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Justification of Safe Plugging Options for Subway Tunnels Flooded in an Accident Based on Risk Assessment

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Abstract

The article presents the results of the evaluation of design and technological risks when considering the project of water-saturated soil mass stabilization in order to prevent the settling of the earth's surface at the emergency site between Lesnaya and Ploschad Muzhestva stations in the period from 2005 to 2016. The analysis of the main causes of the emergency at the site under consideration was performed. Different options for the array stabilization using the space grouting inside the flooded tunnels were presented to solve the problem. The geophysical surveys indicate that the processes in the "tunnel-array" system are far from stabilization. The purpose of research and scientific works is to determine the causes of the accident and the forecasting of negative phenomena in the "array-flooded tunnels" system, the rationale of choosing the most economically feasible, effective and safe way of operations. The problem of quantifying the risks for the options of the implementation of the flooded tunnels plugging project was solved. The existing approaches to risk assessment, applied in the world practice were considered, the main content of the risk management process was revealed.

Keywords: subway, tunnel, station, array, plugging, accident, flood, risk assessment.

INTRODUCTION

High requirements of sustainable development are imposed on the infrastructure development and the development of underground space in cities. The main challenge is that the construction should be carried out with minimal negative impacts on the environment, while ensuring its high quality and works production safety, the execution of works should be carried out on schedule in compliance with the budget. Today the tunnel companies in the world are unanimous that the success of the underground construction in urban settings is determined exactly by how the risk management is performed [1]. The topic of risk analysis and management is constantly on the agenda of meetings of the tunnel associations, where the common rules, procedures and models of identification, analysis and risk mitigation are developed and the best solutions are considered on the examples of international practice [2-4].

Risk assessment at all stages of the project for the construction of the underground facility represents the formalized process of identifying hazards, assessing their impact and likelihood of occurrence. This also included the strategies needed to implement the preventive and emergency measures. The parameters to be used in the risk assessment in terms of probability of occurrence of a hazard and the severity of its consequences with regard to costs, program, environment, third parties and existing facilities shall reflect the specific object and correspond to the stage on which the facility under consideration stands [5].

The article discusses the assessment of design and technological risks upon implementation of the project on the soil mass stabilization to localize zones of sediment area, which are caused by the development of the emergency situation in the area between Lesnaya and Ploschad Muzhestva stations in the period from 2005 to 2016. The reason for the research was the decompression of soil in the overtunnel area of the decommissioned tunnel sections of the first and second ways of Kirov-Vyborg line in St. Petersburg subway. The purpose of research and scientific works is to determine the causes of the accident and the forecasting of negative phenomena in the "array-flooded tunnels" system. The geophysical surveys indicate that the processes in the "tunnel-array" system are far from stabilization. Figure 1 shows a geological cross-section of the area under consideration. In hydrogeological terms, within the area of works the overmoraine aquifer system (water table, water of sand lenses and prolayers, sporadically distributed in the lake-glacial sandy loams) and intermoraine aquifer represented by fine and medium sands containing pressurized water are highlighted.

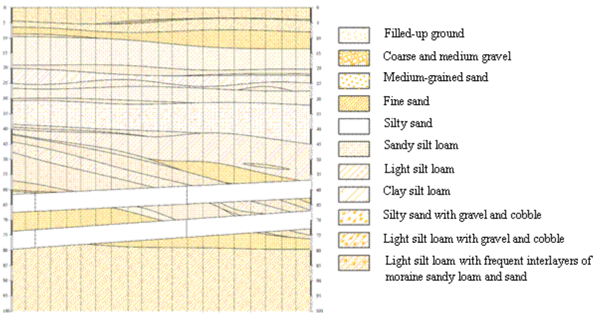

Figure 1: Longitudinal geological area cross-section

The depth of the tunnels location over the entire section of works ranges from 64 to 88 m. The length of the flooded areas in the tunnel of the track I is 535.5 m, in the tunnel of the track II-474.0 m. According to the results of work of the expert organizations these areas need:

- the filling with the process solution with simultaneous water discharge from the flooded

tunnels of the first and second tracks;
- soil body stabilization in the maximum sediment area (section 320 × 30 m) by constructing grouting columns using the cuff technology and jet grouting.

METHODOLOGY

The relevance of the risk assessment and management thereof is emphasized by the public interest in an efficient and expedient use of funds in the construction of underground facilities, and of the city infrastructure facilities. A survey of the International Tunnelling Associations [6] showed that upon the implementation of projects on construction of underground structures by the construction companies the significant increases in the cost of the projects are recorded, where the minimum average increase is 30% of the project cost and the average maximum is 50%. This situation suggests that this trend requires correction, that is, the issue of reducing the excess cost of the project is in the need for better costs and risks management. Therefore, the achievement of this goal requires a tool, and a risk management technique.

Construction without risks is impossible, as the process of projects implementation is extremely complex, and there are many factors that can have a negative impact on the project development. The main difficulty in the underground construction is that it is carried out under conditions of geotechnical uncertainty.

Risk management allows to timely identify and resolve potential problems. So the risk management shall be started at the very early stage of the work. The risk management plan shall cover all the process stages from conceptual design to the facility operation. The purpose of the risk management process comes down to reduce to a minimum all the risks identified in the project at every stage and preventive measures to reduce risks in the construction process.

Risk management is a logical chain of actions, but at the same time it is a dynamic process that must be managed and extended to all components of the project. The risk management involves the performance of the following steps [5]:

- identification of risks;
- quantification of risks;
- initial response to the identified risks;
- assessment of the residual risks;
- identification of measures to reduce the residual risks;
- monitoring.

The following can be emphasized from the above diagram:

- the first stage involves an assessment of the initial risk. The works required for the project shall be identified. Each process is correlated with the possible risks. The assessment of the probability of the event occurrence and severity of consequences in case of their occurrence is performed;
- the second stage involves the allocation of works, the risk of implementation of which is unacceptable or undesirable. The countermeasures aimed at reducing the initial risks are proposed;
- the third phase aims to assess residual risks, i.e. the impact of proposed countermeasures on the reduction of the initial risks is estimated.

According to the degree of detail, the three stages of the risk assessment can be identified as one of the stages of risk management:

- the first stage-the risk assessment at the projects discussion stage;
- the second stage-the risk assessment at the stage of tender works and agreement of the customer with the performers;
- the third stage-the risk assessment at the projects discussion stage;

At each stage of the project implementation, the assessment of both the initial risks and residual ones is performed. At the same time, usually at the first stage of risk assessment, a qualitative risk assessment, the development of measures to reduce the primary risks is performed. The qualitative risk assessment does not always involve a quantitative one. The paper considers the risk assessment at the first stage of the project only. The risk assessment is carried out in a qualitative way, based on expert analysis. The development of risk mitigation measures is not performed, as it shall be performed at the stage of comparison of the estimated cost of construction and installation works.

The risk management is an important task of the company management. Application of risk management theory in practice on the construction of underground facilities, and the existing models of forecasting the likely costs are described in several studies [7-14].

Risk assessment

Danger is generally defined as a characteristic of an event that may occur in a situation with a negative character. It is very important to separate the concept of risk and hazard, because the change of risk without changing the hazard is possible. There are several methods of identifying hazards and threats. The main is a technique in which a group of experts develops possible scenarios and identifies possible hazards. Thus, the risk assessment model is built based on the possible hazards. The risk assessment model is a set of algorithms or rules that are used for risk assessment and measurements along the tunnel or underground facility. The risk assessment model can be selected from commercially available models developed from existing basic models depending on project requirements.

The purpose of any risk assessment model is to quantify the risks magnitude in absolute or relative terms. The risk assessment stage is important and the most difficult step in the risk management practice. The problem is that no one really can say where and when an accident or violation in the underground facility construction and operation will occur. However, the probable destruction mechanisms, and their location can be defined. There are three main types of risk assessment models: matrix, probability and index model.

There are three main types of risk assessment models, and each of them has advantages and disadvantages mentioned below [15]: matrices model, probability model, index model. Below is the description of each of them.

The matrices model is one of the easiest-to-use risk assessment approaches. The risk determination is carried out in accordance with the probability of adverse event and potential consequences of the event. By the magnitude of each of these parameters the magnitude of the risk, a ranking of which is made on the high, medium and low levels of the numerical scale is determined. A cell in the matrix, the coordinate of which is determined by the probability and magnitude of expected impacts, is assigned to each hazard. The hazards with high probability and magnitude of the effects are located in the matrix above the rest ones. The hazard is defined as an event which, under certain conditions, can lead to consequences associated with an injury. Each hazard is associated with the probability of its occurrence P and the severity of the consequences I in case of such events. This assessment is performed by the safety, time and cost criteria. The risk R, associated with certain hazards, is defined as:

$$R = P\sum_{i=1}^{n} I_i, \tag{1}$$

where
n-the number of groups of the effects caused by the event;
P-the likelihood of hazard
I-the severity of the symptoms of danger.

When the risk model is used to assess the risk, both the expert opinion, as well as more sophisticated quantitative method for determining the probability and consequences of the hazard symptoms may be used. The disadvantage of the use of the matrices models is the inability to account for all hazards and the relationship between them, but this approach allows to perform structural analysis, to describe the hazards by the probability and consequences of possible manifestation. The application of the matrices model for risk assessment in civil engineering in practice is described in a number of studies [16-18].

The probability model for risk assessment has been widely used in various fields of human activity, such as nuclear, chemical, aerospace, petrochemical and other industries [19-21]. This risk assessment model is the most rigorous and comprehensive, and in the literature, it can be found under the following names: probabilistic risk assessment, the quantitative risk assessment (QRA) or numerical risk assessment (NRA). A probabilistic risk assessment model is a consistent mathematical and statistical model, which is largely based on empirical data on the manifestation of hazards, accidents and undesirable adverse events. The use of PRA methods for safety analysis allows to determine the assessment of probability and significance of events and their consequences, which could have adverse effects on safety. A probabilistic risk assessment for complex systems usually helps to identify scenarios using event trees or event sequence diagrams, and fault trees to obtain logical models of formation of certain undesirable consequences of a security breach. To quantify the probability of the final state of the system, the probability of the source event (i.e. causes) is multiplied by the probability of each subsequent intermediate event, subject to implementation of the previous sequence of events for each scenario. For each scenario, the significance of effects is typically determined based on physical parameters of occurring processes (events) and characteristics of the scenario. The combined effects are determined by summation of the effects of the entire set of scenarios, using data of similar events. To assess the probability of events, the different data sources are typically used. The typical data sources include data from previous tests of the system (i.e., measurement data, or data of the direct observations during the tests, experiments, and studies), data on other systems or projects (data on analogue systems, data of physical processes modeling) and the expert opinions (i.e. the probability assessment by the experts in a particular area). The risks are considered in accordance with the scenario of events, i.e., the probability of the event is estimated based on implementing or not implementing the previous events. In determining the overall risk assessment, the systematic identification and assessment of uncertainty is carried out in two ways. In determining the probability of the scenario events, the assessment of the relevant uncertainties in the form of intervals or probabilities distribution is performed. The resulting uncertainty is used to assess the effects probability.

The third model of the risk assessment is the index model, well-established in the assessment of pipeline construction risks [15]. The following problems are resolved using the index method: assessment of the phenomenon level change, identification of the role of individual factors in the change of a performance indicator, evaluation of the impact of the aggregate structure changes on the dynamics of the analyzed indicator average level, recalculation of figures for comparison. In this approach, the numerical values in the form of points are assigned to important conditions and events in the piping system, which allows to draw a full picture of the risks. It includes both the reduced and increasing risk, i.e. the system variable. The quantitative importance is assigned to each risk variable. The specific value of the amount of risk reflects its importance and is based on statistical data, expert opinion or engineering decisions, where statistics is unavailable. Each section of the piping system is assessed based on the properties of each section. Various pipe segments can then be separated according to their relative risk value to determine the priority of the repair works, observations, and activities on risks reduction.

The use of any of the above risk assessment models is possible, but an understanding of the advantages and disadvantages (Table 1) of each of them provides a basis to the decision maker for selection [15].

Table 1: Applications and features of the risk assessment models

Risk assessment model	Applications and Features
Matrices model	For better quantification, a simple tool allows to combine multiple views in a single solution
Probabilistic model, fault tree	The study of specific events, the performance of studies after the danger manifestation, the comparison of risks of specific accidents, calculation of specific

	events probabilities.
Index model	Getting an inexpensive general risk model allows to create a resource allocation model, the model of interaction of several potential danger mechanisms

History of the accident and background of the necessity for implementation of the project on preventing the earth's surface setting

The structure of tunnels (Figure 2) represents the outer shell of cast iron tubing with the diameter of 6.0/5.6 m and the inner reinforced concrete shell with the metal insulation around the perimeter in the form of an anchored metal sheet with a thickness of 8 mm.

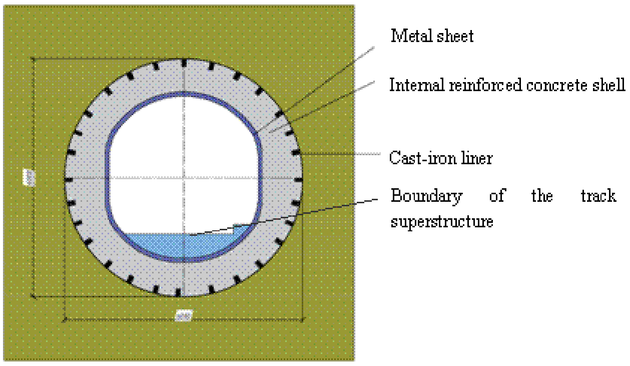

Figure 2: Structure of the tunnels considered

The article describes the analysis of the initial risks in the management of civil and erection works aimed at filling the tunnel with the construction mortar in the area of the St. Petersburg subway between Lesnaya and Ploschad Muzhestva stations. To expand the relevance of the question, we should tell the history of the accident.

Construction of this tunnel section within the ancient erosion of Proterozoic clays roof with the depth from the surface of about 120 m was initiated and carried out in extremely difficult geotechnical conditions-fine water-saturated sands, silty sandy loam with the quicksand properties, silty waterlogged loams under hydrostatic pressure of the groundwater on the tunnel lining of up to 8 atm. The work was done by freezing solid ground mass. The volume of works on the artificial freezing of soils (200 km of freeze wells and about 500 thous. m^3 of frozen soil) had no analogues in the world practice of subways building. In order to reduce the volume of drilling operations and the frozen soil, the location of tunnels within the erosion was made one on the other with the distance between their axes of 12 m. In this area, a multi-layer structure of the lining of cast-iron tubing with the outer diameter of 6.0 m with an internal monolithic concrete clip and waterproofing screen in the form of a shell made of sheet steel 8 mm thick was used. The clip is reinforced in transverse and longitudinal directions. The error of designers and builders was in the underestimating the extent of the processes occurring underground. Therefore, for the freezing of the soil the conventional freon freezing equipment, allowing the ground freezing to-12 °C, was used for the first construction stage.

During construction in 1974, there was a break in the slider ground to the lower tunnel and the upper one followed it. The volume of the soil released in the tunnel amounted to about 44 thous. m^3. The scale of emission was such that the area of 1.5 km from the break to almost finished Lesnaya station was completely flooded in a few hours, and it was impossible to stop the water and sand flow to the bottom. The accident was eliminated by freezing the ground with liquid nitrogen (it took 7900 tons) by creating a breakthrough of reliable ice wall. As a result of a water breakthrough in the tunnels, the underground cavities previously filled with the water have cleansed and formed vast cavities. Because of the ground setting, the oval cavity with the dimensions of 400 x 200 meters and a depth of 3 meters occurred.

In 1975, in the drifting the bottom in the lower tunnel a quicksand got through the injection hole, and then in the bottom of the tray, and therefore the lower tunnel was filled up to the emergency gate. Nitrogen freezing was applied again to eliminate the accident.

Despite these complications, on December 31, 1975 within the prescribed period the section from Lesnaya to Academicheskaya metro stations has been commissioned, and the train speed was limited to 40 km/h.

Since the commissioning, in the tunnels at the site of erosion there were leaks in the tunnel lining, due to which the repair and maintenance works have been performed over a number of years. In late 1994, there were signs of the change in the state of the lower tunnel: the water inflow increased, and later-also with simultaneous removal of sand in the tunnel. In February 1995, the sand production sharply increased, the deformation of the earth surface began to grow, a steel seal of the inner metal insulation ruptured in the tunnel. In 1995, there was an emergency situation: daily water inflow exceeded 400 m^3, the sand production reached 0.4-1.2 m^3 per day. By October 1995, the total water inflow in the tunnel increased to 800 m^3 per day, including to the lower tunnel-700 m^3. In the first nine months of 1995, the sand production was approximately 120 m^3. The increase of the value of the earth's surface setting began.

At the beginning of December 1995, the situation worsened, and in December by the decision of the Commission for Emergency Situations the traffic of trains was stopped; on December 9 it was decided to flood the top of the tunnel because of the intensification of the setting the top tunnel and increase of inflows thereinto to 700 m3 per day with the removal of sand to 30 meters per day, and surface deformation. By December 15, 1995, the repair works carried out in a tray of the second lower tunnel after the traffic stoppage virtually eliminated the waterway. However, with the continued setting of the lower tunnel (5-8 mm per day) after the upper tunnel flooding it was decided to flood the lower tunnel. Altogether during the operation 483,800 m^3 of water entered the top tunnel, and 79,400 m^3 to the lower one, and 890 m^3 entered both of them.

Noticeable surface setting started since December 9, 1995, that is, since the flooding of the top of the tunnel. The gate was closed, but it was not enough tight, and the water and ground pulp passed through it. In order to concrete the bridge before the gate, there was laid a pipe with a valve at the end for the release of water, which was blocked after the bridge concreting. During the accident in 1995, a subsidence trough of 8,000 m^3 appeared on the surface, the maximum rainfall reached 900 mm (Figure 3).

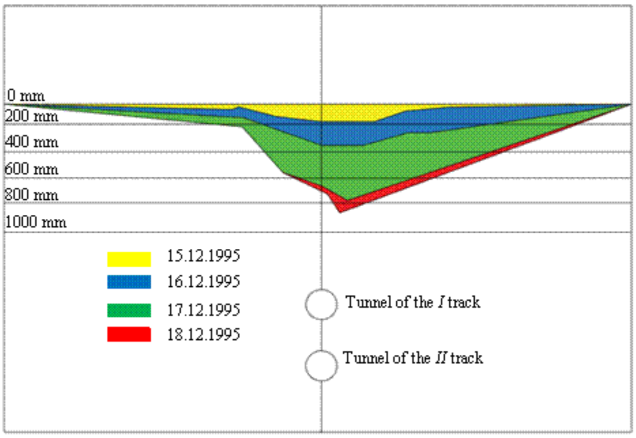

Figure 3: Cross section: Subsidence trough development

The accident severely affected not only the settled way of life of the inhabitants of the northern districts of St. Petersburg, but also created a lot of problems for the city as a whole, both social and economic ones. The variant development of technical solutions for the restoration of through traffic has been launched immediately after the accident. At the moment, traffic on the emergency area is restored, the works on the construction of redundant tunnels are performed, but the question of the final conservation of emergency tunnels remained unresolved.

Design and development of alternative solutions

The tunnel construction in the densely populated areas of the city due to the risk caused by the uncertainty of conditions of its conduction and a number of dangers that in general can be attributed to the geological and hydrogeological characteristics of the construction, the works performance technology and its parameters, as well as political and social restrictions. The implementation of these risks may have a negative impact on the project duration, its cost and safety of works performance, as well as on environmental consequences.

The tunnels located in urban areas, the access to and inspection of the state of which is impossible, shall be filled with mortar. This will improve the stability of underground space, as well as significantly reduce or prevent the setting of the earth's surface over these tunnels, if the lining of tunnels will be broken or destroyed by external factors.

At present, a number of design and research organizations suggested options of filling tunnels with technological solutions. At the same time, the assessment of risks, which may arise during construction and installation works, was not performed at the moment. Risk analysis allows to identify the most suitable option of construction works in terms of additional costs for construction and installation works, as well as to exclude from consideration the projects with the significant risks in comparison with other options. The plugging of water-filled space of tunnels to prevent the manifestations of the earth's surface settling is possible in several ways. A risk analysis for the six options of conducting works aimed at plugging the space inside the flooded tunnels at the section Lesnaya-Ploschad Muzhestva of the St. Petersburg subway.

The first option for filling with technological solution the space inside the upper and lower tunnels through the vertical wells bored from the surface through the cast iron tubing (Figure 4). In this approach, before the production of works on filling the tunnels with process solution, the demolition of non-residential brick and metal hangars (this action is performed for all of the options under consideration), located above the tunnels, is performed, and the construction site is organized.

Along the axis of the tunnel with the increment of 10 meters two wells (a total of 104 pieces on a line) are drilled from the surface to ensure quality plugging. One of them serves for the supply of process solution, the other-for water pumping. After completing the work on flooding the first tunnel, the flooding of the second tunnel is performed. This is done by drilling a hole through the filled tunnel and its tray of cast iron lining. After performance of all the work and quality control of tunnels, flooding with process solution the wells plugging is produced. The duration of the works on this option is 26 months.

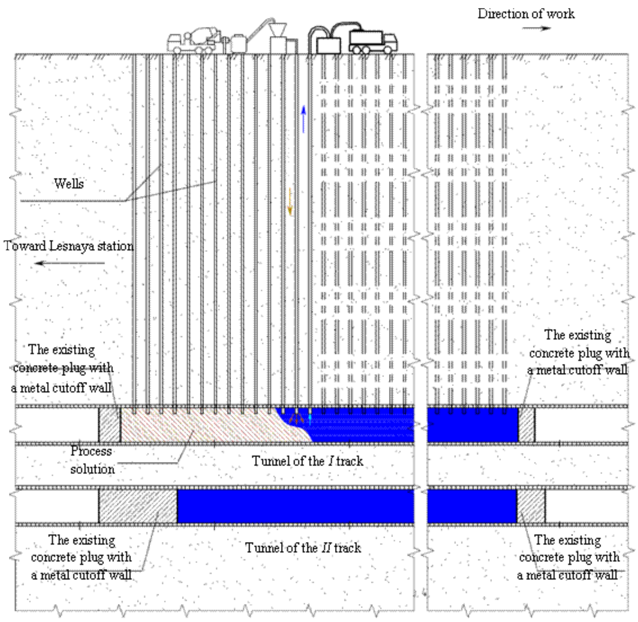

Figure 4: Filling of tunnels through vertical wells drilled from the surface

The second option is the process of filling the space of the tunnels through vertical and deviated wells drilled from the surface. Technologically, the second option of the first tunnel filling is similar to the first one. The second tunnel is filled with the process solution through the deviated wells drilled from the earth's surface at an angle of 18 degrees in the crest of the lower tunnel. The water pumping is produced similarly on the neighboring well. The duration of the works on this option is 27 months. The advantages of the first and second options include the lowest costs and duration of the projects, the ability to provide high safety indicators of the work performance, the possibility of additional drilling of wells in the event of wells non-compliance with the project location. On the other hand, when performing such work it is difficult to perform quality control, and the probability of additional drilling related, mainly, to the position of the well bottom with respect to the body of the lower tunnel.

The third option of filling the tunnel space is implemented through the sealing structures from the surrounding areas of tunnels using preventer on the discharge lines. With this approach, a partial development of a dirt and concrete backfilling of the existing workings and structures made in different periods shall be made before the start of the drilling of wells to fill the tunnels. In this case, the mine workings production shall be carried out under the protection of concrete bridges, and the shutter is set in each concrete bridge. From the concrete plugs on both sides of the first tunnel the drilling shall be performed through the working holes preventer with the casing tube, through which the process solution injecting into the tunnel, and one well for the drainage of water through the settling tank to the sewer system. After completing work on filling the space, the quality control of the works performed and the backfilling of sections of underground workings, adjacent to the existing tunnel, shall be performed. After conservation of the first tunnel, the works on the filling the existing tunnel on II track shall be performed. With this approach, the duration of the project is 32 months. The option of the third embodiment is the possibility of separation of preparatory work in time to fill the tunnels and fasten the ground. This approach eliminates the impact on the existing building.

The fourth option is a combination of the first and third one. The filling of tunnel of the track I is produced according to the technological scheme of the first option through vertical wells drilled from the earth's surface along the tunnel, and the filling of tunnel of track II-according to the technological scheme of the third option through the sealing structure from the surrounding tunnel areas with the use of preventers along the discharge lines. With this approach, the duration of the project is 30 months.

For the implementation of the fifth embodiment for filling of the tunnel space, the construction of tunnels along the tunnel route of 8 trunks with a diameter of 6 meters in increments of 65 meters using the shaft shrinking machine is required. The mounting of trunks 84 m deep shall be performed by precast concrete lining, and the construction works shall be carried out sequentially by two trunks. From constructed trunks to the tunnel of the first track through the preventers the injection wells shall be drilled with the casing through the cast-iron lining and wells for water pumping. Similar operation is performed with the second tunnel track after filling the tunnel of the first track. Plugging of wells and backfilling of trunks is performed after the completion of works. With this approach, the duration of the project is 34 months.

The sixth option includes the trunk building near the existing tunnels and filling their space. The fixing of trunk with the diameter of 9.8 m and 90 m depth shall be performed through precast concrete lining under the protection of temporary ice-soil fencing along the trunk contour. The areal horizontal freeze of adjacent areas on both sides of the tunnels shall be made through the wells. After this, the development of a frozen solid inside the tunnel of the first track shall be performed, and the concrete end wall shall be constructed, and a gate shall be mounted. The water removal shall be produced by pumps installed in the trunk sump with the water pumping through a settling tank to the sewer network. After the water removal, the installed concrete wall shall be destructed. Thereafter, using the retreating slaughter in increments of 15 meters the concrete plugs shall be constructed in series with filling the space between them with the process solution. After preservation of the tunnel of the first track the preservation of the tunnel of the second track shall be performed in a similar way. With this approach, the duration of the project is 39 months.

RESULTS

The matrices model, which will allow to create an adequate baseline scenario of the project, was adopted to assess the risks in the management of civil and erection works aimed at filling the tunnels with the construction slurries in the area of the St. Petersburg subway between Lesnaya and Ploschad Muzhestva. During the analysis and risk assessment, the reliance was made primarily on the extensive experience of experts who carried out a systematic analysis of each element of the project to select the most appropriate, safe version of the project scenario. For each identified hazard, its causes were established. After that, a risk assessment was carried out by establishing the probability of its manifestation and the magnitude of the effects of this manifestation that allowed to draw conclusions about the extent of the identified risks impact on the project. Thereafter, a preliminary risk assessment on the basis of a qualitative assessment methodology (authoritative expert opinion) was performed.

In assessing the risk of each event, the likelihood of its occurrence *P* has been divided into five categories (Table 2), and the severity of effects varied from very low to very severe and also was divided into five categories (Table 3). The severity of the consequences has been evaluated only by the commercial component at the construction phase. Thus, by multiplying the probability by the possible severity of the consequences, the risk value was calculated by the formula 1, which, in turn, was differentiated into four categories depending on the score value: unacceptable, undesirable, permissible, slight (Table 4).

Table 2: Qualitative scale of probability of occurrence

Score	Qualitative description of risk probability	Quantitative description of risk probability
1	Almost impossible	Approx. 1 of 1000
2	Hardly possible	Approx. 1 of 100
3	Possible	Approx. 1 of 10
4	Probable	It is more likely that the event will happen, than it will not.
5	Highly probable	It is likely that the event will occur.

Table 3: Qualitative event occurrence severity scale

Score	Description	Commercial implications
1	Very low	The increase in the value of construction works in the range of 1 mln. rub.
2	Low	The increase in the cost of construction and installation works from 1 mln. rub. to 10 mln. rub.
3	Medium	Stopping the construction and installation work for up to several weeks. The increase in the cost of construction and installation works from 10 mln. rub. to 100 mln. rub.
4	Hard	Stopping the construction and installation work for up to several months. The increase in the cost of construction and installation works from 100 mln. rub. to 1000 mln. rub.
5	Very hard	Closing the project

Table 4: Risk categories

Risk category	Score value	Description
Unacceptable	15-25	The risk shall be reduced at least to the level of unwanted one or lower, depending on the value of works necessary for its reduction.
Undesirable	5-10	It is necessary to identify measures to reduce risk.
Acceptable	3-6	The possible hazards should be identified and they shall be monitored during the project implementation. There is no need to provide for special measures to reduce risks.
Non-threatening	1-2	Subsequent examination of the hazards related to this category is unnecessary.

The elementwise risk estimates for all the options of the construction work on plugging the flooded area of two tunnels were made. For this purpose, the entire process of each project implementation was divided into different types of construction works. The first version of the project includes the following types of construction and installation works: preparatory works (Table 5), drilling works (Table 6), solution injection with the simultaneous water injection and filling the tunnels (Table 7).

Table 5: Preparatory works

Name of construction and installation works	Name of potential risks	Risk assessment	Risk category
Preparatory works			
Works on creation of plan-height supporting geodetic control	Works on creation of plan-height supporting geodetic control	4	Acceptable
Traffic organization by temporary scheme	Traffic organization by temporary scheme	6	Acceptable
Demolition of metal non-residential buildings	Demolition of metal non-residential buildings	6	Acceptable
Demolition of brick single-storey buildings	Demolition of brick single-storey buildings	6	Acceptable
Complex of electric and HV works	Complex of electric and HV works	4	Acceptable

Table 6: Drilling works

Name of construction and installation works	Name of potential risks	Risk assessment	Risk category
Primary pneumoshock drilling with simultaneous casing (HD 168x8) with the removal of the drill cuttings using compressed air flow in the II soil category with an average depth of the well to the arc of the top tunnel-70 meters, the arch of the lower tunnel-82 m. Joining of 3 meter length casing through the threaded connection	Deviation of the downhole from the design position, including From the vertical of the more standard one with the need to additional drilling	6	Acceptable
	The presence of boulders and other inclusions in the range	4	
	The presence of unexpected decompression zones	4	Acceptable
	The dependence of the hydrogeological conditions from the seasonality, increased water production	6	Acceptable
	Unexpected stops (breakage) of machinery and mechanisms	4	Acceptable
	Impossibility to place drilling equipment	3	Acceptable
The open hole drilling for cast iron, reinforced concrete, meta using core drilling with the triple tube shell, diamond crown and removable core receiver with the removal of the drill cuttings by the waterflow. Arch of	Jamming of the drilling rod in the lining	8	Undesirable
	Jamming of the drilling rod due to tangential drift of the head	9	Undesirable
	Contact of the downhole with the cast iron lining and fitting of reinforced concrete lining	10	Undesirable

the upper tunnel	Impossibility of drilling through the lining	3	Acceptable
	The presence of unexpected decompression zones	4	Acceptable
	The dependence of the hydrogeological conditions from the seasonality, increased water production	6	Acceptable
	Deviation of the downhole from the design position, including from vertical of a regulatory position, with the need for additional drilling	9	Undesirable
	Unexpected stops (breakage) of machinery and mechanisms	6	Acceptable
	Premature wear of craters	9	Undesirable
Lining core excavation	Core falling	4	Acceptable
Fastening of drill pipes at the surface	Drill pipes falling in case of work technology violation	4	Acceptable

Table 7: Solution injection with the simultaneous water injection and filling the tunnels

Name of construction and installation works	Name of potential risks	Risk assessment	Risk category
Installation of mortar feeding and drainage pipes with docking on threaded connections with the length of 3 meters to the height of the horizontal diameter of the top tunnel + 1 m,-1.5 m	Pipes jamming upon lowering	2	Non-threatening
	Pipes falling in case of work technology violation	4	Acceptable
	Improper installation on level	4	Acceptable
Under--water injection of the mineral binder light mortar	Violation of the mortar supply logistics	9	Undesirable
	Inconsistency of the mortar quality	6	Acceptable
	Appearance of jams at discharge	6	Acceptable
	Unexpected stops (breakage) of machinery and mechanisms	6	Acceptable
	The presence of voids, inhomogeneity of the mortar volume	4	Acceptable
	The increased simultaneously injected mortar volume relative to the estimated one	6	Acceptable
	The presence of soil in the flooded tunnels	8	Undesirable
Drainage using variable frequency pumps to ensure the matching of the pumped water volume to that of the injected mortar	Inconsistency of volumes of water discharge and injecting	6	Acceptable
	The increased inflow of water at discharge	4	Acceptable
	Unexpected stops (breakage) of machinery and mechanisms	4	Acceptable
Pressure washing of drainage pipes without their extraction	The emergence of jams due to mortar hardening	9	Undesirable
	Pipes falling in case of work technology violation	2	Non-threatening
Extraction of mortar conducting pipes with disassembling and cleaning on a surface	Pipes jamming upon lifting	2	Non-threatening
Removing the core drilling pipes after the start of the mortar maturing to prevent the drill pipes embedding	Pipes jamming upon lifting	2	Non-threatening
	Blocking of bullet due to mortar hardening	6	Acceptable
Under water re-injection of foaming synthetic two-component resins through the water outlet pipe	Inconsistency of the reaction start time to the estimated one	4	Acceptable
	Inconsistency of mortar quality	6	Acceptable
	Unexpected stops (breakage) of machinery and mechanisms	4	Acceptable
	Presence of	6	Acceptable

	voids, inhomogeneity of the mortar volume		
	The increased simultaneously injected mortar volume relative to the estimated one	6	Acceptable
	Inconsistency of hardening mortar quality	8	Undesirable
Extraction of water outlet pipes with disassembling and cleaning on a surface	Pipes jamming upon lifting	4	Acceptable
	Pipes falling in case of work technology violation	2	Non-threatening

DISCUSSION

The above options for stabilizing the "soil body-flooded tunnels" system are aimed at eliminating the causes of the change in the soil body and ensuring safe operating conditions of the development of infrastructure items within the area of the flooded subway tunnels in St. Petersburg. To justify the adopted technical solutions and create scientific technical basis for monitoring the state of the soil body and the earth's surface during the implementation of the project solution, the pilot and experimental section will be created.

Summary data are presented in tabular form (table , with a total amount of risk in a separate line, as well as the amount of risks classified as "unacceptable", "undesirable", that is, those risk categories, which require the development of measures to reduce these risks to residual ones.

Table 8: Summary data

Index	Considered option					
	1	2	3	4	5	6
The total amount of points in the risk assessment according to the accepted method of analysis	255	388	423	317	363	470
Number of risks related to inadmissible ones	-	9	1	-	3	4
Number of risks related to undesirable ones	9	12	10	6	20	15
The relative magnitude of the construction works value, %	149%	234%	100%	192%	325%	125%

Due to inability to provide the necessary continuity of the flooded tunnels filling, the options 3 and 4 are considered to be inappropriate. The option 5 has a high cost and duration of the preparatory works for the construction of barrels, so there is a need of traffic management on a temporary basis for a long period. In implementing the sixth option, the inevitable consequences of the soil freezing process will manifest, and it has a high cost and the duration of the preparatory work on the ground freezing and the trunk construction. There is a high risk during the works in the body of tunnels, the breach of the static state of the tunnels filled as a result of the lining removal.

The developed options for the production of works on filling tunnels and consolidating the soil body were submitted to the members of the Scientific and Technical Expert Advisory Board of the St. Petersburg branch of the Tunnel Association of Russia, and, based on the results of the extended scientific and technical council with the involvement of the scientific community on the issue of choosing the most effective option from the proposed ones, the first option-"filling the tunnels through vertical wells drilled from the surface," was recognized as the most efficient in terms of technology, cost and time parameters, as well as an option with the lowest risk.

The project provides for the filling with process solution with simultaneous water discharge from the flooded tunnels of the I and II tracks, the soil body stabilization in the maximum sediment area by constructing grouting columns on the basis of the sleeve technology, and the consolidation of the soil by jet grouting.

It should be noted that during the risk assessment it was assumed that each of the options considered is technically feasible. Despite the fact that the risk assessment was performed by the economic (commercial) feasibility, the results do not represent the cost of construction and installation works to a greater or lesser extent, and are the indicators of costs for additional construction and installation works, which may occur during the project implementation.

CONCLUSION

The world becomes increasingly aware of the need to preserve the environment and everyone becomes serious about the environmental aspects of construction projects, and Russia constitutes no exception to this.

During the results analyzing, special attention shall be paid to the amount of risks related to inadmissible ones. If it turns out that the measures to reduce these risks will not be effective or the cost of risk reduction will be very high, these options shall not be considered as working ones. At the same time, the total number of points indicates the relative index of cost of the additional works related to the consequences liquidation event.

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