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METHOD FOR FORECAST OF SURFACE DEFORMATION DURING EXCAVATION OPERATIONS IN RESTRAINT URBAN CONDITIONS USING THE SLURRY TRENCH TECHNIQUE

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The article suggests the method for forecast of surface deformation during excavation operations in restraint urban conditions using the slurry trench technique based on FEM simulation.

The results of numerical simulation of the construction of a semi-underground structure with slurry trench technique are given. The regularities of the change in the stress-strain state are determined depending on the trench parameters and the physical-mechanical properties of the soils. The work presents the troughs of surface subsidence during the construction of an excavation using the slurry trench technique, the diagrams of bending moments, transverse and longitudinal forces arising in the trench.

Numerical experiments in Plaxis 2D and 3D were performed to estimate the discrepancy between modeling results in a plane and volumetric formulation of the problem.

Key words: foundation; subsidence; slurry trench; subsidence; soils; semi-underground structures; finite element method

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Introduction. Reduction of the free land area for the construction and development of transport infrastructure, engineering systems and parking for private vehicles require an increasingly active use of underground space in large cities and towns, which leads to the need for deep excavation and construction of semi-underground structures in restraint urban conditions. The development of the underground space of cities is carried out both in an open and closed way [2, 12].

Intensive development of the underground space of cities in restraint urban conditions can have a negative impact [3, 4, 6-9, 13]. To reduce the adverse effect of the construction of semi-underground structures on bases and foundations of adjacent buildings, the slurry trench technique is most effective, which allows minimizing the impact on the neighboring buildings [1, 5, 6].

Analyzing the results of [5, 11] on calculation and field observations of the construction of deep excavations, we can distinguish the following factors that have the greatest influence on the formation of the stress-strain state of the enclosing structures and massif: engineering and geological conditions of construction, the depth of the structure and the rigidity of the enclosing constructions.

Method for predicting the deformation of the earth's surface during excavation operations. Deformations of a soil massif near a semi-underground structure can cause damage to buildings and structures located in the affected area. The forecast of the movement of the ground mass in the construction of semi-underground structures by the slurry trench technique in restraint urban conditions is an important and complex task.

The most complete picture of the deformation of the soil massif in the construction of a semi-underground structure can be obtained by using numerical methods of analysis. The algorithm for calculating semi-underground structures is shown in Fig.1

First, when preparing the initial data, the characteristics of the soil mass are specified. Special attention should be given when assessing the results of engineering and geological surveys, as laboratory tests are often not carried out, and soil characteristics are taken according to regulatory documents, but even during laboratory tests, their results may differ significantly from actual soil characteristics. This is due primarily to the effect of construction work on the hydro-geological situation of the site and its surroundings and the scale effect.

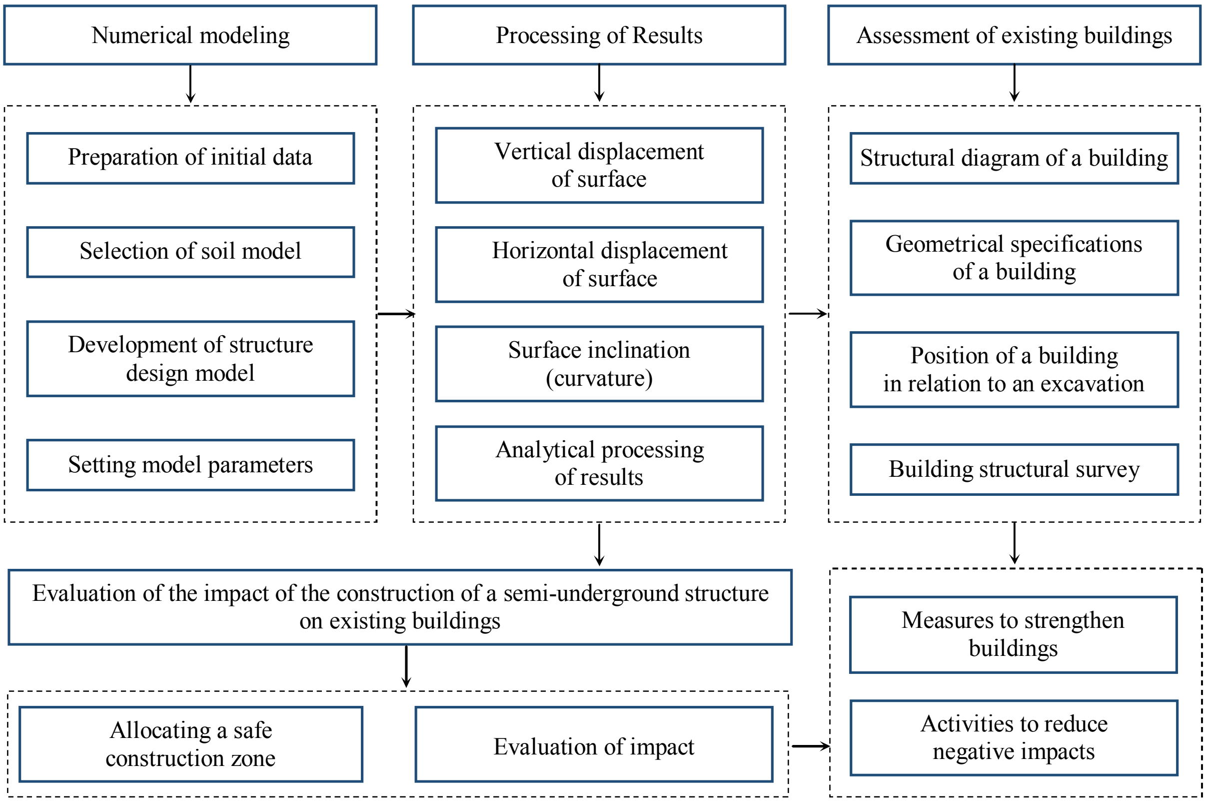

Fig.1. Algorithm for calculating semi-underground structures

Today, there are many models of soil behavior. They differ both in complexity, amount of input data, and field of application to specific soils. The selected model must correspond to the actual behavior of the soil. For sandy and clay soils, the Hardening soil model showed the most accurate results.

The development of the structure design model implies the specification of the stiffness properties of load-bearing structures, their joints and the determination of construction phases. At the same time, special attention should be paid to dewatering of foundation pit, since it can significantly change the physical and mechanical properties of soils.

The results of numerical modeling are subjected to analytical processing. When the characteristics of the enclosing soils or rakers change the approximation of the obtained dependences of subsidence, horizontal displacements of the surface, moments of flection and shearing forces in load-bearing structures, etc. is carried out. The resulting formulas can be used for immediate engineering calculation of excavations, as well as in case of occurrence of abnormal situations, which increases the building safety.

All buildings in the affected area of the foundation pit construction should be inspected for technical condition assessment. A table of the surveyed buildings and structures is drawn up, indicating the categories of technical condition, their features and recommendations for strengthening (GOST 31937-2011. Buildings and structures, Rules for inspection and monitoring of technical condition).

The degree of impact on the surrounding buildings depends on the distance to the building or structure, the inclination and curvature of the surface and is determined by the subsidence trough. When allocating a safe construction zone, it is necessary to take into account the features of the existing buildings and structures.

The most dangerous factor for buildings and structures is uneven subsidence. Buildings with a monolithic reinforced concrete bearing frame have the greatest rigidity. The limiting relative difference in subsidence for them is 0.0024, for large-scale frameless structures without continuous

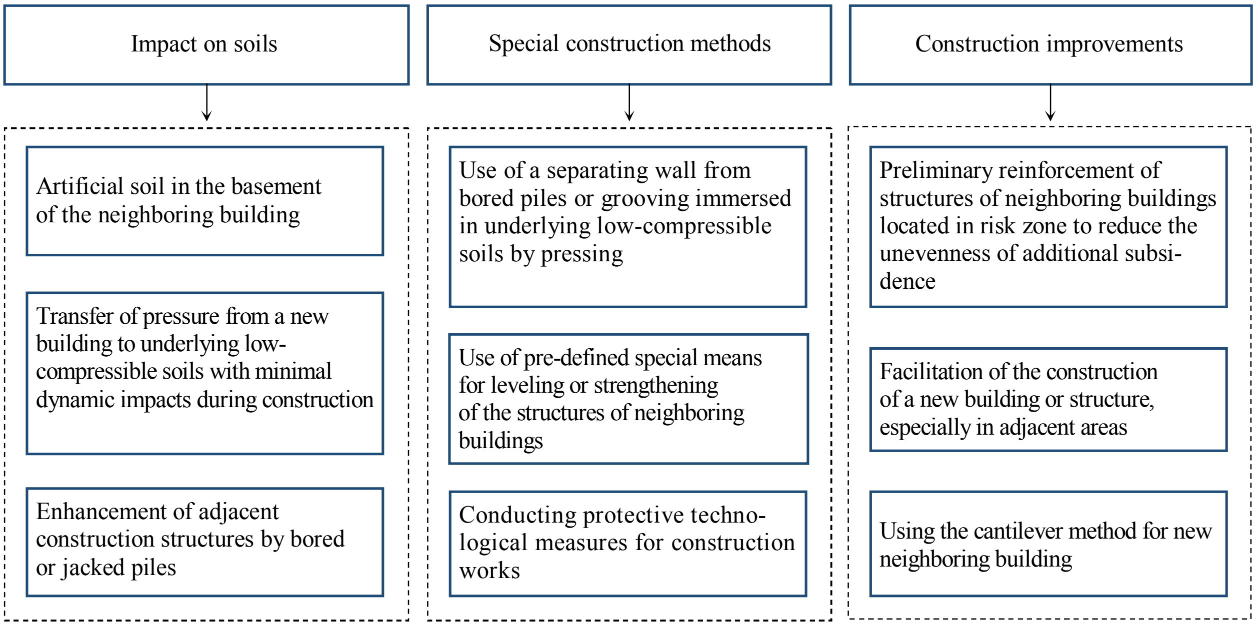

Fig.2. Classification of measures aimed at reducing the negative impacts from construction on neighboring buildings

reinforcement it is 0.0015 (TSN 50-302-2004. Design of foundations of buildings and structures in St. Petersburg). Box-shaped foundations provide the greatest rigidity of buildings and have the largest limit subsidence (20-30 cm) compared to other types of foundations.

Width, length and height are the main geometric parameters of the building and its stability is determined by the magnitude of their relationship. There are two main types of buildings: extended and tower. The limit subsidence is lower for extended buildings, but it can have greater tilt in comparison with tower type.

Towards the foundation the building can be oriented at different angles relative to its larger axis. The perpendicular or parallel arrangement of the building is preferable. The size of the subsidence also depends on the distance to the excavation.

If the combined deformation of the bases and structures of the neighboring building exceed the permissible limits, various measures are taken to improve the soil characteristics and increase the rigidity of the building or its adaptation to uneven impacts (Fig.2). The separation in categories is conditional.

Method approbation. Numerical experiments were performed in 2D and 3D setting using the Plaxis 2D and Plaxis 3D software. Three variants of the deep trench construction are considered (Fig.3). Each option involves a calculation with three different stiffness indicators of the slurry trench technique. In 2D modeling, the following geometric parameters of the enclosing massif were used: width of 200 m and height of 40 m. The task is symmetric with respect to the axis of the pit center. It is forbidden to move the bottom of the model along the Y axis and its side along the X axis.

The width of the excavation for the 2D model is 20 m. The length of the excavation in the 3D model was 30, 35 and 40 m. To prevent horizontal displacements of the pit walls, the slurry trench technique was used, the trench was made of V40 concrete with a thickness of 800; 600 and 400 mm. To improve its rigidity, a raker system is used with a 5 m step in depth. Depending on the depth of the tier placement, the rigidity of the rakers was varied: 1st tier – EI; 2nd – 2EI; 3rd – 3EI; 4th – 1.5EI. At the first stage the raker was a steel pipe of a diameter of 500 mm made of steel with a width of 10 mm. The groundwater level was lowered 1 m below the bottom of the excavation at all stages of the calculations.

Soils of the foundations of buildings and structures can vary significantly in different regions of the country. In this connection, the soils characterized by a different porosity coefficient e, that

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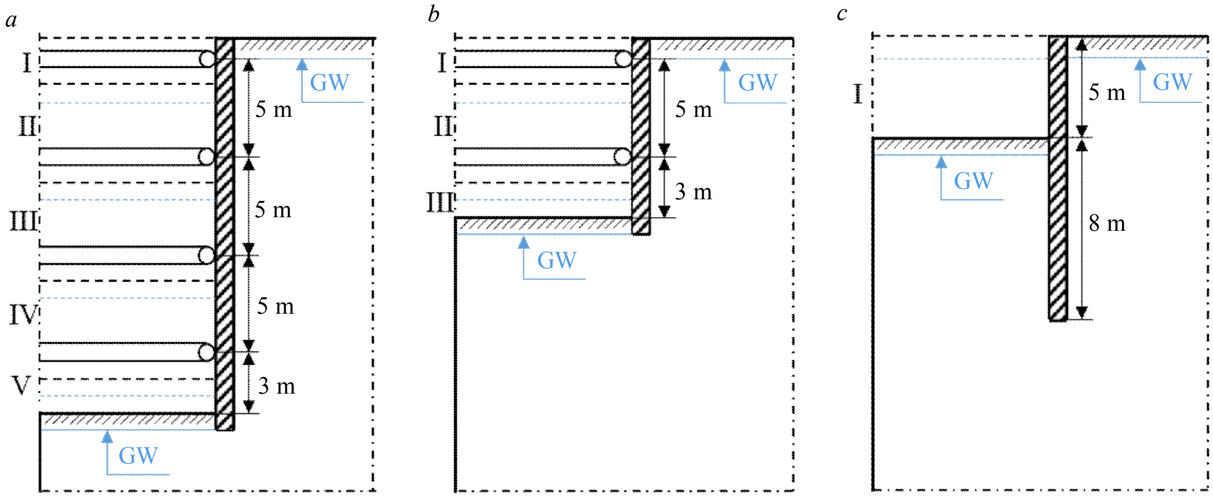

Fig.3. Excavation models: *a-c* – the depth of an excavation is 19, 9 and 5 m respectively; the cantilever pattern

I-V – excavation stages

was taken into account in modeling: four variants of clay (model 1 – e = 0.85, ..., model 4 – e = 0.55) and four sand models (model 1 – e = 0.75, ..., model 4 – e = 0.45). In total, about 100 calculations were performed.

For the calculations, an elastoplastic model of hardening soil was adopted, considering the change in properties at small deformations, which was widely used in predicting the deformations of the soil massif near underground structures. The approbation of this geomechanical model, carried out by domestic and foreign researchers, showed that the presented geomechanical model gives more accurate results when performing the forecast of the formation of the stress-strain state in the system «semi-underground structure – existing buildings». The calculation was carried out on the undrained state of soils, considering the natural rate of filtration and the distribution of pore pressure.

The basic results of 2D modeling for clay soils with a coefficient of porosity are presented in Fig. 4.

It can be seen from the graphs that the affected area of the deep trench construction reaches 60-65 m for all models. In this case, the maximum value of the surface subsidence and the curvature of shift trough significantly differ for various calculations. Thus, it can be concluded that the degree of impact of construction on buildings located in the affected area will vary from model to model.

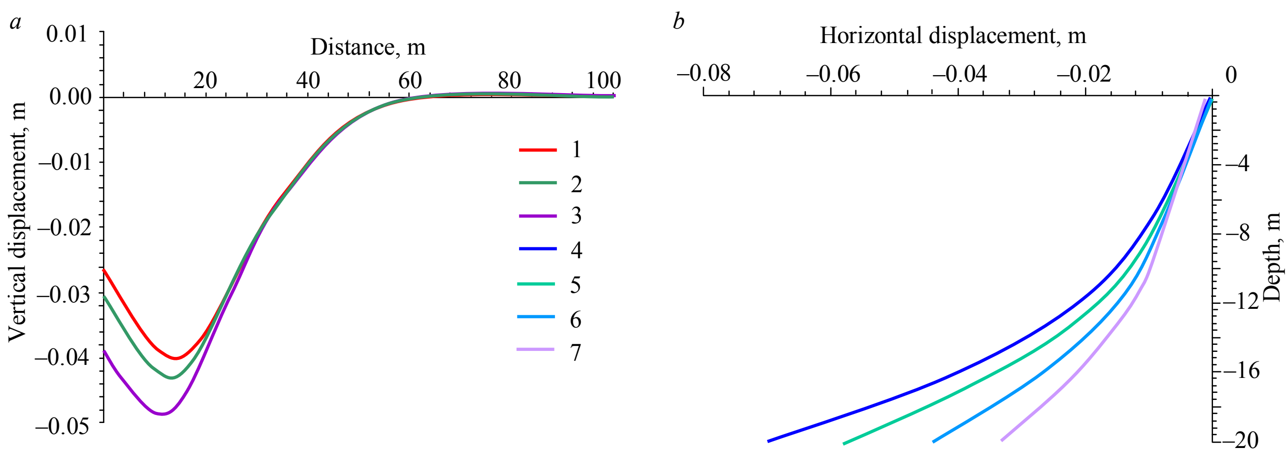

Fig.4. Graphs of vertical (*a*) displacements of surface in clay N 1 with different depths of «slurry trench» (model 1) and diagrams of horizontal displacement of «slurry trench» (*b*) with different clays (models 1-4)

Curves 1, 4-7 – the depth of «slurry trench» is 800 mm; 2 – 600 mm; 3 – 400 mm; 1-4 – e = 0.85; 5 – 0.75; 6 – 0.65; 7 – 0.55

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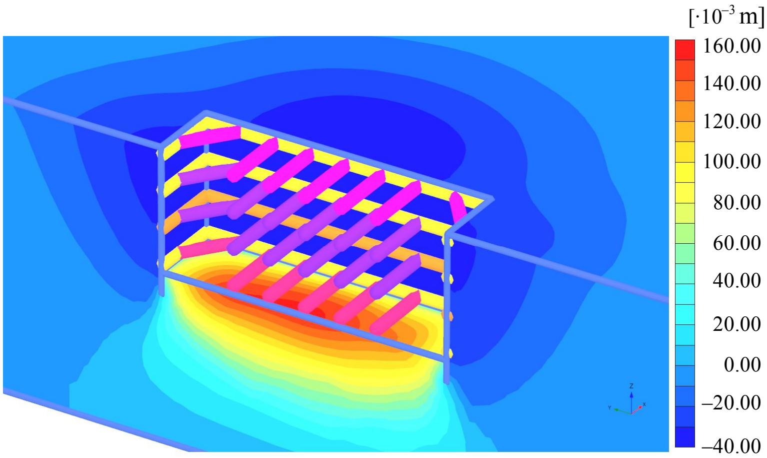

$U_{z\,max}$ = 0.1522 m, $U_{z\,min}$ = –0.03750 m

Fig.5. Surface shift troughs for excavation with 40 m length in sandy soil (Plaxis 3D)

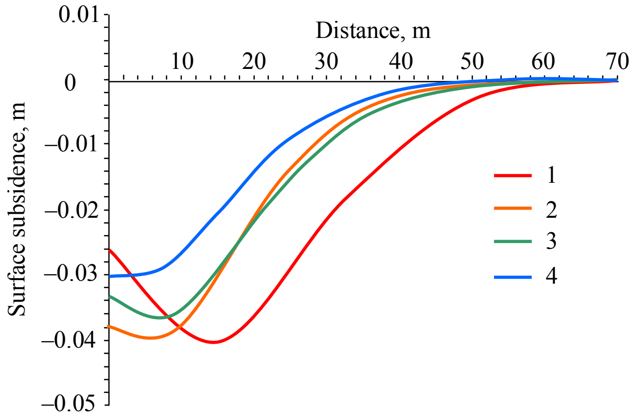

Fig.6. Graphs of vertical displacement of surface (depth of slurry trench is 800 mm) in clay N 1 for 2D (1) and 3D models with different excavation length (2-4 – 35; 30 and 40 m respectively)

In the first variant, the maximum inclination does not exceed 2.7 mm/m, in the second variant it is 1.6 mm/m. For the cantilever system this value is about 9 mm/m and is observed at 0 to 15 m from the excavation enclosing. For more extended building such inclination can be dangerous. At a greater distance from the excavation enclosing (15 m and more), the inclination does not exceed 1 mm/m and this zone can be considered conditionally safe. Therefore, if it is necessary to erect a semi-underground structure near existing building, in our case it is necessary to increase the rigidity of the enclosing structure by strengthening the raker system.

Numerical experiments in Plaxis 3D were performed to estimate the discrepancy between the simulation results in 2D and 3D models. Variants with a pit width of 20 m and different lengths (30, 35, 40 m) are considered. All parameters of the soil massif and structures were set in the same way as in 2D models.

Earth surface subsidence during the construction of a 40 m long trench in sandy soils is shown in Fig. 5.

The curves of the vertical displacements of the surface in 2D and 3D modeling have some differences (Fig. 6). The maximum subsidence in 2D model (4 cm) corresponds to a 3D model with a pit length of 35 m. At the same time, the extremum in the first case is 15 m from the wall, and in the second – 8 m. For other lengths of the excavation, the 2D model gives an overestimated value for the maximum value of the vertical displacements of the surface. The large subsidence of the surface according to the graph in the 3D model with a pit length of 35 m in comparison with the foundation pit of 40 m is due to the arrangement of the rakers. The graphs plot the cross-section along the center of the foundation pit and in models 30 and 40 m it crossed the rakers, and in the model with 35 m it is between the rakers.

Discussion. Of great interest is the analysis of deformations of the soil massif near the underground structure located in weak soils (c_u < 75 kPa), performed by Moormann [10]. An analysis of the results of more than 500 observations showed that, depending on the construction object, horizontal displacements of slurry trench vary from 0.5 % H (H is the excavation depth) to 1.0 % H_e. The average value of horizontal displacements is 0.87 % H. The maximums of horizontal displacements are located at a distance from 0.5 to 1.0H from the ground surface. The maximum values of vertical displacements of the earth's surface are in the range from 0.1 to 10 % H. The average value of the maximum vertical displacement of the earth's surface is

1.1 % *H*. The maximum value of vertical displacements of the earth's surface is observed at a distance of up to 0.5 % *H*, but there are cases where the value of the maximum subsidence of the earth's surface is at the distance of up to 2 % *H*.

The obtained results agree with the results of other researchers. The horizontal displacements of slurry trench in relation to the excavation depth for the first and second calculation schemes did not exceed 0.53 % *H*. The maximum value of the earth surface subsidence for the first scheme was 0.26 % *H*, for the second – 0.18 % *H*. The cantilever system for this condition showed higher values of displacements. The horizontal displacements of slurry trench in relation to the excavation depth for the cantilever system reached 2.8 % *H*. The maximum value of the earth surface subsidence for the third scheme was 1.8 % *H*. At the same time, a safety factor of at least 1.3 was provided for clay soils. In sandy soils with cantilever system, adopted slurry trench parameters, and significant increase in the thickness and depth of the slurry trench, stability was not ensured.

Conclusion. The proposed method for predicting the deformation of the earth's surface during the construction of excavations in conditions of dense urban development using the slurry trench technique allows to obtain a complete picture of the interaction of the semi-underground structure and neighboring buildings.

The stability of the semi-underground structure and deformation of the soil massif in the affected area are interrelated: the higher the coefficient of stability, the less significant deformations develop in the soil massif. As the margin factor for the stability of the walls of a semi-underground structure decreases, the deformations in the soil mass increase to an uncontrolled value. This was observed in the cantilever system of the enclosing structures for sandy soils. The design scheme with a cantilever slurry trench can be successfully realized only at a small depth of the excavation. The maximum subsidence value for a trench 800 mm was 91 mm. Horizontal displacement of the surface reached 132 mm.

The use of even the most reliable technologies for creating enclosing structures such as slurry trench technique does not completely exclude the influence on the existing buildings. Thus, the maximum sedimentation for 19 m depth excavation reached 59 mm. The affected area of the construction extended up to 60 m (3*H*).

The solutions for 2D model give overestimated values of the affected area in comparison with the 3D model. There is almost a twofold difference in subsidence values between the 2D and 3D models at a distance from the excavation wall of 22-55 m. Near the building the divergence is less.

Within the framework of the article, the approbation of the method was presented only partially without a detailed analysis of the results and an assessment of the impact on the buildings.

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