IOP Conference Series: Earth and Environmental Science

PAPER • **OPEN ACCESS**

Forecasting the risks of underground roadway stability loss based on mine research data

To cite this article: Olena Slashchova *et al* 2024 *IOP Conf. Ser.: Earth Environ. Sci.* **1348** 012057

IOP Conf. Series: Earth and Environmental Science **1348** (2024) 012057 doi:10.1088/1755-1315/1348/1/012057

Forecasting the risks of underground roadway stability loss based on mine research data

Olena Slashchova[1,5], Olha Kohtieva[2], Serhii Rahimov[3] and Vitalii Kharchenko[4]

[1]The M.S. Poliakov Institute of Geotechnical Mechanics of the National Academy of Sciences of Ukraine, 49005, Dnipro, Simferopolska St., 2a, Ukraine
[2]State Higher Educational Establishment "Ukrainian State University of Chemical Technology", 49005, Dnipro, Gagarin Ave., 8, Ukraine
[3]National University of Civil Defence of Ukraine, 61023, Chernyshevska St., 94, Kharkiv, Ukraine
[4]Dnipropetrovsk State Research Expert Forensic Center of the Ministry of Internal Affairs of Ukraine, 49033, Dnipro, Construction Dead End St., 1, Ukraine

[5]Corresponding author: gtmigtm@gmail.com

Abstract. The article presents results of the research on forecasting the risks of underground roadway stability loss based on the results of mine monitoring. The method is used for safety control in the process of conducting mining operations and re-exploitation of roadways as industrial facilities. The risk assessment was carried out with allowance for spread of physical and mechanical parameters of rocks; this approach is confirmed by procession of data of more than 1000 experiments. Mining-and-technical factors and their negative impact on the rock destruction were identified and systematized. The structure of risk control in a geotechnical system "rock massif - roadway" was substantiated. The method for forecasting the risks of underground roadway destruction based on the results of the mine research was further developed. The method differs from the well-known ones by taking into account the dominant influencing factors, variations of values and standard deviations of the forecasted risks of roadway functionality loss and criteria for violation of its technological air gaps at a certain point in time. This makes it possible to assess the degree of danger of mine roadway stability loss and to undertake response measures more reasonably.

1. Introduction

Forecasting and assessing the risks of mine roadway stability loss are necessary to control safety during mining operations and are relevant for re-use of underground structures, for example, as industrial and defense facilities. Underground roadway stability loss is associated with the risks of more intensive rock pressure manifestations and destruction of supporting means due to the negative influence of the combined effect of the factors [1]. In particular, the risks of increasing static or dynamic stresses in a rock massif are caused by rheological processes, watering of rocks, sudden separation of the immediate roof and settlement of the main roof in the roadways, underground and surface explosions, etc.

The probable risks that may lead to a decreased stability of the rock massif and geotechnical system as a whole also depend on a number of interrelated factors. These factors can be dominant or insignificant, but they all affect the safety of the roadway and can be divided into two large groups. Mining-and-geological factors are most often uncontrollable and difficult to monitor. Mining-and-technical factors influencing the destruction of rocks, on the contrary, in most cases are controllable.

This requires a systematic approach to the analysis and forecast of risks with taking into account the dominant factors influencing the efficiency and safety of the mining technologies used.

The use of risk control technologies at mining enterprises is hampered by insufficient development of systems for automatic monitoring and control of mining processes [2]. The imperfection of the methods for analyzing and assessing risks caused by hazardous factors arising in the production environment has a negative impact [3]. Algorithms for determining the stress-strain states of the rock massifs require further development [4-6]. The entire complex of risk control methods should be the basis for the development of promising automated mine safety systems.

Information about the state of the roadway support and rocks can be obtained by using mine monitoring methods for assessing parameters, which determine the mine roadway stability. In practice, a large number of full-scale measurement methods are used. To monitor the state of the “support-rock massif” system, one or several parameters are chosen. The objects under the control are the cracks and layer separations in the rock massif and displacements of the roadway roof, soil and walls.

Thus, the analysis of risk control methods in the process of mine roadway deformation showed the need to improve existing and develop new methods for forecasting the risks of underground structures stability loss for the entire period of their operation.

The purpose of the research is to improve method for forecasting the risks of underground roadway stability loss taking into account peculiarities of dominant factors influencing on geotechnical system based on the results of mine monitoring to control safety during mining operations and during the re-use of roadways as industrial facilities.

2. Methods

Mine studies of the roadway contour deformation parameters; generalization and analysis of experimental data; systematization of factors and consequences affecting the risks of underground roadway stability loss; risk assessment based on mine monitoring of rock pressure manifestations.

3. Results and discussion

3.1. Risk factors and consequences of their negative impact on the underground roadway stability

Deformations of supports and rocks around the roadway affect the risks of stability loss of the geotechnical system “rock massif - roadway” which are determined by a complex of groups of negative uncontrollable and controllable factors. Uncontrollable factors are primarily associated with physical and mechanical properties of rock massif, tectonic structure and complex stress state, which have existed before the roadway drivage and have a significant effect on the nature of the impact of development and winning operations (figure 1). Therefore, it is necessary to identify them as it allows undertaking timely measures even at the stage of the mine designing and reducing damage from rock pressure manifestations. Mining-and-technical factors can also be determined in advance, and negative manifestations of rock pressure can be prevented through the use of technically sound production technologies or preventive actions undertaken by personnel (figure 2).

As a result of the research, the consequences of negative influence of the factors contributing to the destruction of rocks were identified and systematized. One of the main mining-and-geological factors is tectonic disturbances and fracturing of rocks. Increased fracturing of the rock massif reduces its strength and increases its permeability for gas and water. This leads to risks of flooding, high gas contamination and loss of underground roadway stability due to the rock collapses and falls.

The negative impact of activation of gas-dynamic processes (in the presence of gas-saturated rocks) on the roadway is presented in the form of two main factors. The first factor is associated with the presence of systems of cracks and increased permeability of rocks on the way of gas filtering into the roadways. Fractured rocks have 2-3 times higher permeability, so, a great volume of gases is filtered through them. Conditions are created for gas pollution and sudden manifestations of rock pressure.

The second factor is directly related to the increase of gas pressure in the rocks, which increases stress and risk of destruction of gas-saturated rocks. The occurrence of this risk factor is associated with the limitation or impossibility of gas release to the surface or to mine roadway, as well as with the

IOP Conf. Series: Earth and Environmental Science **1348** (2024) 012057 doi:10.1088/1755-1315/1348/1/012057

emergence of possibility of gas draining through the man-made main cracks into underground roadways.

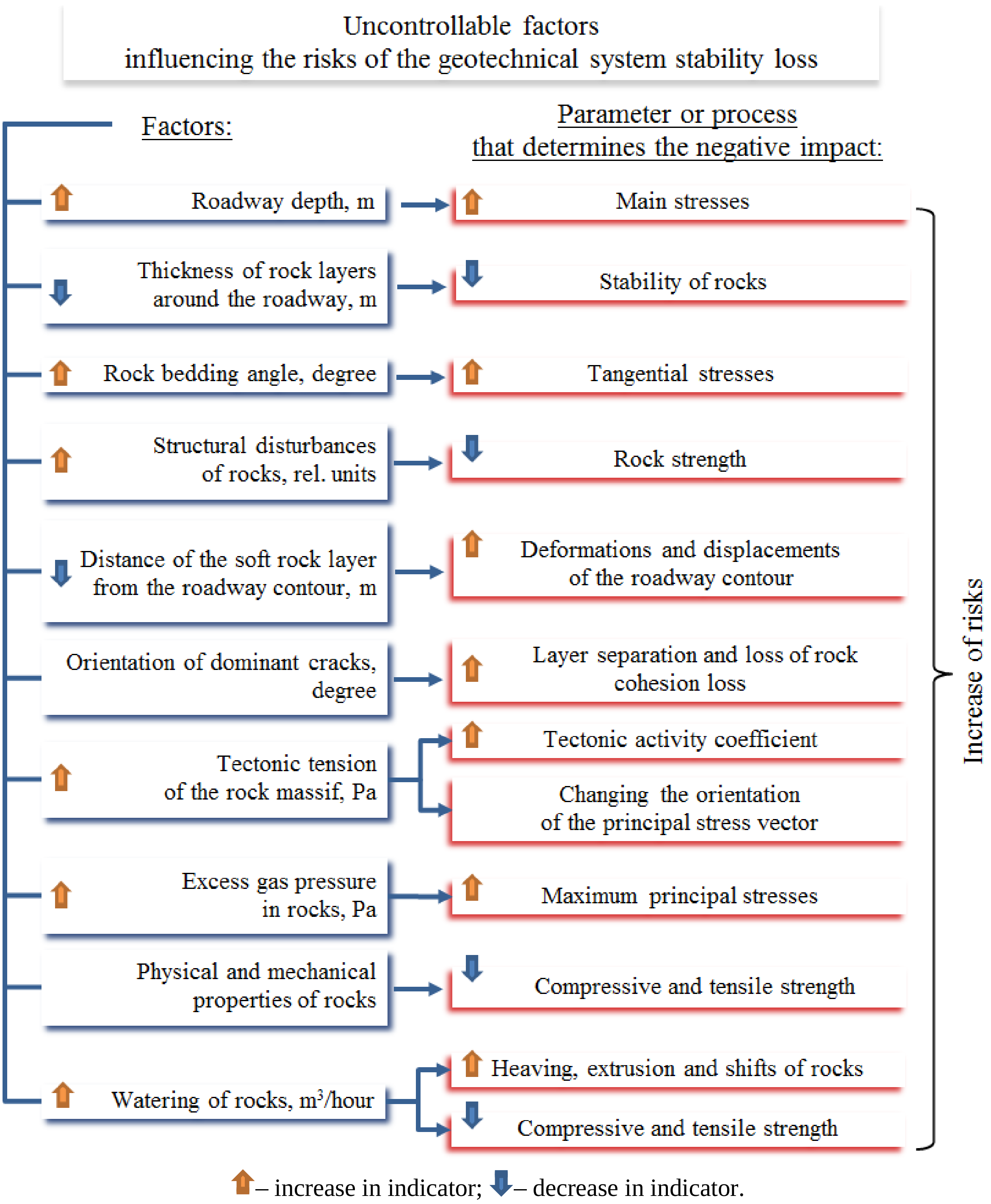

Figure 1. Systematization of uncontrollable factors and the consequences of their negative impact on the stability of underground roadways.

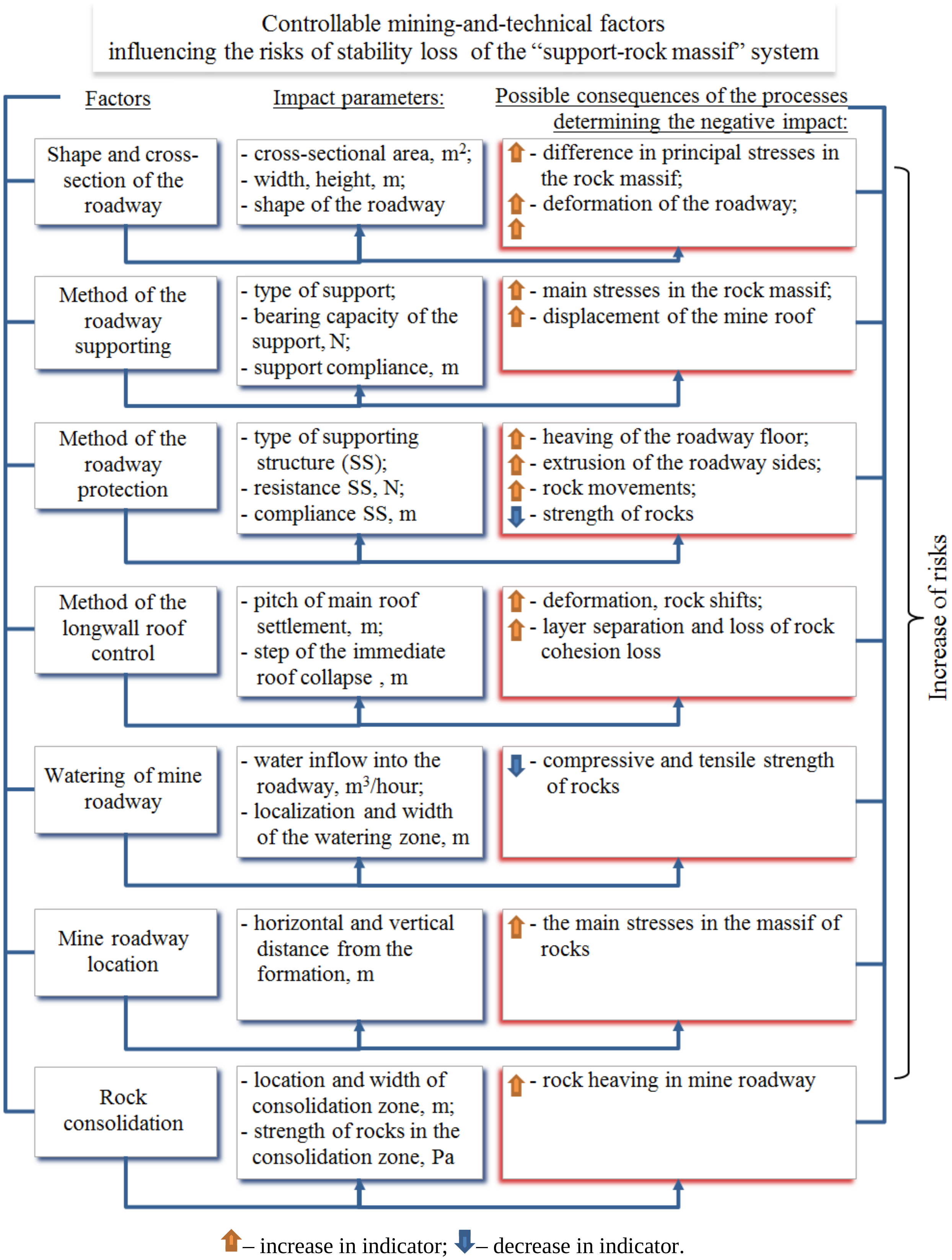

Figure 2. Controllable factors and the consequences of their negative impact on the stability of underground roadways.

An increase of the risk of mine roadway stability loss can be caused by manifestations of tectonic stresses, which, as a rule, activate destruction of the rocks. The most significant parameters of tectonic stress fields should be considered the orientation of the vector and the intensity of the maximum principal stresses. That is, the factor of influence of tectonic stresses, if any, has a significant impact on the risks of the geotechnical system stability loss.

The spread of physical and mechanical properties increases the risk of the mine roadway stability loss because low strength of rocks contributes to formation of zones with abnormally high deformations, increased fracturing and significant water inflows. These processes activate the destruction of supports, displacement of rocks and heaving of the roadway floor. Commonly, the cause of abnormal manifestations of rock pressure is watering of the rock massif, which is one of the main uncontrollable factors and which negatively affects many processes. Stresses around the roadway reach extreme values, rheological effects occur, which, in total, lead to great loads on supports and cause its deformation and displacement of rocks into the mine roadways. Laboratory tests shown that increasing moisture content in the mudstone samples of the same sample by 2...3% (which corresponds to 70-85% of the water saturation level) reduces compressive strength by half. Wetting of sandstones in most cases is insignificant.

Among the mining-and-technical factors, the following should be singled out: cross-sectional areas of the worked-out spaces and mine roadways formed during coal mining; methods of roof control in longwall faces; step of immediate roof collapse and main roof settlement; location of unloading and associated roadways; force and deformation characteristics of support systems and protection of the mine roadways.

Unlike the conventional control process, the risk-oriented control process necessarily includes the sequential implementation of the following actions (figure 3): determination of geological parameters of the roadway location; determination of conditions and methods for the object supporting and lining; monitoring of the state of underground roadways and rocks; identifying of causes of possible danger; forecasting of processes and consequences; comparison of manifestations of the rock pressure in the underground roadway using a set of already installed supports with criteria of the object stability; comparison of stresses and deformations of rocks around the roadway with strength criteria; assessment of consequences of destruction and risks; reduction of risks through undertaking the appropriate measures.

3.2. Determination of the risk of underground roadway stability loss based on mine monitoring of roof displacements

Loss of underground roadway stability occurs when displacement of the rock contour exceeds technological gaps determined by dimensions of the mine transports, safe passage of people, etc. In most cases, compliance of underground roadway support is 300 mm, and compliance of technological gap is 600 mm. Displacements of the roadway contour by more than 300-600 mm lead to bending of the support elements, and by more than 900 mm - to the violation of technological gaps and loss of the roadway stability (figure 4). Therefore, to assess stability of underground roadways, the value of displacements should be differentiated into three characteristic modes, which correspond to the following displacements: 0-300 mm (the supports are operating in normal mode), 300-600 mm (the joint connections are broken with bending of the support bars), 600-900 mm and more than 900 mm (technological gaps are broken, roadway stability is lost).

The research established that a significant spread of the rock properties is a consequence of their great heterogeneity, and, to a lesser extent, errors of various research methods and equipment [7, 8]. The spread of parameters is explained by the fact that among the weak sandstones, mudstones and siltstones there are usually layers of strong rocks of the same lithological types. The results clearly show that to determine stability of underground structures and assess the risks of their destruction, it is necessary to use standard deviations and coefficients of variation of parameters of the rock physical and mechanical properties and displacements of the roadway contour.

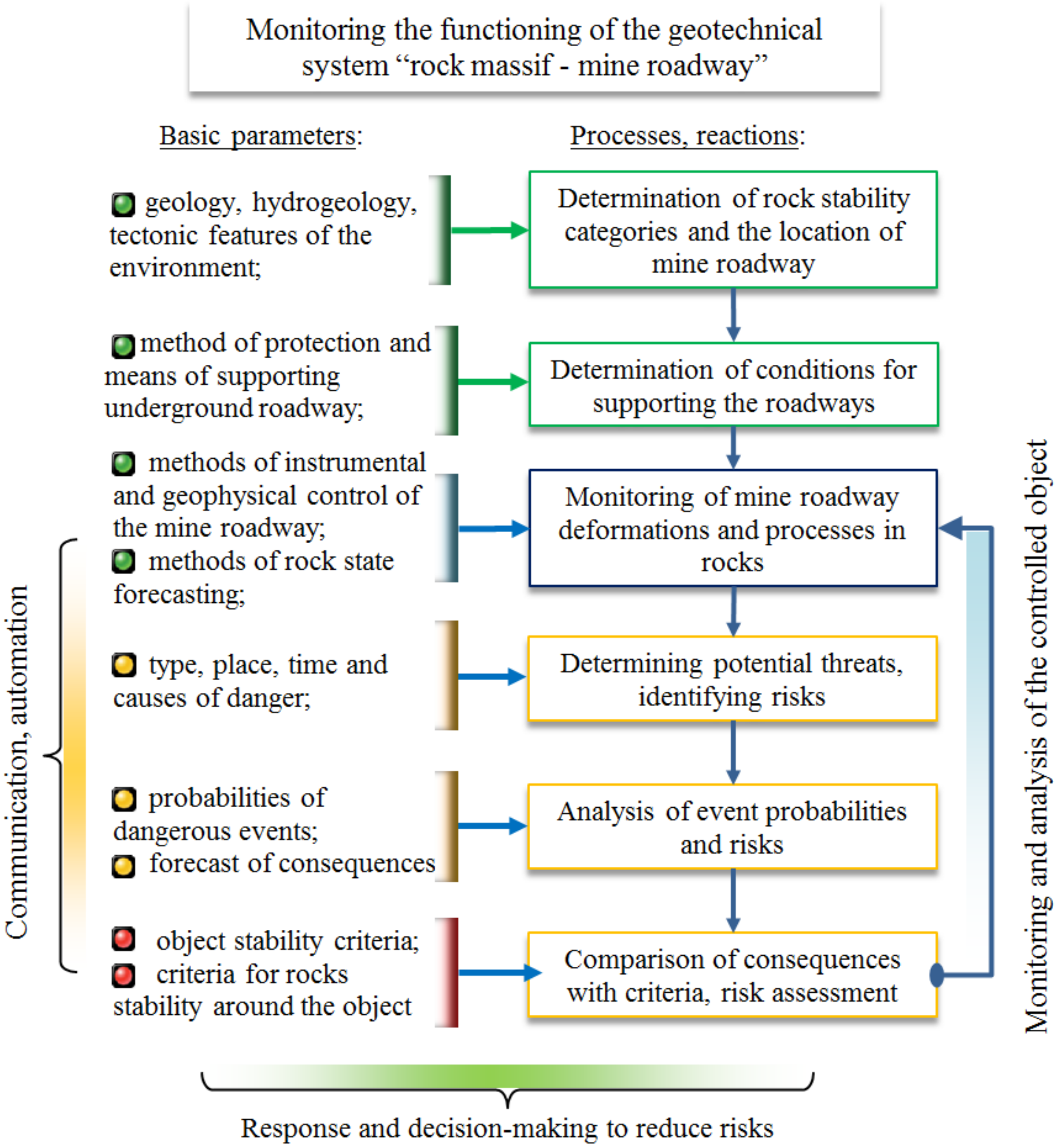

Figure 3. Risk control process for monitoring the stability of underground roadways and timely response to potential threats.

It is determined that coefficients of variation in the strength of the drained rocks are 27-29% for mudstones and siltstones, and 18-20% for limestones and sandstones. An increase of the clay fraction content contributes to a decrease in rocks strength when they are flooded and spread of strength parameters (an increase in the coefficient of variation, figure 5). When the rocks are watered, they have a greater spread of average values of the coefficients of variation than in the dry state. For mudstones and siltstones, the change of this indicator is ~50-60%, and for sandstones and limestones it is ~40-50%. That is, with water saturation, an increase of rock strength spread by 60% to the spread of the rock strength in dry state can be observed. Taking into account the coefficients of variation makes it possible to determine the risks of occurrence of rock mass dangerous states at critical parameters (minimum strengths) in dry and water-saturated states. The method for determining the range of risks associated with the coefficients of variation in the rock strength is novel and has practical value for assessing stability and improving operational safety of the roadways.

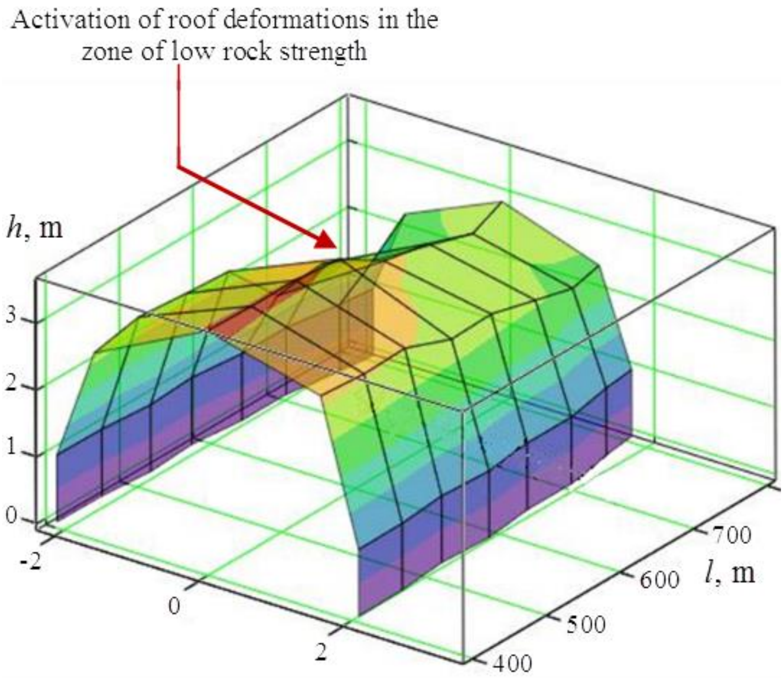

Figure 4. Uneven deformation of the mine roadways according to field observations (“Yuvileina” Mine).

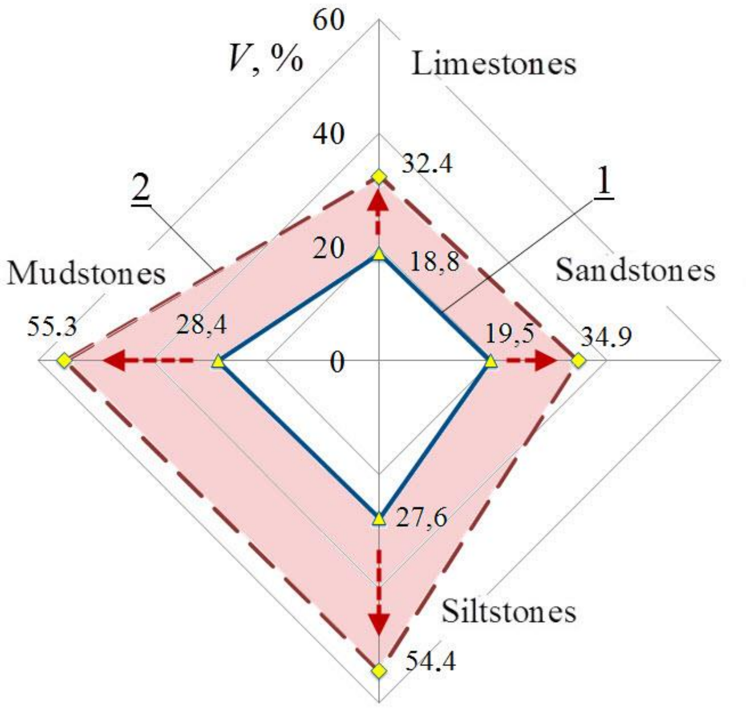

Figure 5. Variability of rock strength variation coefficients (V): 1 – variations in dry strength; 2 – variations in strength in a water-saturated state.

It is proposed to determine the risks of roadway stability loss based on the field measurement data (displacement values) received during the roadway monitoring. The risk in which a dangerous situation arises (a probability of unfavorable development of events) is determined by the sum of risks caused by dominant factors affecting the stability of underground roadways [9]:

$$R(E^t) = k_1^t R(E_1^t) + \ldots + k_m^t R(E_m^t), \quad (1)$$

where $R(E^t)$ is the total risk; $R(E_m^t)$ is the risk arising from the influence of factor E_m^t at time t, rel. units; $k_1^t, \ldots, k_m^t$ – coefficients of influence of individual factors on the risk.

The ranges of parameter values changing are determined by methods of fuzzy logic and expert assessment. Next, the data is processed, and a decision is made to reduce the risks. It should be noted that to solve mining-and-technical problems and to assess the risks of roadway stability and safety loss, the fuzzy logic method was first used in the works of scientists [1, 9].

To test the proposed method for determining risks, data of monitoring the eastern main drift No. 2 of the 370 m horizon of the “Heroes of the Cosmos” Mine were used [10]. Figure 6 shows a graph of parameters and their deviations from the parameters of the linear model of capital roadway deformation. The figure (item 3, figure 6) shows a linear model in zone of steady displacements:

$$u = 0.15\,t + 77 \quad \text{, mm.} \tag{2}$$

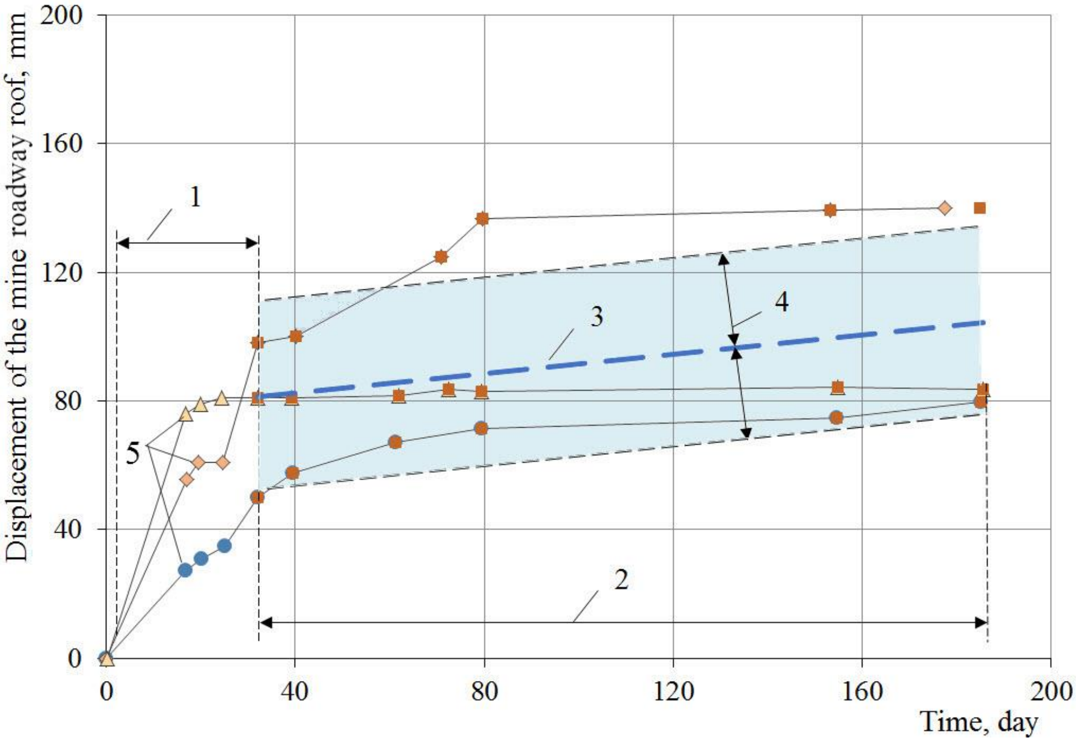

Figure 6. Determination of parameters and deviations of the parameters of the linear model of deformation of capital underground roadway: 1 – zone of active displacements; 2 – zone of steady displacements; 3 – linear model in the zone of steady displacements (average of three measuring stations); 4 – standard deviation from the average value; 5 – roof displacement measurement points.

The zones of permissible deviations are shown in the time range when the deformations of the roadways transfer from the period of active displacements to steady displacements. The intensity of displacements has different values over time, which depends on many mining-and-technical and geological factors, supporting method and other components, which are quite difficult to fully take into account. To determine the forecasted values, actual monitoring data on the roadway and parameter variations in these measurements are used, which makes it possible to take into account spread of physical and mechanical properties of rocks along the length of the roadway (item 4, figure 6). For capital underground roadways, their forecasted life of operating as a warehouse without any repairs can be about 10 years. Linear risk model (figure 7) is:

$$R(u) = 0.0003\,t + 0.128\text{, mm.} \tag{3}$$

Operation life of underground preparatory roadways is shorter, less than 1…3 years. A forecast of the risk of destruction due to the loss of underground preparatory roadway stability was carried out based on the results of the field studies of roof displacements and trends obtained by approximating field experiments (figure 8). The dependences of changes in the risks of destruction of underground roadways under the influence of dynamic rock pressure when using standard and reinforced supporting were determined. The level of hazard risk (item 3, figure 8) is determined by the maximum values of deformation of the support props, after which they are destructed.

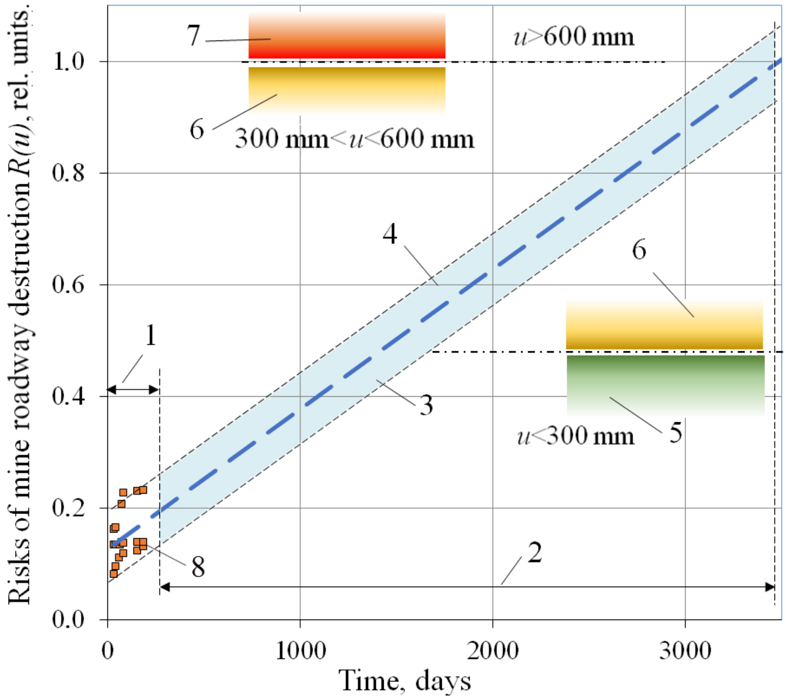

Figure 7. Risks assessment of underground capital roadway destruction: 1 – period of field measurements; 2 – forecast period; 3, 4 – zones of minimum and maximum risks (variation of parameters): 5 – supports operating in normal mode; 6 – violation of connections with bending of the support bars; 7 – violation of technological gaps, roadway stability loss; 8 – roof displacement measurement points.

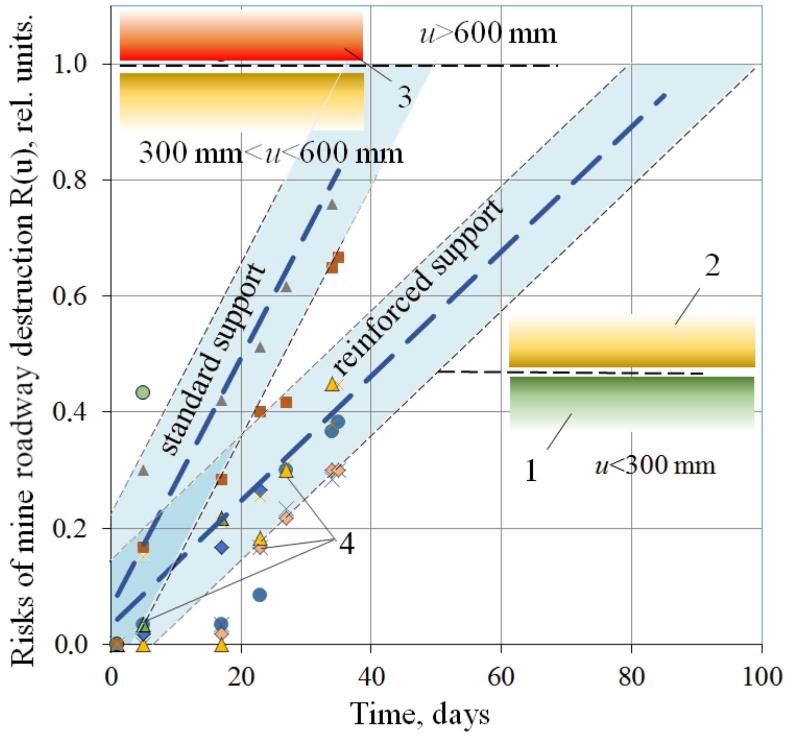

Figure 8. Forecast of the destruction risks of underground preparatory roadway based on the results of field studies when using standard and reinforced support (under the influence of dynamic loads): 1 – supports operating in normal mode; 2 – violation of connections and bending of the upper supports; 3 – violation of technological gaps, roadway stability loss; 4 – roof displacement measurement points.

The graphs show standard deviations which limit the area of parameters spread. This is due to changes in physical and mechanical properties of the rocks around the roadway, which leads to changing of risk parameters. It is necessary to take into account the peculiarities of changes in the strength parameters of rocks with allowance for the coefficient of variation for the corresponding conditions. Then the risk value will correspond to the range of values.

Based on the results of statistical analysis of the measurement data on displacements of the underground roadway roof, regression dependencies of risks $R(u)$ of the roadway stability loss in time t were established with taking into account the supports with exceeded rated compliance:

$$R(u) = 0.023\,t + 0.065; \quad R^2 = 0.95 \text{ , mm.} \tag{4}$$

$$R(u) = 0.011\,t + 0.033; \quad R^2 = 0.95 \text{ , mm.} \tag{5}$$

For supports used in these conditions, the risks of loss of the “support-rock massif” system stability reach dangerous levels in the period after 300...340 days under negative and positive scenarios (according to the research results), which requires undertaking preventive measures to reinforce the support. In event of scenario when the roadway is exposed to external dynamic pressures, the danger zone occurs on the 40th day with standard support, and on the 85th day with reinforced support (see figure 8).

Monitoring of underground preparatory roadways should be carried out not less than every three months. In this case, monitoring of the selected object should be supported by reverse analysis. This means that the roadway requires periodic monitoring (for example, every six months in case of long-term use) with subsequent analysis of the results, revision of stability parameters and re-identification of risks.

To summarize, determining the parameters of the input data begins with a study of geological conditions in which an underground roadway works. To analyze the data, parameters of geology, hydrogeology and dominant factors influencing the destruction of the rock massif are determined.

At the next stage, the underground environment and processes are monitored. Geomechanical, hydrogeological, gas-dynamic and other characteristics of the state of the geotechnical system are determined. The forecast of the main geomechanical parameters is made based on the results of mine observations. Possible options for intensification of mine roadway deformations are determined based on the results of the corresponding trends (additional parameters can be determined by calculating the stress-strain state of the rock massif using analytical methods).

When comparing the results of geomechanical processes with the criteria for the reliability and stability of the system elements, an assessment of probable risks is performed. In this case, the values of corresponding parameters of formula (1) obtained by mine monitoring methods are used. The final stage is to process the data and make a decision to reduce the risks.

4. Conclusions

As a result of the research, consequences of the negative influence of mining-and-technical factors, which contribute to the destruction of rocks, were identified and systematized. These factors, in most cases, are controllable; they can be taken into account in advance, and negative manifestations of rock pressure can be prevented. The structure of risk control in the geotechnical system “rock massif - roadway” is substantiated which includes the sequential performance of risk identification, analysis, assessment and procession. The principles and basic input parameters, which are universal for different levels of risk control, are determined.

The method for forecasting risks of underground roadway destruction based on the results of mine monitoring was further developed, which is distinguished by taking into account: the dominant factors affecting the roadways stability, variations in the values and standard deviations of the forecasted risks, as well as criteria for violation of technological gaps and loss of the roadway functionality at a certain point in time. This makes it possible to assess the level of danger of the roadway stability loss based on the minimum and maximum risk indicators and to undertake the response measures more reasonably.

The method for determining the range of risks associated with the coefficients of variation in the rock strength is novel and has practical value for assessing stability and improving the operational safety of mine roadways. The research results were used in the "Methodological recommendations for identifying risks and assessing the danger of stability loss of the underground roadways intended for deployment of industrial and defense structures".

Acknowledgments
The authors express their gratitude to Mr. O. Krukovskyi, the Deputy Director of the IGTM of the NASU, Corresponding Member of the NASU, for providing informational support for the research.

References
[1] Slashchova O, Yalanskyi O, Slashchov I, Kurinnyi V and Kulbach A 2023 Fuzzy logic methods for risk management at mining enterprises *IOP Conf. Ser.: Earth Environ. Sci.* **1156**(1) 012015 https://doi.org/10.1088/1755-1315/1156/1/012015
[2] Slashchov I, Slashchov A, Siromaschenko I, Kurinnyi V and Ikonnikov M 2020 Development of digital technologies for the systems of remote mining safety monitoring *E3S Web of Conferences* **168** 00065 https://doi.org/10.1051/e3sconf/202016800065
[3] Slashchov I, Bielikov A, Kulbach A and Slashchova O 2023 Forecast of the mine workings destruction risks by the radiometric control method *IOP Conf. Ser.: Earth Environ. Sci.* **1156**(1) 012033 https://doi.org/10.1088/1755-1315/1156/1/012033
[4] Chun-Liang Zhang 2016 The stress strain permeability behaviour of clay rock during damage and recompaction. *Journal of Rock Mechanics and Geotechnical Engineering* **8**(1) 16-26 https://doi.org/10.1016/j.jrmge.2015.10.001
[5] Slashchov I 2019 Estimation of fracture systems parameters in rock massif by the finite element method *E3S Web of Conferences* **109** 00094 https://doi.org/10.1051/e3sconf/201910900094
[6] Slashchov A, Yalanskyi O., Slashchov I and Siromaschenko I 2022 Development of methods and software algorithms for state forecast of the ultimate stressed rock massif *IOP Conf. Ser.: Earth Environ. Sci.* **970** 012010 https://doi.org/10.1088/1755-1315/970/1/012010
[7] Palamarchuk T, Prokhorets L, Bobro M and Trypolskyi V 2019 Features and regularity of zonal changes in the physicomechanical characteristics of Zakhidnyi Donbas rocks *E3S Web of Conferences* **109** 00068 https://doi.org/10.1051/e3sconf/201910900068
[8] Skipochka S, Palamarchuk T, Sergienko V and Prokhorets L 2014 Rapid assessment of the rock strength in solid by the shock pulse method *Metallurgical and Mining Industry* **5**(2) 50-55
[9] Slashchov A, Slashchov I, Osinnya N and Konstantynova I 2019 The hierarchical model of fuzzy logic output formalization for digital systems evaluating mine workings stability *Geoteh. meh.* **149** 122-131 https://doi.org/10.15407/geotm2019.149.122
[10] Stovpnyk SM 2021 Development of the foundations of destructive deformation of near-contour rocks of a weakly metamorphosed massif under the action of geotechnical disturbances Doctor of Technical Sciences dissertation (Specialty 05.15.09 – Geotechnical and Mining Mechanics) NTUU "Igor Sikorsky Kyiv Polytechnic Institute" Kyiv 323