ГИАБ. Горный информационно-аналитический бюллетень /
MIAB. Mining Informational and Analytical Bulletin, 2023;(6):97-110
ОРИГИНАЛЬНАЯ СТАТЬЯ / ORIGINAL PAPER

УДК 624.134.4 DOI: 10.25018/0236_1493_2023_6_0_97

ИССЛЕДОВАНИЕ ВЛИЯНИЯ СТРОИТЕЛЬСТВА ГЛУБОКИХ КОТЛОВАНОВ НА ОСЕДАНИЯ МАССИВА В ПЛОСКОЙ И ПРОСТРАНСТВЕННОЙ ПОСТАНОВКЕ

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Аннотация: Исследовано влияние строительства глубоких котлованов различной геометрии на напряженно-деформированное состояние вмещающего грунтового массива. Данная тематика актуальна при строительстве глубоких котлованов в слабых грунтах в условиях плотной городской застройки. Даже под защитой стены в грунте и расстрелов, то есть жесткой конструкции, могут происходить неравномерные деформации грунта, что может привести к повреждению капитальных зданий окружающей застройки, часто представляющих историческое значение, и является недопустимым. Численное моделирование, выполненное методом конечных элементов в программном комплексе Plaxis, показало, что в большинстве случаев прогноз напряженно-деформированного состояния грунтового массива в плоской постановке не дает достоверного результата. Необходимо выполнять пространственное численное моделирование. Для практических целей и предварительных расчетов на основании многофакторного исследования предложены зависимости, определяющие коэффициенты перехода от двухмерной постановки задачи к пространственной, при любом пространственном расположении здания относительно котлована. Численные расчеты дают удовлетворительную сходимость с натурными данными и могут быть использованы для прогноза напряженно-деформированного состояния грунтового массива в окрестности глубокого котлована.

Ключевые слова: геомеханический прогноз, строительство в плотной городской застройке, глубокий котлован, стена в грунте, модель упрочняющегося грунта, численное моделирование, подземное строительство, метод конечных элементов.

Для цитирования: *Деменков П. А., Комолов В. В.* Исследование влияния строительства глубоких котлованов на оседания массива в плоской и пространственной постановке // Горный информационно-аналитический бюллетень. – 2023. – № 6. – С. 97–110. DOI: 10.25018/0236_1493_2023_6_0_97.

Study of influence of the deep pit construction on soil mass in flat and spatial formulation

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Abstract: The paper presents the study of the impact of deep pit of different geometries on the stress-strain state of the enclosing soil body. This topic is relevant in the construction of deep pits in soft soils in restrained urban conditions. Even under the protection of a slurry wall and strutting, that is a rigid structure, ultimate deformations of soil body can occur, which can lead to damage of the surrounding buildings, often of historical importance. Numerical modeling performed by finite element method in Plaxis software package revealed that in most cases the prediction of the stress-strain state of the soil body in the vicinity of such structures in 2D or plane setting does not give a reliable result. It is necessary to perform spatial numerical modeling. For practical purposes and preliminary calculations, authors proposed dependencies that determine the values of conversion factors from 2D to 3D setting of the problem for any spatial location of the adjacent building on the basis of a multivariate study. Numerical calculations give satisfactory convergence with in-situ data and can be used to predict the stress-strain state of the soil body in the vicinity of deep pit.

Key words: geomechanical forecast, construction in dense urban development, soft soil, deep pit, slurry wall, hardening soil model, numerical modeling, underground construction, finite element method.

For citation: Demenkov P. A., Komolov V. V. Study of influence of the deep pit construction on soil mass in flat and spatial formulation. *MIAB. Mining Inf. Anal. Bull.* 2023;(6):97-110. [In Russ]. DOI: 10.25018/0236_1493_2023_6_0_97.

Introduction

The use of underground space for the construction of objects for various purposes within cities allows solving the problem of lack of space in restrained conditions [1—4]. Construction can be carried out in deep pits for underground parts of buildings — foundations or underground floors, as well as individual objects, including subway stations and railway stations [5—7]. The construction of pits for transportation purposes is carried out in intersection with tunnels and is a very complex multifactorial task due to the occurrence of a complex stress-strain state of the enclosing soil body. However, even pits designed for the foundations of the buildings, with rigid supporting structures, can cause significant soil deformations and lead to emergency situations if the design project or technology is incorrect [8—11]. The dimensions of the pit are determined by the design project and should correspond to the dimensions of the underground part of the building; therefore, both the depth and the horizontal dimensions of the structures can vary from meters to tens of meters.

Studies have shown that the depth of the pit has the most significant impact on subsidence of soil body and nearby structures [12, 13]. The correct choice of the supporting structures is especially relevant in difficult geological conditions of construction: during construction in soft soils [14—16], in the presence of water horizons, quicksand [17—20]. There are many examples of failures occurring due to one of these factors [21, 22].

Deformation control of the enclosing soil body is relevant not only for maintaining the stability of the pit and preventing failures. When buildings and structures are in close proximity to the edge of the excavation, their performance characteristics must be maintained. In central part of modern megacities, for example, St. Petersburg, there are lots of buildings of historical value, so their structures cannot be disturbed [23—28].

All these factors lead to the need for careful selection of supporting structures and their parameters, if it is impossible to change the structural dimensions of the pit. Most often, in difficult conditions, a slurry wall is designed [29—32], using empirical methods for predicting the subsidence of the soil body. Empirical techniques make it possible to evaluate the subsidence under idealized conditions. With several layers in the lithological cross-section, complex pit configuration and different locations of adjacent buildings in relation to the pit wall, it is difficult to assess the subsidence value [33—36]. An analysis of scientific reviews has shown that at present there are no comprehensive studies that present semi-empirical methods, with a sufficient degree of reliability establishing the patterns of deformation of the soil body at any point in the vicinity of the pit.

The use of numerical simulation in predicting the stress-strain state of both the soil body and the supporting structures meets modern requirements for design reliability and makes it possible to take into account difficult construction conditions [37]. At the same time, the use of numerical modeling also has particularities: it is necessary to thoroughly evaluate soil parameters under complex geological conditions. In modern software systems such as Plaxis, models of the soil nonlinear behavior are implemented, which make it possible to correctly assess deformations under the load and during excavation [38, 39].

An important step in numerical modeling is the verification of the numerical model to obtain reliable results. Verification should be carried out on the basis of geotechnical monitoring data [40—43].

The simplest approach is modeling of a pit in section. The plane formulation of the problem makes it possible to obtain results in the shortest possible time and to predict the development of soil body deformations in the vicinity of the pit. This approach is simplified and does not allow to make a forecast with a sufficient degree of reliability. This is due, first of all, to the complex spatial configuration of the pits in most cases, the presence of additional supporting structures in the corners of the pit, which causes a difference in the rigidity of the supporting structures in the center of the pit and at the ends. An unreliable forecast can lead to the loss of stability of the pit support and subsidence of the earth's surface, followed by loss of stability of buildings located in the influence zone of a deep excavation construction. Modeling in a spatial setting allows achieving the best results [44], however, it is quite time- and material consuming.

Deep pits have square or rectangular shape, but even in this case, different stiffness of the supporting structures at the ends and in the middle of the pit length makes it incorrect to calculate any section in the flat formulation. The main task of the research is to increase the reliability of numerical calculations of deep pits in plane and spatial formulations in soft soils and to propose conversion factors for these conditions. The pits have a rectangular shape; however, even in this case, the different stiffness of the slurry wall at the short side and in the center of the pit makes it incorrect to calculate any crosscut in a plane setting. The paper proposes dependences considering the influence of spatial geometry of the pit.

Materials and methods

The studies were carried out by numerical simulation methods in plane and spatial formulations. Modeling was performed in the Plaxis 2D/3D software package. The conditions of water saturated clays and sands are considered as one of the most difficult conditions for construction. Based on the materials of engineering geological tests, the main physical and mechanical properties of soils typical to St. Petersburg conditions have been selected (see Table).

Water-saturated clays and sands exhibit plastic properties under loading, so it is necessary to use a model that would de-

Parameters of material models characterizing the physical and mechanical properties of the soil body
Параметры моделей материалов, характеризующие физико-механические свойства грунтового массива

Soil unit	Sand	Clay
Unit weight of soil in unsaturated state γ_{unsat}, kN/m^3	$16 \cdot 10^3$	$18.5 \cdot 10^3$
Unit weight of soil in water-saturated state γ_{sat}, kN/m^3	$18 \cdot 10^3$	$21 \cdot 10^3$
Parameter e_0	0.75	0.85
Soil deformation modulus corresponding to 50% of its ultimate strength E_{50}, kN/m^2	$18 \cdot 10^3$	$11 \cdot 10^3$
Odometric modulus of soil deformation E_{oed}, kN/m^2	$18 \cdot 10^3$	$11 \cdot 10^3$
Soil elasticity modulus E_{ur}, kN/m^2	$54 \cdot 10^3$	$44 \cdot 10^3$
Parameter of soil stiffness dependence on the level of stress	0.5	0.9
Adhesion c', kN/m^2	1	18
Angle of internal friction φ, degrees	28	19
Dilatancy angle ψ, degrees	0	0
The value of shear deformations at which the initial value of the shear modulus decreases by 70% $\gamma_{0.7}$	$0.1 \cdot 10^{-3}$	$0.15 \cdot 10^{-3}$
Initial value of shear modulus at small deformations ($1 \cdot 10^{-6}$), G_0, kN/m^2	$54 \cdot 10^3$	$33 \cdot 10^3$

scribe their behavior with maximum accuracy with minimum initial data.

In Plaxis software package, a hardening soil model at small deformations (HSS) is implemented. This model considers the nonlinearity of deformations during unloading or repeated loading due to the additional hyperbolic dependence between stresses and deformations at small relative deformations, which generally corresponds to the behavior of the soil during a standard deviatoric triaxial test.

At the same time, additional parameters that make it possible to describe such soil behavior can be empirically established for each type of soil with sufficient reliability even in the absence of triaxial test data.

During initial loading and repeated loading or unloading, two independent deformation moduli are introduced, which can be determined by formulas (1) – (2):

$$E_{50} = E_{50}^{ref} \left(\frac{\sigma_3 + c \cdot \cot \varphi_p}{\sigma^{ref} + c \cdot \cot \varphi_p} \right)^m , \qquad (1)$$

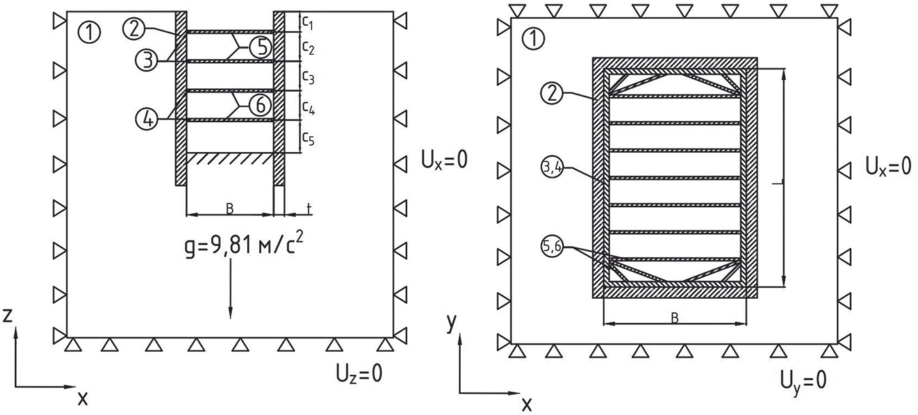
where E_{50}^{ref} – soil deformation modulus corresponding to mean stress σ^{ref}, determined from standard triaxial tests when the deviator reaches stresses q 50% from maximum shear strength q_f.

$$E_{ur} = E_{ur}^{ref} \left(\frac{\sigma_3 + c \cdot \cot \varphi_p}{\sigma^{ref} + c \cdot \cot \varphi_p} \right)^m , \qquad (2)$$

where E_{ur}^{ref} – initial elasticity modulus corresponding to the average effective stresses σ^{ref}, with σ^{ref} equal to 100 kPa.

The study was carried out for a rectangular excavation pit protected by a slurry wall and strutting. The soil body was set as a homogeneous isotropic medium with physical and mechanical properties corresponding to given in Table 1. The material of the slurry wall is concrete B30. Strutting is made of steel with elasticity modulus E = 210 GPa.

The model has the shape of a parallelepiped, the lower face of which is fixed in the direction of the vertical axis, and the side faces are fixed in the direction of the corresponding horizontal axes. The dimen-



1 – soil body; 2 – slurry wall (t=1 m); 3 – belt of 1 and 2 tiers (two I-beams 30Sh);
4 – belt of 3 and 4 tiers (three I-beams 30Sh);
5 – struts of 1 and tiers (round pipe d = 630 mm);
6 – struts of 3 and 4 tiers (round pipe d = 920 mm)

Fig. 1. Design scheme
Рис. 1. Расчетная схема задачи

sions of the model are 220×360 m, which eliminates the influence of boundary conditions on the results. The design scheme is shown in Fig. 1.

During the study, the geometric dimensions of the pit have been changed: at a constant width *B*, the length *L* changed in the range from 1B to 8B with a step of 1B. The step of strutting and the design of belts haven't been changed during the study. The step of strutting is 5 m. The belts are located at levels –2.000 m, –7.000 m, –12.000 m, –15.000 m. The level of the top of the pit is 0.000 m. Levels by stages are ($c_1 - c_5$): c_1 = –2.000 m, c_2 = –7.000 m, c_3 = –12.000 m, c_4 = –17.000 m, c_5 = = –20.000 m. This allowed to obtain a universal dependence of influence of geometric parameters on change in the stress-strain state of the soil mass in the vicinity of the pit.

It was supposed that the soil within the pit has been removed in stages corresponding to installation of strutting.

It should be noted that within this research the criterion for the stability of excavation is change in the stress-strain state of the soil mass, not supporting structures. This allows to assess the parameters of the area of influence and the allowable distance from the pit wall to capital buildings.

On the basis of numerical modeling, vertical displacements of the surface η are determined, which are then recalculated into inclinations (3). According to building regulations (SP 21.13330.2012), the permissible inclination value for capital buildings is i = 20 mm/m.

$$i_{1-2} = \frac{\eta_2 - \eta_1}{S_{1-2}}, \qquad (3)$$

where η_1, η_2 — vertical displacements of points 1 and 2 respectively, m; S_{1-2} — horizontal distance between points 1 and 2, m.

Model verification

Due to the fact that soils are prone to nonlinear behavior, the model describing its behavior is complex and must be verified in order to obtain adequate calculation results. For verification, in-situ values of subsidence or deformations of underground structures located in similar conditions, both from literary sources and from design data, can be used.

In this paper, verification was carried out on the basis of a calculation of a real

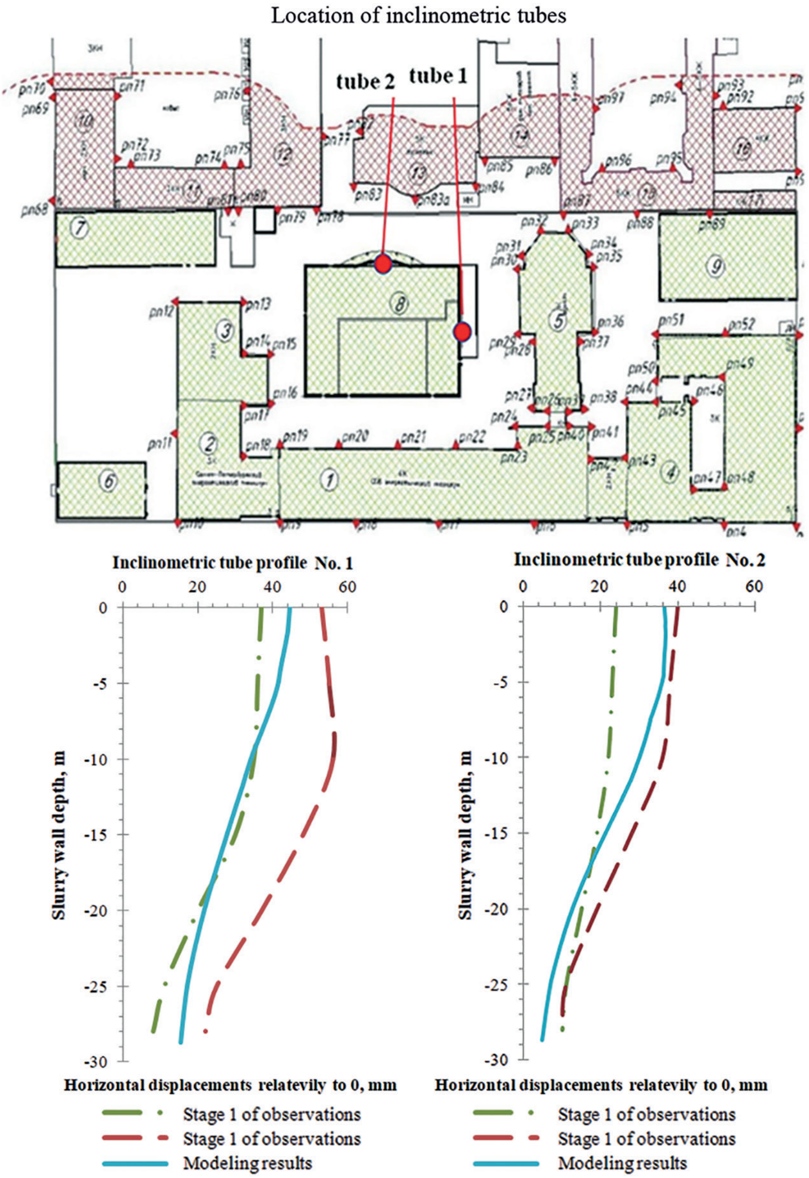


Fig. 2. Model verification
Рис. 2. Верификация модели

object — the HSE educational building located at 3/30, 10th line of Vasilievsky Island, St. Petersburg. The deformations of the slurry wall have been measured for 2 years (Fig. 2). Based on the comparison of graphs of slurry wall deformation, obtained as a result of numerical modeling in spatial setting, with in-situ data, it can be concluded that the deformations of the underground structure are convergent.

Results and discussion

The calculation and analysis of 15 numerical models of rectangular pits with

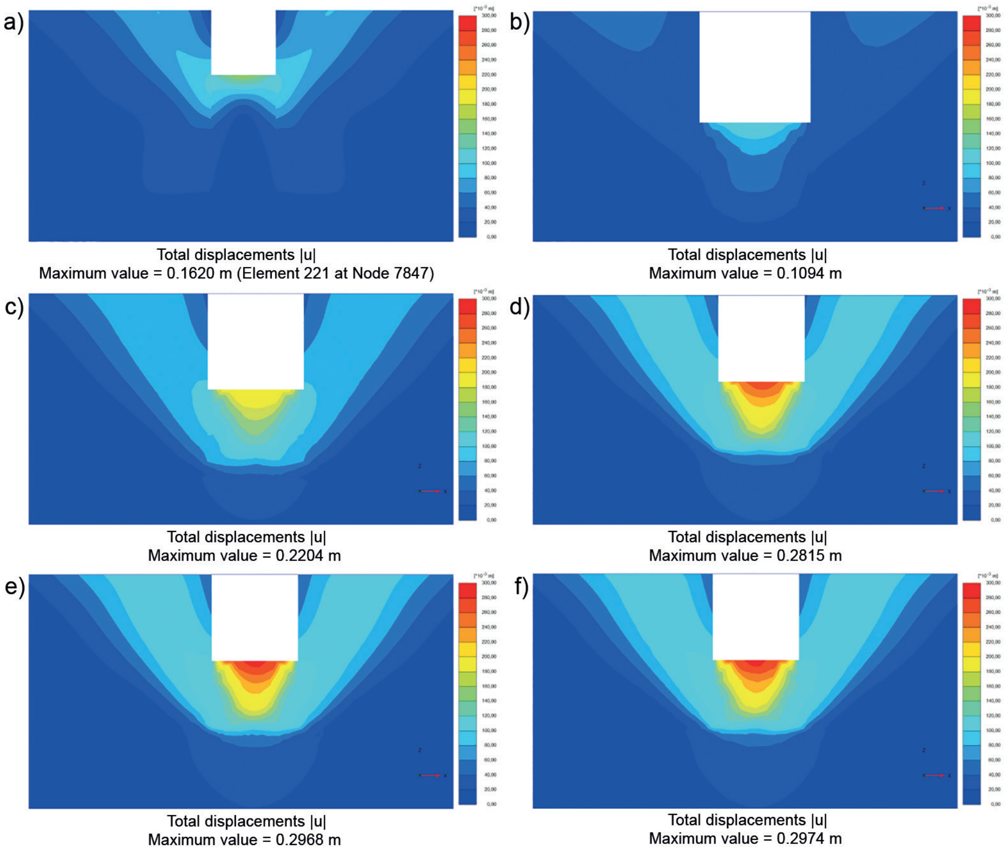


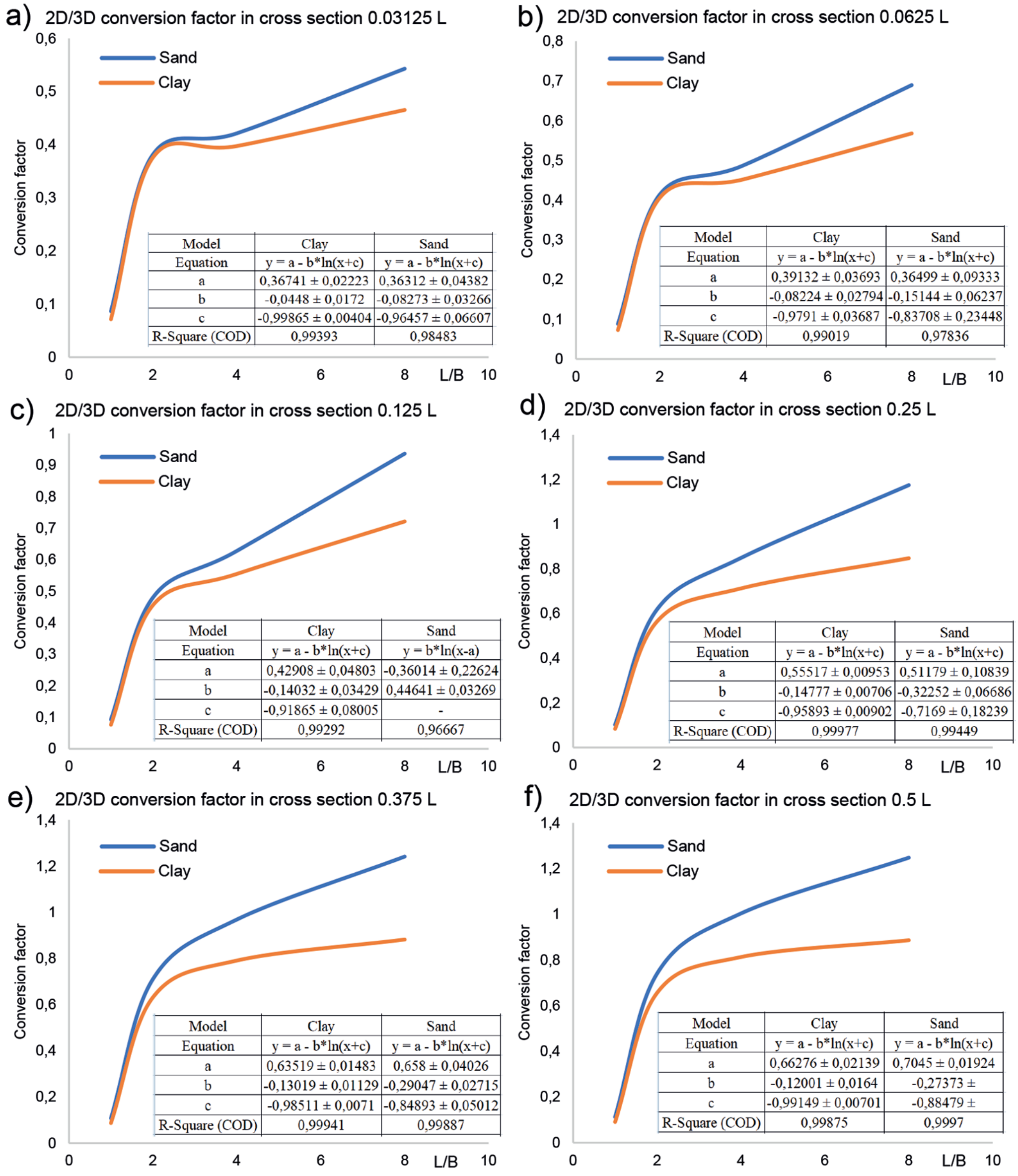
Fig. 3. Diagrams of the displacements distribution in the vicinity of the pit in plane and spatial settings for the ratio L/B = 8B: for plane setting (a); at a distance of 0.03125L from the short wall (b); at a distance of 0.125L from the short wall; (c) at a distance of 0.25L from the short wall (d); at a distance of 0.375L from the short wall (e); at a distance of 0.5L from the short wall (f)

Рис. 3. Эпюры распределения смещений в окрестности котлована в плоской и пространственной постановках для соотношения L/B = 8B: для плоской постановки (а); на расстоянии 0,03125L от торца котлована (б); на расстоянии 0,125L от торца котлована (в); на расстоянии 0,25L от торца котлована (г); на расстоянии 0,375L от торца котлована (д); на расстоянии 0,5L от торца котлована (е)

different aspect ratios made it possible to define the main patterns of deformation of sand and clay soil body in the vicinity of a deep pit. The nature of soil body deformation within a subsidence trough and magnitude of subsidence differ along the long wall of the pit. This is illustrated in Fig. 3.

It can be seen that already at a distance of 0.125*L* from the short wall, displacements differ significantly from those obtained in plane setting. At the same time, the dimensions of the subsidence trough change insignificantly. However, displacements reach their maximum value at a certain distance from the slurry wall, and their magnitude determines the development of ultimate inclinations in the vicinity of the pit and must be reliably assessed.

These factors predetermine the need for a spatial calculation of pits not only of a complex, but even a rectangular shape in the presence of structures along its length, since deformations can be underestimated, which can lead to a failure.



Model	Clay	Sand
Equation	y = a - b*ln(x+c)	y = a - b*ln(x+c)
a	0,36741 ± 0,02223	0,36312 ± 0,04382
b	-0,0448 ± 0,0172	-0,08273 ± 0,03266
c	-0,99865 ± 0,00404	-0,96457 ± 0,06607
R-Square (COD)	0,99393	0,98483

Model	Clay	Sand
Equation	y = a - b*ln(x+c)	y = a - b*ln(x+c)
a	0,39132 ± 0,03693	0,36499 ± 0,09333
b	-0,08224 ± 0,02794	-0,15144 ± 0,06237
c	-0,9791 ± 0,03687	-0,83708 ± 0,23448
R-Square (COD)	0,99019	0,97836

Model	Clay	Sand
Equation	y = a - b*ln(x+c)	y = b*ln(x-a)
a	0,42908 ± 0,04803	-0,36014 ± 0,22624
b	-0,14032 ± 0,03429	0,44641 ± 0,03269
c	-0,91865 ± 0,08005	-
R-Square (COD)	0,99292	0,96667

Model	Clay	Sand
Equation	y = a - b*ln(x+c)	y = a - b*ln(x+c)
a	0,55517 ± 0,00953	0,51179 ± 0,10839
b	-0,14777 ± 0,00706	-0,32252 ± 0,06686
c	-0,95893 ± 0,00902	-0,7169 ± 0,18239
R-Square (COD)	0,99977	0,99449

Model	Clay	Sand
Equation	y = a - b*ln(x+c)	y = a - b*ln(x+c)
a	0,63519 ± 0,01483	0,658 ± 0,04026
b	-0,13019 ± 0,01129	-0,29047 ± 0,02715
c	-0,98511 ± 0,0071	-0,84893 ± 0,05012
R-Square (COD)	0,99941	0,99887

Model	Clay	Sand
Equation	y = a - b*ln(x+c)	y = a - b*ln(x+c)
a	0,66276 ± 0,02139	0,7045 ± 0,01924
b	-0,12001 ± 0,0164	-0,27373 ±
c	-0,99149 ± 0,00701	-0,88479 ±
R-Square (COD)	0,99875	0,9997

Fig. 4. Graphs of conversion factors: at a distance of 0.03125L from the short wall (a); at a distance of 0.0625L from the short wall (b); at a distance of 0.125L from the short wall (c); at a distance of 0.25L from the short wall (d); at a distance of 0.375L from the short wall (e); at a distance of 0.5L from the short wall (f)

Рис. 4. Графики переходных коэффициентов: на расстоянии 0,03125L от торца котлована (а); на расстоянии 0,0625L от торца котлована (б); на расстоянии 0,125L от торца котлована (в); на расстоянии 0,25L от торца котлована (г); на расстоянии 0,375L от торца котлована (д); на расстоянии 0,5L от торца котлована (е)

However, spatial calculations can be quite laborious, which is associated both with the currently insufficiently developed computing base of organizations, and with lack of the required high qualification of the engineer performing the calculation.

As a result of a series of studies of soil subsidence around pits of various spatial

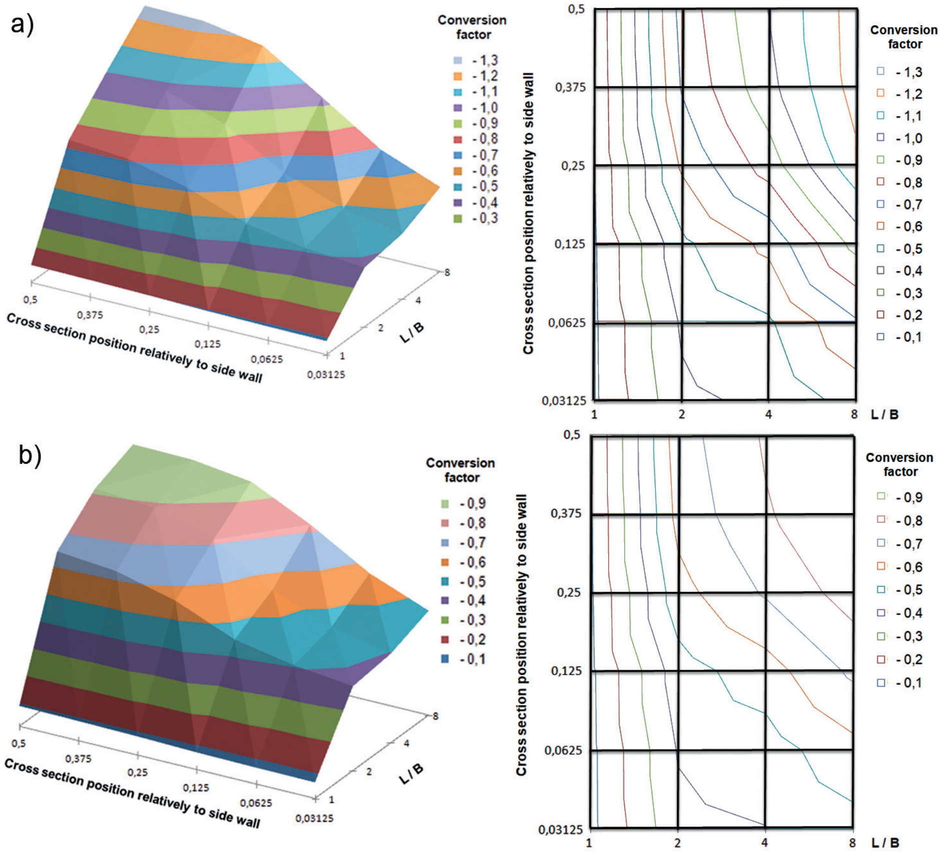


Fig. 5. Nomograms for determining the conversion factor: for sand soils (a); for clay soils (b)

Рис. 5. Номограммы для определения переходных коэффициентов: для песчаных грунтов (а); для глинистых грунтов (б)

configurations, dependencies for estimating the maximum trough subsidence during the construction of a rectangular pit were derived for any geometric characteristics in clay or sand soils. Dependencies allow to estimate subsidence parameters for designing structures and buildings at a different distance from the slurry wall. Dependencies characterize conversion factors from plane to spatial formulation and are shown in Fig. 4.

Fig. 5 shows nomograms that determine subsidence in a cross-section located at any distance from the short wall for a pit with a certain length-to-width ratio modelled in a plane setting.

Thus, the obtained subsidence values calculated in flat setting should be clarified considering conversion factors depending on the length of the deep pit and the type of soil:

$$U_{3D} = U_{2D} \cdot K ,$$

where K is the conversion factor, taken from Fig. 5 (*a*, *b*).

Conclusions

Deep pits are essential structures and require a careful approach to calculating the parameters of their supporting structures. This is especially important for deep pits in weak unstable soils — sands and clays, as well as in restrained urban conditions. Buildings, often of historical value, may be located in differently relative to the pit. At the same time, their structures should not be damaged, which means that it is necessary to predict the subsidence trough parameters caused by the construction of the pit.

Calculation of the problem in plane formulation makes it possible to perform a qualitative assessment of the subsidence trough caused by the construction of the pit. However, the results shown in the work revealed differences in subsidence values depending on the position of the cross-section on the pit plan. Differences in subsidence values can be up to 40%, which affects maximum inclination and curvature values in the subsidence trough and may lead to critical damage to structures in the vicinity of the pit. To correct results obtained in a plane setting, conversion factors can be used. Conversion factors proposed in this paper allow to obtain the magnitude of subsidence, taking into account the spatial location of the considered cross-section.

Thus, when calculating deep pit in plane setting, in order to obtain a spatial subsidence trough, it is necessary to use a technique that considers the length of the pit and the location of the cross-section along the length of the pit.

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Получена редакцией 30.12.2022; получена после рецензии 24.04.2023; принята к печати 10.05.2023.
Received by the editors 30.12.2022; received after the review 24.04.2023; accepted for printing 10.05.2023.