

ОЦЕНКА ГИДРОГЕОЛОГИЧЕСКОГО РИСКА ПРИ СТРОИТЕЛЬСТВЕ И ЭКСПЛУАТАЦИИ ПОДЗЕМНЫХ СООРУЖЕНИЙ МЕТРОПОЛИТЕНА

Е.Ю. Куликова^{1,2}, О.М. Розенталь³

¹ РТУ МИРЭА, Москва, Россия, e-mail: fragrante@mail.ru

² НИТУ МИСИС, Москва, Россия

³ Институт водных проблем РАН, Москва, Россия

Аннотация: Рассмотрен комплексный анализ гидрогеологических рисков, сопровождающих строительство и эксплуатацию тоннелей метрополитена. Авторы подчеркивают, что подземные воды являются ключевым фактором, определяющим безопасность, стоимость и долговечность подземных сооружений. Описаны основные опасности, связанные с динамичным характером гидрогеологических условий: деформации конструкций, ускоренное старение обделки, прорывы воды и пьезунов, а также последующие осадки земной поверхности, угрожающие наземной застройке. Представлена классификация гидрогеологических рисков, разделяющая их на природные (например, дефицит питания водоносных горизонтов, ухудшение качества воды) и техногенные (загрязнение, последствия интенсивной эксплуатации водозаборов). В качестве основного инструмента управления рисками предложен количественный метод оценки на основе нормированных коэффициентов. Даны приемы расчета рисков при котлованном и подземном способах строительства, а также представлены количественные величины рисков для различных негативных процессов. Сделан вывод о необходимости системного подхода к управлению гидрогеологическими рисками, который должен интегрировать глубокое изучение среды, современные инженерные решения, постоянный мониторинг и строгое соблюдение технологических нормативов на всех этапах жизненного цикла объекта. Статья представляет собой методически обоснованное исследование, акцентирующее внимание на том, что эффективное управление гидрогеологическими рисками является неотъемлемым условием безаварийного строительства и устойчивой эксплуатации объектов метрополитена.

Ключевые слова: гидрогеологический риск, уровень грунтовых вод, метротоннели, управление рисками, аварийная ситуация.

Для цитирования: Куликова Е. Ю., Розенталь О. М. Оценка гидрогеологического риска при строительстве и эксплуатации подземных сооружений метрополитена // Горный информационно-аналитический бюллетень. – 2026. – № 1. – С. 5–15. DOI: 10.25018/0236_1493_2026_1_0_5.

Assessment of hydrogeological risk during the construction and operation of underground subway facilities

E.Yu. Kulikova^{1,2}, O.M. Rozental³

¹ RTU MIREA, Moscow, Russia, e-mail: fragrante@mail.ru

² NUST MISIS, Moscow, Russia

³ Institute of Water Problems of the Russian Academy of Sciences, Moscow, Russia

Abstract: The article is devoted to a comprehensive analysis of the hydrogeological risks accompanying the construction and operation of subway tunnels. The authors emphasize that groundwater is a key factor determining the safety, cost, and durability of underground structures. The main hazards associated with the dynamic nature of hydrogeological conditions are described: structural deformations, accelerated aging of the lining, breakthroughs of water and quicksand, as well as subsequent precipitation of the Earth's surface, threatening terrestrial buildings. The classification of hydrogeological risks is presented, dividing them into natural (for example, lack of nutrition of aquifers, deterioration of water quality) and man-made (pollution, consequences of intensive exploitation of water intakes). A quantitative assessment method based on normalized coefficients is proposed as the main risk management tool. The methods of calculating risks in the case of excavation and underground construction methods are given, as well as quantitative values of risks for various negative processes are presented. It is concluded that there is a need for a systematic approach to managing hydrogeological risks, which should integrate in-depth environmental studies, modern engineering solutions, constant monitoring and strict compliance with technological standards at all stages of the facility's life cycle. The article is a methodically based study that focuses on the fact that effective management of hydrogeological risks is an essential condition for trouble-free construction and sustainable operation of metro facilities.

Key words: hydrogeological risk, groundwater level, subway tunnels, risk management, emergency.

For citation: Kulikova E. Yu., Rozental O. M. Assessment of hydrogeological risk during the construction and operation of underground subway facilities. *MIAB. Mining Inf. Anal. Bull.* 2026;(1):5-15. DOI: 10.25018/0236_1493_2026_1_0_5.

Introduction

Subway construction is one of the most complex engineering processes, when the main danger often lies not in what is happening on the earth's surface, but in what is hidden from view – in groundwater. Hydrogeological risks are among the most significant types of risks in the development of urban underground space [1] and determine the cost, timing and the very possibility of project implementation.

The dynamic nature of hydrogeological conditions is a key factor provoking deformations in the structures of subway tunnels. Under the influence of these processes, accelerated aging of tunnel lining and a gradual deterioration of their operational qualities occur. Such phenomena are most dangerous when constructing and using tunnels in water-saturated sandy-clay rocks.

A change in the structural connections in these soils can initiate the destruction of tunnel lining, which creates a threat of subsequent breakthroughs of groundwater and water-saturated loose soils into the tunnel cavity [2–4].

In this regard, ensuring the geo-ecological safety of metro tunnels requires constant monitoring of the hydrostatic pressure. This parameter directly affects the stress-strain state of the rock mass surrounding the mine. Fluctuations in the pressure level in aquifers are the main cause of hydrogeomechanical emergencies: violations of the tightness of water-proof screens and lining lead to sudden breakouts of water and quicksand masses.

A concomitant consequence of these processes is the deformation of the soil strata [5, 6] lying above the tunnel, and the subsequent subsidence of the Earth's

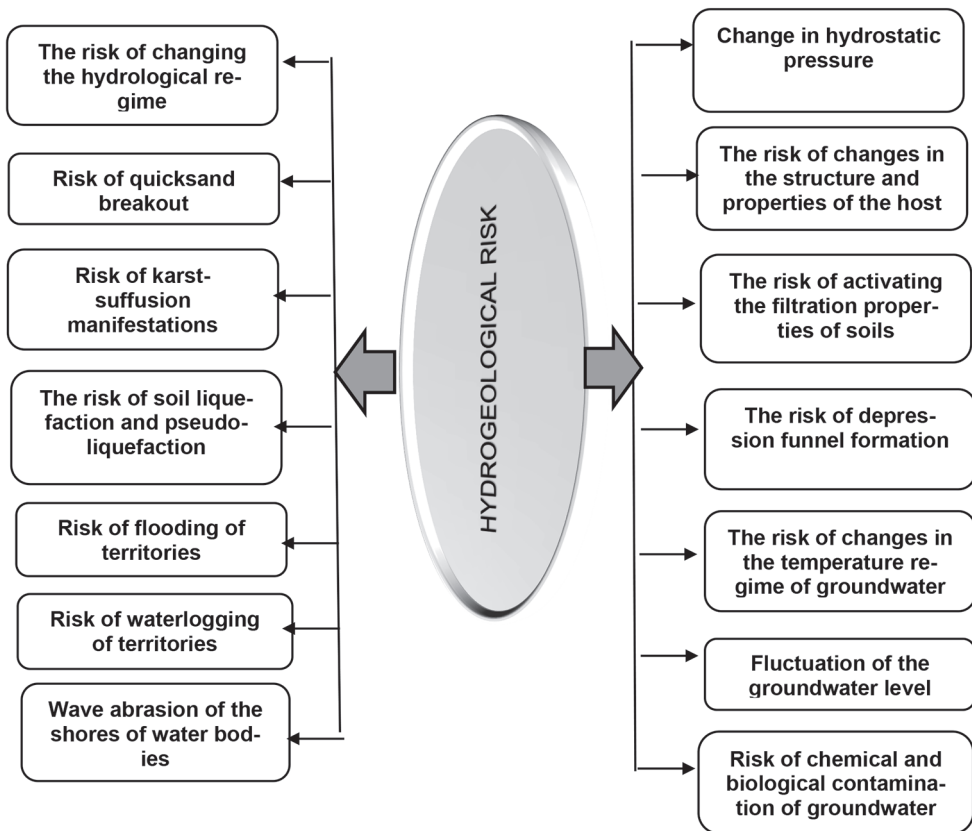
surface. These phenomena pose serious risks to the integrity of buildings, structures, and utilities located above the subway route. An important indicator of the occurrence of an emergency is a decrease in pore pressure in the rock mass, which naturally accompanies the loss of tightness of the lining.

The nature of the manifestation of hydrogeological risks

Potential problems related to the presence or change of the groundwater regime pose a hydrogeological risk. This risk is relevant for construction sites [7], engineering facilities, and any human activity, as it can lead to negative consequences such as flooding, landslide development,

subsidence, corrosion of underground structures, and other undesirable phenomena. Hydrogeological risk is one of the most significant geocological risks at underground metro facilities.

The hydrogeological risks associated with the operation of underground metro facilities [8–10] are primarily manifested through changes in the groundwater level. The rise of this level in shallow tunnels can cause waterlogging and flooding of the surface, as well as deterioration of soil quality and reduced stability of underground structures. If the soils, surrounding tunnels, consist of loose materials such as sand or loess-like loam, or contain components that are easily soluble in water, this can lead to a negative impact on tun-



*Classification of hydrological risks
Классификация гидрологических рисков*

nel construction materials, their deformation and a decrease in structural strength. Flooding in an urban environment can be considered if an increase in the groundwater level disrupts the normal use of the territory, construction and operation of buildings and structures located on it: for small settlements — by 1.5–2 m; for cities — by 3–4 m. In Russia, 900 cities and thousands of settlements are considered flooded.

A decrease in the groundwater level leads to the formation of a depression funnel and changes in the properties and composition of rocks surrounding underground structures [11]. Water, moving to lower levels, promotes chemical processes such as dissolution, hydration, oxidation, hydrolysis and leaching, as well as mechanical changes, including the leaching of individual fractions from the soil.

Hydrogeological risks manifest themselves in the form of defects in the bearing structures of workings such as fistulas, leaks, outflows of water and soil into an underground facility, bursts of hearth and quicksand, etc. [12].

Types of hydrogeological risks are shown in Figure.

The negative consequences associated with hydrogeological risks also include flooding caused by rising ground water levels [13]. This may affect basements, underground utilities, and complicate construction work. An increase in soil moisture can trigger landslides and collapses, as well as lead to subsidence of the foundations of buildings and structures. Groundwater also has an aggressive effect on building materials, causing corrosion and, as a result, shortening the service life of structures. All these factors can significantly complicate construction work, increasing the cost and time required to implement projects. These risks can be caused by natural causes, such as high groundwater levels or floods, as well as human ac-

tivities, including construction and terrain changes [14].

Classification of hydrogeological risks

Assessment and control of hydrogeological risks require special studies aimed at studying the condition of soil and groundwater. In particular, the composition and properties of soils, the depth of occurrence and the chemical composition of groundwater are analyzed [15]. The collected data makes it possible to predict potential risks and ensure the safety and stability of facilities interacting with groundwater. The key natural risks in calculating groundwater reserves are:

1. There is a shortage of their nutrition in low-water years, which is critical for infiltration intakes in river valleys. Although underground horizons, due to the capacity of alluvial deposits, act as a natural regulator (unlike surface sources), risk assessment requires taking into account specific parameters. The following are subject to analysis: the duration of the low-water period (for example, a year of 95% availability), the corresponding minimum volume of infiltration from the river, and the filtration characteristics of aquifers.

2. The operation of water intakes carries the risk of extracting groundwater that does not meet the required quality standards. The deterioration of the hydrochemical parameters of the resource entails significant economic costs. A decrease in water quality directly leads to an increase in the cost of its water treatment. In the most unfavorable scenarios associated with the presence of toxic components (such as arsenic or strontium), it may be necessary to introduce expensive technologies [16], such as membrane purification, or even complete conservation of water intake.

3. The quality of the hydrogeological justification directly depends on the completeness of the initial information [17]. Its

disadvantage creates risks associated with the construction of inadequate models and the adoption of erroneous design decisions. The management of this risk consists in consistently reducing uncertainty through the use of modern methods of data collection and computer modeling.

4) The risk associated with limited geological and hydrogeological information can be considered as an important aspect of the hydrogeological justification of water intakes [18]. This risk includes two dominant uncertainties:

- heterogeneity of the natural environment. The natural environment where water intake is carried out is highly variable. While information about geological and hydrogeological parameters is often obtained from point measurements, the models used for their analysis are usually based on assumptions about uniformity or regular changes in these properties. This can create discrepancies between the actual environmental conditions and model descriptions, which in turn can negatively affect the accuracy of forecasts and estimates;

- the limited availability of hydrogeological models is a significant problem in understanding and predicting processes occurring in groundwater. Models may not take into account such important aspects as: multiphase interactions; spatial and temporal scales; local geological features; and uncertainties in the data.

Technogenic risks affecting the assessment of groundwater reserves include:

1) Contamination of surface water sources feeding infiltration intakes. For a reliable assessment of reserves, it is necessary to work out in detail the list of threats (industrial accidents, chemical leaks) and simulate the conditions for their implementation, thereby determining the vulnerability of groundwater to such impacts.

2) Accidental spills (for example, brines and oil from pipelines) and leaks from

wastewater storage pose a significant threat to groundwater [19]. To protect groundwater resources, it is critically important to develop detailed migration models that focus on modeling the vertical movement of pollutants through soils and soils.

3) In regions with intensive industrial development and high population density, the problem of man-made risks associated with the exploitation of groundwater resources is of particular relevance. The key hazard factor is the process of extracting water through intake systems [20], which is complicated by the effects of hydrodynamic interaction between different intake points. Solving this problem requires a fundamental revision of existing regulatory approaches to the assessment and classification of groundwater reserves, which will increase the efficiency of their use and reduce economic costs.

4) Environmental risks associated with groundwater exploitation include possible negative impacts on the natural environment, especially vegetation and surface runoff.

5) Coastal water intakes are characterized by a specific risk associated with the transformation of the filtration properties of the coastal zone due to the colmatation of bottom sediments. Since these processes are practically impossible to assess directly at the exploration stage, comparative analysis with existing water intakes becomes a key method of risk analysis. This approach involves extrapolating the established patterns of interaction between surface and groundwater to the forecast models being created [21, 22]. The most significant parameters for comparison are the magnitude of the operational load, the morphometric characteristics of the riverbed and the speed of the current in the mezen. Therefore, a reliable justification of the models requires a thorough study of the hydrogeological conditions at existing facilities.

Materials and methods of research

Risk management during the construction and operation of subway tunnels requires solving one of the most difficult tasks – compensating for the lack of reliable data on the hydrogeochemical environment.

The sources of threats in this area are diverse:

- incomplete hydrogeochemical model: lack of detailed information about the factors controlling the chemical composition and migration of groundwater;
- unreliability of forecast models: the use of geomigration forecasts that do not take into account the full range of chemical and filtration processes, which reduces the accuracy of assessing the impact of water on structures.

Quantitative values of hydrogeological risks

Количественные величины гидрогеологических рисков

No	Negative environmental processes	The degree of manifestation of the negative process	Code	Coefficient of significance of the negative process indicator
The excavation method for the construction of subway tunnels				
1	Flooding and waterlogging of the territory	Small	1	0,05
		Big	2	
2	Groundwater pollution	Small	1	0,10
		Big	2	
3	Changing the hydrological regime	Small	1	0,10
		Big	2	
4	Formation of depression funnels	Small	1	0,15
		Big	2	
Underground method of building a subway tunnel				
1	Changes in the hydrostatic regime of groundwater	Small	1	0,18
		Big	2	
2	Fluctuation of the groundwater level and their depletion	Small	1	0,10
		Big	2	
3	Formation of quicksand and pseudo-quick sand	Small	1	0,07
		Big	2	
4	Karst-suffusion manifestations	Small	1	0,12
		Big	2	
5	Infiltration of groundwater into tunnels	Small	1	0,13
		Big	2	

The generalized hydrogeological risk R_o can be determined from the formula:

$$R_o = \sum_i^j P_i k_i, \quad (1)$$

где P_i – вероятность проявления i -го процесса; k_i – коэффициент значимости i -го процесса в границах природно-технической геосистемы.

The classification of potential threats to subway tunnels at all stages of the life cycle – from construction to operation – is based on expert analysis methods [23]. The criterion for risk systematization is the specificity of technological features and the sequence of operations performed, characteristic of each stage, which makes it possible to identify and structure the most likely sources of danger.

Complex environmental damage manifests itself as a system of interrelated negative changes. These include: depletion and chemical degradation of groundwater resources, geomechanical deformations of the Earth's surface and deep geological layers, as well as the transformation of the composition and filtration-capacitance properties of rocks. The combined effect of these factors leads to disruption of the natural hydrological balance of the territory [24].

An integrated approach based on the analysis of statistical information and expert opinions was applied to quantify hydrogeological risks during the construction of the subway (Table).

The hydrological risk during tunnel construction is calculated using the formula:

$$R_g = R_o + R_u, \quad (2)$$

where R_o – risks in the construction of tunnels by excavation; R_u – risks when working underground.

The assessment of hydrogeological risks is based on the methodology of normalized coefficients, where the worst possible scenario is taken as the base value (unit). A quantitative measure of risk is defined as a fraction of this reference value [25].

The hydrogeological risk during tunnel excavation is calculated using the formula:

$$R_u = (\delta_f q_f + \delta_p q_p + \delta_c q_c + \delta_d q_d) \rho, \quad (3)$$

where δ_f – coefficient of importance of flooding and waterlogging of the territory; q_f – the value of the flooding and waterlogging code of the territory; δ_p – coefficient of importance of groundwater pollution; q_p – the value of the groundwater pollution code; δ_c – coefficient of significance of changes in the hydrological regime; q_c – the value of the hydrological regime change code; δ_d – coefficient of significance of the depression funnel formation; q_d – the value of the code of flooding and waterlogging of the territory

the value of the code of the indicator of the formation of a depression funnel; ρ – the normalizing multiplier.

The risk of contamination and depletion of groundwater during underground tunnel construction is calculated using the formula:

$$R_o = (\delta_{gr} q_{gr} + \delta_h q_h + \delta_{ps} q_{ps} + \delta_k q_k + \delta_i q_i) w, \quad (4)$$

where δ_{gr} – coefficient of significance of changes in the hydrostatic regime of groundwater; q_{gr} – the value of the code for changing the hydrostatic regime of groundwater; δ_h – coefficient of significance of fluctuations in the groundwater level and their depletion; q_h – the value of the groundwater level fluctuation and depletion code; δ_{ps} – the coefficient of significance of the formation of quicksand and pseudo-quicksand; q_{ps} – the value of the quicksand and pseudo-quicksand formation code; δ_k – coefficient of significance of karst-suffusion manifestations; q_k – the value of the karst-suffusion code; δ_i – coefficient of importance of groundwater infiltration into tunnels; q_i – the value of the groundwater infiltration code in tunnels; w is the normalizing multiplier.

Thus, the construction and operation of subway facilities is a constant struggle against an invisible enemy – groundwater. The success of this struggle depends on a three-pronged approach: a deep understanding of hydrogeology, the use of adequate expensive technologies, and the highest production culture. Neglecting any of these elements can lead not only to enormous financial losses, but also to the death of people. Therefore, the assessment of hydrogeological risks and consideration of its results at all stages of the metro tunnel life cycle is a necessary factor in the trouble-free operation of metro facilities.

Conclusions

1. The factors leading to hydrogeological risk are considered and the consequen-

ces of the manifestation of hydrogeological risks in the conditions of construction and operation of metro facilities are described.

2. A general classification of hydrogeological risks is given, which makes it possible to identify which of the existing manifestations prevail in the conditions of construction and operation of metro facilities.

3. An assessment of hydrogeological risks is proposed depending on the type of technology used for tunneling underground tunnels.

The analysis clearly demonstrates that the construction and operation of the subway are taking place in conditions of continuous interaction with a dynamic hydrogeological environment. Groundwater is not a passive background, but an active participant in the process, forming a complex of serious risks — from progressive degradation of structures to large-scale accidents. Successful management of these risks is possible only with a systematic

approach that integrates advanced engineering solutions, continuous monitoring and strict compliance with technological standards.

Resume

Hydrogeological conditions are a determining factor in the design, construction and long-term operation of underground metro facilities. Neglecting them or underestimating them leads to the activation of deformation processes, subsidence of the surface, breakthroughs of quicksand and other emergency situations that pose a direct threat to infrastructure and human life.

Effective safety management requires the introduction of quantitative assessment methods, such as the method of normalized coefficients based on statistical data and expert opinions. This makes it possible to move from reactive elimination of the consequences of accidents to proactive forecasting and prevention of dangerous situations at all stages of the facility's life cycle.

СПИСОК ЛИТЕРАТУРЫ

1. Kapanski A. A., Klyuev R. V., Boltrushevich A. E., Sorokova S. N., Efremenkov E. A., Demin A. Y., Martyushev N. V. Geospatial clustering in smart city resource management: An initial step in the optimisation of complex technical supply systems // *Smart Cities*. 2025, vol. 8, no. 1, article 14. DOI: 10.3390/smartcities8010014.

2. Klyuev A. V., Kashapov N. F., Klyuev S. V., Zolotareva S. V., Shchekina N. A., Shorstova E. S., Lesovik R. V., Ayubov N. A. Experimental studies of the processes of structure formation of composite mixtures with technogenic mechanoactivated silica component // *Construction Materials and Products*. 2023, vol. 6, no. 2, pp. 5–18. DOI: 10.58224/2618-7183-2023-6-2-5-18.


3. Panarin I. I., Fediuk R. S., Vykhodtsev I. A., Vavrenyuk S. V., Klyuev A. V. Injection mortars based on composite cements for soil fixation // *Construction Materials and Products*. 2023, vol. 6, no. 4, pp. 15–29. DOI: 10.58224/2618-7183-2023-6-4-15-29.

4. Haryono I. S., Booth P. W., Purwodihardjo A., Vorster B. Discrete fracture network combined with discontinuum based design for deep shafts — quantifiable risk assessment and design method / Expanding Underground — Knowledge and Passion to Make a Positive Impact on the World. Proceedings of the ITA-AITES World Tunnel Congress. WTC 2023. 2023, pp. 1923–1931. DOI: 10.1201/9781003348030-231.

5. Goble M. Risk analysis for evaluation of mine impounded water // *Mining Engineering*. 2016, vol. 68, no. 12, pp. 33-40.

6. Верчеба А. А., Макаров В. А. Прикладная геология — базовое направление подготовки кадров горно-геологической отрасли // *Горные науки и технологии*. — 2023. — Т. 8. — № 2. — С. 183–190. DOI: 10.17073/2500-0632-2023-01-71.

7. *Deplagni E. A., Kivliuk V. P., Konyukhov D. S.* Fixing of unstable water-saturated soils by artificial freezing for construction of inter-tunnel joints during metro construction / *Tunnelling for a Better Life Proceedings of the Ita Aites World Tunnel Congress Wtc 2024*. 2024, pp. 689 – 694. DOI: 10.1201/9781003495505-93.
8. *Kumar R., Mandal P. K., Das A. J., Bhattacharjee R., Tewari S.* Design of underground structures under geotechnical uncertainties / *Frontiers of Performability Engineering. Risk, Reliability and Safety Engineering*. Springer, Singapore. 2024. DOI: 10.1007/978-981-99-8258-5_15.
9. *Mishra R. K., Uotinen L., Rinne M.* A bayesian network approach for geotechnical risk assessment in underground mines // *Journal of the Southern African Institute of Mining and Metallurgy*. 2021, vol. 121, no. 6. DOI: 10.17159/2411-9717/581/2021.
10. *Chee-Min Khoo, Teik-Aun Ooi* Geotechnical challenges and innovations in urban underground construction – The Klang Valley Mass Rapid Transit project // *Geomechanik und Tunnelbau*. 2023, vol. 16, no. 3, pp. 243 – 262. DOI: 10.1002/geot.202300007.
11. *Kalaiselvi M., Sarma Y. K., Raju G. D.* Advanced geotechnical investigation and data interpretation for complex underground structures / *Deep Foundations for Infrastructure Development in India*. 2023, pp. 3 – 15. DOI: 10.1007/978-981-19-8598-0_1.
12. *Chunyu D., Selviyan S.* Monitoring of geotechnical and underground construction facilities as part of risk management // *E3S Web of Conferences*. 2023, vol. 410, article 02014. DOI: 10.1051/e3sconf/202341002014.
13. *Wan Y. Luo Ya.* Analysis of geotechnical engineering safety technology in urban underground space construction // *Journal of Architectural Research and Development*. 2022, vol. 6, no. 1, pp. 1 – 6. DOI: 10.26689/jard.v6i1.2887.
14. *Жуков С. А.* Обоснование экологической безопасности при эксплуатации объектов метрополитена с учетом гидрогеологического риска // *Горные науки и технологии*. – 2024. – Т. 9. – № 3. – С. 283 – 291. DOI: 10.17073/2500-0632-2024-04-259.
15. *Liang Y., Xu N., Chang H., Qian Sh., Liu Ya.* Automatic construction of risk transmission network about subway construction based on deep learning models // *Scientific Reports*. 2025, vol. 15, article 16383. DOI: 10.1038/s41598-025-99561-0.
16. *Ren Z., Liu Y., Zhao D., He Yu., Zhang J.* A deep learning-driven framework for real-time recognition and quantification of subway tunnel surface defects using high-resolution imaging // *Urban Rail Transit*. 2025, vol. 11, pp. 279 – 299. DOI: 10.1007/s40864-025-00246-8.
17. *Sun X., Wu L., Wu D.* Risk evaluation of metro tunnel shield construction based on game variable weight extension cloud theory // *Scientific Reports*. 2025, vol. 15, article 18961. DOI: 10.1038/s41598-025-03345-5.
18. *Funikova V. V., Dudler I. V., Butaev R. T.* Anthropogenic changes in the groundwater regime of built-up areas: Geoecological, engineering geological, and hydrogeological aspects // *Water Resources*. 2022, vol. 49, pp. S59 – S68. DOI: 10.1134/S0097807822080036.
19. *Shi Y., Liu X., Jia J., Song Z., Song L., Ge L., Zhang Q., Xue Ch.* Research on the starting control technology of ultra-deep shield near existing line in soft soil urban area with microconfined water / *Geotechnical Engineering and Intelligent Disaster Prediction. GHS 2024. Sustainable Civil Infrastructures*. Springer, Cham. 2025. DOI: 10.1007/978-3-031-85787-4_18.
20. *Sartirana D., Rotiroti M., Bonomi T., Mattia De Amicis, Nava V., Fumagalli L., Zanotti Ch.* Data-driven decision management of urban underground infrastructure through groundwater-level time-series cluster analysis: the case of Milan (Italy) // *Hydrogeology Journal*. 2022, vol. 30, pp. 1157 – 1177. DOI: 10.1007/s10040-022-02494-5.
21. *Feng Z., Cheng B., Shao Y., Zhang B., Li X., Wang X., Liu P.* Predicting and mitigating twin-tunnel settlement in coastal soft soils: An integrated monitoring and modeling approach // *Geotechnical and Geological Engineering*. 2025, vol. 43, article 435. DOI: 10.1007/s10706-025-03336-3.
22. *Jing M., Lu C., Sun C., Pujades E., Ye Yu, Xu T., Sun X.* Assessing the effect of construction-induced consolidation on groundwater travel time distribution under unconfined conditions // *Hydrogeology Journal*. 2023, vol. 31, article 275 – 292. DOI: 10.1007/s10040-022-02579-1.
23. *Wang D., Ye S., Zhang J.* Risk reduction measures and monitoring analysis of deep foundation pit with water in a metro station in hefei // *Water*. 2023, vol. 15, no. 16, article 3007. DOI: 10.3390/w15163007.
24. *Куликова Е. Ю., Баловцев С. В., Скопинцева О. В.* Управление геотехническими рисками в шахтном и подземном строительстве // *Устойчивое развитие горных территорий*. – 2025. – Т. 17. – № 1. – С. 556 – 563. DOI: 10.21177/1998-4502-2025-17-1-556-563.

25. Kulikova E. Yu. Estimation of factors of aggressive influence and corrosion wear of underground structures // *Materials Science Forum*. 2018, vol. 931, pp. 385–390. DOI: 10.4028/www.scientific.net/MSF.931.385. 

REFERENCES

1. Kapanski A. A., Klyuev R. V., Boltrushevich A. E., Sorokova S. N., Efremenkov E. A., Demin A. Y., Martyshev N. V. Geospatial clustering in smart city resource management: An initial step in the optimisation of complex technical supply systems. *Smart Cities*. 2025, vol. 8, no. 1, article 14. DOI: 10.3390/smartsities8010014.

2. Klyuev A. V., Kashapov N. F., Klyuev S. V., Zolotareva S. V., Shchekina N. A., Shorstova E. S., Lesovik R. V., Ayubov N. A. Experimental studies of the processes of structure formation of composite mixtures with technogenic mechanoactivated silica component. *Construction Materials and Products*. 2023, vol. 6, no. 2, pp. 5–18. DOI: 10.58224/2618-7183-2023-6-2-5-18.

3. Panarin I. I., Fediuk R. S., Vykhodtsev I. A., Vavrenyuk S. V., Klyuev A. V. Injection mortars based on composite cements for soil fixation. *Construction Materials and Products*. 2023, vol. 6, no. 4, pp. 15–29. DOI: 10.58224/2618-7183-2023-6-4-15-29.

4. Haryono I. S., Booth P. W., Purwodihardjo A., Vorster B. Discrete fracture network combined with discontinuum based design for deep shafts – quantifiable risk assessment and design method. *Expanding Underground – Knowledge and Passion to Make a Positive Impact on the World. Proceedings of the ITA-AITES World Tunnel Congress. WTC 2023*. 2023, pp. 1923–1931. DOI: 10.1201/9781003348030-231.

5. Gobla M. Risk analysis for evaluation of mine impounded water. *Mining Engineering*. 2016, vol. 68, no. 12, pp. 33-40.

6. Vercheba A. A., Makarov V. A. Applied geology – basic training program for mining and geological industry personnel. *Mining Science and Technology (Russia)*. 2023, vol. 8, no. 2, pp. 183–190. [In Russ]. DOI: 10.17073/2500-0632-2023-01-71.

7. Deplagni E. A., Kivliuk V. P., Konyukhov D. S. Fixing of unstable water-saturated soils by artificial freezing for construction of inter-tunnel joints during metro construction. *Tunnelling for a Better Life Proceedings of the Ita Aites World Tunnel Congress Wtc 2024*. 2024, pp. 689–694. DOI: 10.1201/9781003495505-93.

8. Kumar R., Mandal P. K., Das A. J., Bhattacharjee R., Tewari S. Design of underground structures under geotechnical uncertainties. *Frontiers of Perforability Engineering. Risk, Reliability and Safety Engineering*. Springer, Singapore. 2024. DOI: 10.1007/978-981-99-8258-5_15.

9. Mishra R. K., Uotinen L., Rinne M. A bayesian network approach for geotechnical risk assessment in underground mines. *Journal of the Southern African Institute of Mining and Metallurgy*. 2021, vol. 121, no. 6. DOI: 10.17159/2411-9717/581/2021.

10. Chee-Min Khoo, Teik-Aun Ooi Geotechnical challenges and innovations in urban underground construction – The Klang Valley Mass Rapid Transit project. *Geomechanik und Tunnelbau*. 2023, vol. 16, no. 3, pp. 243–262. DOI: 10.1002/geot.202300007.

11. Kalaiselvi M., Sarma Y. K., Raju G. D. Advanced geotechnical investigation and data interpretation for complex underground structures. *Deep Foundations for Infrastructure Development in India*. 2023, pp. 3–15. DOI: 10.1007/978-981-19-8598-0_1.

12. Chyunyuk D., Selviyan S. Monitoring of geotechnical and underground construction facilities as part of risk management. *E3S Web of Conferences*. 2023, vol. 410, article 02014. DOI: 10.1051/e3sconf/202341002014.

13. Wan Y. Luo Y. Analysis of geotechnical engineering safety technology in urban underground space construction. *Journal of Architectural Research and Development*. 2022, vol. 6, no. 1, pp. 1–6. DOI: 10.26689/jard.v6i1.2887.

14. Zhukov S. A. Substantiation of environmental safety in metro facility operations considering hydrogeological risks. *Mining Science and Technology (Russia)*. 2024, vol. 9, no. 3, pp. 283–291. [In Russ]. DOI: 10.17073/2500-0632-2024-04-259.

15. Liang Y., Xu N., Chang H., Qian Sh., Liu Ya. Automatic construction of risk transmission network about subway construction based on deep learning models. *Scientific Reports*. 2025, vol. 15, article 16383. DOI: 10.1038/s41598-025-99561-0.

16. Ren Z., Liu Y., Zhao D., He Yu., Zhang J. A deep learning-driven framework for real-time recognition and quantification of subway tunnel surface defects using high-resolution imaging. *Urban Rail Transit*. 2025, vol. 11, pp. 279–299. DOI: 10.1007/s40864-025-00246-8.

17. Sun X., Wu L., Wu D. Risk evaluation of metro tunnel shield construction based on game variable weight extension cloud theory. *Scientific Reports*. 2025, vol. 15, article 18961. DOI: 10.1038/s41598-025-03345-5.

18. Funikova V. V., Dudler I. V., Butaev R. T. Anthropogenic changes in the groundwater regime of built-up areas: Geocological, engineering geological, and hydrogeological aspects. *Water Resources*. 2022, vol. 49, pp. S59 – S68. DOI: 10.1134/S0097807822080036.

19. Shi Y., Liu X., Jia J., Song Z., Song L., Ge L., Zhang Q., Xue Ch. Research on the starting control technology of ultra-deep shield near existing line in soft soil urban area with microconfined water. *Geotechnical Engineering and Intelligent Disaster Prediction. GHS 2024. Sustainable Civil Infrastructures*. Springer, Cham. 2025. DOI: 10.1007/978-3-031-85787-4_18.

20. Sartirana D., Rotiroli M., Bonomi T., Mattia De Amicis, Nava V., Fumagalli L., Zanotti Ch. Data-driven decision management of urban underground infrastructure through groundwater-level time-series cluster analysis: the case of Milan (Italy). *Hydrogeology Journal*. 2022, vol. 30, pp. 1157 – 1177. DOI: 10.1007/s10040-022-02494-5.

21. Feng Z., Cheng B., Shao Y., Zhang B., Li X., Wang X., Liu P. Predicting and mitigating twin-tunnel settlement in coastal soft soils: An integrated monitoring and modeling approach. *Geotechnical and Geological Engineering*. 2025, vol. 43, article 435. DOI: 10.1007/s10706-025-03336-3.

22. Jing M., Lu C., Sun C., Pujades E., Ye Yu, Xu T., Sun X. Assessing the effect of construction-induced consolidation on groundwater travel time distribution under unconfined conditions. *Hydrogeology Journal*. 2023, vol. 31, article 275 – 292. DOI: 10.1007/s10040-022-02579-1.

23. Wang D., Ye S., Zhang J. Risk reduction measures and monitoring analysis of deep foundation pit with water in a metro station in hefei. *Water*. 2023, vol. 15, no. 16, article 3007. DOI: 10.3390/w15163007.

24. Kulikova E. Yu., Balovtsev S. V., Skopintseva O. V. Geotechnical risk management in mine and underground construction. *Sustainable Development of Mountain Territories*. 2025, vol. 17, no. 1, pp. 556 – 563. DOI: 10.21177/1998-4502-2025-17-1-556-563.

25. Kulikova E. Yu. Estimation of factors of aggressive influence and corrosion wear of underground structures. *Materials Science Forum*. 2018, vol. 931, pp. 385 – 390. DOI: 10.4028/www.scientific.net/MSF.931.385.

ИНФОРМАЦИЯ ОБ АВТОРАХ

Куликова Елена Юрьевна — д-р техн. наук, профессор, НИТУ МИСИС; зав. кафедрой, РТУ МИРЭА, e-mail: fragrante@mail.ru, ORCID ID: 0000-0002-9290-671X, Розенталь Олег Моисеевич — д-р техн. наук, профессор, главный научный сотрудник, Институт водных проблем РАН, e-mail: omro3@yandex.ru, ORCID ID: 0000-0001-6261-60-60.
Для контактов: Куликова Е.Ю., e-mail: fragrante@mail.ru.

INFORMATION ABOUT THE AUTHORS

E. Yu. Kulikova, Dr. Sci. (Eng.), Professor, NUST MISIS, 119049, Moscow, Russia; RTU MIREA, Moscow, Russia, e-mail: fragrante@mail.ru, ORCID ID: 0000-0002-9290-671X, O.M. Rozental, Dr. Sci. (Eng.), Professor, Chief Researcher, Institute of Water Problems of the Russian Academy of Sciences, Moscow, Russia, e-mail: omro3@yandex.ru, ORCID ID: 0000-0001-6261-60-60,
Corresponding author: E. Yu. Kulikova, e-mail: fragrante@mail.ru.

Получена редакцией 22.09.2025; получена после рецензии 24.10.2025; принята к печати 10.12.2025.
Received by the editors 22.09.2025; received after the review 24.10.2025; accepted for printing 10.12.2025.