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ON THE ISSUE OF INCREASING THE RELIABILITY OF DETERMINING THE MODULUS OF THE GENERAL SOIL DEFORMATION

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Abstract

The reliability of determining the modulus of general soil deformation directly affects the forecast of the final foundation settlement. Since the calculation of the 2-group ultimate conditions of the foundation bases is crucial in determining the size of the foundations, the solution of this issue is very relevant.

In this article, based on the analysis of the conditions of interaction of the system "soil base-foundation", the ways of increasing the reliability of determining the modulus of the general deformation of soil layers in the depth of the compressible thickness are considered.

Keywords: soil, deformation, tests, method, modulus, settlement, base, layer, summation, compressibility, thickness, foundation, stamp.

О ПОВЫШЕНИИ ДОСТОВЕРНОСТИ ОПРЕДЕЛЕНИЯ МОДУЛЯ ОБЩЕЙ ДЕФОРМАЦИИ ГРУНТА

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Реферат

Достоверность определения модуля общей деформации грунта непосредственно влияет на прогноз конечной осадки фундамента. Поскольку расчет по 2-группе предельных состояний оснований является решающим при назначении размеров фундаментов, решение данного вопроса является весьма актуальным.

В данной статье исходя из анализа условий взаимодействия системы «грунт основания-фундамент» рассматриваются пути повышения достоверности определения модуля общей деформации слоев грунтов по глубине сжимаемой толщи.

Ключевые слова: грунт, деформация, испытания, метод, модуль, осадка, основание, слой, суммирование, сжимаемость, толща, фундамент, штамп.

Introduction

In the practice of designing foundation bases and foundations, their calculations are performed according to two ultimate conditions [1-4]: the 1st in terms of bearing capacity (stability), the 2nd in terms of deformations. For assigning the dimensions of shallow foundations [1, 4], the calculation of deformations (settlement) is crucial, and the main characteristic for each soil is its general deformation modulus, which is determined by the results of laboratory (compression) or field tests (stamp, probing, pressiometry).

During compression tests, a soil sample is subjected to uniaxial compression without the possibility of lateral expansion, leading it to compression due to a denser packing of particles, which can characterize the behavior of soils under foundations only at low pressures, and with their increase does not reflect their real compression.

The results of probing (more reliably static) of soils allow us to evaluate their properties in specific engineering and geological conditions in the form of resistances along the lateral surface of the friction sleeve and under the tip of the submerged probe along the depth of the base. Since at the same time the soil moves apart and is already in the final phase of strength loss, its compressibility is estimated indirectly based on the correlation between deformation and strength characteristics. In this case, the dependence between pressures and deformations is not reflected, which negatively affects the reliability of determining the values of E_o.

Pressiometric tests in specific soil conditions with their actual properties allow us to reflect the relationship between compressive pressures on the soil and its deformations, but in a horizontal direction when the pressiometer chamber expands in the well at appropriate depths. This does not fully reflect the process of vertical compression of the soil, introducing errors in the estimation of values E_o.

A more reliable determination of the soil deformation modulus E_o is provided by field stamp tests in specific soil conditions with their actual properties. When the stamp is pressed into the ground with its compression in the vertical direction, similar to foundations, it is possible to displace the soil to the sides due to all the stress components that arise in the base (compressive and shear).

Below we will focus on the analysis of the stress-strain state in the soil base as the pressure transmitted by the pressed stamp increases, with the interpretation of the obtained dependence of its settlement S on the values of these pressures P when determining the value of the deformation modulus E_o of the tested soil.

The essence of determining the modulus of soil deformation by stamp tests

As it is known, in the regulatory documents of the CIS, including the Republic of Belarus [1, 2, 4], the so-called **layer-by-layer summation method** is mainly used when calculating the settlement of foundations. It is based on the condition of a simple uniaxial compaction of the soil layers in the compressible thickness of the base due to vertical compressive stresses from the transfer of pressing loads by the foundation. For simplicity of calculations, horizontal compressive and tangential (shear) stresses arising in the soil are not considered, and their influence is considered by the correction coefficient β in the formula of simple uniaxial compression of each layer:

$$S_i = \beta \cdot \sum \frac{Pi \cdot h_i}{E_o} \qquad (1)$$

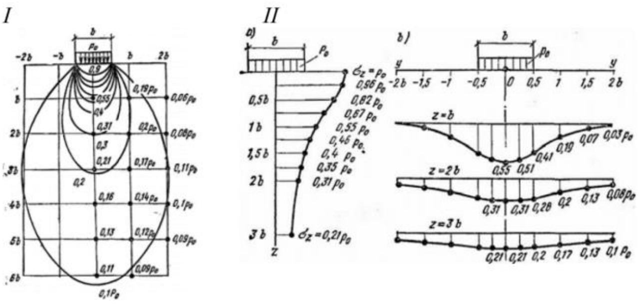
where: S – the settlement of the foundation (stamp); P_i – the compressive pressure on the soil layer, kPa; h_i – the thickness of the soil layer, m; E_o – the modulus of the general deformation of the soil, kPa; β – the coefficient assumed for all soils to be equal to 0.8, although it was previously considered different depending on the lateral expansion coefficient (Poisson) *v* of the corresponding soil.

As we can see, in the formula (1), the settlement during compression of the soil layer is proportional to the compressive pressure acting on it. This ratio is characteristic of Hooke's law in the theory of elasticity, used in soil mechanics to estimate the stress-strain state in the base.

At a known value of the stamp settlement, according to the results of the indentation test, according to the formula (1), the value of E_o s determined by reverse recalculation when interpreting the results obtained experimentally.

The method of layer-by-layer summation is based on the presence within the compressed zone of the base below the bottom of the foundation of different soil strata with their own values of E_o at varying compressive stresses σ_z in depth and width.

An example of such a distribution for a uniform band load at the ground surface is shown in Fig. 1 [3]. In the solutions of the theory of elasticity, when assessing the **stress-strain state**, the assumption is made about the uniformity (isotropy) of the properties of the soil in the base in all directions.



I – lines of identical values σ_z (isobars) along the depth and width of the base;
II – distribution diagrams σ_z:
a – on the vertical axis, b – on the horizontal levels

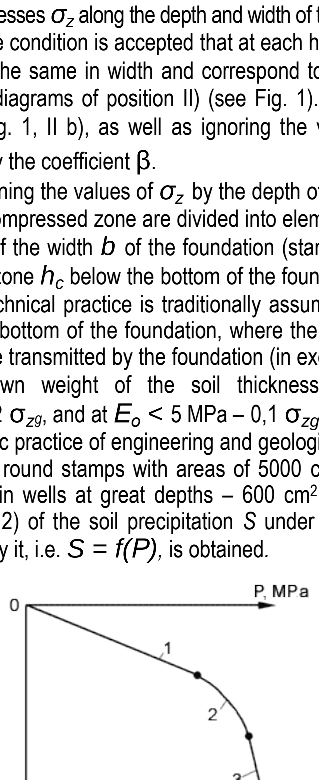
Figure 1 – Distribution of vertical compressive stresses σ_z in the ground

The method of layer-by-layer summation is based on the presence of different soil strata with their own values of E_O within the zone of the base below the bottom of the foundation, subject to compression, in the presence of varying compressive stresses σ_z along the depth and width of this zone.

In addition, the condition is accepted that at each horizontal level, the values of σ_z are the same in width and correspond to the values along the vertical axis (diagrams of position II) (see Fig. 1). Such their actual difference (see Fig. 1, II b), as well as ignoring the values of σ_x , σ_y and τ is leveled by the coefficient β.

When determining the values of σ_z by the depth of the base, the soil strata within the compressed zone are divided into elementary layers with capacities of 0.2 of the width b of the foundation (stamp). The power of the compressible zone h_c below the bottom of the foundation in domestic and foreign geotechnical practice is traditionally assumed to correspond to the level in the bottom of the foundation, where the stresses from the additional pressure transmitted by the foundation (in excess of the natural σ_{zg} from the own weight of the soil thickness) are up to: at $E_o > 5$ MPa – 0,2 σ_{zg}, and at $E_o < 5$ MPa – 0,1 σ_{zg}. [3]

In the domestic practice of engineering and geological surveys, when testing soils, hard round stamps with areas of 5000 cm^2, 2500 cm^2 are used in pits, and in wells at great depths – 600 cm^2. In this case, the dependence (Fig. 2) of the soil precipitation *S* under the stamp on the pressure applied by it, i.e. $S = f(P)$, is obtained.



1 – the compaction phase,
2 – the shear phase, 3 – the rise phase

Figure 2 – The dependence of the settlement S of the soil under the stamp on the pressure transmitted by it P

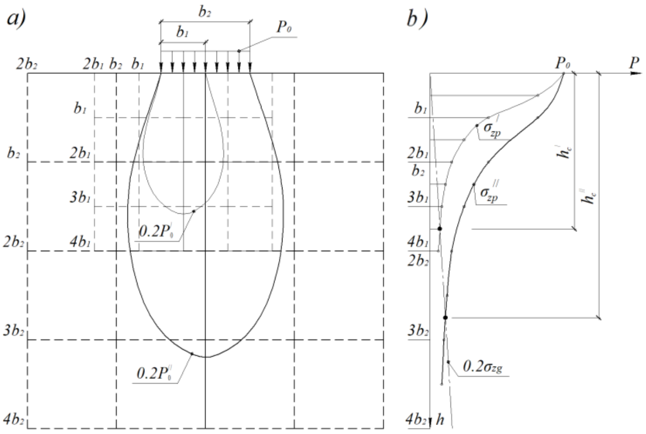
Then, on an approximately linear initial segment of the graph, the pressure range ΔP is selected with the corresponding change in settlement ΔS and for this range, the deformation modulus E_o is calculated using the formula:

$$Eo = (1 - \nu^2)\cdot\frac{\pi\cdot d}{4}\cdot\frac{\Delta P}{\Delta S} \quad , \qquad (2)$$

where ν – the Poisson's ratio of the soil; d – the diameter of the stamp, m;

With a strong decrease in the compressive stresses occurring in the ground σ_z (see Fig. 1), determined by multiplying the pressure transmitted by the bottom of the foundation p_o by the dispersion coefficient α, there is a need for each level of the compressible thickness to take into account its calculated (piecewise linear on a factually curved graph) pressure range ΔP and for it to calculate the modulus of deformation of the soil E_o.

It is also important not to forget that the stresses on the depth and the power of the compressible thickness in the base linearly increase in proportion to the width (Fig. 3) of the foundation (stamp) b, which inevitably affects the value of the determined modulus of the total deformation of each layer of soil at the appropriate level of such a thickness.



a) – lines equal stress intensity σ_{zp} = 0,2P_o; b) – change in the depth of the stress centers under the soles of foundations σ_{zp} from the pressure of P_o and a share of 0,2σ_{zg} by weight of homogeneous soil (conditional) if the definition of the boundaries of compressible zones h_c; 1 – when the width b_2, 2 – when $b_2 = 2b_1$

Figure 3 – The distribution of the vertical compressive stress σ_{zp} depth uniform base under the soles of foundations with different widths b when passing them same pressure intensity P_o

Traditionally, when assessing the distribution of compressive stresses in a soil mass (usually only vertical compressive stresses are taken into account when determining its settlement under the foundation), an assumption is made about the uniformity (isotropy) of the soil, although it actually has anisotropy or a difference in properties in different directions (Fig. 4).

Note that in the practice of engineering surveys and design, these features are not yet taken into account (ignored), and the determined values of the E_o are actually become erroneous. In this regard, it is very relevant to increase the reliability of determining the values of the deformation modules of the soil by means of field stamp tests in specific engineering and geological conditions, taking into account the above-mentioned features of interaction with the soil of stamps and conducting the necessary studies for this purpose*.

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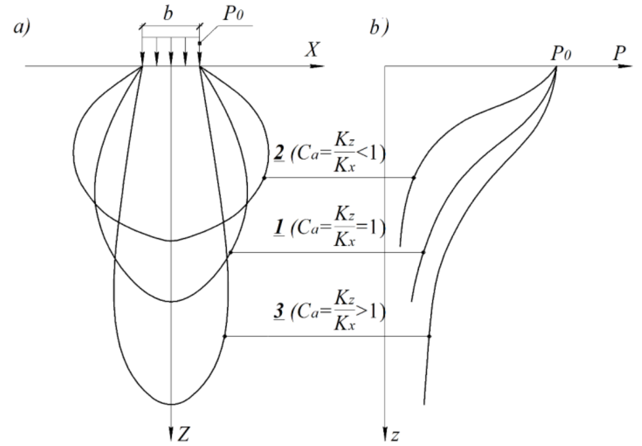
*the author aimed at the main directions of such research in the process of working on a Master's thesis under the scientific supervision of Professor, Doctor of Technical Sciences [Ph.D.] M. I. Nikitenko with their continuation in the framework of a Ph.D. candidate's dissertation under the scientific supervision of professor, Doctor of Technical Sciences [Ph.D.] P. S. Poyta.



a) – lines of equal stresses $\sigma_{zp} = 0{,}2P_o$;
b) – changes in the depth of stresses under the centers of the soles of the foundations σ_{zp} from the pressure of P_o;

1 – for homogeneous (isotropic – C_a = 1) soil; 2 – for soil with horizontal anisotropy (ribbon clays – C_a < 1); 3 – the same with vertical (loess – C_a > 1): $Ca = K_z / K_x$ – the anisotropy coefficient, i.e. the ratio of the filtration coefficients along the vertical K_z and horizontal K_x

Figure 4 – The nature of the distribution of vertical compressive stresses σ_{zp} over the depth of anisotropic filtration bases under the soles of foundations with their identical widths b and the transmitted pressure intensity P_o:

An example of determining the modulus of total soil deformation in different ranges of ΔP

Since the natural (common) pressure σ_{zg} increases with depth, and the additional σ_{zp} weakens during dispersion in the soil thickness, it can be assumed that the modulus of total deformation E_o for each underlying elementary layer tends to increase in depth due to a sharp decrease in the ranges of ΔP.

As the initial data for the recalculation of the E_o module, we will use the results of the left stamp tests (see Table 1 and Figure 5) performed by the "Engineering Surveys" LLC in December 2020 in Minsk [5]. At the base there was a sandy soil (γ = 16 кN/m^3, ν = 0,3), a round stamp (foundation) with an area of A = 2500 cm^2 (d = 0.564 m = 56.4 cm), its depth of laying h = 0.3 m, pressure P = 250 кPa.

Table 1 – Data of field stamp tests

Stamp depth, m	Stamp area, cm^2	Stamp settlement S (cm), at a pressure of P (кPa)											
		0,00	25	50	75	100	125	150	175	200	225	250	275
0,3	2500	0,00	0,10	0,22	0,36	0,52	0,69	0,89	1,06	1,26	1,47	1,69	2,22

Taking into account the data in Table. 1 and Fig. 5, we determine the E_o module by the formula (2) in the tension range from P_n = 25 кPa до P = 250 кPa:

$$E_o = (1-0.3^2)\cdot\frac{\pi\cdot 56.4}{4}\cdot\frac{250-25}{1.69-0.1} =$$
$$= 40.29\cdot 141.5 = 5700 \text{ кPa};$$

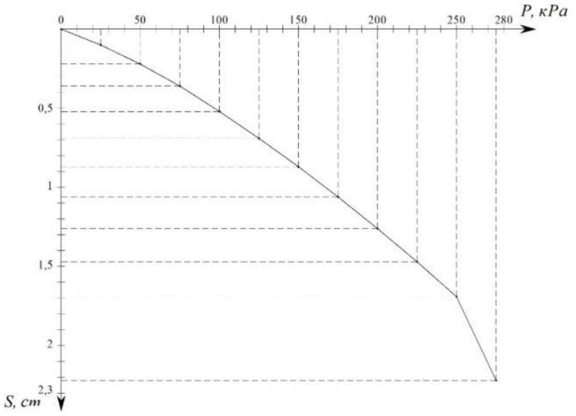


Figure 5 – Graph dependence of $S_i = f(P_i)$

We will determine the common and additional stresses in the base under the stamp. The calculations are summarized in the table. 2 and we build charts of their distribution in depth (Fig. 6) to determine the power of the compressible zone $\boldsymbol{h_c}$. To do this, we will divide the soil under the foundation into elementary layers with the thickness of $0.2d$ (h_i = 0.2x56.4 = 11.28 cm). The additional vertical pressure on the base at the level of the foundation sole was $P_o = P - \sigma_{zg,o}$ = 245.3 кPa. We will also determine the tension from a half and a quarter of the test pressure.

Table 2 – Calculation of common and additional stresses in the base under the stamp

№ layer	h_i layer, cm	The depth z_i of the top layer, cm	$\xi = 2z/b$	α	σ_{zgi}, кPa	0,2σ_{zgi}, кPa	σ_{zpi}, кPa	0,5σ_{zpi}, кPa	0,25σ_{zpi}, кPa
1	11,28	0,00	0	1	4,7	0, 94	245,3	122,6	66,3
2	11,28	11,28	0,4	0,949	6,5	1,30	232,8	116,4	58,2
3	11,28	22,56	0,8	0,756	8,3	1,63	185,4	92,7	46,4
4	11,28	33,84	1,2	0,547	10,0	2,00	134,2	67,1	33,6
5	11,28	45,12	1,6	0,39	11,8	2,36	95,7	47,8	23,9
6	11,28	56,40	2	0,285	13,6	2,72	69,9	35,0	17,5
7	11,28	67,68	2,4	0,214	15,3	3,06	52,5	26,3	13,1
8	11,28	78,96	2,8	0,165	17,1	3,42	40,5	20,3	10,1
9	11,28	90,24	3,2	0,13	18,9	3,78	31,9	16,0	8,0
10	11,28	101,52	3,6	0,106	20,6	4,12	26,0	13,0	6,5
11	11,28	112,80	4	0,087	22,4	4,48	21,3	10,7	5,4
11a		**h_c = 118,0**				**4,8**			**4,8**
12	11,28	124,08	4,4	0,073	24,2	4,84	17,9	9,0	4,5
13	11,28	135,36	4,8	0,062	26,0	5,20	15,2	7,6	3,8
14	11,28	146,64	5,2	0,053	27,7	5,54	13,0	6,5	3,2
14a		**h_c = 156,0**				**5,7**		**5,7**	
15	11,28	157,92	5,6	0,046	29,5	5,90	11,3	5,6	2,3
16	11,28	169,20	6	0,04	31,3	6,26	9,8	4,9	2,4
17	11,28	180,48	6,4	0,036	33,0	6,60	8,8	4,4	2,2
18	11,28	191,76	6,8	0,031	34,8	6,96	7,6	3,8	1,9
18a		**h_c = 197,0**				**7,1**	**7,1**		
19	11,28	203,04	7,2	0,028	36,6	7,32	6,7	3,4	1,7

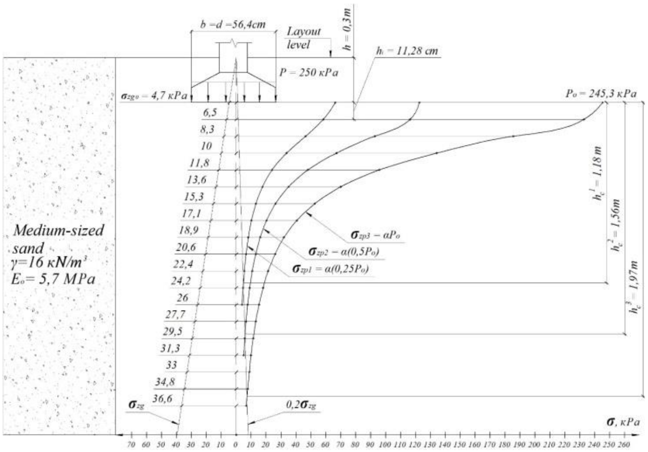


Figure 6 – Graphs of natural and additional stresses along the depth of the base for the given initial data.

It can be seen from Table 2 and Fig. 6 that the boundary of the compressible thickness below the stamp sole (taking into account the condition $\sigma_{zpi} = 0.2\ \sigma_{zgi}$) at a pressure below it of 61.3 кPa was 1.18 m, at a pressure of 122.6 кPa it increased to 1.56 m, and at 245.3 кPa it reached about 2.0 m.

As we can see, the depths of the compressible zones at the base of the stamp or foundation increase non-linearly with the increase in the pressures transmitted by them to the ground.

According to Hooke's law, the compression of elementary soil layers within the deformable h_c zones occurs proportionally to the average compressive stresses acting in each of these layers, which decline non-linearly in depth.

In this regard, we can also assume a nonlinear change in the general deformation modules of the E_o for a homogeneous soil as the thickness of the compressible h_c increases.

Below we will determine the values of E_o for different calculated depths h_c, and the values of the test pressure stages under a stamp with a diameter of 56.4 cm, which amounted to $0.25P_o$ = 61.3 кPa, $0.5P_o$ = 122.6 кPa, P_o = 245.3 кPa and caused, according to Table 1, settlements S_i respectively 0.29 cm, 0.69 cm and 1.69 cm:

$$E_{01} = (1 - 0.3^2)\cdot\frac{\pi\cdot 56.4}{4}\cdot\frac{61.3}{0.29} = 40.29\cdot 214.4 = 8516\ \text{кPa};$$

$$E_{02} = (1 - 0.3^2)\cdot\frac{\pi\cdot 56.4}{4}\cdot\frac{122.6}{0.69} = 40.29\cdot 177.7 = 7159\ \text{кPa};$$

$$E_{03} = (1 - 0.3^2)\cdot\frac{\pi\cdot 56.4}{4}\cdot\frac{245.3}{1.69} = 40.29\cdot 145.1 = 5848\ \text{кPa};$$

These calculations show that the values of E_o, as the pressure levels of P_{oi} increase, decrease non-linearly in proportion to the increase in the compressible h_c thickness in the soil.

However, the fact of reducing the pressure P_{oi} and the compression deformations S_i of the soil layers at a depth h_c below the stamp has not yet been taken into account here, which undoubtedly should affect an adequate change in the values E_o.

As is known, in the existing research practice, the noted features of the nonlinear variability of the values of E_o are actually not taken into account.

In our case, it is not possible to determine the differences in the compression deformations S_i of the elementary soil layers within each of the compressible thicknesses h_i , since such measurements were not made.

An attempt to estimate analytically by dividing the total compression deformations S within all compression depths h_{ci} into fractions S_i, proportional to the average compressive stresses in each elementary layer or their groups will be incorrect, as evidenced by the analysis of formula (2).

It takes into account the diameter of the stamp (foundation) in the numerator instead of the width of the compressible soil layer at the corresponding level (see Fig. 1, pos. I and II, b – isobar graphs). At the same time, the values of ΔS and E_i included in this formula are unknown. If we take settlements in proportion to the pressures, then the ratio $\frac{\Delta P}{\Delta S}$ becomes constant, and all the values of E_i for all pressure stages are also the same.

This contradiction is due to the incorrectness of formula (2), since it gives a difference in the values of E_i only by changing the diameter of the stamp, and increasing proportionally with its increase, but does not reflect the role of increasing its area and its shape, which will differ from the existing non-circular one of the foundations.

It can be noted that in the practice of surveys, although different diameters of stamps are used, but the dependences of the values of the deformation modules of various soils on the size and area of the stamps with the depths of their immersion have not yet been investigated. When interpreting the test results, a rough assumption is made about the constancy of the E_o values in a wide range of pressures transmitted by the stamp, without taking into account the influence of differences in the volumes of the compressible array below it, i.e. not only their varying sizes in depth, but also in width in two directions.

Conclusion

When designing foundation bases and foundations using the method of layer-by-layer summation, the issue of increasing the reliability of determining the value of the soil deformation modulus E_o is relevant. The above example of taking into account one of the above features of interaction with the soil of the pressed stamp allowed us to clarify the determined value of this important parameter of the deformation properties of the soil due to its differences in depth depending on the change in the ranges of ΔP in proportion to the values of the stages of compressive pressures transmitted to the soil and the depths of h_c compressible zones in the base.

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