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CALCULATION MODEL OF DEFORMATION OF THE SOIL FOUNDATION OF A HIGH-RISE BUILDING, TAKING INTO ACCOUNT THE LOADING HISTORY

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Abstract: While designing high-rise buildings, it is necessary to take into account the influence of stages of their erection, this is the sequence of loading, on the change in physical-mechanical properties of soils. The calculation of deformations of subgrade is made with due regard for the change in soils properties comparing with the initial (natural) state. On the basis of the results of experimental studies, the authors substantiate the necessity for introducing the new parameter which makes it possible to characterize the mechanical condition of the soil at any stage of loading and can be used for creating calculation models. An analytical diagram of soil deformation in coordinates «σ_1–ε_1» for triaxial compression (where σ_1 – vertical stresses (deviator), ε_1 – linear deformations under the triaxial compression) is adopted as this parameter. The procedure for constructing transformed diagrams of the soil state under the long performance triaxial loading is described. The procedure obtained was approbated when calculating deformations of the foundation base of the high-rise building with due regard for the influence of staging of construction and rheological properties of soils on the change in the base rigidity and, as a result, on the redistribution of stresses among separate elements of the system “subgrade –foundation – upper part of the building.

Keywords: long regime triaxial loading, analytical diagram of soil deformation, coefficient of subgrade resistance, settlement calculation, high-rise building

РАСЧЕТНАЯ МОДЕЛЬ ДЕФОРМИРОВАНИЯ ГРУНТОВОГО ОСНОВАНИЯ ВЫСОТНОГО ЗДАНИЯ С УЧЕТОМ ПРЕДЫСТОРИИ ЗАГРУЖЕНИЯ

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Аннотация: при проектировании высотных зданий необходимо учитывать влияние этапов их возведения, т. е. последовательности загружения основания, на изменение физико-механических свойств грунтов оснований. Расчет деформаций оснований фундаментов следует выполнять с учетом изменения свойств грунтов по сравнению с первоначальным (природным) состоянием. По результатам экспериментальных исследований авторами обоснована необходимость введения нового параметра, который позволил бы охарактеризовать механическое состояние грунта на любом этапе нагружения и мог использоваться при создании расчетных моделей. В качестве такого параметра принимается аналитическая диаграмма деформирования грунта в координатах σ_1–ε_1 для трехосного сжатия (где σ_1 – вертикальные напряжения (девиатор), ε_1 – линейные деформации при трехосном сжатии). Описана методика построения трансформированных диаграмм состояния грунта при длительном режимном трехосном нагружении. Полученная методика была апробирована при расчете деформаций основания фундамента высотного здания с учетом влияния этапности строительства и реологических свойств грунтов на изменение жесткости основания и, как следствие, на перераспределение усилий между отдельными элементами системы «грунтовое основание – фундамент – надземная часть здания».

Ключевые слова: длительное режимное трехосное нагружение, аналитическая диаграмма деформирования грунта, коэффициент постели, расчет осадки, высотное здание.

INTRODUCTION

Soil bases of foundations of buildings and structures are exposed to various static and dynamic loads under various combinations of these loads. The existing methods of deformation calculation of foundations are developed for a single short-term static loading with constant parameters for the entire period of operation. In real conditions of construction and operation, the loads on the soil foundation are applied in stages as the building or structure is erected [1-5]. In this case, the stages of active loading during the construction period pass into the stages of long-term holding under loading.

Experimental studies (Fig. 1, 2) carried out by the authors [6-7] show that the nature of changes in soil deformations under long-term regime loading differs significantly from the results obtained under short-term static loading, which are the basis for the existing methods of settlement calculation. In this regard, there is a need to improve the methodology for calculating settlement of foundations of buildings with a developed underground part. This task is especially relevant for the foundations of high-rise buildings composed of clayey soils, the stress-strain state of which changes in time and depends on the history of previous loading [1-5].

In addition, in accordance with modern requirements, the calculation of the bases of high-rise buildings should be performed taking into account the joint deformation of the system "subgrade – building", i. e. deformations (settlement) of the subgrade of such a building should be calculated taking into account the influence of the stiffness of the elevated part of the building.

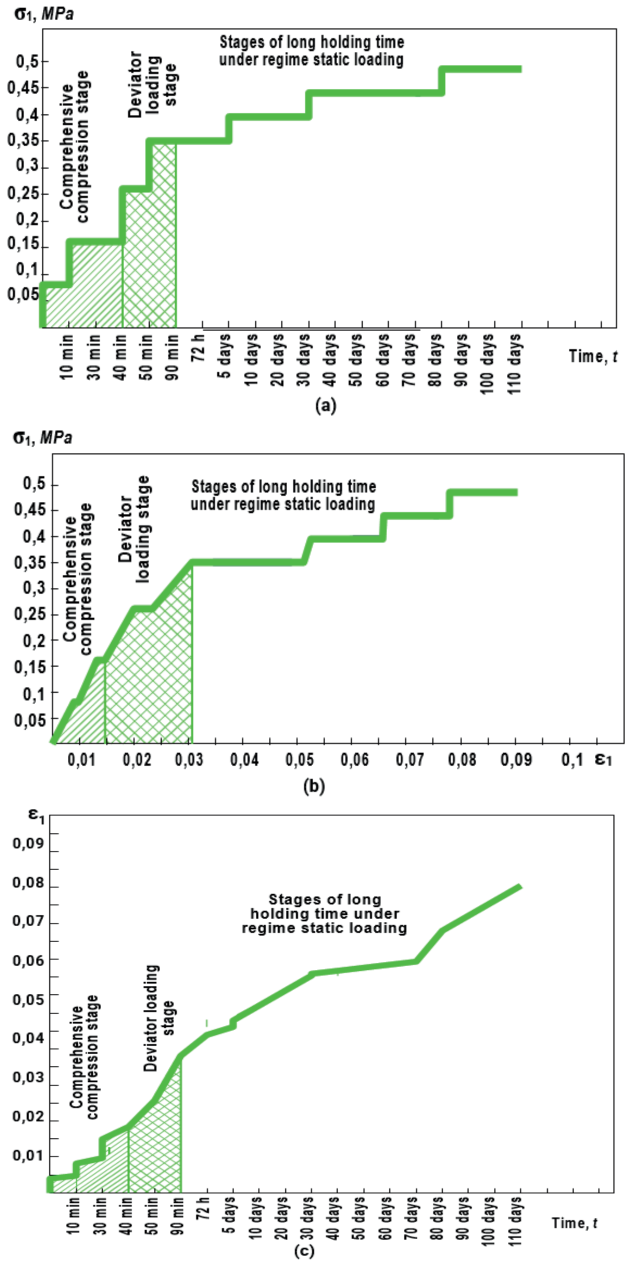

Figure 1. Results of experimental studies: a - regime of loading; b - dependence between average stresses σ_1 and relative linear strains ε_1; c - development of relative linear strains in time

MATERIALS AND METHODS

To calculate the settlement of a high-rise building taking into account the joint deformation of the above-mentioned system, the modified Pasternak method [8] was used as a basis, taking into account the spatial stress-strain state of the base soils and changes in the rheological properties of soils under long-term regime loading.

As it is known, Pasternak's method [9] describes the performance of the soil by means of compression coefficient C_1, which relates the intensity of vertical soil pushback to its settlement, and shear coefficient C_2, which characterizes the vertical shear forces arising in loose and loosely cohesive soils due to entanglement and internal friction between its particles. These coefficients were determined according to the equation:

$$C_1 = \frac{E_{gr}}{H_c(1-2\mu_{gr})};\ C_2 = \frac{C_1 \cdot H_c(1-2\mu_{gr})}{6(1+\mu_{gr})}. \quad (1)$$

Where is the Poisson's coefficient within the compressed layer:

$$\mu_{gr} = \frac{\sum_{i=1}^{n} \mu_i \cdot h_i}{H_c}. \quad (2)$$

When using the modified Pasternak method [6], the coefficients of subgrade resistance C_1 and C_2 were also determined according to equation (1), but to determine the average strain modulus, a correction factor u was introduced to the value of the strain modulus of the i-th sublayer. This coefficient varied according to the law of a square parabola from u = 1 at the level of the foundation footing to u = 12 at the level of the already calculated boundary of the compressible strata and was determined by the equation:

$$u = \frac{11Z^2}{H_c^2} + 1. \quad (3)$$

At the same time, the modulus of deformation of the base was calculated:

$$E_{gr} = \frac{H_c}{\sum_{i=1}^{n} \frac{h_i}{u_i \cdot E_i}}. \quad (4)$$

The authors propose to modify the modified Pasternak model. In this case, the pliable properties of base soils under such regimes are taken into account in the model by means of coefficients of subgrade resistance C_1 and C_2 variable in time, depth and in plan:

$$C_1 = \frac{E_1(t,\tau)}{H_c(1-2\mu_{gr})};\ C_2 = \frac{C_1 \cdot H_c(1-2\mu_{gr})}{6(1+\mu_{gr})} \quad (5)$$

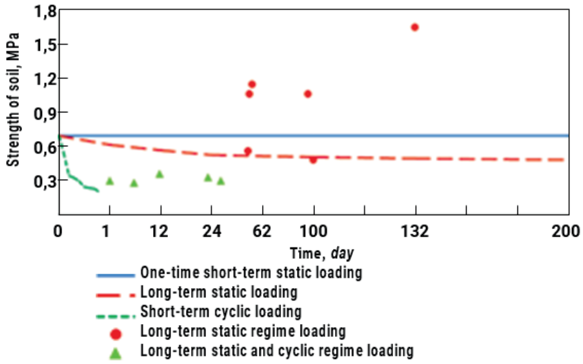

Figure 2. Variation of soil strength under different loading regimes

It is proposed to determine the deformation modulus at each point of the compressible layer on the basis of transformed deformation diagrams by the expression:

$$E_1(t,\tau) = \frac{\Delta\sigma_{1i}(t,\tau)}{\varepsilon_{1i}(t,\tau)}. \quad (6)$$

Then the soil deformation modulus for determining the variable bedding coefficient should be calculated by the equation:

$$E_1(t,\tau) = \frac{H_c}{\sum_{i=1}^{n} \frac{h_i}{E_{1i}(t,\tau)}}. \quad (7)$$

Variability coefficients of subgrade resistance is substantiated by the results of experimental studies (Figs. 1, 2) and the calculation model developed by the authors [6-7]; it was found that under step-by-step loading, all the bases of parameters characterizing the stressed and deformed state of soils change in time, which allows us to conclude that it is necessary to develop a new parameter that would characterize the mechanical state of the soil at any stage of loading and could be used to create calculation models. The analytical diagram of soil deformation in coordinates σ -ε for triaxial compression is taken as such a parameter (where σ_1, ε_1 are vertical stresses (deviator) and linear strains in triaxial compression).

Based on the obtained graphs (Fig. 1), the initial diagrams (state diagrams) of soil deformation under short-term triaxial static loading are constructed. The value of temporary resistance $\sigma_1 = R_{gr,u}$ (deviator) of the soil is taken as the limit point in coordinates (σ). Under triaxial short-term static compression.

The limit point on the ordinate axis (ε) is taken as the value of linear strain ε_{u1}=0,0869. Types of diagrams are presented in Fig. 3.

When considering the state diagrams of clayey soil under triaxial long-term static loading, the deformation diagrams σ_1-ε_1 for the case of triaxial short-term static loading are used as initial ones. By transforming the initial state diagram under triaxial short-term static loading, we obtain analytical dependences to describe the deformation diagrams of clayey soil under triaxial long-term static loading. In form, the transformed diagrams are assumed to be similar to the original state diagram on the basis of the following provisions (Fig. 3).

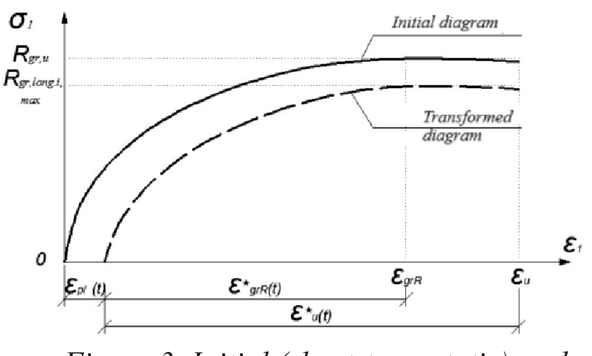

Figure 3. Initial (short-term static) and transformed (long-term static) analytical diagrams

The limiting point of vertical pressure at the top of the diagram is taken to be the stress in the soil, which is equal to the limit of long-term resistance under triaxial load action $R_{gr,long}$=(t,τ) and deformations corresponding to the deformations at the top of the state diagram under triaxial short-term static loading $\varepsilon_{gru,red}=\varepsilon_{gru}$;

For the limiting point defining the boundaries of the state diagrams along the ordinate axis, the deformations are equal to the limiting deformations under triaxial short-term static loading $\varepsilon_{gr,red}=\varepsilon_{gr,R}$, and the basic dependencies are used to calculate the stresses in the soil;

The start of the diagram coordinates is assumed to be shifted by the value equal to the creep deformation at the considered time ε_{pl} (t) - at long static loading;

The obtained slope angles of deformation diagrams are taken into account the change in the deformation modulus of clayey soil under triaxial long-term static loading.

In the next step, the diagram is transformed for each block long-term loading block (Fig. 4).

When describing soil deformation modes under triaxial loading, it is necessary to take into account the effect of vertical pressure (σ_1) of the previous block on the strength, strain modulus and relative strains at the top of the diagram during subsequent loading after the regime change.

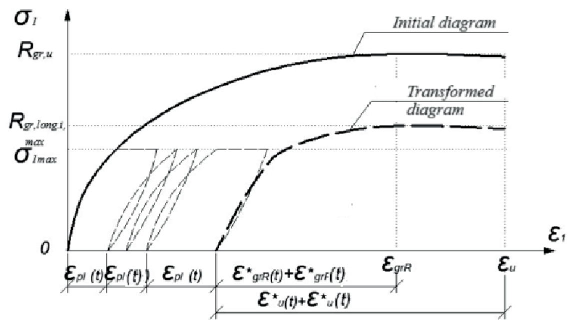

Figure 4. Initial (short-term static) and transformed (regime long-term static) analytical diagrams

On the basis of the obtained transformed analytical deformation diagrams, a method of calculating settlements of foundations of high-rise buildings has been developed, which is based on the method of layer-by-layer summation taking into account changes in the spatial stress-strain state of soils in the process of triaxial regime long-term static loading.

Based on the values obtained from the diagrams, the modulus of total soil deformations at each point of the foundation is determined (Fig. 5), and then the value of coefficient of subgrade resistance for each point is specified.

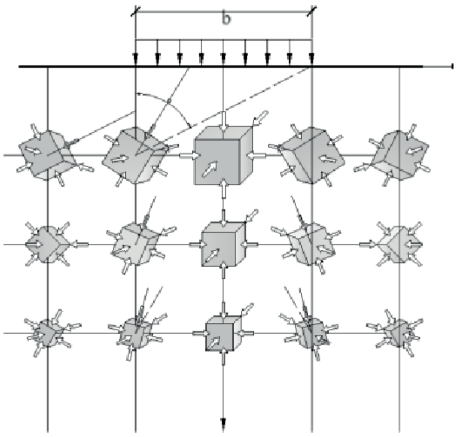

Figure 5. Spatial stress-strain state of the soil

The proposed methodology was used in the calculation of the foundation settlement of a high-rise building, which has a frame-wall system, made of monolithic reinforced concrete and has the following parameters: total height 144.9 m (39 floors); number of underground floors 4; foundation depth 15.15 m; area of foundation 1377 m^2; columns, internal and external walls of the underground part are made with concrete class B40, floor slabs B30, staircases and flights - B25; the building has a distributing technical floor with a 2100 mm thick floor slab, providing load transfer from the above-ground part to the underground part; the thickness of the foundation slab is 2000 mm (Fig. 6). Physical and mechanical characteristics of engineering and geological elements of the base are given in Table 1.

Table1. Characteristics of foundation soils

№ layer	Type of soil	ρ, kg/m^3	*E*, MPa	φ, grad	*C*, kPa
Layer-6	Dense dusty sands	2030	32	36	4
Layer-7	Semi-solid clay	1960	23	23	67
Layer-8	Tightly plastic clay	1940	22	26	43
Layer-9	Solid clay	1720	25	19	86

Taking into account that after 35 and 45 months from the beginning of construction the load from the building was 75% of the full load, the following loads were taken into account in the calculation: standard load on the typical upper floor taking into account the weight of load-bearing structures 13.65 kPa; standard load on the underground floor taking into account the weight of load-bearing structures 14.35 kPa; total weight of the building without taking into account the weight of the foundation 82620 t; average pressure at the bottom of the foundation without taking into account its weight 60 t/m2; average pressure under the bottom of the foundation taking into account the weight of the foundation and the floor 64.59 t/m2. Wind pressure was not taken into account.

The settlement was calculated using the LIRA-SAP 2014 software program, which implements the finite element method [7]. At the same time, a spatial model of the whole building was created in the program structure to automatically transfer the load "base".

In the vicinity of the investigated building there is an enclosing structure in the form of a monolithic reinforced concrete "wall in the soil" 0.8 m thick and 35 m deep, providing stability of the excavation walls during the zero cycle works (Fig. 6). Taking into account that the soils below the foundation footing in the wall-in-soil zone are in constricted conditions and are subjected to greater lateral pressure during the application of vertical loads from the building, it can be assumed that the compressibility parameters of the soils will be variable. In the calculation, this was taken into account by introducing different bedding coefficients under the main area of the foundation and the zone of influence of the wall.

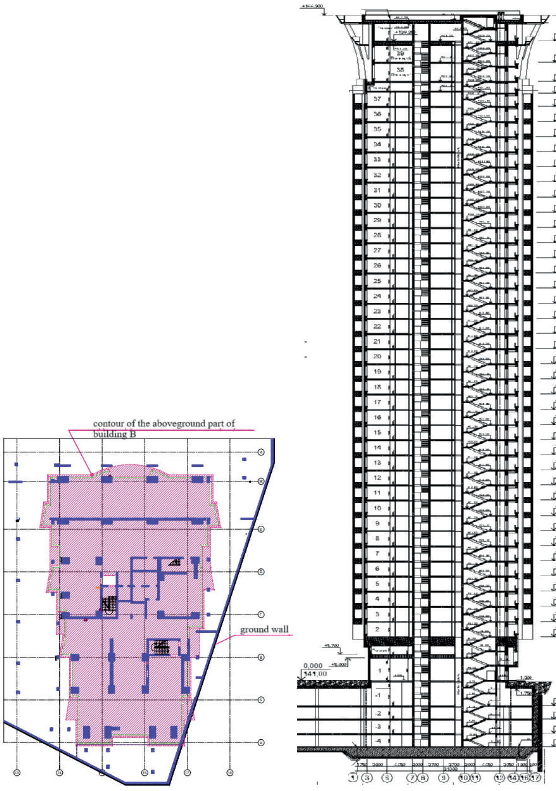

Figure 6. High-rise building of a residential (plan and section)

RESULTS AND DISCUSSIONS

The above-mentioned soil model under triaxial loading was used, taking into account the change of horizontal stresses σ_x and σ_y due to the influence of the excavation enclosing wall. The obtained calculation results are shown in Table 2 and Fig. 7.

Table2. Settlements and inclinations of foundation

N	S_{av}, mm	S_{max}, mm	S_{min}, mm	i
1	137	145	129,7	0,00026
2	135,96	147,29	124,63	0,00038
3	215	226	205	0,00035
4	214	235	193	0,00073
5	242,3	254,7	231,04	0,00035
6	241,18	264,85	217,5	0,00073

Where S_{av}, S_{max}, S_{min}, i – average, maximal, minimal settlement and inclination of foundation; 1 – in 45 month without taking into account the slurry wall and 75% of load; 2 – in 45 month with taking into account the slurry wall and 75% of load; 3 - in 45 month without taking into account the slurry wall and 100% of load; 4 – in 45 month with taking into account the slurry wall and 100% of load, 5 – in 100 years without taking into account the slurry wall and 100% of load; 6 – in 100 years with taking into account the slurry wall and 100% of load.

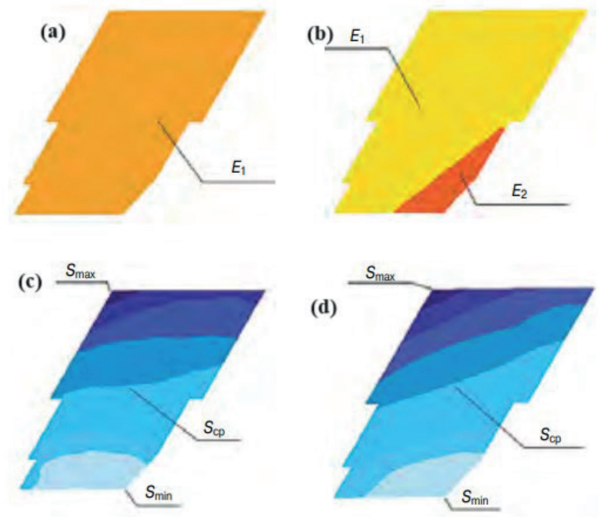

Figure. 7. Calculation results: a - calculated distribution of coefficients of subgrade resistance without taking into account the "slurry wall"; b - the same with taking into account the "slurry wall"; c, d - characteristic picture of vertical displacements of the foundation slab and the base without and with taking into account the influence of the "slurry wall"

The analysis of the results showed that the picture of foundation deformation changes qualitatively when the "slurry wall" operation is taken into account. At the same time, there is a good convergence of the calculated results with the data of geotechnical monitoring. In 45 months since construction, the deviation of the calculated values from the monitoring data on the average settlement was no more than 13%.

CONCLUSIONS

1. The methodology of calculation of deformations of high-rise buildings foundations taking into account the stage of building erection with the use of analytical diagrams of soil deformation under long-term triaxial regime loading has been developed.
2. The testing of the proposed methodology for calculating foundation settlement of a high-rise building on the basis of analytical diagrams of soil deformation allowed us to obtain calculation results with good convergence with the monitoring data. The deviation of the calculated average settlement from the real one was no more than 1% and no more than 13% with the data obtained for 35 and 45 months of monitoring, respectively.

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