Geotechnical risk assessment during the construction of international crossing under the runways of Sheremetyevo airport

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Abstract. The surrounding buildings, topographical, engineering-geological and hydrogeological conditions of the construction site area are factors of potential geotechnical risks and influence the occurrence of emergencies during the building of underground structures. It is irrefutable fact, that while the development of the underground space of cities due attention is not given to geotechnical risks, considering only issues related to economic damage. In addition, there is no comprehensive risk control methodology for the construction of complex multifunctional facilities. In order to prevent the risk of accidents, during the construction of the Inter-terminal transition under the runways of Sheremetyevo Airport in Moscow method of geotechnical risk control was developed, which proved to be an effective method in the prevention of accidents during construction. Recommendations were developed to reduce the level of risk at the considered facility, including verification calculations carried out by an independent organization in a certified geotechnical software package; geophysical surveys of runway foundation; filling voids before sinking under the runway; exploratory drilling and geophysical surveys before sinking hazardous areas.

1. Introduction

Emergencies arise as result of two independent negative events: external non-project impact, and errors in projects, both at the early stage of construction development, and during the construction or operation of the facility [1,2]. Uncertain or incomplete geotechnical data during the construction and operation of tunnels can lead to risks of accidents.

Since errors made in the design and construction process are manifested at all subsequent stages of the life cycle of the underground structure — one of the main types of risks is the construction risk. Dividing the risk into types allows understanding the specific feature of its development, and the measures that will need to take in order to solve the problem caused by this risk [3]. Risk study in domestic [1-10] and foreign practice is an item of special interest [11-21]. However, risks in urban underground construction are practically not considered, or a single aspect is under consideration. Technological risks and risk-forming factors are usually evaluated in minimum degree when performing construction and installation works. When constructing underground structures, the environmental conditions must be taken into account. Variability of these conditions, first of all, engineering-geological, characterizing the rock mass, is the main cause of problems and, as a
consequence, manifestations of geotechnical risks arising within the area of mining operations. All geo-technical risks are a type of construction risk [4]. Geotechnical risks have a huge impact on the occurrence of adverse factors that cause economic damage, reducing the safety and quality of construction work [5,6].

2. Methods of risk assessment

In mining, the practice of risk assessment has proven to be an effective tool to prevent accidents by anticipating an adverse situation. Underground mining is characterized by the joint work of mining equipment and people. The combination of limited working space with uncertainty of geotechnical data leads to an inevitable increase in the risk of accidents. The inherent heterogeneity of the rock mass contributes to significant variability of geotechnical parameters. However, it should be borne in mind that the amount of data obtained during the exploration phase increases as the project progresses from the preliminary feasibility study to the actual operation. The choice of the correct method of development depends on the geotechnical indicators, which include the depth of the mine and the rock mass, the ability of the rock to withstand the stresses caused by sinking and other parameters related to the strength characteristics of the soil properties, which must be studied in detail before construction [7, 8].

A more formal risk assessment is to define it as the product of the probability of the hazard and the consequences caused by adverse events. In order to determine the probability of this event development and its consequence, it is necessary to take the following two steps: to carry out their qualitative and quantitative assessment and compare the results [9,10]. The purpose of qualitative risk analysis is to identify risk-forming factors, and quantitative — to determine the total number of them. This approach to risk assessment allows evaluating the actual probability and consequences of the hazard [11]. Risk control is necessary to justify the safety and economic feasibility of sinking underground structures [12,13]. The risk control methodology should be suitable for complex geotechnical conditions. In these conditions more attention need to be paid for the reduction of high geotechnical risk. One of the effective ways of risk control is the qualitative execution and analysis of design work at all stages of design, starting from the early stages. Determining the features of the structure and properties of the rock mass and the area of the proposed construction site can play the role of potential causes that lead in the process of construction and operation of the underground structure to undesirable consequences the occurrence of which is characterized by a varying degree of probability. [14,15]. In the geotechnical risk control system, the identification of the causes of adverse risk events in the construction area is an important stage at which all materials relating to the construction area are summarized, systematized and analyzed, for which the following activities are usually performed [16-21]:

- engineering surveys are carried out, and available information (topographic and geological maps, books and journal articles, results of aerial photography and satellite observations) characterizing the area of the construction site from the point of view of geology, hydrology, topography, ecology, history, etc. is collected;
- on the basis of the obtained information, engineering and geological sections and geo-mechanical models are constructed, in which the geological structure of the rock mass is reproduced in detail, and the physical and mechanical characteristics of its structural elements are set;
- a group of experts is formed, which, analyzing the engineering and geological situation in the area of the construction site, identifies the structural features of the rock mass and its state, producing undesirable consequences in the construction process and initiating possible geotechnical risks;
- experts determine the type of risks and the place of their possible manifestation with account of the purpose and type of the designed underground structure.

The definition and systematization of the causes of geotechnical risks allows proceeding to their analysis and quantitative assessment. For this purpose, it is necessary to:
• make the list of risks which can be shown during the building and operation of underground construction;
• rank risks by probability of manifestation of each of them and by expected damage which can be put to a construction, in the form of increase in terms and cost of construction;
• make quantitative assessment of the revealed geotechnical risks and to enter them in the registration sheet (the register of risks);
• link each risk to the relevant phase of the construction project and systematize the risks by their impact on the various stages of construction;
• identify measures to control each risk depending on the probability of its occurrence, indicating the proposed design and technological solutions and possible ways to eliminate or minimize it;
• re-evaluate the degree of manifestation of each risk after the activities and make new results in the registration statement;
• conduct a regular audit of the risk registration statement, adding new risks to it and excluding from the statement the risks for which the planned activities have been carried out;
• adjust if necessary, the risk control measures.

Identification of geotechnical risks and their quantitative assessment also allow establishing the expected damage during construction and operation of the structure in case of implementation of risk events. In this case, the greatest damage when a risk event occurs is possible in the following cases:
• during the construction of structures, a large amount of underground work is performed, which significantly affects the excess of the estimated (project) cost of construction;
• the adjacent massif in the construction area is characterized by unfavorable engineering and geological situation;
• the construction site is adjacent to urban development or near underground facilities and utilities, which greatly increases the likelihood of their deformation and destruction as a result of the appearance of dangerous sediments and soil displacements;
• use of complex construction technologies, insufficiently qualified service personnel are involved.

In order to reduce the expected damage, the geotechnical risk control system should be used both at all stages of design and during the construction of the structure, with the mandatory participation of qualified engineers-geologists, geo-mechanics and specialists in the construction of underground structures. It should be noted once again that in solving practical problems of urban use of underground space control of geotechnical risks, regardless of the existence of the possibility to avoid risk events, constantly requires their quantitative assessment. To determine the amount of risk is recommended by combination of the probability of occurrence of an adverse event and the expected damage caused by its occurrence [17,18]. This allows determining the numerical value of the risk or the degree of risk as the product of the probability of occurrence of a risk event on the value of the mathematical expectation of damage caused by this event.

Combining two risk values into one, makes risk assessment easier because it allows considering two operations at the same time:
• determination of the probability of occurrence of adverse events;
• definition of undesirable consequences (mathematical expectation of damage) to which these adverse events can lead.

The probability of an adverse event evaluates by quantified characteristics (table 1). The numerical expression of the possible (expected) damage from the occurrence of an adverse event is evaluated taking into account the opinion of the expert group. It is determined in percentage terms by the ratio of the increase in the construction period to the period adopted in the project, or the ratio of the increase in the cost of construction to its estimated cost (table 2).

Machining of a matrix of experts’ opinions to determine numerical estimates [19-21] of how the probability of occurrence of adverse events and expected damages is being carried out using system
analysis for probability and statistical technique, which, for example, was used to determine the priority directions of development of underground space of megacities [22].

**Table 1. Probability of occurrence of an adverse event.**

| No. | Probability of occurrence of an adverse event | Percentage | Marks |
|-----|-----------------------------------------------|-------------|-------|
| 1   | Very high                                     | 70          | 5     |
| 2   | High                                          | 50 – 70     | 4     |
| 3   | Average                                       | 30 – 50     | 3     |
| 4   | Unlikely                                      | 10 – 30     | 2     |
| 5   | Very insignificant                            | 10          | 1     |

**Table 2. The ratio of the increase in the cost of construction to its estimated cost.**

| No. | Undesirable consequence (the expected damage) | Increase in cost or construction time, (%) | Marks |
|-----|-----------------------------------------------|-------------------------------------------|-------|
| 1   | Very high                                     | 10                                        | 5     |
| 2   | High                                          | 8 – 10                                    | 4     |
| 3   | Average                                       | 4 – 8                                     | 3     |
| 4   | Unlikely                                      | 1 – 4                                     | 2     |
| 5   | Very insignificant                            | 1                                         | 1     |

To quantify the risk (degree of risk), the corresponding score values of the right extreme column of tables 1 and 2 (probability of occurrence of an adverse event and expected damage) are multiplied and a scale of numerical values of risks (table 3) is drawn up, which allows decisions to be made to control each specific risk.

**Table 3. Numerical values of risk.**

| No. | Risk degree | Risk level       | Planned actions                                           |
|-----|-------------|------------------|-----------------------------------------------------------|
| 1   | 1 – 5       | Very small       | Not planned                                               |
| 2   | 6 – 10      | Small            | The slight fastening event or design changes              |
| 3   | 11 – 15     | Average          | Fastening event or design changes do not require additional costs |
| 4   | 16 – 20     | Big              | Construction work stops until the risk is reduced, additional costs are required |
| 5   | 21 – 25     | Very big         | The project is terminated                                 |

All of the above information is entered in the registration sheet, which should list all geotechnical risks specific to the construction area and numerical values of the degree of risks before and after their control. The far left column indicates the reasons that can cause the onset of adverse events. The next two columns specify the adverse events and undesirable consequences that may result from the occurrence of these events. The following are the numerical values of expert assessments, both adverse events and undesirable consequences, which are multiplied, resulting in a quantitative assessment of the risk. The following columns indicate engineering measures to reduce the relevant risk to an acceptable value. The quantitatively reduced risk is calculated again as the product of the probability of an adverse event occurring after an engineering event by the amount of damage that will result from the occurrence of this event. Having estimated the numerical value of each geotechnical risk degree in the design process is possible to calculate the total geotechnical risk possible in the
specific conditions of construction and operation of an underground structure, according to the formula:

$$R = \sum_{j=1}^{m} p_j y_j$$

where $p_j$ — probability of occurrence of possible risk situations, $j = 1, 2, 3, m$ — number of possible risk situations, $y_j$ — the value of the mathematical expectation of damage in the $j$ risk situation.

3. Investigation

According to the method described above, a study was conducted in the design and construction of the Inter-terminal transition of Sheremetyevo airport. In order to identify possible adverse events that can lead to damage of varying severity, it was necessary to study the characteristics of the object.

The object of study is a complex of structures consisting of the northern and the southern station complexes and the tunnel section between them, passing under the runway of the existing Sheremetyevo airport. The structure of the northern station complex includes underground facilities: station with a passenger platform, an automated passenger transportation system, a bypass station and a zone of an automated baggage transportation system, as well as engineering, service and household premises, a transformer substation, tunnel ventilation chambers and a drainage installation. Underground structures are integrated into the projected terminal “B”, located mainly above the ground surface.

The transport section of the object is provided in the underground version. Under the runways, construction of two single-track tunnels is envisaged. One tunnel is to move luggage, the second – to transport passengers. Main line tunnels are constructed in a closed way with the use of tunneling mechanized complexes. For the organization of driving of main line tunnels the installation-panel chamber in a ditch from the northern station complex and dismantling-panel chamber from the southern station complex is provided. At the inset and exit of the shields, the soil is strengthened by jet cementation.

Tunneling of the northern station complex is carried out in parallel by two tunneling mechanized complexes. Station complexes are located in unstable water-saturated soils. In order to minimize the use of construction water reduction and as consequence reduce the daily surface sediment in the pit area, the enclosing structures of the pits are adopted sealed and deformation-free. The specified requirements correspond to the design of fastening of pits “wall in the ground”, constructed by trench method and walls of brown-cut piles, buried in the waterproof.

According to the degree of complexity of engineering and geological conditions of the territory of the proposed construction are characterized as the third (complex) — III category [20].

4. Design and technological solutions

High-precision precast reinforced concrete waterproof lining with rings, each of which consists of six blocks of different sizes, was used for the construction of the tunnel section. Water resistance of the lining structure is enforced by the dense structure of waterproof concrete blocks, as well as the use of sealing waterproofing gaskets in the joints, crimped during installation of the lining in an elastically compressed state for the entire period of operation of the lining. To ensure full contact of the lining with the surrounding soil, the device of the jacket from the grouting solution is provided when installing the blocks (primary injection). Construction of structures is carried out in in the opening of the rings of the main tunnels under the protection of the screen of pipes.

According to the results of the work of the commission of experts, the following table (Table 4) was compiled, describing the risks attributed to “large”.
Table 4. Large risk level.

| No. | Reason | Adverse event | Undesirable consequence (damage) | R   | Risk level |
|-----|--------|---------------|----------------------------------|-----|------------|
| Overall project risks | | | | | |
| 1 | Errors in calculations of bearing and enclosing structures | Insufficient load-bearing capacity of load-bearing and enclosing structures | Unacceptable deformations of loadbearing and enclosing structures, as well as surrounding buildings. | 16.57 | Large |
| Station complexes | | | | | |
| 2 | [Lining] The wrong design of the connections of bracing and strapping belts | Insufficient load-bearing capacity of load-bearing and enclosing structures | Unacceptable deformation of bearing and enclosing structures, as well as surrounding buildings. | 16 | Large |
| 3 | [Lining] Errors in the design of soil anchors | Insufficient bearing capacity of soil anchors | Unacceptable deformation of bearing and enclosing structures, as well as surrounding buildings. | 16.29 | Large |
| Tunnel section | | | | | |
| 4 | [Facilities in the zone of influence] The imposition of mould deformations of the surface due to closely spaced tunnels | Additional sediments of the airfield surface | Violation of operability and operational reliability of airfield coverings and infrastructure | 16 | Large |
| 5 | [Facilities in the zone of influence] Suffusion of the base with the formation of voids in runway | Additional surface sediments | Violation of operability and operational reliability of airfield coverings and infrastructure | 17.71 | Large |
| 6 | [Engineering and geological surveys] The entrance of the tunneling mechanized complex into the lens of water-saturated sand | Additional ground sediment of the airfield surface due to uncertainty of geological conditions along the tunnel route | Deformation of the casing and shell of the shield, the jamming of rotor Dips at the surface | 17.43 | Large |

In addition to those described, average risks were identified attributed to:

- lack regard the filtration and consolidation properties of the soil massif;
- revealing of unaccounted engineering water-bearing communications in the development of the pit;
- on-accounting of technological sediment from trench development at the device of a wall in the ground;
- outstanding construction joints, water filter;
- water flow into the pit through ground inclusions in the array "walls in the ground", formed during the production of concreting;
- low quality of works at the device of knots of fastening of executions;
• mismatch of geometric parameters of the “wall in the ground” design, strapping belts, distribution system;
• flooding of the massif at break of water-bearing communications;
• fuel leakage into the tunnel when the fuel lines break;
• substandard device of waterproofing of brothel structures;
• dumps on the portal sections of the tunnel;
• substandard installation of blocks;
• injection of insufficient volume of grouting solution into the filling space;
• untimely filling of the construction gap between the tunneling complex and the soil with the grouting solution.

To prevent the listed risks of the “large” level it is recommended: to carry out measures that reduce the level of risk specified in table 5, as well as including:
• verification calculations carried out by an independent organization in a certified geotechnical software package;
• geophysical surveys of runway foundation;
• filling voids before sinking under the runway;
• exploratory drilling and geophysical surveys before sinking hazardous areas.

### Table 5. Risk assessment after preventive measures.

| No. | Reason | Adverse event | Undesirable consequence (damage) | Measures | R | Risk level |
|-----|--------|---------------|---------------------------------|----------|---|------------|
| 1.1 | Errors in calculations of bearing and enclosing structures | Insufficient load-bearing capacity of load-bearing and enclosing structures | Unacceptable deformations of load-bearing and enclosing structures as well as surrounding buildings. | Verification calculations carried out by an independent organization in a certified geotechnical software package | 2.14 | Very small |
| 2   | [Lining] The wrong design of the connections of bracing and strapping belts | Insufficient load-bearing capacity of load-bearing and enclosing structures | Unacceptable deformation of load-bearing and enclosing structures as well as surrounding buildings. | Geotechnical expertise of project documentation and Geotechnical monitoring | 2 | Very small |
| 3   | [Lining] Errors in the design of soil anchors | Insufficient bearing capacity of soil anchors | Unacceptable deformation of load-bearing and enclosing structures as well as surrounding buildings. | Verification calculations carried out by an independent organization and Anchor monitoring. | 2.29 | Very small |

### Station complexes

### Tunnel section
4 [Facilities in the zone of influence] Additional sediments of the airfield surface The imposition of mould deformations of the surface due to closely spaced tunnels

| 4 | Facilities in the zone of influence | Additional sediments of the airfield surface | Violation of operability and operational reliability of airfield coverings and infrastructure | Compensation of deformations due to strengthening of soil massif |
|---|---|---|---|---|

5. Conclusion

The risk control system, based on any of the methods of determining the total risk and used during the design, construction and operation of the underground structure, can significantly reduce the possibility of abnormal and emergency situations.

The study conducted during the construction of the Inter-terminal transition under the runways of Sheremetyevo Airport showed that with timely response to emerging threats, high-quality construction and installation works and additional measures, the risk level can be reduced significantly or prevented completely.

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