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Geotechnical Approaches to Safe Development of The Underground Space in St. Petersburg

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Abstract*: *Geomechanical approaches to creating the concept of safe development of the underground space in metropolitan cities have been considered. The concept of choosing geomechanically safe parameters of structures and technologies of building underground structures is based on the principle of minimizing the harm to urban facilities located on the surface of the earth. A method of predicting subsidence of the earth's surface in building underground structures in dense urban areas has been developed. Principles of developing slightly settling building technology to be used in the underground structures in metropolitan cities have been discussed.

Index Terms*: *subway, station, underground structure, geomechanical model, numeric simulation, surface settling, deformation.

I. INTRODUCTION

Development of large cities is related to the complex development of underground space. These are subway facilities, transport and service tunnels, underground warehouses and storage facilities, infrastructure, shops, and other underground structures. The use of underground space of metropolitan cities creates the conditions for significantly decreasing the negative effect of industrial and service infrastructures, and solves the problem of urban transportation, and a number of social and environmental problems. At the same time, construction of underground structures can also have a negative effect on buildings and urban infrastructure facilities located in the area of their underworking with mining and construction work, which manifests itself in significant subsidence, damage to and destruction of buildings, structures and engineering communications, especially in the construction of subway stations and surface and underground transportation hubs.

Construction of any underground structures leads to changing the strain-stress state of the containing rock mass accompanied by its deformations that propagate to the surface of the earth; their magnitude and nature depend on many factors. The most important include the engineering and geological conditions of building underground structures, the technological and design aspects of the building underground structures, and quality of works at all stages, from engineering research and design, until the actual construction of an underground facility and its subsequent operation. The issues related to the quality of works, although being very important in achieving any engineering tasks, stand outside, and will not be considered in the paper. In the paper, the main attention has been paid to the ways of decreasing the negative effects of building underground structures on the facilities of city infrastructure and the methods of predicting the development of rock mass deformations in the vicinity of underground structures, as an element of creating negative processes in the base of urban buildings. The method of choosing geomechanically safe parameters of structures and technologies of building underground structures is based on the principle of minimizing the harm to urban facilities located on the surface of the earth. Minimizing the harm to urban facilities is generally achieved if integral indicators of earth's surface deformation (in accordance with the normative documents, well-monitored parameters are relative vertical deformation, slope, curvature, relative horizontal defamation and combinations thereof) do not result in damage to buildings and structures, or, moreover, functional changes, or changes to the bearing capacity of individual structural elements of the considered facilities. It has been adopted that reaching the condition of minimizing the harm to a facility in the area after underground construction is achieved through monitoring the main technological operations of underground construction. The issues of geomechanically safe development of the underground space are relevant and have been studied to some extent by several researchers. For instance, papers [1, 2, 3] show the results of analyzing emergency situations in the construction and operation of underground facilities. Papers [4, 5, 6] discuss the stress-strain state of the rock mass around transport tunnels; anisotropy has been studied in paper [7]; supplement of the rock mass has been assessed in papers [8, 9, 10, 11]; the elastic plastic state of the soil around tunnel – in paper [12], the risks of developing the underground space have been assessed in paper [13], the stress-strain state of the structures of subway stations has been analyzed in papers [14, 15], the scale effect – in paper [16], strength properties and the structure of reinforcing concrete – in papers [17, 18], and predictions of the stress-strain state of the structures underworked by tunnels – in [19]. Interesting geomechanical approaches were discussed in papers [20 – 26] in studying the stress-strain state of the rock mass around underground facilities with complex spatial configurations.

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II. METHODS

Geomechanically safe development of the underground space is based on predicting subsidence of the earth's surface and developing the methods, technologies, and engineering activities that ensure the minimum subsidence of the earth's surface and emergency-free construction and operation of underground facilities.

Reducing the negative effect of underground construction on urban facilities may be achieved in two ways. One is developing additional engineering measures not related directly to the construction of the underground facility, which may have some beneficial effect on the safety of structures and buildings located on the surface of the earth. Such measures may include reinforcing the structure of buildings and facilities, including the foundation, creating a rigid pad in the base of buildings, making artificial structures in the zone of intensive soil deformation in the form of a solid wall or a wall of bored piles. One can also mention various methods of compensatory grouting of mortars into the rock mass. Such measures require additional costs, allocation of land plots on the surface for construction work; however, the measures themselves do not always prove to be effective in practice. From the point of view of the authors, a more rational approach is using the so-called sparing methods of building underground structures which directly influence the number of expected deformations of the earth's surface. Such measures may be attributed to the second category of the methods for reducing the negative effect of building underground structures in the city environment. Only these methods will be further mentioned in the paper.

Analysis of the experience in underground construction in the engineering and geological conditions of Saint-Petersburg allows formulating the following general requirements for the underground structure construction technologies that ensure safe development of the underground space in the metropolitan cities:

1) development of rock mass deformation in front of the working face of an underground structure should be limited as much as possible by avoiding development of plastic deformations;

2) the speed of an underground structure construction should be the maximum possible based on the adopted technology of construction; downtime or stopping of the excavation will lead to the development of long-term processes in the rock mass which have an adverse effect on settling of the earth's surface;

3) lining of an underground structure should be finished as fast as possible, in the best, before tunneling is started;

4) the introduction of underground structure lining into work (ring installation, high-quality back-feeling of the space behind the lining and gaining the required strength by the grout) should be made immediately after moving the face forward without forming a significant gap between the end of the lining and the rock circuit;

5) the elements of the temporary bracing that work in bending (a screen of tubes or its analogues, a cross-timbering scheme of face reinforcement, etc.) usually do not provide significant resistance to the development of rock mass deformations in the vicinity of underground facilities, and cannot be elements that are typical of the technology of low subsidence construction;

6) the measures aimed at reducing the negative affective building underground structures should not at the moment of their implementation result in the development of even more negative processes in the vicinity of the protected facility;

7) lining of an underground structure should be a rigid structure that prevents not only changing the volume of the internal space of the underground structure but also its shape;

8) the space-planning solution of an underground structure and the sequence of construction operations should exclude as much as possible intersections of individual elements of the underground structure;

9) opening of the cross-section of an underground structure should be made in parts, with reinforcement of the worked-out space with rock development.

Experience in building long tunnels, inclined and vertical shafts has shown that the least effect on the surrounding buildings may be achieved if they are built with the use of tunneling shields with loaded face front. However, even in this case, the degree of exposure varies considerably, and depends on the specific engineering and geological conditions and, to a greater extent, on the quality of performed works. For instance, building a large cross sections tunnel has shown that, with due observance of technological conditions, the magnitude of the earth's surface settling did not exceed 5 mm. At the same time, the use of this technology in building a second tunnel showed that the magnitude of the earth's surface settling above certain sections was 50 – 60 mm. The soil, which in the first tunnel was represented by semi-solid loams, and in the second tunnel – by plastic clays and water-saturated fine sand, also has a certain effect.

Building subway stations has the greatest effect on the development of the earth's surface deformations. The depth of the stations of the St. Petersburg subway is usually 60 to 80 meters (down to the arch of the subway station), and from the engineering point of view, there are stations of column type (including stations without side boarding platforms, and column-and-wall type stations), stations of pillar type and single-vault stations. Over the last decades, pillar type stations have mainly been built, with fewer stations of column type, while no stations of the single-vault type have been built in the subway. A reliable prediction of deformations of the rock mass in the vicinity of underground structures is only possible with regard to the peculiarities of the rock mass. These peculiarities include the nonlinearity of the elastic properties of the material, anisotropy of the deformation and strength characteristics, including the natural and forced anisotropy, material softening upon reaching the strength limit and compaction of the material under the action of medium stresses. Despite the fact that the aforesaid peculiarities are very important for correct prediction of rock mass deformation, the model of geomaterial that can predict these phenomena has a very complex mathematical description, requires special laboratory research, availability of many initial indicators, which imposes some limitations on its use in practice, and such a model is not intuitive.

Thus, for solving a specific practical problem, it would be rational to detect the main factors that influence the behavior of the rock mass, and the conditions of the rock mass in the vicinity of a rock outcrop. This approach will allow simplifying the creation of a model of developing the rock mass and its further use for solving practical problems.

The work represents the model of an environment that will allow predicting deformations in building underground structures in dense lithified clays in the conditions of a metropolitan city. Building subway facilities in the conditions of a metropolitan city imposes certain requirements on the mining method. Drivage should be performed to have the minimum effect on the rock mass, which in turn will allow reducing the value of earth's surface subsidence and the effect on buildings and structures in the vicinity of the drivage. This is achieved by introducing the lining into work immediately at the face of the tunnel, and high-quality backfilling of the space behind the lining. If these conditions are met, only small deformations occur in the vicinity of the underground structure, and development of plastic deformation in the margin is absent or very insignificant. In this case, the process of medium lithified clays' deformation is mainly influenced by their natural anisotropy of deformation properties, and by the strains and deformations acting at the considered point of the rock mass. Additional compaction of the clays may be neglected since subway facilities are usually located at relatively small depths, where the mean strains of the rock mass do not exceed the strain of pre-compaction for such clays. This effect is observed both in the range of very small to small deformations and with significant deformations.

Taking into account the peculiarities of dense clay work in the construction of underground structures, important aspects that should be reproduced by the developed model of the geomaterial are the following: anisotropy of the deformation properties, nonlinear elastic behavior in the range from very small (1·10-6) to small deformations (1·10-3), and the influence of mean stresses on clay deformation characteristics.

For clays with the medium and high degree of lithification, deformation properties vary in the vertical and the horizontal directions; clay properties in the horizontal directions are equal. Such clays may be considered as transversely isotropic media. For describing a transversely isotropic medium, seven constants are sufficient: Ev – the vertical elastic modulus (perpendicular to the plane of isotropy), Eh – the horizontal modulus of elasticity (in the plane of isotropy), vvh – Poisson's ratio characterizing the horizontal deformation caused by the longitudinal strains, vhv – Poisson's ratio characterizing the longitudinal deformation caused by horizontal strains, vhh – the Poisson ratio characterizing the horizontal deformation caused by horizontal strains (the strains in the orthogonal direction); Ghv – the shear modulus in the vertical plane (perpendicular to the plane of isotropy); and Ghh – the shear modulus in the horizontal plane (the plane of isotropy).

However, not all seven constants are independent of each other. Since the horizontal plane is the plane of isotropy, constant Ghh depends on Eh and vhh, as shown in equation (1)

$$G_{hh} = \frac{E_h}{2(1+2v_{hh})}. \tag{1}$$

For elastic materials, the condition of thermodynamic equilibrium should be satisfied for ensuring the symmetry of the rigidness matrix.

$$\frac{v_{hv}}{E_h} = \frac{v_{vh}}{E_v}. \tag{2}$$

Given the above requirements, the rigidity matrix for transversal isotropic linear elastic medium (Fig. 1) may be recorded with the use of five independent constants E_v, E_h, v_{vh}, v_{hh}, G_{hv}.

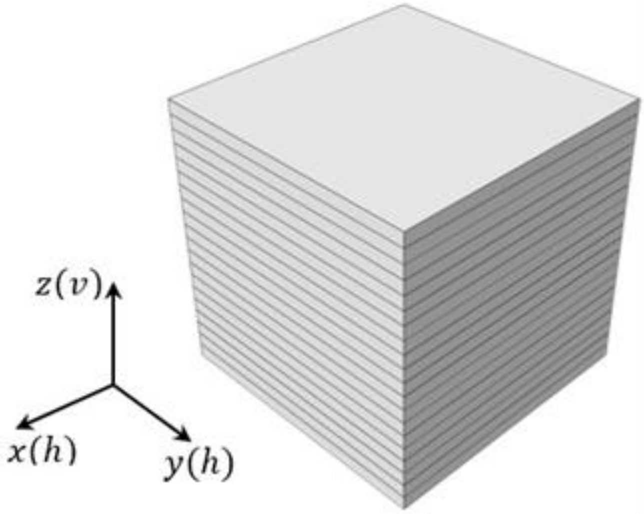

Fig. 1. Transversely isotropic medium: xy – isotropy plane; z – isotropy axis

To account for the nonlinear deformation of the transversely isotropic medium, it is necessary to establish the relationship between the elastic constants. In the work of Graham and Houlsby [27] the concept of anisotropy factor α has been introduced, which allows transition from two elastic constants E* and v* to the elastic constants needed for describing a transversely isotropic medium. The five above-mentioned independent elastic constants and one dependent constant may be expressed as follows.

$$E_v = E^*; \tag{3}$$

$$E_h = \alpha^2 E^*; \tag{4}$$

$$v_{vh} = \frac{v^*}{\alpha}; \tag{5}$$

$$v_{hh} = v^*; \tag{6}$$

$$G_{hv} = \frac{\alpha E^*}{2\left(1+v^*\right)}; \tag{7}$$

$$G_{hh}=\frac{\alpha^2 E^*}{2\left(1+v^*\right)}. \quad (8)$$

As one can see from the expressions shown, the ratio of elastic moduli, Poisson's ratios, and the shear moduli are related to each other in the following relationship:

$$\alpha=\sqrt{\frac{E_h}{E_v}}=\frac{v_{hh}}{v_{vh}}=\frac{G_{hh}}{G_{hv}}. \quad (9)$$

Expression (9) is a significant assumption, and several researchers noted that its correctness is questionable, since all the five elastic components are independent themselves.

Let us express the flexibility matrix with regard to correlation (3) and (9)

$$\mathbf{C}=\frac{1}{E^*}\begin{bmatrix} \frac{1}{\alpha^2} & -\frac{v^*}{\alpha^2} & -\frac{v^*}{\alpha} & 0 & 0 & 0 \\ \frac{v^*}{\alpha^2} & \frac{1}{E_h} & -\frac{v^*}{\alpha} & 0 & 0 & 0 \\ -\frac{v^*}{\alpha} & -\frac{v^*}{\alpha} & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{2\left(1+v^*\right)}{\alpha} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{2\left(1+v^*\right)}{\alpha} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{2\left(1+v^*\right)}{\alpha^2} \end{bmatrix}. \quad (10)$$

As one can see from expression (10), description of the transversal isotropic medium requires three parameters: the equivalent elasticity modulus E*, Poisson's ratio v*, and the anisotropy factor α. In such a setting, for describing the nonlinear behavior of a transversely isotropic medium, it is sufficient to set a nonlinear law of behavior for an isotropic medium; the relationship between other indicators of deformation properties is implemented according to expression (10).

For medium lithified clays, the nonlinear behavior is mainly observed in the range from very small to small deformations. In the range of small deformations up to the ultimate strength (the value of axial deformation at the strength limit of 1 – 2 %), dense clays exhibit linear behavior, except for the segment of intense fracturing. Nonlinear work of the rock in the range from very small to small deformations may be conveniently demonstrated using the dependence suggested by Hardin and Drnevich [28], which binds the shearing strain and the shear deformation:

$$\tau=\frac{G_0\gamma_{hist}}{1+a\left|\frac{\gamma_{hist}}{\gamma_{0.7}}\right|}, \quad (11)$$

where G0 is the initial shear modulus with very small deformations; γhist is the shear deformation; γ0.7 is the boundary value for shear deformation; and a is the curve parameter.

By rewriting equation (11) using the secant shear modulus Gs, we will get the following expression

$$\frac{G_s}{G_0}=\frac{1}{1+a\left|\frac{\gamma_{hist}}{\gamma_{0.7}}\right|}. \quad (12)$$

During numerical modeling, it is necessary to convert the secant shear modulus of expression (12) to tangential shear modulus

$$G_t=G_0\left(\frac{\gamma_{0.7}}{\gamma_{0.7}+a\gamma_{hist}}\right)^2. \quad (13)$$

Assuming that the Poisson ratio v does not change in the process of loading, the bulk compression modulus can be determined by the magnitude of the actual shear modulus at the moment of loading

$$K_t=G_t\frac{2\left(1+v\right)}{3\left(1-2v\right)}. \quad (14)$$

The influence of mean stresses p on the ability of the rocks to resist the distortions may be introduced via the power law

$$G_0=G_0^{ref}\left(\frac{p}{p^{ref}}\right)^m, \quad (15)$$

where pref is the average reference strain; G0ref is the shear modulus obtained with p = pref; and m is the power exponent. Such a relationship between the deformation characteristics of the soil and the average train is quite common in works of researchers from Germany, Austria, USA, and other countries.

However, expression (15) in some cases may lead to an unstable solution, when value p tends to 0. By making a number of changes in expression (15), this problem may be solved as follows:

$$G_0=G_0^{ref}\left(\frac{\sigma_3+c\ ctg\varphi}{p^{ref}+c\ ctg\varphi}\right)^m, \quad (16)$$

where σ_3 are the main minimum strains; is the grip; and φ is the angle of internal friction.

The boundary value of the shear modulus may be its value G_{ur} obtained based on testing a rock sample during unloading and subsequent loading in the range from small to significant deformations.

$$G_{ur}=\frac{E_{ur}}{2\left(1+v_{ur}\right)}. \quad (17)$$

Given expressions (14) and (17), the value of shear deformations γ_c at the lower limit of small deformations is defined as

$$\gamma_c=\frac{\gamma_{0.7}}{a}\left(\sqrt{\frac{G_0}{G_{ur}}}-1\right). \quad (18)$$

III. RESULTS

The above expressions (12) – (18) allow describing the nonlinear elastic behavior of an anisotropic medium. According to the obtained formulas, each moment (deformation value) may be easily mapped to the value of the tangential shear modulus and the bulk compression modulus. Transforming the bulk compression modulus and the shear modulus, respectively, to indicators, such as the tangential elasticity modulus, the Poisson's ratio, and substituting them in (11), considering equations (5) – (9), we get the tangent flexibility matrix of a transversely isotropic medium.

As an example, let us consider the task of predicting subsidence of the earth's surface during construction of a subway station complex in St. Petersburg. The station complex includes three station tunnels, a tension station, a traction-secondary substation, and a number of access workings. Between the station tunnels, three meters wide openings are made. The diameter of the side station tunnels is 8.5 m, the diameter of the central station tunnel is 9.8 m.

The station is located in dense proterozoic clays. The depth of the station from the ground surface to the arch of the central station of the tunnel is 46.9 m. The distance from the top of the arch of the station tunnel to the contact of Proterozoic clays with disturbed dense clays is 12.6 m. The thickness of the disturbed clays is taken equal to 7.2 m. The thickness of Quaternary deposits is 27.1 m. The layers' thickness along the length and the width of the station has not been changed. Thus, the entire rock mass can be divided into three layers: the first layer is quaternary deposits; the second layer is disturbed Proterozoic clay; and the third layer is Proterozoic clay. Numerical simulation was performed in the Abaqus universal software package. The soils in the first and second layers were considered an elastoplastic medium (the Coulomb-Mohr model). The soil in the third layer was considered a nonlinear transversely-isotropic medium. The transversely isotropic nonlinear elastic soil model was translated to the Abaqus software package through user subprogram UMAT. The calculated mechanical properties of soils taken for numerical simulations are summarized in Table 1.

Table 1. Calculated mechanical soils' properties

Layer No.	Density ρ, kg/m^3	Deformation modulus E_0, MPa	Transversal deformation ratio ν	Grip c, KPa	Internal friction angle φ, deg
First layer	2,000	12	0.3	15	20
Second layer	2,100	60	0.4	100	22
Third layer	2,200	130	0.4	-	-

In predicting subsidence of the earth's surface using numerical analysis, an important aspect is the correct choice of the model dimensions. In the paper, the model dimensions were chosen using the iterative method. The model boundaries retreated from the center of the model until the results of numerical simulation in the previous and subsequent steps of the simulation became equal (the discrepancy not exceeding 5 %). The obtained dimensions of the model were 600 m wide, 100 m high, while the size of the model that coincided with the direction of the longitudinal axis of the station was determined using the space-planning solution of the station complex and adjoining tunnels.

Given the considered scale of the numerical model, detailed numerical modeling of the sequence of building individual elements of the station complex was not performed. In the numerical model, the following stages of building the station complex have been distinguished: forming the initial strain state of the rock mass; excavation of the central station tunnel along its entire length; lining the central tunnel of the station along its entire length; building the left tunnel along the entire length, lining the left tunnel along its entire length; building the right tunnel along its entire length, lining the right tunnel for the entire length; making apertures; developing apertures; building the tension station. Construction of the inclined tunnel was not considered during numerical modeling. The problem is solved in the classic boundary conditions for tunneling tasks. No restrictions apply to the upper boundary of the numerical model. The nodes may be moved in any direction. Displacement in any direction is prohibited at the lower boundary. On the sides of the model, displacements are prohibited in the direction perpendicular to the surface of the numerical model.Dimensions of the model were chosen to exclude the influence of the boundary conditions on the calculation results. Model width was 600 m, model length was 444 m, and the height was 100 m.The pattern of the soil mass deformation corresponding to the end of tunneling is shown in Figure 2. Even without a detailed analysis, it can be noted that the maximum deformations were formed at the interface of the underground hall of the station and the approach working that connects the hall of the station and the escalator tunnel.

Deformation of the soil mass in the arched part of the station complex is mostly stronger, compared to the deformations in the trough part. In general, the pattern of soil mass deformation in the vicinity of the station complex is what has been expected.

The authenticity of the submitted geomechanical model was assessed based on comparing the results of the numerical simulation to the typical nature of the earth's surface subsidence trough caused by underground construction. Comparison with the field data is provided in the paper since in the first stage of developing the geomechanical model, the most interesting was a qualitative comparison, the potential possibility of reliably predicting the earth's surface subsidence trough (this is impossible in considering the soil mass as a linearly deformable medium). In subsequent works, a quantitative assessment will also be performed.

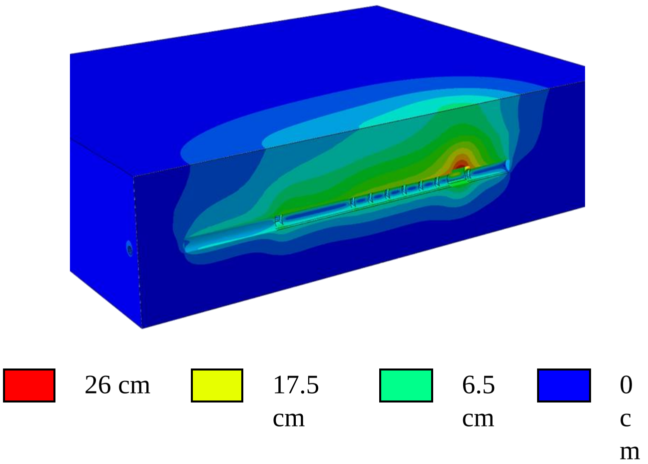

Fig. 2. Soil mass deformation in the vicinity of the subway station complex

In the work of Pekka [29], it has been shown that the earth's surface subsidence trough in the transverse direction may be described with a sufficient degree of confidence by the normal distribution function

$$S_v(x) = S_{v,\max} \cdot e^{-\frac{x^2}{z \cdot i_x^2}}, \qquad (19)$$

where $S_{v,\ max}$ is the value of the maximum earth's surface subsidence above the longitudinal axis of the tunnel; x is the distance from the center of the tunnel to the point considered; i_x is the distance from the center of the tunnel to the bending point; and z is the distance from the surface of the earth to the center of the tunnel.

IV. DISCUSSION

Figure 3 shows a comparison of the transverse earth's surface subsidence troughs obtained by numerical simulation and built using the semi-empirical method. One can see that in general the results of the numerical simulation, from the qualitative point of view, well coincide with the normal distribution curve. Insufficient differences in some parts may be caused by more complex processes of soil mass deformation in the vicinity of the subway station.

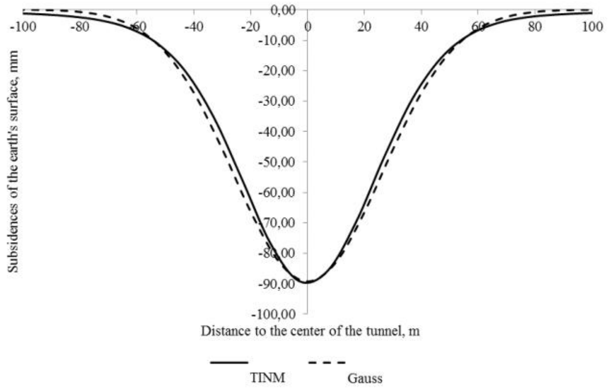

Fig. 3. Comparison of the predicted subsidences of the earth's surface obtained using various methods: TINM – Transversely Isotropic Non-linear Elastic Model of the Medium; Gauss – the normal distribution function

The presented mathematical description of the nonlinear elastic transversely isotropic medium allows increasing the accuracy of prediction of rock mass deformation, in particular, prediction of earth surface subsidence in building PIG and underground structures, prediction of the foundation subsidence, displacement of the contour of PIG and underground structures. Unlike most models of geomaterials, the considered model represents the class of nonlinear elastic models. The advantage of this approach is the ease of implementing such models in the calculation complex that implements the finite element or the method of finite differences. The main disadvantage is the impossibility of describing more complicated processes that occur in the soil mass under external influence. In particular, the above-described approach is not recommended in assessing deformations of a soil mass composed of weak soils, where the processes of compaction and softening may play a critical role. Another limitation of the model is the possibility of using it only under monotonic loading. In this formulation, the cyclic loading of the soil cannot be reproduced. These shortcomings do not have a significant effect on the accuracy of predicting the earth's surface subsidence and may be removed by the formulation of the model for the elastoplastic setup.

V. CONCLUSION

Geomechanically safe development of the underground space is based on predicting the stress-strain state of the soil mass, developing methods and technologies of building underground structures that ensure the minimum subsidence of the earth's surface, and monitoring during working and construction. The method of predicting subsidence of the earth's surface during the construction of underground structures has been developed. The results show the necessity of implementing the so-called low-subsidence methods of underground construction performed using the trenchless method, and of searching for new technological and design solutions.

An efficient way to monitor the development of the rock mass deformation is the method of advanced fastening the rock mass, which allows minimizing free deformation of the rocks in the critical zone, which is beneficial for both displacement of the rock contour directly in the vicinity of the underground structures by reducing the extent of decompression and damage to the rock mass, and for forming deformations directly in the base of urban development facilities. In this paper, solutions are offered that would allow implementing this approach both at the stage of building auxiliary underground structures and during the construction of large cross-section underground structures. This solution was shown on the example of building a single-vault subway station in the engineering-and-geological conditions of St. Petersburg. The efficiency of the offered method of building underground structures has been proven through mathematical modeling.

The results of mathematical modeling have shown that the use of a set of measures for decreasing the negative effect of new underground construction helped reduce twice the earth's surface subsidence, while the relative deformation of the earth's surface, which determined the severity of the negative effect, decreased more than twice.

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