International Journal of Applied Engineering Research ISSN 0973-4562 Volume 11, Number 22 (2016) pp. 10857-10866

Procedure of Geomechanically Safe Development of Megalopolis Underground Space

Anatoliy Grigorievich Protosenya, Maksim Anatolievich Karasev and Nikita Andreevich Belyakov
Saint-Petersburg Mining University, 21-st Line V.O., 2, Saint-Petersburg, 199106 Russia.

Abstract
This article proposes a concept of safe development of underground space. The main stages of engineering activity are considered aimed at decrease in negative impact of erection of underground facilities on urban infrastructure, buildings and structures. The assessment procedure of effect of erection of underground facilities on urban infrastructure is described. An example of forecast of deformations of ground surface is considered for erection of underground facility of complex space configuration: underground station hub.

Keywords: underground facilities, deformation, settlement of ground surface, emergency situations.

INTRODUCTION

Development of megalopolis underground space is related with high engineering and environmental risks both with regard to underground facilities and for buildings located on surface in affected area. Nowadays the designs of proposed facilities become more and more complicated, multipurpose underground complexes are developed which combine facilities of various applications. Along with this the applied design procedures of underground facilities do not correspond to current scientific level and requirements to the design projects. Complicated engineering-geological and urban planning conditions of development of megalopolis underground space impose specific requirements at the stage of design and erection of underground facilities. Megalopolis facilities, aboveground and underground, interact between each other forming multilevel structure, its safe maintenance is possible only on the basis of complex geomechanical analysis and monitoring, including field and engineering-geological study, application of modern design procedures and erection methods.
Engineering practice in the field of erection of underground, aboveground or partially in ground facilities can be presented as systematic activity of experts aimed at prevention of possible destructions, especially with catastrophic consequences, which can cause damages of private and state property, breakage of highly important facilities, pollution of environment or affect human life or health. The assumption of accident free designing of such facilities can be verified only by successful completion of facility erection with subsequent monitoring of its conditions and behavior on long term basis. Despite significant experience in the field of erection of underground facilities of various purposes under restrained urban conditions and attempts to consider for previous practices, their erection is nevertheless related with severe accidents [1-11].

EXPERIMENTAL

1. Concept of geomechanically safe development of underground space

The main scope of forecast of technogenic accidents and geomechanical safety upon development of megalopolis underground space is implementation of numerical simulation of erection of underground facilities, as well as systems of geoengineering monitoring of ground surface state and bearing elements of aboveground and underground facilities. Numerical simulation of erection of underground facilities should be based on developed 3D models with accounting for peculiarities of engineering-geological conditions, housing density and sequence of erection activity.
Safe development of megalopolis underground space should be based on the set of actions (Figure 1), comprised of engineering study, expert appraisal, as well as geomechanical analysis. Special attention should be applied to location of the facility or tunnel route.
Procedure of forecast and prevention of emergency situations should consider for all stages of erection and operation of underground facility, including:

- engineering-geological study;
- design of underground facilities;
- erection of underground facility;
- operation of underground facility.

Forecasting procedure of geoengineering processes should be based on the following principles:

- representative and unbiased appraisal of engineering-geological and hydrogeological conditions and properties of ground massif;
- state equations and laws of deformations of ground massif, including non-linear deformation of mediums and their creepage;
- 3D geomechanical models of massif accounting for interaction between aboveground buildings and underground facilities;
- main stages of erection of buildings and structures in 3D numerical models;
- multivariate numerical experiments which facilitate design and engineering modifications in the course of development aiming at decrease in impact of underground facilities on aboveground buildings and prevention of accidents.

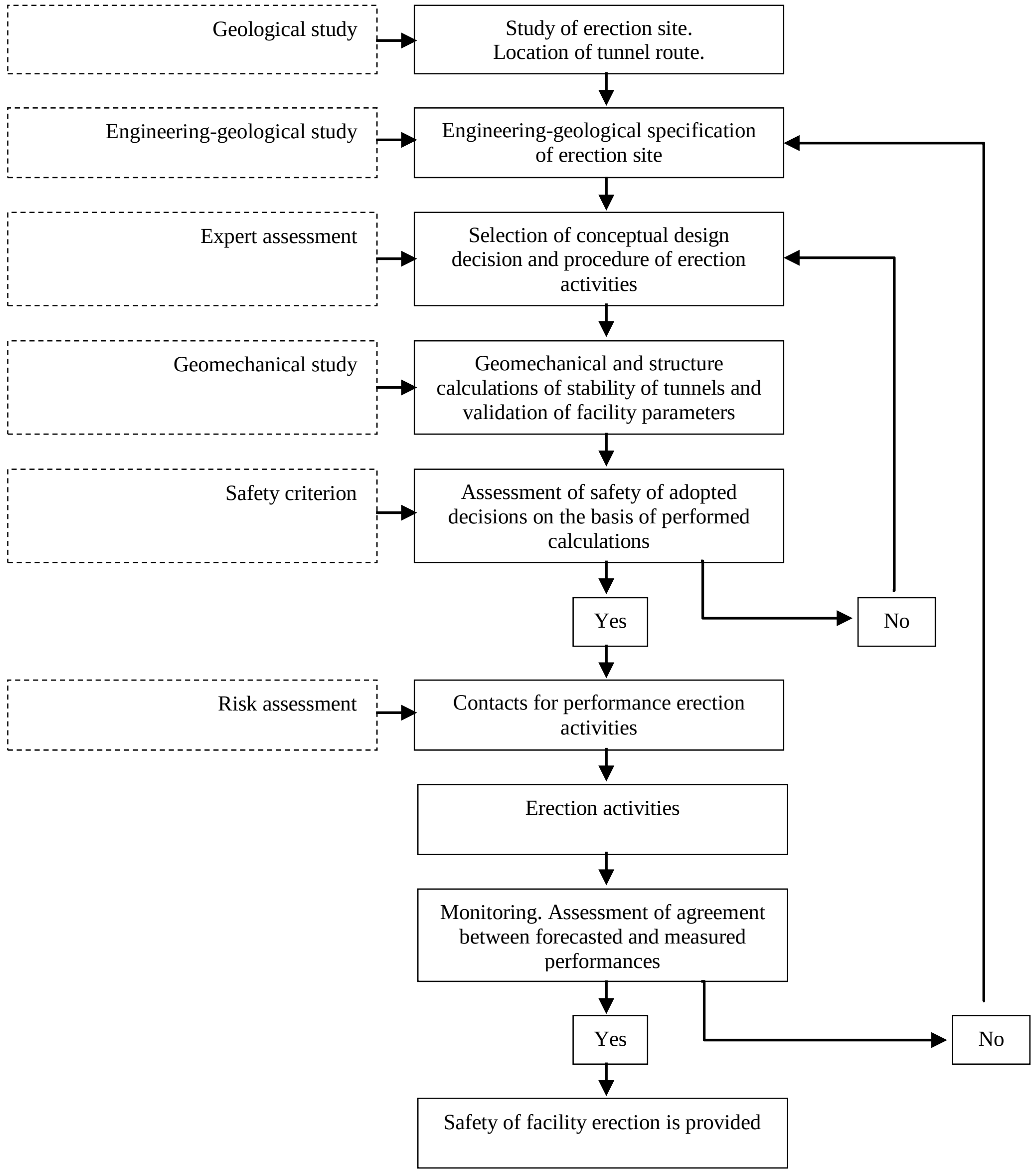

Figure 1. Forecasting and prevention of emergency situations upon development of megalopolis underground space.

Development of megalopolis underground space is related with negative phenomena caused by:

- uncertainty of engineering-geological and hydrological conditions at erection site;
- invalid initial data at the designing stage;
- inadequate regulatory system and technological peculiarities at the erection stage;
- neglecting of the influence of hydrogeological conditions and rheological processes at the operation stage of underground facilities.

Upon erection of underground facilities in modern urban area quite often it is impossible to perform works so that they do not effect on buildings and structures in vicinity of new erection site. As a consequence of driving operations and subsequent arrangement of bearing elements of underground facilities the existing buildings and structures can undergo heterogeneous settlements. Cracks are generated in their walls or other individual design elements are damaged. In such cases it is always required to determine dimensions of the so called erection affected area: such area where any negative processes can occur caused by erection activities. If these forecasted additional deformations are dangerous for regular operation of the buildings, then it is required to develop a set of special actions which would allow to protect foundations and main bearing elements of the existing buildings, and if it is impossible to avoid negative impact, then o tot required to reconsider the concept of new erection project.

In general emergency situations in the course of erection of underground facilities can be classified according to the following four categories (Table 1), ranking from light to catastrophic accidents in terms of their consequences.

If categories I to III are related to the accidents caused by violations at a stage of engineering study, design or erection of underground facility and considered as special conditions, then the damages of urban infrastructure, buildings and structures in the case of emergency category IV are more common and occur in everyday practice. The following sections of this article are devoted to the forecast issues of deformation of ground surface caused by excessive deformations of rock profile of underground facility. The forecast procedure of geomechanical processes upon erection of underground facilities is exemplified by analysis of such complicated 3D underground facility.

Table 1. Classification of emergency situations upon erection of underground facilities under dense urban infrastructure

Emergency situation category	Affected entity			
	Erected facility	Surrounding area	Engineering services	Ground massif
I Catastrophic	Destruction of lining at local site with subsequent progressing of destruction area to adjacent lining zones. Rock breakout from tunnel crown and sidewalls with displacement of rock bulk to its operation region. The breakout area is propagated up to ground surface.	Complete or partial destruction of buildings and structures in the area of rock breakout on ground surface. Significant damages of bearing elements of buildings and structures in the area of active displacement of rock bulk.	Destruction of all services in the area of rock breakout onto the surface. Severe damages of services in the area of active displacement of rock bulk.	Breakout of rock bulk into tunnel operation area. The breakout area is propagated up to ground surface. On ground surface: rock breakage area, area of separation cracks, area of plastic deformation of rock bulk and area of smooth ground settlement.
II Heavy	Stability loss of tunnel crown with generation of rock breakout in front of tunnel crown. The breakout area is propagated up to ground surface.	Local destruction of buildings and structures in the area of rock breakout on ground surface. Significant damages of bearing elements of buildings and structures in the area of active displacement of rock bulk.	Destruction of significant portion of services in the area of rock breakout onto the surface. Severe damages of services in the area of active displacement of rock bulk.	
III Moderate	Partial destruction of lining with restricted breakout (squeezing) of rocks into operation region or stability loss of tunnel crown in local area. The breakout area is not propagated or propagated partially up to ground surface.	Destruction or severe damages of individual bearing elements of buildings and structures. Excessive deformations of building elements in area affected by tunnel erection.	Severe damages of engineering services accompanied by their local destruction and shutdown.	Local breakout or squeezing of rock bulk at the site of damage of tunnel lining. Smooth settlement of above rocks to ground surface. Formation of settlement trough with smooth (not step-by-step) distribution of vertical deformations.
IV Light	Extreme deformations of rock contour of tunnel	Growth of additional deformations in foundations of buildings and structures. Significant damages of aesthetic design elements of buildings and structures. Minor damages of bearing elements of buildings and structures.	Engineering services are under additional external impact. Excess of their allowable additional deformations with possible local destruction of engineering services.	Significant deformations of rock massif in the vicinity of tunnel. Deformations on ground surface exceed allowable values. The affected area of tunnel erection expands significantly.

2. Assessment of influence rate of erection of underground structures on facilities of urban area

One of the major elements of safe development of megalopolis underground space is reducing of the impact rate of erection of underground facilities on existing aboveground infrastructure or facilities of minor depth with regard to ground surface. Erection of any underground facility leads to variation of stressed state of rock massif, hence, to development of deformations in the vicinity of underground facility and their propagation to ground surface. The necessity of application of various protective actions of buildings and structures will depend in numerous factors, the main of which are illustrated in Figure 2.

It is known that location of underground facilities or route of underground facilities depends on numerous factors, such as functional, technical, social, infrastructure factors and others. A determining factor or group of factors is defined individually for each proposed underground facility. This section of the article will consider only such set of factors which determines location of erection site and underground facilities, permitting decrease in negative impact of their erection on urban infrastructure and to reduce costs of arrangement and implementation of protective actions for buildings and structures in the affected area.

Peculiar attention should be paid to location of erection site of underground facility, this will enable elimination of major portion of urban infrastructure facilities from the affected area already at project early stages. Thus, it is required to remove highly critical facilities from the erection area, such as gas lines, tower buildings and structures, industrial facilities highly sensitive to deformations of ground surface. It would be reasonable to remove historical and cultural facilities from the affected area of underground erection, since they are usually highly sensitive to uneven deformations of ground surface and allowable deformations for such facilities at least by an order of magnitude lower than those for other facilities of urban infrastructure. Strengthening of historical facilities is labor consuming, it is related with their poor state as well as nearly complete unavailability of their design, especially of their underground portion. Determination of affected area at preliminary stage of erection of underground facility is possible suing various empirical and semiempirical methods, developed for the considered engineering-geological conditions. Usually the initial data in such approaches are as follows: rock strength *φ* (angle of internal friction angle), plan dimensions of the facility *A*x*B* and its depth *H*. Thus obtained dimensions can vary slightly from actual boundaries of the affected area, but make it possible to outline the profile on ground surface, outside which deformations of ground surface will be lower than the allowable values for any of considered buildings, structures or facilities.

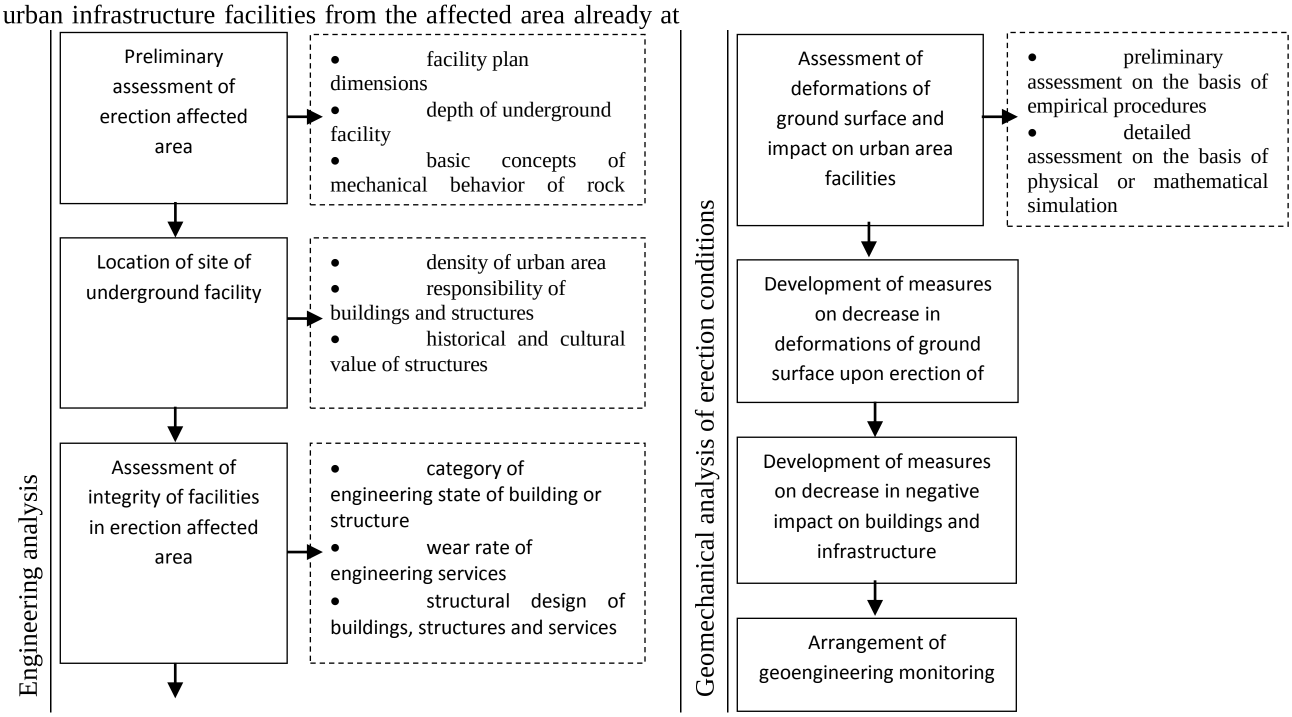

Figure 2. Stages of adoption of required decision on application of measures of protection of structures, facilities and infrastructure.

For all buildings and structures in the boundaries of predetermined affected area of underground facility erection it is necessary to establish a category of technical state, and wear factor should be determined for engineering services. Technical state is assessed on the basis of requirements of regulations and can account for procedures of specialized companies upon validation of their state. Report of technical state should include information about building design, foundation type and design, foundation depth, as well as state of all bearing elements of the building. In accordance with the category of technical state the maximum allowable deformations of ground are determined for foundation of the considered building or structure according to valid regulatory norms. It should be mentioned that such assessment of technical state is of strictly engineering type and cannot be applied for detection of strengthening areas of structural elements provided that such necessity appears. However, at the stage of engineering study this approach is sufficient.

Quantitative forecast of deformations of ground surface upon erection of underground facilities can be performed both by means of analog approach in order to obtain overall pattern of expected deformation of rock massif, and by means of various empirical, semiempirical, and analytical dependences. All these methods are characterized by one significant drawback: inability to consider for overall set of initial data (engineering-geological conditions, 3D arrangement of underground facilities, sequence and schedule of their erection, rigidity of bearing elements of underground facilities and so on.), and hence, peculiar features of development of geomechanical processes in rock massif in the vicinity of erected underground facility. However, these methods can be successfully applied for prior assessment of the influence of underground facility erection and in some cases for final assessment on the basis of initially preset data which consider for the most negative variant of events, these data should be determined on the basis of expert appraisal. Then, if the presented results of prior forecast of ground surface deformations based on conservative approach are in the allowable range, it is not necessary to carry out subsequent complicated and time consuming calculations. If there appears opposite situation, then the consistency of calculations and erection conditions of underground facilities should be increased, the calculations should be carried out once more. Such concept was initially presented by Burland at al., [12]. At present the forecast of ground surface deformations and, if necessary, validation of decisions aimed at decrease in negative impact of erection are carried out on the basis using physical or mathematical simulations. The mathematical simulation is based on numerical analysis, mainly consisting of finite element approach. Calculations based on numerical simulations can be considered as detailed assessment, the scope of which is determined by initial data as well as by the reliability of this approach and results of previous studies in this field.

Peculiar attention upon numerical calculations should be paid to investigation into geomechanical processes, which always accompany erection of underground facilities and are exposed depending on existing conditions in the form of displacement of rock contour, generation of sliding surfaces, micro- and macrocracks. As already mentioned elsewhere [13-24], reliable forecast of deformations of rock massif and ground surface is directly related with deformation peculiarities of the medium, where erection is performed, and require for its detailed description at the level of medium state equations. They are as follows: nonlinear interrelation upon deviator loading, densification upon volumetric compression, softening upon reaching of ultimate state, start of deformation without variation of volume upon reaching of critical state, high rigidity upon minor deformations in comparison with basic deformations, as well as other features, such as anisotropy of mechanical properties, their heterogeneity and others. Another important aspect of numerical simulation is the necessity to approximate geometrical parameters of underground facility and certain features of its erection technology to the performances applied in the project. This facilitates improvement of forecast consistency of variation of stress–strain state, hence, to improve forecast quality of ground surface deformations, which is the final aim of calculations. Numerical models, developed in the scope of finite element method, at least from theoretical point of view, meet the requirements to calculations of geoengineering facilities, and underground facilities in particular. However, investigations in this field are far from completion.

Decrease in negative impact of underground facility erection on urban infrastructure, aboveground buildings and structures can be achieved either by lower settlement methods of erection of underground facilities, compensatory approaches or strengthening of existing elements of buildings and structures, or by their combination. Irrespective on the adopted method of decrease in negative impact, positive effect should be confirmed by calculations. We believe that the most promising are the actions on decrease in deformations in the vicinity of underground facility under erection, which can be achieved by application of sparing methods for their erection. Strengthening of buildings and structures results in positive effect upon erection of underground facilities at moderate depth and restricted dimensions of cross section, for instance, single tunnel at moderate laying depth. When large in plan underground facility is considered, for instance, underground station, hub and son at significant depth, the area of deformation propagation both in plan and in depth is significant, it will involve both the building and strengthening elements of this building into the deformations. Selection of protective measures can be time consuming and is based on iterations.

The final stage of development of actions aoimed at improvement of safe development of underground space is arrangement of geoengineering monitoring. The monitoring should be developed on the basis of forecasted deformation of ground surface with accounting for building criticality and its technical state. Criticality and functions of building or structure are determined by observation procedures and set of observation tools. Arrangement of observation in key points with expected unfavorable development of deformations of rock massif would permit rapid application of actions aimed at prevention of emergency situations.

RESULTS

1. Formulation of the forecast of deformations of ground surface upon erection of complex space underground structure

This section presents an example of deformation forecast of ground surface upon erection of complicated 3D underground facility: hub of two underground stations located at different height levels (Figure. 3). This work considers the aspects of numerical simulation of erection of underground facilities, comprised of 22 nodes.

Engineering-geological conditions at erection site of underground facilities of the station complex can be separated into three layers. The first layer is comprised of all quaternary deposits from ground surface to the layer of dislocated clays of transition layer, including technogenic deposits. Average layer thickness is set to 30 m. the second layer is comprised of Proterozoic dislocated clays. Average thickness of the second layer is set to 5 m. The third layer is comprised of argillaceous clays (Proterozoic clays). Averaged thickness is 65 m. The rocks of the first layer are located at significant distance from the erection site and were considered in the course of simulation as nonlinear deformed medium on the basis of nonlinear elastic model. The rocks of the second and third layers are dense clays characterized by anisotropy of deformation and strength properties, they are considered as elastic-plastic transversally isotropic medium.

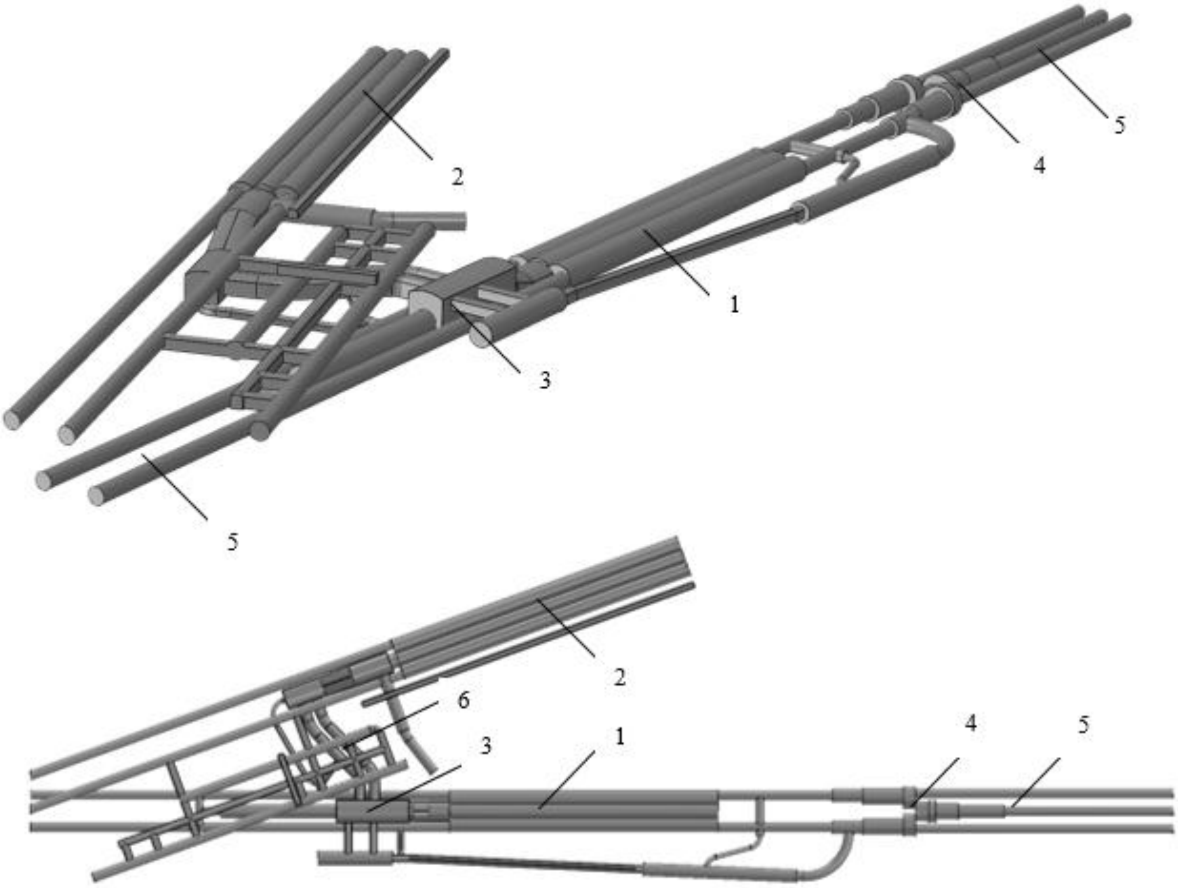

Figure 3. 3D design concept of underground railway junction: 1 – underground station No. 1; 2 – underground station No. 2; 3 – transfer hub; 4 – junction tunnels; 5 – main line tunnels; 6 – pedestrian tunnels.

This work forecasts deformations of ground surface upon erection of underground facilities of complex 3D configuration as follows (Figure 4). The underground station is preliminary subdivided into separate underground facilities so that interaction is maximum restricted. Then the erection sequence of such underground facilities is determined in accordance with technological layout of the station erection. Local numerical models are developed for each facility with high rate of specification of their erection. For facilities of extended distance and varying configuration along the length it is possible to consider erection of a longwise portion of the facility.

Then, the numerical model of overall underground station and rock massif is developed (global model). The global model considers the station erection in simplified form, the most important stages of erection are highlighted, ground surface deformations are forecasted for the time of completion of each stage. Usually an erection stage is the erection of one of main station elements, for instance, station tunnel, junction tunnel, auxiliary tunnel, and so on. Such approach permits significant reduction of calculation tomes, since the number of calculation stages is usually not higher than 15-20.

Interaction between local models and global model is performed in two scopes. At the first stage, with account for geological cross section at erection site and configuration of underground station the global model is developed with initial stress field. Then, local numerical model is developed for erection of a facility of underground station. The boundary conditions, initial stressed state and actual mechanical properties of rocks (with account for achieved stresses and strains) are transferred from the global model. On the basis of the results of numerical simulation of erection of a facility of underground station (local model) the radial and tangential displacements of underground facility contour are determined. These displacement are applied as forced displacement to the contour of underground facility in the global model. Together with this, final element are removed responsible for rocks inside underground facility. Therefore, after completion of this procedure the stressed state and mechanical properties of rocks in the global model are updated with accounting for already erected underground facility. These parameters are used subsequently as initial and boundary conditions for next local model. Then the procedure is iterated and the erection of next underground facility of the station is considered.

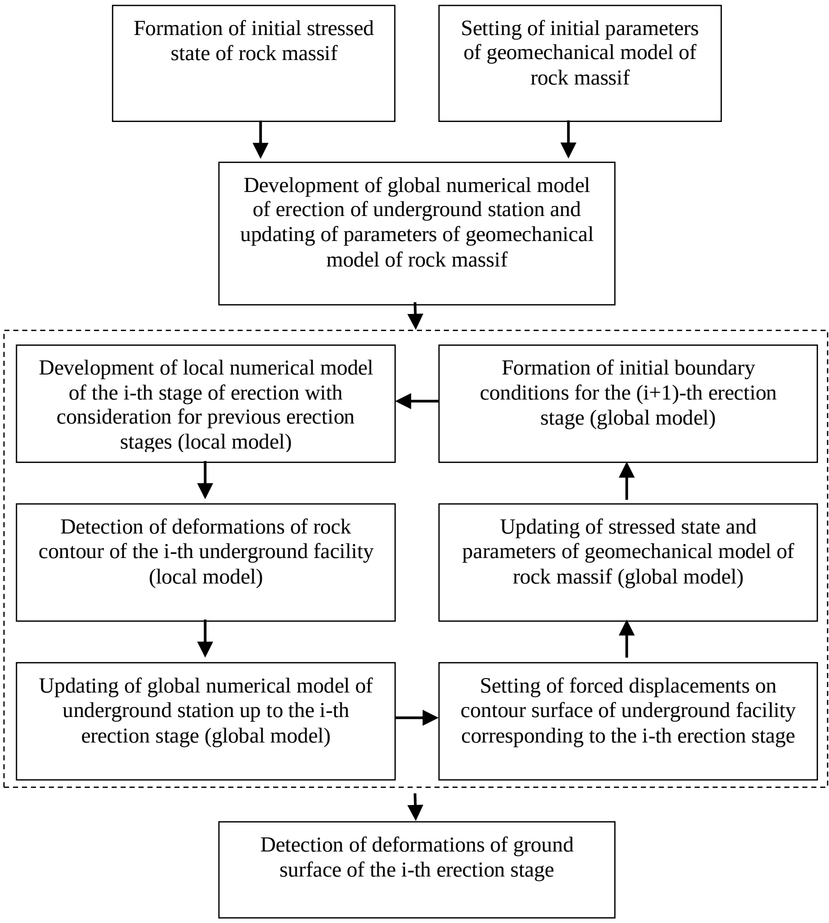

Figure. 4. Numerical simulation forecasting algorithm of ground surface deformations resulting from undermining of complex 3D configuration by underground facilities.

2. Forecasts of deformations of ground surface

Settlement of ground surface at various erection stages of station complex are illustrated as colored diagrams (Figure 5). The boundary of affected area of underground facilities erection is the value of vertical displacement of ground surface equaling to 1 mm.

As can be seen in the figure, the settlement trough of ground surface progresses with the erection of underground facility, involving increasing surface area of ground surface into the affected area. The highest deformations of ground surface are generated above the sites with maximum concentration of underground facilities, where displacements reach 55 mm. Peculiar attention should be paid to erection of tunnels with high transversal cross section, since exactly these facilities influence significantly on generation of settlement trough of ground surface

The values of displacement of rock contour of underground facilities and resulting displacement of ground surface are obtained with assumption of lower settlement erection procedure, all provisions of this procedure should be taken into account upon actual operations.

On the basis of the obtained calculated result of ground surface deformations the acceptability of obtained deformations was assessed, the actions were developed on decrease in negative impact of underground facility erection on aboveground buildings.

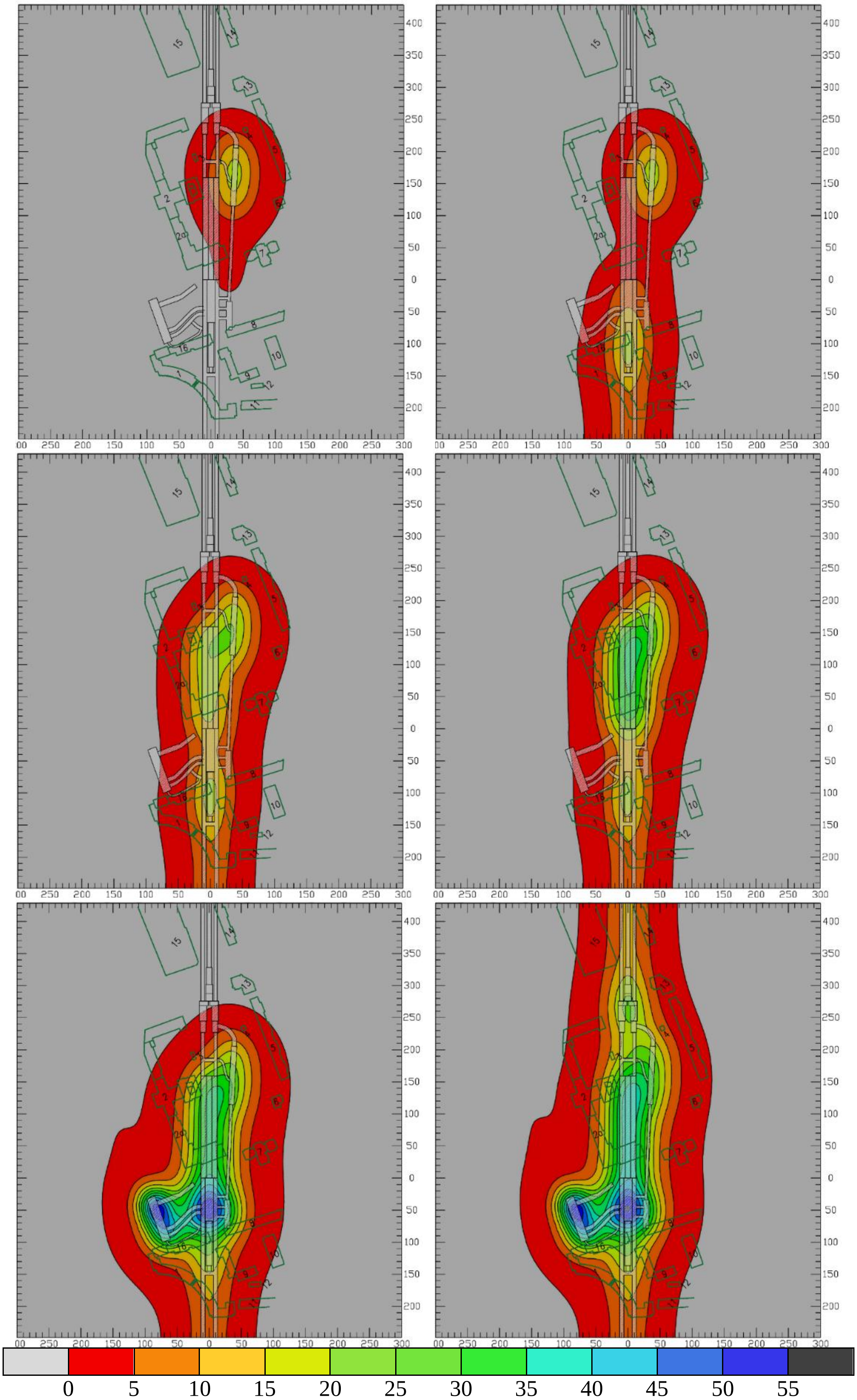

Figure 5. Forecast of deformations of ground surface upon erection of station complex at various stages of its erection: a – excavation of shaft inset; b – erection of rectifier substations and adjacent running tunnels; c – erection of left-hand platform tunnel; d – erection of right-hand platform tunnel; e – excavation complex of hub; f – after completion of erection of all underground facilities.

DISCUSSION

The presented concept of geomechanically safe development of megalopolis underground space successfully passed evaluation tests at 10 facilities of St. Petersburg and Moscow underground railways. The obtained results make it possible to state that the proposed approach can provide accident free erection of underground facilities of complex 3D configuration in complicated engineering-geological conditions. The major components are engineering-geological and laboratory studies based on up-to-date level of mathematical simulation of geomechanical processes, development of detailed 3D numerical models, which reflect both design features of the considered facilities and the consequence of their erection, as well as arrangement of monitoring system on the basis of acquired forecasted deformations of ground surface. Provision of minor settlement upon erection should be based on prevention of geomechanical processes in the vicinity of underground facilities, especially of in-depth underground facilities in soft rocks, since in such cases propagation of affected area increases significantly, and protective actions of aboveground buildings or structures generally cannot eliminate negative impact of driving operations on these facilities. Wide scale practical application of mathematical methods of analysis upon forecast of geomechanical processes in erection of underground facilities made it possible to transfer from qualitative description of forecasted processes to their quantitative assessment. It resulted in possibility to validate parameters of erection of underground facilities and to apply modifications in order to maintain the principles of minor settlement upon erection, as well as to develop actual protective actions for buildings when such actions are required.

In conclusion, we would like to cite well known researcher and engineer, R. Peck [13], who studied mechanics of grounds and behavior of artificial structures. He said that “9 of 10 accidents are caused not by theoretical restrictions of design of geoengineering facilities, but rather by poor implementation of theoretical approaches by experts involved in projects”. That is, in addition to improvement of theoretical knowledge of processes occurring in rock massif it is necessary to improve the quality of performed activities, qualification of direct contactors, otherwise, even good concept of safe development of megalopolis underground space will remain unimplemented in practice.

CONCLUSIONS

Solution of the set of issues appearing upon erection of underground facilities in restrained urban conditions enables improvement of safety of development of megalopolis underground space. The proposed concept of geomechanically safe development of underground space is based on detailed consideration of each project stage starting from engineering study to design, erection, and operation of underground facility, which makes it possible to forecast negative geomechanical processes and to develop measures on their prevention. The forecast of geomechanical processes is based on their mathematical simulation, including combination of knowledge about mechanical work of grounds, erection techniques of underground facilities and operation of elements of underground facilities. Such forecast enables revealing of areas of ground surface where the most unfavorable development of deformations of ground surface takes place, herewith, location of such areas can vary at various erection stages of underground facility. Current progress in the field of mathematical analysis and IT made it possible to improve significantly reliability of such analysis and to consider not an individual facility but overall complex of underground facilities representing complicated 3D structure.

Therefore, observance of the principles used as a basis of concept of geomechanically safe development of megalopolis underground space, including complicated geomechanical analysis, will make it possible to decrease significantly or to eliminate accidents not related directly with human errors at various project stages.

ACKNOWLEDGEMENTS

This work was supported by Russian Science Foundation (project No. 16-17-00117).

REFERENCES

[1]. M. A. Iofis and A. V. Grishin, "Improvement of procedures of geomechanical support of resource exploration." Mining Informational and Analytical Bulletin (Scientific and Technical Journal), No. 12, Vol. 1, 63-71, 2010.

[2]. E. V. Petrenko, Development of Underground Space. Moscow: Nedra, 1998.

[3]. V. G. Lerner, "Development of megalopolis underground space." Mining Informational and Analytical Bulletin (Scientific and Technical Journal), No. 9, Vol. 1, 63-71, 2000.

[4]. K. N. Trubetskoi, "Geomechanical support of complex resource exploration of the City of Moscow." Gorn. Zh., No. 1, 1999.

[5]. A. N. Levchenko, "Feasibility study of procedures and development of innovation technical solutions for development of megalopolis underground space." Thesis work, 2009.

[6]. S. N. Vlasov, L. V. Makovskii, and V. E. Merkin, Emergency Situations upon Erection and Operation of Transport Tunnels and Underground Railways. 2nd Edition. Moscow: TIMR, 2000.

[7]. O. Spackova, Risk management of tunnel construction projects. Doctorial Thesis. Czech technical University in Prague, pp. 180, 2012.

[8]. T. Seidenfuss, “Collapses in Tunnelling”, Master thesis. (Master thesis, Fachhochschule Stuttgart – Hochschule f r Technik), 2006.

[9]. M. Stallmann, “Verbrüche im Tunnelbau, Ursachen und Sanierung, 2005.

[10]. R.L. Sousa, “Risk analysis for tunneling projects”. Doctoral thesis, MIT, Boston, 2010.

[11]. M. Srb, “Possibilities of the collapse reduction during the excavation of conventional tunnels in the Czech Republic”. 2011.

[12]. J.B. Burland, J.R. Stranding, and F.M. ‚Jardine, “Building response to tunneling”. Case studies from construction of Jubilee Line Extension, London.

Volume 1 – Projects and methods. Thomas Telford, pp. 351, 2001.

[13]. R.B. Peck, "Deep excavation and tunneling in soft ground. Proceedings of the 7th international conference on soil mechanics and foundation engineering". Mexico City. State of the art Volume, pp. 225-290, 1969.

[14]. M. P. O'Reilly and B. New, "Settlement above tunnels in the United Kingdom- their magnitude and prediction". In: Proc. Int. Symposium Tunnelling '82, London, 7-11 June. London: Institution of Mining and Metallurgy, pp. 173-181, 1982.

[15]. A.R. Selby, "Surface Movements Caused by Tunnelling in Two-layer Soil". Eng. Geol. Of Underground Movements, Nottingham, pp.71–77, 1988.

[16]. R. K. Rowe, K. J. Lo, and G. J. Kack, "A method of estimating surface settlement above tunnels constructed in soft clay". Canadian Geotechnical Journal, vol. 20, no. 1, pp. 11-22, 1983.

[17]. E. M. Volokhov, "On assessment of influence of anisotropy of rocks upon calculation of stress and strain state of massif". Methods of applied mathematics in transport systems. Proceedings, Issue 6, 2002.

[18]. A. K. Bugrov and A. I. Golubev, Anisotropic Grounds and foundations of Structures. St. Petersburg: Nedra, 1993.

[19]. F. Scharinger, H. F. Schweiger, and V. Galavi, "Multilaminate framework for modelling soil behavior". Proc. International Workshop on Constitutive Modelling – Development, Implementation, Evaluation and Application. In Yin, Li, Yeung & Desai (eds.), Hong Kong, China, Hong Kong: Advanced Technovation Limited, pp. 65-74, 2007.

[20]. R.J. Jardine, D.M. Potts, and H.D. St. John, et al., "Some practical applications of a non-linear ground model". Proceedings of the 10th European Conference on Soil Mechanics and Foundation Engineering, Florence, Vol. 1, pp. 223-228, 1991.

[21]. M. A. Karasev, "Development of non-linear elastic transversal isotropic model of medium," Problems of geomechanics, geoengineering, and mine surveying, Zap. Gorn. Inst., Vol. 198, pp. 202-206, 2012.

[22]. M. A. Karasev, "Forecast of settlement of ground surface upon erection of in-depth underground facilities in the environment of St. Petersburg." Problems of geomechanics, geoengineering, and mine surveying, Zap. Gorn. Inst., Vol. 204, pp. 248-252, 2014.

[23]. T. Schanz, P. A. Vermeer, and P. G. Bonnier, "The Hardening Soil Model: Formulation and Verification". Beyond 2000 in Computational Geotechnics-10 years of Plaxis, Balkema, Rotterdam, pp. 281–96, 1999.

[24]. A. G. Protosenya, Yu. N. Ogorodnikov, and P. A. Demenkov, et al., "Mechanics of Underground Facilities". Space Models and Monitoring. St. Petersburg: SPGGU-MANEB, 2011.