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Analysis of the mathematical modelling results of displacements and deformations induced by the construction of the escalator tunnel of "Mining Institute" station in Saint Petersburg

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Abstract. The article presents the results of mathematical modelling of geomechanical processes that occur during the construction of an escalator tunnel using EPB TBM at the «Mining Institute» station in Saint Petersburg. A numerical model was built using the finite element method implemented in «Plaxis 3D» software. Hardening soil model was used for modelling of soil massif. The analysis of the distribution of displacements and deformations in the main cross-sections of the displacement trough is performed. Issues of assessing the harmful effects of underground construction on undermined buildings and structures are considered. Based on the research, we can conclude that the construction of a tunnel is safe for undermined buildings with strict tunnelling technologies compliance.

1. Introduction

The construction of subway structures is a complex technological process which requires competent engineering solutions. In Saint Petersburg, underground construction is complicated by specific geological conditions, so tunnelling is carried out at considerable depth (about 70 meters and more). During the construction of underground structures, a displacement trough inevitably occurs on the earth's surface. Since the construction of the subway in most cases takes place on a densely built-up urban area, it is necessary to analyze the harmful effects of the development of underground space on the undermined surface. Many researchers have dealt with issues of assessing the harmful effects of underground construction [1-4]. Even though the use of tunnel-boring machines with earth pressure balance shield (EPB TBM) allows decreasing the harmful effect due to the holding of the face and filling of the backfill space, the forecast of displacements and deformations during the construction of new facilities is an actual problem. A significant number of publications are devoted to the analysis of displacements during tunnelling using EPB TBM [5-6]. The prediction allows assessing the degree of harmful effects of development on undermined buildings and structures at the stage of construction planning. This article discusses the unique experience of driving the inclined tunnel «Mining Institute» using the EPB TBM «Herrenknecht AG» in the difficult mining and geological conditions of Saint Petersburg. A large-diameter tunnel crosses at an angle of 30° water-saturated, unstable soil layers lying at a shallow depth. The mechanized tunnelling has a dangerous effect on the soil massif and the earth's surface. Therefore, it is necessary to predict displacements and deformations.



2. Research methods

We used Plaxis 3D software to carry out mathematical modelling of displacements and deformations of the undermined surface. The program implements a finite element calculation method of the stress-strain state of the array, which is widely used for research around the world [7-9]. One of the advantages of this modelling method is the possibility of obtaining a numerical solution to the problem at the output, rather than an analytical dependence. This allows simulating the stress and strain state around structures of various configurations.

A Hardening Soil model was used for simulating soil behaviour in this research. As shown in the research[10], the calculations of hardening soil models are well within the results of field mine surveying observations. Due to the complexity of the tunnelling geometry, the soil massif is simplistically represented by four horizontal layers: a human-made soils layer, a Quaternary layer and two layers of hard clays. The deformation characteristics of the soil layers composing the massif are presented in Table 1..

Table 1. Material properties

Parameter	Man-made soil	Quaternary layer	Hard clay (1)	Hard clay (2)
Material model	Hardening Soil	Hardening Soil	Hardening Soil	Hardening Soil
Specific gravity, λ , kN/m ³	18.9	26.9	26.7	26.7
Modulus of deformation, E_{50} , kN/m ²	9600	36000	160000	320000
Modulus of deformation, E_{oed} , kN/m ²	9600	36000	160000	320000
Modulus of deformation, E_{ur} , kN/m ²	28800	108000	480000	960000
Poisson's ratio, ν	0.30	0.37	0.35	0.35
Internal friction angle, ϕ , °	25	20	21	23
Cohesion, c , kN/m ²	2	15	50	150

The tunnel construction process was divided into three stages: fixing the soil of the massif at the beginning of the tunnel using jet grouting, excavating the soil of the starting pit, tunnelling with the construction of the lining. The escalator tunnel runs at an angle of 30° to the horizontal surface and has a length of 117.2 m. The outer diameter of the lining is 10.4 m, the thickness of the lining block is 0.5m. Figure 1 shows the main stages of the simulation.

Verification of the model was carried out by comparing the value of calculated maximum subsidence on the surface (50 mm) with the value obtained from the experience of driving on similar objects (escalator tunnels of the «Admiralteyskaya» and «Spasskaya» stations). Based on the simulation results, an analysis was made of the displacements and deformations that occur on the surface from the escalator tunnel. The subsidence at the surface reaches a maximum value in the area after the portion of ground strengthening by jet grouting (Fig. 2). Subsidence is decreasing as the tunnel crosses the Quaternary soil layers and enters the clays.

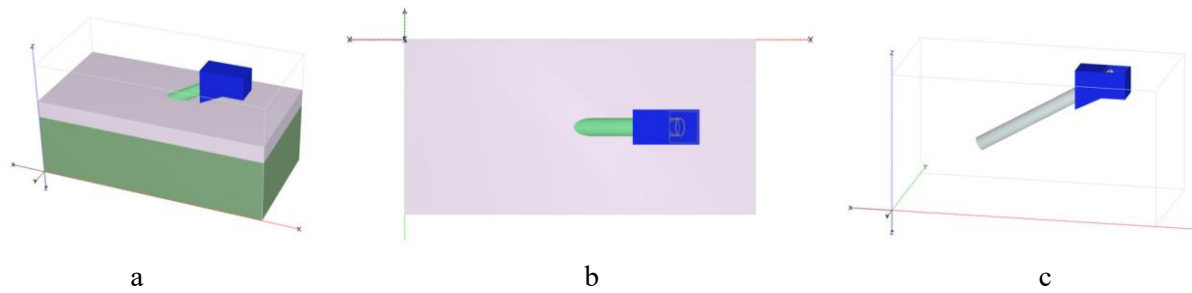


Figure 1. Modelling of the tunnel: a – jet grouting; b – excavating the soil of the starting pit; c – tunnelling.

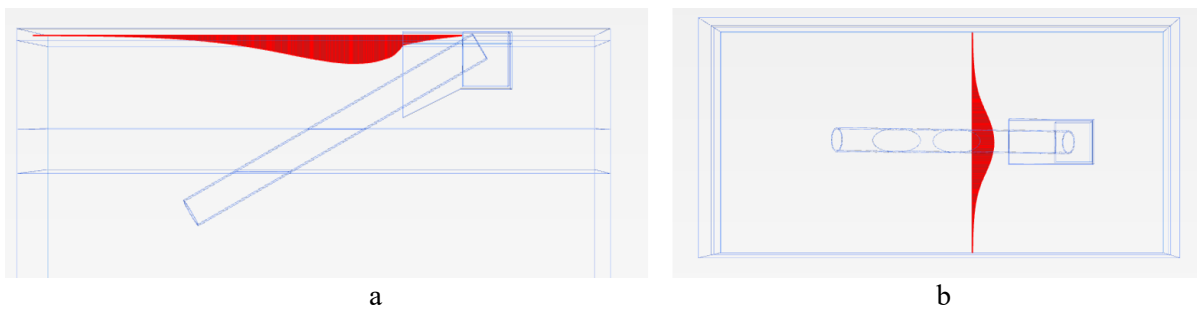


Figure 2. Distribution of vertical displacements: a – in the main longitudinal section; b – in the main cross-section.

Horizontal deformations are derivatives of horizontal displacements and appear as zones of tension and compression in the massif. As a result of modelling a compression zone forms near and above the tunnel, and it is replaced by a tensile zone further. Figure 3 shows the distribution of horizontal deformations on the surface.

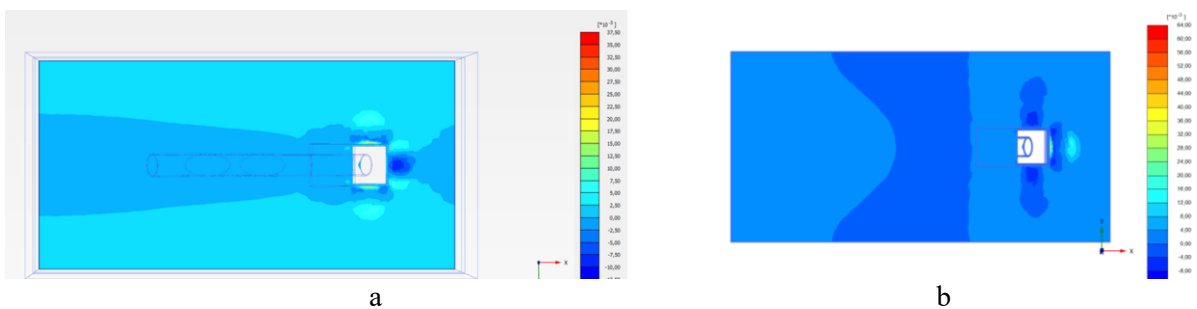


Figure 3. Distribution of horizontal deformations: a – along the axis of the tunnel xx; b – along the yy axis.

The horizontal tensile deformations on the earth's surface from the escalator tunnel construction do not exceed $0.2 \cdot 10^{-3}$ in the main longitudinal section, and $1.0 \cdot 10^{-3}$ in the main cross-section.

3. Results and discussion

Based on the obtained values of subsidence, the values of deformations of curvature and slopes were calculated with MS Excel. For the two main sections of displacement trough, we plotted displacement and deformations distribution diagrams calculated deformations of the inclinations and curvatures using the obtained subsidence with MS Excel. Figure 4 shows the distribution of displacements and deformations on the surface.

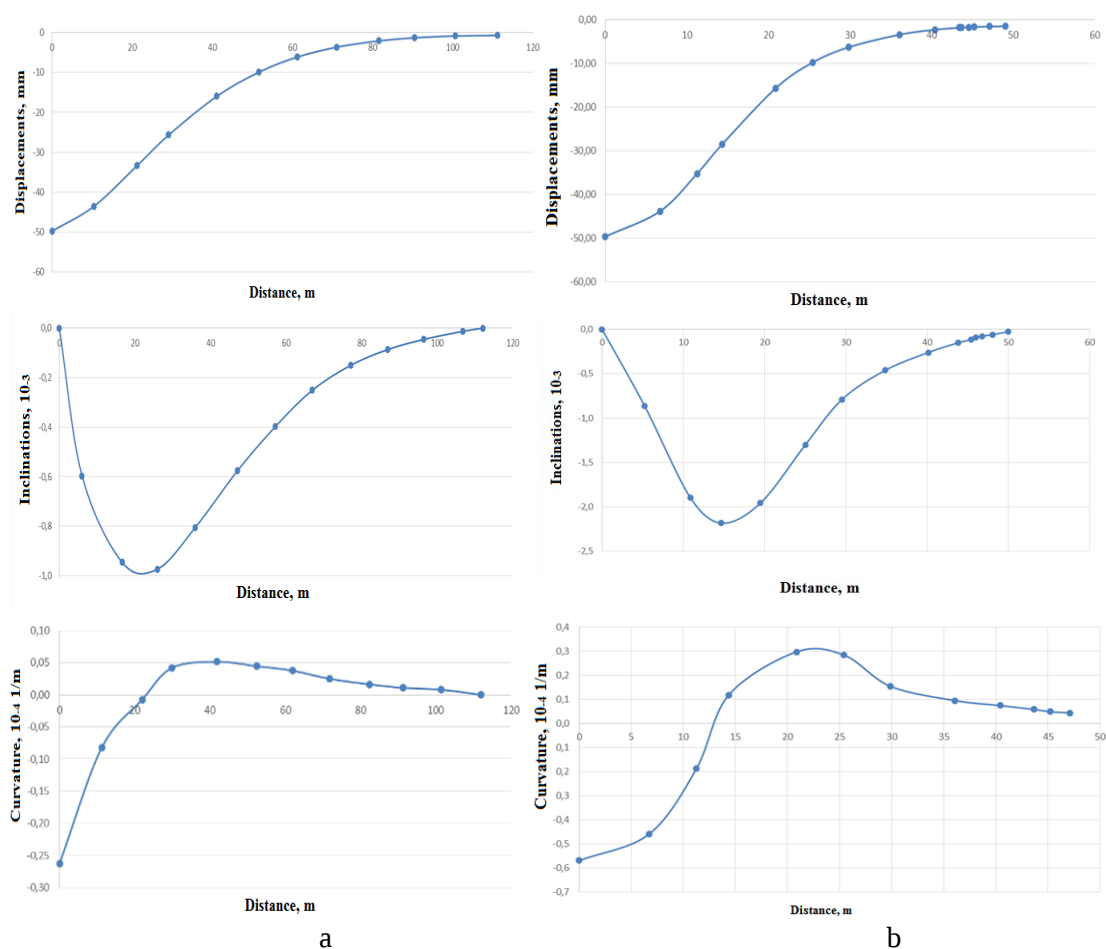


Figure 4. Distribution of deformations in the displacement trough: a – in the main longitudinal section; b – in the main cross-section.

We compared the simulation results with the values adopted to determine the boundary of the zone of the harmful effects of mining. Table 2 shows the comparison results. As it is seen from the data presented in Table 2, the predicted values do not exceed the specified boundary criteria for the zone of harmful influence.

Table 2. Comparison results

Parameter	Values for hazardous area boundary	Maximum values in the main longitudinal section	Maximum values in the main cross-section
Deformations of inclination	$4.0 \cdot 10^{-3}$	$1.0 \cdot 10^{-3}$	$2.0 \cdot 10^{-3}$
Deformations of curvature, 1/m	$0.2 \cdot 10^{-3}$	$0.03 \cdot 10^{-3}$	$0.06 \cdot 10^{-3}$
Horizontal deformations	$2.0 \cdot 10^{-3}$	$0.2 \cdot 10^{-3}$	$1.0 \cdot 10^{-3}$

4. Conclusion

For a more detailed assessment of the conditions for safe underworking of structures located in the zone of displacement trough, it is necessary to compare the calculated values with permissible and limit values of horizontal deformations for buildings and structures. Figure 5 shows five buildings located in the displacement trough.

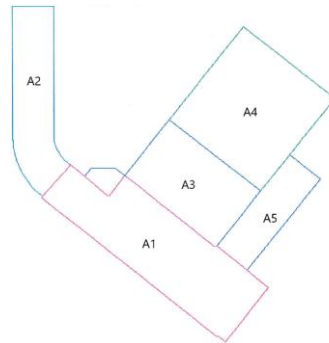


Figure 5. Undermined building layout.

Unfortunately, the limited format of the article does not allow presenting a detailed calculation of the values of permissible and limit deformations. The calculated values of permissible and limit values of horizontal deformations for each building are presented in Table 3.

Table 3. Permissible and limit values of horizontal deformations

Building №	1	2	3	4	5
Permissible horizontal deformations, $1 \cdot 10^{-3}$	4.4	5.2	6.6	6.3	6.3
Limit horizontal deformations, $1 \cdot 10^{-3}$	6.6	7.8	9.9	9.4	8.6

Analyzing the data obtained, we can conclude that the predicted as a result of modelling deformation values are no more than 23% of the values of permissible horizontal deformations. Consequently, with strict tunnelling technologies compliance, the escalator tunnel construction using EPB TBM is safe for all undermined buildings, and additional protection measures for buildings are not required.

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