



PREDICTING LAND-SURFACE DEFORMATIONS DURING THE CONSTRUCTION OF UNDERGROUND FACILITIES OF COMPLEX SPATIAL CONFIGURATION

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ABSTRACT

The article presents methodical approaches to the computation of the land-surface deformations during the construction of underground facilities of complex spatial configuration. Considered methodical approaches are based on numerical methods of analysis. The article presents the computation concept of stress-strain state of rock mass and land-surface deformations during the construction of underground facilities of complex spatial configuration, which is based on the representation of the computational domain in the form of global and local models. The presented concept has been tested in the context of underground facility consisting of three single-bore connected tunnels.

Key words: Underground Facilities, Urban Development, Numerical Simulation, Global and Local Models, Ground Subsidence, Medium Deformation Model, Spatial Statement.

Cite this Article: Petr Alexeevich Demenkov, Maxim A. Karasev and Dmitry N. Petrov, Predicting Land-Surface Deformations During The Construction of Underground Facilities of Complex Spatial Configuration, International Journal of Civil Engineering and Technology, 8(11), 2017, pp. 1161-1171.

<http://www.iaeme.com/ijciyet/issues.asp?JType=IJCIET&VType=8&IType=11>

1. INTRODUCTION

The feature of underground facilities of complex spatial configuration is the presence of two or more elements, the construction process of which is separated in time, while the elements of an underground facility mutually influence each other. At that, reliable representation of their interaction is beyond the scope of simplified scenarios, such as plane-strain or axisymmetric approaches. The element of underground facility is understood as a chamber with a different cross-section, breakoff, inlet, station or main line tunnel, vertical or inclined shaft, etc. The more elements are within the zone of mutual influence, the higher the complexity of the prediction of geomechanical processes' development in their vicinity, and the more difficult is

carrying out the construction of such facilities. The impact of the already constructed element of underground facility on the element of underground facility under construction is manifested in the form of the changed stress field along the construction track, the presence of rock mass zones, where mechanical properties of rocks are altered due to the impact of the already constructed element, as well as limit state zones, which are expressed in the form of intense plastic deformations zones or the formation of micro- and macrocracks. This leads to the activation of geomechanical processes in the vicinity of the newly constructed element of underground facility, increase of the displacements of rock contour line and, consequently, increase of the land-surface deformations. The influence of the element of underground facility being under construction on already built elements also has a negative impact. The redistribution of stresses in rock mass caused by the construction of a new element of underground facility has direct impact on the stress state of the lining of underground facility, and causes the development of its deformations. These deformations are rather small and do not lead to a significant change of the cross sectional area of the tunnel. However, the construction process of a new element of underground facility has much greater impact. The construction of a new element of underground facility, as mentioned above, is accompanied by deformations of a rock mass, the vector of which is directed towards the worked-out space. Deformations of the rock mass involve into the deformation process the lining of the underground facility element, which has already been constructed. This causes some changing in the shape of the element, leading to the redistribution of deformations in the vicinity of the already constructed element, as well as has general impact on the deformations, which are formed as a result of construction of underground facility of complex spatial configuration. Therefore, reliable prediction of land-surface deformations for objects with complex spatial configuration is interconnected with the accepted sequence of construction of the underground facility elements, as well as construction technology.

The issues related to prediction of land-surface deformations during the construction of underground facilities based on numerical simulations were considered in the works of many researchers. Application of numerical methods of analysis becomes increasingly common in engineering practice. Studies in this area have started long ago. The first significant results in this direction are presented, for example, in the works of A.B. Fadeev [1] and O.C. Zienkiewicz [2]. Review of application of numerical methods of analysis for solving underground construction problems are presented in the works of D.M. Potts and L. Zdravkovic [3; 4]. Subsequent works towards the use of numerical methods of analysis [5; 6; 7; 8; 9; 10; 11; 12; 13; 14; 15; 16; 17; 18; 19; 20] are aimed at improving the reliability of the numerical predictions by taking into account various aspects affecting the development of geomechanical processes during the construction of underground structures. However, the noted works left almost untouched the issues concerning prediction of geomechanical processes' development in the vicinity of underground facilities of complex spatial configuration, or these issues were considered very simplistically. In the present article, the main attention will be paid to the methodology of predicting land-surface deformations during the construction of underground facilities of complex spatial configuration.

2. METHODS

2.1. The numerical simulation methodology to predict land-surface deformations during the construction of underground facilities of complex spatial configuration.

Numerical simulation of rock mass stress-strain state prediction during construction of underground facilities of complex spatial configuration can be performed only on the basis of the spatial numerical models. The consideration of main construction stages of underground facility is necessary for reliable prediction of deformations in its vicinity, and depends on the degree of particularization of the numerical simulation. For example, when constructing pylon type underground station in urban terrain of St. Petersburg, the depth of cut during the construction of the station tunnels is 0.75 m, while lining is installed with some lag behind the forehead after the development of the rock within the bounds of the cut. The overall length of 3 station tunnels is approximately 450 m. So, in order to ensure the sufficient particularization of the stress-strain state development modeling, it is necessary to split the solution to at least 600 stages. Given the fact that usually, while simulating, the installation of the lining and development of the rock are divided into two separate phases, the number of computation steps will be doubled. It should also be noted that the underground station, in addition to station tunnels, includes a number of other underground mine workings. The problem of mutual influence of underground mine workings as parts of the underground station should be resolved in the spatial formulation at the approximate number of finite elements sufficient to discretise the considered area, and equal to 350-500 thousands, and in some cases even more. Taking into account the rather complex geometric structure of station facilities, a breakdown of the computational domain is performed using the "tetrahedron" type elements. The accuracy of the solution, when using the "tetrahedron" type elements can be achieved only by using elements of the second order, that is, 10 nodal elements. Based on the experience of performing numerical simulations, solving the problem in noted formulation becomes extremely time-consuming (from a few weeks for simple models of the medium behavior and much longer for complex medium behaviors) that limits this approach for practical application. Similar problems will arise, when considering another type of underground stations. Particular difficulties arise, when considering transfer hubs near underground stations.

The article presents an alternative approach to the prediction of geomechanical processes in the vicinity of underground facilities of complex spatial configuration (Fig. 1). It is proposed to carry out computations of rock mass deformations in the vicinity of underground facilities, as well as land-surface deformations using different numerical models. The global numerical model, which is used to predict the land-surface deformations includes all the basic elements of underground facility with sufficient particularization. However the construction process is not considered in detail (for example, the modeling of each cut in the course of construction of underground structure element or opening its cross section in parts), but rather discusses selected consolidated stages (the construction of the tunnel, chamber, breakoff, or other underground structure element in general), while the construction process is modeled through given deformations on the contour line of rock outcrop. Deformations of rock outcrop contour line of each element of underground facility are calculated on the basis of local numerical models. The formation of local numerical models is performed by division of the global model of the underground facility into separate elements in such a way that their mutual influence was most limited. Modeling the construction sequence of individual element of underground facility is performed with the greatest possible particularization, which would take into account the main elements of construction technology, as well as features, influencing the development of geomechanical processes in its vicinity.

As noted above, numerical simulation of geomechanical processes' development based on the global model is performed in simplified form. We allocate the most important construction stages and predict land-surface deformations at the end of each of these stages. Usually the construction stage is considered as the construction of one of the main station elements, such as station tunnel, chamber, supporting tunnel, tunnel junction area, etc. This approach allows significantly reducing computation time, because the number of computational stages does not usually exceed 15-20.

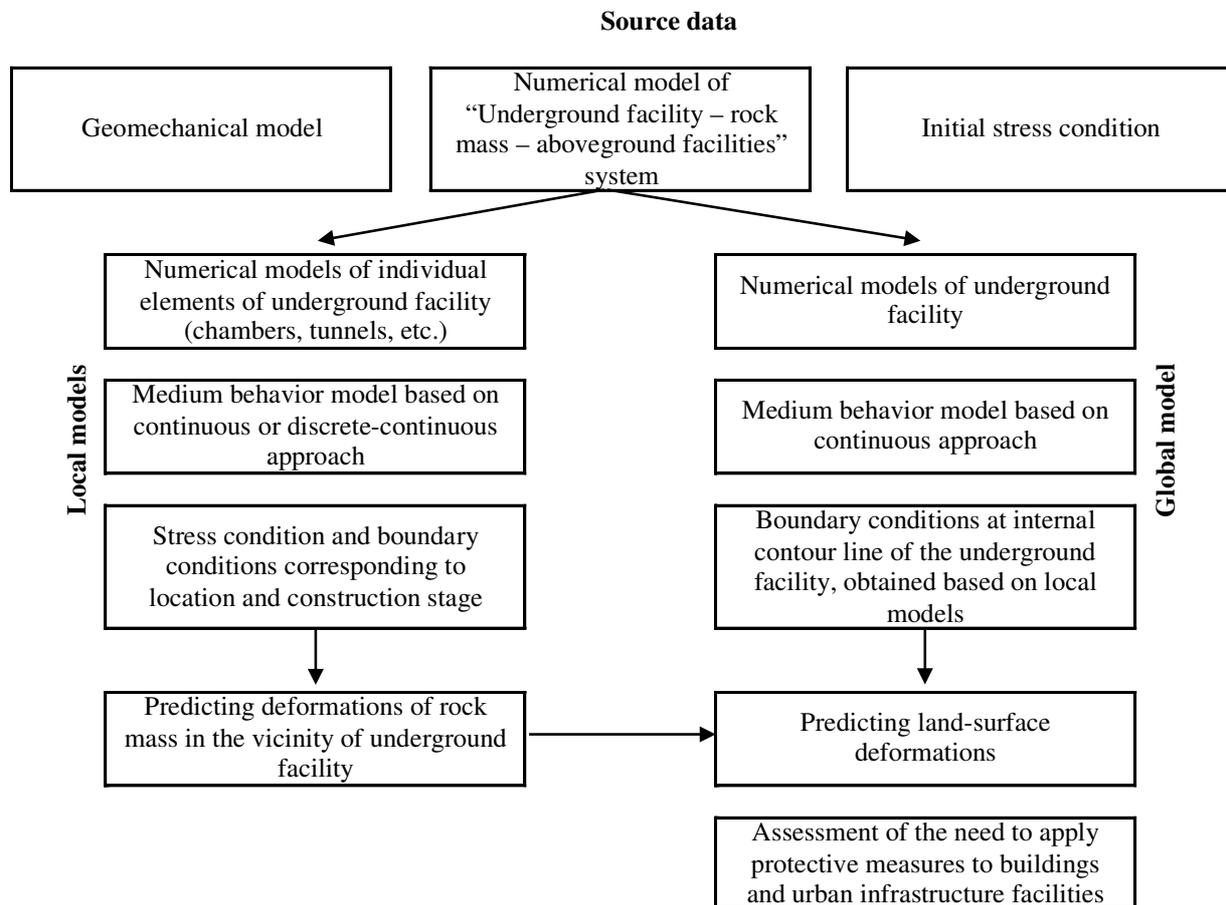


Figure 1 Numerical simulation concept to predict land-surface deformations caused by the construction of underground facilities of complex spatial configuration.

The relationship between local numerical models and global numerical model is implemented in two aspects (Fig. 2). At the first stage, based on the global numerical model, we generate the initial stress field taking into account the geological structure of construction area, the topography of the earth, and other factors. The global model includes all the basic elements of underground facility, including sets of nodes of element mesh that belong to rock contour line of each of them. At this stage, the internal (stresses) and external (gravitational load) forces are in equilibrium that ensures the absence of deformations in the elements of the global numerical model. The size of the global numerical model is determined based on the size of the affected area of construction of underground facility in general. The length of the underground facility and the depth of its laying have the greatest influence on the size of the numerical model. Among factors having lesser effect, we can distinguish the geological structure and the initial stress field (the ratio between horizontal and vertical stresses). Next, we build a local numerical model to predict geomechanical processes in the vicinity of particular element of underground facility.

The initial stresses are transmitted from the corresponding section of the global model to the local model. At the same time, we set boundary conditions (nodal forces or nodal displacements) along the boundaries of the local model, providing the state of equilibrium in the model. Additionally, indicators of the rock state that are characterized by the attained plastic strains, as well as other indicators defining mechanical parameters of the model, are transferred from the global model to local model. This procedure allows generating the initial conditions of the local model, which correspond to the state of the concerned segment in the global model. Numerical simulation of the geomechanical processes' development in the vicinity of the underground facility element is performed only within the frameworks of the local model, and is not associated with a global model up to the moment until it is fully completed.

Next, displacements of nodal points are transferred from the surface responsible for rock bearing contour line of the local model to the corresponding nodal points of the global model. Since the number of nodal points and their position on the surface of the model usually do not match, the values of the nodal displacements in the global model are determined based on the interpolation of data taken from the local model. These movements are applied in the form of forced displacements towards the contour line of the underground facility element in the framework of the global model. Simultaneously, we “cut off” final elements responsible for the rock state within the contour line of the underground facility element. Thus, at the end of this procedure, the stress state and the parameters characterizing the mechanical properties of the rock in the global model are updated taking into account the already constructed element of underground facility. These parameters are later used as initial and boundary conditions for the next local model. Then the process is repeated and construction of the next underground facility element as part of the station is considered.

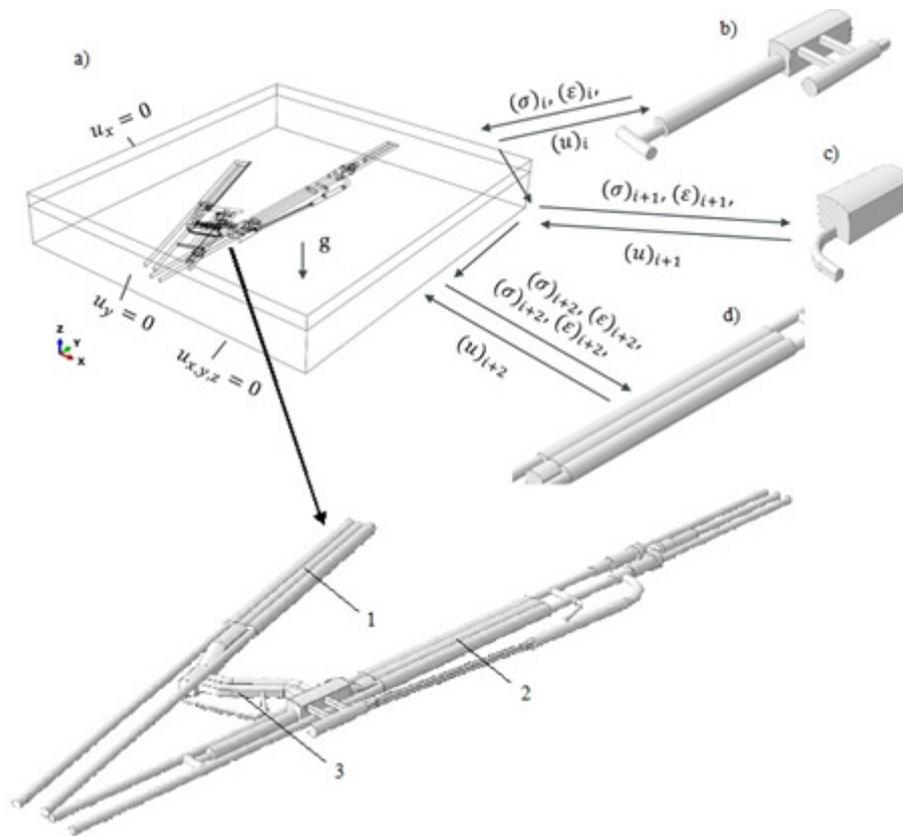


Figure 2 Graphical representation of the relationship between local (b, c, d) and global (a) numerical models: 1 – underground station I; 2 – underground station II; 3 – transfer hub.

3. RESULTS

3.1. Prediction of the land surface deformations at the construction of complex spatial underground facility: the problem statement

The proposed method has been tested in the context of formation of the stress-strain state in the vicinity of the junction between three tunnels, and the formation of land-surface deformations. The solution of this problem is possible only when considering the task in a spatial formulation (Fig. 3). Depth of the mine workings relative to the earth surface is 50 m. The solid is homogeneous and isotropic. Its behavior is described according to the elastoplastic model, based on the Drucker-Prager failure criterion. The stress-strain modulus of rock mass is assumed to be 100 MPa, Poisson's ratio is 0.4. Adhesion of the rock mass $d=500 \text{ kPa}$, angle of internal friction $\beta = 30^\circ$, angle of dilatancy $\psi = 0^\circ$. The initial stress-strain state of the rock mass is given according to the gravitational distribution law from the boundary of the model, corresponding to the earth surface, to the lower boundary of the model. The coefficient of lateral earth pressure K_0 is conventionally accepted equal to 1. Displacement at the lateral boundaries of the model is prohibited in the direction perpendicular to them. Displacement at the lower boundary of the model is prohibited in all directions. The boundary of the model responsible for the earth surface can be freely deformed.

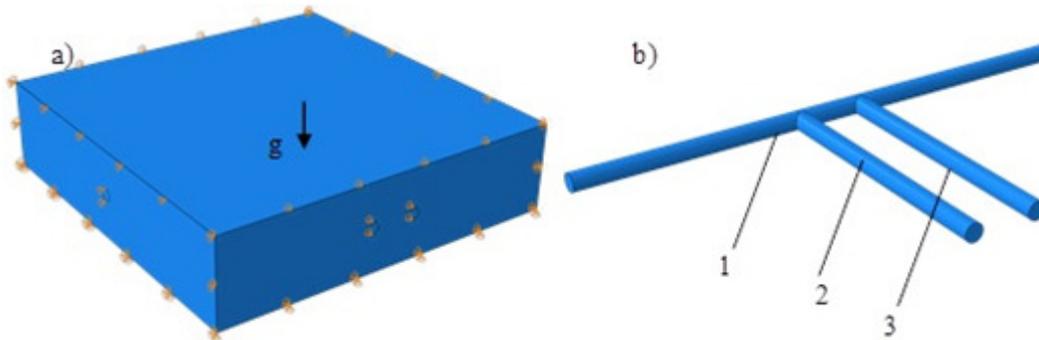


Figure 3 Computational scheme (a) and the geometric representation of underground facility elements; (b): 1-3 – tunnels.

When modeling the development of the stress-strain state on the basis of conventional approach, the sequence of the rock mass construction was performed by eliminating the elements responsible for the rock mass within the corresponding tunnel at the appropriate computation stage. This led to the violation of the equilibrium conditions and the deformation of the elements responsible for the rock mass in the vicinity of rock outcrop, and when moving elements from the earth surface towards the zone of active deformations. The construction sequence of underground facility elements was as follows: at the first stage we developed tunnel No. 1; at the second stage – tunnel No. 2; and at the third stage – tunnel No. 3. When modeling stress-strain state based on the separation of the proposed rock mass section into the global and local models, simulation of deformation processes was performed using local models, while further displacements, obtained in the respective nodal points, located on the surface of rock outcrop in local models, were transferred in the form of forced displacements to the nodal points lying on the contour line of rock outcrop of the global model. The global model was divided into 5 sectors (Fig. 4a). Each sector included an element of underground facility. To reduce the dimensionality of local models, before constructing them, the computational domain was reduced to the minimum possible size so that the boundary conditions practically did not affect the results of the development of geomechanical processes in the vicinity of the concerned element of the underground facility (Fig. 4b).

At the first stage stresses from the global model were transferred to a local model No. 1 to perform simulation of rock mass stress-strain state change during the construction of part of the tunnel No. 1, as well as determination of displacements at nodal points, corresponding to the rock contour line. Since in the problem under consideration we assumed that the rock mass was homogeneous, while the tunnel No. 1 was located at the constant depth along its length, displacements obtained at the nodal points of the contour line of rock outcrop in the local model No. 1 were extended to its full length. If conditions along the length of the tunnel No. 1 were changed, then it would have been necessary to repeat this operation for local models No. 2 and No. 3. At the second stage, displacements of rock outcrop contour line obtained in the local model No. 1 were transferred into the corresponding nodal points of the global model and were set as forced displacements. This allowed obtaining stresses redistribution along the length of the tunnel No. 1 in the global model, as well as determine the deformations of the earth surface caused by construction process. At the third stage, stresses obtained in the global model, after completing the second stage were passed on as initial conditions to the local model No. 4 to perform simulation of stress-strain state changes in the vicinity of the tunnel No. 2. Then the procedure for the determination of displacements on the boundary of rock contour line of the tunnel No. 2 was repeated. At the fourth stage, the procedure of updating the stress state of the global model was carried out, as well as land-surface deformations caused by construction of the tunnel No. 2 were determined. At the fifth stage, stresses obtained in the global model after completing the fourth stage, were transferred to the local model No. 2 as initial values to complete prediction of stresses in the vicinity of the tunnel No. 2, including the site of its connection with the tunnel No. 1, which were caused by construction process. As previously, displacements at the nodal points in the contour line of underground facility elements were defined, in this case, for the tunnels No. 1 and No. 2. At the sixth and seventh stages, a procedure similar to that presented in the fourth and fifth stages was carried out.

3.2. The results of land-surface deformations' prediction obtained according to the proposed methodology

Upon completion of the computations we obtained deformations pattern in the vicinity of each element of the underground facility as well as the resulting pattern of land-surface deformations (Fig. 4c, d). Comparing the results of the stresses and strains' development in the vicinity of rock outcrops allows talking about good qualitative and quantitative convergence of the computation results performed according to the traditional method and the approach based on division of the model into global and local models (Fig. 4e, f). Data on the development of land-surface deformations caused by construction of underground facility in general, and data obtained according to two considered approaches, also show good convergence. There are almost no differences in the obtained computation results.

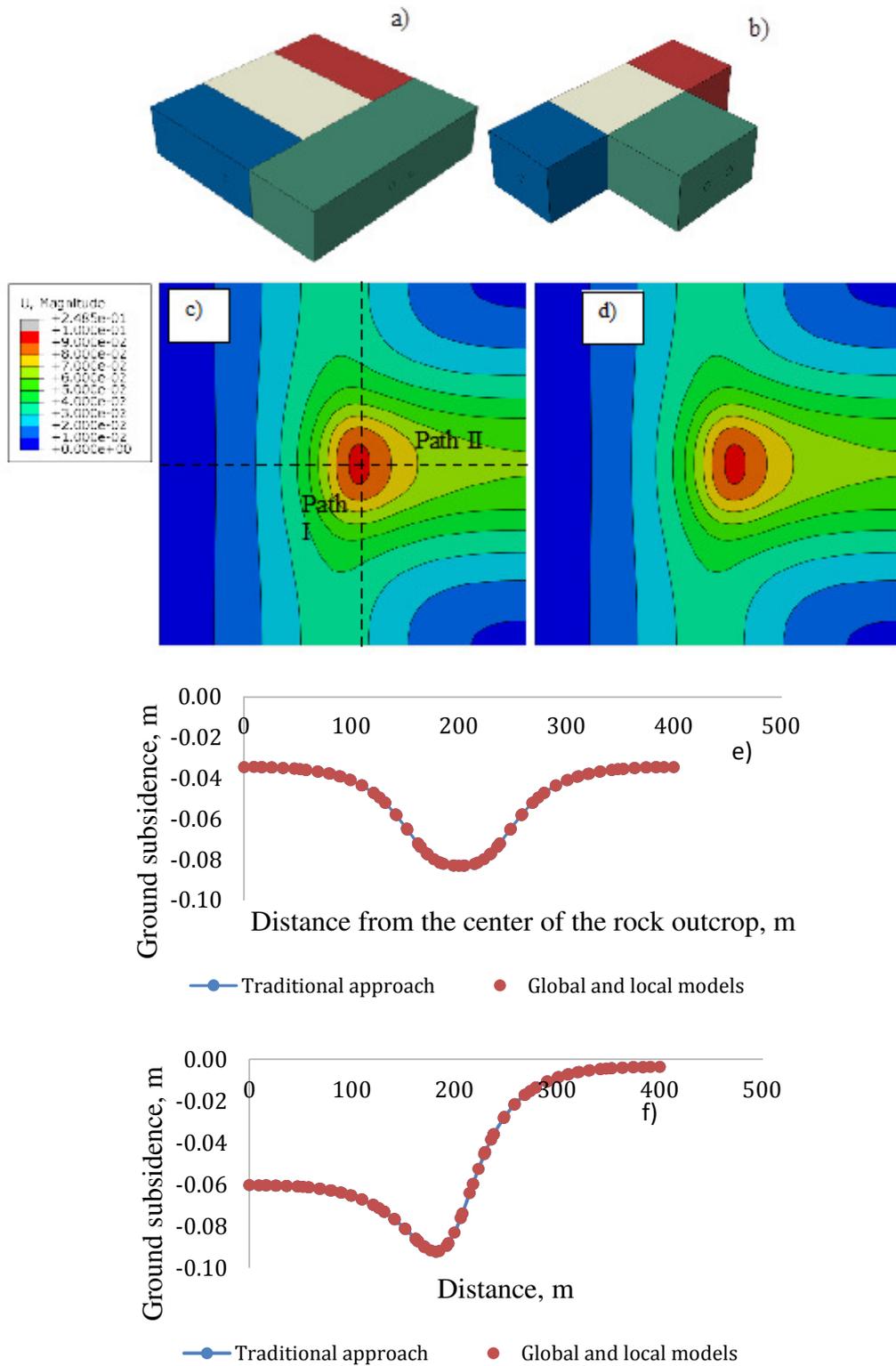


Figure 4 Division of the global model into computation sectors (a) and sectors, which are used to build local models (b): colores show the computation sectors and the geometry of each of the local models, as well as the development of land-surface deformations, obtained based on the traditional approach (a) and the division into the global and local models (b); (c) and (d) correspond to diagrams of vertical deformations' development along the path I and path II, respectively.

The proposed approach was used by the authors to predict the land-surface deformations caused by construction of the stations or transfer hubs of the St. Petersburg underground system [21; 22; 23; 24]. Predicted results have shown good convergence with the data of full-scale measurements of the ground surface subsidence induced by tunneling.

4. DISCUSSION

The material presented in the above section allows drawing the following conclusions. It is shown that the solution of problems related to prediction of land-surface deformations, when constructing underground facilities of complex spatial configuration based on the use of the traditional approach, where the computations are performed in the framework of a single model, has no practical application at the moment. This is due to the limitation of computational resources required for solving this class of problems at an appropriate degree of reliability in terms of modeling the sequence of construction of underground facilities within a reasonable period of time. A new approach, which allows predicting land-surface deformations, is based on the use of global and local models. Land-surface deformations are predicted based on the use of the global model, while the local models are used to predict geomechanical processes in the vicinity of the element within underground facility. A significant reduction in dimensionality of the local numerical model with respect to the global model allows improving modeling accuracy of geomechanical processes' development in the vicinity of concerned element in underground facility in the course of its construction. There is two-way communication between local models and the global model, where the global model accumulates changes in the stress-strain state of rock mass in general in the vicinity of the underground facility, which is transferred as initial conditions from the global model to the local one, while the results of the displacements of rock outcrop contour line, obtained on the basis of modeling of geomechanical processes using local models, are transferred in the form of forced displacements to the global model. This procedure results in updating the stress state in the global model. The proposed approach, based on the division into global and local models, has been validated in terms of particular computations, which have shown good convergence between the results of the geomechanical processes' development in the vicinity of rock outcrops and land-surface deformations, obtained in accordance with the traditional approach, which has been extended in the present work.

Testing is performed based on solutions obtained for a spatial formulation. Bed rock deformation is based on an elastoplastic model. The task, the solution of which has been obtained in spatial formulation, included several construction stages of underground facility. Thus, the verification of the proposed approach is made with all main features, necessary for reliable modeling of geomechanical processes.

5. CONCLUSION

Presented computation results allowing prediction of geomechanical processes' development in a spatial formulation based on the division into global and local models and their comparison with the computations, performed on the basis of the traditional approach, allow suggesting that the reliability of the results obtained based on the use of global and local models, is quite high. This approach allows both assessing the development of deformations in the vicinity of rock outcrops, and predicting land-surface deformations. Unlike the traditional approach, the approach proposed in the present article allows considering the construction of underground facilities of complex spatial configuration without significantly simplifying the modeling of the sequence of their construction, including, if necessary, the development of a cross-section of the element inside underground facility at several stages, and the input at a certain time of auxiliary support and permanent lining into the work.

ACKNOWLEDGEMENTS

The research has been funded by the grant of the Russian Scientific Fund (project No. 16-17-00117).

REFERENCES

- [1] Fadeev, A.B., Metod konechnykh ehlementov v geomekhanike [The finite element method in geomechanics] [Text]. Moscow, Nedra, 1987, p. 221.
- [2] Zienkiewicz, O.C., The finite element method. McGraw-Hill, London, 3rd edition, 1977, p. 465.
- [3] Zdravkovic, D.M., Finite element analysis in geotechnical engineering: theory. Thomas Telford, London, 1999, p. 500.
- [4] Zdravkovic, D.M., Finite element analysis in geotechnical engineering: application. Thomas Telford, London, 2001, p. 448.
- [5] Yarovoy, Yu.I., Prognoz deformacii zemnoj poverhnosti, zdaniy i sooruzhenij pri stroitel'stve metropolitenov na Urale [Predicting deformation of the land surface, buildings and structures, when constructing subways in the Urals] [Text]. Ph.D. in engineering, Ural State Academy of Transport, 1999, p. 280.
- [6] Rechitsky, V.V., Prognozirovaniye deformacij dnevnoj poverhnosti pri prohodke tunnelej [Predicting deformations of the ground surface during tunneling] [Text]. Ph.D. in engineering. Omsk State Construction University, 2005, p. 156.
- [7] Novozhenin, S.Yu., Prognoz sdvizhenij i deformacij gornyh porod pri sooruzhenii ehskalatornykh tonnelej metropolitena tonneleprohodcheskimi mekhanizirovannymi kompleksami [Prediction of displacements and deformations of rocks, when constructing escalator tunnels of underground railway using mechanized tunneling complexes] [Text]. Ph.D. in engineering, St. Petersburg, 2014, p. 147.
- [8] Kireeva V.I., Ocenka sdvizhenij i deformacij gornyh porod pri sooruzhenii peregonnykh tonnelej bol'shogo diametra tonneleprohodcheskimi mekhanizirovannymi kompleksami v slozhnykh gorno-geologicheskikh usloviyah [Assessment of displacements and deformations of rocks, when constructing large diameter tunnels by mechanized tunneling complexes in complicated mining and geological conditions] [Text]. Ph.D. in engineering, 2016, p. 198.
- [9] Kim, S.H., Model testing and analysis of interaction between tunnels in clay. Thesis, University of Oxford, 1996, p. 242.
- [10] Liu, G., Numerical modeling of damage to masonry building due to tunneling. Thesis, University of Oxford, 1997, p. 228.
- [11] Augarde, C.E., Numerical modeling of tunneling processes for assessment of damage to building. Thesis, University of Oxford, 1997, p. 262.
- [12] Beadle, M.E., Settlement induced by tunneling in cohesive-friction soils. Thesis, University of Western Ontario, 1997, p. 271.
- [13] Greenwood, J.D., Three dimensional analysis of surface settlement in soft ground tunneling. Thesis, University of Minnesota, 2001, p. 89.
- [14] Franzius, J.N., Behavior of buildings due to tunnel induced subsidence. Thesis, University of London, 2003, p. 360.
- [15] Abrams, A.J., Earth pressure balance (EPB) tunneling induced settlements in the Tren urbano project, Rio Piedras, Puerto Rico. Thesis, Massachusetts Institute of Technology, 2016, p.73.
- [16] Moller, S.C., Tunnel induced settlements and structural forces in lining. Thesis, University of Stuttgart, 2006, p. 174.
- [17] Pickhaver, J.A., Numerical modeling of building response to tunneling. Thesis, Balliol College, 2006, p. 285.

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- [18] Thorpe, J.P., Ground movement during tunneling in sand. Thesis, Queen's University, 2007, p. 185.
- [19] Laver, R., Long term behavior of twin tunnels in London clay. Thesis, University of Cambridge, 2010, p. 451.
- [20] Giardina, G., Modelling of settlement induced building damage. Thesis, University of Brescia, 2013, p. 291.
- [21] Karasev, M.A., Prognoz osedaniya zemnoj poverhnosti pri stroitel'stve podzemnyh sooruzhenij glubokogo zalozheniya v usloviyah goroda Sankt-Peterburg [Prediction of ground surface subsidence during the construction of deep-lying underground facilities in the city of Saint Petersburg] [Text]. Notes of the Mining Institute, 2014; 204: 248-254.
- [22] Protosenia, A.G. and Karasev, M.A., Procedure of geomechanically safe development of megalopolis underground space. International Journal of Applied Engineering Research, 2016; 11(22): 10857-10866.
- [23] Protosenya, A.G. and Karasev, M.A., Razvitie metodov prognoza osedaniya zemnoj poverhnosti pri stroitel'stve podzemnyh sooruzhenij v usloviyah plotnoj gorodskoj zastrojki [Development of prediction methods of the ground surface subsidence during the construction of underground facilities in restrained urban conditions] [Text]. Metro and Tunnels, 2016; 6: 85-89.
- [24] Karasev, M.A. and Belyakov N., Prognoz deformacij zemnoj poverhnosti pri stroitel'stve stancij metropolitenov v tverdyh glinah. [Prediction of the land-surface deformations during the construction of metro stations in firm clay] [Text]. Proceedings of the Tula State University. Earth Sciences, 2016; 1: 139-155.