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FORMATION OF THE FOUNDATIONS STRESS-STRAIN STATE FROM THE LOCATION CHANGE AND PILES PARAMETERS

The work of high-rise buildings with different piles arrangement foundations is investigated rationally and on a regular grid. The comparative analysis of the results is presented. Typical zones of foundation such as central, lateral, and angular ones are separated. The redistribution of efforts between piles and a grillage is shown. The interaction of piles with different lengths and the grillage in the foundations of high-rise buildings is considered. The numerical modeling of the «base – foundation – superstructure» system is performed. A finite-element model of high-rise buildings comples and a multilayer soil mass is developed. The choice of soil parameters for the deformation model of soil environment on the basis of their identification is shown.

Comparative results of calculations with data of field observations on bearing structures behaviour. The features of buildings complex base deformation are revealed.

***Keywords**: pile foundation, high-rise buildings, location of piles, piles with different lengths, numerical modeling.*

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ФОРМУВАННЯ НАПРУЖЕНО-ДЕФОРМОВАНОГО СТАНУ ФУНДАМЕНТІВ ПРИ ЗМІНІ РОЗТАШУВАННЯ ТА ПАРАМЕТРІВ ПАЛЬ

Досліджено роботу фундаментів висотних будинків при різному розташуванні паль: раціонально та за регулярною сіткою. Наведено порівняльний аналіз результатів. Виділено характерні зони у фундаменті: це центральні, бічні й кутові. Виявлено перерозподіл зусиль між палями і ростверком. Розглянуто взаємодію паль різної довжини й ростверків у фундаментах висотних будівель. Дослідження проведено за допомогою числового моделювання системи «основа – фундаменти – надземні конструкції». Розроблено скінченно - елементну модель комплексу висотних будинків та багатошарового ґрунтового масиву. Показано вибір параметрів ґрунтів для моделі деформування ґрунтового середовища на основі їх ідентифікації. Порівняно результати розрахунків з даними натурних спостережень за поведінкою несучих конструкцій. Виявлено особливості деформування основи комплексу висотних будинків.

***Ключові слова:** пальовий фундамент, висотні будівлі, розташування паль, палі різної довжини, числове моделювання.*

Introduction. High-rise buildings are widely spread in the urban development. Pile foundations are often used for high-rise buildings due to heavy load of superstructures on the base. In those cases, engineers are faced with a number of tasks: a) modern methods of structures calculation should be developed; b) computer aided design (CAD) systems should be used to solve various problems of geotechnics; c) various calculation models involving materials deformation and the soil base nonlinear laws should be applied.

Promising direction of the pile foundations design is increase in the economic efficiency and the reliability of design solutions due to the use of a rational number of piles and the efficient use of their supporting ability. For this purpose, changes in a stress-strain state of the «base – foundation – superstructure» system with different numbers of piles, their different locations, and their different lengths must be simulated with regard for the actual parameters of a soil base, be carried out monitoring of bearing structures, be compared them with the results of calculations for accumulation of design experience.

Review of the latest research sources and publications. Often, piles are arranged on a regular grid in the foundation [1, 4, 8], considering that the foundation plate combines piles and evenly distributes the load between them above superstructures. But the design experience shows that it is not true. For example, A. Bartolomei in his works [4] notes that when loading on a group of piles, which is about to the boundary, the angular piles perceive 20% more than the middle pile of the extreme series, and 50% more than the central piles. This fact, he explains, that the friction forces are larger at the lateral surface of the angular piles than at the other piles of the foundation. Many scientists were engaged in research on the location of piles and the distribution of load between them: A. Bartolomei [4], I. Boyko [1, 5], V. Holubkov, A. Pyliahyn [8], R. Katzenbach [2, 3] and other. In works R. Katzenbach [3] considered a high-rise building, in which the foundation was designed and built with piles of different lengths. In the works of I. Boyko [1, 5] there are highlighted the joint work of the system «base – foundation – superstructure» elements, identification of soil parameters, choice of the correct model of soil foundation deformation, monitoring of bearing structures behaviour. Several decades ago Nikolayevsky [6] raised the pressing questions about the choice of soil model and the complexity of soil parameters determination.

Definition of unsolved aspects of the problem. Choosing the location of piles in foundations requires a designer of an integrated approach and advanced knowledge not only from the field of geotechnics, but also from the technology of laying foundation structures. Therefore, researching piles in the foundation is a difficult task. The rational position of the piles in the plan must be found, set their different lengths to align the internal efforts in the foundation and superstructure. In this paper, the results of the rational location of piles and on a regular grid are comparable, piles with different lengths are installed in zones of maximum efforts, identification of soil parameters is shown, the results of calculations are compared with the data of experimental observations. A detailed analysis of the stress-strain state of foundation structures allows to design reliable and economical foundations.

Problem statement. Purpose is to study the redistribution of the efforts in piles depending on the location of piles and their length. Changes in the stress-strain state of a pile foundation with short and long piles will be determined. The interaction of the pile foundation with the base within a model taken for calculations will be analyzed.

Calculations of a stress-strain state of building bearing structures with the soil base are performed by the finite-element method (FEM) in the three-dimensional statement with the use of the software «VESNA».

In simulation of soils deformation it is used a model of nonlinear elastoplastic soil medium based on the theory of dilatancy [6]. The non-associated law of plastic flow is used to determine the increment of plastic strains. The Mises-Guber criterion modified by Professor I.

Boyko [1] is used as the condition of a plastic flow, which provides the agreement of the stimulation results with experimental data in a wide range of loads on the soil medium.

Basic material and results. High-rise buildings are often constructed on pile foundation joined by grillage. The interaction of these buildings with the soil base has a number of specific features. It depends, in the first turn, on the ratio of the grillage width and the pile length, on the dimensions of the grillage plate, and on the number and arrangement of piles in the foundation.

The design scheme includes all elements of the building as a «base – foundation – superstructure» system. The finite-element model includes the volumetric soil massif described according to geological studies, pile foundation, and bearing superstructure of the building (Fig. 1).

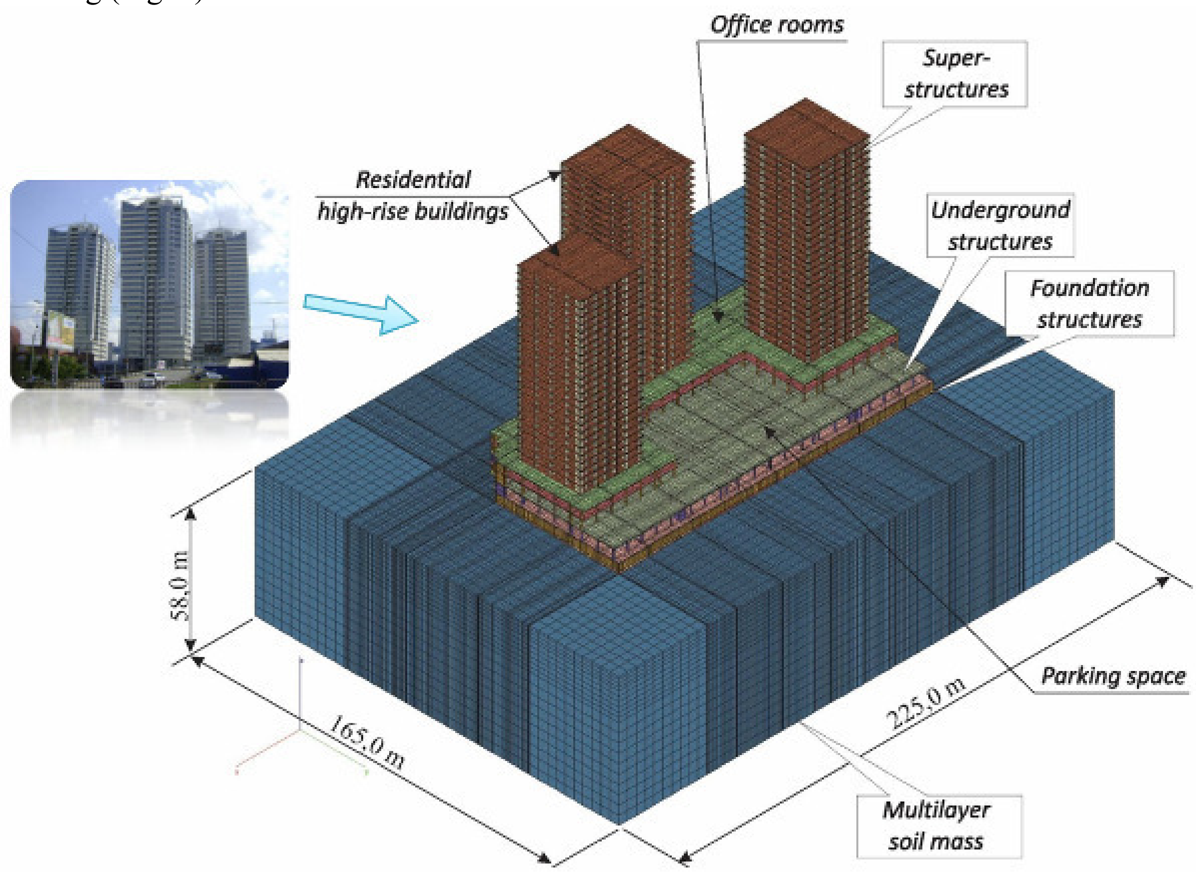

Figure 1 – Finite - element model of the building complex

The soil massif bottom is limited by a plane without vertical displacements (it is assumed that settlements of soil can be ignored at this depth). On the lateral planes, it was taken the boundary conditions that prevent normal displacements.

The location, capacity, and mechanical properties of soil layers correspond to the data of geotechnical studies.

The application of nonlinearly deformed soil base model results in the complexity of determination of many soil parameters that change during deformation. Standard methods of geotechnical investigations do not provide complete collection of soil parameters. Therefore, it is necessary to carry out additional studies and to implement the interpretation of parameters. Considering these facts, it is presented the results of piles tests as a «load – settlement» plot (Fig. 2) [7]. According to it, it is executed the modeling of piles tests, as well as the identification of parameters for the accepted model of soil medium deformation. It allowed to obtain the specified values of stresses in soil and the redistribution of efforts in foundation.

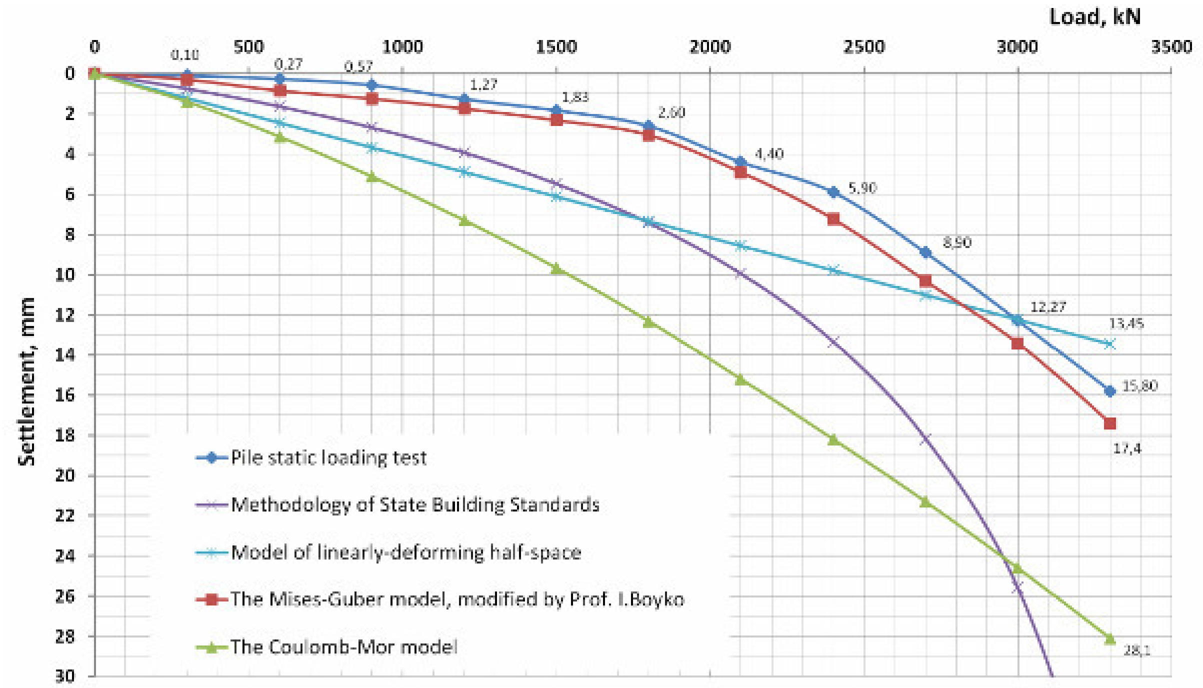

Figure 2 – Graph of «loading-settlement» of experimental pile using different soil models

As it is known, piles in a pile foundation are not equally loaded. It is confirmed by experimental data [3, 4] and the results of numerical modeling [5, 9]. In those works, it was noted that the piles of marginal zones are loaded most of all, and the load on the piles of central zones is the least. It depends on many factors, one of which is the location of piles within the grillage. In practice, location of piles on a regular grid with a given step can be observed very often. This choice is proper only at first sight. In fact, it has several drawbacks: peripheral piles are overloaded by 1.5-3 times as compared with the design load on a single pile, whereas the load on central piles, which share is about 50% in the foundation, is 50-60% of the design one on a single pile. It leads to a significant overspending of materials (concrete and reinforcement) in piles and, consequently, increases the cost of a construction. The approach for a nonlinear deformation of the soil base allows one to simulate a redistribution of efforts between piles, which are working up to the limit of their bearing capacity. The task of a designer is to find the optimal position of piles in the foundation. The typical zones of a foundation are angular, contour, and middle ones, where its piles work differently. The angular and contour zones together constitute the peripheral zone, which includes piles with the same name. In the middle zone, the middle piles and piles of the rigidity core are located (Fig. 3). It is noted that the lateral surface of peripheral piles works most efficiently. As for the middle piles, soil is clamped between the lateral surfaces of piles, which reduces or eliminates the lateral friction. Therefore, the middle piles are underloaded, and the peripheral piles are overloaded. In this case, the question arises about the efficient use of the bearing capacity of piles. It can be achieved by rational geometric arrangement of piles in the foundation (Fig.3,b). The criterion of rational location of piles is more uniform redistribution of efforts between the piles, providing the efficient use of piles material. Therefore, it is advisable to move the piles from the middle zone to the contour of the building and to dispose them under the load-bearing structures. This approach requires to increase the number of piles in peripheral zones and to reduce it in the middle zones. It increases the average distance between the piles, which leads to a more complete work of their lateral surface. An example of the problem and the main indicators are presented in Table 1.

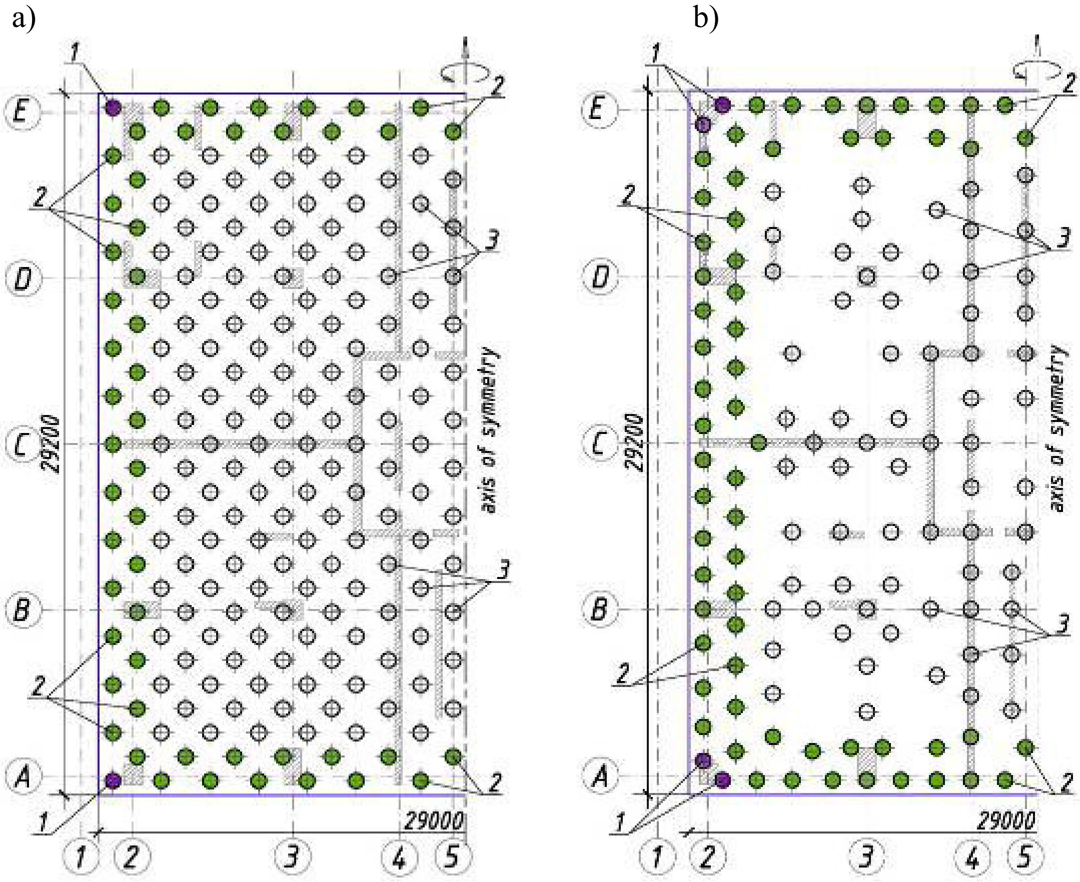

Figure 3 – Location of piles on a regular grid (a) and rationally (b) according to the zones: 1 – angular; 2 – contour; 3 – middle; (1+2) – peripheral

The executed studies showed that the angular piles and some contour ones, which are located on a regular grid, get loads that exceed their bearing capacity by ground and by material, which is unacceptable. The optimal arrangement of piles in plan was resulted in a more uniform redistribution of the efforts over foundation structures. In this case, the maximum effort in a pile decreases by 10-20%, and the minimum effort increases more than twice.

Table 1 – Comparison of the calculations results with different locations of piles

№	Indicator	Location of piles		Com-parison
		on a regular grid with given step	rational	
1	Total load of the building on the foundation, kN (%)	456 200 (100)		-
2	Load on the grillage, kN (%)	63 282.7 (13.9)	60 163.9 (13.2)	<1 %
3	Load on the piles, kN (%)	392 917.3 (86.1)	396 036.1 (86.8)	<1 %
4	Total number of piles, pcs (%)	392	252	↓ 140 pcs (↓ 35%)
5	Maximum effort in a pile, kN	3 729.6	3 470.0	↓ by 1.08 times
6	Average effort in a pile, kN	1 002.5	1 571.6	↑ by 1.57 times
7	Settlement of the grillage, cm	51.2	52.8	~3 %

Therefore, the efficiency of each pile bearing capacity use increases. The total number of piles can be reduced by 15-30% at their rational location, settlement of the foundation slab varies within 5%, and bending moments are changed within 10%. With such changes, the total bearing capacity of the foundation is not reduced.

Thus, the rational arrangement of piles makes it possible to efficiently distribute the load between the piles, to detect the zones of extreme internal efforts, and to make decision aimed at their reduction. It allows to design the reliable foundation constructions with optimum number of piles.

The investigation of stress-strain states of the «base – foundation – superstructure» system shows that the rational location of piles within the scope of a grillage gives the desired redistribution of efforts in piles not in all cases. The peripheral piles (especially, angular ones) remain problematic. In this connection, it is proposed to change the length of problematic piles for the regulation of efforts in them. It allows to use the bearing capacity of piles efficiently and to get optimal internal efforts in foundation structures. Indeed, the smaller the length of piles is, the less their bearing capacity is.

For this purpose, it is considered two variants with the variable lengths of piles: a foundation with shorter peripheral piles and a foundation with shorter middle piles (Fig. 4). These variants of foundations are compared with the foundation on piles with identical length. The results of calculations show a decrease in efforts in shorter piles comparatively with piles with identical length, that is logical. Therefore, short piles in the middle zone of a grillage are not recommended, because the peripheral piles are already overloaded. It is more efficient to reduce the length of piles in the peripheral zone. An example of such pile foundation variant is given by the high-rise building in Frankfurt-am-Main proposed by Professor R. Katzenbach et al. [3]. In the homogeneous basis, it was offered to arrange a pile field with significant increase in the length of piles to the building center.

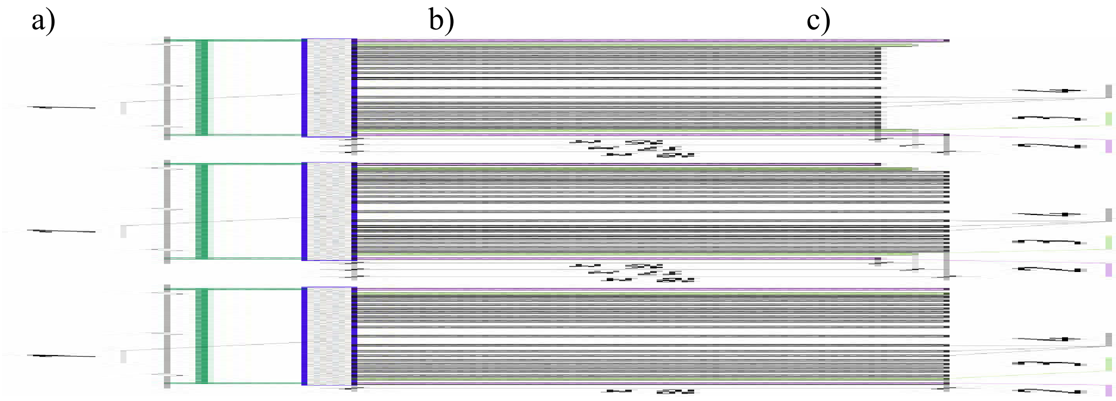

Figure 4 – Changing the length of piles within the typical zones of the foundation:
a) piles with identical length, b) shorter peripheral piles, c) shorter middle piles;
1 – grillage, 2 –peripheral piles of the 1st line, 3 – peripheral piles of the 2nd line, 4 –middle piles

The pile foundation with shorter peripheral piles allows reducing the effort in them up to 15% as compared with the foundation with piles with identical length (Fig. 5). The redistribution of efforts between the grillage and piles in two variants of foundations with shorter piles is almost unchanged on the whole or increases by about 1%. The change in the length of piles causes the increase in the settlement of a foundation plate within 5-6%. In general, the bearing capacity of the pile foundation remains unchanged. It is suggested that the rational choice of piles location in plan and of their lengths makes it possible to decrease the extreme values of internal efforts in the foundation structures and to reduce the total number of piles.

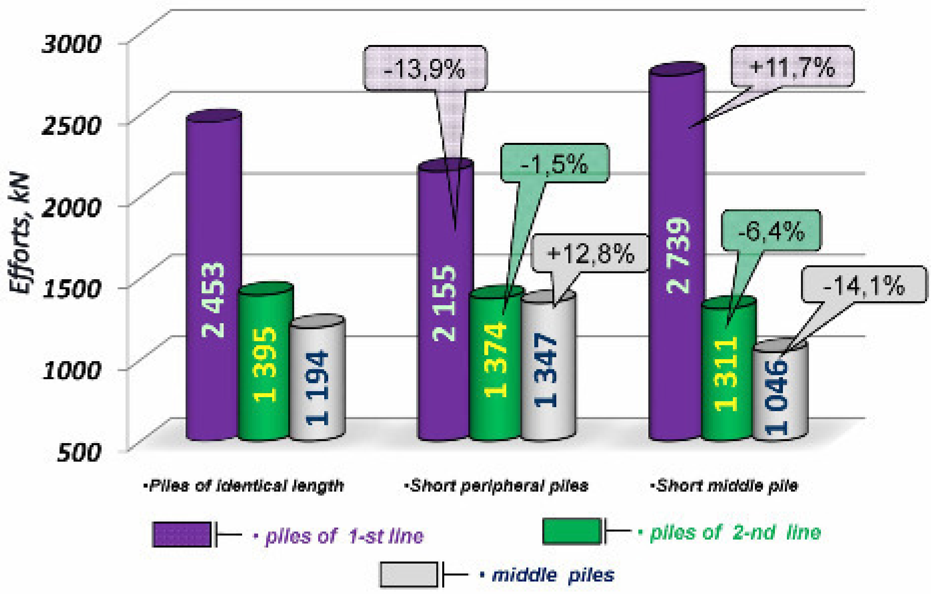

Figure 5 – Redistribution averaged efforts between piles depending on their length

After constructions calculations and their design, monitoring of the structures state in the process of buildings erection and at the stage of their operation is an important task. The results of experimental studies should be compared with the calculated values for the accumulation of design experience in difficult soil conditions, using rational location of piles (Fig. 6). At this facility, monitoring of bearing structures behavior at the construction stage was organized. The results are presented in Fig. 7.

The nature of settlements growth was confirmed by the actual observation, predicted in the simulation. The deviation between the experimental and calculated values of settlement is within the range of 6-25%, which satisfies the accepted accuracy. The difference between experimental and numerical deformations is explained by the fact that the actual load was not fully consistent with the design load at the time of the last measurement.

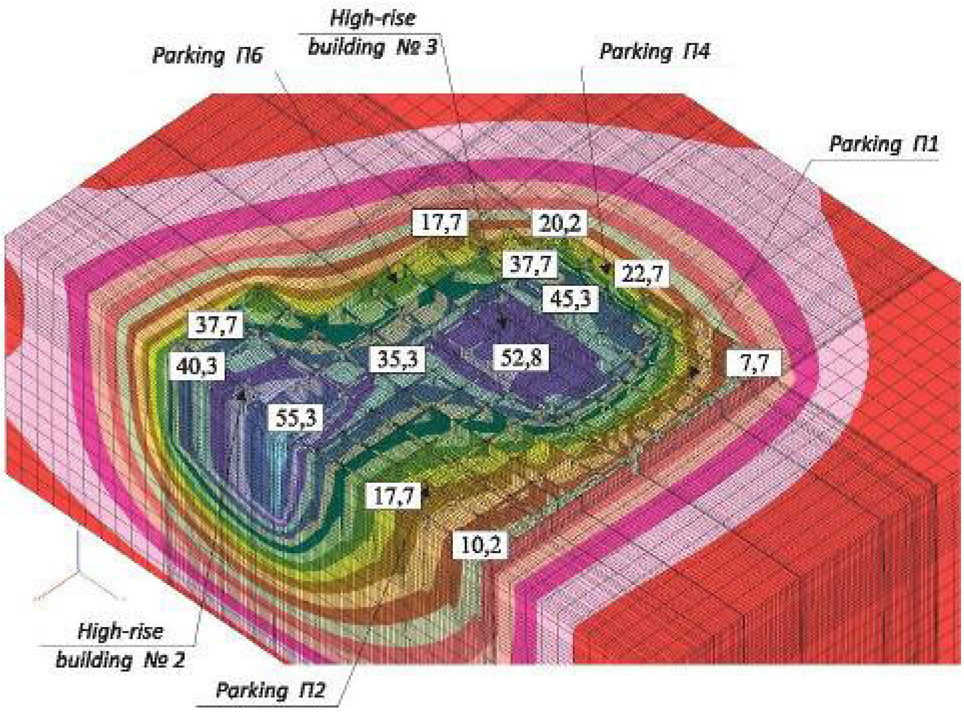

Figure 6 – The deformed scheme of the soil mass and basement part of the complex

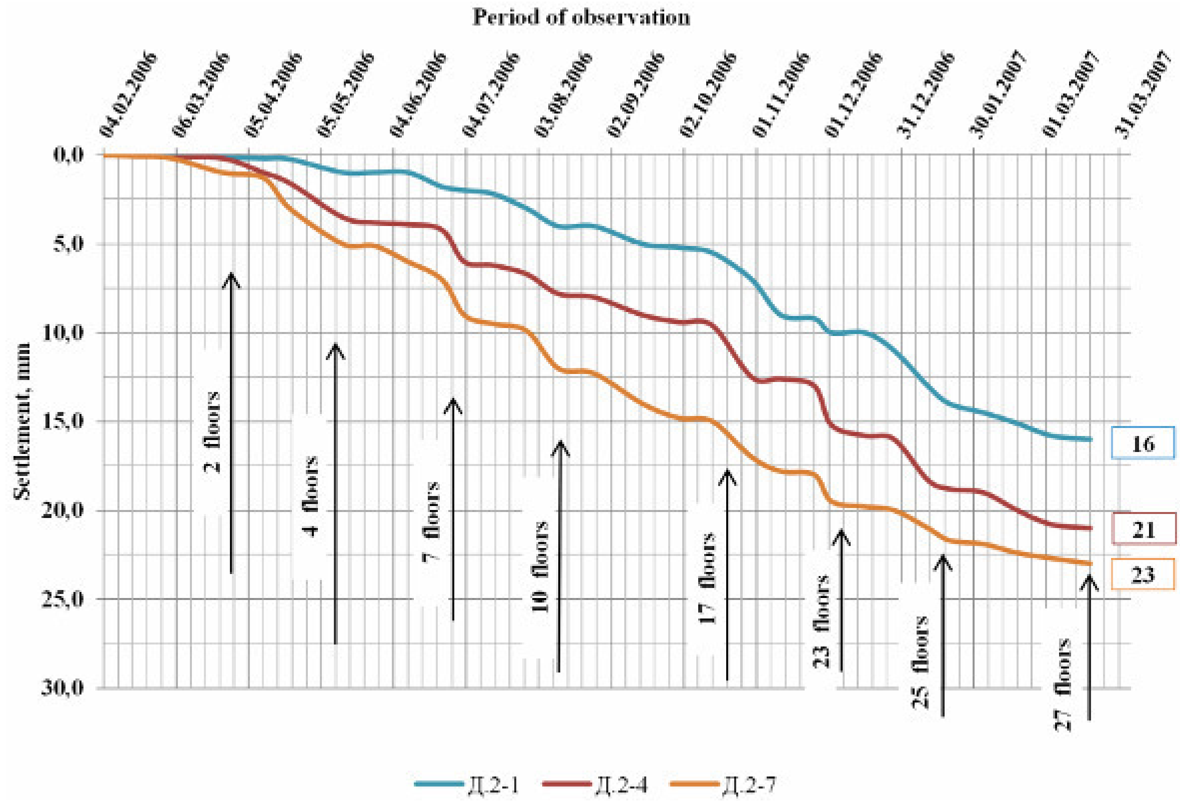

Figure 7 – Graphs of high-rise buildings bearing structures settlement

Conclusions. The reliable results of «base – foundation – superstructure» system numerical modeling can be obtained with regard for the identified parameters of a soil base model.

The redistribution of efforts in piles between typical zones such as the angular, contour, and middle ones should be considered. It has been established that the values of efforts in piles differ by three times in the angular and middle zones. Therefore, it is advisable to carry out complex calculations aimed at the determination of piles rational location in the pile foundation. It gives the economic effect concerning the consumption of materials.

It is found that the rational location of piles in a foundation allows load the piles uniformly and to decrease their total number by 15-30% as compared with the case of piles on a grid with regular step.

To adjust the efforts in the angular piles, it is proposed to change their lengths depending on the combination of loads. It is established that the pile foundation with shorter peripheral piles is more uniformly loaded, more efficiently uses its bearing capacity, and is more reliable as compared to the foundation with shorter middle piles.

It is shown that the instrumental observations of bearing structures behaviour are important in the design of high-rise buildings. It has been established that monitoring of constructions should be carried out from the beginning of foundation pit development until the completion of the construction, and after full load of the building with useful loads.

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