashcheniya: 08.08.2024).
3. Selwyn, N. Should robots replace teachers? AI and the future of education. Polity / N. Selwyn. – Cambridge UK : Polity Press, 2019. – 160 p.
4. Still w (AI) ting for the automation of teaching: An exploration of machine learning in Swedish primary education using Actor-Network Theory / K. Sperling, L. Stenliden, J. Nissen, F. Heintz // European Journal of Education. – 2022. – Vol. 57 (4). – P. 584–600. – DOI: 10.1111/ejed.12526.
5. Tuomi, I. The use of artificial intelligence (AI) in education / I. Tuomi // European Parliament, Policy Department for Structural and Cohesion Policies. – 2020. – P. 2–6. – Mode of access: https://bit.ly/3lCMotK (date of access: 19.10.2024).
6. Molenaar, I. Towards hybrid human-AI educational scenarios / I. Molenaar // European Journal of Education. – 2022. – Vol. 57 (4). – DOI: 10.1111/ejed.12527.
7. Biesta, G. J. J. Good Education in an age of measurement: Ethics, politics, democracy / Biesta, G. J. J. // Paradigm Publishers. Biesta GJ. Good education in an age of measurement: Ethics, politics, democracy. – Routledge, 2015. – 158 p.
8. Holmes W., Tuomi I. State of the art and practice in AI in education / W. Holmes, I. Tuomi // European Journal of Education. – 2022. – Vol. 57, Iss. 4. – P. 542–570. – DOI: 10.1111/ejed.12533.
9. Baker, M. J. The roles of models in artificial intelligence and education research: A prospective view / M. J. Baker // Journal of Artificial Intelligence and Education. – 2000. – Vol. 11(2). – P. 122–143.
10. Hakimi, L. The ethics of using digital trace data in education: A thematic review of the research landscape / L. Hakimi, R. Eynon, V. A. Murphy // Review of Educational Research. – 2021. – Vol. 91 (5). – P. 671–717. – DOI: 10.3102/00346543211020116.
11. ZHuravkov, M. A. Tekhnologii iskusstvennogo intellekta i intellektual'nye sistemy komp'yuternogo modelirovaniya i inzhenernyh raschetov. Vvodnyj kurs : ucheb. posobie / M. A. ZHuravkov ; BGU, Mekhanikomatematicheskij fak. – Minsk : BGU, 2024. – 177 s.
12. Negnevitsky, M. Artificial Intelligence: A Guide to Intelligent Systems / M. Negnevitsky. – 3d edition. – Addison Wesley Publisher, 2011. – 500 p.
13. Poole, D. Artificial Intelligence: Foundations of Computational Agents 1st Edition / D. Poole, A. Mackworth. – Cambridge University Press, 2010. – 682 p.
14. Dzhon Makkarti: otkrytiya i nasledie sozdatelya termina «Iskusstvennyj intellekt». – URL: https://habr.com/ru/companies/itglobalcom/articles/741006 (data obrashcheniya: 01.10.2024).
15. Zakon Respubliki Belarus' ot 10 noyabrya 2008 g. № 455-Z "Ob informacii, informatizacii i zashchite informacii" (Nacional'nyj reestr pravovyh aktov Respubliki Belarus', 2008 g., № 279, 2/1552, stat'ya 1. – URL: https://multilang.pravo.by/ru/term/index/2639?langname=ru&page=1&type=3 (data obrashcheniya: 01.10.2024).
16. Ostrouh, A. V. Sistemy iskusstvennogo intellekta : monografiya / A. V. Ostrouh, N. E. Surkova // Lan' : elektronno-bibliotechnaya sistema. – 4-e izd., ster. – Sankt-Peterburg : Lan', 2024. – 228 s. – URL: https://e.lanbook.com/book/379988 (data obrashcheniya: 12.10.2024).
17. CHto predstavlyaet soboj iskusstvennyj intellekt?. – URL: https://www.sap.com/central-asia-caucasus/products/artificial-intelligence/what-is-artificial-intelligence.html (data obrashcheniya: 01.10.2024).
18. Rassel, Styuart. Artificial Intelligence. A Modern Approach / Stuart J. Russell, Peter Norvig. – Fourth Edition. – Hoboken : Pearson, 2021. – 1069 p. – URL: https://ru.wikipedia.org/wiki/Iskusstvennyjintellekt (data obrashcheniya: 08.08.2024).
19. Kruglikov, S. Kak v Belarusi razvivayutsya razrabotki iskusstvennogo intellekta i naskol'ko oni vygodny / Sergej Kruglikov. – URL: https://www.sb.by/articles/algoritmy-budushchego.html (data obrashcheniya: 05.08.2024).
20. Iskusstvennyj intellekt v vysshem obrazovanii. Forum. Pedagogicheskie vyzovy i perspektivy rossijskih universitetov. – URL: https://aiutmn.tilda.ws/forum (data obrashcheniya: 10.08.2024).

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CHINA'S EXPERIENCE IN THE DEVELOPMENT AND APPLICATION OF CONSTRUCTION COST ENGINEERING

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Abstract

This paper provides an in-depth discussion of China's rich experience in the field of building cost engineering development and application, especially focusing on the current development of assembly building, which is the most representative of the process of building industrialization. With its relative advantages in cost, especially its wide application in the construction projects of sheltered housing, assembly building has gradually become one of the important directions for the transformation of China's construction industry. Despite the fact that assembled buildings have demonstrated many advantages, such as reducing on-site construction pollution and shortening the construction period, challenges in terms of low technological maturity, shortage of professionals, and cost control still exist. The article further analyses the concept of building industrialization and its impact on construction cost, pointing out that although the cost of industrialized housing may be higher in the use phase, its overall cost is lower and the economic benefits are significant from the perspective of the whole life cycle. In addition, a BP neural network model is introduced in the paper to predict the cost of assembled buildings. Through the learning and training of a large number of actual project data, the model demonstrates excellent prediction ability, which can effectively assist decision makers to make an accurate estimation of the project cost at the early stage of the project, reduce the project cost, and promote the healthy development of assembly buildings. Therefore, this paper not only provides valuable practical experience for the development of construction cost engineering, but also lays a solid theoretical foundation for the promotion and application of assembly building.

Keywords: building industrialization, prefabricated building, cast-in-situ building, BP neural network model.

ОПЫТ КИТАЯ В РАЗРАБОТКЕ И ПРИМЕНЕНИИ ИНЖИНИРИНГА СТОИМОСТИ СТРОИТЕЛЬСТВА

Цзян Юйхао, Ван Музи, Фань Сяоюй, Нин Юйлинь, О. С. Голубова

Реферат

Данная работа представляет углубленное обсуждение богатого опыта Китая в области развития и применения строительства по проектированию затрат. Особое внимание уделяется текущему развитию монтажного строительства, которое является наиболее представительным в процессе индустриализации строительства. С учетом своих относительных преимуществ в затратах, особенно широкого применения в строительных проектах социального жилища, монтажное строительство постепенно стало одним из важных направлений преобразования строительной промышленности Китая. Несмотря на то, что монтажные здания продемонстрировали многие преимуществ, такие как уменьшение загрязнения на строительном участке и сокращение срока строительства, все же существуют проблемы в виде низкой технологической зрелости, недостатка специалистов и контроля затрат. Статья анализирует концепцию индустриализации строительства и ее влияние на стоимость строительства, указывая, что хотя стоимость индустриализированного жилища может быть выше на этапе эксплуатации, ее общая стоимость ниже, а экономические выгоды значительны с точки зрения всего жизненного цикла. Кроме того, в работе представлена модель нейронной сети прямого распространения (BP) для прогнозирования стоимости монтажных зданий. Через обучение и тренировку на большом количестве фактических данных проектов, модель демонстрирует отличную способность к прогнозированию, что может эффективно помочь принятию решений лицам, занимающимся принятием решений, точно оценивать стоимость проекта на ранней стадии проекта, снижать стоимость проекта и способствовать здоровому развитию монтажного строительства. Таким образом, данная работа не только представляет ценный практический опыт для развития строительства по проектированию затрат, но и создает прочную теоретическую основу для продвижения и применения монтажного строительства.

Ключевые слова: индустриализация строительства, сборное здание, монолитное здание, нейросетевая модель BP.

1 Introduction

The construction industry is one of the pillar industries of China's national economy, which has a significant impact on the country's economic form. Starting from the executive meeting of The State Council of China in 2016 to promote prefabricated buildings, various localities began to pave the way for the development of prefabricated buildings in terms of tax support policies. In 2017, China's Ministry of Housing and Urban-Rural Development issued the "13th Five-Year Plan" Action Plan for prefabricated buildings. The plan clearly indicates that more than 15 % of the regions that are expected to actively promote prefabricated buildings by 2020, and the number of buildings should also exceed 15 % [1]. According to the Consumption Quota of prefabricated Construction Projects issued by the Ministry of Housing and Construction of China, for prefabricated residential projects, the construction cost of low-rise buildings is about 2150 RMB/m^2 (equivalent to 306.66 USD/m^2), and the construction cost of high-rise buildings is about 2420 RMB/m^2 (equivalent to 345.17 USD/m^2). The construction cost of the cast-in-place concrete building estimated by the Ministry of Housing and Urban-Rural Development is about 2000RMB/m^2 (equivalent to 285.26 USD/m^2) [1].

2 Industrialization of building

2.1 The concept of building industrialization

The United Nations Economic Commission has put forward the relevant concepts of building industrialization, namely: continuity of production, standardization of production materials, integration of various stages of production process, mechanization of construction, highly organized engineering, integration of production and organization. The industrialization of construction is summarized in one sentence, which is to organize

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the production of houses like the manufacture of cars [2]. Prefabricated building is a special building technology system that elevates all kinds of general prefabricated components (PCS) to factory production and on-site mechanized assembly through proprietary connection technology. Prefabricated building is a representative product of building industrialization, which is widely used in affordable housing, and is a development trend of future construction projects. Its advantages are short construction period, less pollution in site construction, and less restriction by climatic conditions. Precast concrete components generally refer to building components pre-made by concrete, which is the basis for realizing the prefabrication of the main structure. Its main advantages are good structural properties, pipeline-type factory production can efficiently ensure structural mechanical properties, strong cohesion. However, because the whole performance of precast concrete is not ideal in practice, it can not be used in buildings with high seismic requirements [4].

2.2 The concept of engineering cost

Project cost refers to the costs required in the process of project construction, including land costs, design costs, construction costs, material costs, equipment costs, management costs, supervision costs, etc. The calculation of project cost needs to consider the rationality and economy of various costs to ensure the quality and efficiency of the project. In the early stage of the project, it is necessary to carry out budget and cost control to evaluate the feasibility and rationality of the project. In the construction process, it is necessary to carry out cost management and cost control to ensure the construction progress and quality of the project, and to maximize cost savings. From the perspective of the owner, the project cost refers to the total amount of all actual costs incurred by a project from scratch to fully complete the construction of the project, that is, all fixed asset investment costs [5].

2.3 The influence of building industrialization on project cost

In terms of the impact of construction industrialization on project cost, the cost of industrial housing is higher in the use stage, but its whole process cost is lower than that of traditional housing. In terms of the influence of prefabricated construction on project cost, prefabricated construction is at a disadvantage in installation projects and needs to be improved [6]. The large scale of enterprises, only have the strong strength to carry out relevant scientific research, easy to reach cooperation with relevant suppliers, and then make the standards of enterprises become the standards of the supplier industry, and drive the industrialization process of the entire industry.

3 Cost of prefabricated construction project

3.1 The position of prefabricated construction in building industrialization

Prefabricated construction is an important construction technology in building industrialization, and its application in China is mainly concentrated in affordable housing, and prefabricated construction technology has been greatly developed in this process. With the continuous development of technology, such as PC integrated assembly construction, the principle of systematics is used to consider the unity of the position of prefabricated steel bars and reserved steel bars, and the straight thread composite connection is used to connect the components. The integral cast-in-place method is adopted at the joint, which has good seismic performance and overall performance, and gradually overcomes the problems of instability, water leakage and component shedding in the assembled construction technology [6].

3.2 Comparative analysis of the cost of prefabricated buildings and cast-in-place buildings

Take Building 3# of Country Garden Peoples Project in Ningbo City, China as an example, its construction area is 4714 m^2, according to relevant drawings and standard specifications, in accordance with the same quality requirements and functional standards. According to the four types of projects, the total cost of prefabricated construction and cast-in-place construction is analyzed, as shown in Figure 1.

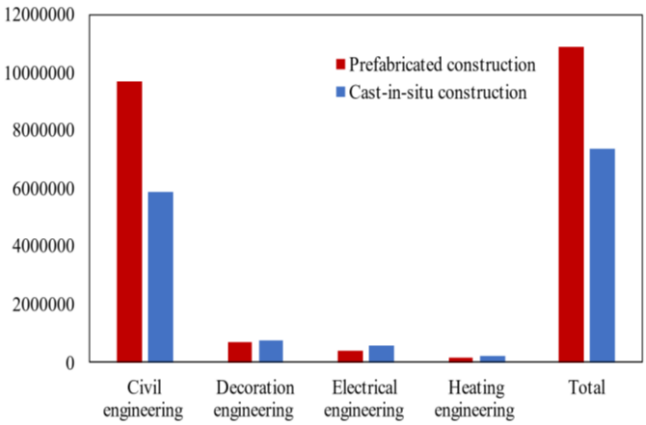

Figure 1 – Comparison of total cost of prefabricated construction and cast-in-place construction

It can be seen from the figure that the cost of prefabricated construction is higher than that of cast-in-place construction except for civil engineering, and all other projects are lower than that of cast-in-place construction [8]. Because the cost of civil engineering of prefabricated construction is much higher than that of cast-in-place construction, the prefabricated construction is in a disadvantageous position compared with cast-in-place construction in total price.

4 Cost estimation of prefabricated construction project based on BP neural network

4.1 Project introduction

This paper selects China's Ningbo Country Garden People Project, which covers an area of 69240.67 m^2 and a building area of 167080.99 m^2, among which the built-up area is 124633 m^2, and the building density, plot ratio and greening rate are 29.31 %, 1.8 and 30.15 %, respectively. The prefabricated project planning is shown in Table 1 [9]:

Table 1 – Prefabricated project planning scheme

Implementation plan	Building number: 5#, 11#, 15#	Implementation scale: 22,800 m^2
Structural system	Prefabricated shear wall structure system	Internal casting and external hanging system
Precast component	Prefabricated cladding (including insulation)	Prefabricated shear wall external wall (including insulation)
	Prefabricated balcony	Prefabricated air conditioning panel
Built-up interior	High precision block + thin plaster	Package window system
Construction technique	Tower crane selection: Heavy tower crane	Formwork: Wood formwork
	Use penetration construction techniques: Yes	Scaffold project: self-lifting climbing frame

4.2 Analysis of the actual project cost

The installation cost of prefabricated components is determined by the general contractor according to the group price of construction site consumption and scheme, etc., and the unit price of all installed prefabricated components is determined after negotiation [9]. The unit price of installation consists of embedded iron parts, on-site unloading of components, construction of high-strength grouting materials, joint treatment, cleaning of exterior wall parts and gluing treatment, etc. The above are all processes of installation of prefabricated components. The non-component parts of the prefabricated component cost include the on-site installation cost and the purchase of the main materials of the prefabricated component [10]. All price details are shown in Table 2.

Table 2 – Valuation table of component engineering quantity list

Project	Unit	Quantity of work	Comprehensive unit price	Main material price	Total
PC straight wall	m^3	300.7	865	2900	1132135.50
PC bay window	m^3	94.99	890	3600	426505.10
PC balcony	m^3	68.79	930	3380	296484.90
PC stairs	m^3	61.37	940	3100	247934.80
Total	RMB				2103060.30

Underground engineering below 0 meters mainly refers to the construction of basement engineering, pile foundation engineering, etc., which will not affect the cost level of the study of assembled engineering, so the underground engineering part will not participate in the study of this paper. The unit project cost summary shows the itemized cost of each project, and the total project cost includes taxes and fees [11]. According to the statistics and summary analysis of the actual engineering data, the total cost of building 5# using the prefabricated construction method is about 8.2 million RMB, and the single cost is 1064.28 RMB per square meter after conversion, including the incremental cost of structure and construction measures. The unit cost of the project is shown in Table 3.

Table 3 – Summary of project unit engineering cost

Number	Project	Cost
1	Total value of bill of quantities	6073660.78
2	Structure and rough decoration	3946173.98
3	Below 0.00	0.00
4	Above 0.00	2768161.50
5	Facade decoration	24426.50
6	PC prefabricated installation (including main materials)	2103060.30
7	Measure project cost 1 (Formwork scaffold)	1526847.08
8	Measure project cost 2 (except formwork scaffolding)	607746.58
Total		8208254.43
Floor area		7712.52 m^2
Project cost alone		1064.28 RMB/m^2

4.3 BP neural network model construction

The basic structure of BP neural network includes input layer, hidden layer and output layer. The structure design of BP neural network estimation model for prefabricated building engineering will focus on these three aspects, including the number of neuron nodes in input layer, hidden layer and output layer [13].

The input layer is the model that receives information and transmits it to the neurons of the next layer. Starting from the basic principles followed by the cost budget of prefabricated building projects, the most direct factors affecting the cost are selected as the key feature indicators. The direct feature factors affecting the project cost include inner wall, outer wall, column, beam, plate, staircase and balcony bay window [13]. The corresponding input index of the training sample is the prefabrication rate of each prefabricated component and the unilateral incremental value, with a total of 9 data. The purpose of the calculation model is to calculate the unilateral building cost index of the target project according to the known prefabrication rate, so the indicator data to be input for the target project to be estimated is only the prefabrication rate of each prefabricated component, with a total of 8 data [15].

Hidden layer design includes layer number design and node number design. The hidden layer is the middle part of the neural network estimation model, and its role is to process and transform information. According to the needs of actual problems, the hidden layer can be designed as a single-layer hidden layer or multi-layer hidden layer structure. This function is a continuous function in the definition domain, and it is a suitable activation function for prefabricated construction cost estimation model [16]. Therefore, it is only necessary to adopt a single hidden layer structure in the design of network structure. The setting of the number of nodes in the hidden layer mainly considers the nature and characteristics of the training samples, including the number of training samples, the proportion of non-regular content in the samples and the complexity of regular content in the samples. For more complex nonlinear functions, due to their frequent fluctuations and large amplitude changes, more neuron nodes in the hidden layer are needed to enhance the mapping ability of the network [17]. For linear functions, in general, the setting of the number of hidden layer neurons can be determined by empirical formulas, which are commonly used as shown in equation (1). Where n represents the number of neurons in the hidden layer, m represents the number of input data, and l represents the number of neuron nodes in the output layer. When the model is trained, the number of neuron nodes in the input layer is 6, and the number of neuron nodes in the output layer is 1, then the number of neuron nodes in the hidden layer is 2 according to the formula [18].

$$\begin{cases} n = log2^m \\ n = \sqrt{ml} \end{cases} \#. \quad (1)$$

The output layer is the result value measured by the model system, which represents the functional goal to be achieved by the system, and is also the only condition for error determination. In this model, we hope to predict the unilateral cost and other cost indicators, and the output result is one of the unilateral cost of the prefabricated building [19].

4.4 Prefabricated building cost calculation

Twenty groups of data from 25 residential engineering samples in Zhejiang, Shanghai and Jiangsu from 2017 to 2020 were randomly selected as training sets and input into the constructed BP neural network prediction model to complete the training. On this basis, a prefabricated construction cost prediction model based on BP neural network is successfully established, and the training data are shown in Table 4 [20].

Create a feature variable array and a predictor variable array respectively in MATLAB, and import the data into the BP neural network model. The model structure is shown in Figure 2.

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Table 4 – Training data

Number	Bearing wall	Column	Beam	Non-load-bearing wall	Plate	Precast rate	Incremental cost (RMB/m²)
1	0 %	0 %	0 %	0 %	5.46 %	14.46 %	254
2	0 %	0 %	0 %	0 %	6.3 %	15.3 %	260
3	0 %	0 %	0 %	0 %	10.29 %	19.29 %	289
4	0 %	0 %	0 %	0 %	12.6 %	20.1 %	283
5	6.8 %	0 %	0 %	0.82 %	12.6 %	29.22 %	401
6	15.3 %	0 %	0 %	1.8 %	3.36 %	29.46 %	454
7	15.81 %	0 %	0 %	1.8 %	12.6 %	39.21 %	527
8	11.9 %	0 %	0 %	1.44 %	16.8 %	39.14 %	503
9	8.33 %	8.7 %	10.5 %	0 %	12.6 %	49.13 %	636
10	15.47 %	16.24 %	0 %	1.86 %	16.8 %	59.37 %	758
11	15.47 %	0 %	15.75 %	1.8 %	16.8 %	58.82 %	729
12	0 %	0 %	0 %	2.7 %	6.86 %	20.6 %	319.5
13	10.89 %	0 %	0 %	0 %	7.53 %	20.32 %	262.8
14	5.01 %	0 %	0 %	5.05 %	6.72 %	30.76 %	452.7
15	14.1 %	0 %	0 %	3.09 %	7.3 %	30.25 %	386.1
16	11.82 %	0 %	0 %	7.03 %	6.56 %	39.7 %	606.6
17	9.24 %	0 %	0 %	1.65 %	0 %	19.17 %	220.78
18	8.4 %	0 %	0 %	1.87 %	0 %	19.89 %	225.76
19	6.3 %	0 %	0 %	0 %	4.8 %	20.72 %	173.82
20	10.5 %	0 %	0 %	1.1 %	4.8 %	19.38 %	209.18

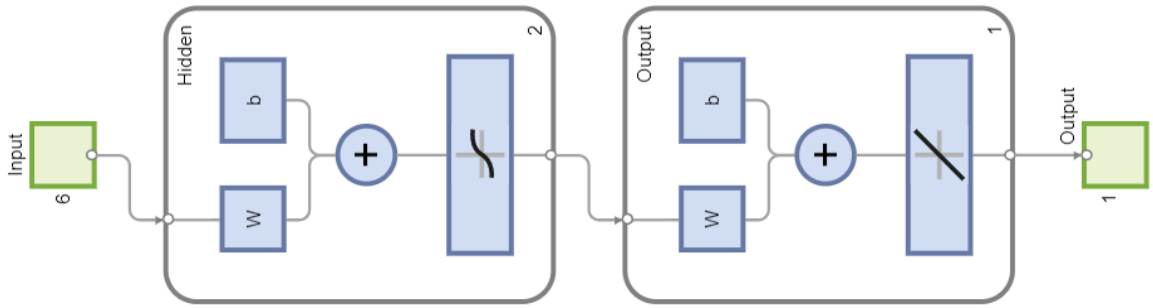

Figure 2 – Structure diagram of BP neural network

Then, Levenberg-Marquardt method is used for training, and the effect of the prediction model is analyzed according to the training performance graph and regression graph. The training performance diagram is shown in Figure 3, where the blue solid line represents the training process of the neural network, and the green solid line represents the verification process of the neural network. The red implementation is to test the neural network process and show the change of the MSE value. The Best dashed line represents the best result of the neural network after training to the 13th time.

The fitting of model training is shown in Figure 4. The fitting degree between the model output data, training data, verification data and test data is above 0.8, indicating a high degree of linear correlation, indicating that the model has a good prediction effect and can predict the cost of prefabricated buildings.

Based on MATLAB software, this paper establishes the prefabricated construction project evaluation model by combining the principle of BP neural network with the cost characteristics and engineering characteristics of the prefabricated construction project. The real case data is comprehensively collected, the database is built to simulate the model, and the predicted cost estimate value is adjusted and corrected after the training, so as to improve the rationality and accuracy of the estimate, so as to be consistent with the real project construction, and finally the estimate model of unilateral project cost increment can be used in engineering practice.

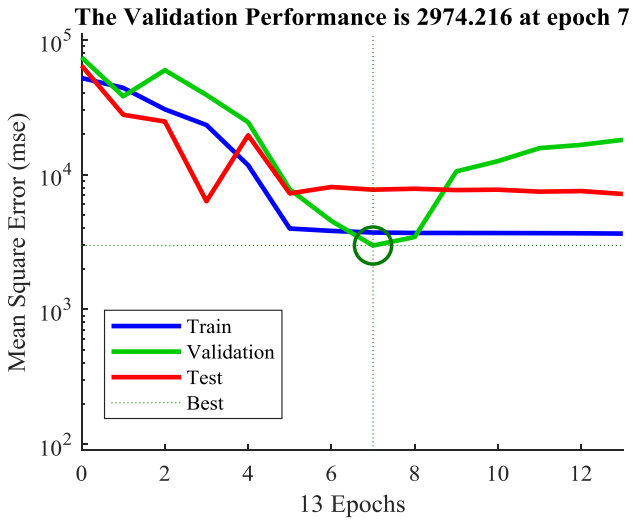

Figure 3 – Training performance of BP neural network model

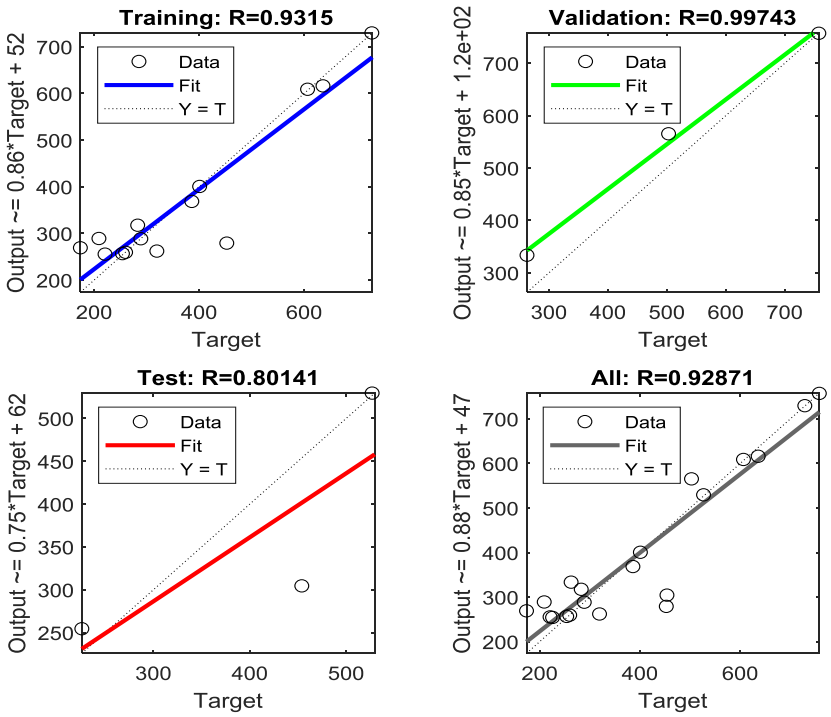

Figure 4 – BP neural network model training regression diagram

References

1. 白文志, 中国住宅产业化进程中部品体系研究 / 白文志 // 武汉理工大学. – 2011.
2. 刘禹, 我国建筑工业化发展的障碍与路径问题研究 / 刘禹 // 建筑经济. – 2012. – No. 4. – P. 20–24.
3. Genfang, W. Perspective of Chongqing Housing Development / W. Genfang // Journal of Chongqing Jianzhu University. – 2001. – Vol. 23, No. 3. – P. 7–9.
4. Wong, F., Potential Homebuyer's Preference in Chongqing / F. Wong, E. Hui // Journal of Chongqing Jianzhu University. – 2001. – Vol. 23, No. 3. – P. 25–32.
5. Deb, R. K., An analysis of generation market power in the midwest interconnect / R. K. Deb, R. E. A. Macatangay, S. Deb // The Electricity Journal. – 2002. – Vol. 15, No. 3. – P. 29–39.
6. **李天**华, **装配式建筑全寿命周期管理中BIM与RFID的**应用 / **李天**华 // **工程管理学**报. – 2012. – No. 6. – P. 28–32.
7. Fong, S. Building distinction green design and construction in the orchards / S. Fong, W. H. Lam, A. S. K. Chan // Proc. of the Symposium on Green Building Labelling, Hong Kong. – 2003. – P. 69–77.
8. **万成**兴, **公共租**赁住房工业化的装配式住宅初探 / **万成**兴, **刘志**伟, **靳坤** // **住宅**产业. – 2011. – No. 8. – P. 25–27.
9. 闫红缨, 预制装配式体系建造成本的比较分析 / 闫红缨 // **住宅**产业. – 2012. – No. 7. – P. 36–38.
10. Ofori, G. Greening the construction supply chain in Singapore / G. Ofori // European Journal of Purchasing & Supply Management. – 2000. – No. 6. – P. 195–206.
11. **李**飞龙, **装配式建筑工程造价**预算与成本控制分析 / **李**飞龙 / **江西建材**. – 2017. – No. 15. – P. 251–251.
12. Vrijhoef, R. The four roles of supply chain management in construction / R. Vrijhoef, L. Koskela // European Journal of Purchasing& Supply Management. – 1999. – No. 6. – P. 169–178.
13. **胡**伟勋, **工程造价估算模型研究与**应用 / **胡**伟勋 // **中南林**业科技大学学报. – 2011. – No. 31. – P. 163–166.
14. Farrow, K. T. Effect of Dimension and Detail on the Capacity of Precast ConcreteParking Structure Diaphragms / K. T. Farrow, R. B. Fleischman // PCI journal. – 2003. – No. 48. – P. 46–61.
15. Yee, A. A. Structural and economic benefits of precast/prestressed concrete construction / A. A. Yee, P. H. D. Eng // PCI journal. – 2001. – No. 4. – P. 34–43.
16. Bari, N. A. A. Environmental Awareness and Benefits of Industrialized Building Systems(IBS) / N. A. A. Bari, N. A. Abdullah, R. Yusuff // Procedia-Social and Behavioral Sciences. – 2012. – No. 50. – P. 392–404.
17. **王芸爽**, **装配式混凝土**结构连接技术研究 / **王芸爽** // **中国建材科技**. – 2016. – No. 25. – P. 100–101.
18. Borjeghaleh, R. M., Approaching Industrialization of Buildings and Integrated Construction Using Building Information Modeling / R. M. Borjeghaleh, M. Sardroud // Procedia Engineering. – 2016. – No. 164. – P. 534–541.
19. **周文瑞**, **探究装配式建筑与**传统现浇建筑造价对比 / **周文瑞** // **信息**记录材料. – 2017. – No. 18. – P. 37–39.
20. **梁海**标, **基于BP神**经网络的装配式建筑工程造价估算研究 / **梁海**标 // **浙江大学**. – 2022.

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THE IMPACT OF THE DIGITAL ECONOMY ON THE DEVELOPMENT OF THE TRANSPORT INDUSTRY

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Abstract

In the context of the digital transformation of the global economy, the development of the transport industry is acquiring a new vector, characterized by the active introduction of digital technologies. The digital economy affects all aspects of the transport system, from improving the efficiency of logistics processes to ensuring the safety and sustainability of transport routes. The introduction of technologies such as the Internet of Things (IoT), blockchain, big data and artificial intelligence allows us to automate many processes, minimize risks and increase the transparency of supply chains. These innovations help to speed up the transfer of information, improve monitoring and forecasting, which is important for timely and high-quality customer service.

The digitalization of the transport industry also stimulates its adaptation to changing market needs and increases the competitiveness of companies. For example, the use of data analysis and forecasting systems allows for better management of transport flows, optimize routes and reduce operating costs. Blockchain technologies increase security and trust in information, eliminating the possibility of counterfeiting and fraud, which is especially important in the context of globalization and increasing cross-border transportation. Digital technologies also ensure increased environmental friendliness of transport processes, helping to reduce emissions and switch to alternative energy sources.

Thus, the digital economy is becoming a key driver of innovation in the transport industry, transforming working methods and opening up new prospects for its sustainable and efficient development.

Keywords: digital economy, transport industry, logistics, automation, big data, Internet of things, intelligent transport systems, digitalization, cybersecurity, route optimization.

ВЛИЯНИЕ ЦИФРОВОЙ ЭКОНОМИКИ НА РАЗВИТИЕ ТРАНСПОРТНОЙ ОТРАСЛИ

Нин Юйлинь, Л. В. Гринцевич

Реферат

В условиях цифровой трансформации мировой экономики развитие транспортной отрасли приобретает новый вектор, характеризующийся активным внедрением цифровых технологий. Цифровая экономика влияет на все аспекты транспортной системы, от повышения эффективности логистических процессов до обеспечения безопасности и устойчивости транспортных маршрутов. Внедрение таких технологий, как интернет вещей (IoT), блокчейн, большие данные и искусственный интеллект, позволяет автоматизировать многие процессы, минимизировать риски и повысить прозрачность цепочек поставок. Эти инновации способствуют ускорению передачи информации, улучшению мониторинга и прогнозирования, что важно для своевременного и качественного обслуживания клиентов.

Цифровизация транспортной отрасли также стимулирует ее адаптацию к изменяющимся потребностям рынка и повышает конкурентоспособность компаний. Например, использование систем анализа данных и прогнозирования позволяет лучше управлять транспортными потоками, оптимизировать маршруты и снизить эксплуатационные затраты. Блокчейн-технологии повышают безопасность и доверие к информации, исключая возможность подделок и мошенничества, что особенно актуально в условиях глобализации и увеличения трансграничных перевозок. Также цифровые технологии обеспечивают повышение экологичности транспортных процессов, способствуя снижению выбросов и переходу на альтернативные источники энергии.

Таким образом, цифровая экономика становится ключевым драйвером инноваций в транспортной отрасли, трансформируя методы работы и открывая новые перспективы для ее устойчивого и эффективного развития.

Ключевые слова: цифровая экономика, транспортная отрасль, логистика, автоматизация, большие данные, интернет вещей, интеллектуальные транспортные системы, цифровизация, кибербезопасность, оптимизация маршрутов.

Introduction

The digital economy is fundamentally changing not only the usual areas of interaction, but also fundamental approaches to the management and development of industries. The transport industry, which plays an important role in the global economy, does not remain aloof from these processes. The introduction of digital technologies into the transport system allows not only to increase the efficiency of transportation, but also to improve their environmental sustainability, safety and speed. In the context of growing global trade flows and requirements for sustainable development, the need for digitalization is becoming an integral part of the strategy of successful transport companies and states.

The impact of the digital economy on the transport industry is manifested through such processes as automation of cargo management, integration of intelligent transport systems, application of IoT technologies and use of big data to optimize routes and monitor transport. This allows to significantly increase transparency and control over all stages of logistics chains, as well as minimize the influence of the human factor.

However, digitalization also brings with it a number of challenges, such as cyber threats, the need to modernize existing infrastructure and train personnel in new competencies. Research into these aspects will provide a deeper understanding of how the digital economy influences the development of the transport industry and how it can be adapted to new realities.

The term "digital economy" entered scientific circulation relatively recently, in 1995. It was first actively used by the American economist N. Negroponte, who emphasized the importance of moving the economy to a new level through the use of information and communication technologies [1]. The modern understanding of the term "digitalization" includes a wide range of meanings, but its essential component is not always fully understood. Digitalization is not just the introduction of the

latest technologies to increase competitiveness in the market, but a much deeper process that requires changing the basic approaches to solving socio-economic problems.

Today, there are many areas of development of the digital economy, and their goal is the integration of IT technologies into economic processes. The key factor in digitalization is consumer orientation, market segmentation and improving the quality of services. Significant changes in the market can be achieved through information, which is becoming the main resource, as well as the Internet, which provides unlimited opportunities for the development of economic ties, increased competition and support for small and medium businesses. Some researchers believe that the digital economy is an economy expressed in numbers [2]. We believe that this approach reflects the requirements of the modern era, when prompt access to data and its analysis become the basis for making economic decisions. Thanks to digital technologies, this work is done quickly and conveniently. Moreover, our daily life today is closely connected to the Internet: we often use mobile devices not for calls, but for working with websites and applications.

The Internet is becoming an integral part of people's lives, an increasing number of citizens use online platforms to solve their problems, since it is convenient and often economically beneficial. However, the pace of digitalization in various industries is uneven. For example, in such areas as mechanical engineering or agriculture, digital transformation is much slower than in trade. This is due to the specifics of the functioning of these industries, their scale, the complexity of introducing new technologies, as well as the need for large financial investments and the return on investment in the development of IT solutions.

The transport industry plays an important role in the structure of the economy, being a key element of the national economy. Digitalization of the transport sector is closely linked to the development of the digital economy at the state level [3]. One of the most obvious examples of the introduction of digital technologies in the transport sector is the integration of data between suppliers and users of transport services. This is expressed in the widespread use of electronic tickets and certificates, which are becoming a familiar part of life.

The process of digitalization in transport should include the interaction of all stakeholders: science, education, business and government agencies. Only in the case of close cooperation between these participants can an effective and modern platform for digital management in the transport industry be created [4]. The scientific community is already developing successful strategies and mechanisms for the introduction of digital technologies in this area. Educational institutions should train highly qualified specialists capable of working in a digital economy. The business environment plays a key role in the prompt identification of problems and obstacles arising on the path of digitalization, which allows them to be solved in a timely manner and risks to be minimized.

The digital economy is actively influencing many industries, and the transport industry is no exception. Digitalization provides new opportunities to optimize processes, increase efficiency, and reduce costs. This article examines the main aspects of the influence of the digital economy on the development of the transport industry, as well as the challenges and prospects it faces in the context of global changes [5].

The digital economy includes the use of information and communication technologies (ICT) to improve economic processes. In the transport industry, it helps automate and simplify many aspects, from route planning to monitoring cargo transportation [6]. The use of Big Data, the Internet of Things (IoT), and artificial intelligence (AI) is fundamentally changing the way transport systems operate.

Automation and optimization of logistics

One of the key benefits of the digital economy for the transport industry is the automation of processes. Modern control systems allow real-time tracking of the location of vehicles, their load, technical condition, and environmental conditions. This allows for better route planning, reduced downtime, and optimization of supply chains. For example, the use of cloud platforms allows companies to manage warehouse stocks and logistics operations more flexibly and efficiently.

Big Data and Analytics

The use of big data in the transport industry significantly improves decision-making processes. Transport companies can collect and analyze huge amounts of data on driver behavior, road conditions, weather conditions, and route congestion. This data is used to forecast demand, identify bottlenecks in the transport system, and improve road safety.

The Impact of Digitalization on the Efficiency of Transport Systems. Reducing Costs and Improving Profitability

Automation of processes and the use of digital technologies allow companies to reduce operating costs. For example, fleet management systems help optimize the use of vehicles, reduce fuel consumption, and minimize equipment wear [7]. Thanks to digital platforms, it is possible to significantly reduce the cost of paper documentation and reduce the number of human errors.

Increasing the speed of delivery and improving the quality of services

Digital technologies improve customer interaction processes and provide transparency in logistics operations. Customers can track the location of their goods in real time, which increases the level of trust and satisfaction. Fast order processing and accurate delivery time forecasts are possible thanks to digital tools, which leads to improved service quality.

Challenges of digitalization in the transport industry. Integration of systems

One of the key challenges of digitalization in the transport industry is the integration of various management systems. Companies often use different platforms to manage logistics, fleets and warehouses, which creates problems of data compatibility and interaction. Developing unified standards and platforms remains an important task for the successful digitalization of the industry.

Digitalization brings not only opportunities, but also risks. With the growth of digital systems, the threat of cyberattacks and unauthorized access to confidential data increases. Ensuring the security of transport systems requires the implementation of modern data protection methods and reliable encryption mechanisms.

Prospects for the digital transformation of the transport industry

The future of the transport industry is directly linked to the further development of the digital economy. The development and implementation of unmanned vehicles, the use of blockchain technologies to manage logistics operations and the widespread use of artificial intelligence will open up new horizons for increasing the efficiency and sustainability of transport systems.

The digitalization process, as a key trend of technological progress in the transport industry, has been identified for quite some time. It can be argued that the introduction of digital technologies in this area began almost simultaneously with the emergence of the first electronic computing systems. Over the past years, many different projects have been implemented, both public and private initiatives (Table 1).

In the context of the active development of the digital economy and the formation of a knowledge-oriented information society, which is an important strategic goal, not only in-depth scientific research of risks, systematization of threats and challenges in the field of information security, but also the training of qualified personnel are becoming especially relevant [8]. To ensure reliable information security, a key role is played not only by the technical aspects of protecting the information space and creating a single space of trust, but also by issues of protecting critical information infrastructure.

The use of modern digital communication technologies has opened up opportunities for dynamic remote interaction. More and more people prefer convenient online payments. Mobile payment methods, universal travel documents and the use of applications for transport services have significantly increased the number of users [9].

The creation of digital transport corridors, based on a single information space of electronic documents containing data on cargo, senders and recipients, creates conditions for the implementation of Big Data

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analysis technologies and the transition of the transport sector from a competitive model to a partnership and cooperation model – the main business model in digital logistics. The use of Big Data technologies allows transport companies to manage traffic more effectively by conducting a daily analysis of operations. Structured and thoroughly analyzed data helps to identify new routes and activate unused resources in complex logistics chains. In addition, analytics helps to increase the flexibility of transport systems, providing the ability to promptly adjust delivery routes when unexpected difficulties arise. As Maersk Line CEO R. van Troyen noted, in the Asia-Pacific region, "98 % of all the company's orders are processed digitally, and 50 % of Maersk's orders and documentation are processed through my.maerskline.com, where more than 250,000 transactions are made daily, generating revenue of $ 1.5 million per hour" [10].

Table 1 – Examples of digitalization in the transport sector

Application Area	Examples of Digitalization	Impact
Logistics and Supply Chain Management	Real-time cargo tracking platforms (e. g., GPS, IoT devices)	Increased transparency and control over deliveries
	Warehouse automation using robots and AI	Faster order processing, reduced errors
Transport Infrastructure	"Smart" roads with sensors for traffic and road condition monitoring	Improved infrastructure planning and accident prevention
Urban Transport	Mobile apps for route planning and ticket purchases (e. g., public transport apps)	Convenience for passengers, reduced waiting times
	Transport Management Systems (TMS) for optimizing public transport schedules	Increased schedule accuracy, reduced delays
Autonomous Vehicles	Deployment of autonomous cars and trucks	Reduced labor costs, enhanced safety
Electronic Documentation	Use of electronic waybills (e-CMR) and other digital documents	Reduced paperwork, faster cargo clearance
Big Data and Analytics	Use of big data to analyze traffic and weather conditions to optimize routes	Cost reduction, more efficient route planning
Cybersecurity	Implementation of cybersecurity systems to protect data and transport networks	Protection from cyberattacks, enhanced system security
Fleet Management	Automated fleet tracking and maintenance systems using IoT	Optimized vehicle usage, reduced downtime

Global leaders in the field of transport and logistics services predict that in the near future, new driverless vehicles will appear on the roads, which will become a key element of digital logistics. One of the key areas in this area will be the use of self-driving trucks. According to the Boston Consulting Group (BCG), the market for ground-based driverless vehicles may exceed US $ 45 billion by 2025, and its rapid growth is expected. McKinsey experts believe that by 2025–2027, every third truck on European roads will be equipped with an autonomous driving system.

Autonomous control systems in such trucks include automatic emergency braking, control of oncoming traffic, and maintaining a constant speed using autopilot. Sensors such as radars and cameras ensure a safe distance from the vehicle in front, reducing the likelihood of accidents. These innovations will reduce the number of road accidents by minimizing the risk of human error and will relieve drivers from the need to spend long periods of time behind the wheel [11].

With the development of technology, digital logistics and transport are taking on new forms, changing the entire system of cargo transportation and logistics chains. These changes are profound and affect the speed, efficiency and safety of logistics processes. The article discusses the key effects that digitalization brings to logistics and transport.

One of the significant advantages of digital logistics is the ability to quickly and accurately process large amounts of information. Technologies such as artificial intelligence and big data allow companies to analyze and forecast demand, allocate resources and optimize routes in real time. Due to this, delivery times are reduced, deadlines are more accurate, and fuel and logistics costs are reduced.

Digital logistics helps to better coordinate the actions of all participants in the transport process, including shippers, carriers, customers and intermediaries. With the help of cloud platforms and specialized applications, it has become possible to manage all document flow, track cargo, place orders and maintain contact with customers online. This eliminates the costs associated with delays and ineffective communication, and allows for a more flexible response to changing conditions and customer requests [12].

Automation and the use of driverless vehicles play an important role in improving road safety. Modern digital systems such as automatic braking, lane keeping, driver monitoring, cameras and sensors help to avoid many accidents. The introduction of driverless truck technologies eliminates the human factor, which often causes errors and accidents. A reduction in the number of accidents leads to improved overall safety and lower insurance costs for companies.

One of the noticeable economic effects of digital logistics is the reduction of transport and logistics costs. Digitalization allows for efficient route planning and the avoidance of empty runs, which reduces fuel consumption and operating costs. Also, the automation of processes such as warehouse logistics and loading and unloading operations helps to reduce labor costs and minimizes the need for manual labor.

Digital transport and logistics contribute to environmental sustainability. Route optimization and the use of data for planning reduce carbon emissions by reducing travel time and fuel consumption. In addition, the development of driverless and electrified vehicles further reduces the carbon footprint, making digital logistics more environmentally friendly and compliant with modern sustainability standards [13].

Digital logistics improves customer service through real-time tracking of parcels and transparency during the delivery process. Customers can monitor their order, receive accurate delivery time forecasts, and make adjustments if necessary. This increases customer trust and satisfaction, promoting loyalty and retention.

With Big Data and AI technologies, companies can forecast needs and analyze logistics flows. Analytics can identify bottlenecks, anticipate potential delays, and plan future deliveries more accurately. This helps companies optimize inventory, avoid warehouse overflows, and deliver products on time, which is an important aspect of logistics management. Digital logistics enables new business models such as resource sharing and Transport-as-a-Service (TaaS) [14]. These models allow companies to adapt more flexibly to market changes, use infrastructure as needed, and reduce capital expenditure. In the context of digital logistics, more and more companies are moving towards a collaborative model, which allows for more efficient use of capacity and lower costs. A digital transport system allows for a quick response to unforeseen circumstances, such as traffic delays or changing weather conditions. By integrating data from various sources, companies can change routes in real time and minimize risks. This is especially important in a globalized world, where transport chains are becoming longer and more complex, and unforeseen circumstances can seriously disrupt the delivery plan.

Automation and robotization of traffic flow control, traffic situation forecasting and support for autopilot systems reduce dependence on the human factor, minimize errors and improve train traffic management, as well as their maintenance.

Automation of transport management systems and active involvement of the client in cargo control processes contribute to more efficient logistics management [15]. Digital platforms aimed at providing logistics services, including ticket booking, carrier search and selection of optimal routes, have made a significant contribution to the digitalization of the transport industry.

One of the key areas remains the implementation of "smart" transport, which allows monitoring, management and optimization of transport systems using advanced technologies.

Digitalization of the transport sector has opened up new prospects for the efficient management of logistics processes, simplifying and accelerating information exchange, tracking of cargo shipments, and remote management of operations. The introduction of these technologies has also helped to significantly improve the efficiency of management processes.

The digital economy has a significant impact on the development of the transport industry, leading to the automation of processes, improved logistics and higher quality of services. However, successful digitalization requires overcoming challenges such as system integration and cybersecurity. Given technological changes and innovations, the prospects for digital transformation in the transport industry seem very promising [16].

The digital economy is a radically new approach to economic interactions at the global level, consisting in the deep integration of IT technologies with economic processes. Among the key areas of implementation of digital solutions in the automotive industry are the following:

– Firstly, creating conditions for increasing the comfort and efficiency of transport services for consumers.

– Secondly, organizing a system of regular monitoring and quality control of the road surface in accordance with the standards of safe operation.

– Thirdly, solving road safety issues through remote monitoring of compliance with traffic rules by all road users with immediate punishment of violators.

Investments in infrastructure development, technological competition and increasing the level of education of the population are the main factors contributing to the acceleration of the digital transformation of the country's economy.

References

1. Negroponte, N. Being digital / N. Negroponte. – Hodder & Stoughtong,1995. – 243 p.
2. Patrusova, A. M. Modern information technologies for assessing the effectiveness of investment IT projects / A. M. Patrusova // Modern technologies. Systems analysis. Modeling. – 2014. – No. 2 (42). – P. 92–96.
3. Bolshedvorova, L. V. Information culture as a factor in the development of the information society / L. V. Bolshedvorova, V. V. Kosyakova // Current issues of the regional economy: analysis, diagnostics and forecasting: materials of the VI International student scientific-practical conferences (April 6, 2016). – N. Novgorod, 2016. – P. 270–273.
4. Lomov, I. I. Automation of the process of sale and accounting of insurance products in commercial banks / I. I. Lomov, M. Yu. Vakhrusheva // Problems of socio-economic development of Siberia. – 2018. – No. 2 (32). – P. 64–70.
5. Study of self-actualization needs of Russian students as a factor of competitiveness in the labor market / E. G. Grudistova, D. A. Pastuhova, A. M. Slinkov [et al.] // Espacios. – 2019. – Vol. 40, No. 26. – P. 18.
6. Patrusova, A. M. Process management: Some implementation aspects / A. M. Patrusova, M. Y. Vahrusheva // IOP Conference Series: Materials Science and Engineering. – 2020. – Vol. 753 (8). – DOI: 10.1088/1757-899X/753/8/082028.
7. Order of the Government of the Russian Federation No. 1734-r dated on November 22, 2008 (as amended, dated on May 12, 2018) "On the Transport Strategy of the Russian Federation", Legal reference system "ConsultantPlus". – URL: https://www.consultant.ru/document/cons_doc_LAW_82617 (date of access: 01.08.2024).
8. Akopova, E. S. Mirovaya transportno-logisticheskaya infrastruktura: cifrovaya transformaciya 2020 goda / E. S. Akopova, E. K. Pilivanova, S. I. Samygin // Gosudarstvennoe i municipal'noe upravlenie. Uchenye zapiski. – 2021. – № 1. – S. 87–92. – DOI: 10.22394/2079-1690-2021-1-1-87-92.
9. Arhipov, A. E. Transformaciya transportnoj otrasli Rossii pod vliyaniem cifrovyh tekhnologij / A. E. Arhipov, A. E. Ryapisov // Ekonomika i biznes: teoriya i praktika. – 2020. – Vol. 4–1 (62). – S. 22–24. – DOI: 10.24411/2411-0450-2020-10249.
10. Volovik, N. A. Delovaya reputaciya kak faktor povysheniya effektivnosti deyatel'nosti kompanii / N. A. Volovik // Mezhdunarodnyj zhurnal gumanitarnyh i estestvennyh nauk. – 2017. – №5. – S. 96–98.
11. King, M. Carriers 'best placed to control digital shipping', claims Maersk. – URL: https://www.lloydsloadinglist.com/freight-directory/news/Carriers-'best-placed-to-control-digital-shipping'-claims-Maersk/68197 (date of access: 27.09.2024).
12. Gorishnyaya, A. A. Modelirovanie stoimosti delovoj reputacii transportnyh kompanij v usloviyah cifrovizacii ekonomiki / A. A. Gorishnyaya // Intellektual'nye resursy – regional'nomu razvitiyu: sbornik nauchnyh trudov. – 2020. – № 2. – S. 356–360. – URL: https://cyberleninka.ru/article/n/tsifrovye-tehnologii-v-transportnoy-logistike (date of access: 30.09.2024).
13. Komarova, E. A. Klyuchevye elementy innovacionnogo razvitiya v sfere logisticheskoj deyatel'nosti / E. A. Komarova // Intellektual'nye resursy – regional'nomu razvitiyu: sbornik nauchnyh trudov. – 2017. – № 1–2. – S. 649–653.
14. YAguzinskaya, I. YU. Perspektivy vnedreniya i razvitiya informacionnyh sistem v transportnoj logistike / I. YU. YAguzinskaya, E. O. Biryukov // Nauchno-metodicheskij elektronnyj zhurnal Koncept. – 2015. – T. 35. – S. 151–155.
15. Schwab, K. The Fourth Industrial Revolution. World Economic Forum. – 2016. – URL: https://www.weforum.org/about/the-fourth-industrial-revolution-by-klaus-schwab (date of access: 05.10.2024).
16. Bukht, R. Defining, Conceptualising and Measuring the Digital Economy / R. Bukht, R. Heeks // Development Informatics Working Paper. – 2017. – Vol. 68. – DOI: 10.2139/ssrn.3431732
17. Castells, M. The Rise of the Network Society. Wiley-Blackwell / M. Castells. – 2010. – 656 p. – URL: https://www.wiley.com/en-us/The+Rise+of+the+Network+Society-p-9781405196864 (date of access: 08.10.2024).
18. The Impact of Digitalisation on the Transport Sector: Key Findings. OECD // International Transport Forum. – 2019. – URL: https://www.itf-oecd.org/impact-digitalisation-transport-sector (date of access: 08.10.2024).
19. Deighton, J. The Economic Value of the Digital Economy / J. Deighton, L. Kornfeld // Journal of Economic Perspectives. – 2018. – Vol. 32(2). – P. 3–30. – DOI: 10.1257/jep.32.2.3.
20. Digital America: A Tale of the Haves and Have-Mores / J. Manyika, S. Ramaswamy, S. Khanna [et al.] // McKinsey Global Institute. – 2019. – URL: https://www.mckinsey.com/mgi/overview/digital-america (date of access: 08.10.2024).
21. Deloitte. Digital Transformation in Transport and Logistics: Increasing Efficiency and Effectiveness. Deloitte Insights. – 2020. – URL: https://www2.deloitte.com/content/dam/Deloitte/global/Documents (date of access: 08.10.2024).
22. Glushkova, A. Digital Economy Impact on the Development of the Transport Sector in Russia / A. Glushkova, V. Smirnov // Russian Economic Development. – 2022. – Vol. 28(2). – P. 72–84.
23. Digitalization of Transport Logistics in the Context of the Fourth Industrial Revolution / S. Barykin [et al.] // Journal of Logistics and Supply Chain Management. – 2021. – Vol. 14(1). – P. 15–28.
24. Jiang, X. The Role of Big Data and AI in Optimizing Transport Efficiency in the Digital Economy / X. Jiang, Y. Liu // Transportation Science. – 2022. – Vol. 56(3) – P. 203–215.
25. Glushkova, A. Digital Economy Impact on the Development of the Transport Sector in Russia / A. Glushkova, V. Smirnov // Russian Economic Development. – 2022. – Vol. 28(2). – P. 72–84.
26. Harnessing the Digital Economy for Growth and Sustainable Development in Transport // The World Bank. – 2021.

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APPLICATION OF EXTREME VALUE PROBABILITY ASYMPTOTIC THEORY IN CHINA'S ENERGY RISK PREDICTION

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Abstract

Extreme value theory is a theory that deals with situations that are extremely far from the median of a probability distribution. It is often used to analyze situations with rare probabilities, such as earthquakes and floods that occur once in a hundred years. It is often used in risk management and reliability research. This article demonstrates some simple applications of extreme value asymptotic probability theory in predicting China's energy risks. First, the article introduces the main classical results of extreme value asymptotic probability theory, and demonstrates the method of using graphical methods to construct quantile graphs to calculate energy data, and gives examples of quantile graphs.

The article calculates and analyzes the risks faced by China's major energy consumption and imports and exports in the past decade, and predicts the development trends of some energy economic indicators in China from 2023 to 2026 through quantile graphs constructed by extreme value asymptotic probability theory. The results show that the results predicted by the quantile diagram constructed by extreme value asymptotic probability theory are basically accurate, so extreme value asymptotic probability theory should be more widely used in the field of energy economic forecasting. At the same time, this article puts forward some suggestions in order to contribute to China's low-carbon sustainable development.

Keywords: energy risk, risk prediction, extreme value asymptotic probability theory, energy statistics.

ПРИМЕНЕНИЕ АСИМПТОТИЧЕСКОЙ ТЕОРИИ ВЕРОЯТНОСТИ ЭКСТРЕМАЛЬНЫХ ЗНАЧЕНИЙ В ПРОГНОЗИРОВАНИИ ЭНЕРГЕТИЧЕСКИХ РИСКОВ КИТАЯ

Т. Г. Зорина, Ян Чжуси

Реферат

Теория экстремальных значений – это теория, которая рассматривает ситуации, чрезвычайно далекие от медианы распределения вероятностей. Она часто используется для анализа ситуаций с редкой вероятностью, таких как землетрясения и наводнения, которые случаются раз в сто лет, а также в управлении рисками и исследованиях надежности. В статье продемонстрированы некоторые простые возможные приложения асимптотической теории вероятностей экстремальных значений для прогнозирования энергетических рисков в Китае. Приводятся основные классические результаты асимптотической теории экстремальных значений, демонстрируется метод расчета энергетических данных с использованием графических способов построения квантиль-диаграмм, приведены примеры построения графиков квантилей.

В работе рассчитываются и анализируются риски, с которыми столкнулись основные отрасли потребления, импорта и экспорта энергии в Китае в последнее десятилетие, и при помощи квантиль-диаграмм прогнозируются тенденции развития некоторых энергетических и экономических показателей Китая с 2023 по 2026. Высокая точность результатов, полученных при помощи квантиль-диаграмм, построенных по асимптотической теории экстремальных значений, позволяет сделать вывод о необходимости более широкого использования данной теории в области прогнозирования экономики энергетики. Предложены направления устойчивого развития Китая, направленные на снижение уровня выбросов углекислого газа.

Ключевые слова: энергетический риск, прогнозирование риска, асимптотическая теория экстремальных значений, энергетическая статистика.

Introduction

Risk prediction refers to a measure to predict the abnormalities that may occur in the work process and work results before work, and formulate countermeasures to prevent accidents.

The current global economic uncertainty is increasing and the downside risks are relatively large, which may have an unexpected impact on China's economy, which has a weak foundation for recovery [1]. China should accelerate the use of policy tools and actively respond to changes in the external environment. Therefore, making good predictions on the risks of the low-carbon economy will help the government to better formulate economic policies, strengthen international policy coordination, and improve the effectiveness of policies.

The World Bank's latest Global Economic Prospects report released in 2024 predicts that global economic growth will slow for the third consecutive year, from 2.6 % in 2023 to 2.4 % in 2024, nearly three-quarters of a percentage point lower than the average level in the 2010s [2]. The report pointed out that this will make 2020–2024 the slowest five-year growth in the global economy in 30 years.

According to the World Bank's estimates, in 2023, the growth rate in East Asia and the Pacific will rebound from 3.4 % in 2022 to 5.1 % [2], mainly due to a brief surge in economic activity after China lifted its epidemic blockade measures at the beginning of the year.

However, the analysis pointed out that the effect of China's economic restart faded quickly: investment growth was dragged down by the continued weakness of the real estate industry, and the decline in sales and prices increased the financial pressure on real estate developers; the export sector faced the challenge of weak external demand. Although consumption improved at the end of the year, consumer confidence was still far below the pre-epidemic level.

The World Bank believes that the instability caused by the higher procyclicality and volatility of fiscal policies will drag down the growth prospects of commodity exporters in developing economies for a long time. To this end, the report recommends that these countries take a series of policy measures to alleviate this drag, including by establishing a fiscal framework that helps to restrain government spending, adopting a flexible exchange rate system, and avoiding restrictions on international capital flows [2].

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Usually, in the prediction of economic policy concepts, economists or researchers will use time series method, indicator analysis method and factor analysis method to predict economic trends or investment trends [3].

Time series method is a prediction method that studies the changing form of time series by analyzing its components, continuing the past development trend and extrapolating the future. Its main methods include moving average method, weighted moving average method, exponential smoothing method, least square method, etc.

Indicator analysis method is a prediction method that determines the signs of changes in the economic situation by analyzing the interrelated indicators or indicator groups that reflect economic changes, studying the "trend" indicators that predict economic turning points and the "warning" indicators that predict serious problems in the economy.

Factor analysis method is a method of prediction by establishing an economic mathematical model with the causal relationship or structural relationship between the prediction object and the factors that affect it.

In the current commonly used economic forecasting methods, economic forecasts cannot always be accurate because human will and activities are involved in the economic process. Its accuracy has a gradual improvement process. Here we propose a new forecasting method: combining extreme value theory, using extreme value probability asymptotic theory to find special application methods to determine and predict the risks of extreme economic emergencies. In recent years, extreme value probability theory has made significant progress in theory, but it has not been promoted in practical applications. The extreme value distribution model is a very effective tool for studying extreme value phenomena and extreme value random variables. Therefore, more and more people are aware of the great potential of extreme value theory in the application of extreme events. It is particularly pointed out that extreme value theory is a theory that simulates the tail of data distribution, so it can be applied to the prediction of extreme value data.

Research History

Extreme value theory is an important branch of order statistics, which mainly studies the extreme value distribution and its characteristics, especially the terminal characteristics of the distribution. Its research methods and scope have undergone great changes.

In the early stage, extreme values only studied what kind of distribution the maximum and minimum values in a series of independent and identically distributed random variables should obey. Fisher-tippett LHC (1928) published the first theoretical article on extreme value limits, and gave the Fisher-tippett theorem, which shows that the distribution of the maximum or minimum value of the sample converges to one of the three distributions when the sample size tends to infinity. His research method greatly simplified the study of the value limit properties, and divided a variety of distribution functions into three relatively simple categories according to the tail properties, thus establishing the foundation of this theory [4].

B. V. Gnedenko (1943) gave the first rigorous mathematical proof of the Fisher-tippett theorem. In 1950, British statisticians mainly carried out research on generalized extreme value distribution, which showed three types of extreme value distribution in one form, making parameter estimation simple, because it was no longer necessary to select one model from three models, thus avoiding the cumbersome procedures [5]. Gumbei (1960) applied extreme value theory to specific statistical problems and proposed a statistical method now called block method, which is to divide the data into many intervals according to a predetermined length, and then select a maximum or minimum value from each interval for modeling. However, selecting only extreme values from a large amount of data will lose the information contained in other large amounts of data [5].

Pickands (1971) proposed a new extreme value research method, that is, a method of selecting data above a certain limit for analysis, called POT method. The limiting form of its distribution function tends to generalized Pareto distribution (GPD). His work deepened the understanding of the concept of extreme value and its inherent meaning, that is, not only the maximum and minimum values are called extreme values, but also data above a certain limit should be extreme values, so they all need to be studied [6].

Research status

Since energy plays a very important role in economic growth and social development, China has always attached great importance to energy security and risk prediction. With the changes in the internal and external environment of China's economic development and the initial elimination of the risks of the COVID-19 pandemic, quantitative research on energy security assessment has increased in recent years.

Most traditional energy risk prediction methods adopt an indicator evaluation model. According to the number of indicators required for evaluation, it can be divided into single indicator evaluation and multi-indicator evaluation [7]. Single indicator evaluation can directly show the core part of the research problem, but it may not be accurate or objective when facing complex systems. Multi-indicator evaluation can fully reflect the characteristics of the research object, but it is too complicated and may also lead to different results due to different subjects and weight distribution.

At the same time, most of the research on energy risk prediction focuses on the operation of power equipment or the evaluation of energy system operation [1]. In view of the huge and complex energy data, China currently does not have a better prediction method.

From a statistical point of view, extreme values refer to the maximum and minimum values of a random process in a certain period, usually located at the tail of the data distribution. Extreme value distribution refers to the probability distribution of the maximum or minimum values in the observed values. Based on the tail characteristics of the distribution, possible extreme value movements can be further predicted. In other words, extreme value theory is a model technology used to predict the risks of abnormal phenomena or low-probability events. It has the ability to estimate beyond sample data and can accurately describe the quantiles of the tail of the distribution.

Regarding the application of extreme value theory in prediction, the current research of domestic and foreign scholars focuses on the use of extreme value asymptotic distribution probability theory to predict natural disasters. Wang Bojun et al. used four calculation methods to predict climate extremes and precipitation probabilities [8]; Zhang Youming et al. calculated the recurrence cycle of corresponding earthquakes and the number and probability of corresponding earthquakes that may occur in a certain period of time in the future based on the modified extreme value theory statistics [9]; Bykob also used extreme value asymptotic distribution theory to calculate forest fire cycles and predict risks [10]. Deng Wenping et al. chose to use extreme value theory based on actual forest stand data and adopted the generalized Pareto model to obtain the maximum number of trees in the forest stand at each given diameter class [11]. Song Xiaomeng et al. analyzed the probability statistical characteristics of extreme precipitation in Beijing based on extreme value theory and explored the applicability of different extreme value distributions in the study of extreme precipitation in Beijing [12].

This paper will use extreme value asymptotic probability theory to predict a series of Chinese energy indicators and try to prove its rationality.

Extreme value asymptotic probability theory

The Fisher-Tippett theorem (1928) is the core of extreme value theory, which mainly explains the convergence properties of extreme value distributions [13].

There exist two real number sequences $\{\alpha_n\}$ and $\{\beta_n\}$ (where $\alpha_n > 0$), such that $\lim_{n\to\infty} P\left(\frac{X_{(n)}-\beta_n}{\alpha_n} \le x\right) = H(X)(x \in R)$,

where H(x) is a non-degenerate distribution function, then H(x) is one of the following three types of extreme value distribution functions:

$\xi > 0$, its distribution function is

$$\Phi_{\xi}(x) = \begin{cases} 0, & x \le 0 \\ \exp\left(-x^{-\xi}\right), & x > 0 \end{cases}, \quad (1)$$

$\xi = 0$, its distribution function is:

$$\Lambda(x) = \exp\left[-\exp(-x)\right], \quad x \in R, \quad (2)$$

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ξ < 0, its distribution function is

$$\Psi_{\xi}(x)=\begin{cases}\exp\left[-(-x)^{\xi}\right], & x<0\\ 1, & x\geq 0\end{cases}. \quad (3)$$

This theorem describes that no matter what form the original distribution function F(*x*) takes, the sample maximum after linear transformation converges to a random variable with one of the above three distribution functions according to probability. Therefore, this theorem occupies a core position in the extreme value theory system and provides a solid foundation for further research [14].

Among them, (1) is collectively called Gumbel distribution, (2) is collectively called Frechet distribution, and (3) is collectively called Weibull distribution [15]. These three distributions are collectively called extreme value distribution. The extreme value type theorem states that if M_n undergoes a linear transformation, the corresponding normalized variable $M_n^* = (M_n - b_n) / a_n$ converges to a non-degenerate distribution according to the distribution. Then, no matter what form the underlying distribution F(*x*) takes, this limiting distribution must belong to one of the three types of extreme value distribution. Therefore, the extreme value type theorem provides an extreme value convergence theorem similar to the central limit theorem.

One practical difficulty of the one-dimensional extreme value distribution model is that we cannot directly determine which of the three distribution types the extreme value data obtained belongs to. In order to facilitate statistical inference, the generalized extreme value distribution (GEV) proposed by Uon Mrses (1954) and Jenkinson (1955) is an approximate distribution of extreme values [16–18].

The generalized extreme value distribution function is:

$$H_{\xi,\ \mu,\ \sigma}(\mathrm{x})=\begin{cases}\exp\left[-\left(1+\xi\frac{x-\mu}{\sigma}\right)^{-\frac{1}{\xi}}\right], \xi\neq 0, 1+\xi\frac{x-\mu}{\sigma}>0\\ \exp\left[-\exp\left(-\frac{x-\mu}{\sigma}\right)\right], \xi=0, -\infty<x<+\infty\end{cases}. \quad (4)$$

Among them, $-\infty < \mu < \infty$ is the location parameter, $\sigma > 0$ is the scale parameter, and $-\infty < \xi < \infty$ is the shape parameter. The tail behavior of the distribution function F(x) of the data X_i determines the shape parameter ξ of the generalized extreme value distribution H(*x*). If the tail of F(*x*) decays exponentially, then H(*x*) is of Gumble type and ξ = 0. The Gumble family includes thin-tailed distributions such as normal distribution, lognormal distribution, exponential distribution and Gamma distribution; if the tail of F(*x*) decays with a power function, then H(*x*) is of Frechet type and ξ > 0, and the Frechet family includes heavy-tailed distributions such as Pareto distribution, Cauchy distribution, and Student-t distribution; if the tail of F(*x*) is finite, then H(*x*) is of Weibull type and ξ < 0, and the Weibull family includes uniform distribution, β-distribution, etc.

In sampling distribution theory, the normal population is a population that is often used in practice and is widely used. Compared with the normal population, when the population is non-normal or the distribution of the population is unknown, it is very difficult to require the precise distribution of the sampling distribution, or the derivation is too complicated and difficult to apply.

However, when the population is an arbitrary distribution or the distribution is unknown, the asymptotic distribution of some statistics can be obtained using the large sample method. These methods have a generalizable significance. As long as a suitable function can be constructed, more sampling distributions can be obtained for further statistical inference.

Here is an example of the application of extreme value distribution theory in exploring the prediction of wind speed in Chongqing, China: Researchers used short-term wind speed data from Shapingba District, Chongqing from 1990 to 1999 to conduct extreme value distribution analysis of the annual maximum wind speed [3]. Firstly, the extreme value type I (Gumbel), extreme value type II (Frechet) and extreme value type III (Weibull) distributions were used to fit the extreme value distribution of the annual maximum wind speed. Then, the maximum wind speeds of each month from 1990 to 1994 were selected as samples, and the sample size was expanded to 60 to fit the asymptotic distribution of the monthly extreme value of the maximum wind speed. The parameters of the three extreme value distribution functions were estimated according to the principle of least squares method, moment method and variable substitution method. The fitting effect of the distribution function of the annual maximum wind speed under short-term wind speed data and the asymptotic distribution function of the monthly extreme value was compared through the parameter estimation goodness index. A better extreme value distribution function was selected from the 4 groups of 12 distribution functions as the extreme value distribution function of the annual maximum wind speed. Finally, the optimal asymptotic distribution of the extreme value of the annual maximum wind speed in Chongqing under short-term wind speed data was obtained by comparing and analyzing the parameter estimation index and wind speed estimation results with GPD.

Finally, the extreme value type III (Weibull) distribution gave the best fitting goodness of fit and extreme wind speed estimation value. For areas lacking long-term wind speed observation data, researchers used limited short-term data to analyze the monthly maximum wind speed to fit the asymptotic distribution of wind speed extremes in the area, which was significantly better than using annual maximum wind speed records. In a sense, the increase in sample size reduces sampling errors.

The extreme values of energy-related economic factors are unstable in the mathematical sense as random variables, but their changes over time are stable in probability. Therefore, the distribution of extreme values of energy-related economic factors can be simulated by distribution functions, thus providing a theoretical basis and data reference for the prediction of the probability of extreme events.

In this context, we have compiled and integrated some indicators, built a database based on China's energy data from 2013 to 2021 or 2022, tried to use extreme value theory to predict the extreme value distribution of China's energy factors, and look forward to making some suggestions for the construction of low-carbon energy policies.

We constructed six indicators and attempted to predict China's future energy development by applying extreme value asymptotic probability theory to these indicators (Table 1).

Combining extreme value theory and extreme value asymptotic distribution theory, we use the following algorithm to process the data:

1. First, we list a part of China's processed energy data from 2013 to 2021 ($X_1, X_2, \ldots X_9$) (Table 2).

2. Second, we sort the values in ascending order ($X_1^* < X_2^* < \ldots < X_n^*$) to get a new data string (Table 3).

3. Based on the statistics of the variant sequences, we will build a graph and add a trend line that most accurately characterizes the variant sequences (Figure 1).

4. We use the obtained function to calculate the value of x_{10} to use it in predicting the series.

$$x_{10} = 16.308. \quad (5)$$

5. Calculate initial data and build a quantile plot based on that data (Table 4 and Figure 2).

Based on the relationship between the two sets of data, a quantile graph is constructed using a coordinate system:

$$\left(-\ln(-\ln(\frac{i}{n+1}), \ln(x_i)\right). \quad (6)$$

Table 1 – China Energy Indicators [19, 20]

Indicators	Indicator values by year (2023–2025 – forecast)												
	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
1. Share of RES, %	10.535	11.293	12.086	13.834	14.425	14.845	15.395	15.799	16.182	16.308	16.343	16.253	16.036
2. Share of local unRES*, %	4.613	4.561	4.517	4.745	4.755	4.606	4.460	4.390	4.293	4.245	4.171	4.094	4.014
3. Energy independence (Ratio of energy imports to total energy consumption)	0.293	0.294	0.284	0.327	0.355	0.379	0.401	0.412	0.391	0.430	0.444	0.458	0.470
4. Energy transformation efficiency, %	73.0	73.1	73.4	73.5	73.0	72.8	73.3	73.7	73.2	73.2	73.8	73.9	74.0
5. Ratio of urban and rural per capita energy consumption	1.067	0.981	0.915	0.893	0.885	0.901	0.855	0.820	0.851	0.807	0.831	0.840	0.854
6. Coal's share of total energy consumption, %	71.3	70.0	68.1	66.8	65.3	63.9	62.8	62.2	61.8	61.3	61.0	60.9	60.9

*Local unRES means biomass energy, such as wood, crops, and municipal solid waste.

Table 2 – Share of renewable resources in China (2013–2021)

	2013	2014	2015	2016	2017	2018	2019	2020	2021
Ratio	10.535	11.293	12.086	13.834	14.425	14.845	15.395	15.799	16.182

Table 3 – New data string in ascending order

	1	2	3	4	5	6	7	8	9
Ratio	10.535	11.293	12.086	13.834	14.425	14.845	15.395	15.799	16.182

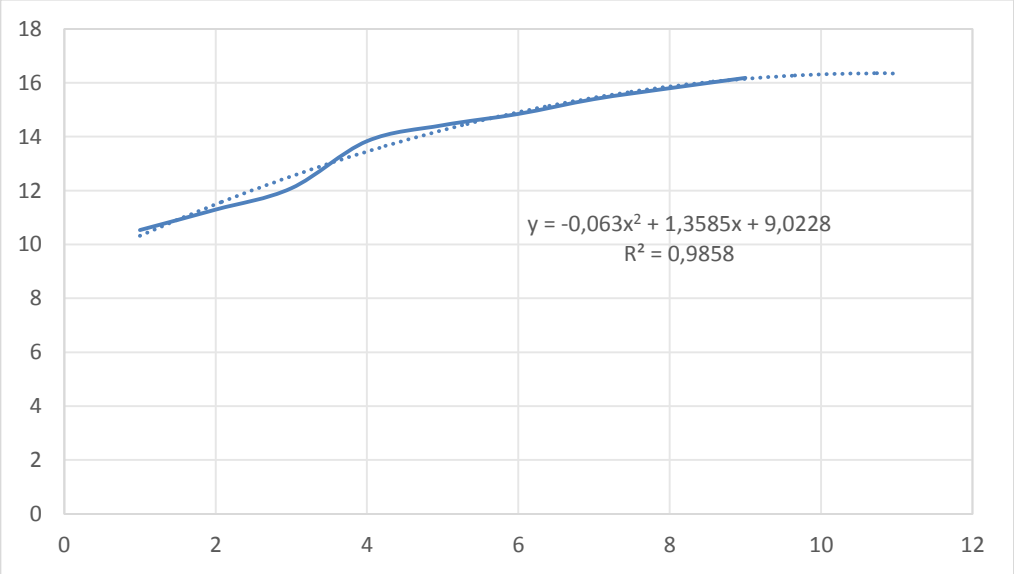

Figure 1 – Input data for predicting X_{10}

Table 4 – Initial data

	1	2	3	4	5	6	7	8	9
-ln(-ln(*i*/(n+1)))	–0.83	–0.48	–0.19	0.09	0.37	0.67	1.03	1.50	2.25
lnx	2.35	2.42	2.49	2.63	2.67	2.70	2.73	2.76	2.78

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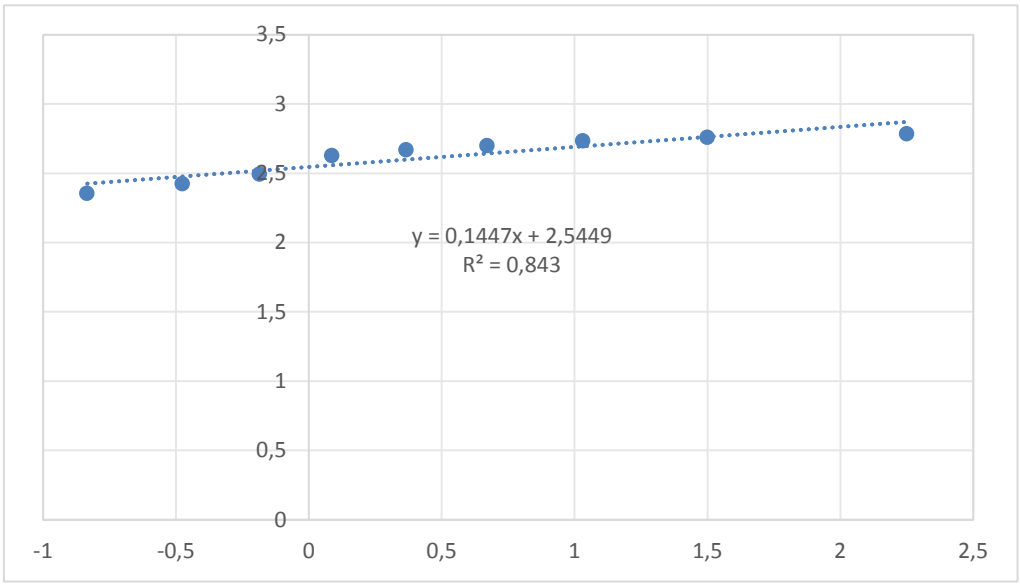

Figure 2 – Quantile chart of "share of renewable energy sources in China"

Table 5 – Maximum, minimum and average values of China's energy indicators from 2023 to 2026

Indicators		**2023**	**2024**	**2025**	**2026**
Indicator 1 Minimum	Maximum	19.735	19.742	19.638	19.458
	Minimum	11.122	11.377	11.630	11.861
	average	15.428	15.560	15.634	15.660
Indicator 2	Maximum	4.798	4.799	4.800	4.803
	Minimum	4.109	4.035	3.958	3.878
	average	4.454	4.417	4.379	4.340
Indicator 3	Maximum	0.506	0.523	0.540	0.555
	Minimum	0.280	0.283	0.286	0.290
	average	0.393	0.403	0.413	0.422
Indicator 4	Maximum	73.876	74.016	74.141	74.266
	Minimum	72.802	72.792	72.796	72.801
	average	73.339	73.404	73.468	73.533
Indicator 5	Maximum	1.011	0.995	0.980	0.965
	Minimum	0.740	0.746	0.755	0.768
	average	0.875	0.871	0.868	0.867
Indicator 6	Maximum	70.748	70.287	69.810	69.333
	Minimum	57.565	57.283	57.149	57.129
	average	64.157	63.785	63.480	63.231

1. Constructing the equation, we get:

$$Lnx = 0.1447y+2.5449. \quad (7)$$

2. By using the coefficient b and the constant a of the above equation, calculate the values of α and β and continue to build the indicator:

$$\alpha = \exp(-a);\ \beta = 1/b,$$

$$\alpha \approx 0.078;\ \beta \approx 6.911. \quad (8)$$

Then for the distribution law of the indicator "share of renewable energy sources in China", we get the following equation:

$$F(x) = \exp[(-0.078x)^{-6.911}]. \quad (9)$$

3. Calculate the maximum and minimum values of the indicator:

$$x_{min} = \exp[b\ (-\ln(-\ln 0{,}05))+a] = 10.871;$$

$$x_{max} = \exp[b\ (-\ln(-\ln 0{,}95))+a] = 19.583. \quad (10)$$

By repeating similar calculations for other data, we obtain the maximum, minimum and average values predicted for these data in the next three years.

Conclusions

Through calculation, we can conclude that extreme value asymptotic probability theory has a strong correlation with predicting China's energy-related indicators, and can be used as a means of predicting China's energy risks.

The calculation results tell us that in 2024–2026, the change range of the corresponding energy indicators is not large, which means that China's energy development level will remain within a stable range in the short term.

However, although the Chinese economy has shown a certain degree of resilience and good development momentum in the past decade, the economic growth momentum is insufficient. The current global economy is still facing various uncertainties and large downside risks, so China needs to focus on the following aspects:

After the epidemic, developing economies will be hit harder than the economies of developed countries, as sluggish global trade and tightening financial conditions have seriously dragged down economic growth.

The current "multiple crises" in geopolitics, public health, environment and economy have begun to affect the world's energy trade policy. Some countries are increasingly banning the trade of strategic energy commodities and services on the grounds of "security risks". In addition, global trade is being realigned along geopolitical lines, especially in the wake of the Ukrainian crisis.

Suggestions and advises

Due to the increase in global economic uncertainty and the large downside risks, China's post-epidemic energy economy may have an unexpected impact. Therefore, China should accelerate the use of policy tools and actively respond to changes in the external market. Specifically, the following measures can be considered.

First, strengthen international coordination of energy policies and improve policy effectiveness. Under the current circumstances, China should enhance its ability to deal with energy import and export risks, specifically by strengthening energy policy coordination and improving energy transaction efficiency and coverage under the multilateral framework. Through international coordination of energy policies, trade barriers can be reduced, cross-border investment can be promoted, and inflation can be reduced from the source.

Second, increase the exchange rate flexibility of the RMB in energy trade. The Chinese government should play the role of the exchange rate as an automatic balancer for the balance of payments and attract foreign capital inflows to ensure energy security. This requires the Chinese government to promote the alignment of domestic market rules and systems with international standards, thereby improving credit ratings and ensuring the level of domestic energy resource management.

Finally, the government should introduce policies to ensure energy security. China should strengthen the energy safety net and deal with energy risks in a market-oriented and legal manner. This requires the government to strengthen the review and management of cross-border capital flows and maintain the stability of domestic and foreign energy markets through positive actions and communication.

References

1. Guoqing, L. Risk Prediction of Node Outage in High Proportion New Energy Grid / L. Guoqing, L. Dagui, X. Guilian // Power System and Clean Energy. – 2022. – Vol. 38, No. 6. – P. 106–115.
2. Annual Report 2024. – World bank group. – URL: https://www.worldbank.org/en/about/annual-report (date of access: 10.11.2024).
3. Qingzhen, M. Asymptotic distribution of annual extreme values of maximum surface temperature and maximum wind speed in Chongqing / M. Qingzhen, W. Zengwu, F. Xin // Journal of Chengdu University of Information Technology. – 2004. – No. 3. – P. 436–441.
4. Barakat, M. H. Asymptotic Distributions of the Generalized Range, Midrange, Extremal Quotient, and Extremal Product, with a Comparison Study / M. H. Barakat, M. E. Nigm, M. A. Elsawah // Communications in Statistics – Theory and Methods. – 2015. – Vol. 44, No. 5. – P. 900–913.
5. Shuli, W. Tail characteristics of α-skewed normal distribution and limiting distribution of extreme values / W. Shuli, P. Zuoxiang // Journal of Southwest Normal University (Natural Science Edition). – 2020. – Vol. 45, No. 9. – P. 19–22.
6. Pu, J. Asymptotic expansion of the extreme value distribution of the three-parameter type I generalized logistic distribution / J. Pu, L. Xinling, L. Tingting // Journal of Southwest University (Natural Science Edition). – 2020. – Vol. 42, No. 6. – P. 60–64.
7. Dan, S. China's primary energy security: influencing factors, evaluation and prospects. / S. Dan, X. Qinyuan // Economic Perspectives. – 2021. – No. 1. – P. 31–45.
8. Baijun, W. Application of asymptotic extreme value theory in climate extreme precipitation prediction / W. Baijun, C. Gangyi // Journal of Chengdu Meteorological College. – 1994. – No. 2. – P. 30–34.
9. Shanhua, C. Research and application of extreme value theory in earthquake prediction in coastal areas of Fujian Province / C. Shanhua, Z. Youming, Y. Yuxing // North China Earthquake Science. – 2013. – Vol. 31, No. 2. – P. 29–34.
10. Bykov, A. A. Prilozheniya asimptoticheskoj teorii veroyatnostej ekstremal'nyh znachenij k prognozirovaniyu riska ekstremal'nyh chrezvychajnyh situacij / A. A. Bykov // Strategiya grazhdanskoj zashchity: problemy i issledovaniya. – 2012. – No. 1. – URL: https://cyberleninka.ru/article/n/prilozheniya-asimptoticheskoy-teorii-veroyatnostey-ekstremalnyh-znacheniy-k-prognozirovaniyu-riska-ekstremalnyh-chrezvychaynyh (date of access: 10.11.2024).
11. Wenping, D. Estimation of self-thinning line of larch plantation based on extreme value theory / D. Wengping, L. Fengri // Journal of Nanjing Forestry University (Natural Science Edition). – 2014. – Vol. 38, No. 5. – P. 11–14.
12. Xiaomeng, S. Study on probability distribution of extreme precipitation in Beijing based on extreme value theory / S. Xiaomeng, Z. Jianyun, K. Fanzhe // Science China: Technological Sciences. – 2018. – Vol. 48, No. 6. – P. 639–650.
13. Fisher, R. A. Limiting forms of the frequency distribution of the largest and smallest member of a sample / R. A. Fisher, L. H. C. Tippett // Mathematical Proceedings of the Cambridge Philosophical Society. – 1928. – Vol. 24, No. 2. – P. 180–190.
14. Fréchet, M. Sur la loi de probabilité de l'écart maximum / M. Fréchet // Annales de la Société Polonaise de Mathématique. – 1927. – Vol. 6, No. 1. – P. 93–116.
15. Shusen, D. Asymptotic Normality of GLUE of Weibull Distribution or Extreme Value Distribution and Its Application / D. Shusen // Journal of Fujian Normal University (Natural Science Edition). – 1982. – No. 1. – P. 69–80.
16. Zishen, C. Comparative analysis of parameter estimation methods of generalized extreme value distribution / C. Zishen, L. Zengmei, L. Jianfei // Acta Scientiarum Naturalium Universitatis Sunyatseni. – 2010. – Vol. 49, No. 6. – P. 105–109.
17. Jenkinson, A. F. The frequency distribution of the an-nual maximum (or minimum) values of meteorological elements / A. F. Jenkinson // Quarterly Journal of the Royal Meteorological Society. – 1955. – Vol. 81. – P. 158–171.
18. Hosking, J. R. M. L-moments: Analysis and estimation of distributions using linear combinations of order statistics / J. R. M. Hosking // The Journal of the Royal Statistical Society, Series B. – 1990. – Vol. 52. – P. 105–124.
19. Energy Statistics Data Browser. – URL: https://www.iea.org/data-and-statistics/data-tools/energy-statistics-data-browser (date of access: 10.11.2024).
20. China Energy Statistics Yearbook. – P. 3, 7, 9, 58–59.

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THEORETICAL AND METHODOLOGICAL APPROACHES TO ENSURING SUSTAINABLE INNOVATIVE DEVELOPMENT IN THE CONTEXT OF ECONOMIC SECURITY OF THE REPUBLIC OF BELARUS

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Abstract

Theoretical and methodological approaches to ensuring sustainable innovative development are the basis for ensuring the economic security of the country. Many years of experience in industrially developed countries indicate a significant positive impact of innovative development of national economic systems on the sustainability and efficiency of national economic development, its competitiveness, determines economic growth, and, consequently, affects national economic security.

The specificity of innovative development in Belarus is expressed in a fairly low innovative activity of economic entities, which causes destructive shifts towards material-intensive industries and creates threats to the economic security of the country.

The task of studying the impact of innovative development on the level of economic security of the country, as well as identifying ways to stimulate innovative development, is relevant and important. The aggravation of international conflicts and the growth of economic instability in the world emphasizes the scientific significance of the study. Innovative development strengthens the economic security of national economic systems, increases the competitiveness of the state, which ensures the sovereignty and independence of its socio-economic development, as well as the protection of national interests in the event of both external and internal threats to economic security. In real time, the main aspects of economic security of the national economic system occupy an important place in world economic science, which determines the interest and relevance of studying economic security issues on the part of scientists from different countries.

The purpose of the scientific article is a theoretical and methodological analysis of the role of innovative development of Belarus in ensuring its economic security. The basis of the study was the work of Belarusian and foreign scientists in the field of economic security of the state.

Keywords: security, economic security, innovation, innovative development, competition, competitive relations, competitive environment, competitive struggle, national economic systems.

ТЕОРЕТИКО-МЕТОДОЛОГИЧЕСКИЕ ПОДХОДЫ К ОБЕСПЕЧЕНИЮ УСТОЙЧИВОГО ИННОВАЦИОННОГО РАЗВИТИЯ В КОНТЕКСТЕ ЭКОНОМИЧЕСКОЙ БЕЗОПАСНОСТИ РЕСПУБЛИКИ БЕЛАРУСЬ

Н. П. Четырбок

Реферат

Теоретико-методологические подходы к обеспечению устойчивого инновационного развития являются основой в вопросе обеспечения экономической безопасности страны. Многолетний опыт индустриально развитых стран свидетельствует о существенном положительном влиянии инновационного развития национальных хозяйственных систем на устойчивость и эффективность развития национальной экономики, на ее конкурентоспособность, определяет экономический рост и следственно влияет на обеспечение национальной экономической безопасности.

Специфика инновационного развития Беларуси выражается в достаточно низкой инновационной активности хозяйственных субъектов, что вызывает деструктивные сдвиги в сторону материалоемких отраслей и создает угрозы для экономической безопасности страны. Актуальным и важным является задача исследования влияния инновационного развития на уровень экономической безопасности страны, а также выявление путей стимулирования инновационного развития. Обострение международных конфликтов и рост экономической нестабильности в мире подчёркивает научную значимость исследования.

Инновационное развитие усиливает экономическую безопасность национальных хозяйственных систем, увеличивает конкурентоспособность государства, что обеспечивает суверенитет и независимость его социально-экономического развития, а также защиту национальных интересов при возникновении как внешних, так и внутренних угроз экономической безопасности. В реальном времени основные аспекты экономической безопасности национальной хозяйственной системы занимают важное место в мировой экономической науке, что и обуславливает интерес и актуальность изучения вопросов экономической безопасности со стороны ученых разных стран.

Целью научной статьи является теоретико-методологический анализ роли инновационного развития Беларуси в области обеспечения ее экономической безопасности. В основе исследования использовались работы белорусских и зарубежных ученых в области экономической безопасности государства.

Ключевые слова: безопасность, экономическая безопасность, инновации, инновационное развитие, конкуренция, конкурентные отношения, конкурентная среда, конкурентная борьба, национальные экономические системы.

Introduction

Economic security is one of the most important components of the national security of the state. At the same time, the term "economic security" is an integral part of the concept of "national security". The concept of economic security arose in the twentieth century. The concept of economic security was introduced by the US President T. Roosevelt in 1934 by creating the Federal Committee for Economic Security. Since then, the term national security and issues of economic security have been considered in interconnection. Each country defines the criteria of economic security in its own way, but some indicators are common to many countries. But in general, the following indicators determine economic security: the size of the public debt; competitiveness of the economy; food security; structure of foreign trade; stability of the financial system; the level of state support for the country's innovative potential; social stability of the state; sovereignty of the state. Let us consider how innovative development determines economic security. And what is the situation in the Republic of Belarus.

The main part

Innovation activity, in its most general form, can be defined as an activity aimed at creating, implementing, and using innovations. For the purpose of comparative analysis, let's consider how other authors define its content.

One approach defines innovation activity as a way of applying new knowledge to generate profit [1, p. 49]. However, most often, the concept of innovation activity is formulated within the framework of L. M. Gokhberg's definition, where innovative activity is interpreted as an activity related to the transformation of ideas (usually the results of scientific research and development or other scientific and technical achievements) into technologically new or improved products or services introduced in the market, as well as into new or improved technological processes or methods of production (transfer) of services used in practice [2, p. 46]. Let's look at this process in Figure 1.

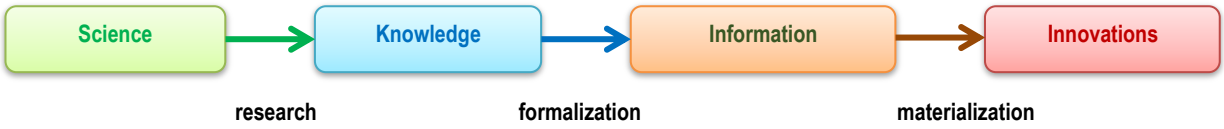

Figure 1 – The scheme of transformation of knowledge into a commodity [3, p. 15]

That is, according to the terminology used in Figure 1, this is the process of materializing abstract knowledge formalized in scientific and technical products. In a broad sense, this can be attributed to the production phase of the innovation cycle, and in a narrow sense, to the auxiliary activities of innovative service enterprises (business accelerators). At the same time, it should be understood that with this approach, the research and development phase is excluded from innovation activities, which is no longer acceptable.

However, many Russian scientists (Yu. P. Morozov, V. D. Gribov, A. V. Surin, O. P. Molchanova) and Belarusian scientists (M. V. Miasnikovich, N. B. Antonova, etc.) adhere to a similar point of view [4, p. 95; 5, p. 72; 6, p. 35; 7, p. 29].

Not all of them share this view, though. In this context, the position of the Russian researcher T. F. Berestova appears quite adequate. She believes that: "Innovative activity is an activity that includes the entire cycle, from the origin of an idea, its technological elaboration, and documentation, up to the necessary commercial procedures to enter the market as a product in the form of a product, service, or technology" [8, p. 74].

Here, our views converge not only with T. F. Berestova, but also with the opinion of the Organization for Economic Cooperation and Development, as well as the European Statistical Office, which, since 2005, have argued that "innovation encompasses all scientific, technological, organizational, financial, and commercial actions and measures, including investments in new knowledge, that lead to the implementation of innovations. They also include fundamental research, which by definition is not directly related to the development of any particular innovation" [9, p. 61, 62].

It is obvious that the unanimity of opinions expressed by the above-mentioned authors was due, firstly, to the authority of the publication led by L. M. Gokhberg, and secondly, to the habit of using stereotypical judgments on difficult-to-perceive issues that one does not want to delve deeply into. As a result, there is a lack of one's own reasoned opinion on these matters, the formation of which is possible only in the case of possessing the methodology of scientific knowledge.

Turning to the concept of innovation, it is necessary to draw the following conclusion a priori: If we consider innovation activity as an activity aimed at creating, implementing, and using innovations, then these innovations should be formed at each stage of the innovation cycle (Figure 2). They transition sequentially from a scientific idea (know-how) into the results of scientific research, design documentation for the production of a new product, then into its prototype, an experimental batch, and finally into finished products intended for the end user. All of these will be innovations that have a commodity form ready for implementation.

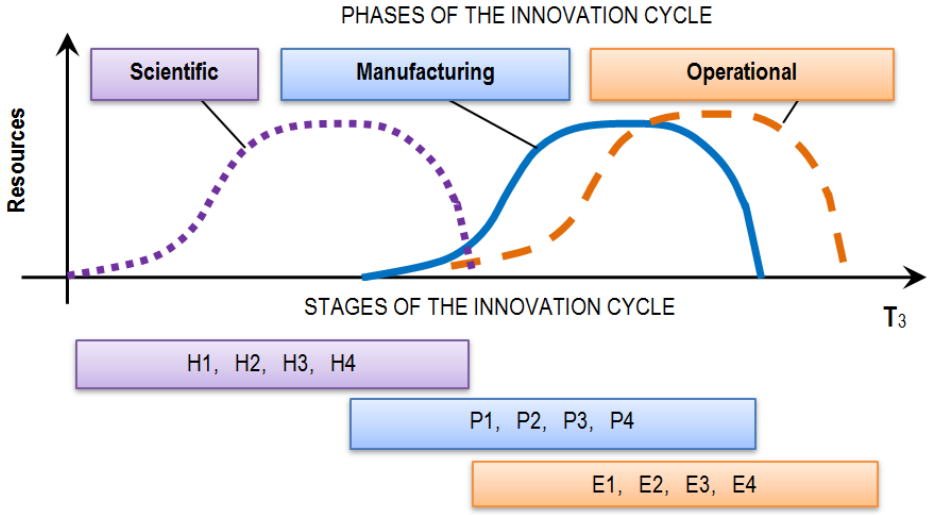

Figure 2 – A model of the innovation cycle

Let's consider the existing judgments on the content of the concept of 'innovation.' Given the vast number of definitions attributed to this concept, we will conduct a brief analysis of literary sources, highlighting the most characteristic approaches available within them.

Where:

– the scientific phase includes fundamental research (H1), applied research (H2), experimental design (H3), and the creation of samples of new products and processes (H4);

– the production phase consists of technological preparation of production and initial development of innovations in the production process (P1), expansion of production (P2), stabilization of production (P3), and stagnation of production (P4);

– the operational phase involves the primary use of innovation by the consumer (E1), expansion of consumption (E2), mass use (E3), and consistent decommissioning due to the inconsistency of product characteristics with changed market requirements (E4).

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Considering the definition of innovation in the most common sources, it is worth highlighting three formulations of this concept, each of which conflicts with the laws of logic [10]:

Innovation is a new product introduced into use…

Innovation is the result of investing…

Innovation is the process of creating an innovation...

In the first variant, two main phases are excluded from the innovation cycle at once: scientific and industrial, which renders its definition impossible. At the same time, the authors do not seem to be interested in the question of the correlation of concepts within the innovation sphere; therefore, in the same scientific papers, they may make contradictory statements.

In the second variant, a typical substitution of concepts occurs, where one of the indirect components of innovation (financing) is automatically elevated not only to the rank of determining factor but also as the only factor, thereby ignoring the very essence of the innovation process.

As for the third definition, innovation is not a process. There is a separate concept in the innovation sphere, objectively defined as the 'innovation process,' which does not depend on the opinion of an individual author.

In our opinion, there is no need to invent something new if we can use a simple and clear translation of this basic concept from the original language into Russian, and only then clarify the definitions derived from it. In Latin, 'innovatio' means renewal or change, and innovation is translated as 'инновация' (innovation). Similarly, the translation of the concept of innovation (from Latin 'novatio' – update, change) is the same, effectively putting a sign of identity between them [11, 12].

It would seem that everything is extremely transparent. But again, this is not the case for everyone. Some 'researchers' believe that 'innovation' and 'инновация' are not synonymous [13]. As a result of such linguistic refinements, synonymous concepts are given different semantic meanings. According to [14, p. 159], 'innovation' is interpreted as a new method or invention, 'инновация' as an innovation used, and 'нововведение' as a propagated innovation. Consequently, essentially different stages of the innovation cycle are defined by terms that are adequate in content.

Such pseudo-creative methods of terminological research introduce confusion into the conceptual apparatus of the innovation sphere without providing any practical value.

In conclusion, it should be noted that the definition of any concept should be both comprehensive and universal, while avoiding two or more interpretations. In our opinion, such requirements regarding innovation are met by the definition provided in the Encyclopedia of the Republic of Belarus, which states that innovation is 'the result of intellectual activity aimed at ensuring progress in the development of the economy and society' [15].

Among the components of the process of innovative development, a special role is assigned to state innovation policy (GIP), which includes a system of control actions aimed at stimulating innovation and forming a national innovation system. This national innovation system determines the structure of the innovation sphere within the GIP, utilizing its elements to address tasks related to the implementation of innovative activities. The central link of the national innovation system is science; therefore, the motivation and stimulation of intellectual labor should be prioritized in state innovation policy [16, p. 3; 17, p. 94].

To understand the general state of innovative development, we will consider the main indicators and Belarus's position in the world ranking of innovative development.

The most common system for assessing the level of innovative development is the Global Innovation Index (GII) [18, 19].

The Global Innovation Index (GII) analyzes the most relevant global trends in innovation. This report provides a ranking of the effectiveness of innovation ecosystems in countries around the world, highlighting strengths and weaknesses in terms of innovation, as well as specific gaps in innovation indicators. The index, designed to provide the most comprehensive picture possible in the field of innovation, covers approximately 80 indicators, including those related to the political situation, education systems, infrastructure, and knowledge creation in each country.

The Global Innovation Index (GII) is compiled annually by the World Intellectual Property Organization (WIPO). The index ranks 132 economies based on 80 indicators that characterize the innovative development of countries, reflecting their innovative potential and the conditions for its implementation. Therefore, the index is calculated as a weighted sum of estimates from two groups of indicators: available resources (institutions, human capital and science, infrastructure, and the level of market and business development) and conditions for innovation (technology development and the knowledge economy, as well as the results of creative activity).

The dynamics of this index for the Republic of Belarus and its position in the country ranking for the available period of analysis, according to the GII, is shown in Figure 3.

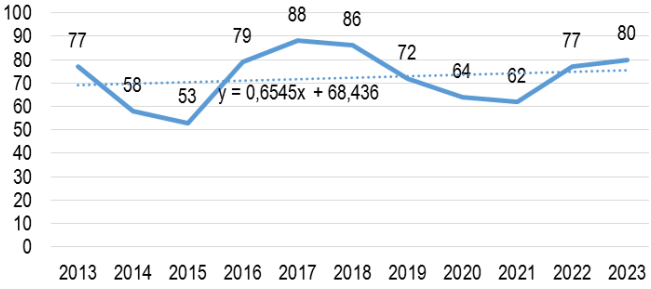

Figure 3 – Dynamics of the Global Innovation Development Index of the Republic of Belarus, points

At the same time, the report on the GII of Belarus [19] notes that the availability of data and changes in the structure of the GII model affect the comparison of GII rankings from year to year.

In 2023, as in 2022, Switzerland, the USA, and Sweden remained the leaders of the ranking. They are followed by the United Kingdom, Singapore, Finland, the Netherlands, Germany, Denmark, and South Korea. Among the post-Soviet countries, Estonia (16th place), Lithuania (34th), and Latvia (37th) achieved the best results. Ukraine is significantly behind in 55th place, followed by Moldova in 60th, Georgia in 65th, Armenia in 72nd, Kazakhstan in 81st, Uzbekistan in 82nd, Azerbaijan in 89th, Kyrgyzstan in 106th, and Tajikistan in 111th. Russia, having dropped four places, ranked 51st, placing it below all other countries in the "old" BRICS, except for South Africa (59th place). Thus, China ranks 12th, India 40th, and Brazil 49th. Burundi, Niger, and Angola complete the ranking.

In the new ranking, Belarus dropped from 77th to 80th place, positioned between Tunisia and Kazakhstan. In 2023, the Global Innovation Index was 26.8 (80th place in the ranking). The statistical confidence interval for Belarus's rating in the GII 2021 is between 49th and 67th ranks. The maximum value of the Global Innovation Index (38.2) was achieved by the Republic of Belarus in 2015; at that time, the highest position in the country ranking for this index was observed during the analysis period. The minimum value – 29.4 – was recorded in 2017 (88th place). The general trend in the dynamics of the Global Innovation Index for Belarus is negative, indicating a deterioration in innovative development during the period from 2013 to 2023.

The GII consists of two sub-indices: the Innovation Input Sub-index and the Innovation Output Sub-index, as well as seven main components, each of which consists of three sub-indices. The position of Belarus in the ranking of countries worldwide by GII components in 2021 [18] and 2023 [19] is shown in Figure 4.

Sixteen of the GII leaders in the top 25 are European countries, with seven of them in the top 10. Belarus ranks 15th among 34 countries with above-average income and 36th among 39 European economies [19]. Belarus demonstrates the best results in the fields of knowledge and technology, as well as human capital, while its weakest indicators are in market development and institution building. In relation to GDP, Belarus's indicators align with expectations regarding its level of development. It is noted that Belarus produces more innovative products compared to its level of investment in innovation. A comparative analysis of the GII components for the Republic of Belarus and nine EU countries for 2023 [19] is presented in Table 1.

The indicator of knowledge intensity characterizing the innovative development of the country in the Republic of Belarus has been below the critical level (1 %) for a long time and does not exceed 0.5 % Figure 5.

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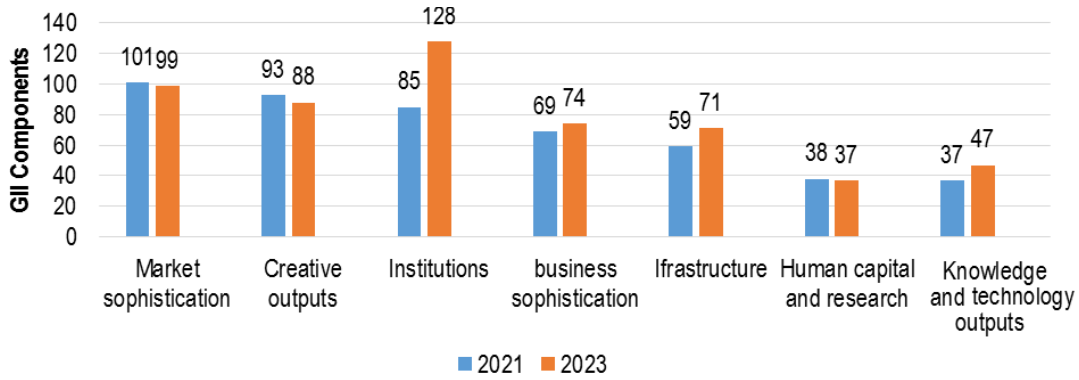

Figure 4 – Belarus' place in terms of components of the Global Innovation Development Index in the ranking of countries in the world in 2021 and 2023

Table 1 – Comparative analysis of GII components for the Republic of Belarus and individual EU countries in 2023

GII Components	Belarus	Sweden	Germany	France	Italy	Poland	Russian Federation	Latvia	Lithuania
1	2	3	4	5	6	7	9	10	11
Ranking	**80**	**2**	**8**	**11**	**26**	**41**	**51**	**37**	**34**
Global Innovation Index	26,8	64,2	58,8	56,0	46,6	37,7	51	39,7	42,0
Institutions	24,3	74,3	71,9	70,0	55,4	47,1	34,9	62,8	73,5
Human capital and research	39,9	62,7	61,1	54,0	43,7	37,7	47,2	37,4	37,4
Infrastructure	38,7	67,6	57,1	57,2	57,2	48,5	38,0	54,7	51,9
Market sophistication	23,8	59,9	56,5	60,7	44,3	34,5	37,7	36,0	45,3
Business sophistication	26,3	75,8	56,9	56,1	41,3	36,7	34,7	38,1	39,3
Knowledge and technology	29,9	63,4	55,4	46,7	44,3	31,6	26,4	28,0	35,3
Creative output	26,3	57,3	58,2	58,2	45,3	37,6	29,9	39,4	33,5

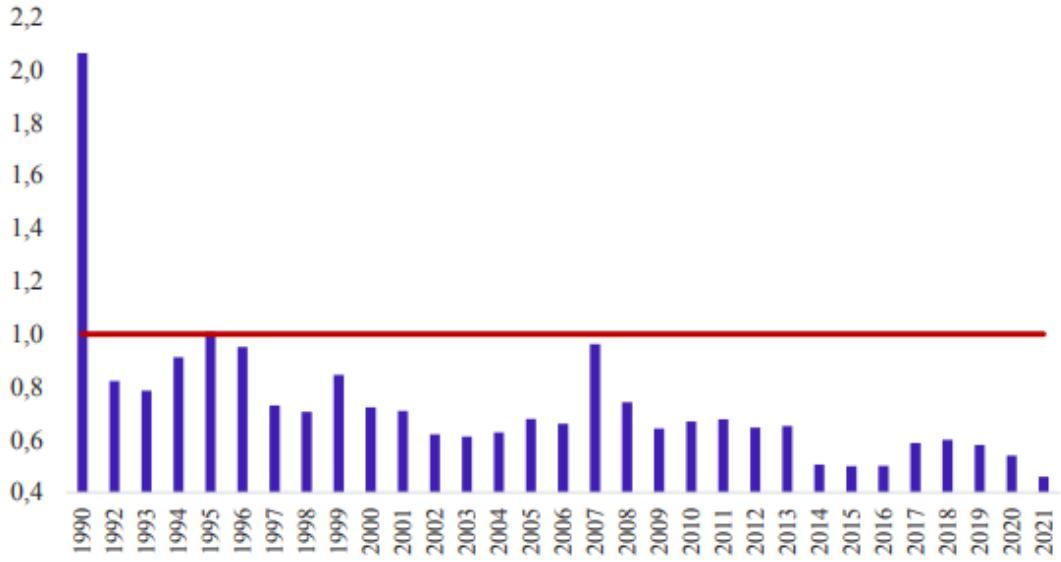

Figure 5 – R&D expenditure (% of GDP), an indicator of the knowledge intensity of the Republic of Belarus threshold value of R&D expenditure (% of GDP) within the framework of economic security

As can be seen from the presented graph, the most optimistic years are 1995, 1996, and 2007, while the most critical years from the perspective of innovative development are 2014, 2015, 2016, and especially 2021, which indicates insufficient funding for the scientific sector and an emerging negative trend.

The relationship between the level of innovative development and the state of economic security will be examined in more detail below. Economic security is one of the most important components of national security. At the same time, the term 'economic security' is an integral part of the concept of 'national security.' The concept of economic security origi-

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nated in the twentieth century and was introduced by U.S. President T. Roosevelt in 1934 with the establishment of the Federal Committee for Economic Security. Since then, the issues of national security and economic security have been considered in conjunction.

There are two common concepts – Anglo-Saxon and Asian. The first focuses on the economic security of households and individuals and is actively promoted in the United States of America [20]. The latter is based on a macroeconomic approach to ensuring national economic security, with representatives from some Eastern European schools among its followers [20]. The third concept has been developing rapidly since the 1990s, with a primary focus on the economic security of enterprises, taking into account macroeconomic factors. Its rapid development began in the post-Soviet space, likely due to the unstable economy of the 1990s, which led to a significant number of bankruptcies. Consequently, some questions remain unresolved regarding the conditions under which economic security, competitiveness, and development affect each other and become intertwined. For this reason, studies of the conditions determining accessibility and the direction of the relationship between economic security and these categories are becoming increasingly relevant.

Each country defines the criteria for economic security in its own way, but some indicators are common to many countries. Collectively, the following indicators determine economic security: the size of public debt; the competitiveness of the economy; food security; the structure of foreign trade; the stability of the financial system; the level of state support for the country's potential in the scientific field; social stability of the state; state sovereignty; and the level of state participation in regulating economic processes within the country [21].

The most important document regulating the sphere of national security is the "Decision of the All-Belarusian People's Assembly of April 25, 2024 No. 5 "On Approval of the Concept of National Security of the Republic of Belarus" (04/25/2024, 1/21360)". The approved Concept of National Security of the Republic of Belarus reflects issues of information security, which is defined as the state of protection of the information space, information infrastructure and information resources from external and internal threats in the information sphere. The document reflects national interests in the information sphere, defines the main directions for neutralizing internal sources of threats and protecting against external threats to national security in the information sphere [22].

According to the Resolution of the Council of Ministers of the Republic of Belarus dated February 22, 2007, No. 226, 'On the Organization of Monitoring of the Most Important Indicators of Economic Security of the Republic of Belarus,' the following indicators are listed in the List of the Most Important Indicators of Economic Security of the Republic of Belarus: the degree of depreciation of the active part of fixed assets at the end of the year; the share of investments in fixed assets in GDP; research and development costs as a percentage of GDP; the share of new products in the total volume of industrial products; the share of food product imports in the total volume of their retail turnover; the ratio of domestic public debt to GDP; the ratio of external public debt to GDP; the level of gold and foreign exchange reserves in months of imports; the unemployment rate as a percentage of the active population; the share of the population with incomes below the budget of the subsistence minimum; and the balance of foreign trade (including services, according to the balance of payments) to GDP, etc. [23].

Thus, indirectly, scientific and official approaches to the definition of national and economic security affect concepts such as innovation, competitiveness, and economic growth [24, 25]. Let us consider the significance of these categories in the context of national and economic security.

Economic security and the economic growth of a country are closely linked. Gross Domestic Product (GDP) is commonly used as a measure of a country's economic strength. GDP per capita is often used as an indicator of the standard of living, although it obscures the uneven distribution of income among the population. Based on this, it can be argued that a high GDP and its growth are prerequisites for economic security. However, excessively high GDP growth can also lead to an economic crisis. It is crucial to monitor GDP growth rates, as excessive growth may result in the rapid depletion of production resources, increased inflation, and negative consequences for the economy. Very often, GDP growth is associated with the accumulation of debt and the excessive consumption of a country's natural resources. The cost of restoring the ecological balance disrupted by industrialization contributes to GDP; in the event of natural disasters, the cost of emergency services increases; an increase in crime raises the costs of investing in law enforcement; and epidemics lead to higher healthcare costs. All these expenses relate to public procurement and increase the volume of GDP, so GDP does not differentiate between the factors that promote progress and those that hinder it.

Thus, economic growth is a prerequisite for improving the security and well-being of each country, but it can also be a precursor to a crisis in the long term.

Weak or negative growth is not favorable for economic security, nor is excessively rapid growth. The question arises: 'What should optimal economic growth be?' A number of scientists suggest that sustainable GDP growth should range from 2.5 % to 3.0 %. Such growth rates are sufficient to stimulate economic activity without unjustifiably increasing inflation. Potential GDP, or natural GDP, is the level of GDP that can be maintained for a long period of time without causing a significant increase in inflation. Potential GDP is achieved through the full utilization of available production resources. GDP growth beyond its potential leads to the so-called 'overheating' of the economy and the depletion of natural resources at a rate faster than their recovery. Growth below the level of potential GDP indicates that not all factors of production are being utilized efficiently. There are various reasons why an economy may grow below potential GDP. Since economic security depends on economic growth, and if GDP growth is taken as a measure of economic growth, then to maintain economic security, a country should strive to ensure that GDP growth is as close as possible to potential GDP.

Economic Security and Competitiveness of the Country. Modern approaches to ensuring the national interests of the Republic of Belarus highlight the need to study the issue of increasing the country's competitiveness in the international context. The examination of the category 'competitiveness of the country,' as well as the development of a methodology for assessing macro-level competitiveness, will establish a theoretical foundation for forming a scientific approach to ensuring national interests and economic security in the Republic of Belarus from the standpoint of national competitiveness.

The concept of competitiveness was developed in English in the nineteenth century, and its linguistic roots lie in the Latin phrase 'com + petere,' meaning the desire to achieve something. Today, competitiveness is one of the most frequently used concepts in economics; however, there is no uniform understanding of its content in the scientific literature [26].

When using a broad concept of competitiveness, factors that have a determinative effect on economic growth are typically considered, where competitiveness serves as a means of creating opportunities to focus on those types of activities in which the national economy has competitive advantages that facilitate the achievement of economies of scale and open access to new technologies and management methods [27, p. 8]. An analysis of foreign economic security studies indicates that scientific approaches to determining the relationship between economic security and competitiveness are under detailed examination.

Competition contributes to the growth of national well-being and economic development, as well as making markets more flexible, sustainable, and innovative. It is believed that competition stimulates innovation and that innovation, in turn, contributes to increased well-being and economic growth; however, there is no theoretical consensus on the exact relationship between these three important components of a market economy and their impact on national security.

Economic Security and Innovation. The relationship between innovation and the level of economic development of a country, as well as economic security, remains unexplored. If we focus on the indicators of economic security, it becomes evident that the low level of innovative activity and the low effectiveness of innovation efforts have a significant negative impact on ensuring economic security. Thus, a number of scientists emphasize that a level of research and development costs to GDP below 2 % jeopardizes economic and national security.

A direct correlation is established between the level of competitiveness and innovative activity, which can not only preserve or increase the share of enterprises' production in the domestic market but also penetrate external markets. The concept of competitiveness is often intertwined with the con-

cept of innovation, which is regarded as one of the most important sources of competitive advantage and economic dynamism, especially in a rapidly changing world where technological progress and trade liberalization have led to an expansion of economic interaction. The factors that positively affect the ability of companies to compete largely coincide with those factors that have been identified as conducive to innovation [28, p. 3].

Therefore, innovative activity is considered the main driving force of competitiveness in a market economy. This is because structural changes aimed at reorienting the economy toward more efficient production models with a high technological component and added value are associated with increased competitiveness resulting from the implementation of innovative activities. UN experts note: 'Where there is no competitive pressure in favor of innovation, owning a market share may well become a factor influencing it and yield monopoly rent without having a positive impact on economic growth' [29, p. 13, 94].

When using the broad concept of international competitiveness, which pertains to policy in terms of competitiveness, the factors that have a sustainable positive impact on the growth of value added, considering the criterion of external competition, are examined. Competitiveness in this context appears to be merely a means to achieve the goal, with the expected result being economic growth and an increase in the income of the population [30, p. 8, 9].

Conclusion

1. Innovation is the main driving force of competitiveness in a market economy. Today, it is regarded as one of the most important sources of competitive advantages and economic dynamism.

2. The factors that positively affect the ability of companies to compete largely coincide with the factors that favor innovation.

3. Competitiveness can be considered in both a 'narrow' and a 'broad' sense. In the 'narrow' sense, the emphasis is on the ability of national companies to compete for leadership in global markets, the competitive potential of which is determined by the level of their innovative activity. Broadly speaking, the focus shifts to factors affecting labor productivity and, ultimately, to the driving forces of economic development. Competitiveness in this context appears to be merely a means to an end, with the expected outcome being economic growth.

4. The new economy is based on the interdependence and systemic unity of its three basic concepts: economic growth, innovation, and competitiveness. It is worth noting that both domestic and foreign research addresses the formation of a competitive environment and examines the impact of competitiveness, innovative development, and economic growth on sustainable development.

Thus, the paradigm of the development of the new economy is grounded in the interdependence and systemic unity of its three basic concepts:

• Added value as the main source of socio-economic development (economic growth);

• Innovations as the main resource involved in the process of social reproduction;

• Competitiveness as the most important condition for the integration of the national economy into the system of the global division of labor (Figure 6).

As shown in Figure 6, the central link of this paradigm is innovation, which acts in relation to its other two components not only as a resource but also as a factor that determines them. This is stated in the documents of the United Nations Economic Commission for Europe, where it is noted that 'in a modern knowledge-based economy, the main driving force of competitiveness is innovation.' Therefore, 'in connection with the increasing influence of innovations on economic growth and competitiveness,' paternalistic measures of state economic policy are also being strengthened, aimed at 'creating conditions conducive to their generation and dissemination' [29, p. 3; 30]. As a result, the solution to the three-pronged task of growth for all components of this paradigm occurs through the stimulation of innovation, which in turn leads to ensuring economic and scientific-technical security.

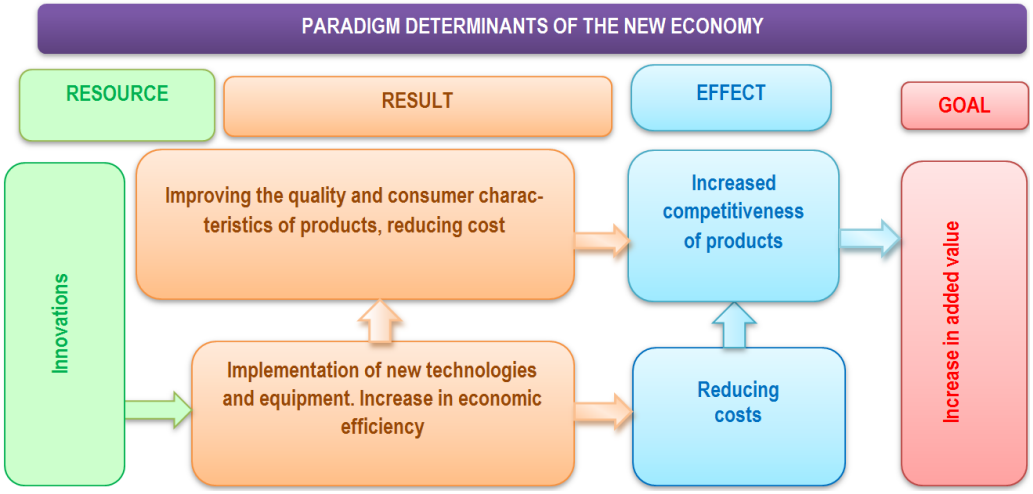

Figure 6 – Structural and functional diagram of the new paradigm of economic development

References

1. Innovacionnyj biznes: formirovanie modelej kommercializacii perspektivnyh razrabotok : uchebnoe posobie / V. L. Antonec, N. V. Nechaeva, K. A. Homkin, V. V. SHvedova ; pod red. K. A. Homkina. – M. : Delo, 2009. – 302 s.
2. Ekonomika znanij v terminah statistiki: nauka, tekhnologii, innovacii, obrazovanie, informacionnoe obshchestvo : slovar' / G. I. Abdrahmanova, N. V. Gorodnikova, L. M. Gohberg [i dr.] ; pod red. L. M. Gohberga. – M. : Ekonomika, 2012. – 238 s.
3. Innovacionnyj menedzhment: teoriya i praktika: / A. V. Markov, V. K. SHCHerbin, Z. M. YUk, A. D. Lucevich ; pod nauch. red. A. V. Markova. – Minsk : Kolorgrad, 2015. – 513 s.
4. Morozov, YU. P. Innovacionnyj menedzhment: uchebnoe posobie dlya vuzov / YU. P. Morozov. – M. : YUNITI, 2000. – 446 s.
5. Gribov, V. D. Menedzhment : uchebnoe posobie / V. D. Gribov. – M. : KnoRus, 2022. – 275 s.
6. Surin, A. V. Innovacionnyj menedzhment / A. V. Surin, O. P. Molchanova. – M. : Infra-M, 2008. — 368 s.
7. Myasnikovich, M. V. Gosudarstvennoe regulirovanie innovacionnoj deyatel'nosti : uchebnoe posobie / M. V. Myasnikovich, N. B. Antonova, L. N. Nekhorosheva. – Minsk : Akademiya upravleniya pri Prezidente Respubliki Belarus', 2005. – 235 s.
8. Berestova, T. F. Innovaciya i innovacionnaya deyatel'nost': predely ponyatij / T. F. Berestova // Vestnik CHelyabinskoj gosudarstvennoj akademii kul'tury i iskusstv. – 2008. – T. 15. № 3. – S. 70–76.

https://doi.org/10.36773/1818-1112-2024-135-3-145-151

9. Rukovodstvo Oslo : rekomendacii po sboru i analizu dannyh po innovaciyam : sovmestnaya publikaciya Organizacii ekonomicheskogo sotrudnichestva i razvitiya i Statisticheskogo byuro evropejskih soobshchestv / Centr issledovanij i statistiki nauki (CISN). – 3-e izd. – M., 2010. – 107 s.
10. Innovaciya. – URL: https://ru.wikipedia.org/wiki/ Innovaciya (data obrashcheniya: 18.08.2024).
11. Krysin, L. P. Tolkovyj slovar' inoyazychnyh slov / L. P. Krysin. – M. : Eksmo, 2006. – 944 s.
12. Mihel'son, A. D. Ob"yasnenie 25 000 inostrannyh slov, voshedshih v upotreblenie v russkij yazyk, s oznacheniem ih kornej. Sostavil po slovaryam: Gejze, Besherelya, Brokgauza, Aleksandra, Rejfa i drugih / sost. A. D. Mihel'son. – M. : Izdanie knigoprodavca A. I. Manuhina, 1865. – 718 s.
13. Ponyatie innovacii i ee harakteristiki. – URL: https://moodle.kstu.ru/mod/book/view.php?id=22425 (data obrashcheniya: 18.08.2024).
14. Menedzhment organizacii: uchebnoe posobie / Z. P. Rumyanceva, N. A. Solomatin, R. Z. Akberidin ; pod red. Z. P. Rumyancevoj, N. A. Solomatina. – M. : INFRA-M, 1995. – 347 s.
15. Respublika Belarus' : enciklopediya : v 6 t. / G. P. Pashkov [i dr.] – Minsk : BelEn, 2006. – T. 3 : Gerasimenko-Kartel'. – S. 750.
16. Vasin, V. A. Metodologicheskie aspekty formirovaniya nacionalnoj innovacionnoj sistemy: problemy, puti ih resheniya / V. A. Vasin, L. E. Mindeli // Innovacionnaya ekonomika. – 2004. – № 6. – S. 3–7.
17. Mikul'skij, K. I. Innovacii i ekonomicheskij rost: monografiya / K. I. Mikul'skij. – M. : Nauka, 2002. – 377 s.
18. Global Innovation Index 2021: Belarus Global'nyj innovacionnyj indeks. BLR.PDF. – URL: https://www.globalinnovationindex.org (date of access: 29.04.2024).
19. Global Innovation Index 2023 Innovation in the face of uncertainty. – URL: https:// https://www.wipo.int/documents/d/global-innovation-index/docs-en-wipo-pub-2000-2023-en-main-report-global-innovation-index-2023-16th-edition.pdf (date of access: 22.09.2024).
20. Pechenin, M. G. Sposoby ocenki ekonomicheskoj bezopasnosti gosudarstva kak makroekonomicheskogo subekta (na primere Respubliki Belarus') / M. G. Pechenin, T. V. Gerasimchik. – URL: https://elib.bsu.by/bitstream/123456789/295708/1/754-757.pdf (data obrashcheniya 23.04.2024).
21. Nizamov, C. C. Kriterii i pokazateli ekonomicheskoj bezopasnosti gosudarstva / C. C. Nizamov. – URL: https://cyberleninka.ru/article/n/kriterii-i-pokazateli-ekonomicheskoy-bezopasnosti-gosudarstva (data obrashcheniya 21.04.2024).
22. Decision of the All-Belarusian People's Assembly of April 25, 2024 No. 5 "On Approval of the Concept of National Security of the Republic of Belarus" (04/25/2024, 1/21360)". – URL: https://pravo.by/document/?guid=12551&p0=P924v0005 (data obrashcheniya 06.07.2024).
23. Ob organizacii monitoringa vazhnyh pokazatelej ekonomicheskoj bezopasnosti Respubliki Belarus' : postanovlenie Soveta Ministrov Respubliki Belarus' ot 22.02.2007 № 226 // Etalon Online: inform.-poiskovaya sistema (data obrashcheniya: 23.10.2024).
24. CHetyrbok, N. P. Trialekticheskij podhod k ekonomicheskim issledovaniyam / N. P. CHetyrbok // Vesti Instituta predprinimatel'skoj deyatel'nosti. – 2022. – № 2 (27). – S. 12–18.
25. CHetyrbok, N. P. Innovacii, konkurentosposobnost' i ekonomicheskij rost v kontekste nacional'noj bezopasnosti / N. P. CHetyrbok // Aktual'nye problemy ekonomicheskoj bezopasnosti gosudarstva i biznesa : materialy III Mezhdunarodnoj nauchno-prakticheskoj konferencii, Novosibirsk, 25–26 aprelya 2024 g : v 2 ch. / Novosibirskij gosudarstvennyj universitet ekonomiki i upravleniya. – Novosibirsk : NGUEU, 2024. – CHast' 1. – S. 418–424.
26. Kryuchkova, YU. V. O strukture koncepta Competitiveness v angloyazychnom delovom diskurse / YU. V. Kryuchkova. – URL: https://cyberleninka.ru/article/n/o-strukture-kontsepta-competitiveness-v-angloyazychnom-delovom-diskurse (data obrashcheniya 16.09.2024).
27. Konkurentosposobnost' v sovremennoj ekonomike: vyzovy dlya regiona EEK OON // Evropejskaya ekonomicheskaya komissiya OON. – ZHeneva, 2006. – 30 s.
28. Sozdanie uslovij, sposobstvuyushchih povysheniyu konkurentosposobnosti i effektivnosti nacional'nyh innovacionnyh sistem // Evropejskaya Ekonomicheskaya Komissiya OON. – N'yu Jork i ZHeneva, 2007. – 136 s.
29. Druker, P. Zadachi upravleniya v XXI veke / P. Druker. – M. : Vil'yams, 2002. – 257 s.
30. Machlup, F. The Production and Distribution of Knowledge in the United States / F. Machlup. – Princeton: Princeton University Press, 1962. – 523 p.

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INNOVATIVE SYSTEM OF TRAINING AND MANAGEMENT DECISION-MAKING

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Abstract

One of the promising areas for increasing the effectiveness of higher education institutions in the context of the current global confrontation may be the implementation of competitiveness management systems (CMS). The theoretical basis for modern research on the creation of CMS adapted to existing circumstances is the use of an innovative system of training and decision-making (ISOPUR), which, taking into account the conditions of global geopolitical instability, should be supplemented (modified) by the connection (chain) «environment» and have the following content: environment (E) – methodology (M) – economy (E) – technology (T) – management (U) – competitiveness (Ksp), i. e. OMETUKsp.

The authors in the work carried out a possible step-by-step filling of the content of the specified elements of ISOPUR - OMETUKsp, applicable to higher education institutions with an increased level of adaptation to global geopolitical instability. In particular, the primary attention was paid to the study of the factors ensuring the competitiveness of personnel in modern conditions, taking into account the influence of internal and external threats, through the concept of «three Z-e», with the assessment of both the essence and the relationship of its constituent concepts (components): 1 – «knowledge», 2 – «health», 3 – «care for one's neighbor». Recent events in Belarus associated with geopolitical instability, the adoption of the new Concept of National Security, the Code of Administrative Offenses (CAO) and the Republican Program of Patriotic Education of the Population, indicate that the third component of the concept of «three Z-e» (Z – care for one's neighbor) should be supplemented by such elements (factors) as: legality, patriotism, love for the Motherland. The specified factors of personnel competitiveness, combined in the form of the concept of «three Z-e», in modern conditions are related to each other approximately as 3:2:5. In other words, the third component of the «three Z-e» concept, due to the vital necessity and stability at the enterprise and national level, comes out on top (first level). This indicates a vital need to expand the practice of teaching the discipline «Competitiveness of an Organization (Enterprise)» in domestic higher education institutions with economic, legal and engineering focus, highlighting the social component of training specialists (legality, patriotism, love for the Motherland, etc.), future managers and personnel of organizations.

Keywords: geopolitical instability, global confrontation, training, competitiveness (Ksp), innovative system of training and management decision-making (ISOPUR) – OMETUKsp, personnel, UVO.

ИННОВАЦИОННАЯ СИСТЕМА ОБУЧЕНИЯ И ПРИНЯТИЯ УПРАВЛЕНЧЕСКИХ РЕШЕНИЙ

Н. В. Немогай, Н. В. Бонцевич, С. Д. Колесников

Реферат

Одним из перспективных направлений повышения эффективности УВО в условиях существующего глобального противостояния, может быть внедрение систем управления конкурентоспособностью (СУКсп). Теоретической основой современных исследований по созданию адаптированных к существующим обстоятельствам СУКсп является использование инновационной системы обучения и принятия управленческих решений (ИСОПУР), которая с учетом условий глобальной геополитической нестабильности должна быть дополнена (модифицирована) связью (цепью) «окружение» и иметь следующее содержание: окружение (О) – методика (М) – экономика (Э) – техника (Т) – управление (У) – конкурентоспособность (Ксп), т. е. ОМЭТУКсп.

Авторами в работе осуществлено возможное пошаговое наполнение содержания указанных элементов ИСОПУР – ОМЭТУКсп, применительно к УВО, обладающему повышенным уровнем адаптации к глобальной геополитической нестабильности. В частности, преимущественное внимание уделялось исследованию факторов обеспечения конкурентоспособности персонала в современных условиях, учитывающих влияние внутренних и внешних угроз, посредством концепции «три З-э», с оценкой как сущности, так и взаимосвязи ее составных понятий (компонентов): 1 – «знания», 2 – «здоровье», 3 –«забота о ближнем». Последние события в Беларуси, связанные с геополитической нестабильностью, принятием новых Концепции национальной безопасности, Кодекса об административных правонарушениях (КоАП) и Республиканской программы патриотического воспитания населения, указывают на то, что третий компонент концепции «три З-э» (З – забота о ближнем) должен дополнятся такими элементами (факторами), как законность, патриотизм, любовь к Родине. Указанные факторы конкурентоспособности персонала, объединенные в виде концепции «три З-э», в современных условиях соотносятся между собой приблизительно как 3:2:5. Иными словами, третий компонент концепции «три З-э», вследствие жизненной необходимости и стабильности на уровне предприятия и страны, выходит на первое место (первый уровень).

Это указывает на жизненно важную необходимость расширения практики преподавания дисциплины «Конкурентоспособность организации (предприятия)» в отечественных УВО экономической, юридической и инженерной направленности с выделением социальной составляющей подготовки специалистов (законность, патриотичность, любовь к Родине и т. п.), будущих руководителей и персонала организаций.

Ключевые слова: геополитическая нестабильность, глобальная конфронтация, обучение, конкурентоспособность (Ксп), инновационная система обучения и принятия управленческих решений (ИСОПУР) – ОМЭТУКсп, кадры, УВО.

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Introduction

Ensuring survivability in the current market conditions characterized by global confrontation and geopolitical instability (external sanctions challenges, ideological contradictions, disruption of international supply chains etc.) is one of the main tasks of the modern economy of Belarus, Russia and the Commonwealth of Independent States (CIS) [1]. There is no doubt that this task in the current conditions must be solved by ensuring the competitiveness of basic socio-political, production and technical facilities, one of the first of which is personnel (personnel of various levels), the formation (training) of which is carried out by higher education institutions (HEIs) [2–4]. The research was carried out according to proven methodological recommendations within the framework of the implementation of complex research end-to-end tasks (CRCT); practical classes of students; work of student research circles; training (retraining) courses for specialists [5].

The results of the analysis showed a high assessment of the efforts and activity of pioneers in promoting new approaches to ensuring the competitiveness of various facilities (including UVO) from the countries of the former USSR [2–4]. The analysis shows that one of the promising areas for increasing the efficiency of such objects (representing an open system), including in the conditions of modern competitive realities, may be the introduction of competitiveness management systems (CMS) [2]. The theoretical basis for the known studies on the creation of CMS was the use of the system of training and making management decisions (SOPUR) – METUK, which has the following elements: methodology (M) – economy (E) – technology (T) – management (U) – competitiveness (C). This approach was actively developed in the Russian Federation by the scientist R. A. Fatkhutdinov over fifteen years ago, therefore it could not take into account the existing international situation.

Taking into account the above, we carried out a review entities innovative system of training and management decision-making, as well as possible modern content of its elements in relation to higher education institutions.

Main part. Development of an innovative system of training and management decision-making (ISMDM)

The analysis of the research showed that, taking into account the innovative approach to modern geopolitical instability and confrontation, the well-known SOPUR should be modified (supplemented) with the connection (chain) «environment» and have the following content: environment (E) – methodology (M) – economy (E) – technology (T) – management (U) – competitiveness (Ksp), i. e. OMETUKsp [4].

The step-by-step (in order of importance) content of the basic terms (concepts) of the innovative SOPUR (ISOPUR – OMETUKsp) as applied to the educational institution with an increased level of adaptation to geopolitical instability and global confrontation can be disclosed as follows.

Step 1. *Environment (E)* (or external environment, **determining who and how influences** the UVO **from the outside**) is the first component of the ISOPUR – the beginning of work to ensure the competitiveness of the UVO in modern conditions. We have already noted the need for the survival of all objects in the existing international conditions. The influence of the external environment on the competitiveness of all objects, including UVO, is manifested in the following trends [1–4]:

– in the political sphere: the presence of significant contradictions between the main actors in world politics, which are manifested against the background of a decline in the effectiveness of international and regional security systems and are capable of complicating the situation around Belarus; the clash of geopolitical interests of leading states (groups of states) in the process of transition from a unipolar to a multipolar world order;

– in the economic sphere: deterioration of the conditions of foreign trade, attraction of credit and investment resources due to unfavourable conditions in world markets; adoption of protectionist measures by foreign states by establishing barriers and discriminatory conditions for the implementation of export-import operations; development of transit corridors, energy transportation systems alternative to those existing in Belarus, and targeted limitation of their transit capabilities;

– in the scientific and technological sphere: restriction of access of Belarusian researchers and business entities to the latest technologies, research results and world-class developments; targeted policy of foreign states and companies stimulating the emigration of scientists and specialists from Belarus.

As a result of the above phenomena, the specific influence of the external environment on the competitiveness of domestic higher education institutions is also manifested in: increased competition in the sphere of specialist labor, which is a consequence, on the one hand, of automation and computerization of traditional production activities, on the other hand, of overproduction of specialists in certain specialties; increased role of long-term and sustainable relations between education, science and production; formation of adaptive virtual structures in management that determine a modern approach to personnel policy based on proactive training of a new generation of specialists; development of electronic educational technologies in the sphere of training of specialists; increased role of standardization of educational processes, certification of higher education institutions in terms of their new specialties; increased role of state regulation of training of specialists that ensure an optimal balance of scientific and practice-oriented training.

Step 2. *Methodology (M)* **–** the second component of I SOPUR, taking into account that modern teachers (and, accordingly, trained personnel of different levels) must master the methods and mechanisms of action of economic laws, application of scientific approaches and principles to management in higher education institutions. The main purpose of the second component is the formation (training) of specialists with a high level of human capital, which is a set of skills embodied in a person: education, intelligence, charisma, creativity, work experience, entrepreneurial energy, the ability to survive in extreme conditions [4, 5].

It should be noted that artificial intelligence (AI) has recently become an increasingly important stimulus for innovative development in science, technology and business, which influences almost all aspects of creativity [6–8]. The development of AI, which has many points of contact with intellectual property, is facilitated by the availability of large volumes of data for training and the increase in available computing power.

Currently, the fundamental strategic document of the Russian Federation in the field of AI is the National Strategy for the Development of Artificial Intelligence for the Period up to 2030, approved by the Decree of the President of the Russian Federation of October 10, 2019 No. 490 «On the Development of Artificial Intelligence in the Russian Federation». Given the great importance of this issue, V. V. Putin signed a decree updating the AI development strategy until 2030. It should be noted that the final document of the 10th forum of the Federation Council of the Russian Federation and the Council of the Republic of the National Assembly of Belarus (Moscow, June 29, 2023) proposes to develop a strategy for the development of artificial intelligence in the Union State [6–8].

The main principles of development and use of AI technologies: protection of human rights and freedoms, security, transparency, technological sovereignty, integrity of the innovation cycle, reasonable frugality, support for competition. The following can be attributed to the issue under consideration as indicators that characterize the achievement of the goals of the strategy and can be attributed to the issue under consideration [8]:

- the level of public trust in AI technologies should increase to at least 80 % by 2030, compared to 55 % in 2022;
- 80 % of workers are expected to have AI skills, up from 5 % in 2022;
- the number of graduates who have completed AI programs will be at least 15.5 thousand people, which is significantly higher than the figure of 3,048 people in 2022;
- it is planned to increase from 12 % to 95 % the share of priority sectors of the economy ready for the implementation of AI;
- companies' expenses on the implementation and application of AI should increase to at least RUB 850 billion annually, compared to RUB 123 billion in 2022;
- the combined maximum power of all Russian supercomputers using AI technologies, equipped with graphics processors for training AI models, should increase to 1 exaflop, up from 0.073 exaflops in 2022 (FLOPS is a non-systemic unit used to measure computer performance, showing how many floating-point operations per second a given computing system performs).

The document also outlines areas of support for organizations involved in AI development. Among them: state support, provision of grants, ensuring unimpeded attraction of investments, promotion of the best organizations, development of domestic open AI libraries, creation of

data repositories and solutions in the field of AI, etc. In addition, areas of support for scientific research, development and increasing the availability of infrastructure for development, increasing the level of competencies, stimulating the implementation of AI technologies in economic and social sectors, including within the framework of international cooperation, etc. are presented [8].

Step 3. *Economy (E)* – aspect ISOPUR, which acts as a set of knowledge, skills and competitive advantages in various areas of macro- and microeconomics, resource and energy conservation, etc. The transition to the fifth (and in some cases the sixth) technological order requires the training of specialists in higher education institutions on the basic aspects of a competitive economy, i. e. the philosophy of a new vision and thinking, knowledge management in order to improve the quality of processes in all environments and industries, and to intensify innovative activities [4].

Step 4. *Technology (T)* is an aspect of the ISOPUR, which is the material basis for the development (design) and organization of the educational and research process in the educational institution. The components of the presented aspect are: the technical level of the educational institution, the toolkit of educational technologies, technological equipment, electronic information equipment and other elements aimed at forming a high-quality "cloud" information and educational environment [4].

Step 5. *Control (U)* is the fifth aspect innovative ISOPUR and one of the most difficult, since domestic teachers of different levels have to work in conditions of tough competition. In such conditions, management is a general function of an organized system (UVO), aimed at maintaining its integrity and fulfilling its goals and objectives. It (the general function U) is implemented using the Deming-Shewhart cycle (PDCA), consisting of separate (independent) functions: planning – P, activity – D, control – C, improvement (management decision-making) – A [5].

The relevance and necessity of making management decisions is determined by the fact that they are designed [4]:

– to ensure the necessary interconnection between reforms in higher education and strategies for sustainable socio-economic development of economies;

– to intensify the goals of higher education institutions in the area of increasing their –competitiveness and allocating the necessary and sufficient financial support to increase the growth rate of innovation and investment activities of higher education institutions;

– to increase the level of adaptation of higher education institutions to market conditions and competition in the market of modern educational services;

– eliminate the imbalance between the training of specialists and their future needs, the overproduction of some specialties and the shortage of others;

– to raise to a higher level the use of the advantages of strategic marketing and financial management in the field of organizing the educational and research process in higher education institutions;

– to increase the level of motivation and incentives for the work of the teaching staff;

– to implement an optimal combination of innovative, comprehensive and systemic approaches of the state to regulating the activities of public and private higher education institutions;

– to create and implement a comprehensive program for the entry of national education systems into the CIS educational space.

Step 6. *Competitiveness* (K_{sp}) is the sixth aspect of innovative SOPUR and it acts as a generalizing result of training or work on the previous five aspects. The competitiveness of a higher education institution is determined by its competitive advantages in relation to other higher education institutions of the same profile. At the same time, the competitive advantages of a higher education institution are multifactorial and are determined primarily by its activity in training modern competitive specialists [9].

We followed the factors for ensuring the competitiveness of personnel in modern conditions, taking into account the impact of internal and external threats, using the concept of «three Z-es», with an assessment of both the essence and the interrelation of its constituent concepts (components): 1 – «knowledge» , 2 – «health» , 3 – «caring for one's neighbor» [10] .

Analysis and research showed that the main purpose to component «knowledge» is training of comprehensively developed specialists (personnel) in various areas with a high level of human capital, in the practice of formation of which special attention should be paid to increasing labor efficiency based on the use of modern tools competitive economy like AI, development of holistic inventive thinking and the ability to formalize ideas into patents intellectual property objects (IPC). Thus, to the traditional components of the triad element: «knowledge» (natural giftedness and intelligence, talent, education, special knowledge, skills, abilities, ability for a certain type of activity), in modern conditions the following components should be added: knowledge of the historical past of the country, national culture, the foundations of the history of religion and the Motherland, as well as the tools of a competitive economy and AI [11–14].

The «health» element of the «three Z» concept, is one of the key factors in healthcare and the social sphere, since the health of the nation is determined by 10–15 % by the level of development of healthcare, and by 50–55 % by the conditions and lifestyle of the population. The tfficiency of the «health» component is largely connected with the national system based on the promotion of a healthy lifestyle (HLS) and the implementation of the «Quality of Life» and «Healthy Nutrition» doctrines, which allows us to form and maintain a person (specialist) with high physical and mental abilities until old age [15–17].

The implementation of the above – mentioned doctrines is impossible without understanding that we live in an era of multifactorial uncertainty, when the world is changing rapidly. But there is also an undoubted constant: the world is dual. It is very important for society to preserve this duality, which is conceived by nature, and to find harmony between men and women, using their complementary qualities for creation. No one doubts anymore that women are an important strategic resource of our country and that they largely contribute to the development of industrial and social initiatives and technologies, so necessary for its prosperity. Women are often more active than men, react faster and more acutely to the challenges facing society and are more proactive when they arise, offering possible, often original solutions. Nowadays, educational institutions should set as their goals the promotion of the ideology of a healthy lifestyle, national preservation, traditional family values and the creation of a positive image of a large family as the basis of a prosperous state, they should show the high role of women in the formation and management of society, which often remains underestimated. It is women who have the ability to empathize, care, understand and tolerate. Women know how to find compromises, help resolve conflicts, reconcile warring parties and establish harmony. Women have enormous creative, spiritual and moral potential, abilities and the will to create, they continue to implement their not always clearly visible, but very important for society affairs.

An analysis of the research shows that the second block of traditional elements of the triad «three Z (z)» is the hereditary advantages and abilities, physical data, healthy lifestyle. In modern conditions, it should include the following factors: health in all its manifestations (as a source of courage, fortitude, strength), aimed (taking into account the principles of spirituality, respect for the history of the country and love for the Motherland) at traditional family values and ensuring the protection of the Fatherland from external and internal threats.

In the conditions characterized by geopolitical challenges, the need for timely strengthening of state sovereignty and national security, through the consolidation of society and ensuring the national unity of public and state interests, the essence of the third component of the triad «three Z (z)» «caring for one's neighbor" should be considered in the context of events occurring in the environment and have a modified characteristic of its components, including in their composition such factors as: «legality (compliance with the law)» and «patriotism» [18–22]. In particular, the introduction of such a factor as legality (compliance with the law) is justified the new Code of the Republic of Belarus on Administrative Offenses dated 06.01.2021 No. 91-Z (CAO; reg. in NRPA No. 2/2811 dated 15.01.2021). The introduction of such a factor as patriotism is substantiated by the Resolution of the Council of Ministers of the Republic of Belarus dated 29.12.2021 No. 773, which approved the program of patriotic education of the population for 2022–2025. The adoption of the new Code of Administrative Offenses and the program of patriotic education of

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the population, indicate that the third component of the concept of «three Z-e» (Z – care for one's neighbor) should be supplemented by such elements (factors) as: legality, patriotism, love for the Motherland.

And the analysis of the research showed that the factors of personnel competitiveness, united in the form of the concept of «three Z-e» (knowledge, health; care for others), in modern conditions, are related to each other approximately as 3:2:5. In other words, the third component of the concept of «three Z-e», due to the vital necessity and stability at the level of the enterprise and the country, comes out on top (first level).

The solution to the problem of increasing the competitiveness of higher education institutions interacts with a system of factors that follow from the essence of the relationship between the following main (triadic) components: «man – society – nature»; «competitiveness of goods – competitiveness of the UVO – competitiveness of educational services», within the framework of the creation of the corresponding ISOPUR, adapted to global geopolitical instability [9, 10].

The developed system has been undergoing testing (as part of the modernization of the QMS structure) at the International University «MITSO» (Minsk) and its Gomel and Vitebsk branches for over the past six years. It is an innovation-oriented incentive mechanism that promotes self-actualization of the individual and has a single goal, which consists of satisfying the national economy with competitive specialists, ensuring the possibility of higher education institutions to successfully compete in the domestic and international educational services markets in a modern competitive economy [4, 9].

Conclusion

The analysis of the research shows that one of the promising areas for increasing the effectiveness of higher education institutions in the context of the current global confrontation may be the introduction of competitiveness management systems (CMS). The theoretical basis for modern research on the creation of CMS adapted to existing circumstances is the use of innovative training and management decision-making system (TMSDM), which, taking into account the conditions of global geopolitical instability, should be supplemented (modified) by the connection (chain) «environment» and have the following content: environment (E) – methodology (M) – economy (E) – technology (T) – management (U) – competitiveness (Ksp), i. e. OMETUKsp.

In this report, the authors focus on the possible step-by-step filling of the content of the specified elements of the ISOPUR – OMETUKsp in relation to the UVO, which has an increased level of adaptation to global geopolitical instability. Recent events in Belarus related to geopolitical instability, the adoption of the new Concept of National Security, the Code of Administrative Offenses (CAO) and the National Program of Patriotic Education of the Population, indicate the vital need to expand the practice of teaching the discipline «Competitiveness of an Organization (Enterprise)» in domestic higher education institutions. economic, legal and engineering orientation with the emphasis on the social component of training specialists (patriotism, love for the Motherland, etc.), future managers and personnel of organizations. At the same time, the plans of the Ministry of Education of the Republic of Belarus annually reduce the number of specialties and the number of teaching hours in this area.

References

1. Koncepciya nacional'noj bezopasnosti Respubliki Belarus'. – URL: https://www.mil.by/ru/military_policy/basic/koncep (data obrashcheniya: 10.01.23).
2. Fathutdinov, R. A. Upravlenie konkurentosposobnost'yu organizacii: uchebnik / R. A. Fathutdinov. – 3-e izd. – M. : Market DS, 2008. – 432 s.
3. Golovachyov, A. S. Konkurentosposobnost' organizacii: uchebnoe posobie / A. S. Golovachyov. – Minsk : Vysh. shk., 2012. – 319 s.
4. Nemogaj, N. V. Konkurentosposobnost' predpriyatiya: uchebnik / N. V. Nemogaj, N. V. Boncevich. – 3-e izd., pererab. i dop. – Minsk : RIVSH, 2023. – 524 s.
5. Nemogaj, N. V. Rol' podsistemy nauchnogo soprovozhdeniya v sisteme upravleniya konkurentosposobnost'yu predpriyatiya / N. V. Nemogaj, S. D. Kolesnikov // Standarty i kachestvo. – 2021. – № 4. – S. 78–82.
6. O razvitii iskusstvennogo intellekta v Rossijskoj Federacii: Ukaz Prezidenta Rossijskoj Federacii ot 10 oktyabrya 2019 g. № 490 / Prezident Rossii. – URL: http://prezident.org/articles/ukaz-prezidenta-rf-490-ot-10-oktjabrja-2019-goda-11-10-2019.html (data obrashcheniya: 10.10.24).
7. Itogovyj dokument desyatogo foruma regionov Rossii i Belarusi (Ufa, 28 iyunya 2023 g.). – URL: http://council.gov.ru/media/files/XXYLsupLBCmlH4FySzw5l8CwBFr4Xjgx.pdf (data obrashcheniya: 12.10.24).
8. Prezident RF obnovil strategiyu razvitiya iskusstvennogo intellekta. – URL: https://www.comnews.ru/content/231631/2024-02-19/2024-w08/1008 (data obrashcheniya: 12.10.24).
9. Nemogaj, N. V. Model' sistemy upravleniya konkurentosposobnost'yu predpriyatiya / N. V. Nemogaj, S. D. Kolesnikov // Standarty i kachestvo. – 2020. – № 6. – S. 88–93.
10. Nemogaj, N. V. Rol' celevoj podsistemy v upravlenii konkurentosposobnost'yu predpriyatiya / N. V. Nemogaj, S. D. Kolesnikov // Standarty i kachestvo. – 2022. – № 4. – S. 58–62.
11. Lomakina, I. S. Antropologicheskij podhod i professional'naya podgotovka studentov / I. S. Lomakina, M. E. Duranov // Vestnik YUUrGU. – 2005. – № 4. – S. 51–60.
12. Bondar', A. V. Transformaciya chelovecheskogo potenciala v ekonomike znanij / A. V. Bondar' // Belorusskij ekonomicheskij zhurnal. – 2023. – № 4. – S. 83–92.
13. Kristinevich, S. A. Sohranenie nacional'nogo chelovecheskogo potenciala kak faktor ekonomicheskoj bezopasnosti / S. A. Kristinevich // Belorusskij ekonomicheskij zhurnal. – 2017. – № 4. – S. 23–36.
14. Kalinovskaya, I. N. Modelirovanie ierarhicheskoj struktury kompetencij s primeneniem tekhnologij iskusstvennogo intellekta / I. N. Kalinovskaya // Belorusskij ekonomicheskij zhurnal. – 2023. – № 3. – S. 84–96.
15. YAroshevich, V. I. Social'naya sfera kak faktor makrokonkurentosposobnosti / V. I. YAroshevich // Belorusskij ekonomicheskij zhurnal. – 2018. – № 1. – S. 97–107.
16. Barysheva, E. M. Stanovlenie ekosistemy zdorov'ya: rossijskij opyt / E. M. Barysheva // Belorusskij ekonomicheskij zhurnal. – 2023. – № 4. – S. 93–102.
17. Nizamov, I. G. Voprosy kompleksnoj ocenki rezul'tativnosti sanatorno-kurortnoj pomoshchi / I. G Nizamov, L. F. Sabirov // Sovremennye problemy nauki i obrazovaniya. – 2012. – № 1. – S. 12–36.
18. Kodeks Respubliki Belarus' ob administrativnyh pravonarusheniyah ot 06.01.2021 g. № 91-Z : prinyat Palatoj predstavitelej 18 dekabrya 2020 g. : odobren Sovetom Respubliki 18 dekabrya 2020 g. // Nacional'nyj pravovoj Internet-portal Respubliki Belarus' (data obrashcheniya: 23.10.2024).
19. Kozhuhovskaya, L. S. Patrioticheskoe vospitanie molodezhi Respubliki Belarus': sovremennoe sostoyanie i perspektivy razvitiya: nauchno-metodicheskoe posobie / L. S. Kozhuhovskaya – Minsk : Respublikanskij institut vysshej shkoly, 2021. – 160 s.
20. Lira, N. M. Ekstremizm kak destruktivnyj fenomen social'noj zhizni / N. M. Lira // «Vesnik Magilyoўskaga dzyarzhaўnaga universiteta imya A. A. Kulyashova». – 2024. – № 2 (64). – S. 49–54.
21. Kuz'menkova, T. N. Otdel'nye teoretiko-pravovye aspekty kiberbezopasnosti lichnosti / T. N. Kuz'menkova // «Vesnik Magilyoўskaga dzyarzhaўnaga universiteta imya A. A. Kulyashova». – 2024. – № 1 (63). – S. 73–79.
22. Kuz'menkova, T. N. Pravo na bezopasnost' v informacionnoj srede v sisteme prav i svobod lichnosti / T. N. Kuz'menkova // Vesnik Magilyoўskaga dzyarzhaўnaga ўniversiteta imya A. A. Kulyashova. – 2022. – № 22 (60). – S. 97–103.

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METHOD OF INTEGRATED ASSESSMENT OF THE LEVEL OF ECONOMIC POTENTIAL OF A CROSS-BORDER REGION

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Abstract

The article presents a methodology for assessing the level of economic potential developed by the author. The author uses a multidimensional assessment of economic potential based on the provision of the cross-border region with economic, social, infrastructural, innovative, digital resources, as well as taking into account transit, institutional provision. The methodology is based on the author's interpretation of the concept of "economic potential of a cross-border region" and includes the definition of five levels of potential of a cross-border region. Particular attention is paid to the objectivity of the initial data, as well as comparisons of economic potential in dynamics based on a multidimensional average value. The author's methodology for an integrated assessment of the level of economic potential of a cross-border region has a practical focus. The purpose of the analysis is to determine the level of development of the economic potential of a cross-border region in order to determine the direction of balanced, sustainable development based on a typological comprehensive assessment of regional economic potential and generalization of its results.

The subject of the study is the influence of cross-border factors on the socio-economic development of a region. The purpose of the study is to develop and test a methodology for an integrated assessment of the level of economic potential and its impact on the socio-economic development of a cross-border region. Research methods – economic and statistical, analysis, synthesis, inductive, deductive, comparison, system, expert assessments, etc.

In modern conditions, the formation of convenient and effective methods and tools for measuring balanced, sustainable socio-economic development, allowing for an unambiguous interpretation of the results obtained, is of high value from both a research and a management point of view. The advantages of the integrated indicator proposed by the author include the ability to cover all the main potentials in the structure of the economic.

Keywords: transborder region, economic potential of a transborder region, strategy, assessment methodology, structure of economic potential, integral assessment of economic potential.

МЕТОДИКА ИНТЕГРИРОВАННОЙ ОЦЕНКИ УРОВНЯ ЭКОНОМИЧЕСКОГО ПОТЕНЦИАЛА ТРАНСГРАНИЧНОГО РЕГИОНА

В. В. Зазерская

Реферат

В статье представлена разработанная автором методика оценки уровня экономического потенциала. Автор использует многомерную оценку экономического потенциала на основе обеспеченности трансграничного региона экономическими, социальными, инфраструктурными, инновационными, цифровыми ресурсами, а также с учетом транзитной, институциональной обеспеченности. Методика основывается на авторской трактовке понятия «экономический потенциал трансграничного региона» и включает определение пяти уровней потенциала трансграничного региона. Особое внимание уделяется объективности исходных данных, а также сравнениям экономического потенциала в динамике на основе многомерной средней величины. Авторская методика интегрированной оценки уровня экономического потенциала трансграничного региона имеет практическую направленность. Целью анализа является определение уровня развития экономического потенциала трансграничного региона для определения направления сбалансированного, устойчивого развития на основе типологической комплексной оценки регионального экономического потенциала и обобщения ее результатов.

Предметом исследования является влияние трансграничных факторов на социально-экономическое развитие региона. Целью исследования является разработка и апробация методики интегрированной оценки уровня экономического потенциала и его влияния на социально-экономическое развитие трансграничного региона. Методы исследований – экономико-статистический, анализа, синтеза, индуктивный, дедуктивный, сравнения, системный, экспертных оценок и др.

В современных условиях формирование удобных и эффективных методов и инструментов измерения сбалансированного, устойчивого социально-экономического развития, позволяющих дать однозначную трактовку полученных результатов, представляет высокую ценность как с исследовательской, так и с управленческой точки зрения. К преимуществам предлагаемого автором интегрального показателя относится возможность охвата им всех основных потенциалов в структуре экономического.

Ключевые слова: трансграничный регион, экономический потенциал трансграничного региона, стратегия, методика оценки, структура экономического потенциала, интегральная оценка экономического потенциала.

Introduction

The socio-economic development of a regional system is influenced by basic factors (transport and geographic, natural resources, climate) and superstructure factors (economic, administrative, institutional), as well as specific factors that determine the vector of development depending on the conditions of the region's functioning. Of great practical importance for planning and forecasting the socio-economic development of regions with cross-border relations is the comprehensive consideration of all groups of factors. It is especially important to take into account the factors that determine the directions of cross-border development of territories: transit, infrastructure, institutional, integration [1], since a scientifically based solution to the problem, a reduction in the asymmetry of territorial development with preventive management reduces negative consequences.

Myasnikovich rightly notes: «The transition from an integrated development agenda to isolated development, the growth of state, corporate and private debt exacerbates crisis processes...» [2]. «One of the effective paths to development is the deepening of regional integration» [2], the form of which is cross-border cooperation [3].

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Achieving the goal of developing a transboundary region depends on the existing economic potential and the transboundary influence of adjacent territories. Based on the multitasking nature of potential research, it can be argued about the influence of the polysemantic nature of this category, revealing its multicomponent structure. The problem of completeness of coverage of a multicomponent structure due to the limited statistical indicators can be solved by experts, when experts select groups of parameters, methods of their combination and further processing. The economic potential of a region can be considered as a set of material and technical base, expressed by available resources, opportunities and conditions for involving it in economic turnover, capable of ensuring a certain level of development of the region. When considering it in relation to a transboundary region, it can be argued that "the economic potential of a transboundary region is a set of resources and opportunities that determine the ability of the region to implement transboundary cooperation, which can be maximally used by subjects of the regional economy in order to stimulate economic growth and development within territorial boundaries" [1].

This raises the issue of the need to create an objective, easy-to-use and comprehensive approach to assessing the economic potential of regions. Such an approach could become an effective tool for comparing available resources and identifying opportunities for economic growth, as well as for developing and implementing various aspects of territorial policy. Economic potential is a key resource for the development of a region, which in turn contributes to its social well-being [4]. Summarizing the opinions of scientists [5–8] and identifying structural elements, we can note that the structure of economic potential remains a subject of discussion in the scientific community; there is no consensus on its constituent elements. The authors [9–12] note that systematization of the structural elements of the resource potential of a region and approaches to its definition is significant, since transboundary regions are subject to the transmission of «exogenous impulses for the national economy, both positive in the form of special investment and foreign trade opportunities, and negative – in the form of the spread of global financial and economic problems to the domestic, national economy» [12].

In this paper, economic development is presented as a process that is constantly changing. To effectively manage this process, it is necessary to formalize it. Therefore, it is necessary to create mathematical tools that allow a comprehensive assessment of the economic potential, the level of which will correspond as much as possible to the current state of economic development.

Methodology for assessing the level of economic potential of a trans-border region

The methodology must comply with the conditions of availability and accuracy of the initial data, take into account the complexity of the indicators, the dynamic development of the region, and also ensure the simplicity of calculations and the informativeness of the results obtained.

Let us present a methodology for assessing the level of economic potential of a cross-border region.

1. Definition of the object, subject, purpose and objectives of the study. The object will be a transboundary region of the macro level (transboundary economic development corridor/country), in some cases a transboundary region of the meso level (administrative-territorial unit of the regional level).

The subject of analysis is monitoring the total economic activity of business entities in the region, its results and methods for assessing effectiveness.

The purpose of the analysis is to determine the level of development of the economic potential of a cross-border region in order to determine the direction of balanced, sustainable development based on a typological comprehensive assessment of regional economic potential and generalization of its results.

The official database of the National Statistical Committee is used when calculating the indicators. This allows for the formation of a sufficient time series to characterize the processes. In the study, the time series is determined by the period necessary to achieve “goals, priorities, objectives, indicators and parameters of socio-economic development for a certain time period” [13].

2. Selection of a system of indicators for assessing the economic potential of a transboundary region. The indicators are grouped by subpotentials:

1) economic potential;
a) development indicators;
b) production and financial indicators;
c) consumer indicators;
d) labor indicators;
2) social potential;
a) inclusiveness;
b) demographic indicators;
c) social infrastructure;
3) infrastructure potential;
4) innovative potential;
5) integration potential;
6) transit potential;
7) potential for digital development;
8) institutional potential;
a) level of business development;
b) level of management development;
c) level of social development.

3. The calculation of structural elements characterizing the level of potential of a certain sphere of development of the socio-economic system is made on the basis of the arithmetic mean. The aggregated arithmetic mean in our case is used for intermediate calculations, which will allow us to level out the error of the integral value [14].

Depending on the duration of the period of studying the state of the object, the calculation of the complex indicator of the level of the corresponding subpotential is determined by one of the options:

a) at a certain point in time:

$$R_i = \frac{\sum X_{ji}}{n}, \quad (1)$$

where R_i is the value of the complex indicator of the level of the i-th subpotential of the economic potential of the transboundary region;

X_{ji} – the value of the j-th indicator of the i-th subpotential;

n is the number of indicators in the subpotential.

b) for a certain time interval. In this case, the calculation of the i- th level The subpotential is produced by the method of normalization (reduction to the scale [0, 1]) of the initial indicators based on the determination of deviations of the actual values of the j- th indicator from the maximum and minimum values of the indicator or from the optimal (normative) values.

$$R_i = (\sum_{j=1}^{n} \frac{X_{maxj} - X_{ji}}{X_{maxj} - X_{minj}} + \sum_{j=1}^{n} \frac{X_{ji} - X_{minj}}{X_{maxj} - X_{minj}})/n, \quad (2)$$

where R_i – the value of the complex indicator of the i-th level subpotential of the economic potential of a transborder region, characterizing a separate sphere of socio-economic development;

X_{ji} – the value of the j-th indicator of the i-th subpotential;

$X_{max\,j}$ – maximum value of the j-th indicator of the i-th subpotential;

$X_{min\,j}$ is the minimum value of the j-th indicator of the i-th subpotential;

n is the number of indicators in the subpotential.

The first part of the numerator of the formula is used to evaluate direct indicators, an increase in which has a positive value, the second part is used to evaluate inverse indicators, an increase in which has a negative effect.

4. Calculation of the integral indicator.

The calculation of the integral indicator is based on the method of aggregation by the geometric mean. The use of this method will help to take into account the interrelations between resources and will allow to characterize the territory as a system with a comprehensive content of the main economic resources. This is especially relevant for the analysis of complex systems, where many factors interact. The formalized expression of the comprehensive assessment of the economic potential of a transboundary region is the value of the integral indicator:

$$I_R = \sqrt[m]{\prod_{i=1}^{m} R_i}, \quad (3)$$

I_R – an integral indicator of the level of economic potential of a transborder region

m – quantity subpotentials.

The implementation of stages 5 and 6 involves the aggregation of time series, namely, collapsed aggregation. Carrying out aggregation (systematization, classification, consolidation, analysis) allows heterogeneous systems consisting of two or more different homogeneous areas to be combined "into a single whole with the aim of obtaining a holistic systematized data array – an aggregate" [15]. The process Transforming a large array of data into a more compact form allows us to identify general patterns, trends, or structural characteristics [16].

In our case, the aggregation of statistical information at stage 5 occurs horizontally – chronological/temporal/dynamic analysis, and at stage 6 vertically – structural analysis, which determines the structure of the final integral indicators, identifying the influence of each position of the information base on the aggregate as a whole.

Thus, the combined use of aggregation methods provides a more complete picture of socio-economic processes, allowing us to support the formation of a regional development strategy aimed at achieving target indicators.

Thus, the methodology for assessing and analyzing the economic potential of a cross-border region is based on the implementation of the following successive stages:

• formation of a system of initial indicators with their subsequent unification into enlarged thematic groups (subpotentials);

• calculation of private indicators (sub-indices) reflecting the state of sub-potentials;

• identification of incentives and constraints for balanced and sustainable development of a cross-border region;

• assessment of the consolidated integral indicator of economic potential, obtained on the basis of the "convolution" of private sub-indices, with subsequent determination of the type of economic development of the cross-border region.

The advantages of the integrated indicator proposed by the author include the ability to cover all the main potentials in the economic structure.

5. Determining the level of development of economic potential.

The final stage of the assessment will be the interpretation of the comprehensive assessment of the economic development of the cross-border region. For a correct understanding of the results, it is necessary to establish threshold values for the level of economic potential, which will vary from 0 to 1 [17].

Thus, at the final stage, it is planned to obtain the values of the aggregated indicator of the level of economic potential of the regions, which will make it possible to determine the direction of development of the cross-border zone, conduct a comparative analysis of the achieved results of economic progress, and promptly identify changes and shifts occurring over time.

The level of economic potential corresponds to a certain interval of change in the value of the interval boundary indicator (Table 1).

6. Development of measures to ensure effective development of the cross-border region.

Table 1 – Levels economic potential of the transboundary region

Level potential	Interval I_R values	Interpretation of the integrated assessment of the level of development of the EP
Short	0.1–0.28	Unstable, unbalanced state of the region, pre-crisis state
Below average	0.29–0.46	Partial balance, parity between the subsystems of the region is violated. Asymmetric development is observed
Average	0.47–0.64	Sustainable / with some signs of unsustainable development, There are signs of asymmetric development
High	0.65–0.82	Continuous development of the region's subsystems, taking into account their coordinated interaction, providing a synergistic effect to ensure the dynamic stability of the region
Very tall	0.83–1	Balanced, sustainable, dynamic development, efficient use of resources and opportunities

Determining the level of economic potential is immanent to the strategy of economic development of the transboundary territory. Finding incentives and restrictions for the development of the region is carried out on the basis of an analysis of the values of individual subpotentials R_j, their indicators. If the analysis showed the lowest/highest value for some of them, then the region has limitations/advantages for this factor. The results of the analysis can be used to develop development directions that support the development of mechanisms, identify development reserves, and use the competitive advantages of the territory.

Conclusion

It is important to use new opportunities for institutionalization of interstate relations within the framework of integration associations to stimulate economic development [18]. Ensuring cross-border cooperation of meso/macro cross-border regions, as noted by Davydenko L.N. in [19], is possible when building infrastructure, namely technical and technological, resource, institutional and organizational. Supporting and stimulating investment, innovation activities, and the development of small and medium-sized businesses requires the creation of acceptable macroeconomic conditions by regional government bodies [20].

The assessment of socio-economic subsystems of a trans-border region is also informative from the point of view of analyzing the impact of trans-border interactions on the regional economy. Dynamics of infrastructure, integration, transit, institutional sub-potentials determined by the vector of transboundary processes.

The proposed methodology consists in developing an integral index that allows assessing the socio-economic potential of a territory at a systemic meso /macro level. Based on the totality of the data obtained, the level of economic potential of a transboundary region is determined, differentiated into groups in accordance with the level of subpotentials accumulated on its territory.

References

1. Zazerskaya, V. V. Ekonomicheskij potencial transgranichnogo regiona: osobennosti transgranichnogo vzaimodejstviya / V. V. Zazerskaya // Vestnik Brestskogo gosudarstvennogo tekhnicheskogo universiteta. – 2024. – № 2 (134). – S. 181–185. – DOI: 10.36773/1818-1112-2024-134-2-181-185.
2. Myasnikovich, M. V. Prakticheskie voprosy evrazijskoj ekonomicheskoj integracii / M. V. Myasnikovich. – Minsk : Belaruskaya navuka, 2021. – 294 s.
3. Zazerskaya, V. V. Formy razvitiya transgranichnogo sotrudnichestva: istoriya i osobennosti / V. V. Zazerskaya // Ekonomika i upravlenie: social'nyj, ekonomicheskij i inzhenernyj aspekty : sbornik nauchnyh statej IV Mezhdunarodnoj nauchno-prakticheskoj konferencii, Brest, 25–26 noyabrya 2021 g. / Ministerstvo obrazovaniya Respubliki Belarus', Brestskij gosudarstvennyj tekhnicheskij universitet, Kafedra menedzhmenta ; redkol.: I. M. Garchuk [i dr.]. – Brest : BrGTU, 2021. – S. 59–64.
4. Smirnov, S. Ocenka social'no-ekonomicheskoj situacii v regionah dlya prinyatiya hozyajstvennyh i upravlencheskih reshenij / S. Smirnov // Obshchestvo i ekonomika. – 1998. – № 4/5. – S. 27–40.
5. Dambaeva, N. P. Razvitie ekonomicheskogo potenciala prigranichnogo regiona: avtoref. dis. … k-ta ekon. nauk: 08.00.05 / N. P. Dambaeva. – M., 2021. – 24 s.
6. Ekonomiko-geograficheskaya ocenka demograficheskoj situacii i ekonomicheskogo potenciala mezhstolich'ya belorusskorossijskogo prigranichnogo regiona / E. A. Antipova, A. N. SHavel', I. I. Zaprudskij, A. P. Bezruchenok // ZHurnal Belorusskogo gosudarstvennogo universiteta. Geografiya. Geologiya. – 2021. – № 2. – S. 63–81. – DOI: 10.33581/2521-6740-2021-2-63-81.
7. Dynnikov, E. A. Metodicheskie podhody k ocenke resursnogo potenciala regiona / E. A. Dynnikov, A. N. Milyukin // Aktual'nye problemy ekonomiki v usloviyah reformirovaniya sovremennogo obshchestva : materialy IV mezhdunarodnoj nauchno-prakticheskoj

https://doi.org/10.36773/1818-1112-2024-135-3-156-159

konferencii, posvyashchennoj 140-letiyu so dnya osnovaniya NIU BelGU, Belgorod, 25 noyabrya 2015 g. / NIU BelGU ; pod nauch. red. E.V. Nikulinoj. – Belgorod, 2016. – S. 95–98.
8. Ekonomika predpriyatiya : uchebnoe posobie / L. H. Nekhorosheva, N. B. Antonova, L. V. Grincevich [i dr.]. – Minsk : BGEU, 2008. – 719 s.
9. Saryshahin, E. B. Ekonomicheskie problemy ispol'zovaniya resursnogo potenciala pribrezhnogo regiona transgranichnogo tipa: avtoref. dis. … k-ta ekon. nauk: 08.00.05 / E. B. Saryshahin. – Sankt-Peterburg, 2014. – 17 s.
10. Kolesnichenko, E. A. Metodicheskie aspekty ocenki resursnogo potenciala regiona / E. A. Kolesnichenko, N. N. Nesterova // Vestnik TGU. – 2013. – № 6 (122). – S. 20–26. – URL: https://cyberleninka.ru/article/n/metodicheskie-aspekty-otsenki-resursnogo-potentsiala-regiona (data obrashcheniya: 30.09.2024).
11. Ekonomicheskij potencial regiona: soderzhanie, ocenka, predlozheniya sbalansirovannogo razvitiya: avtoref. dis. … k-ta ekon. nauk : 08.00.05 / Illarionova Elena Aleksandrovna. – Kursk, 2015. – 24 s.
12. Avramchikova N. T., Ivanov D. S. Resursnyj potencial regiona: struktura i effektivnost' ispol'zovaniya // E-Management. 2022. №4. – URL: https://cyberleninka.ru/article/n/resursnyy-potentsial-regiona-struktura-i-effektivnost-ispolzovaniya (data obrashcheniya: 30.09.2024).
13. O gosudarstvennom prognozirovanii i programmah social'no-ekonomicheskogo razvitiya Respubliki Belarus' [Elektronnyj resurs]: zakon Respubliki Belarus' 12 iyulya 2023 g. № 279-Z // Konsul'tantPlyus: Versiya Prof. tekhnologiya 3000 / OOO«YUrSpektr». – M., 2024.
14. Tubol'cev, M. F. Agregirovannoe srednee kak processy obrabotki sistemnoj informacii / M. F. Tubol'cev, S. I. Matorin, O. M. Tubol'ceva // Ekonomika. Informatika. – 2012. – № 131 (132). – URL: https://cyberleninka.ru/article/n/agregrovannoe-srednee-kak-protsedura-obrabotki-sistemnoy-informatsii-1 (data obrashcheniya: 14.09.2024).
15. Vidmant, O. S. Primenenie agregirovaniya finansovyh vremennyh ryadov dlya uluchsheniya prognosticheskih harakteristik modelej / O. S. Vidmant // Ekonomika i predprinimatel'stvo. – 2017. – № 8. – CH.4. – S.775–779.
16. Sapogov, A. A. Sushchestvuyushchie metodiki agregirovaniya finansovyh dannyh / A. A. Sapogov // Innovacii i investicii. – 2023. – № 8. – URL: https://cyberleninka.ru/article/n/suschestvuyuschie-metodiki-agregirovaniya-finansovyh-dannyh (data obrashcheniya: 28.10.2024).
17. Statistika : uchebno-metodicheskoe posobie dlya napravleniya special'nosti 1-27 01 01-01 «Ekonomika i organizaciya proizvodstva (mashinostroenie)» v ramkah special'nosti 1-27 01 01 «Ekonomika i organizaciya proizvodstva (po napravleniyam)» / L. V. Butor, T. A. Sahnovich. – Minsk : BNTU, 2022. – 52 s.
18. Myasnikovich, M. V. Makroekonomicheskaya sbalansirovannost' i novye podhody k upravleniyu social'no-ekonomicheskim razvitiem Respubliki Belarus' / M. V. Myasnikovich // Problemy upravleniya (Minsk). – 2011. – № 2 (39). – S. 4–7.
19. Davydenko, L. N. Osobennosti i zadachi razvitiya transgranichnogo sotrudnichestva prigranichnyh regionov Belarusi i Rossii / L. N. Davydenko // Rossiya: tendencii i perspektivy razvitiya. – 2022. – № 17–2. – URL: https://cyberleninka.ru/article/n/osobennosti-i-zadachi-razvitiya-transgranichnogo-sotrudnichestva-prigranichnyh-regionov-belarusi-i-rossii (data obrashcheniya: 08.10.2024).
20. Nacional'naya strategiya ustojchivogo social'no-ekonomicheskogo razvitiya Respubliki Belarus' na period do 2030 goda : protokol zasedaniya Prezidiuma Soveta Ministrov Respubliki Belarus' ot 2 maya 2017 g. №10. Minsk, 2017 // ETALON : inform.-poiskovaya sistema (data obrashcheniya: 13.10.2024).

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COMPETITIVENESS, COMPETITIVE ADVANTAGES OF THE ORGANIZATION: CONCEPTS, FACTORS OF ENSURING COMPETITIVENESS

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Abstract

Competitiveness is not an abstract concept, but a set of interrelated factors that provide an organization with a certain advantage over other market participants. The key element here is competitive advantages – unique characteristics of an enterprise or its products that allow it to occupy a more advantageous position in the market and receive higher profits. Competitiveness is a direct characteristic of a business entity and is achieved through the possession of competitive advantages. In essence, competitive advantage and competitiveness are two interrelated concepts. They have common features: competitive advantages are a factor condition of competition, and competitiveness is the degree of success in the competitive struggle.

Improving competitiveness is a strategic goal of an enterprise, and competitive advantages are the tools and resources that allow achieving this goal and ensuring sustainable development in the conditions of fierce market competition.

The article considers approaches to defining the essence of the concept of "competitiveness of an organization": resource, which is based on the study of production factors to improve competitiveness; managerial, the authors of which paid special attention to effective government policy; investment, considering the direction of investment resources in scientific, technical and human capital; innovation, which is based on determining the influence of such a factor as innovation; combined, combining theories of several approaches. The relationship between the concepts of "comparative advantages", "competitive advantages" and "competitiveness" is analyzed. A classification of factors ensuring competitiveness according to various characteristics is given: basic and developed, general and specialized, natural and created; external and internal factors; depending on the intended purpose of the created labor product; success factors and others.

Keywords: competitiveness, approach, theory, competitive advantages, factors, organization.

КОНКУРЕНТОСПОСОБНОСТЬ, КОНКУРЕНТНЫЕ ПРЕИМУЩЕСТВА ОРГАНИЗАЦИИ: ПОНЯТИЯ, ФАКТОРЫ ОБЕСПЕЧЕНИЯ КОНКУРЕНТОСПОСОБНОСТИ

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Реферат

Конкурентоспособность не является абстрактным понятием, а представляет собой комплекс взаимосвязанных факторов, которые обеспечивают организации определённое превосходство над другими участниками рынка. Ключевым элементом здесь выступают конкурентные преимущества – уникальные характеристики предприятия или его продукции, позволяющие ему занимать более выгодную позицию на рынке и получать более высокую прибыль. Конкурентоспособность выступает непосредственной характеристикой субъекта хозяйствования и достигается за счет обладания конкурентными преимуществами. По своей сути, конкурентное преимущество и конкурентоспособность являются двумя взаимосвязанными понятиями. Они имеют общие признаки: конкурентные преимущества представляют собой факторное условие конкуренции, а конкурентоспособность – степень достижения успеха в конкурентной борьбе.

Повышение конкурентоспособности является стратегической целью предприятия, а конкурентные преимущества – это инструменты и ресурсы, позволяющие достичь этой цели и обеспечить устойчивое развитие в условиях жесткой рыночной конкуренции.

В статье рассмотрены подходы к определению сущности понятия «конкурентоспособность организации»: ресурсный, основой которого является исследование факторов производства для повышения конкурентоспособности; управленческий, авторы которого особое внимание уделили эффективной правительственной политике; инвестиционный, рассматривающий направление инвестиционных ресурсов в научно-технический и человеческий капитал; инновационный, который основывается на определении влияния такого фактора, как инновации; комбинированный, сочетающий в себе теории нескольких подходов. Проанализировано соотношение понятий «сравнительные преимущества», «конкурентные преимущества» и «конкурентоспособность». Приведена классификация факторов обеспечения конкурентоспособности по различным признакам: основные и развитые, общие и специализированные, естественные и созданные; внешние и внутренние факторы; в зависимости от целевого назначения создаваемого продукта труда; факторы успеха и другие.

Ключевые слова: конкурентоспособность, подход, теория, конкурентные преимущества, факторы, организация.

Introduction

Competitiveness is a complex indicator showing the combined expression of many factors – from the sustainability of the national economy to the ability to plan and manage the business process of production within the enterprise. In the modern economy, the category of "competition" reflects the essence of the laws of market relations, but its modern understanding has other aspects: organization, interdisciplinary, complexity, multi-level, interconnectedness, etc. In general, competition manifests itself only in the process of competition and market relations and is characterized by the competitive advantages of the object under study, i. e. the level of satisfaction of customer needs in comparison with similar products on the market. Based on the satisfaction of personal and social needs in conditions of limited resources, the competitiveness of an enterprise allows it to make a profit and develop. The competitiveness of an enterprise is determined by the presence of competitive advantages in comparison with other business entities, i. e. superiority of competitiveness in the field of efficiency of activities, management, quality of goods and services, competence and professionalism of personnel. If increasing competitiveness is the goal, then competitive advantages are the means to achieve the goal. Practice, first of all, focuses on ensuring competitive advantages of enterprises and goods.

A significant number of scientific, theoretical and applied works are devoted to the study of the problems of analysis and management of competitiveness of enterprises. Such authors as N. I. Berezov,

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M. Sh. Gabibov, A. S. Golovachev, I. M. Lifits, N. V. Nemogay, R. A. Fatkhutdinov and others made a significant contribution to the formation of theoretical and methodological approaches to the analysis and management of competitiveness of enterprises.

Methodological issues of assessing and managing the competitiveness of enterprises are studied in the works of scientists E. A. Andreeva, I. I. Butsenko, O. A. Dumchina, M. I. Tertyshnik and others.

Despite the large number of scientific works devoted to the problems of ensuring the increase of the competitiveness of an organization, the following issues remain insufficiently studied in the scientific and practical literature: management of competitiveness and competitive advantages, problems of analyzing the competitiveness of business entities, the use of digital technologies in ensuring the increase of the competitiveness of enterprises, etc.

Analysis of approaches to defining the essence of the concept of "competitiveness of an organization"

In economic literature, there are different approaches to interpreting the concept of "competitiveness of an organization". This category remains multifaceted and does not have a universal definition. Studying the essence of competitiveness allows us to determine its role and place in competitive relations. The concept of "competitiveness" is embedded in a number of economic theories, which are classified in economic literature in terms of five approaches (Table 1) [1, 2, 3, 4, 5].

Table 1 – Basic approaches to defining the concept of "competitiveness"

Approach	Theories
Resource	A. Smith's theory of absolute advantage (1776); D. Ricardo's theory of comparative advantage (1817); E. Heckscher and B. Ohlin's theory of the relationship between production factors (1918–1933); P. Samuelson's theory of price equalization for production factors (1948)
Management	The national economy system of F. List (1841); The growth pole theory of F. Perroux (1950); The "balanced scorecard" model of R. Kaplan and D. Norton (1992)
Investment	The theory of "new growth" by P. Romer and "human capital" by R. Lucas; The eclectic OLI paradigm of J. Dunning (1981–1993)
Innovation	Theory of economic development by J. Schumpeter (1912); Theory of economic growth factors by J. Kendrick, E. Denison, R. Solow (1957–1969); The concept of intellectual leadership by G. Hamel and K. Prahalad (1994); Theory of ecosystems and coevolution by J. Moore (1996); Theory of complementary factors by R. M. Kanter; Blue ocean theory by K. Chan (2007).
Combined	Mercantilist theories (15th–18th centuries); German historical school – W. Roscher, B. Hildebrand, K. Knies, G. Schmoller, J. Brentano (1852); Theory of industrial regions (specialized production) A. Marshall (1890); Theory of national competitive advantages M. Porter (1990); Model of the art of dominance and creation of competitive advantages M. Tracy, F. Wiersema (1995); Theory of co-competition A. M. Brandenburger and B. J. Nalebuff; Concept of sustainable development (2002)

I. I. Butsenko in his work "Competitive Advantages: Theoretical Aspects" [6] writes that "representatives of the resource-based approach (A. Smith, D. Ricardo, E. Heckscher and B. Ohlin, P. Samuelson) focused on the fact that the basis for forming a company's competitiveness is the study of production factors. Factors that contribute to increasing the competitiveness of countries are their competitive advantages. Representatives of the management approach (F. List, F. Perroux, R. Kaplan, D. Norton) paid special attention to the analysis of additional influencing factors, namely, effective government policy and the influence of government regulation" [6].

The basic assertion of the investment approach (P. Romer, R. Lucas, J. Dunning) "is a fundamentally new hypothesis of economic growth, within the framework of which scientific and technological progress was considered as an endogenous factor. The main factor of both economic growth and the formation of competitive advantages is the direction of investment resources into scientific, technical and human capital. Theories have proven that a country that has so-called "ownership advantages" attracts foreign investment, and "location advantages" and "internationalization advantages" create favorable conditions for national investors abroad" [6].

The main provisions of the innovation approach – not everything in the formation of the competitiveness of economic entities and nations can be explained by the productivity of production factors. The study of growth factors is based on the definition of a significant influence of such a factor as innovation. Representatives of this approach (J. Schumpeter, J. Moore, R. M. Kanter, K. Chan and others) believed that at the "microeconomic level, innovations can ensure the growth of production profitability, and within the boundaries of the national economy – stimulate the transition of the economic system to a new equilibrium position, thereby ensuring its development. Particular attention is paid to the emergence of a new component of the competitive position – intellectual competitive advantage. Competitive advantage is considered as a derivative of human thinking: those who are unable to change their paradigm and do not become bearers of the newest will not be able to win in the future competitive struggle" [7].

In general, scientists consider competitiveness from the point of view of the formation of sources, determination of its qualitative and quantitative characteristics and proposals for the formation and maintenance of competitive advantages. Each author brings his own perspective depending on the objectives of the research.

V. N. Belkin notes that "the evolution of the concept of "company competitiveness" was initially considered from the point of view of cost savings. Since the mid-19th century, more attention has been paid to resource conservation. In the 20th – 21st centuries, knowledge and intellectual potential came to the fore" [2].

Based on the above approaches to the interpretation of the economic category of "competitiveness of an organization", we can conclude that there is no single approach to the interpretation of the concept. Depending on the angle from which the term "competitiveness" is considered, we can only highlight the key elements of analysis and the search for sources of their formation.

A. S. Golovachev interprets this concept as follows: "Competitiveness is a real value that a business entity has, and which ensures its superiority over competitors" [8].

Competitiveness has a hierarchy and can relate to:

- a product;
- a functional area of activity (research, production, management, marketing, etc.); – to the enterprise, industry, region, country's economy, society as a whole.

The question of the relationship between comparative and competitive advantages and competitiveness remains open: from essential comparative advantages – through certain competitive advantages – to competitiveness criteria (Table 2).

Competitiveness in a market economy is a direct characteristic of an economic entity. As M. Sh. Gabibova notes, "competitive advantage and competitiveness are closely interconnected and complementary concepts, the essential symptoms of which are that competitive advantages are a factor condition of competition, and competitiveness is the level of success achieved in the competitive struggle" [9].

Accordingly, the essence of competitiveness is defined as "a set (unique combination) of differentiated real or potential factors capable of influencing the achievement of success in the competitive struggle, determining the competitive behavior of economic entities" [9].

Table 2 – The relationship between the concepts of “comparative advantages”, “competitive advantages” and “competitiveness”

Comparative advantages	Competitive advantages	Competitiveness
Abstract category, used to characterize the advantageous position of one market entity compared to another, which gives it the opportunity to win in the competitive struggle	The result of the existence of comparative advantages, a concept that corresponds to real market practice, is linked to real market opportunities (relative to costs or differentiation) and therefore takes on a concrete practical form	The form of realization of competitive advantages, the result of the search and use of new opportunities by a market entity
Essential concept	It represents a real manifestation of the essence, characterizes the conditions of market behavior	Expresses the result of the market behavior of the subject
To identify comparative advantages, relative characteristics of the efficiency of using production factors are used	It is expressed in specific indicators that can be taken into account and quantified (availability of a cheaper resource, economies of scale, the presence of a product of special quality), which indicates a certain source of a leading position	An empirical category that has certain quantitative indicators

There are many approaches to defining the essence of the term “competitiveness”, which has led to the emergence of various classifications. One of the classifications is given in the work of A. A. Sergeev “Strategic approach and methodology for managing the competitiveness of an organization” [10], the main criterion of which is “a basic agreement that determines the nature of the source of competitiveness:

1. Competitiveness based on innovation.
2. Competitiveness based on economic factors.
3. Competitiveness based on regulatory and legal acts exists by virtue of laws, regulations, special privileges and other decisions of government and management bodies.
4. Competitiveness of a structural nature.
5. Competitiveness caused by administrative measures.
6. Competitiveness determined by the level of development of the market infrastructure.
7. Technical (technological) competitive advantages.
8. Competitiveness determined by good information.
9. Competitiveness based on demographic factors.
10. Competitiveness based on geographic factors" [10].

Based on the results of examining the essence of the concept of "competitiveness of an organization", we can conclude that it is a system-forming category that acts as a driving force for the development and formation of competitive relations. On the one hand, the state of competitiveness is achieved through the possession of a competitive advantage, which acts as a factor of competitiveness. On the other hand, a competitive advantage is an object of competition and can be achieved in a competitive struggle. In general, the economic nature of the category of "competitiveness of an organization" is expressed in the fact that it can simultaneously act as a means and a consequence of competitive struggle and arises where there is competition.

Factors ensuring competitiveness

M. Porter classifies factors of competitiveness into: "basic and developed, general and specialized, natural and created" [11].

Basic factors are natural resources, climatic conditions, geographical location of the company, labor force.

Developed factors are a modern infrastructure for information exchange, highly qualified personnel and research institutes, departments of universities engaged in high-tech areas.

General factors can be used in a wide range of industries, they, as a rule, provide competitive advantages of a limited nature, and are available to organizations in many countries. A competitive advantage based on a combination of basic and general factors is a lower-order advantage that is short-lived and unstable.

Specialized factors are factors used in one industry or in a limited number of industries, they form a long-term basis for ensuring the competitiveness of an organization.

Natural factors are related to lower-order factors.

Created factors are an accumulation process, i. e. Each generation inherits factors from the previous generation and creates its own, adding them to the previous ones.

When classifying factors ensuring competitiveness, external and internal factors are distinguished. External factors are considered in the light of state influence of both an economic nature and administrative measures. These actions "determine the formal rules for the activities of business entities in the national or global market" [12].

As V. V. Timofeev notes, "the most significant external factors ensuring the competitiveness of a company are:

– competitive environment and level of competition, degree of privatization of enterprises in the industry;
– competitiveness of the industry;
– characteristics of demand for the company's goods (services) (size and dynamics of demand, market requirements for price and quality of goods, elasticity of demand for price and income level);
– development and competitive advantages of those industries (enterprises) that provide the analyzed company with the necessary resources, materials and information tools;
– random events (technological breakthroughs, fluctuations in resource prices, significant changes in global financial markets, political decisions of their own and foreign governments);
– economic and organizational-administrative forms and methods of state regulation of the behavior of producers in the industry and buyers” [13].

Internal factors of ensuring the competitiveness of an organization are characterized by the potential capabilities of the company itself to ensure its own competitiveness. According to T. I. Marchenko, “this is the potential of marketing services, scientific and technical, production and technological, financial and economic, personnel, environmental; the level of design and technological preparation and development of production processes; the level of material and technical support, storage, packaging, transportation of goods; the effectiveness of production control, testing and inspection; the level of provision of commissioning and installation work; the level of technical, service and warranty service, the effectiveness of advertising” [14].

Factors of ensuring competitiveness can be classified depending on the intended purpose of the created product of labor. According to U. D. Namyslov, the competitiveness of enterprises producing consumer goods is “influenced by the following factors:

– commercial conditions (the ability of an enterprise to provide customers with consumer or commercial loans, discounts from the list price, the return of goods previously purchased from the enterprise that have used up their economic resources; concluding barter transactions));
– organization of a distribution network (location of a chain of stores and supermarkets in a place accessible to a wide range of customers, display of products in the company’s showrooms and demonstration halls, as well as with trade intermediaries, at exhibitions and fairs; the effectiveness of advertising campaigns; influencing customers through public relations);
– organization of technical maintenance of products (increasing the volume of services provided and the terms of warranty repairs; reducing the cost of post-warranty service);
– providing consumers with information about the enterprise (facts confirming reputation, information about the range of products and ser-

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vices, advertising of the trademark as a means of attracting the attention of buyers to the product);

– taking into account the impact of the market situation on the position of the enterprise" [15].

Success factors are indicators of competitive advantages, which, according to A. Strickland and A. Thompson, "include:

– product quality;
– reputation (image) of the organization;
– production capabilities;
– technological level;
– dealer network (distribution system);
– marketing and advertising;
– financial stability of the organization;
– relative cost position;
– customer service" [16].

According to M. Porter, the factors of a company's competitiveness "are the four main determinants of the diamond: company strategy; structure and competition; production factors; demand and the presence of competitive related or adjacent industries and enterprises" [17].

The factors of production that determine the competitiveness of organizations in the industry can be represented in the form of the following groups: labor resources; physical resources; knowledge resources; monetary resources; infrastructure.

The classification of factors of a company's competitiveness developed by R. A. Fatkhutdinov is of practical significance, "which includes the following groups: structural; resource; technical; managerial; economic and financial" [18].

The factors of an organization's competitiveness contribute to the transformation of its capabilities into reality. They determine the means and methods of using reserves to increase the company's competitiveness. But "the presence of the factors themselves is not sufficient to ensure competitive advantages. "Obtaining a competitive advantage based on factors depends on how effectively they are used and where, in what industry, they are applied" [19].

Thus, the main areas of ensuring competitiveness are: increasing the efficiency of innovative activities of organizations, ensuring resource potential and its effective use to achieve set goals, introducing new production technologies, ensuring energy and resource conservation, developing and implementing a strategy for finding and maintaining competitive advantages, which will allow the organization to create a certain superiority over its direct competitors [20, 21].

Conclusion

A study of scientific literature allows us to conclude that the competitiveness of an organization is a complex economic concept that does not have a single acceptable, comprehensive description that would satisfy all stakeholders. Each author, depending on the goals and objectives of the study, the nature of the object to which this concept relates, and the requirements of market participants, gives his or her own definition of the competitiveness of an organization. Competitiveness is considered: at the level of goods and enterprises – microcompetitiveness, at the level of individual industries – mesocompetitiveness, at the level of the national economy of the country – macrocompetitiveness. Moreover, there is a close external and internal dependence between the concepts of these three levels. The competitiveness of an organization is its ability to successfully confront competitors in the market and occupy a stable position, ensuring profitability and growth. It is not a static indicator, but is dynamically formed under the influence of many factors, including the efficient use of resources, the development and implementation of competitive advantages. Competitiveness is based on skillful management of all aspects of the organization's activities: efficient use of labor resources, financial resources, intellectual property, information; optimization of the use of material resources; increasing the level of technological equipment of production; implementation of automated systems for managing technological processes; reduction of the cost of production due to optimization of production and implementation of lean manufacturing tools, etc.

Referenses

1. Ashurova, G. A. Nekotorye voprosy ocenki konkurentosposobnosti predpriyatiya / G. A. Ashurova // Problemy sovremennoj ekonomiki. – 2020. – № 2 (62). – S. 295–297.
2. Belkin, V. N. Teoreticheskie osnovy ocenki konkurentosposobnosti predpriyatij / V. N. Belkin, N. A. Belkina, L. B. Vladykina. – URL: https://cyberleninka.ru/article/n/teoreticheskie-osnovy-otsenki-konkurentosposobnosti-predpriyatiy (date of access: 01.11.2024).
3. Berezov, N. I. Konkurenciya v ekonomike / A. I. Berezov. – M. : Nika-Centr, 2018. – 768 s.
4. ZHukova, M. A. Teoreticheskie i metodicheskie aspekty upravleniya konkurentnymi preimushchestvami organizacii / M. A. ZHukova // Vestnik Universiteta (Gosudarstvennyj universitet upravleniya). – 2017. – № 5. – S. 16–20.
5. Mokronosov, A. G. Konkurenciya i konkurentosposobnost' : uchebnoe posobie / A. G. Mokronosov, I. N. Mavrina. – Ekaterinburg : Izd-vo Ural un-ta, 2022. – 194 s.
6. Butsenko, I. I. Konkurentnye preimushchestva: teoreticheskie aspekty / I. I. Butsenko, Yu. V. Ilyasova, M. V. Gorbacheva. – URL: https://cyberleninka.ru/article/n/konkurentnye-preimuschestva-teoreticheskie-aspekty (date of access: 04.11.2024).
7. Andreeva, A. E. Mnogofaktornyj analiz konkurentosposobnosti predpriyatiya / A. E. Andreeva // Nauka i biznes: puti razvitiya. – 2020. – № 3. – S. 25–28.
8. Golovachev, A. S. Konkurentosposobnost' organizacii : uchebnoe posobie / A. S. Golovachev. – Minsk : Vysshaya shkola, 2018. – 319 s.
9. Gabibova, M. SH. Puti povysheniya konkurentosposobnosti predpriyatiya / M. SH. Gabibova // Aktual'nye voprosy ekonomiki i upravleniya: materialy III mezhdunarodnoj nauchchnoj konferencii, g. Moskva, iyun' 2015 g. – M. : Buki-Vedi, 2015. – S. 85–87.
10. Sergeev, A. A. Strategicheskij podhod i metodologiya upravleniya konkurentosposobnost'yu organizacii / A. A. Sergeev // Znanie. – 2016. – No. 5–2 (34). – S. 70–76.
11. Frolov, M. A. Opredelenie konkurentnyh preimushchestv kompanii / M. A. Frolov // Voprosy nauki i obrazovaniya. – 2017. – № 6 (7). – S. 70–73.
12. Sal'nikov, YU. YU. Sovremennye podhody k ocenke konkurentosposobnosti organizacij na osnove sub"ektnogo podhoda / YU. YU. Sal'nikov, R. N. Prihod'ko // Vestnik Altajskoj akademii ekonomiki i prava. – 2021. – № 5–1. – S. 85–92.
13. Timofeev, V. V. Upravlenie konkurentosposobnost'yu predpriyatiya v usloviyah novoj ekonomicheskoj real'nosti / V. V. Timofeev // Faktory uspekha. – 2016. – № 1 (6). – S. 56–59.
14. Marchenko, T. I. Urovnevoe upravlenie konkurentosposobnost'yu predpriyatiya / T. I. Marchenko // Ekonomika i upravlenie: novye vyzovy i perspektivy. – 2019. – № 6. – S. 144–146.
15. Namyslova, U. D. Sposoby ocenki i analiza konkurentosposobnosti predpriyatij / U. D. Namyslova // Ekonomicheskie nauki. – 2020. – № 4. – S. 39.
16. Kulikova, A. V. O vazhnosti integracii rynochnogo i resursnogo podhodov k razrabotke konkurentnoj strategii organizacii / A. V. Kulikova, O. V. Rokunova // UEkS. – 2018. – № 11. – S. 183–188.
17. Rud', E. M. Konkurentosposobnost': konceptual'nye podhody i urovni issledovaniya / E. M. Rud' // Izvestiya Saratovskogo universiteta. Novaya seriya. Seriya: Ekonomika. Upravlenie. Pravo. – 2021. – № 1. – S. 18–22.
18. Korotina, N. M. Osnovy upravleniya konkurentosposobnost'yu sovremennogo predpriyatiya / N. M. Korotina // Sovremennye tendencii razvitiya nauki i tekhnologij. – 2015. – № 2–7. – S. 66–69.
19. ZHgunova, P. A. Povyshenie konkurentosposobnosti kompanij na osnove logisticheskogo podhoda / P. A. ZHgunova // Ryazanskij gosudarstvennyj radiotekhnicheskij universitet. – 2019. – S. 152–154.
20. Ustimkin, O. A. Ocenka i puti povysheniya konkurentosposobnosti predpriyatiya / O. A. Ustimkin // Forum molodyh uchenyh. – 2019. – № 1 (29). – S. 7–10.
21. SHCHepilov, O. I. Traktovka menedzhmentom kommercheskih organizacij soderzhaniya ponyatiya «konkurentosposobnost' kompanii» / O. I. SHCHepilov // Ekonomika ustojchivogo razvitiya. – 2021. – № 4 (48). – S. 191–196.

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