RISK MANAGEMENT IN THE DEVELOPMENT OF UNDERGROUND SPACE IN RUSSIAN CITIES

Lebedev Mikhail, Romanevich Kirill

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OJSC Scientific research, design and survey institute "Lenmetrogiprotrans",
Saint-Petersburg, Russia
mail@lmgt.ru
romanevichkirill@gmail.com

Abstract

The article briefly discusses the experience of large cities in the integrated development of underground space together with ground construction. This document lists the major cities of Russia in which underground systems operate or are being designed. Based on the existing classification of geological and construction risks of megacities – Moscow and St. Petersburg, the necessity of continuous monitoring and risk management in the development of underground space is shown. The existing latest methodological documents are considered, on the basis of which, construction risks are managed, as well as geotechnical monitoring during the construction and operation of underground structures. Promising directions in developing means and methods of scientific and technical support of underground construction are shown.

Keywords: risk management, geotechnical monitoring, underground structures, geological hazards, underground space, construction and operation

I. Introduction

The experience of large cities around the world indicates the need for integrated development of underground space together with ground construction. The ever-increasing population concentration in megacities and the continuous growth of the car fleets give rise to territorial, transport, environmental and energy problems that hinder the sustainable development of modern Russian cities [1].

Progressive countries of the East and West have long been turning to underground space as a tool for creating a comfortable, environmentally friendly and safe space. Taking into account the experience of developed countries, we can say that the best option for the harmonious development of transport infrastructure is the development of an integrated ground-underground transport system.

One of the key components necessary for the integrated development of the transport infrastructure of cities is a developed underground network. The underground is the basis around which and together with which the intensive development of urban areas and all the processes taking place in them is carried out. The world practice of underground development shows the tendency to create underground complexes combining an underground station, transfer stations for various types of transport and business, cultural, historical and shopping centers, in order to unload the daytime surface of cities and ensure the comfort of moving city residents between them.

There are currently eight active underground networks in Russia in cities with a population of more than 1 million people: Samara, Yekaterinburg, Novosibirsk, Kazan, Volgograd (a high-speed tram with underground elements), Nizhny Novgorod, St. Petersburg and Moscow. In addition, the list of planned underground systems includes Chelyabinsk, Krasnoyarsk, Omsk, Perm, Rostov and Ufa.

The undisputed leaders in construction in Russia are St. Petersburg and Moscow, therefore, for these megacities, the territory according to geological and construction risk has been zoned in sufficient detail. At the same time, during the construction of underground structures, specific risks of underground space arise with a special character of natural and man-made factors caused by the interaction of elements of the natural and technical geosystem "rock mass – construction technology – underground structure – environment" [2,3]. In this regard, continuous refinement and risk management in the development of underground space is an extremely urgent task.

II. Geological and construction risks in Moscow

Moscow differs from other regions of the country in unprecedented large-scale construction and operation of underground transport and utility facilities.

Construction is carried out at various depths by almost all modern methods. If necessary, special methods are used to stabilize and strengthen the soils of strengthening structures (freezing, water reduction).

At the same time, in practice, it is often necessary to solve issues related to the elimination of abnormal, and in some cases, emergency situations in the form of excessive, up to destruction, deformations of facilities on the surface and underground, flooding and collapse of workings, provoking landslides, fire, etc. Damage can be tens of times higher than the funds "saved" in case of refusal to implement the necessary protective measures.

The risks of abnormal situations during underground construction in Moscow are caused, first of all, by specifically very complex engineering, geological, hydro-geological and urban planning conditions of the facilities location, which include such as:

- presence of a powerful layer of man-made soils, karst soils, high activity of groundwater and water-logging of underground construction sites, etc.;
- significant man-made loads on the engineering and geological environment of the city, which, provoking negative fast-flowing geological processes, worsen the conditions of the construction and operation of underground facilities;
- presence of dense urban development and the need to work on underground construction in cramped conditions, where many other facilities fall into the zone of influence, in addition to those under construction.

These conditions have been supplemented in the last decade by the risks associated with the actual scale of underground development in the Russian capital and the involvement of a large number of non-core specialists and organisations.

The listed risk factors and the possibility of their action in an unfavorable combination determine the need for their identification and accounting during the entire life cycle of an underground structure (during design, construction and operation). This is designed to optimize the choice of the facility location (tunnel route) and the appropriate protective measures, the cost of which largely depends on the degree of geological hazard for various conditions of the workings location conditions.

Fig. 1 shows a map of Moscow territory zoning by geological risk [4].

In the modern practice of construction and operation of critical underground facilities in the city of Moscow, many tasks of prevention of emergency situations, and in case of their manifestation – elimination of consequences, are solved by the organization of scientific and technical support at all life cycle stages of the structure. At the same time, the main importance is attached to solving geotechnical issues, for example, such as assessing the possible negative impact of new construction on the natural and urban environment, changing the conditions of static operation of structures under construction over time, determining the category of geotechnical complexity of construction.

For this purpose, a complex of additional surveys, calculations using modern geotechnical software and computing complexes such as PLAXIS, Z_Soil, MIDAS, etc., the stress-strain state of the system "soil body-structure" is monitored. Based on the results of these operations, adjustments are made to design and process solutions and to methods to ensure the operational reliability of facilities under construction and operating. However, the effectiveness of taking into account the features of a particular geotechnical situation for risk mitigation is still largely determined by the qualifications and experience of organizations that design, build or operate the facility. The regulatory and methodological framework available concerning this issue, including the Guidelines of the International Tunnel Association [5], is mainly general in nature.

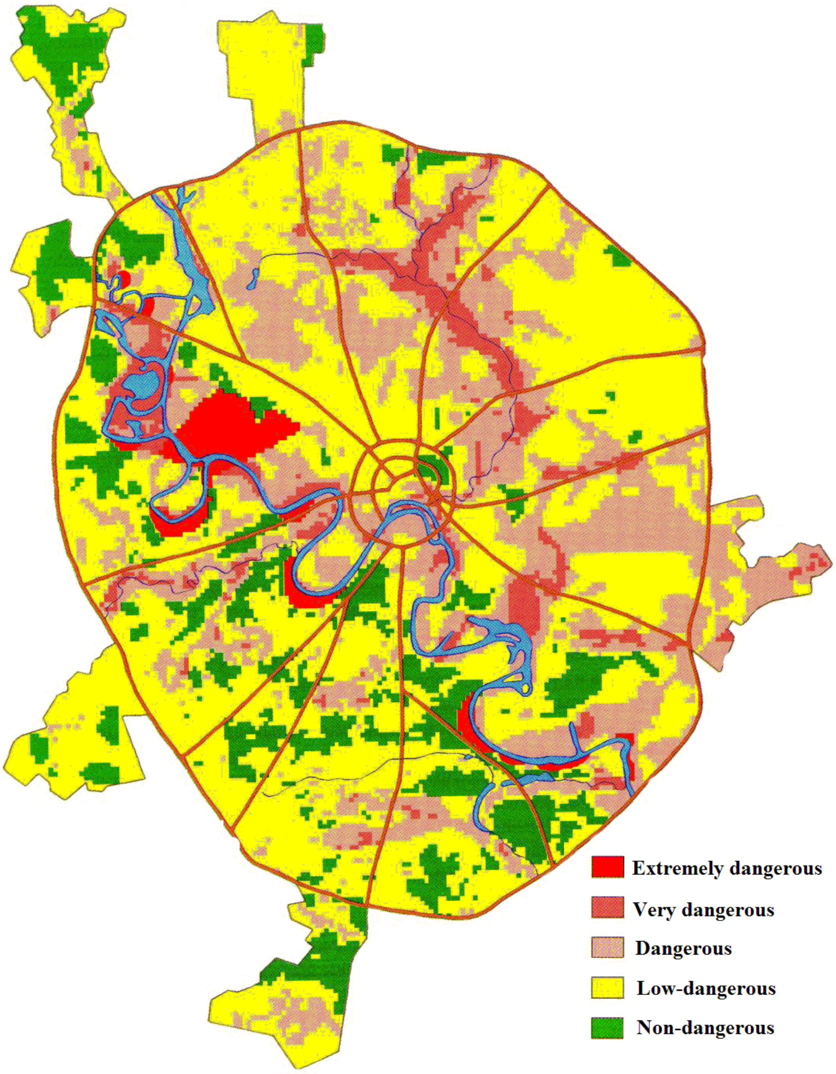

Figure 1: *Map of Moscow territory zoning by geological risk [4]. Extremely dangerous areas for geological risk (2% of the territory), very dangerous (2% of the territory) and dangerous (26% of the territory) are highlighted in red gradations, low-risk areas for geological risk (54% of the territory) are highlighted in yellow and non-hazardous areas for geological risk (12% of the territory) are highlighted in green*

The Reference manual for assessing and accounting for risks in the development of underground space in the city of Moscow [6] was developed in addition and in order to specify certain provisions of regulatory documents on ensuring the structures reliability and risk management in relation to underground facilities under construction and operated in engineering-geological and urban conditions of the city of Moscow. At the same time, the underground facility and the inclosing soil body are considered as a multi-factorial natural and technical geosystem, and an emergency situation in this system is considered as a probabilistic event, an adequate assessment of which will optimize protective measures.

Using the Reference manual for assessing and accounting for risks in the development of underground space in the city of Moscow [6], it is possible to adequately assess the possible risks of a natural and process nature at the stages of the life cycle of an underground structure and propose the most effective strategy for managing them to prevent emergency situations or to minimize damage in the event of their manifestation, for example, through appropriate protective measures. Based on the experience of eliminating the consequences of accidents at such facilities as the underground, we can talk about hundreds of millions of rubles and more than six months of downtime.

The document [6] includes, based on the data analysis on the state of the regulatory and methodological framework in force in Russia and abroad and practical experience in risk management in construction, adapted to the engineering-geological and urban planning conditions of the city of Moscow, "Methodology for assessing and managing risks of the impact of hazardous geotechnical processes and negative structural and process factors on the reliability of and operated underground structures".

The document [6] also contains a list and characteristics of special protective measures recommended for use to ensure the safety of underground structures under construction and operated in areas of potential danger. Using examples from domestic and foreign practice, it is indicated in which situations, i.e. from which dangers (risks) and with what effect an event can be implemented.

The determination of the probability of various risk realization during the construction and operation of underground structures is illustrated by examples of calculations performed both without taking into account possible protective measures and for cases of their application. To assess the effectiveness of the proposed engineering solutions to eliminate the event cause or to reduce possible damage, an appropriate methodology is proposed. Guided by the provisions of this Methodology, it is possible to optimize the choice of protective measures on linear and spatial construction facilities with open and closed methods of work.

Reference manual for assessing and accounting for risks in the development of underground space in the city of Moscow [6] includes:

- requirements for the initial information for assessing the level of danger of the development of negative manifestations and processes at underground urban infrastructure facilities;
- a methodology for quantifying the risks of the development of hazardous geological processes and their impact on the safety of underground structures under construction and in operation;
- criteria for assessing the reliability of structures and the effectiveness of measures to ensure the safety of underground structures under construction and in operation;
- characteristics of systems of constructive, process, organizational and technical measures to prevent abnormal, including emergency situations and methods for assessing their socio-economic efficiency;
- examples indicating proven in practice possible ways of implementing the proposed technical solutions in the development of projects and construction of underground facilities in the

city of Moscow.

The design provisions, requirements for materials, equipment, algorithm of actions and control during the production of works contained in the Reference manual for assessing and accounting for risks in the development of underground space in the city of Moscow [6] have been tested during the construction and operation of the underground, transport and utility tunnels in Moscow and a number of other regions.

III. Geological and construction risks of St. Petersburg

The main negative natural features of the territory of the city of St. Petersburg are:

- powerful, sometimes up to 30 m, heterogeneous thickness of weak, slowly compacting, including thixotropic soils, in most areas of the city;
- high groundwater level;
- presence of blocked soils and buried peat layers. The layers of lake-sea sediments contain lenses and interlayers of peat and frozen soils of different composition. These soils have a relatively high and irregular compressibility. The presence of buried bogs and peated soils, which, even with low power, have a negative impact on the underlying clay soils. Under buried bogs, sands are usually enriched with organic compounds of biotic and abiotic nature and have all the signs of quicksand, while the clay ones are characterized as weak thixotropic differences. The presence of bogs presupposes the existence of a sharply reducing environment in the underground space and its pronounced corrosive properties. Stagnant hydrodynamic regime of groundwater due to the presence of impermeable sheet pile fences and embankments, which leads to the accumulation of pollutants, activation of microbiological activity and biochemical gas formation [7];
- hydrodynamic processes associated with the impact of surface and groundwater causing water-logging, mechanical and chemical suffusion of soil, quicksand phenomena;
- processes associated with freezing-thawing of soils (frost heaving, subsidence during thawing);

Additionally, natural risks for artificial underground structures during their construction and operation in St. Petersburg are:

- aquifers in the context of the underground space of St. Petersburg;
- underground watercourses and aggressiveness of underground waters;
- possible breakthroughs of water and quicksand soils from "pockets" in glacial moraine deposits;
- removal of soil due to tunnel lining;
- capacity of the residual whole of clays between the bottom of the workings and the roof of a high-pressure aquifer (the pressure value can currently exceed 100 m);
- presence of paleodolines (buried paleodolines are laid along tectonic faults and determine the underground relief of bedrock – in the structure of buried valleys, slope areas, terraces and thalweg zones are distinguished. Thalweg is the deepest part of the buried valley, which is the bed of an ancient river filled with quaternary sediments);
- degree of fracturing of the sedimentary cover bedrock;
- aggressive biochemical processes;
- geological hazards in the coastal zone of St. Petersburg water bodies;
- manifestations of karst formation processes in the southern part of the city;
- seismic risk on the territory of St. Petersburg and the Leningrad Region;
- processes of natural gas formation (biogas) in the soils of St. Petersburg;
- gas dynamic processes in the underground space of the city;

- radon hazard and deep radon emanations;
- rheological properties of rocks (heaving, creep);
- ice formation on the structures of artificial structures of the underground;
- especially dangerous weather phenomena;
- floods in St. Petersburg;
- negative transformation of sand-clay rocks of both quaternary and pre-quaternary age with changes in physico-chemical and biochemical conditions.

Fig. 2 shows a map of the zoning of the territory of Moscow for integrated construction risk [8]:

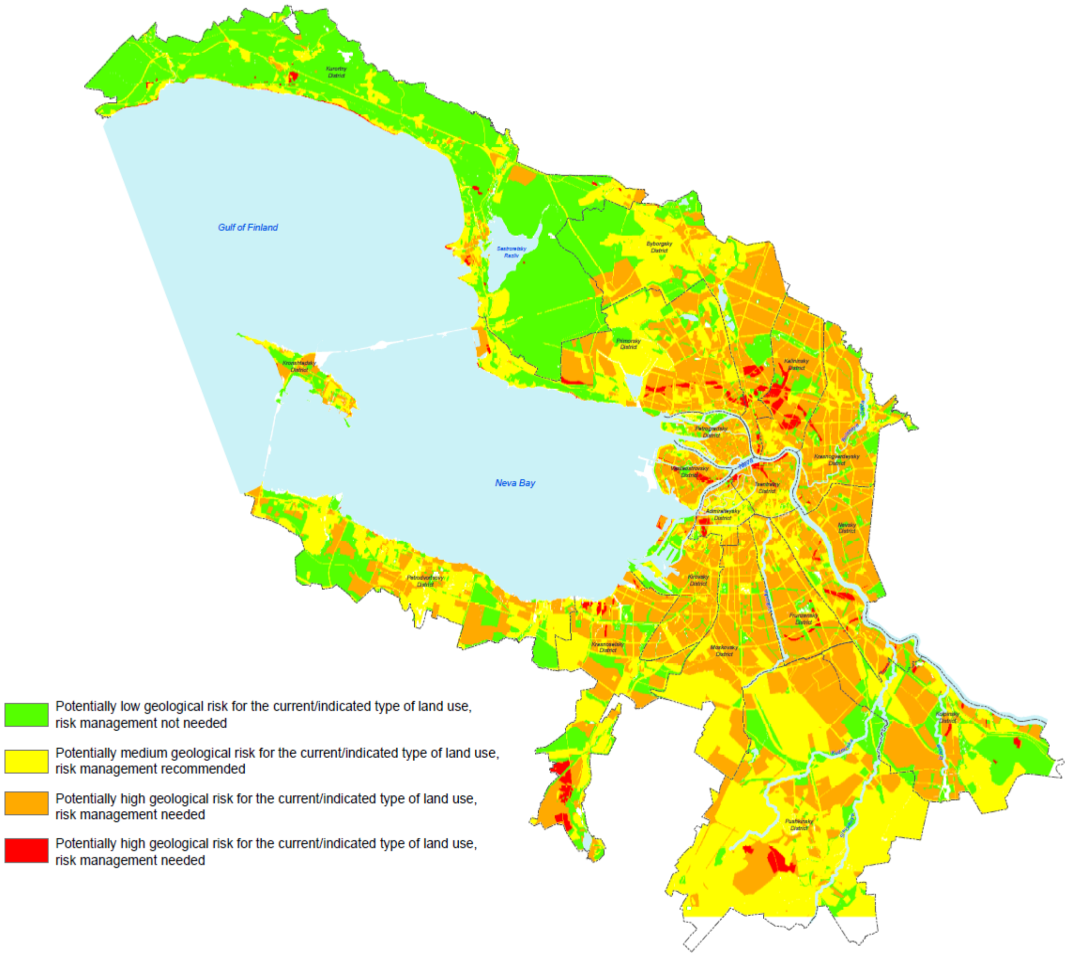

Figure 2: *Map of St. Petersburg zoning by geological risk [8]. Low geological risk zones are shown in green, medium geological risk zones — in yellow, high geological risk zones — in orange, and extremely high geological risk zones — in red*

In addition, negative man-made features of the territory of the city of St. Petersburg can be additionally highlighted:

- presence of alluvial, bulk territories along the banks of rivers and the bay;
- high level of underground waters of man-made origin;
- presence of existing buildings with defects caused by uneven precipitation, including due to lowering of the groundwater level (temporary or permanent);
- utility accidents;
- construction and other types of work (major repairs, reconstruction, dismantling, etc.) near artificial underground structures;

- man-made hydrodynamics;
- landfills and burials of various kinds, etc.
- accumulated powerful layer of various man-made formations in the urban coastal zone;
- disjunctive tectonics on the territory of St. Petersburg in the aggregate of man-made impact;
- poor quality construction and repair work of structures;
- uneven thawing of the rock mass after the commissioning of artificial underground structures built with the use of pre-freezing of soils;
- electrocorrosion;
- heat-generating effects.

All the listed risk elements for underground structures in the city of St. Petersburg should be considered in the complex of natural and man-made causes of potential accidents and emergency situations.

IV. Risk level control by means of geotechnical monitoring at various stages of the existence of underground structures

The risk level is not a constant value, but a variable, so it is not enough to simply state the presence of potentially dangerous sites and processes and assess the risk. It is necessary to constantly monitor the risk level that may change during the construction/existence of an underground structure.

The creation and use of automated geotechnical monitoring systems is one of the most important aspects of risk assessment and management in the development of underground space. When conducting geotechnical monitoring, a dynamic (iterative) and risk-oriented approach is implemented (when the main control efforts are directed to the most dangerous (suspicious) processes detected during geotechnical monitoring, and the remaining processes and intervals are observed in the background).

Geotechnical monitoring is carried out, among other things, to update forecasts and estimates made at previous stages of observations. The model (or risk map) for a particular underground structure should not be a static image (frame), but rather a set of such images that change over time – animation frames.

To date, the most comprehensive methodological guide for integrated geotechnical (mining and environmental) monitoring during the construction and operation of underground structures (transport tunnels) is the "Methodological guide for integrated mining and environmental monitoring during the construction and operation of transport tunnels" [9]. It sets out the main provisions applied in the design, construction, commissioning, operation, reconstruction, restoration, conservation and liquidation of transport tunnels as part of measures to ensure their safety. The system of geotechnical monitoring for the control of dangerous geodynamic processes and phenomena of a natural and man-made nature is presented, which provides for the development of scenarios for the development of a possible accident when each of the criteria indicators dangerous for an underground structure is manifested.

For example, for the purposes of mapping geological risk, various methods of engineering geophysics in the areal version are often used (magnetic exploration, electrical profiling, microseism registration, etc.). The survey is carried out over a network of profiles with a uniform measurement step. During processing, a matrix is formed from all the obtained measurement points, according to which the isolines of the recorded parameter or its derivatives are built.

One of the methods of operational control of the modern geotechnical situation at large-area facilities is the EMR registration method, used both at the survey stage and in monitoring mode [10].

The method is based on the registration of abnormal electromagnetic radiation of rocks during their deformation, for example, during precipitation of the Earth's surface or during landslide processes. The obtained absolute EMR values during processing are normalized to the average value over the entire observation area to obtain the normalized Anorm parameter. An increase of this parameter by 4-6 relative units indicates geodynamic activity associated with intensive deformation of existing inhomogeneities in the studied rock mass. At Anorm > 6, accelerated development of microdefects in the rock mass is recorded [11].

Fig. 3 shows the result of constructing a distribution map of the Anorm parameter when registering EMR in the territory affected by landslide processes. The shoreline is shown at the bottom of the figure, with dark outlines above showing landslide bodies identified during the geological survey and drilling. It can be seen that the increased values of the EMR level correspond to the spatial position of the landslide bodies, and the maximum values of the Apogm parameter fix the places of the landslide process activation.

EMR registration in this area was carried out by us during the updating of engineering and geological surveys during the railway tunnel design. The data shown as part of a complex of engineering and geophysical methods are valuable information when choosing the location of the tunnel portal and construction site. Similar work is being carried out by us to assess the geodynamic activity of rock bodies and to map tectonic disturbances.

The disadvantage of the EMR registration method is the strong dependence of the EMR level on the number of sources of industrial interference, therefore, application in the city is extremely difficult.

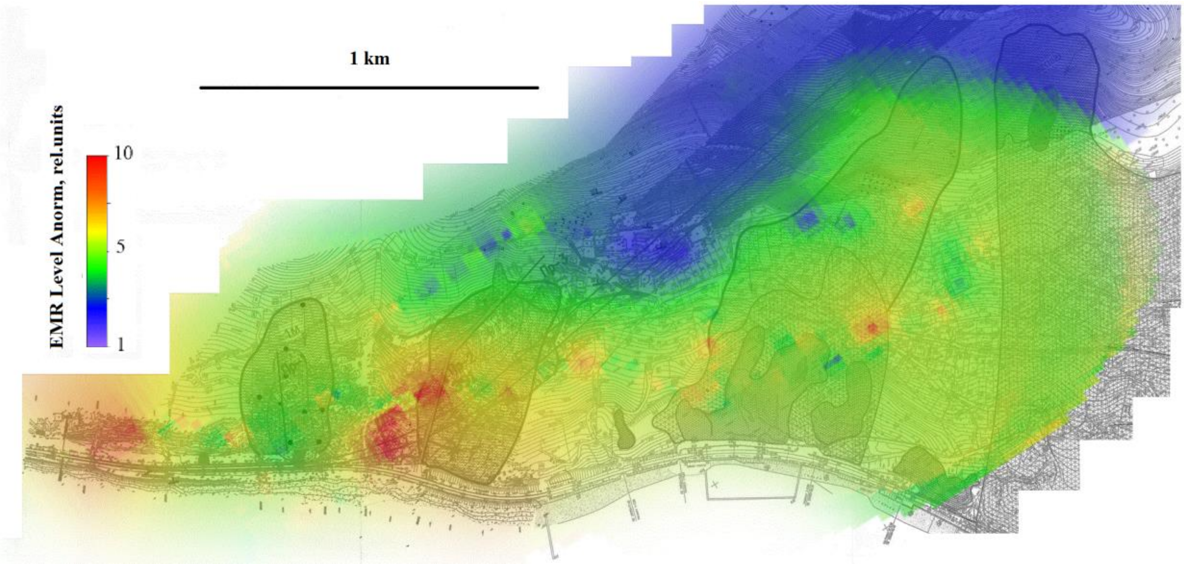

Figure 3: *Map of the EMR level in the coastal area affected by landslide processes. The shoreline is shown at the bottom of the figure, with dark outlines above showing landslide bodies identified during the geological survey and drilling*

V. Geotechnical monitoring system for the development of underground space

The theory and practice of underground construction emphasizes the importance of regular supervision of the technical condition of tunnel structures and facilities, as well as special surveys of tunnel structures, professional analysis of the survey results and adequate measures to prevent emergencies. The level of safety of underground structures should be increased within the framework of a preventive safety strategy. Currently, the most advanced means is geotechnical monitoring.

The basic purpose of geotechnical monitoring is to study in full-scale conditions of the static operation of temporary support and permanent lining of underground structures with the determination of deformations, stresses, temperatures, geodynamic parameters in the lining and the inclosing rock body, as well as with the prediction of loads from mountain pressure and other environmental influences. As a result, scientific information necessary for the development of proposals and recommendations for improving tunnel structures and construction technologies in reducing labor and material intensity, cost, and improving the quality of structures should be obtained. Such information should be used as a basis for clarifying the existing regulatory documents on the construction (reconstruction and operation) of underground structures. Research should be carried out both during construction and subsequent operation. Therefore, information and measurement systems created at underground facilities should be remote and designed for a long service life.

VI. Geotechnical monitoring at the stage of construction of underground structures

Geotechnical monitoring during the construction of underground structures solves geotechnical and geoecological tasks, the main purpose of which is the integrated safety of mining operations and reducing the negative impact on the environment, both during construction and operation.

The main methods of observations using the geotechnical monitoring system during the construction of underground structures:

- geodetic and surveying observations, including using satellite imagery;
- seismological observations;
- geophysical observations;
- geomechanical observations;
- hydrogeological observations;
- environmental monitoring system (including control of aggressive chemical and biological environmental influences).

Direct and indirect methods for determining controlled parameters allow to:

- predict engineering and geological conditions ahead of tunnel faces with sufficient accuracy;
- determine qualitative and quantitative indicators of the stress-strain state of the "lining - body" system;
- determine the actual deformation and strength properties of the inclosing body;
- determine the deformations of the inclosing body from the contour of the tunnel to the day surface;
- determine the maximum permissible concentrations of pollutants in the air, water and dumps.

The results obtained in the course of conducting geotechnical monitoring make it possible, during the construction, to determine the impact of work on the activation of hazardous processes and adjust the process parameters of mining operations, and develop recommendations to reduce the negative impact on the environment.

Work on the Geotechnical Monitoring Project is carried out during the construction of the underground structure until the facility commissioning. With their help, the parameters of the applied support structures and linings, as well as the technology of their construction, are adjusted.

Relatively young in world practice, and at the same time effective both in the construction and operation of underground structures, are the methods of XRS interferometry (XRS radar with synthesized aperture – InSAR abbreviation used in the international literature) are widely used in solving various problems related to surface displacements: in the study of displacements at landslide slopes, soil subsidence over underground structures, including in conditions of dense urban development, when monitoring deformations of pipelines and overpasses, displacements of the earth's surface as a result of earthquakes, volcanic and other natural processes [12-14].

XRS interferometry methods make it possible to identify areas of active deformations of the Earth's surface and infrastructure facilities associated with many natural and man-made processes with a high degree of detail.

Short-wave images of Terra-SAR and COSMO-SkyMed satellites are particularly effective for monitoring urban areas. The images of these satellites (Fig. 4) have a small resolution element, but are more sensitive to atmospheric interference.

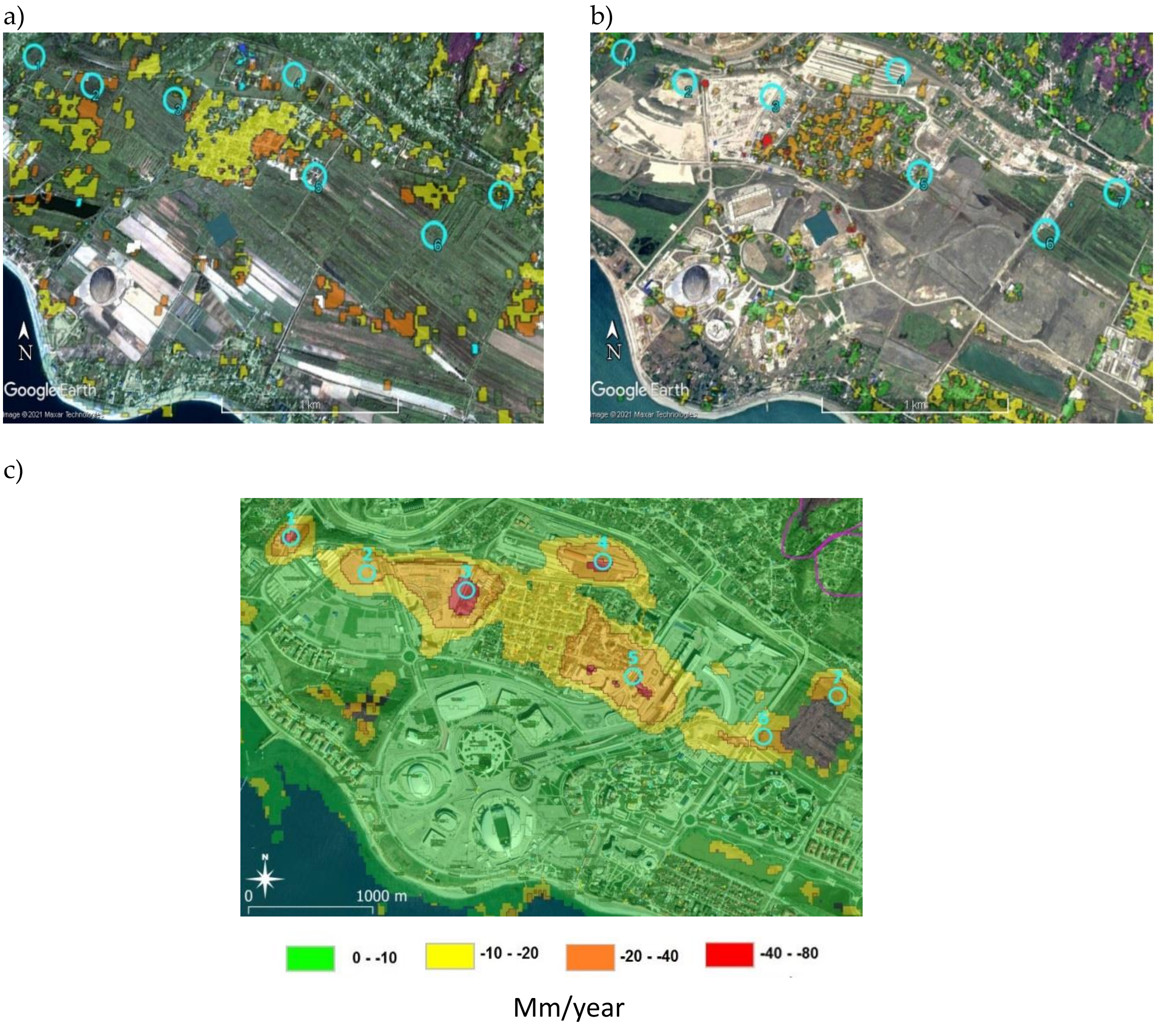

Figure 4: *Maps of average vertical displacement velocities on the territory of St. Petersburg based on satellite images: a) ALOS 2007-2010 track 588A; b) Envisat 2010-2012 track 35D; c) S-1A 2015-2020 track 43A in Google Earth images for 2007 (a), 2010 (b) and Google Maps for 2020 (c)*

The satellite XRS interferometry method do not require large financial costs, and the results can be interpreted together with ground geodesy data, as well as with field geological research materials, which makes it possible to significantly increase the efficiency of existing monitoring systems.

The latter is especially important when developing underground space on the territory of large cities in order to preserve historically significant buildings and structures.

VII. Geotechnical monitoring at the operation stage of underground structures

In accordance with the requirements of the Federal Laws of Russia, the safety of structures during operation shall be ensured by maintaining the established parameters at the required level.

Supervision of operated underground structures, as a system of inspections, surveys and observations, has historically been the main organizational event carried out during the maintenance of underground system and other underground structures. The concept of "supervision" includes a system of visual and instrumental observations, periodic and special surveys aimed at early detection of defects, primarily of basic structures and arrangements, and analysis of the causes of these defects.

With obvious disadvantages of visual inspection of the inner surface of the lining of underground structures to assess their technical condition, there is an alternative method: use of control and measuring equipment placed in the lining during construction as part of geotechnical monitoring.

The lining and lining equipment shall be fitted in accordance with the geotechnical monitoring project included in the project documentation.

The geotechnical monitoring system informs about changes and predicts changes in the stress-strain state of structures. The results of field studies play an important role in the selection of methods for calculating supports and linings.

For the safe operation of underground structures and the forecast of the state of the "lining - inclosing body" system, it is advisable to create an analytical center for processing and analyzing the database of geotechnical monitoring performed on operated underground structures in order to improve and optimize methodological and technical means.

Different modes of operation of underground structures can also negatively affect the activation of hazardous processes and phenomena in high-risk areas. Uncontrolled development of geotechnical processes in such zones is potentially dangerous for traffic and, accordingly, people. Therefore, the list of works to ensure the operation of functional tunnel systems must necessarily include a complex of geotechnical monitoring to control the level of geotechnical risks as part of an automated process control system (automated process control system).

To measure the thermodynamic parameters of the air environment (temperature, relative humidity and air velocity) and the surface temperature of the concrete lining, as well as static pressure, it is preferable to use autonomous sensors with the possibility of accumulating the measured information for a given period of time. Information from these sensors can be read by connecting them to secondary storage systems after a specified measurement period has elapsed.

The geotechnical monitoring system at all stages of the existence of an underground structure seems to be an absolutely necessary element of accident prevention, prediction of the technical condition of structures and safe operation.

Risk level control with the help of a well-established geotechnical monitoring system allows you to plan in advance measures to restore and eliminate the consequences of accidents at any stage of the existence of an underground structure.

The geotechnical monitoring system is a source of new geotechnical information about the work of linings and bodies. The obtained results of geotechnical monitoring make it possible to determine the impact of work on the activation of hazardous processes during construction and adjust the process parameters of mining operations, develop recommendations to reduce the negative impact on the environment. With the help of data from the geotechnical monitoring system, the parameters of the applied support structures and linings, as well as the technology of their construction, are adjusted.

During the operation of an underground structure, the automated GEM system in online mode provides operational services with information necessary and sufficient to determine the impact of the operating mode and climatic anomalies on the activation of dangerous geodynamic processes in order to select the safest process operating modes, assign visual and instrumental surveys, as well as strengthening measures.

During the inspections of monitoring systems in controlled facilities, a search is carried out for new risk factors that, with appropriate justification, can be included in the control scheme by the geotechnical monitoring system.

A large volume of geotechnical data obtained from geotechnical monitoring systems can later be used in the development of unified approaches to monitoring and forecasting the level of risk using digital geomechanics tools, mathematical modeling of natural and man-made processes, deep learning techniques based on neural networks. Automated geotechnical monitoring systems can be included in algorithms for assessing the technical condition of underground structures using BIM technology. In any case, the initial information here is full-scale studies of the stress-strain state of structures and inclosing bodies as part of the integrated geotechnical monitoring system, which is a physical tool for assessing, controlling and predicting the level of geotechnical risks in the most potentially dangerous intervals of the structure.

Geotechnical monitoring systems during the construction and operation of underground structures can be upgraded with new technical means of control, which are currently being developed and implemented both in Russia and abroad for the purposes of safe integrated development of underground space [15].

As an example, the following promising areas of developing means and methods of scientific and technical support of underground construction can be given:

- spatial geometric parameters of the supports and linings of railway tunnels during construction and operation are measured using laser scanning according to the specified regulations. This makes it possible to compare actual three-dimensional models of structures and sections of exposed inclosing soil bodies. The data obtained at different time periods of observations allow us to determine the displacement of unmarked points of temporary support, as well as changes in the shape of the tunnel walls and arch. Due to the high scanning density, this method makes it possible to remotely detect relatively small areas of changes in the body structure and the support state;
- Comprehensive integrated solutions that allow you to manage various modules, such as access control and tracking operators, communication in the tunnel, closed-circuit video surveillance systems, environmental sensing and emergency management and alarms. The solution is based on the identification and control of the presence of personnel, as well as the detection and storage of the number and location of operators in real time. Maximum automation is achieved for more efficient and timely management of emergency and evacuation processes;
- High-speed video recording and image recognition technologies that make it possible to warn about a collapse 0.1 seconds after detecting the movements of falling objects;
- Determination of displacements of the Earth's surface by radar satellite interferometry;
- Technologies based on augmented reality and virtual reality, etc.

VIII. Conclusion

The integrated development of the underground space of large megacities puts forward a number of requirements that shall be taken into account when planning, designing and building, since underground structures under construction and operated are high-risk zones and in the event of an accident, pose a serious danger to people in them. The purpose of risk management in the construction and operation of underground structures in megacities is to ensure the successful functioning of urban systems in the conditions of risk and uncertainty. To do this, it is necessary first of all to understand the dangers that the underground space puts forward, classify these dangers and control them in the most effective ways.

Conducting geotechnical monitoring during the construction and operation of underground structures is an absolutely necessary type of work. For this purpose, on the basis of international documents, special methods and reference manuals are being developed in Russia to assess and account for risks in the development of the underground space of megacities. As a result of applying these techniques in the practice of underground construction, they should be tested and validated, after which the most effective of them, of course, should be included in the guiding regulatory and technical documents.

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