Risk Level Control by Geotechnical Monitoring on Different Tunnel Projects Stages

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ABSTRACT: Geotechnical risks make the most significant contribution to the level of uncertainty in making design and constructive decisions due to their nonlinear variability both in terms of area and depth, and in time. For the purposes of geotechnical risk control in time can be successfully applied tools of digital geomechanics, mathematical modelling, deep learning methods based on neural networks, algorithms for evaluating the technical condition of underground structures based on BIM technology. The initial information is the field study of the stress-strain state of structures and enclosing environment as a part of the system of multi-disciplinary geotechnical monitoring which provides the development of possible accidents scenarios with the manifestation of each risk-criterion indicator hazardous for the tunnel.

KEYWORDS: Tunnel, Geotechnical risks, Multi-disciplinary geotechnical monitoring, Field study, Stress-strain state, Risk level control

1. INTRODUCTION

Natural and man-made impacts are registered in the “underground structure - enclosing environment” system at all stages of its existence. Hazardous processes may differ significantly at different intervals of an extended underground structure and at different times. This requires a dynamic approach to assessing, forecasting and reducing probability of emergency situations, as well as minimizing losses in different areas of the object. Therefore, it is reasonably to evaluate the influence of negative factors on extended underground structures from the standpoint of risk management.

Geotechnical risks make the most significant contribution to the level of uncertainty in making design and constructive decisions due to their nonlinear variability both in terms of area and depth, and in time. For the purposes of geotechnical risk control in time can be successfully applied tools of digital geomechanics, mathematical modelling, deep learning methods based on neural networks, algorithms for evaluating the technical condition of underground structures based on BIM technology.

The initial information is a field study of the stress-strain state of structures and enclosing environment as a part of the system of multi-disciplinary geotechnical monitoring which provides the development of possible accidents scenarios with the manifestation of each risk-criterion indicator hazardous for the tunnel.

2. TUNNEL PLANNING

In compliance with the current Russian legislation, the design of the construction of transport tunnels should be carried out:

- based on the principles of system analysis and logistic approaches which ensure the adoption of the best organizational, technical and technological solutions meeting the requirements of reliability and durability of structures with high quality tunnel elements and assemblies, reducing the time and cost of construction, saving material resources and minimizing operating costs;
- with the adoption in the project of the organization of construction technologies that ensure safe and trouble-free construction.

To ensure the above conditions, it is necessary to assess various risks and the possible consequences of their implementation at all stages of the construction's existence, starting from the design stage.

An assessment of the factors of natural-technological risks and drawing up forecast scenarios of critical situations at the design stage allows choosing the best option for the route of the new tunnel, determining construction technologies, categorizing construction intervals by hazard degree, and developing risk-appropriate preventive measures in advance using a risk-based approach.

Geotechnical risks are among the major risks in underground construction. Due to their non-linear variability in area, depth, and time, the geotechnical risks contribute most significantly the uncertainty level in making design and constructive decisions.

Underestimation of risk factors and incorrect conclusions when assessing and predicting geotechnical risks at the stage of design and survey work can result in accidents during construction and operation.

As an example illustrating the need for early identification, assessment and control of the level of geotechnical risks, we can cite the construction of the Severo-Muysky Tunnel (North Muya Tunnel), the most complex tunnel project ever implemented in Russia, and one of the most complex in the world.

The Severo-Muysky Tunnel (SMT) is located on the Baikal-Amur Mainline (BAM) which is one of the largest railways of the world with a length of 4,287 km, leading from Eastern Siberia to the Pacific coast of the Russian Far East.

The SMT is a complex of the structures which includes a single track tunnel with a length of 15,343 m, an exploratory transport and a drainage adit parallel to the main tunnel, a number of drainage galleries, vertical shafts and shaft sidings. The depth of the mine workings reaches 1 km.

Survey work as part of the feasibility study of the Severo-Muysky Tunnel Technical Design was carried out in the period 1968-1974. Those studies provided knowledge of the complexity of the geological, hydrogeological and tectonic structure of the rock mass, the presence of a large number of tectonic zones and the Angarakan depression with a length of about 500 m, opened by exploratory wells. According to these data, when tunneling, it was necessary to cross 26 tectonic zones, composed of destroyed and watered soils, with a total extension of 7,100 m.

The second stage of engineering and geological survey was carried out in 1975; the survey results confirmed the complexity of the rock mass structure. In total, 39 wells with a total length of 5,477 m were drilled for the technical design. However, the less accessible central part of the ridge remained unexplored.

From 1980, further survey was carried out in the unbored part of the tunnel route in combination with on-ground geological survey and geophysical studies, taking into account satellite image interpretation materials.

At the end of 1986, compared with the 1984 data, an increase in the extent of zone IV by 140 m, a decrease in the number of zones with a length of more than 10 m, and an increase in the number of minor zones were noted. With an increase in the total number of zones from 27 to 33, their total extension decreased from 1,400 to 1,250 m. The position of some zones at the tunnel level changed in the same position on the day surface. For zone IV, the total inflow was increased from 1,300 to 3,300 m^3 per hour.

During the construction up to the completion, the engineering and geological conditions were constantly updated. This was done, first of all, by advanced drilling of horizontal exploratory wells with coring from the bottom of an exploration adit.

Figure 1 shows the expected geological sections along the route of the Severo-Muysky Tunnel according to the data for 1975 and for 1995.

The actual geological section, according to the data of all mine workings by 2003, represented an even more complex picture. According to the engineering-geological and hydrogeological conditions of construction, the SMT is one of the most complex tunnel projects in the practice of world tunnel construction [Shabynin, 2001; Nosarev 2001; Bykova, Sherman, 2007, etc.].

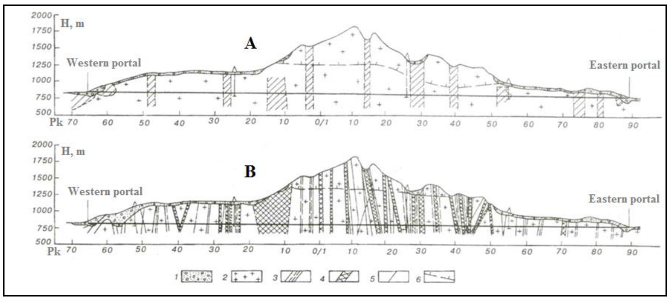

Figure 1 - Expected geological sections along the route of the Severo-Muysky Tunnel according to the data of 1975 (A) and 1995 (B). Designations: 1 - loose Quaternary deposits; 2 - Cambrian granites; 3 - zone of highly fractured and fragmented rocks; 4 - fragmented rocks with tectonic clay, disintegrated to crushed stone, gruss and sand, with a thickness of 5 m or more; 5 - same, with a thickness of less than 5 m; 6 - permafrost boundary

The enclosing granite rock mass is highly burst-prone, complicated by plenty large discontinuous faults and fractures filled with friable, thermal water saturated and soft fragmental rock with a level of hydrostatic pressure up to 5 MPa - these circumstances were the main reasons for emergency compression of the tunnel boring mechanisms, as well as catastrophic rushes and collapses in faces with human losses during rock tunneling.

The presence of discontinuous structures is determined by the SMT location in the mountain ridge of the rift basins forming the northeast flank of the Baikal Rift Zone (BRZ) - the intracontinental split of lithospheric plate developing under the complex field of neotectonic and modern stresses. Vertical movements of the BRZ splits reach 20 mm per year, and horizontal movements reach 17 mm per year.

Thousands of weak shocks and up to 2 strong earthquakes occur here annually according to the International Seismological Center. The largest of them is 1957 Muyskoye earthquake (M = 7.5-7.9). It is rated as catastrophic along the length of the surface discontinuity zone up to 25 km, vertical displacements up to 3.3 m and the perceptibility area of over 700 km from the epicenter with 11 out of 12 intensity degrees by MSK-64. A wide range of natural risks is complemented by the industrial impact of operating and new construction on the enclosing granite rock mass [Lebedev, Romanevich, 2019].

The causes of emergencies at the initial stage of construction of the SMT (1975-1980) were the insufficient knowledge of the tunnel route at the survey stage, lack of experience in special operations (water lowering, freezing and cementation of soils, etc.) in difficult geotechnical and hydrogeological conditions.

Common causes of accidents during the construction of the SMT were unusually difficult natural conditions, as well as the impact of natural and man-made earthquakes on the water-encroached rock massif disintegrated to sand and clay.

In general, the accident handling during the construction of the SMT can be represented in the diagram Fig. 2.

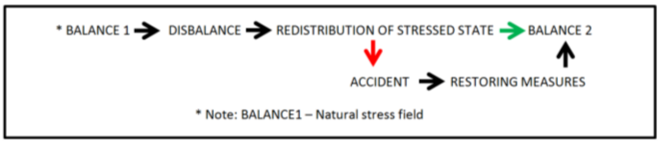

Figure 2 - A generalized scheme of accident handling during mining

The redistribution of Stress-strain state after the BALANCE 1 or BALANCE 2 phase during the construction of the SMT was due to the effect of earthquakes and / or the activation of fault zones, the neotectonic movement of blocks, the vibrational impact of penetration in the massif and / or traffic.

During the construction of the SMT were met such negative geotechnical situations as

- disbalancing of the natural hydraulic system of the rock massif;
- an increase in hydrostatic pressure and water inflow into mine workings;
- escape of loose aggregate from steeply falling faults into mine workings;
- formation of cavities behind the lining;
- development and growth of sediment accumulation domes;
- collapse of the vaults of cavities behind the lining;
- drainage of parallel tectonic zones;
- inrushes and ejections of the water-soil mixture into mine workings;
- deformation of the lining;
- surface deformation (the formation of sinkholes on the surface);
- transition to the unstable state of individual blocks and dynamic manifestations of rock pressure: landslides, outfalls, bumps, caving in, deformation of supports and lining, induced seismicity and others.

This led to TBM emergency stops and lengthy restoration work. Initially, the construction period of the tunnel was determined by the project at 8 years.

The construction of the SMT intermittently lasted 28.5 years in extremely difficult mining and geological conditions, and also critical economic and political situation in the country.

The prior to the completion of the SMT, the railway communication on this section was carried out via a temporary bypass line through an avalanche-hazardous mountain pass through two loop tunnels, multiple bridges and rocky laces with slopes up to 40 ‰. After all the tunnel was opened for the train traffic on the 5th of December 2003 - 19 years later after the construction of remaining sections was completed. Therefore the SMT so called “golden link” of the BAM.

Currently, the BAM traffic flow is constantly growing, the necessity of building a backup railway tunnel - the Second Severo-Muysky Tunnel - is faced; thanks to this tunnel the throughput in this section will be increased from 16 to 100 million tons per year. The core element in the safe construction of the Second Severo-Muysky Tunnel is the assessment and forecast of natural and man-made risks at the design stage. The main method is taking into account the experience of SMT construction experience.

The risk forecast for the pre-project stage of the Second Severo-Muysky Tunnel was the process of determining the probability of occurrence of risk factors, that is, certain events and situations that could adversely affect the construction of the tunnel, as well as the process of integrated assessment of the risk level and development of risk reduction measures.

To develop an algorithm for forecasting risks according to the analysis of available materials of geological documentation on the conditions of mining of the existing Severo-Muysky Tunnel, three main criteria were identified for ranking the probability of possible risks by quantitative and qualitative parameters:

1. Rock strength and stability (by the value of the strength factor f according to Prof. M.M. Protodyakonov’s scale determined during the excavation of the mine workings of the existing tunnel);
2. Water development (by the water inflow V into the mine workings of the existing tunnel at the stage of their construction and operation);
3. Manifestations of rock pressure (by the importance and intensity of geodynamic events that took place at the time of boring of the existing tunnel).

In addition, the influence of other factors at various intervals of the structure was taken into account:

- features of the structural structure of the massif (complex block structure, saturation of the massif with differently oriented fissures up to several hundred meters thick and their water cut);
- permafrost zones;

- the impact of earthquakes of varying intensity and remoteness on the mine workings and the massif;
- the probability of inrushes of water-saturated ground masses into the mining works;
- natural radiation situation in the mine workings;
- radon emission;
- change in hydrogeological conditions during excavation;
- the impact of slope processes on the tunnel portal sites;
- climatic factors;
- mutual influence of existing mine workings and those under construction, and some other factors.

As a result, for each factor, the integral level of risk was characterized in the following sequence: “negligible”; "insiglificant"; "moderate"; "high".

For further data handling, each level was assigned a numerical value in a non-linear (reinforced) system, so that a high level was greater than the sum of moderates levels and a moderate level was greater than the sum of insignificant levels (table 1).

Table 1 Description of risks and their designations

Risk degree	Color designation	Numerical value	Risk levels
High	Red	13	High
Moderate	Yellow	4	Medium
Insignificant	Green	1	Low
Negligible	no color	0	Negligible

The resulting risk value was determined as the sum of the numerical values of all factors and was presented in the form of a graph with a projection onto the route of one of the tunnel options - the forecast risk profile (Fig. 3).

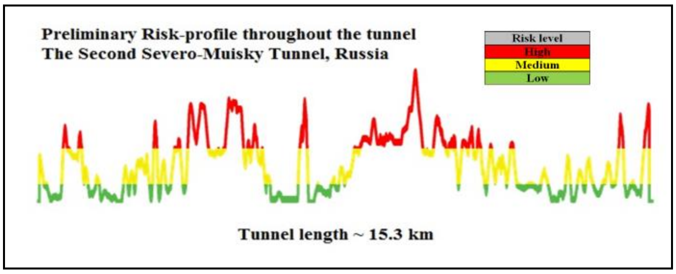

Figure 3 - Preliminary Risk-profile throughout the tunnel on the planning stage

At the final stage of the forecast, the identified zones with a high level of risk were superimposed on one of the possible routes of the new tunnel, and their shape was adjusted taking into account indirect signs and updated materials of engineering survey. In addition, the adjustment was carried out according to a qualitative assessment of the mutual influence of the totality of various hazardous processes and phenomena characteristic of the construction area. To assess the mutual influence of the totality of risks, as well as the degree and nature of their interactions for the complex of structures of the existing Severo-Muysky tunnel and the designed Second Severo-Muysky tunnel, an approach was implemented in which significant relationships between specific types of hazardous events were graphically highlighted.

As a result of the work performed, a principled approach to forecasting, controlling and reducing geotechnical risks at the construction stage of the Second Severo-Muysky Tunnel was developed. Similar approaches with appropriate specifics can be used to study, assess and predict risks in engineering survey for the design of other transport tunnels.

The goal of developing a forecast risk profile for a transport tunnel at any stage of its existence is to determine the spatial distribution of factors of natural and technological risks along the length of the structure and assess the consequences of the implementation of various kinds of hazards.

By the same principle, an integrated risk assessment can be carried out to compare the route options of the designed transport tunnel or to compare several objects of the same type among themselves. For example, Brox [Brox, 2018] proposes a unified simplified quantitative classification of risks in the construction of tunnels, designed to provide insurance companies with a means to assess the overall technical risk associated with any tunnel project. Using this simplified approach requires the selection of an appropriate risk rating from each subcategory of five key hazards for each particular tunnel. Summing up the risk ratings determines the total risk rating of the tunnel and the corresponding risk class of the tunnel, which can vary between 0 and 100 as shown in table 2.

Table 2 Tunnel Risk Classification by Brox [Brox, 2018]

Tunnel Risk Classes	Risk Levels per Classes
Highest	> 75
High	60 – 75
Moderate	45 – 60
Low	25 – 45
Lowest	< 25

As an example, Figure 2 shows the risk rating of the tunnels of the Baikal-Amur Railway (BAM) in the form of a histogram, calculated according to the above described methodology of simplified quantitative risk assessment in the construction of subsurface facilities.

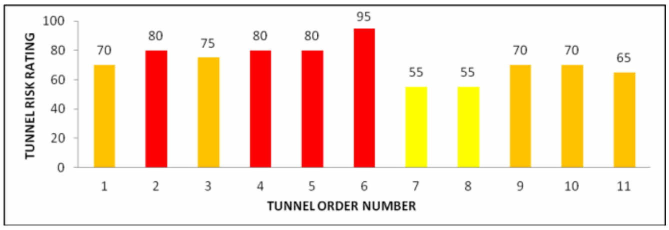

Figure 4 - Histogram of the distribution of the risk rating of the BAM tunnels according to a simplified quantitative risk assessment during the construction of underground structures [Brox, 2018]. Data for tunnels, respectively: 1 - Baikal Tunnel; 2-5 - Cape Tunnels on the coast of Lake Baikal; 6 - Severo-Muisky Tunnel; 7-8 - Tunnels bypassing the North Muya Range; 9 - Kodarsky Tunnel; 10 - Nagorny Tunnel; 11 - Dusse-Alin Tunnel

It should be noted that the SMT tunnel discussed in more detail above in Fig. 3 is represented by number 6 - its TUNNEL RISK RATING is the highest here (95).

An analysis of the results shows that the approach is rather approximate and can only be applied as a preliminary integral assessment of the entire structure as a whole, without taking into account its characteristic features. The methodology considered does not take into account many factors that are characteristic of both existing and planned BAM tunnels, such as: natural radiation conditions, the influence of permafrost and slope processes, the presence of adjacent or intersected underground workings in mountain ranges, etc.

A study by Brox [Brox, 2018] also emphasizes that, using the proposed approach to risk assessment, insurance companies, to help which the methodology was developed, must additionally conduct a thorough assessment of the relevant technical data and seek the opinion of an independent specialist in the field of tunneling to assess the current level of risk each specific project.

In fact, such measures are necessary, since rock massifs are in most cases heterogeneous, and it is impossible to assess all the risks for the tunnel as a whole at the design stage. This is one of the reasons why, at the stage of the construction of transport tunnels, it is necessary to carry out a short-term assessment of engineering and geological risks, detailing and updating the forecast of possible complications ahead of the tunnel faces and in the sections covered.

In order to control the level of geotechnical risks during the construction, commissioning, operation, reconstruction, restoration, conservation and liquidation of transport tunnels, as a part of measures to ensure tunnel safety, the NIPII Lenmetrogiprotrans JSC developed a methodology for integrated mining and environmental (geotechnical) monitoring of transport tunnels (GTM).

The GTM project for the tunnel construction phase is being developed on the basis of existing guidelines and regulatory documents. The measures envisaged by the GTM Project are aimed at fulfilling the requirements of the Laws of the Russian Federation and methodological recommendations for conducting mining and environmental (geotechnical) monitoring.

The following information is taken into account in the GTM Project:
- characteristics of the area and the construction site;
- characteristics of the main risk factors that determine the state of the environment in the tunnel construction zone prior to commencement of work based on an analysis of geotechnical survey;
- the technique adopted for the monitoring of the construction progress of the SSS of the tunnel lining under construction and existing mine workings near new construction, and the one of the soil mass containing these objects;
- methodology for monitoring the structure during operation;
- characteristics of the current state of the environment;
- the main aspects of the possible negative impact of construction on atmospheric air, soil, surface water, and the geological environment.

The GTM project also includes a plan for the deployment of the monitoring network, an engineering-geological tunnel axis, a layout of temporary buildings and structures at the tunnel construction site.

When developing the GTM Project, materials from the Tunnel Construction Work Project and survey data are used.

The main goals of the GTM during the construction of the tunnel are:
1. Reducing the harmful effects of mining on the environment (here, the environment refers to the atmosphere, surface water, geological environment, including groundwater, soil);
2. Timely identification and forecasting of the development of negative technogenic processes associated with the construction of the tunnel;
3. Safe mining operations;
4. Environmental protection;
5. Obtaining the basic characteristics of the SSS of the tunnel lining in real laying conditions for monitoring the technical condition of the structure during operation.

The main objectives of the GTM during the construction of the tunnel are:
1. Assessment of the state of the environment during mining operations;
2. Evaluation of the effectiveness of environmental protection measures;
3. Accounting for wastewater discharges into water bodies (quantitative and qualitative);
4. Forecast of the environment;
5. Assessment of the SSS of the lining being constructed and the soil mass that encloses the tunnel under construction and existing mine workings near new construction;
6. Development of recommendations to reduce the harmful effects of mining on the environment.

The tasks of the geological and technical measures during the construction of the tunnel are solved through measures to control the state of natural objects in the zone of negative influence of construction work, the SSS of the lining of the tunnel under construction, the SSS of the existing mine workings near the new construction sites and the SSS of the enclosing massif; such tasks are also solved through monitoring sources of pollution of natural objects.

Taking into account the data of the Construction Work Project and the geographical features of the area, a layout for the monitoring network is being developed as part of the GTM Project.

3. TUNNEL CONSTRUCTION

The GTM complex is an integral part of the technological process of the construction of transport tunnels. In the Russian Federation, the need for monitoring is provided for in normative and technical documentation approved by federal authorities. During the construction of transport tunnels, the GTM solves geotechnical and geoecological problems, the main purpose of which is the integrated safety of mining operations and the reduction of the negative impact on the environment.

Geotechnical problems are solved by geophysical, geomechanical and geodetic methods. Direct and indirect methods for determining controlled parameters allow:
- to predict with a sufficient accuracy the engineering and geological conditions ahead of tunnel working face;
- determine the qualitative and quantitative indicators of the SSS of the lining/massif system;
- determine the actual deformation-strength properties of the enclosing mountain massif;
- determine the deformation of the enclosing mountain massif from the contour of the tunnel to the surface;
- determine the maximum permissible concentration of pollutants in the air, water and dumps.

The obtained results of the geological and technical measures allow determining the impact of work on the activation of hazardous processes and adjust the technological parameters of mining operations, and developing recommendations for reducing the negative environmental impact.

The GTM Project work is carried out during the tunnel construction until the commissioning of the facility. Thanks to such work, the parameters of the applied supporting structures and lining, as well as the technology of their construction, are adjusted.

4. TUNNEL EXPLOITATION

During the long-term operation of transport tunnels, gradual destruction, damage and deformation caused by long-term manifestations of geotechnical and technogenic factors, as well as sudden destruction and damage to structures make it impossible to further operate the structures and require their immediate repair or reconstruction.

At the Severo-Muisky tunnel considered in the previous sections, during its construction due to removal of large volumes of loose aggregate from tectonic disjunctions within the faults above the mine workings, significant cavities filled with water and water-saturated decompression zones composed of potentially quick-moving material were formed. Such formations can extend for tens and hundreds of meters; their cementation is problematic for the reason of both their volume and the different permeability of the loose fracture filler, especially at intervals of clamping. The stability in time of a clastic aggregate of such faults at steep (up to 80-85°) angles of incidence is uncertain and, as soon as favorable conditions occur, loose material can come into motion again. Especially dangerous in this regard is the effect of strong earthquakes on rock massifs [Shabynin, 2001].

Various modes of operation of transport tunnels can also adversely affect the activation of hazardous processes and phenomena in high-risk areas. The uncontrolled development of geotechnical processes in such areas is potentially dangerous for the transport traffic and people in it. That is why a GTM set must be included in the list of works to ensure the operation of functional tunnel systems to control the level of geotechnical risks as part of an automated process control system.

An example of the successful integration of monitoring into the automated process control system is the railway and road tunnels on the Adler - Krasnaya Polyana section built between 2008 and 2013 in preparing the infrastructure for the 2014 Winter Olympics [Bezrodny, Lebedev 2014].

Considering the natural risk in course of operation these engineering structures, i.e. the seismic activity in the region, wide range of engineering-geological and hydrogeological conditions; as well as industrial risk, i.e. the occurrence of man-made accidents, the geotechnical monitoring system was developed and implemented as a part of the process and control system for the operation of transport tunnels.

Geotechnical monitoring set consists of:

1. Stress-strain state control in tunnel lining;
2. Assessing the stability of the “lining - enclosing rock mass” system by the technique based on measuring the natural electromagnetic radiation (NEMR) [Romanevich, Basov, 2018];
3. Seismic monitoring.

All test equipment installed in the linings of “Olympic” tunnels was connected to automated geotechnical monitoring system that allows controlling the SSS of lining in real time mode.

According to the data of automated geotechnical monitoring, such important tasks as:

- assessment of the performance of drainage devices;
- the appointment of a visual inspection of the lining;
- performing survey of the lining cross sections for the purpose of determining the safety margin;
- conclusion on sufficiency of the bearing capacity of the linings [Lebedev, 2019].

The information from instrumentation equipment of nine tunnels goes to the monitoring servers that are based in the railway control centres where it is to be processed, visualized and entered in the database (Fig.5).

Figure 5 - Location of a separate GTM AWS (Automated Workstation) in the control room

The most valuable in the implemented geotechnical monitoring system from the point of view of the operation is the possibility to forecast the technical conditions of the tunnel’s lining.

From the computer for processing geotechnical monitoring data to the automated workstation of the dispatcher of the automated process control system, a continuous flow of information on each of the tunnels is supplied through the geotechnical monitoring line and sent to the dispatcher console.

An example of the dispatcher AWS interface for one of the control stations in the section of the tunnel, for one of the monitoring subsystems (SSS) is shown in Fig. 6.

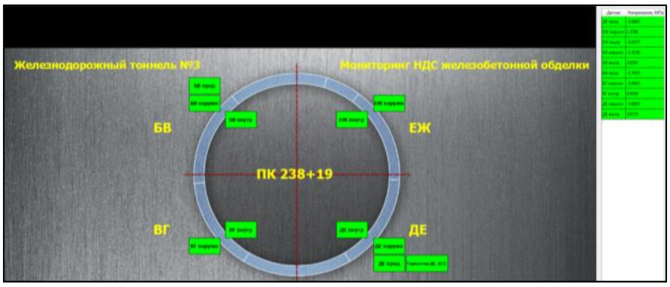

Figure 6 - An example of the dispatcher AWS interface for one of the tunnels for the Stress-strain State (SSS) monitoring subsystem

As a result, the characterization of the state of a massif by controlled parameters in the places of installation of the sensors is evaluated and displayed using a color board (green, yellow or red) depending on the degree of geodynamic activity of the massif.

For each hazard category, a tunnel service regulation has been developed. Hazard categories and tunnel service regulations are shown in Table 3.

Table 3 Hazard categories and tunnel service regulations

Hazard category	**Color designation**	**Tunnel Service Regulations**	**Actions to reduce the risk**
Category 1	Red	*In emergency mode.* Notification of all services. Comprehensive data analysis of all monitoring methods. Visual and instrumental inspection of the tunnel section. If necessary, based on the survey results, additional monitoring systems are installed or the necessary strengthening works are carried out (soil consolidation and waterproofing (pumping), tunnel structure strengthening, etc.)	The risk should be reduced at least to a yellow level regardless of the cost of work
Category 2	Yellow	*In the scheduled mode.* Comprehensive data analysis of all monitoring methods. Visual Inspection of the tunnel section. The survey results are transmitted to the design organization	Measures must be taken to reduce the risk until their cost exceeds the risk damage
Category 3	Green	No action is taken, monitoring continues	No risk reduction is required

Such information, with its operational preliminary processing according to the shown scheme, is sent to the dispatcher console on dozens of sections of each tunnel on the 48-kilometer long route.

This kind of monitoring system is the most extensive project in the Russian Federation and has indisputable advantages over the existing instructions and methodological recommendations for assessing the technical conditions of the transport tunnels in the country [Lebedev et.al, 2019].

5. CONCLUSION

At all stages of the transport tunnel existence the mining and environmental (geotechnical) monitoring (GTM) system should be deemed an absolutely necessary element of accident prevention, forecasting the technical condition of structures and safe operation.

Risk level control with the help of a well-functioning GTM system allows to pre-planning measures to recover and eliminating the consequences of accidents at any stage of the tunnel lifetime.

The GTM system is a source of new geotechnical information on the operation of lining and rock massifs. The obtained results of the geological and technical measures allow us to determine the impact of excavation on the activation of hazardous processes and adjust the technological parameters of mining operations, to develop recommendations for reducing the negative impact on the environment. Using the data from the GTM system, the parameters of the applied support structures and lining, as well as the technology of their construction, are adjusted.

During the operation of the tunnel, the on-line automated system of geological and technical measures provides operational services with the information necessary and sufficient to determine the influence of the operating mode and climatic anomalies on the activation of dangerous geodynamic processes in order to select the safest technological operating modes, assign visual and instrumental examinations, as well as strengthening events.

During the revision of monitoring systems in controlled facilities, a search is made for new risk factors that, with appropriate justification, can be included in the control scheme by the GTM system.

In the design and implementation of GTM in transport tunnels, a risk-based approach is used when, for the best use of labor, material and financial resources, cost reduction and increase of the efficiency of control, the focus is made on the most dangerous (previously identified) processes in the most potentially dangerous tunnel intervals (for example, in zones of tectonic dislocations).

A large amount of geotechnical data obtained from GTM system can be further used to develop unified approaches to monitoring and forecasting the level of risk using digital geomechanics tools, mathematical modelling of natural and technogenic processes, and deep learning techniques based on neural networks. Automated GTM systems can be included in algorithms for assessing the technical condition of underground structures using BIM technology.

In any case, the initial information is the one provided by on-site studies of the stress-strain state of structures and enclosing massifs as part of the integrated geological and technical measures, which is a physical tool for assessing, monitoring and predicting the level of geotechnical risks in the most potentially dangerous intervals of a structure.

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