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SPECIFIČNOSTI PROCESA DEFORMACIJE TLA PODLOGE POKUSNIH TEMELJNIH PLOČA

PECULIARITIES OF THE SOIL DEFORMATION PROCESS AT THE BASES OF EXPERIMENTAL SETTLEMENT PLATES

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Professional paper

Abstract: *The basic principles of methods for determination of interconnection of the structural strength, the coefficients of lateral pressure and lateral extension according the results of research in the field. The increase of the structural strength of the artificial massive in time shown, its influence on the depth of the deformation zone revealed, the correlation of the settlements by compaction and lateral extension, as well as on the lateral extension coefficient. The methods for determining the coefficients of lateral expansion and lateral pressure developed and tested. The assumption of a linear decrease of the relative settlements on the depth on the basis of which the total value of settlement, in the first approximation, divided into two parts – due to compaction (decrease of porosity) and lateral extension (reshape) accepted.*

Keywords: *lateral deformation, lateral pressure, settlement, structural strength, zone of deformation.*

Stručni članak

Sažetak: *U radu su predstavljeni osnovni principi metodologije određivanja povezanosti strukturne čvrstoće, koeficijenata bočnog tlaka i poprečnog širenja prema rezultatima terenskih istraživanja. Pokazano povećanje strukturne čvrstoće umjetnih naslaga u vremenu, otkriven njen utjecaj na dubinu zone deformacije, odnos slijeganja izazvanih sabijanjem i poprečnim širenjem, te također utjecaj na koeficijent poprečnog širenja. Razrađeni su i ispitane metodologije određivanja koeficijenta bočnog širenja i bočnog tlaka. Prihvaćena je pretpostavka o linearnom smanjenju relativnih slijeganja po dubini, na temelju koje ukupna veličina slijeganja, u prvoj iteraciji, podijeljena u dva djela – uslijed sabijanja (smanjenja obujma pora) i bočnog širenja (promjene oblika).*

Ključne riječi: *bočna deformacija, bočni tlak, slijeganje, strukturna čvrstoća, zona deformacije*

1. INTRODUCTION

Evaluation of deformations in soils of foundations according to existing norms and standards for elastically deformable soil environment, at pressures not exceeding the limit of proportionality, is performed according to the criteria of the number of conditional assumptions: to be elastic soil environment is considered isotropic linear-deformed half-space; the calculated values of additional stresses on depth do not depend on the type of soil, their composition and condition; the depth of compressible strata adopted conditional on the ratio of stress from its own weight of the soil and the extra load, and does not depend on the indicators of deformation properties of soils; modulus of deformation is determined by the results of field tests within the linear section of the dependence of settlement on load [1, 2, 4]. In this case deformation properties of soils are evaluated by value of settlement, size of the settlement plate and pressure, without taking into account the parameters characterizing the processes of their deformation.

At the present normative documents and standards for the assessment of deformations arising at pressures outside of proportionality has not developed yet. The accumulated results of experimental testes in geomechanics help to change the perceptions of the processes of transformation of the stress-strain state condition of soil foundation under the influence of external load. There are new indicators to evaluation of deformation properties of soils during their irreversible deformation.

Structural strength, the coefficients of lateral pressure and expansion are the settings that you should consider for improving nonlinear methods of calculation basis for pressure exceeding the limit of the linear dependence of settlement on the load. Experimental investigates of these parameters are performed in the field. Structural strength as the initial threshold deformation of soil was studied in homogeneous, artificially prepared array.

2. RESEARCH METHODS

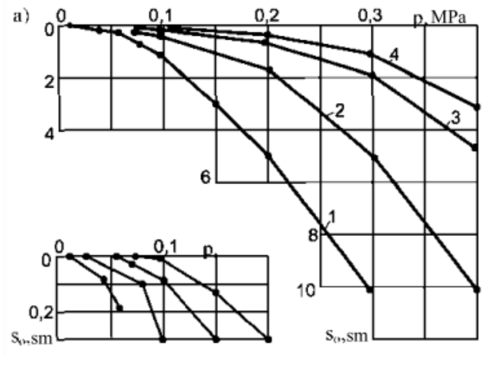
To create a soil mass the shaft, dimensions in plan 1,2 x 1,2 m and depth of 1m, was excavated. Excavated soil was grinded, mixed with water, and the resulting pulp was put through a sieve into the shaft. Artificial in filled shaft was protected from the influence of weather and mechanical effects. The density of the prepared soil averaged 1,54 g/cm³ (natural 1,47 g/cm³). The humidity during the testing period ranged during the 0,24…0,26. Research carried out in 3, 10, 23 and 33 months (experiments 1; 2; 3; 4) after the preparation of artificial array with a round settlement plate area of 300 m². Measurement layered displacements made with ground magnetic marks placed along the vertical axis are set to occur at a depth of 5 cm [5; 6; 8]. The calibrated load equal to 20 kg on the settlement plate was applied.

Tests conducted according to the technology of cyclic increased load, in which each stage represented an independent loop: application load, keeping it up to conditional stabilization and unloading. Measuring: settlement of the settlement plate, moving deep marks (s) and their residual components (s_o), which was determined by the values of the elastic part ($s_v = s - s_o$). After finishing the test and dismantling of equipment values of density of the skeleton of the soil and humidity under the settlement plate and outside the zone of deformation were estimated.

The applied method of research has allowed determining the processes of deformation of soils within each phase.

Fixed insignificant residual deformations can be explained by the crumpling of the contact irregularities in the plane of adjunction of the soles of the settlement plate′s to the surface. The first phase ends at the pressures are equal to the value of structural strength.

The second phase begins at pressures in excess of structural strength. This phase is characterized by destruction of the structural relationships between soil particles, accompanied by a decrease in porosity. The compaction occurs within compressed volume, limited sole of settlement plate, lateral surface along the perimeter and the lower boundary of the deformation zone. The latter is located at a depth where the amount of stress from external loads and additional pressure is equal to the structural strength. When increasing the structural strength, under other equal conditions, the depth of the deformation zone decreases. Figure 1 presents the relation diagrams of the residual values of settlement (*a*) and depth of the deformation zones *(b)* to the pressure.



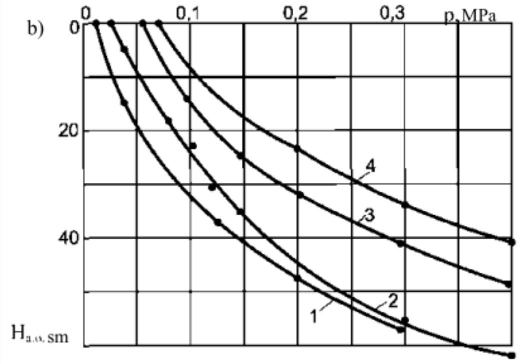


Figure 1. Charts of increase of residual settlement s_o (*a*) and the depth zone of residual deformations $H_{a.o}$ (*b*) from the pressure *p* (numbers show the number of experiments)

The lateral deformations arising under the influence of lateral pressure, within this phase is missing. Lateral pressure is balanced by the structural strength of the soil surrounding the compressed volume. The limit for the second phase is the pressure of the p_q, which lateral pressure *q* is the structural strength of the surrounding soil. In the second phase, at small values of residual settlements in the range of pressures from p_{str} to the p_q is a sharp increase in the depth of the zone of residual deformations. The process of compaction increases with depth without a lateral extension (see Figure 2).

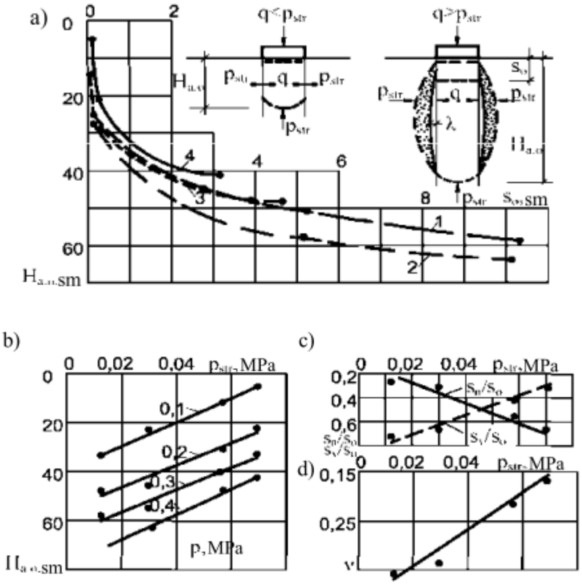


Figure 2. The influence of structural strength parameters of the stress-strain state of the soil at the base of the settlement plate: *a*) – the dependence of the depth of the zone of the residual deformations $H_{a.o}$ from residual component of settlement s_o; *b*) – the dependence of the depth of the zone $H_{a.o}$ of residual deformations from p_{str} ; *c*) – the influence on the interrelations p_{str} settlement caused by compact and lateral extension, *d*) – the dependence of the lateral expansion of p_{str}.

The third phase begins with the lateral pressure in excess of structural strength. The process of compact is accompanied by intensive cross-enlargement and change of compressed volume, which is taking form of a "barrel" (see Figure 3 and table 1) [3; 7; 9].

3. THE RESEARCH RESULTS

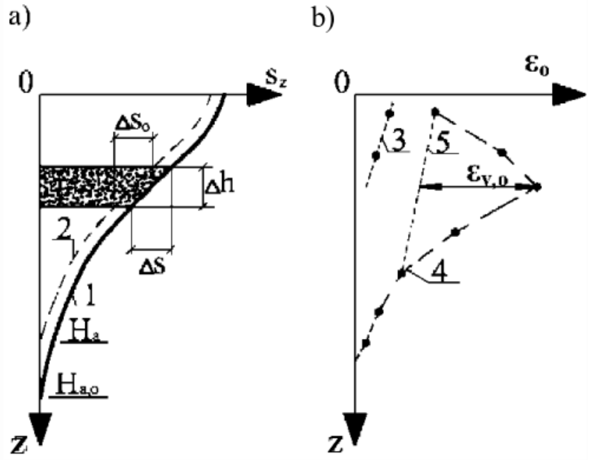
Consider the homogeneity of artificially prepared soil mass, assumption about the equality of structural strength in vertical and horizontal directions was accepted. According to results of measurements of plate settlement and movements of the soil magnetic marks for each level of load the plots of complete (1) and residual (2) deformation in depth are drawn (Figure 3,a).

Table 1. The settings of the zones of residual deformations

Characteristics	Experiment №			
	1	2	3	4
p, MPa	0,3	0,4	0,4	0,4
p_{str}, MPa	0,012	0,03	0,057	0,07
p_q, MPa	0,03	0,075	0,142	0,175
ε_n	0,05	0,05	0,05	0,05
$H_{a.o}$ sm	59	63	48	41
s_o, sm	10,49	10,13	4,17	3,08
s_n, sm	2,95	3,15	2,4	2,05
s_v, sm	7,54	6,98	1,77	1,03
ν	0,36	0,34	0,21	0,17

Notes: 1) $\varepsilon_n=1-\rho_d/\rho_{d,com}$ 2) $\rho_{d,com}$ – the average value (half-sum) of the density of the skeleton under the foot and the settlement plate and on the bottom boundary of the residual strain. Its value is equal for all experiments 1,62 ± 0,005.

For each of compressible layer located between adjacent brands, by the relative value of residual deformations based on $\varepsilon_0=\Delta s_0/\Delta h$ is determined and their values plot relative deformations in depth were drawn. (Figure 3, b).



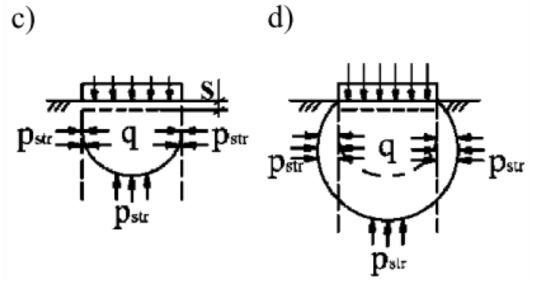


Figure 3. Plots: a) – complete (1) and residual (2) deformations of Foundation depth; b) – the relative values of residual deformations: (3) – in $q \le p_{str}$; (4) when $q > p_{str}$; schemes deformation of the soil when: $q \le p_{str}$ (*c*) and $q > p_{str}$ (*d*)

Residual deformations grow at pressures in excess of structural strength within the second and third phase of the stress-strain state of soil Foundation [6; 7]. Within the second phase, in the range of pressures $p_{str} \ge p_a$ deformation grow under the square settlement plate without lateral extensions compressible volume of soil (see Figure 3, b). The pressure *p* at the bottom of the settlement plate is the limit, in which lateral pressure *q* is the structural strength of the soil surrounding the compressed volume:

$$q=\xi\cdot p, \qquad (1)$$

ξ – coefficient of lateral pressure.

In this pressure range, plot layer relative strain has linear character (Figure 3, b, line 3).

Phase III is characterized by densification of compressible volume and its transverse extension. Bending of layers relative deformations diagram by layer depth occurs. Transverse expansion does not occur throughout the depth of the zone of residual deformations. It is not fixed in the immediate vicinity of the soles of the settlement plate and the bottom of the deformation zones.

Graphs of relative deformations demonstrate their value along the vertical axis *z*. If the relative deformation of the settlement is increasing in the vertical direction, the lateral expansion is the result of horizontal deformations resulting from changes in the volume of compacted soil - plastic deformations. In this article, plastic deformations are defined in the *z*-direction largest settlement resulting from transverse expansion.

On the chart full layered values relative deformations in depth is the line connecting the upper value at the foot of the settlement plate with the lower, the linear plot of land plots (Figure 3,b, line 5), which represents a plot of relative deformation of impaction. For all levels of load is determined by the maximum value of relative deformation transverse extensions $\varepsilon_{v.o}$. According to the results of definitions for each experience is built dependence $\varepsilon_{v.o}= f\ (p)$. Its intersection with the axis *p*, determines the maximum pressure at which the transverse component vertical pressure *q* equal structural strength. In this case, the coefficient of lateral pressure can be defined based on:

$$\xi = \frac{p_{str}}{p_q}, \text{ when } q = p_{str} \qquad (2)$$

4. ANALYSIS OF PROCESSING OF THE EXPERIMENTAL DATA

The results of four studies carried out in different time intervals after preparing of soil environment (volume) with broken structure are represented below. Figure 4 shows diagrams of relative deformation in depth in experiment №2, for the four stages of the load. Table 2 shows the results of definitions for the four experiments.

Table 2. The coordinates of the points dependency $\varepsilon_{v.o}=f(p)$

Maximum value of $\varepsilon_{v.o}$ for p, мPa	Experiment №			
	1	2	3	4
0,08	0,018	–	–	–
0,10	0,034	0,008	–	–
0,12	0,041	–	–	–
0,15	0,073	0,290	0,060	–
0,20	0,140	0,520	0,017	0,009
0,25	0,230	0,102	0,031	0,022
0,30	0,270	0,156	0,050	0,029
0,35	–	0,240	0,097	0,062
0,40	–	0,290	0,147	0,116

According to the obtained coordinates graphs of the relative transverse deformations expansion $\varepsilon_{v.o}$ from pressure on the sole Foundation shown in Figure 4, c. Their intersection with the axis p determines the magnitude of the pressure at which the lateral pressure q the structural strength, i.e. the extreme pressure on the soles of the basement, where there are no lateral deformation.

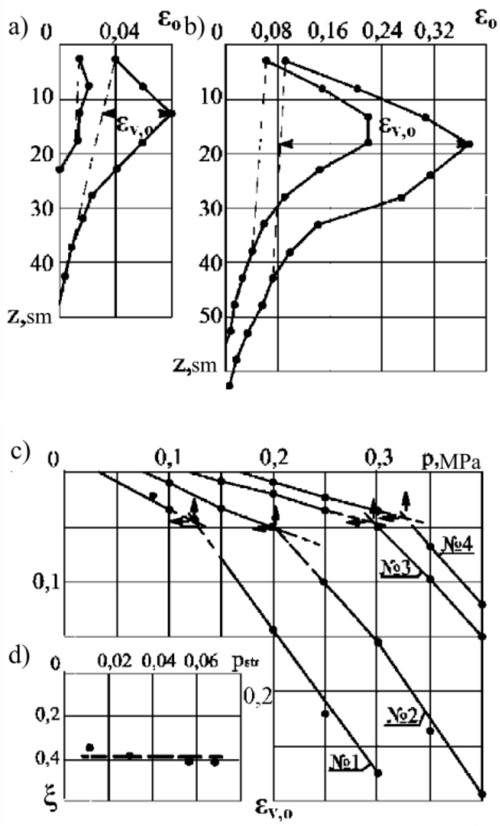


Figure 4. The graphs of dependencies:

a) and *b)* – relative deformations in depth at pressure 0,1; 0,2; 0,3 and 0,4 MPa in the experience №2;
c) – relative deformations $\varepsilon_{v,o}$ from the pressure on the soles of the settlement plate;
d) – coefficient of lateral pressure on the value of structural strength.

According to the graph, maximum values for each stage of $\varepsilon_{v,o}$ load are defined. Graphs of $\varepsilon_{v,o}= f(p)$ are characterized by a breakpoint. On the first curve of the graph with an equal increase in pressure increasing of the relative deformation less than on the second. This can be explained by a change in soil conditions during its deformation.

Table 3. The results of research of deformation properties of soil

Experiment №	t, months	Coordinates of breakpoint of $\varepsilon_{v.o}= f(p)$			
		p, MPa	$\varepsilon_{v.o}$	s_o, mm	$H_{a,o}$ sm
1	3	0,13	0,046	20	38
2	10	0,215	0,056	18	46
3	23	0,29	0,043	14	40
4	33	0,33	0,068	16	36

Continuation of the **Table 3.**

Experiment №	t, months	Parameters of deformation characteristics of soils				
		p_{str}, MPa	p_q, MPa	ξ	for p_q	
					s_o, mm	$H_{a,o}$ sm
1	3	0,012	0,035	0,34	0,9	15
2	10	0,03	0,08	0,38	1,1	19
3	23	0,057	0,135	0,42	2,9	21
4	33	0,070	0,171	0,41	2,0	20

In the initial state, the density of its skeleton – 1,54g/sm^3 at the degree of humidity of 0,87. At the breakpoint the density of the skeleton is about 1,6...1,63g/sm^3 at the degree of humidity, close to one. This reduces the permeability. All this may have an impact on the increase in increments of lateral deformation. This issue requires further research.

In Figure 4 showed the results of field researches on determination of the coefficient of lateral pressure that indicate close agreement with the data of its determination for loess soils obtained in laboratory conditions [3].

The second series of field works on determination of the lateral pressure, are carried out in the upper layer of the weak water-saturated soils of the Odessa region. The article analyzes the results of six tests: three in the top part of water-saturated sandy loam and three – on the "spot" of the settlement plate with the area of $1\ м^2$ after it test steps up pressure on the sole of 0,4 MPa at the site which was used heavy compaction (Figure 5) [5, 6, 7].

The research results are presented in figures 6; 7; 8 and in tables 4 and 5. Diagrams of full and residual values of settlement and depth of the zone of deformation on pressure in close values of structural strength and different density of the soil skeleton is shown in Figures 6, *a* and 6, *b*.

The intersection of their residual values with the axis of pressure determines the value of structural strength, its value accepted as average.

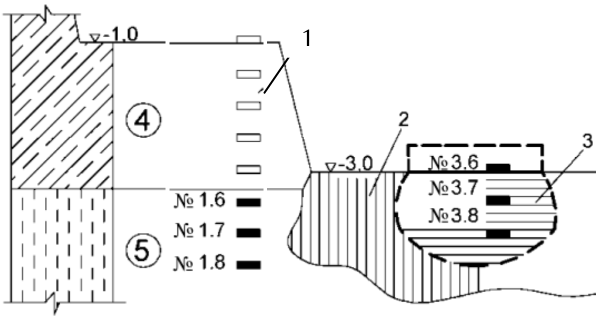


Figure 5. Implementation scheme of field trials experienced settlement plates: 1 – natural soil; 2 – a ground condensed heavy compaction; 3 – same, after static load

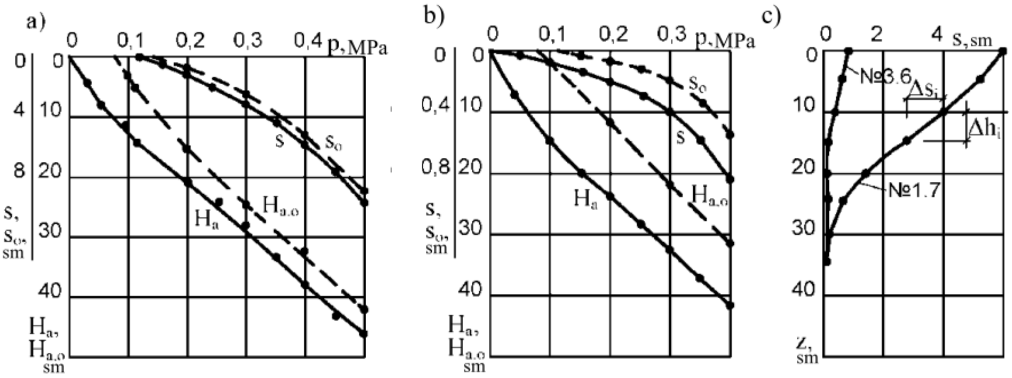


Figure 6. The results of soil tests: a) – the dependence of settlement and depth zone of complete and residual strains on the pressure in the experiment 1.7; b) – the same in experience 3.6; c) – plots of settlements at a pressure of 0,4 MPa on the sole of the settlement plate in the experiments № № 1.7 and 3.6

Figure 6,c shows plots of the complete settlements, determining the relative layered deformations for each interval of depths of ratios $\varepsilon_i = \Delta s_i / \Delta h_i$, the graphs of changes of which are given in Figures 7,a and 7,b. Figure 7,c shows the influence of the density of the skeleton of the soil on the magnitude and depth distribution of relative layered deformations.

Considering the assumption that the soil compaction layer relative deformations plot is linear by depth, it is possible to allocate a part of it, forming lateral extension (Figure 7c – $\varepsilon_{v.max}$) [7].

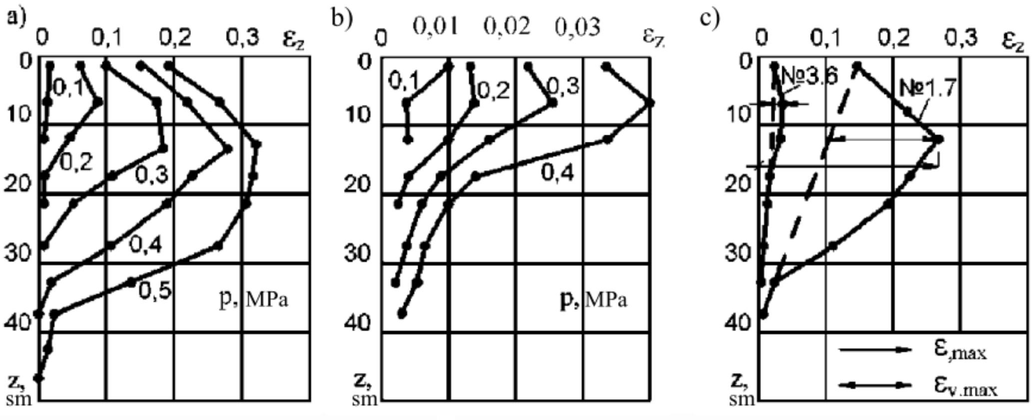


Figure 7. Change plots layer relative deformations ε_z in depth z with pressure increase in the experiments 1.7 (a) and 3.6 (b)b) – same, at pressure 0,4 MPa on the soles of the settlement plate in the experiments №№ 1.7 and 3.6.

Figure 8 shows the graphs of relative deformations relations maximum values to pressure on the bottom surface of the settlement plate. The intersection of the graphs with the axis pressure determines the load p_q, where there are no residual transverse deformation caused by the lateral pressure *q*, due to the resistance of the surrounding arrays, structural bond strength.

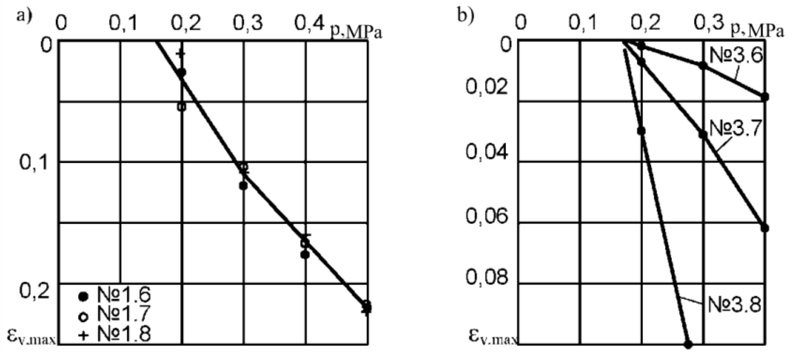


Figure 8. Scopes of depending maximum values $\varepsilon_{v,max}$ of relative deformations of pressure: a) – on a series of experiments on soils of natural structure (1.6 - 1.8), b) – artificially compacted soil (№ № 3.6 - 3.8)

It should be noted that here we conventionally accepted the equality of the magnitude of the structural strength in vertical and horizontal directions. For the three experiments on the soil of natural adding at the close values of structure strength and density of the skeleton, the relations are almost the same. The average value of the p_q for them is 0,165 MPa. These results are shown in Figure 8, and table 4. Data show that with the increase of density relative deformations values are reducing.

Table 4. The results of studies of the parameters of the stress-strain state of natural soil structure

Experiment №	$\rho_{d,}$ g/sm^3	$\rho_{d,com}$ g/sm^3	p_{str}, MPa	$\varepsilon_{v,max}$ for p, MPa				p_q, MPa for ε_{max}		ξ, for ε_{max}	
				0,2	0,3	0,4	0,5	ε_v	$\varepsilon_{v,o}$	ε_v	$\varepsilon_{v,o}$
1.6	1,4	1,71	0,1	0,03	0,12	0,18	0,22	0,18	0,17	0,56	0,59
1.7	1,41	1,70	0,09	0,06	0,11	0,177	0,22	0,15	0,14	0,47	0,50
1.8	1,39	1,70	0,08	0,01	0,115	0,16	0,225	0,18	0,17	0,50	0,53

Studies carried out on the soil, subjected to dynamic and static compaction is shown in Figure 8, b and table 5. Crossing the obtained dependences with the axis pressures defines the value of the vertical pressure at which the horizontal component of the balanced structural strength of the surrounding array of ground.

Consider that the lateral pressure coefficient is the ratio of lateral pressure q and the corresponding pressure on the bottom surface of plate p_q, the absence of the transverse deformations of the expansion in $q = p_{str}$ the ratio of the transverse expansion adopted by the ratio:

$$\xi = p_{str}/p_q, p_{str} \quad (3)$$

where is p_{str} determined from diagram of the residual values of settlement and depth of the deformation zone of the pressure (Figures 6a and 6b), and p_q is determined by relation diagram of the layer relative deformation by depth to pressure.

Table 5. The results of studies of the parameters of the stress-strain state in compacted soils by heavy compaction under the "spot" experienced foundation

Experiment №	$\rho_{d,}$ g/sm^3	$\rho_{d,com}$ g/sm^3	p_{str}, MPa	$\varepsilon_{v,max}$ for p, MPa			p_q, MPa for ε_{max}		ξ, for ε_{max}	
				0,2	0,3	0,4	ε_v	$_{v,o}$	$_v$	$_{v,o}$
3.6	1,65	1,67	0,093	0,003	0,009	0,018	0,16	0,15	0,58	0,61
3.7	1,52	1,58	0,077	0,008	0,03	0,064	0,16	0,15	0,48	0,51
3.8	1,45	1,50	0,073	0,03	0,12	–	0,165	0,15	0,44	0,46

5. CONCLUSIONS

1. Under the influence of external load the soil below the bottom surface of the Foundation (settlement plate) is deforming. Deformations are observed within a limited compressed volume: from above - the sole Foundation, with a perimeter of vertical surface; in his path bottom border of the zone of deformation.

2. In the graphs of the relation of settlement and the pressure three phases are characterizing the peculiarities of deformation of soils observed:

2.1. Within the first phase relation is close to linear and reflects mainly elastic deformation. Settlement is a result of the compression of soils without destroying the structural connections.

2.2. Within the second phase, along with elastic, there is a residual deformation due to soil compaction. The compaction occurs within compressed volume. Transverse expansion is prevented by the structural strength of the surrounding ground.

2.3. Within the third phase, elastic deformation, compaction deformation and lateral extension are observed. Lateral expansion occurs when the lateral pressure is exceeding the structural strength of the surrounding soil. Its consequence is the side bulge, beyond the bounding surface of compressed volume. Around the bulge surface secondary settlement area is formed.

6. REFERENCES

[1] Gersevanov, N.M.: Opyt primenenija teorii uprugosti k opredeleniju dopuskaemyh nagruzok na osnove jeksperimental'nyh rabot, Trudy MIITa. Vypusk 15., 1930.

[2] Gersevanov, N.M.; Pol'shin, D.E.: Teoreticheskie osnovy mehaniki gruntov i ih prakticheskie primenenija, Strojizdat, Moskva, 1948.

[3] Grigorjan, A.A.: O bokovom davlenii v lessovyh gruntah, Osnovanija fundamenty i mehanika gruntov, №4., 1960., 20 – 21

[4] Cytovich, N.A.: Voprosy teorii i praktiki stroitel'stva na slabyh vodonasyshhennyh gruntah., Tallin, 1965., 5 – 17

[5] Tugaenko, Ju.F.; Marchenko M.V.: Metodika opredelenija parametrov deformacij glinistyh gruntov, Inzhenernaja geologija, №1., AN SSSR, 1984., 86 – 94

[6] Tugaenko, Ju.F.; Marchenko, M.V.: Nekotorye osobennosti razvitija deformacij v osnovanijah opytnyh fundamentov, Inzhenernaja geologija, №3., AN SSSR, 1988., 46 – 54

[7] Tugaenko, Ju.F.: Transformacija naprjazhenno-deformiruemogo sostojanija gruntov osnovanija i ee uchet pri proektirovanii fundamentov, Astroprint , Odessa, 2011.

[8] Tugaenko, Ju.F.; Stojanova, T.I.; Marchenko, V.M.; Tkalich, A.P.: Avtorskoe svidetel'stvo SSSR 1065531, Glubinnaja marka, Zajavl. 6.04.82; Bjul. №1, Opubl. 07.01.1984.

[9] Marchenko, M.V.; Vojtenko, I.V.; Mosicheva, I.I.; Rabochaja, T.V.; Marchenko, A.M.: Korreljacionnaja svjaz' pokazatelej szhimaemosti i kojefficienta Puassona v slabyh gruntah, Problemy mehaniki gruntov i fundamentostroenija v slozhnyh gruntovyh uslovijah, Tr. Mezhdunarodnoj nauch.-tehn. konf., T. 3., BashNIIstroj, Ufa:, 2006., 189-194.

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