International Journal of Applied Engineering Research ISSN 0973-4562 Volume 11, Number 18 (2016) pp 9240-9247
© Research India Publications. http://www.ripublication.com

Patterns of Soil Mass Movement during the Construction of the Metro Station Using the "Top-Down" Technology

Dmitriy Aleksandrovich Potemkin, Olga Vladimirovna Trushko, Mikhail Grigorievich Popov

Saint-Petersburg Mining University, Saint-Petersburg-199106, Russia.

Abstract

The object of the study is the geomechanical processes in the rock mass in the construction of the underground excavations. The methods of mathematical modeling of geomechanical processes on the basis of the finite element method and the data from field investigations of displacement and deformation of rocks were used for the prospective evaluation.

The paper represents the results of the prospective evaluation of displacements and deformations that are applicable to specific geological conditions of the construction of underground excavations in the area of the northern part of the Nevsko-Vasileostrovskaya Line of the Saint Petersburg Metro (Russia).

Keywords: displacement and deformation of rocks, surface subsidence, underground construction, metro tunnels.

INTRODUCTION

The scope of the work was to forecast displacement and deformation of rocks associated with the construction of the underground complex of boiling and station excavations of the projected area of the Nevsko-Vasileostrovskaya Line of the Saint Petersburg Metro from Primorskaya station to Savushkin Str. station. The forecast is based on mathematical modeling using the finite element method. In the future, the simulation results are considered by the example of Novokrestovskaya station. An important feature of the considered underground complex of the Nevsko-Vasileostrovskaya Line is the use of a whole range of technical and technological solutions new for the St. Petersburg Metro, announced by the designers, notably the solution for boiling excavations in the form of shallow double-track tunnel and the use of the construction for it in unstable and watered rocks of the mechanized tunnel-driving complex (MTDC) with the earth pressure balance, as well as the solution for the three shallow station complexes, constructed using the "top-down" technology.

Construction of the underground excavations leads to disruption of the natural balance in the rock masses, a change in their state of stress and the emergence of strains. The change of the stress-strain state of the rocks leads to rock displacement, which, developing from a mass of areas close to the contours of the excavations, can reach the earth's surface, forming a subsidence zone (or displacement trough). These deformation processes are often complex. Their qualitative characteristics and quantitative parameters are determined by many factors. The main ones should include factors related to the characteristics of engineering and geological conditions, structures of load-bearing elements of the underground facilities and the technology of their construction. Only the simultaneous consideration of all these factors makes it possible to provide basic reliable estimate of displacement and deformation of rocks.

Classical methods for estimating displacements and deformations do not allow for the calculation of rock deformation along the undermining mass strata, so the methods of mathematical modeling based on numerical methods are used for these purposes, and the finite element method is used as such in this paper. This method has long established itself in the solution of geotechnical problems and is widely used in our country and abroad for similar purposes.

A significant problem in the application of both theoretical methods and numerical simulation is to provide not only qualitative but also the quantitative models matching the actual deformation processes. It is known that even small changes in the source data for the simulation can significantly change the results of forecasts. Physico-mechanical properties of rocks (soil) and permanent excavations supports, parameters of the temporary excavations support elements (MTDC elements, etc.) and a choice of modes of collaborative mechanical work of the tunnel complexes elements, permanent support and rocks have the greatest impact on the quantitative component of the model calculations.

The data of field surveying measurements taken during the construction of such facilities in similar geological settings can be used to reduce the influence of inaccuracies in determining the values of these baseline characteristics and improving the reliability of displacement and deformation simulations. These data allow us to adjust the input parameters of the models on the test models of already constructed facilities. Using this approach, the well-proven in the classical mining geomechanics, and the accuracy at the level of a qualitative description of the laws of the geomechanical processes is provided. Practice has shown that the accuracy of the forecast displacement of rocks obtained in the calculation using field data on analog facilities is comparable to the accuracy of surveying and geodetic measurements and meets the requirements specified in the sphere of protection of buildings and structures from the harmful effects of mining operations. This approach in the framework of mathematical modeling of displacement based on the finite element method is used in this paper.

2. METHODOLOGY

2.1 General information on technology and simulated construction stages of the facility under consideration.

The new for the geological conditions of the St. Petersburg Metro [1-3] technology of construction of the double-track tunnel is based on the use of mechanized tunnel-driving complex (MTDC) with a soil bottomhole weight and precast concrete block of high-precision waterproof lining. The estimated penetration rate is 200 m/month.

The application of MTDC with a soil (slurry) bottomhole weight is characteristic for the conditions of saturated sedimentary, unstable and weak-stable soils [4-6]. In addition to providing high technology penetration values and minimizing the anthropogenic impact on the geological environment, the minimization of the Earth's surface subsidence through the use of active counterweight of the bottomhole and the system for cavity filling in overlining space.

In shields of this type, the rotary executive device is located in a sealed bottomhole chamber, tightly packed with developed rock. The excessive pressure of the soil to the bottomhole is adjusted by comparing the shield feed rate to the bottomhole with the performance of the screw conveyor delivering compacted soil from the bottomhole chamber. Foam, polymers and bentonite solution are also fed into the bottomhole chamber. These additives improve soil conditioning system. Foamed reagent forms air bubbles, whose internal pressure balances the external hydrostatic pressure. The soil weight mode provides plastically flowing state of the developed soil and its stable passage through the screw conveyor at a uniform pressure of the weight on the bottomhole plane. In addition to the system of the set pressure maintenance in the bottomhole chamber, the working body (rotor) affects the bottomhole, and its powerful feed force also has a moderating influence on the bottomhole. This tool for maintaining the bottomhole plane is especially important in emergency situations with the weight system.

Describing the tunnel, it can be noted in the constructive sense that its cross-section of circular outline was adopted with a view to ensuring the clearance to obstructions, equipment, and rolling stock with 4.0 m intertrack spaces and accommodation outside the clearance to equipment of service tracks and bridges, passenger evacuation routes, as well as the technological arrangement of tunnels (path devices, automation, remote control, communication, power, lighting, plumbing devices, etc.). A rigid base made of B15 class concrete is fitted in the tunnel bottom, and the smoke removal vent pipe is arranged above the clearance to obstructions.

Precast concrete circular lining is constructed as the MTDC moves forward and is mounted under its protection. The assembly precision waterproof lining of multifunctional rings with an inner diameter of 9.4 m, and external – 10.4 m consists of assembly precast concrete blocks. The ring consists of 7 rectangular block segments, and one latch segment. The nominal width of the blocks is 1500 mm, thickness – 500 mm. The blocks are designed of B60 concrete class by compressive strength, frost resistance grade – F200, waterproofing – W12 with reinforcement of blocks using A500S and B500C class armature.

The construction of shallow Novokrestovskaya station is based on the application of the slurry wall technology and “top-down” technology elements. In the first phase of the station construction, a wall in the slurry 1,000 mm width is erected to the level of dense moraine clays, the longitudinal walls should be constructed using flat clamshell with the split of 2.8 m with a continuous reinforcement, and the end walls will be constructed with the use of secant piles. In addition, before the start of the soil excavation two rows of pile-columns shall be erected inside the building envelope on the entire depth of the station. After the completion of the main building envelopes (slurry walls) and using concrete of the needed strength, the MTDC passes through the station body, constructing double-track tunnels. The soil excavation is performed in stages. The arrangement of another floor structure (with constructive and technological openings), which is simultaneously the spacer element for pit walls mounting, is performed at the end of each stage. At the approach to the tunnel lining, it shall be gradually dismantled.

2.2 Simulation of facilities complex construction

The mathematical modeling of geomechanical processes on the basis of the finite element method (FEM), which is implemented in ABAQUS software product (part of the validation calculations was performed in PLAXIS software package) is the tool of rocks displacement and deformation assessment [7-9]. The finite element method has provided a solution in the displacements in volume and flat setting the standard boundary conditions corresponding to the hypothesis of Academician A.N. Dinnik about the lack of horizontal deformation of rocks in the historical load of the mass (the absence of horizontal displacements in the vertical boundaries of the model and movements at the lower end of the model) [10]. To reduce the amounts of computation, and consequently, the total simulation time, a half of the designed area in the vertical plane of the symmetry (axisymmetric problem) was considered.

The soil mass was modeled using eight-node prismatic elements of “solid” type, structural elements – using four-node shell elements, and two-node beam elements. The total number of the model elements for Novokrestovskaya station was 96,000 pcs, for Savushkina Str. station – 112,000 pcs. The difference in the number of elements is due to the different configuration and power of soil layers and as a result, different number of elements, which were needed for the sampling of the soil mass area.

The construction of the station complex was modeled by the following design elements that come into operation according to the technological stages of the station construction: “slurry wall”; two-way running tunnel, driven through the volume of soil to be a recess in the construction of the station; four series of constructed floors, appearing after the respective stages of excavation; bored piles, columns, arranged in the soil before its recess [11-12].

Geometrical dimensions of the structural elements adopted in modelling: the total length of the station – 204.6 m; width – 25.6 m. Depth of the “slurry wall” – 25.0 m with the fences capacity – 1.0 m in length and 0.7 m – at the ends of the station; the diameter of the two-way tunnel – 10.4 m with a thickness of the lining – 0.5 m; four fences, arranged at elevations 15.2 m; 9.0m; 5.5 m and 2.59 m (the level of the rail head in running tunnels was taken as zero mark) have a thickness of 1.2 m (top) and 0.6 m (three bottom). Figure 1 shows the basic elements of stations and running tunnels design.

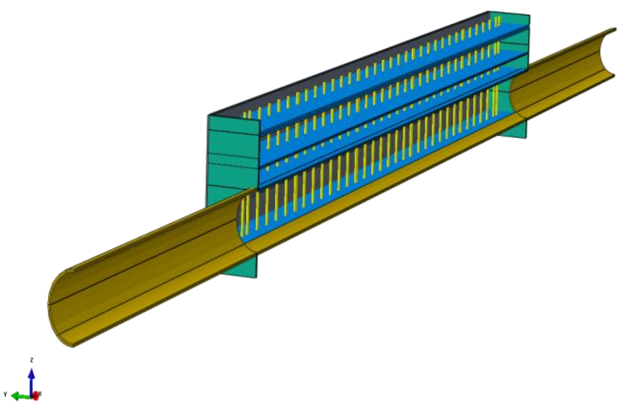

Figure 1. The relative orientation of the elements of reinforced concrete structures of the station complex.

Because of their multiplicity, diversity and capacity properties, the soil layers are grouped by similarity of physical and mechanical properties [13]. The soils are considered as the elastic-plastic medium in calculations, the strength of which is defined by the known Mohr-Coulomb criterion. The design physical and mechanical characteristics of the groups of soil layers for the two station complexes are shown in Table 1.

Table 1. Designed physical and mechanical characteristics of the groups of soil layers for the settings of Novokrestovskaya metro station.

Item No.	Name	Thickness of layer, m	γ, kg/m^3	E, MPa	ν	c, MPa	φ, °
1.	Group No. 1	6	1950	20.0	0.33	0.001	26
2.	Group No. 2	10	1960	7.0	0.37	0.010	14
3.	Group No. 3	4	1850	7.5	0.40	0.010	10
4.	Group No. 4	5	1950	12.0	0.36	0.012	13
5.	Group No. 5	-	2130	100.0	0.35	0.050	21

Note: γ – volumetric weight of the soil; E – soil deformation modulus; c – adhesion; φ – internal friction angle; ν – Poisson's ratio.

2.3 General modeling sequence

The resulting stress-strain state of the soil mass enclosing station complexes evolved in stages, with the sequential calculation of the following steps:

1. Geometrical calculation of own weight accommodating soil mass station;
2. Construction of “slurry wall” structure in the soil mass, and arrangement of pile-columns;
3. Driving of the two-way running tunnel, including through the volume of soil to be excavated in the construction of the station;
4. First phase of earthworks – excavation of soil from the surface to the first slab;
5. Installation of the first floor structure;
6. Second phase of earthworks – excavation of soil between the first and second floor structure;
7. Installation of the second floor structure;
8. Third phase of earthworks – soil excavation between the second and third floor structure;
9. Installation of the third floor structure with a partial dismantling of lining in canch of the running tunnel within the internal volume of the station;
10. Fourth phase of earthworks – excavation between the third and fourth (last) floor structure with the partial dismantling of the lining in the sides of the tunnels within the internal volume of the station;
11. Mounting of fourth floor structure.

General view of the model is given in Figure 2 and 3 shows a general view of the model with the “notch” in the place of excavation, and Figure 4 – general view of excavations and structural elements in the enclosing mass.

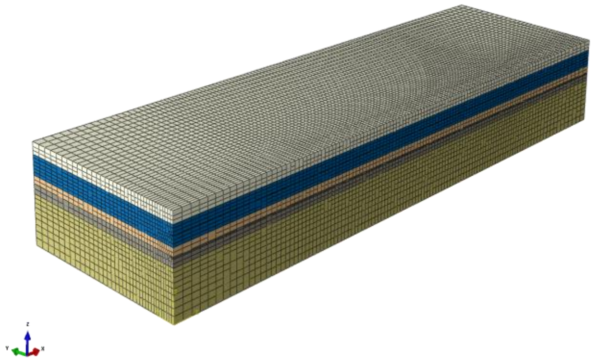

Figure 2. General view of the finite element model of the soil mass, enclosing the object in question.

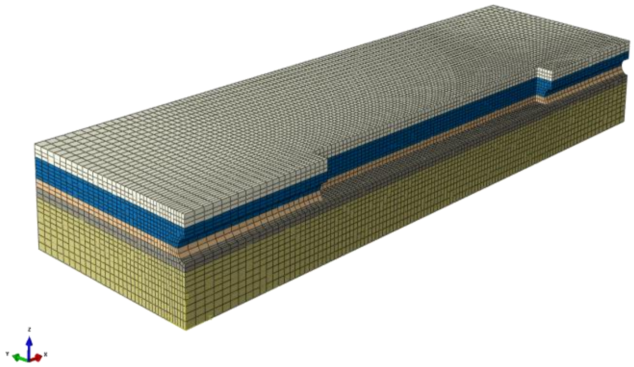

Figure 3. General view of the finite element model of the soil mass, enclosing the object in question with the “notch” in the place of the excavations.

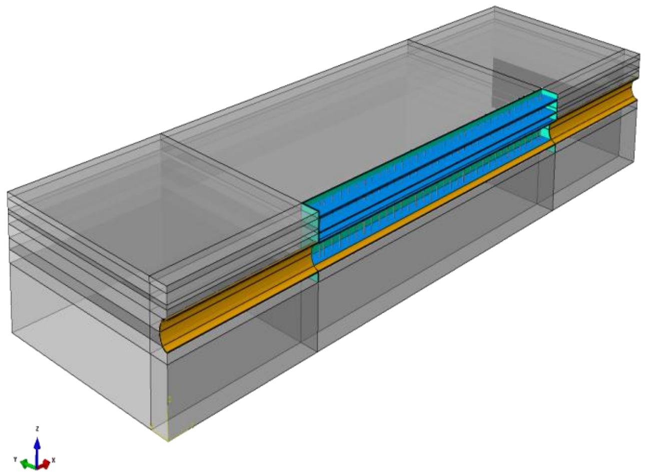

Figure 4. General view of the excavations and structural elements in the enclosing mass.

RESULTS

The maximum vertical displacement of the surface can reach 0.050 m directly from the “slurry wall” at 0.065 m in the bottom of the “wall” at a depth of 15.0 ... 25.0 m. Subsidence to 0.002 m can be traced up to at a distance of 29.0 ... 32.0 m from the “wall” (41.0 ... 44 0 m from the station axis) on the Y axis.

Numerical values of the vertical and horizontal displacements of the earth's surface (from the “slurry wall” on Y axis in the middle of the station) are shown in Tables 2 and 3.

Table 2. Numerical values of vertical displacements of the earth's surface during the construction of the Novokrestovskaya metro station.

Distance from the wall, m	Subsidence, m	Distance from the wall, m	Subsidence, m	Distance from the wall, m	Subsidence, m	Distance from the wall, m	Subsidence, m	Distance from the wall, m	Subsidence, m
0.00000	-0.050	15.6679	-0.029	32.7959	0.001	54.1817	0.000	80.9037	0.000
1.99535	-0.048	18.2624	-0.021	36.0392	0.002	58.2330	0.000	85.9658	0.000
2.12516	-0.049	20.9548	-0.014	39.4027	0.001	62.4362	0.000	91.2188	0.000
9.33928	-0.045	23.7540	-0.010	42.8954	0.001	66.7996	0.000	96.6710	0.000
10.7653	-0.042	26.6575	-0.004	46.5180	0.001	71.3271	0.000	102.329	0.000
13.1717	-0.037	29.6718	0.000	50.2796	0.001	76.0269	0.000	108.202	0.000

Table 3. Numerical values of horizontal displacements of the earth's surface during the construction of the Novokrestovskaya metro station.

Distance from the wall, m	Subsidence, m	Distance from the wall, m	Subsidence, m	Distance from the wall, m	Subsidence, m	Distance from the wall, m	Subsidence, m	Distance from the wall, m	Subsidence, m
0.0000	-0.0017	15.6681	-0.0269	32.7965	-0.0101	54.1827	-0.0064	80.9050	-0.0035
1.9954	-0.0063	18.2627	-0.0262	36.0401	-0.0079	58.2340	-0.0053	85.9670	-0.0026
2.1252	-0.0065	20.9553	-0.0257	39.4036	-0.0083	62.4373	-0.0055	91.2201	-0.0022
9.3391	-0.0193	23.7546	-0.0203	42.8963	-0.0067	66.8008	-0.0046	96.6723	-0.0014
10.7653	-0.0223	26.6582	-0.0162	46.5190	-0.0072	71.3283	-0.0046	102.331	-0.0008
13.1719	-0.0239	29.6724	-0.0111	50.2806	-0.0059	76.0281	-0.0037	108.203	0.0000

Figure 5 shows a diagram of vertical displacement of soil particles from the construction of Novokrestovskaya metro station, Figure 6 – the volume of soil involved in the movement during the construction of the station.

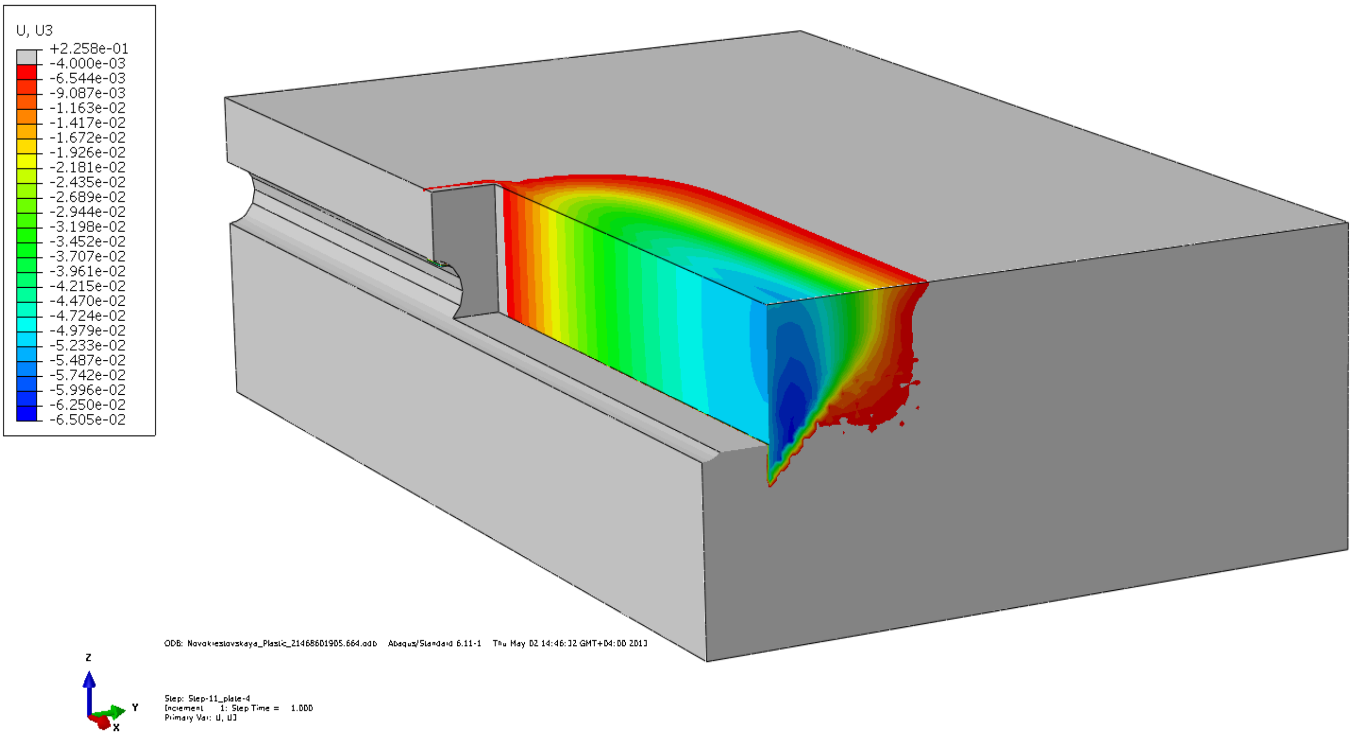

Figure 5. Resulting vertical displacement in the soil mass from the construction of Novokrestovskaya metro station.

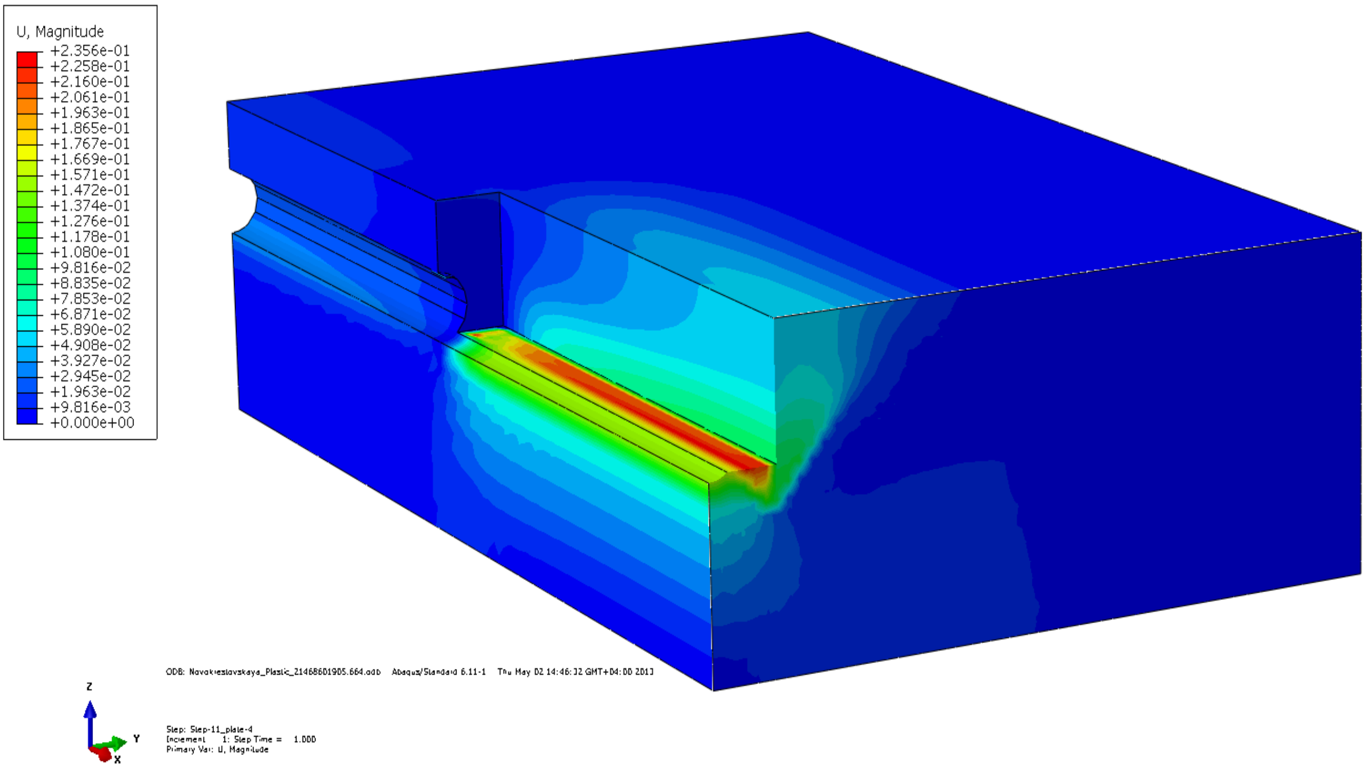

Figure 6. The volume of soil involved in the movement during the construction of Novokrestovskaya metro station.

Figure 7 shows a graph of the distribution of the vertical displacements of the earth's surface during the construction of Novokrestovskaya metro station and two similar stations (for comparison) in similar geotechnical conditions, and Figure 8 – horizontal displacements of the construction of the same stations.

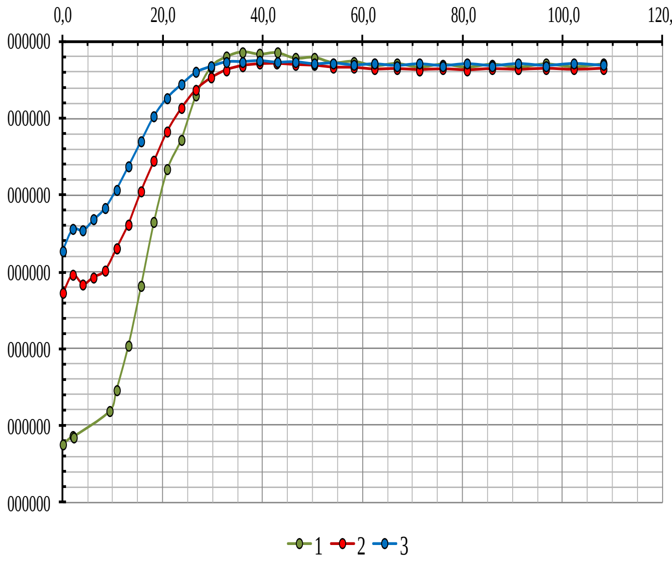

Figure 7. The distribution of the vertical displacements perpendicular to the axis of station (on Y-axis) from "slurry wall" to the mass (1 – Novokrestovskaya station; 2 – Savushkina Str. Station; 3 – Yachtennaya station).

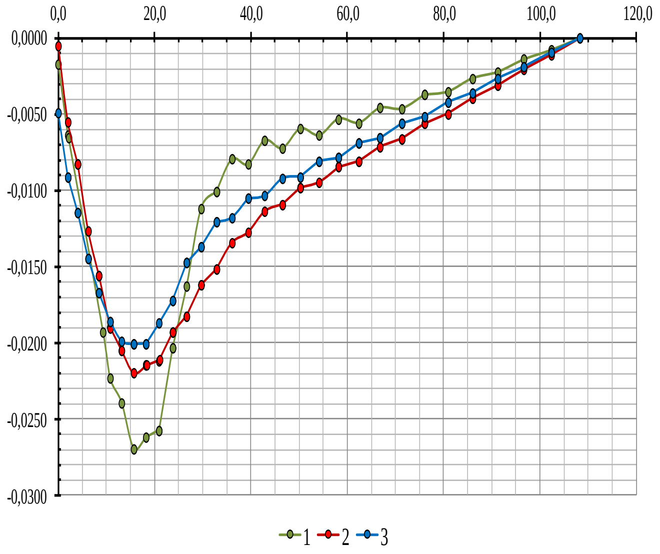

Figure 8. The distribution of the horizontal displacements perpendicular to the axis of station (on Y-axis) from "slurry wall" to the mass (1 – Novokrestovskaya station; 2 – Savushkina Str. station 3; – Yachtennaya station).

In general, the volume of soil involved in motion is symmetrically located on both sides of the station (along the extended sides of the station excavation). The following can be identified as the main reasons.

The goaf, gradually emerging and limited by elements of the "slurry wall", causes movement of soil masses, while the soil "leaves" in the goaf under the walls from the bottom of the pit, which is a cause of the Earth's surface subsidence in the construction area – the "volume loss" happens.

The second reason for the formation of the displacement area is a deformation of the protective structures. Confining pressure squeezes inside the wall forming pit of the protective structure together with surrounding soil volumes.

The displacement growth isn't seen from the end walls of the future station (from the start of construction of the station) because the availability of a hard "insert" in the soft ground in the form of a block lining of two-way running tunnel serves as a limiting factor. That is, at the interface of the running tunnel with the station end walls persists the subsidence that occurred at the time of through passage of the tunnel through the bulk of the future station [6, 14-15].

DISCUSSION

The construction of the excavation complex of the projected area of the Nevsko-Vasileostrovskaya Line, including two stations, a network of running tunnels and other excavations, is associated with the use of a number of technologies new for the St. Petersburg Metro, so the results of assessing the impact of such construction as set out in this report should be viewed as preliminary ones. The results of field observations are the most important element in ensuring the accuracy of rocks displacement and deformation.

The construction area is characterized by engineering and geological conditions typical for the north-west of St. Petersburg. The upper stratum is represented by quaternary unstable rocks, from a depth of 25-35 meters the indigenous Proterozoic rocks overlie. At the beginning and end of the designed site, the line has a deep foundation, the running and station excavations being built using the technology traditional for the St. Petersburg Metro. After deep foundation pylon station Zoopark in Primorsky District and to the borders of Vasilyevsky District, the line is designed in shallow foundations, the running tunnel is constructed using MTDC with rock weight, the mounting the camera and the station excavations are built using open pit mining with the use of the slurry technology.

Spatial models were used to assess the displacement and deformation of rocks in the construction of open pit excavations. The rocks were modeled in the elastoplastic formulation, and the bearing structures were modeled using elastic elements. The station structure modeling was carried out in stages relevant to the process steps.

In the construction of the main load-bearing structures of Novokrestovskaya station, the subsidence area appears, the maximum levels of which occur in the vicinity of the outer walls. The subsidence rapidly decays with the distance from the station, and the influence area reached the values of 40-43 meters. The greatest subsidence on Novokrestovskaya station at the wall reached 45-65 mm.

The values of displacement and deformations are obtained, subject to the observance of basic technological regimes during tunneling. The terms of reference did not provide for the assessment of the effects of the temporary withdrawal of the bottomhole weight, unfilling of overlining space behind MTD, long-term stop of bottomholes and other possible technological failures.

CONCLUSION

The lack of regulations, governing the protection of buildings, structures and natural objects from harmful effects of mining in the construction of underground facilities, defines the need for justification of the boundary criteria for the assessment of the zone of influence of mining operations and the lengths of the intervals in the displacement trough, as the direct use of standard documents related to mining production is impossible for these purposes, both due to formal inconsistency of the scope of these documents, and because of significant differences of geomechanical processes occurring in the mining [16-19].

During underground mining, the uneven subsidence, cracks, ledges and dips may appear on the earth's surface. The formation of cracks, ledges and dips is possible only during mining operations in the shallow and intensive excavation of rock. Such options of mining operations are mainly specific to the excavations in mining and are very rare in the practice of underground urban construction (in violation of tunneling technologies, emergency situations, etc.). Even in the formation of cracks and dips on the surface, the edge of the zone of mining operations influence is characterized by a smooth distribution of the subsidence, gradually decreasing (with the distance from the excavation) to zero.

Under the conditions of underworking without the formation of cracks, ledges and dips, a trough with a smooth change of subsidence is usually formed on the earth's surface. This trough is characterized by three sections: two edge sections with positive curvature (convex curvature), and a center section with negative curvature (concave curvature). These sections are separated by inflection points at which the curvature changes its sign. With symmetric distribution of displacements and deformations toward the point of maximum subsidence (in the case of horizontal bedding of rocks), it is sufficient to consider only half of the trough.

It should be noted that in assessing the impact of mining operations on the existing infrastructure the use of expansion criteria [20], operating forecast (at the design stage) and actual (under construction) values of displacement of rocks and their first derivatives – deformations, shall be considered as the most important. The use of vertical displacement (subsidence) of the surface (in pure form) as the sole and independent criteria when assessing the harmful effects of mining is not enough, because it itself is not able to determine the level of exposure of the undermining objects. Thus, in case of the same values of subsidence (soil) under the building, they may, in one case, have almost no influence on the bottom, foundation and other structural elements (at a substantially uniform distribution of subsidence at the bottom), and in another case they can result in significant damage or even to the loss of stability of bases or load-bearing structures and the destruction of buildings (in uneven subsidence).

REFERENCES

[1] A.V. Alekseev, S.Ya. Nagornyy, & T.P. Ryutina. *Otsenka fiziko-mekhanicheskikh svoystv verkhneproterozoyskikh glin, kak sredy stroitel'stva podzemnykh sooruzheniy Sankt-Peterburga* [Evaluation of Physical and Mechanical Properties of Upper Proterozoic Clay as a Medium of Construction of the St. Petersburg Underground Facilities]. St. Petersburg: Tim, 1978.

[2] *Instruktsiya po inzhenerno-geologicheskim izyskaniyam dlya proektirovaniya i stroitel'stva metropolitenov, gornykh zheleznodorozhnykh i avtodorozhnykh tonneley. Vedomstvennye stroitel'nye normy 190-78* [Instructions on Engineering and Geological Surveys for the Design and Construction of Metro System, Mountain Railways and Road Tunnels. Departmental Building Code 190-78]. Moscow: Mintransstroy, N. D.

[3] R.N. Kremneva, Inzhenerno-geologicheskie i gidrogeologicheskie usloviya sooruzheniya Leningradskogo metropolitena [Geotechnical and Hydrogeological Conditions of the Construction of the Leningrad Metro System]. In *Voprosy inzhenernoy geologii Leningradskogo ekonomicheskogo rayona* [The Issues of Economic Geology of the Leningrad Economic Region]. Leningrad: TsBTI, 1960.

[4] V.F. Bocharov, & S.N. Vlasov, *Rekomendatsii po vyboru tonneleprokhodcheskikh mekhanizirovannykh kompleksov s aktivnym prigruzom zaboya pri stroitel'stve tonneley v slozhnykh inzhenerno-geologicheskikh i gradostroitel'nykh usloviyakh* [Recommendations for Tunneling Selection of Mechanized Complexes with Active Bottomhole Weight in the Construction of Tunnels in Complex Geotechnical and Urban Conditions]. Moscow: TA Inzhiniring, 2004.

[5] *Sooruzhenie tonneley tonneleprokhodcheskimi mekhanizirovannymi kompleksami s ispol'zovaniem vysokotochnoy obdelki. Sandart Natsional'nogo ob"edineniya stroiteley 2.27.19-2011* [Construction of Tunnels Using Tunneling Mechanized Complexes with High-Precision Lining. Standard of National Association of Builders 2.27.19-2011], 2011.

[6] *Otchet o rabote “Modelirovanie sdvizheniya zemnoy poverkhnosti pri prokhodke peregonnogo tonnelya TPMK”* [Report on the work “Modeling of Displacement of Earth's Surface when Driving the Running Tunnel MTDC”]. St. Petersburg: Saint Petersburg Mining University, 2013.

[7] D.V. Panfilov, *Metodika prognozirovaniya deformatsiy zemnoy poverkhnosti pri sooruzhenii transportnykh tonneley na osnove prostranstvennogo modelirovaniya: dis. kand. tekhn. nauk* [Methods of Predicting the Earth's Surface Deformations in the Construction of Transport Tunnels Based on Spatial Modeling (Ph.D. Thesis)]. Research Institute of the vehicle. Moscow, 2005.

[8] D.A. Potemkin, P.A. Demenkov, & V.N. Ochnev, Napryazhenno-deformirovannoe sostoyanie obdelok stantsionnogo kompleksa metropolitena ispytyvayushchego vliyanie svaynogo fundamenta [Stress-Strain State of Lining of Underground Station Complex Influenced by Pile Foundation]. Notes of the Mining Institute, vol. 195, pp. 235-239, 2010.

[9] A.G. Protosenya, Yu.N. Ogorodnikov, D.A. Potemkin & et al. *Mekhanika podzemnykh sooruzheniy. Prostranstvennye modeli i monitoring (monografiya)*

[Mechanics of Underground Structures. Spatial Models and Monitoring (Monograph)]. St. Petersburg: SPGGU-MANEB, 2011.

[10] A.N. Dinnik, “O davlenii gornykh porod i raschete krepi krugloy shakhty” [On the Pressure of Rocks and Calculating the Circular Shaft Lining]. Engineering worker, vol. 7, pp. 1-12, 1925.

[11] *Posobie po proektirovaniyu metropolitenov* [Manual for the Design of Metro Systems]. Moscow: State Design and Research Institute “Metrogiprotrans”, Transstroy, 1992.

[12] *Stroitel'nye pravila 32-105-2004. Metropoliteny. Svod pravil po proektirovaniyu i stroitel'stvu* [Building Regulations 32-105-2004. Metro Systems. Code of Practice for Design and Construction]. Moscow: Gosstroy of Russia, 2004.

[13] *Tekhnicheskiy otchet po inzhenerno-geologicheskim izyskaniyam dlya razrabotki proektnoy dokumentatsii. Stroitel'stvo Nevsko-Vasileostrovskoy linii metropolitena metropolitena ot stantsii “Primorskaya” do stantsii “Zoopark”. 2743-II* [Technical Report on Engineering and Geological Surveys for the Development of Project Documentation. Construction of Nevsko-Vasileostrovskaya Metro Line from “Primorskaya” station to “Zoopark” station. 2743-II]. St. Petersburg: Lenmetrogiprotrans, 2012.

[14] E.M. Volokhov, *Prognoz sdvizheniy i deformatsiy massiva gornykh porod i zemnoy poverkhnosti pri sooruzheniy gorodskikh tonneley glubokogo zalozheniya: dis. kand. tekhn. nauk* [Forecast of Displacements and Deformations of the Rock Mass and Surface in the Construction of Deep Urban Tunnels (Ph.D. Thesis)]. Saint-Petersburg State Mining Institute named after GV Plekhanov. St. Petersburg, 2004.

[15] I.L. Nikiforova, Issledovanie dinamiki sdvizheniya zemnoy poverkhnosti pri stroitel'stve tonneley [Investigation of the Dynamics of the Earth's Surface Displacement during the Construction of Tunnels]. Gornyy informatsionno-analiticheskiy byulleten', Vol. 1, pp. 313-318, 2011.

[16] *Pravila okhrany sooruzheniy i prirodnykh ob"ektov ot vrednogo vliyaniya podzemnykh gornykh razrabotok na ugol'nykh mestorozhdeniyakh. Pravila bezopasnosti 07-269-98* [Regulations for Protection of Constructions and Natural Objects from Harmful Influence of Underground Mining in Coal Deposits. Safety Regulations 07-269-98]. St. Petersburg: VNIMI, 1998.

[17] *Stroitel'nye pravila 21.13330.2012. Zdaniya i sooruzheniya na podrabatyvaemykh territoriyakh i prosadochnykh gruntakh* [Building Regulations 21.13330.2012. Buildings and Structures on Undermined Territories and Collapsible Soils]. Moscow: SNiP, 2012.

[18] *Stroitel'nye pravila 22.13330.2011. Osnovaniya zdaniy i sooruzheniy* [Building Regulations 22.13330.2011. Foundations of Buildings and Structures]. Moscow: SNiP, 2011.

[19] *Territorial'nye stroitel'nye normy 50-302-04 “Proektirovanie fundamentov zdaniy i sooruzheniy v Sankt-Peterburge”* [Local Building Codes 50-302-04 “Design of the Foundations of Buildings and Structures in St. Petersburg”]. St. Petersburg: Government of St. Petersburg, 2004.

20. *Otchet o rabote “Prognoz sdvizheniya gruntovogo massiva na uchastke stroitel'stva nevsko-vasileostrovskoy linii sankt-peterburgskogo metropolitena ot st. “Primorskaya” do st. “Zoopark”* [Activity Report “Forecast of Subsidence of the Soil Mass at the Construction Site of Nevsko-Vasileostrovskaya Line of Saint Petersburg Metro from “Primorskaya” station to “Zoopark” station]. St. Petersburg: Saint Petersburg Mining University, 2013.