Risk control system for the construction of urban underground structures

E Yu Kulikova¹, S V Balovtsev²

¹ Department "Construction of Underground Structures and Mining Enterprises", “Safety and Ecology of Mining”, National University of Science and Technology NUST MISiS, 4, Leninsky prosp., Moscow 119094, Russia
² Department "Safety and Ecology of Mining", National University of Science and Technology NUST MISiS, 4, Leninsky prosp., Moscow 119094, Russia

E-mail: fragrante@mail.ru

Abstract. Complex development of dense urban underground space puts forward a number of requirements that must be taken into account when planning, designing and building, because underground structures under construction and in operation are high-risk areas and, in the event of an accident, pose a serious danger to the people in them. The purpose of the risk control system for the construction and operation of underground structures in megacities is to ensure the successful functioning of urban systems in conditions of risk and uncertainty. In the event of an emergency, the implementation of risk control measures should ensure that the adverse impact caused by accidental events on the successful operation of megacity facilities is minimized. The article considers the functional risk control system in urban underground construction, presents an analysis and classification of risk-forming factors that affect the environmental and technological safety of urban underground space development. Qualitative and quantitative indicators of risk development were identified. The main requirements and principles of forming a risk control system for the development of urban underground space are formulated.

1. Introduction

The modern stage of urban planning is unthinkable without placing an extensive range of objects in the underground sphere. Despite the obvious effect of underground space developing in cities, there are a number of problems associated with the appearance of various types of risk. Therefore, the task of developing a risk control system is very urgent. In research on risk, as a rule, insufficient attention is paid to a number of issues, related to underestimating the impact of certain risk factors on the corresponding types of risk and their level. Thus, in the process of risk research in the construction of underground structures, special attention should be paid to the specifics of their construction and operation. At the same time, the risk due to the uncertainty of production conditions significantly affects the economic performance of the construction organization. Insufficient attention is paid to measures to prevent accidents, which is mainly due to the difficulties in assessing the probability of occurrence of relevant accidents. The proposed solutions are mainly concerned the building a “failure tree”. However, such models require high-precision input data, and may also be subjective.
2. Classification of risk factors

Depending on the type of underground construction project, the composition of risk factors, to be accounted for, can be classified as follows (Figure 1).

From the general composition of risk factors, it is advisable to distinguish two main groups. The first one refers to inaccuracies in developers’ views about the forecast state of the external environment of the construction project (i.e., the area of interaction between an underground structure and a rock mass as the main element of the environment, within which significant changes in the composition, condition, properties of rocks and geological processes occur). The type and nature of the impact of underground structures on the enclosing rock mass and the surrounding urban environment may be different depending on the type and purpose of the underground object, mining and hydrogeological conditions of its foundation, construction technology, the duration of operation of the underground structure, etc. The main source of such impact is the special nature of natural and manmade factors, due to the interaction of elements in the natural and technical geo-system “rock mass – technology – underground structure – environment” [1-8]. Since this interaction is characterized by changes in the stress-strain state of the rock mass enclosing the underground object and the activation of filtration processes, they are the primary sources of environmental imbalance and negative impact of underground construction on the environment, which must be taken into account in the construction project.

The second group of risk factors is associated with possible errors and inaccuracies in determining the internal characteristics of the construction project. The main internal risk factors are incompetence, lack of experience, knowledge and operational business activity, adventurism, excessive trustfulness in relations with partners, the desire for short-term benefits at the expense of development, etc.

The list of the main risk factors for the stages of the underground construction project is presented in Table 1.

It is impossible to take into account all the risk factors, but it is quite possible to identify the main ones based on the results of the impact on a particular type of work during the construction of underground structures. However, the following aspects must be correctly assessed as:

- the nature of the effect caused by a particular risk event, its impact on the result;
- quantitative value of the probability of occurrence of a risk event;
- time of occurrence of risk events.

The key point of the preparatory stage of organization of risk control in construction of underground structures – assessment of the level and margin risks for construction companies. At the same time, it is advisable to conduct a qualitative and quantitative (combined) risk assessment.

Based on the brief characteristics of quantitative risk indicators, which are currently used in practice, we will highlight the most acceptable and affordable risk indicators: the probability of destruction of urban structures, underground utilities, and material damage. Failure and event tree methods are the most appropriate methods for assessing technical risk. If the corresponding tree of events or failures is supplemented with statistical data, the specialist, even without a thorough knowledge of probability theory, can not only find the most critical scenario, but also assess the expected risk.

Quantitative measurement of the level of environmental safety in the development of underground space of a megalopolis also plays an important role in risk control in the natural and manmade sphere. For the analysis and assessment of environmental risks (the probability of negative manmade changes in the environment in the area of construction and operation of underground structures) in a megalopolis, the statistical method and the method of expert assessments are applied.

Due to the lack of environmental analysis of the consequences of underground construction, the underground space of the metropolis is currently filled with toxic gases in different concentrations. Therefore, it is also important to assess the aerologic risk (a hazard measure that characterizes the possibility of an accident due to deviations of the atmospheric parameters of underground structures from their normative values) [1,9,10].
Integrated method of assessment and control of aerological risk of accidents, developed by S.V. Balovtsev and O.V. Skopintseva, takes into account the influence of geological and mining factors [1-4, 10], for risk and forecasting upper-air risks in the design, construction of mine and underground constructions.

Qualitative assessment is designed to determine the possible types of risk, factors that affect its level in the construction of underground structures. In addition, qualitative analysis also includes a methodological approach to quantifying the acceptable level of risk.

3. Risk management

To ensure high performance in risk control, as well as flexible response to the emergence of new hazards, it is necessary to make a general assessment of the set of risks (technical, environmental [1,5-8], geomechanical, geodynamic [11-13], aerological [1,14] organizational and managerial [6], construction, operational [7], economic, etc. risks) and eliminate the negative consequences of their implementation (Figure 2). Measures to reduce risks should be aimed at improving the reliability of megalopolis facilities and the economic efficiency of urban systems, as well as at tightening safety requirements.

The functional diagram of the risk control system for the construction and operation of underground structures is shown in Figure 3.

In the section “Information and organizational support of the risk analysis procedure”, quantitative information is quickly entered in the form of numerical values of certain indicators for evaluating the parameters of mathematical models, and qualitative information reflecting a verbal description and/or value judgments about this object or process. The entire possible set of risks and risk-forming factors in a megalopolis is identified and analysed, without taking into account the availability of resources for measures and actions to reduce them or to compensate for them as much as possible.
### Table 1. List of risk factors by stages of the underground construction project.

| Risk factors | Type of risk | Stages | Impact on expected earnings |
|--------------|-------------|--------|-----------------------------|
|              |             | The arrangement of the construction site | Construction | Operation | |
| Distance from transport hubs | + | - | - | The additional costs of creation of access roads, the high cost | |
| Distance from engineering networks | + | - | - | Additional capital investments for supplying electricity, heat, water | |
| Attitude of local authorities | + | - | - | The possibility of additional restrictions imposed by the authorities that complicate the implementation of the project | |
| Availability of contractors on site | + | - | + | Danger of overestimating the cost of work in the exclusive position of the contractor | |
| Availability of alternative sources of raw materials | + | + | - | Risk of overcharging when the contractor is in a monopoly position | |
| The customer's ability to pay | + | + | + | Increase in the amount of borrowed funds and decrease in net profit due to interest payments | |
| Disadvantages of design and survey work | + | + | - | The rising cost of construction, delay in commissioning of capacities | |
| Late delivery of components | + | + | - | Increase in construction time | |
| Upper-air risks | - | + | + | Increased costs for ventilation and cleaning of the working atmosphere from dust, reptiles and aerosols | |
| Gases and aerosols entering the atmosphere associated with equipment operation and waste water discharge | + | + | + | Increase in unexpected costs for cleaning equipment | |
| Release of harmful substances characteristic of this type of underground structure | + | + | + | Increase in operating costs, increase in construction costs | |
| Demand volatility | - | - | + | Decrease in net profit | |
| Price reduction by competing construction firms | - | + | + | Price reduction | |
| Tax increase | - | + | + | Decrease in net profit | |
| Rising prices for raw materials, transportation | + | + | + | The decline in profits due to rising prices | |
| Lack of working capital | + | + | + | Increase in loans | |
| Difficulties in recruiting skilled labor | + | + | + | Increase in the cost of completing construction | |
| Attitude of local authorities | - | + | + | Additional costs for fulfilling the requirements of the authorities | |
| Insufficient salary level | + | + | + | The decline in labour productivity, labour turnover | |
| Social infrastructure | - | - | + | Growth of non-production costs | |
| Equipment wear and tear | - | + | + | Increase in repair costs | |
| Instability of raw material quality | - | + | + | The decrease in construction volumes due to changeovers of equipment, reduction of reliability of underground constructions | |
| The novelty of the technology | - | + | + | Increased costs for the development of new technologies, reduced construction volumes | |
| Lack of reliability | - | + | + | Increasing the accident rate of the object | |
| The lack of reserve capacity | - | + | + | Loss in case of accidents | |
Figure 2. Main aspects of risk control.

Figure 3. Functional diagram of the risk control system.
The “Risk identification” section identifies the sources of hazards that lead to failures of urban systems, the conditions for the occurrence of hazards, elements, technical devices, technological blocks or processes that require the most detailed analysis; preliminary assessments of the consequences of possible man-made accidents are carried out. Another important aspect is the identification of hazards that lead to potential undesirable technogenic changes in environmental resources.

It is very important to meet the requirements of the “Monitoring of compliance with measures” block, based on monitoring measures and evaluating the effectiveness of risk control.

The most relevant is the quality control of the construction materials and structures used, as well as the production technology that should ensure the specified service life of underground structures [2, 3]. Thus, the load on the structure lining at the design stage is determined by evaluating the results of engineering and geological surveys and accumulated experimental data on loads obtained under similar construction conditions. Therefore, all factors are taken into account [15=20]: mountain and hydrostatic pressure, weight of buildings and other ground structures, own weight of structures, loads from ground transport, loads arising in the course of tunneling (pressure from pumping the solution for the lining). In addition to loads, when choosing the material and design of the lining, engineering-geological and hydrogeological conditions are taken into account the lining is calculated for the most unfavorable combination of loads (taking into account the reserve coefficient).

The tasks of monitoring of the state of a rock mass are the selection and justification of criteria for monitoring of the enclosing rock mass or its individual elements; development of control schemes and the necessary means to improve them; notification in case of dangerous situations. Monitoring is carried-out by various types of geo-mechanical monitoring (analytical methods, instrumental methods for monitoring the movement of rocks, modern automated control systems, direct visual surveys of the state of workings, etc.) [10,11,19-20].

All these factors add up to form a complex risk control system that needs constant adjustment for a specific underground facility.

4. Conclusion

1. The given classification of integrated risk factors allows us to form a systematic approach to the natural and technical geosystem “rock mass – technology – underground structure – environment”, which implies:
   - identification of prevailing risk factors that affect the state of the natural and technical geosystem;
   - identification of the level of significance of each of the elements composing the geosystem;
   - identify relationships within the system.

   This systematic approach primarily involves the establishment of quantitative criteria that characterize the level of environmental, economic, technological and operational safety in the construction of urban underground structures.

2. The risk control system for the construction and operation of underground structures has certain specifics related to the features of the object, and is reflected in the following principles:
   - when controlling risks, external and internal constraints should be taken into account, which means that safety measures should be coordinated with the operating conditions of the underground structure;
   - risk control is a dynamic process that is complex and multi-level;
   - highly specialized decision-making is required within the framework of the risk control system for the construction and operation of underground structures in megacities.

References
[1] Balovtsev S V 2015 Aerological Risk Assessment in Working Areas of Gas and Dust Explosion-Hazardous Coal Mines Gornyi Zhurnal pp 91–93
[2] Dudler I V, Korolev M V and Ukhov S B 1998 Interrelation of engineering-geological, geotechnical and geoeological aspects of ensuring reliability of construction of urban buried underground structures Materials of the conference “Underground City, Geotechnology and Architecture” (St. Petersburg: “Theme”) pp 520–523
[3] Skopintseva O V, Vertinskiy A S, Ilyakhin S V, Savelev D I and Prokopovich A Yu 2014 Substantiation of efficient parameters of dust-controlling processing of coal massif in mines Gornyi Zhurnal pp 17–20
[4] Skopintseva O V, Ganova S D, Demin N V and Papichev V I 2018 Integrated method of dust and gas hazard reduction in coal mines Gornyi Zhurnal pp 97–100
[5] Kulikova E Yu 2019 Risk Assessment of Dangerous Natural Processes and Phenomena in Mining Operations Springer Proceedings in Earth and Environmental Sciences book series (SPEES) (Springer, Cham) pp 21–33
[6] Kulikova E Yu 2018 Defects of urban underground structure and their prediction Materials and Science Engineering. Proceedings of International Conference on Construction, Architecture and Technosphere Safety (IOP Conference Series) 149
[7] Kulikova E Yu 2002 Environmental safety in the development of underground space in large cities (Moscow: MSU Publishing House) p 376
[8] Kulikova E Yu 2019 Assessment of the Operating Environment of the Concrete Lining of Sewage Collector Tunnels Materials Science and Engineering 687 1–7
[9] Shuxue D, Hongwen J, Kunfu C and Guo’an X, Bo M 2017 International Journal of Mining Science and Technology 27
[10] Kasperson R E, Renn O and Slovic P 1988 The Social Amplification of Risk: A Conceptual Framework Risk Analysis 8(2) 177–187
[11] Batugin A, Odintsev V, Kolikov K, Lijiang Y & Khotchenkov E 2018 Displacement and mine seismicity processes during undermining of a tectonically active fault area at the Sinvay deposit International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management, SGEM 18(1.3) 319–326
[12] Filin A E, Ovchinnikova T I, Zinovieva O M and Merkulova A M 2020 Advance of pulsating ventilation in mining Gornyi Zhurnal 3 67–71
[13] Johnson K L 1985 Contact mechanics (Cambridge University Press) p 452
[14] Budhu M 2010 Soil mechanics and foundations, 3rd ed. (John Wiley & Sons) p 781
[15] Puzrin A M and Randolph M F 2015 Effects of pore water dissipation on rate dependency of shear strength in localised failure of soils International Journal for Numerical and Analytical Methods in Geomechanics 39(10) 1045–1062
[16] Causes of destruction of tunnels during their operation. http://fecland.ru/tunneli/198
[17] Osipov V I and Medvedev O P 1997 (Moscow: Geology and city Moscow textbooks and kartolitografiiya) p 400
[18] Mishra R K, Janiszewski M, Uotinen L K T, Szydlowska M, Siren T and Rinne M 2017 Geotechnical Risk Management Concept for Intelligent Deep Mines Procedia Engineering 191 361–368