Expert-statistical approach to the analysis of geotechnical risks in the construction of metro facilities

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Abstract. Risk issues in metro construction should be discussed at the planning and design stages, along with issues of safety, efficiency of technological solutions and reliability. Problems that arise during the construction of an underground facility lead to an increase in time and cost. In the worst case - to the development of various scenarios of emergency situations. These problems are caused mainly by insufficient attention to geotechnical risk management. The effectiveness of this process is related to the quality of risk identification, understanding of the mechanism for developing a risk situation, and the degree of reliability of the risk assessment results. The article presents the results of identification of some geotechnical risks in metro projects in conjunction with risk-forming factors and consequences of their occurrence. A methodic for geotechnical risks assessing, based on an expert-statistical approach is presented, and theoretical generalization is given for individual components of the methodic. The form of information-analytical archive of risks is given. A veracity criteria for the risk assessment is presented. Further development of the approach will allow more reasonable geotechnical risks assessment for decision-making and selecting a program of measures to exclude and minimize the occurrence of risk situations.

1. Introduction
In recent years, the share of underground construction in large Metropolitan areas, such as Moscow, has increased significantly. Increasing the pace of economic development, population growth, increase in passenger traffic, features of dense historical buildings have led to a difficult situation on transport. Development of metro and road tunnel system intended to solve the problem. But also underground building in megacities is complicated by a number of factors: dense construction, saturation of underground space with existing communications, active traffic. Above problems are compounded by complex hydrogeological and engineering-geological conditions of construction [1] (unstable soils and soils with floating properties, pressure aquifers, karst cavities, etc.) Strategic direction in solving of these problems is using of advanced technologies. New technologies and equipment are both completely new developments and modernized versions of traditional construction methods [2]. Construction time is shortened, labor productivity and product quality are improved, resource efficiency is increased, and risks are reduced. However, the practice of incidents during metro construction shows that even the use of advanced technologies does not exclude the possibility of adverse events, as well as the need for a detailed analysis of engineering and geological conditions and control by all participants in underground construction, which is characterized by a significant number of risk factors [3].
2. Materials, methods and problem statement

Risks in projects of metro should be attributed to a separate category of construction risks [4] – to geotechnical risks (Figure 1). Geotechnical risk - is the risk of harm to human health or property (in connection with the occurrence/possibility of an emergency situation, change in the initial parameters of the environment), in particular existing buildings, as well as the existing geological, hydrogeological and environmental situations of the construction site, during the construction of underground and buried structures or as a result of the consequences of these works [5]. The manifestation of geotechnical risks leads to negative events, which, in turn, lead to a rise in the cost of the project, increase in construction time and accidents. Accident is a situation beyond control, which can lead to serious consequences and loss of life [6-10].

Accidents are the result of a set of interrelated causes (risk factors). Risk management process should include risk management planning, risk identification and assessment, selection of project solutions, risk response measures, risk control [11]. Risk identification should be accompanied by information exchange and consultation with experts [12]. In Table. 1 is given an example of identification of geotechnical risks [13]
| №  | Risk                                      | Risk-forming factors                                                                 | Risk consequences                                                                 |
|----|-------------------------------------------|--------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------|
| 1  | Flooding water and floating soils         | 1. The volume and quality of engineering-geological and hydrogeological surveys.     | 1. Injuries and deaths.                                                           |
|    |                                           | 2. The quality of design.                                                            | 2. Excess deformations of the earth's surface and buildings.                      |
|    |                                           | 3. Seismic effects of explosions.                                                    | 3. Damage to communications and social consequences for the citizens.             |
|    |                                           | 4. Technical condition of pumping equipment.                                         | 4. Equipment failure.                                                             |
|    |                                           | 5. Quality of works on artificial hardening of soils.                                | 5. Increase in duration and cost of construction.                                 |
|    |                                           | 7. Compliance with the technology of work and the quality of technical supervision.   |                                                                                   |
| 2  | Axis deviation construction               | 1. The volume and quality of engineering-geological and hydrogeological surveys.     | 1. Inability to operate the facility.                                             |
|    |                                           | 2. The quality of surveying support.                                                 | 2. Inability to operate the facility.                                             |
|    |                                           | 3. The quality of design.                                                            | 3. Flooding water and floating soils.                                              |
|    |                                           | 4. The amount of pressure on the lining.                                             | 4. The violation of the sealing lining, water seepage.                            |
|    |                                           | 5. Compliance with the technology of work and the quality of technical supervision.   | 5. Excess deformations of the earth's surface and buildings.                      |
|    |                                           |                                                                                     | 6. Damage to communications and social consequences for the citizens.             |
|    |                                           |                                                                                     | 7. Increase in the duration and cost of construction.                             |
| 3  | Deformation and destruction of lining     | 1. The quality of design.                                                            | 1. Injuries and deaths.                                                           |
|    |                                           | 2. The volume and quality of engineering-geological and hydrogeological surveys.     | 2. Excess deformation and failures of the earth's surface.                        |
|    |                                           | 3. Observance of technology of works on construction of a lining and quality of technical supervision. | 3. In the duration and cost of construction.                                     |
|    |                                           | 4. Quality of lining materials.                                                      |                                                                                   |
|    |                                           | 5. Seismic effects of explosions.                                                    |                                                                                   |
|    |                                           | 6. The conditions of storage and transport elements of lining.                      |                                                                                   |
| 4  | Damage underground utilities              | 1. Quality of works on engineering surveys in terms of determining the planning and altitude position of existing communications. | 1. Social consequences for the citizens.                                         |
|    |                                           | 2. Compliance with the technology of work and the quality of technical supervision.   | 2. Excess deformation and failures of the earth's surface.                        |
|    |                                           | 3. Quality of geotechnical support.                                                  | 3. In the duration and cost of construction.                                     |
| 5  | Inability to use construction equipment   | 1. The quality of design.                                                            | 1. Inability of construction with the use of this equipment.                     |
|    |                                           | 2. Technical condition of the equipment.                                             | 2. Additional costs for the purchase of new equipment (or repair of failed).      |
|    |                                           | 3. Equipment compliance with environmental requirements.                            | 3. The need for additional design work.                                            |
|    |                                           | 4. Compliance with the conditions of use of the equipment and the quality of technical supervision. | 4. Increase in the duration and cost of construction.                            |
| 6  | Fire                                      | 1. Compliance with the technology of work and the quality of technical supervision.   | 1. Injuries and deaths.                                                          |
|    |                                           | 2. Compliance with industrial safety requirements.                                  | 2. Damage to the lining.                                                          |
|    |                                           | 3. Condition of electrical equipment and cable lines.                               | 3. Damage and destruction of equipment.                                            |
|    |                                           | 4. Storage and use of combustible and explosive materials.                          | 4. Increase in the duration and cost of construction.                            |
|    |                                           | 5. The condition of the fire extinguishing system.                                 |                                                                                   |
3. Components and implementation of the Approach

The main components of the approach: expert assessment, statistical analysis and comparison of the results.

Expert assessment is widely used in risks analyzing of hazardous production facilities and complex technical systems. The method is important primarily from the point of view of using the experience of experts and their knowledge in the field of metro construction for predict the probability of risk occurrence, timely identification of risk-forming factors and description of consequences. Various methods can be used to process the results of expert assessment [14-20]. Presented methodic is used methods of mathematical statistics and interval estimation. Risk ranking by its degree of manifestation is taken in accordance with the probability of risk situation occurrence – from 0 to 4 (Table 2).

**Table 2. Risk ranking according to the degree of manifestation.**

| Probability of risk situation occurrence | Degree of risk manifestation |
|----------------------------------------|-----------------------------|
| no probability                         | 0                           |
| low probability                        | 1                           |
| medium probability                     | 2                           |
| high probability                       | 3                           |
| extreme probability                    | 4                           |

Expert component consists of collecting expert opinions and then processing the results. Questionnaire survey used for determination the opinion about risk probability. Further processing of the results is reduced to determining the confidence score (interval) b within the boundaries of $X_A$ and $X_B$ according the well-known formula (1) of mathematical statistics.

$$\hat{m}_x - \frac{\sigma}{\sqrt{n}} t_{\frac{\alpha}{2}} \leq b \leq \hat{m}_x + \frac{\sigma}{\sqrt{n}} t_{\frac{\alpha}{2}},$$

$$\hat{m}_x - \frac{\sigma}{\sqrt{n}} t_{\frac{\alpha}{2}} = X_A,$$

$$\hat{m}_x + \frac{\sigma}{\sqrt{n}} t_{\frac{\alpha}{2}} = X_B$$.

Largest number of identical opinions of experts about degree of risk manifestation will be located within the boundaries of $X_A$ and $X_B$. 

Figure 2. Geotechnical risks analysis scheme.
Even the most consistent assessment results from experienced experts will involve a subjective factor. An expert's opinion depends on their level of education, experience, intuition, and analytical potential. Along with the need to take into account the entire variety of risk factors and scenarios of risk manifestation, subjective factor is the reason for necessity to compare the opinions of experts with real data on manifestation of a risk situation. For the purposes of collecting, accumulating, analyzing and presenting final statistical data, an information-analytical risk archive is required. The form of such an archive is shown on Figure 3. Based on the frequency of occurrence of risk situations, they are ranked according the degree of risk manifestation $X_s$ (Table 3). The value $X_s$ used in evaluation when compared with the expert evaluation result.

| Frequency of occurrence (period-5 years) | Probability of risk situation occurrence | Degree of risk manifestation $X_s$ (statistic risk) |
|----------------------------------------|-----------------------------------------|-----------------------------------------------|
| 0-1                                    | no probability                          | 0                                             |
| 2 - 4                                  | low probability                         | 1                                             |
| 5 - 8                                  | medium probability                      | 2                                             |
| 9 - 12                                 | high probability                        | 3                                             |
| more 12                                | extreme probability                     | 4                                             |

Table 3. Statistic risk ranking according to the degree of manifestation.

The results of the expert assessment and study of statistics are two values: interval estimation in boundaries of $X_A$ and $X_B$ and statistical risk $X_s$. Then you need to compare the results and check the accuracy of the assessment. Verification is performed accounting veracity criteria for the risk assessment (Table 4).

Figure 3. Form of information-analytical archive of geotechnical risks.
Table 4. Variants of results, accounting veracity criteria for the risk assessment

| Var. | $X_i \in [x_i; x_d]$ | risk assessment is reliable |
|------|----------------------|----------------------------|
| Var. 2 | $X_i \in [0; x_i)$ | underestimating the degree of risk experts compared to statistics |
| Var. 3 | $X_i \in (x_d; 4]$ | re-evaluating the degree of risk experts compared to statistics |

As a result of the evaluation, various variants may be obtained. In variant 1, the evaluation process may be considered complete. For variants 2 and 3, it is necessary to further study why the expert opinion differs from the actual statistics. Graphically the results of the assessment, based on the expert-statistical approach, can be represented as an overlay of a straight line, parallel axis $Oy$ (statistical risk line), which intersects axis $Ox$ in point $Xs$, on the polygon of expert response frequencies.

4. Conclusion
Management of geotechnical risks helps to prevent accidents and incidents in projects of metro. The example of risk identification shows that in order to identify all possible risks, it is necessary to conduct a detailed analysis with the involvement of experienced experts. At the same time, it is important to understand that taking into account only the opinions of even the most experienced experts will not completely solve the problem of reliability of risk assessment. The validity of technological solutions for project implementation and risk management measures depends on the degree of reliability of the assessment. A comprehensive approach, based on the experience of experts and real statistics of risk situations, is needed. The approach, presented in the article, will allow to more accurately assess the risks for a specific metro construction site and help in predicting and preventing accidents.

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