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GEOMECHANICS OF LOW-SUBSIDENCE CONSTRUCTION DURING THE DEVELOPMENT OF UNDERGROUND SPACE IN LARGE CITIES AND MEGALOPOLISES

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ABSTRACT

The work presents the theory of the concept of low-subsidence construction of underground structures. It briefly reflects the main provisions of this concept and a set of engineering activities, which allows implementing it in practice. It is stated that the success of its implementation depends on both accuracy of the prediction of rock mass deformation considering the developed measures and the strict implementation of project decisions during project implementation. The presented concept is illustrated by the example of the construction of interchange hubs of subway stations.

KEYWORDS: Underground Structures, Construction Methods, Deformation Control, Rock Mass, Mathematical Modeling & Media Deformation Models

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Original Article

1. INTRODUCTION

The development of large cities is connected with the complex development of underground space, where projects are implemented for the construction of subway system facilities, transport and service tunnels, underground warehouses, infrastructure facilities, shopping centers and other underground structures. The use of underground space of megalopolises significantly reduces the negative impact of industrial and service infrastructures and solves the problem of urban transport, as well as a number of social and environmental problems. At the same time, underground structure construction can have a negative impact on buildings and urban infrastructure located in the area of the undermining and construction work, which manifests itself in significant sediments, damage and destruction of buildings, structures and utilities, particularly during the construction of subway stations and ground-underground transport hubs. This requires the rehousing of people within the affected area, which is unacceptable in modern economic conditions.

The construction of an underground structure leads to a change in the stress state of the host mass, accompanied by its deformations that extend up to the earth's surface. Their size and character depend on many factors. The most important are geotechnical conditions and technological and structural aspects of the underground construction, as well as the quality of work at all stages, starting with engineering surveys and design and ending directly with the construction of the structure and its operation. It is important to monitor the development of rock mass and surface deformations during construction. Therefore, it is necessary to improve the methods of forecasting the development of negative processes and methods of constructing underground structures and accumulate and summarize the experience gained during the construction of similar objects.

The work focuses on the theoretical developments, concerning the forecasting of geomechanical processes in the underground construction, including the improvement of the methods of engineering-geological surveys, substantiation of new models of rock mass deformation, development of new effective approaches to solving spatial problems of predicting the rock mass stress-strain state of underground structures with complex spatial configuration, as well as new technological, space-planning and constructive decisions.

2. METHODS

2.1. Basic Principles of Low-Subsidence Underground Construction During Underground Space Development in Large Cities

The construction of underground structures under the restrained urban conditions is always associated with the risk of negative impact on urban infrastructure, buildings and structures located on the surface of the earth. This is due to a regular change in the stress–strain state of the rock mass in the underground structures, mainly at the stage of their construction and, to a lesser extent, during their operation. The development of deformations around the underground structures involves rock, located above, in the process. The process of deformation extends all the way to the earth's surface, where it is realized in the form of surface subsidence. The negative effect of surface subsidence is associated with the deformation of construction's bearing, enclosing and decorative structures, which is not typical for them, as well as the occurrence of additional tensile or compressive stresses in extended objects and engineering communications.

It has been established that the control over the development of surface deformations can be implemented according to one of the two basic schemes aimed at reducing the negative impact of the underground construction on city facilities. The first scheme is aimed to reduce the absolute value of the subsidence of the ground surface, which in general will favorably affect the stress-strain state of the urban objects. The second scheme is aimed to change the nature of the development of the deformation directly at the base of buildings and structures or along the length of the extended objects. An algorithm has been developed [1], which determines the sequence of measures to reduce the impact of an underground structure on the objects of urban development below the maximum permissible value.

Reduction of the negative impact of underground construction on urban buildings can be achieved in two ways. The first is to develop additional engineering measures not directly related to the underground construction, which can have a beneficial effect on the safety of buildings and structures located on the surface. Such measures include strengthening the buildings' structure, including the foundation, creating a rigid bed at the base of buildings, erecting engineering structures in the form of a solid wall or a wall of bored piles separating the intensive deformations of the soil mass from the zone. Separately, it is possible to identify various options for compensating injection of solutions into the rock mass. However, the organization of such events requires additional costs, the allocation of land on the surface to perform construction work, etc., and the activities themselves in practice are not always effective. From our point of view, a more rational approach is to use so-called gentle methods of building underground structures, which directly affect the magnitude of the expected deformations of the surface. Such measures can be attributed to the second category of ways to reduce the negative impact of underground construction on urban buildings. Further, in the text, only this category will be discussed.

Reduction of rock mass deformations in the vicinity of an underground structure on the basis of the approaches presented above in some cases requires only minor adjustments to the construction process, but they can coordinate the technological and structural aspects of the construction of underground structures. Following them will allow minimizing the negative impact of the underground construction on urban infrastructure. As a result of the whole set of measures of the second category, the surface deformations are still not within the required limit, it is necessary to proceed to the measures of the first category or to take more consistent decisions.

One of the factors limiting the development of low-subsidence construction methods is some uncertainty in the impact assessment of factors from the second category on the development of the deformation. However, the development of numerical analysis methods and their introduction in geotechnical calculations made it possible to obtain a more representative picture, to have not only a qualitative but also quantitative understanding of the influence of different measures on the deformation of the rock mass in the vicinity of an underground structure. Despite the fact that the reliability of numerical modeling of the geomechanical processes development is influenced by many factors, one of the dominant ones is the choice of an adequate medium deformation model.

Thus, the existing methods of reducing the negative impact of underground construction on urban buildings show that there are many approaches to control the deformations of the surface. The scope of the approaches is not comprehensive but limited to specific engineering-geological conditions (porous well-filtering media, porous rocks characterized by low filtration characteristics, poorly cemented rocks) and technical features of construction removable structures. The main attention in the development of technical measures should be given to the control of the development of the deformation in the contour of underground structures. These are the most efficient and, at the same time, they require the use of the smallest number of technical operations in the immediate vicinity of urban buildings. Only in the case of insufficiency of such measures, one should refer to the methods based on the change in the nature of the strain of the rock mass directly at the base of the urban development objects.

The developed classification [2] of ways to reduce the negative impact of the construction of underground structures on buildings and urban infrastructure separates them according to the area of possible application, depending on the engineering-geological conditions, the technical condition of buildings and structures, the depth of the underground structure and other factors. At the preliminary stage, it allows choosing an effective way to control the development of deformations of the ground surface during the underground construction. The developed classification is the basis of the method for the selection of geomechanically safe parameters of structures and construction technologies for the underground structure's design in restrained urban conditions.

2.2. Experimental and Theoretical Research

We carried out a set of studies to increase the reliability of the prediction for the development of geomechanical processes during the underground construction in claystone-like rocks, which, as is known, are a layered medium with pronounced anisotropy of mechanical characteristics.

The study of the mechanical behavior of claystone-like rocks. The study of the mechanism of deformation of solid claystone-like rocks was carried out under the laboratory conditions on samples of Proterozoic clay, which were prepared from monoliths from the faces of stations under construction of the Saint Petersburg subway system. Detailed research results are presented in Karasev [3]. We briefly note that the Proterozoic clays possess significant anisotropy of deformation and strength characteristics. The deformation characteristics of such rocks depend on the magnitude of the average stresses and increase as they grow. The shear modulus in the range of small to very small strains nonlinearly varies from a maximum value to a fixed constant value. Proterozoic clays have a brittle fracture after reaching their ultimate strength. In this case, the anisotropy of the mechanical characteristics is observed in the entire range of rock deformation but decreases as the lateral reduction increases. The obtained characteristic behavior of rocks is the basis for the development of a model of the deformation of the medium.

The development of a mathematical model of claystone-like rocks deformation. The requirements for the geomaterial behavior model presented above can be implemented within the framework of the multilaminate model, where the rock deformation process is considered at local sites, and which was used to describe weak [4, 5], fractured, solid rock and semi-rock soil [6]. The numerical implementation of the environmental behavior models was made on the basis of an explicit modified method for integrating the Euler equations with automatic error control. The model was introduced into the Abaqus software package. The general algorithm for the numerical implementation of the medium deformation model is presented in figure 1. The presented model is a general type model [7] that allows one to take into account the natural structural disturbance of rocks. At the same time, the peculiarity of the model formulation makes it possible to consider structural disturbances both at the global level and at local integration sites. In this paper, the evaluation of the effect of fracturing was adopted according to the method of R.E. Dashko [8], which was developed directly to assess the structural impairment of Proterozoic clays.

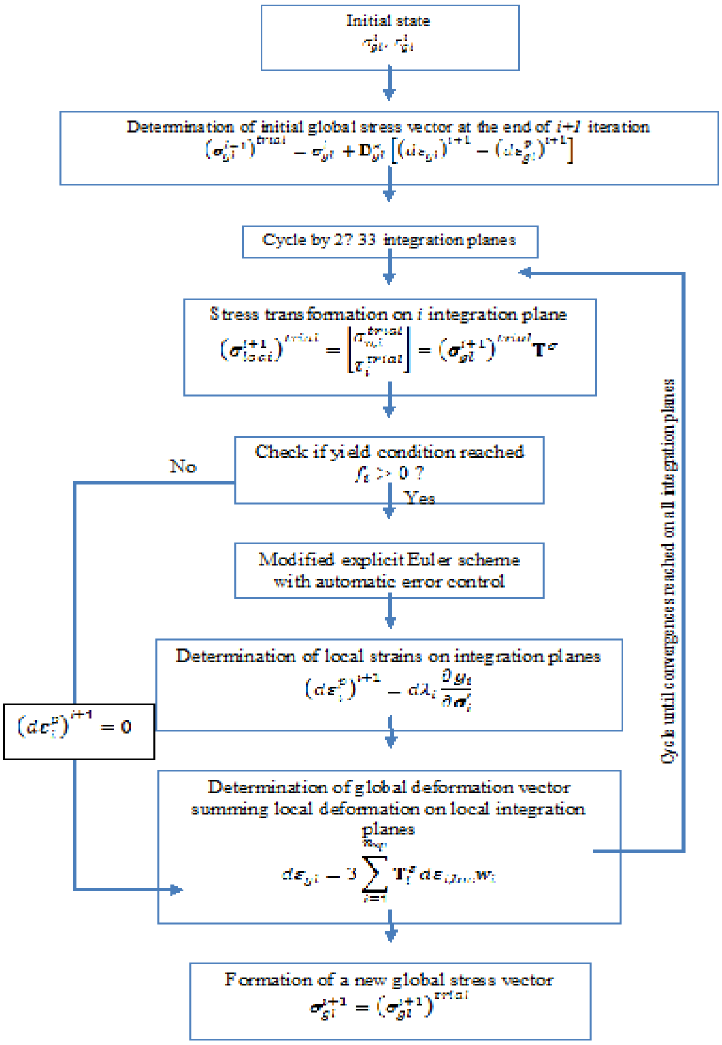


Figure 1: Algorithm for the Numerical Implementation of the Geomechanical Model in the Framework of the Multilaminate Environment Model.

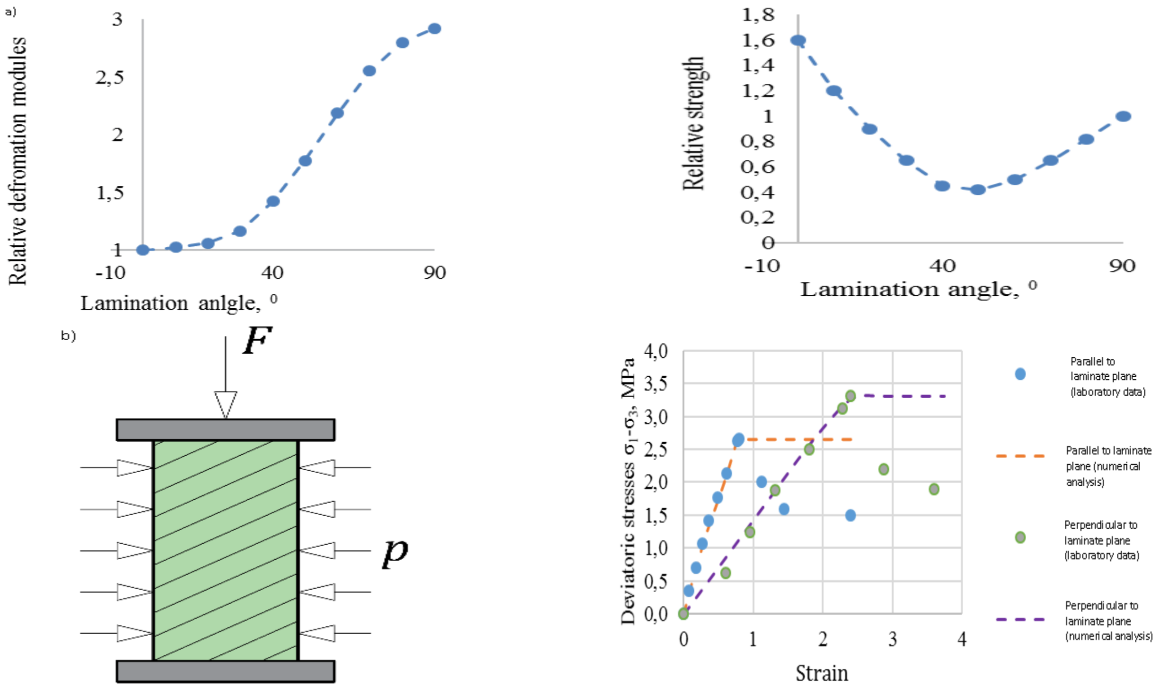


Figure 2: Anisotropy of the Strength of Claystone-like Rocks: a - The Effect of Anisotropy on the Mechanical Characteristics of Rocks; b - Development of the Stress-Strain State of the Claystone-like Clay Rock.

The predictive mechanics of the developed model of claystone-like rocks deformation are presented in figure 2. The diagrams show that the developed model as a whole corresponds to the actual nature of the transversely isotropic medium (figure 2a). A comparison with laboratory studies suggests a good convergence in the sublimit zone deformation.

3. RESULTS

As an example of the implementation of the principles of low-subsidence construction, the solution of two problems of forecasting the development of geomechanical processes in the vicinity of underground structures of complex spatial configuration and the development of a new solution for the construction of a transit subway station in a single space is presented.

Numerical modeling of the development of geomechanical processes during the construction of a subway transit hub. The forecast of the development of deformations of the earth's surface during the development of the underground space of large cities is presented on the example of the construction of a complex spatial underground structure representing the interchange node of two subway stations located at different height levels (figure 3). Engineering-geological conditions of construction at the site of the construction of underground facilities of the station complex can be divided into three layers. The first layer includes all the Quaternary deposits from the ground surface to the layer of stationary clays of the transition layer, including technogenic deposits. The average thickness of the first layer is assumed to be 30 m. The second layer includes the Proterozoic dislocated clays. The average thickness of the second layer is assumed to be 5 m. The third layer includes claystone-like rocks (Proterozoic clays). The averaged thickness is 65 m. The rocks of the first layer are located at a considerable distance from the station construction site and are considered as a nonlinearly deformable medium on the basis of a nonlinearly elastic model of the medium. The rocks of the second and third layers are dense clays with anisotropy of deformation and strength properties and are considered as an elastoplastic transversely isotropic medium. Simulation of construction of underground structures was carried out in stages with the division into global and local computational models [9].

The development of subsidence of the surface at various stages of the construction of the station complex is presented in the form of colored diagrams at various integrated stages of construction (Figure 6). Beyond the boundary of the influence zone of the complex of underground structures construction, the magnitude of the vertical displacements of the ground surface was considered to be 1 mm.

As can be seen from the presented results (Figure 4), the development of the subsidence trough of the ground surface occurs as the underground structure involves an increasing amount of ground surface in the influence zone. The greatest deformations of the surface occurs over the sections with the maximum concentration of underground structures, where the magnitudes of displacements reach 55 mm. Particular attention should be paid to the construction of large cross-section chambers since it is the structures that have a significant influence on the formation of the earth surface subsidence trough.

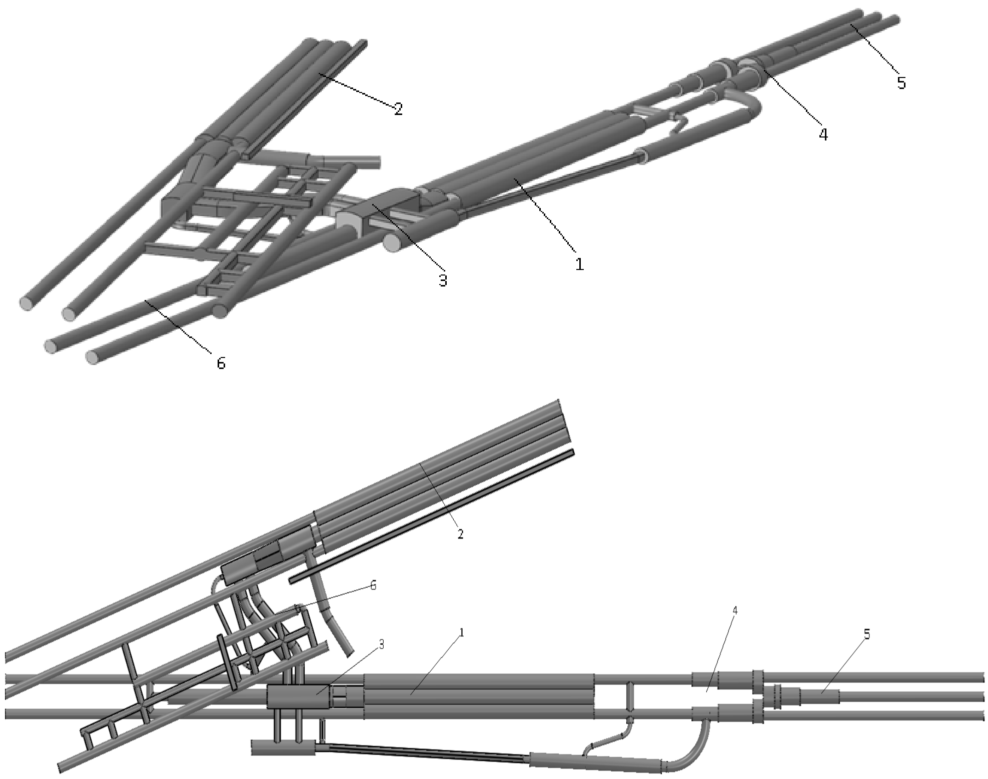
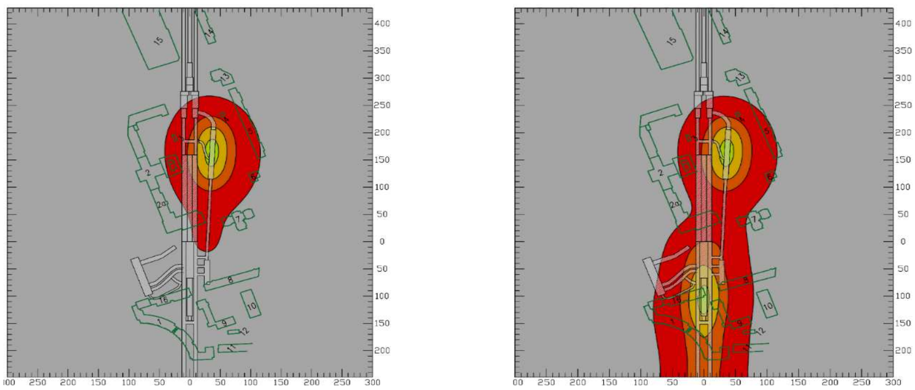


Figure 3: Geometrical Representation of the Space-Planning Solution of the Subway Exchange Node: 1 - Subway Station № 1; 2 - Subway Station № 2; 3 - Transfer Hub; 4 - Access Track Chamber; 5 - Running Tunnels; 6 - Pedestrian Tunnels.



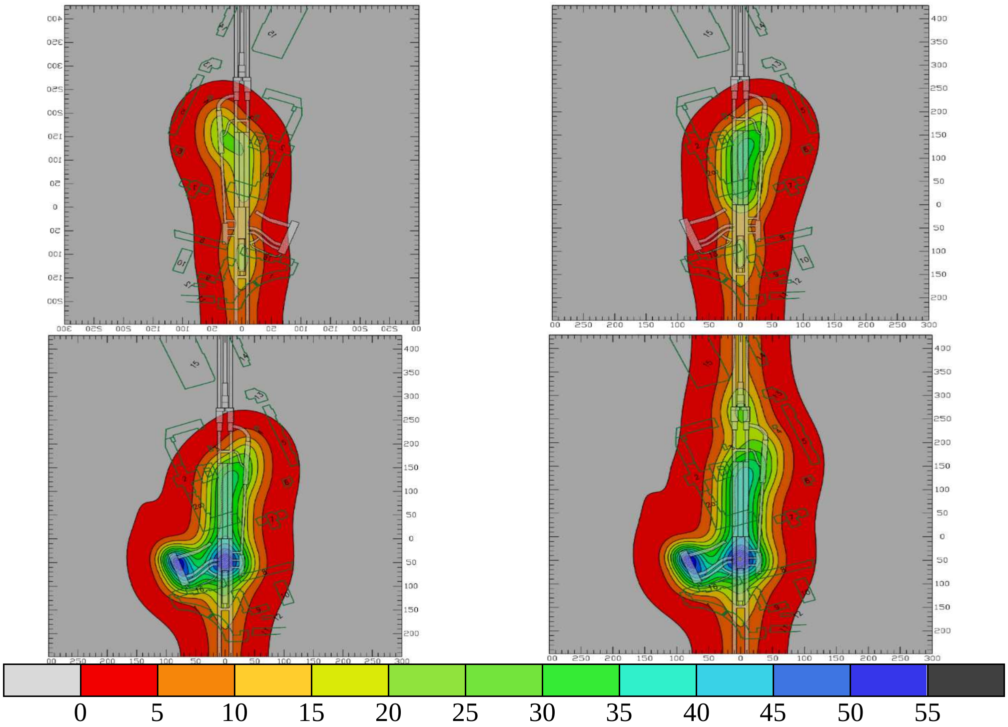


Figure 4: Results of the Prediction of the Surface Deformations during the Construction of the Station Complex at Various Stages: a - Construction of the Workings of the Pit Bottom; b - Construction of a Secondary Traction Sub-Station and Adjoining Running Tunnels; c - Construction of the Left Station Tunnel; d - Construction of the Right Station Tunnel; e - Construction of a Complex of Workings of a Transfer Hub; f - After Completion of the Construction of all Underground Structures.

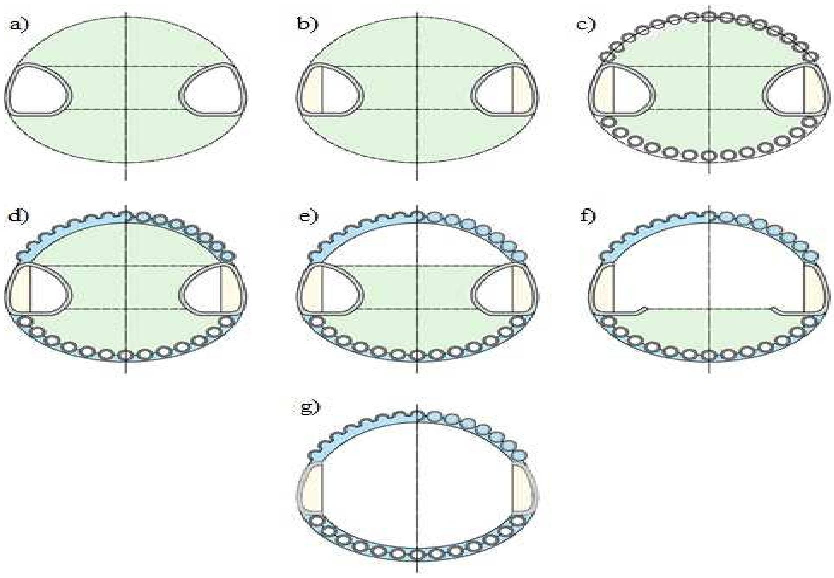


Figure 5: Scheme of the Construction Sequence of a Subway Station based on a Low-Subsidence Technology in the Internal Dimensions of the Subway Station "Sportivnaya": a) Construction of Supporting Tunnels; b) Construction of Reinforced Concrete Support Elements in the Supporting Tunnels; c) Construction of a Screen of Pipes in the Arch and in the Reverse Arch of the Station; d) Construction of Bearing Arches in the Arch and Inverse Arch along the Length of the Station; e-g) Soil excavation in the station Section, Partial Dismantling of the Concrete Liner and Alignment of the Internal Contour at the Level of the Reverse Arch [10].

Development of a method for the underground construction under engineering-geological conditions of Saint Petersburg. Underground structures of the Saint Petersburg subway system, constructed by the underground method, are the structures of complex spatial configuration, which are located in difficult engineering-geological conditions. When considering the geotechnical conditions of Saint Petersburg, one must mention several main geological clusters that form the conditions for the construction of underground structures. The upper layers of the rock are represented by Quaternary sediments, which mainly include water-saturated sands and soft clay rocks. Below, under almost the entire territory of the city, are Proterozoic deposits, which are represented by claystone-like rocks. These geological formations are the main environment, in which underground construction in Saint Petersburg is implemented. The underlying rocks are water-saturated sandstones with interlayers of clay rocks that rest on crystalline rocks.

Considering the above-mentioned requirements, a draft space-planning solution and a sequence of construction of a single-vaulted subway station have been developed, aimed at implementing the principles of low-subsidence construction. The decisions in [9] were taken as the basis and the decision itself was tested during the construction of the "Venice" subway station in Milan. The solution and construction method proposed by us was developed for the construction of underground of large cross-section structures in soft soils. The work adapted it to the conditions of construction of subway stations in Saint Petersburg (figure 5).

Effectiveness evaluation of the proposed measures to reduce the development of rock mass deformations in the vicinity of the underground structure was made on the basis of numerical modeling of the development of the stress-strain state of the "underground structure - rock mass" system. The approbation and calibration of the deformation model were carried out according to the results of observations of the surface subsidence over the construction site of the Sportivnaya subway station (Figure 6b), where satisfactory convergence was obtained between the actual and predicted results. The results of the calculations are presented in Figure 6. The predicted value of the surface subsidence after the completion of the station construction, performed within the framework of the low-subsidence construction concept, was 120 mm, which is 2.3 times less than the strain values during the construction of the Sportivnaya subway station.

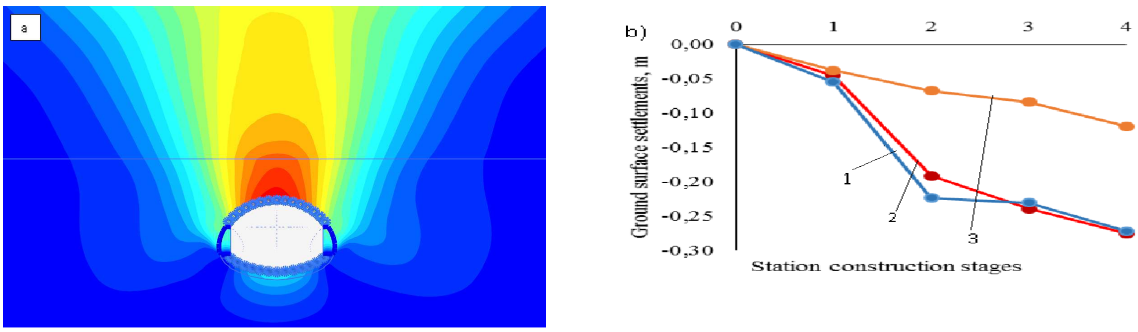


Figure 6: Results of the Prediction of the Rock Mass Deformations (a) and Surface Subsidence Over the Axis of the Subway Station; (b): 1 - Deformations According to the Results of Surveying Measurements at the Site of construction of the station "Sportivnaya" 2 - Predicted Values of Vertical Deformations of the Earth's Surface at the Construction Site of the Station "Sportivnaya"; 3 - Pedicted Values of the Surface Deformations, Obtained on the Basis of Numerical Simulation According to an Alternative Option [11].

4. CONCLUSIONS

The research results demonstrate the need to introduce low-subsidence construction methods for underground structures, performed by the underground method, as well as the need for the search for new technological and constructive solutions. An effective way to monitor the development of surface subsidence is the creation of new constructive and technological solutions for underground structures. Evaluation of the effectiveness of decisions can be made according to predictive calculations based on numerical analysis methods, using modern, appropriate to the conditions of construction models of rock deformation. The paper proposes a solution that allows for a comprehensive implementation of such an approach both at the stage of construction of auxiliary underground structures and construction of large cross-section structures. This solution is demonstrated by the example of the construction of a single-vaulted subway station in the engineering-geological conditions of Saint Petersburg. The effectiveness and feasibility of the proposed method of construction of underground structures are based on mathematical modeling. The results of mathematical modeling for specific engineering-geological and technical conditions of construction showed that the use of a set of measures to reduce the negative impact of new underground construction decreased the ground surface subsidence by more than two times. Thus, further development of this concept, including approbation of existing technical, constructive and technological solutions and the development of new ones seems promising.

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