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Probabilistic analysis application to substantiate support parameters in seismically active and fractured rock masses

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Abstract

Purpose. The research aims to substantiate support parameters for underground mine workings in the conditions of fractured and seismically active masses using probabilistic stability analysis.

Methods. The research is based on the integration of field engineering-geological observations, geological-structural analysis, numerical modeling and probabilistic stability assessment methods. Based on the geotechnical description of oriented cores, the mass fracturing parameters (RQD, J_n, J_r, J_a) were determined, stereographic analysis using Dips software was performed and the mass quality index Q' was calculated. Probabilistic stability analysis of wedges was conducted in the Unwedge software package, taking into account dynamic effects and seismicity coefficients up to 0.4. Scenarios without support, with roof-bolt and combined supports are discussed.

Findings. It has been found that at unfavorable mine working orientation and high seismic loads, the factor of safety (FS) does not reach the design values (FS ≥ 1.5) without the use of support, which necessitates the use of combined support schemes.

Originality. The novelty is in the complex application of probabilistic stability analysis taking into account real geometric and mechanical characteristics of fracturing, seismic impact and spatial anisotropy of the mass. For the first time, field data, Q' index and Unwedge modeling have been combined for specific engineering-geological conditions to substantiate the parameters of a combined support adapted to seismically active fractured masses.

Practical implications. The developed methodology can be adapted to various mining-technical conditions and helps to increase the reliability of design solutions for construction and operation of underground structures in difficult geological and seismically active areas.

Keywords: *fracturing, underground mine workings, support, probabilistic analysis, seismic activity, numerical modeling*

1. Introduction

Mining of mineral deposits requires the most accurate and timely assessment of the rock mass where mining operations will be conducted. The influence of rock fracturing on underground mine working support and further mining can be significant. To predict and analyze the geomechanical state of underground mine workings and the stability parameters of supports, various modeling methods are used, taking into account the structural peculiarities of rocks in the zone of stope space influence [1]-[4].

The designing of support parameters for underground mine workings is traditionally based on deterministic analysis methods, assuming fixed values of geomechanical characteristics of the mass and support elements. However, in real conditions such parameters as rock strength, stress-strain state and properties of supporting elements have significant variability and spatial heterogeneity, which can significantly reduce the reliability of design solutions [5].

In [6], the limitations of deterministic analysis, when designing underground mine workings using the sequential equilibrium method, are discussed. The author emphasizes that due to the uncertainty of mining-geological conditions, the deterministic approach may be less adaptive and reliable, which increases the risks of failure. Other papers suggest the use of probabilistic methods to make more informed decisions [7], [8].

The main difference between deterministic and probabilistic analysis is that deterministic analysis works with fixed data, assuming that all parameters are known exactly and do not change, while probabilistic analysis takes into account uncertainties and data variability by modeling different possible outcomes [9].

Over the last two decades, the application of probabilistic approaches in engineering geomechanics has been actively developed in the world practice. Griffiths and Fenton [10] emphasize that deterministic methods can significantly underestimate failure risks, especially under conditions of spatial variability of rock strength properties [11]. Similar findings are confirmed by more recent studies [12], [13], which emphasize the need to take into account the source data variability.

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Mazraehli and Zare [14] developed a probabilistic model for assessing loads on supports, taking into account the uncertainty of post-peak strength parameters. The research shows that integrating probabilistic models into calculations significantly improves prediction accuracy and allows for the optimization of support parameters.

Special attention is also paid to the influence of stressed state anisotropy on the stability of mine workings. Chen et al. [15] examines the behavior of mine workings in conditions of a non-uniform stress field using a probabilistic approach. The authors indicate that ignoring these factors can lead to serious engineering errors [16].

Research conducted in [17] demonstrates the effectiveness of using global sensitivity analysis to identify the greatest influence of individual parameters on the stability analysis result. This approach makes it possible to focus on the most significant factors of uncertainty and thus improve the overall reliability of design solutions.

Rock fracturing has a particular impact on the stability of underground mine workings. Studies show that the azimuth and dip angle of joints significantly influence the mechanical properties of the rock mass, leading to a decrease in strength and a change in the nature of failure. For example, as the dip angle of the joints increases, a transition from bending failure to shear failure is observed, which requires appropriate adjustment of the support parameters [18].

In addition, the direction of the tunneling azimuth relative to the joint orientation also plays a key role in the stability of the mine workings. Studies show that with an unfavorable mine working orientation relative to the mass fracturing, there are increased deformations and risks of failure [19]. This highlights the need to take into account geometric peculiarities and fracturing properties when designing and selecting appropriate support parameters.

In seismically active regions, an additional factor influencing the stability of underground mine workings is the seismicity coefficient. Dynamic loads caused by earthquakes, as well as the seismic impact of previously mined stope areas, can cause significant deformation and damage to the support, especially in conditions of fractured rocks. Studies show that an increase in the seismicity coefficient leads to a decrease in the stability of mine workings and requires strengthening of the support [20].

In conditions of high uncertainty associated with the variability of geological conditions and dynamic loads, the use of probabilistic analysis methods is becoming increasingly relevant. Approaches such as the Monte Carlo method or Latin Hypercube Sampling (LHS) method allow for the statistical distribution of input parameters to be taken into account, providing a more realistic assessment of stability and optimization of design solutions [21]-[23].

Probabilistic analysis, as a modern tool for assessing risks and uncertainties, allows for a wide range of factors affecting the support stability to be taken into account. This approach provides the opportunity to model various scenarios, which contributes to a deeper understanding of the physical processes occurring in rock masses and allows for the informed selection of support parameters [24].

The Latin Hypercube Sampling (LHS) method was developed in 1979 by engineer and researcher McKay, M.D., together with colleagues. The authors compare the classical Monte Carlo method with the LHS method. The results of the research show that the LHS method provides more accurate and stable estimates compared to the Monte Carlo method, improving the efficiency of modeling complex systems [25].

In their fundamental work, Helton and Davis [26] consider the application of the Latin Hypercube Sampling (LHS) method to assess and propagate uncertainty in modeling of complex engineering systems. The authors demonstrate that LHS provides a more efficient and uniform coverage of the input parameter space compared to the traditional Monte Carlo method, especially for high-dimensional problems. The main focus is on comparing different sampling techniques, the influence of problem dimensionality, correlated variables, and the sensitivity of results to variations in input parameters. The paper emphasizes that using LHS can significantly reduce the number of calculations needed while maintaining the reliability of results, which makes it particularly relevant in the problems of reliability, risk and geomechanical modeling.

The Monte Carlo method is simple and versatile, but requires considerable computational resources. At the same time, the Latin Hypercube Sampling method, despite its more complex implementation, provides an efficient parameter space coverage and improves the quality of analysis at a lower cost.

Given the high variability of the geomechanical properties of rocks and the uncertainty of the source data, the use of probabilistic methods becomes particularly relevant for assessing the stability of underground mine workings. Probabilistic analysis using the limit equilibrium method allows for realistic consideration of variations in strength characteristics, stress state of the rock mass, and support parameters.

A review of foreign research confirms that the use of probabilistic approaches, when designing a support in seismically active and fractured rock masses, makes it possible to increase the reliability of calculations, more accurately assess risks, and reasonably optimize support parameters, which significantly increases the safety of underground mining operations [27]-[32].

The purpose of this research is to develop and substantiate engineering-reliable parameters for supporting underground mine workings in the conditions of fractured and seismically active rock masses based on a comprehensive approach that includes field geological and structural observations, numerical modeling, and probabilistic analysis of rock mass stability.

2. Research methods

The methodology used in this research is aimed at a complex and scientifically sound determination of parameters for supporting underground mine workings conducted in the conditions of fractured and seismically active rock masses. The conceptual basis of the approach consists in the integration of field engineering-geological observations, geological-structural analysis, numerical geomechanical modeling, and probabilistic stability assessment, taking into account the inherent uncertainty of the rock mass [33].

To assess the stability of underground mine workings, the research uses the limit equilibrium method, based on analyzing the balance of forces along potential failure surfaces. Unlike the classical deterministic approach, which operates with averaged parameter values, this research implements a probabilistic approach that allows taking into account the natural variability of the geomechanical rock mass characteristics.

To increase the reliability of modeling, a statistical combination of Monte Carlo and Latin Hypercube Sampling (LHS) methods is used, which provides more complete coverage of the range of possible mass states and allows for a statistically reasonable distribution of the safety factor. This approach makes it possible to assess the probability of a mine working failure and substantiate the support parameters, taking into account the uncertainty of geomechanical conditions [34]-[36].

Research methodology combines field work to study the rock mass fracturing with numerical probabilistic stability analysis of mine workings. Comprehensive approach includes surveying of fracturing, stereographic processing, and stability modeling by the limit equilibrium method, taking into account the variability of structural characteristics and strength properties.

During the first stage of field work, a geotechnical description of geotechnical-oriented drilling cores, drilled within the projected zone of underground mine workings, was performed to obtain reliable information about the structural-geological characteristics of the mass [37]. Recent studies have also emphasized the importance of selecting optimal drilling parameters and improving bit performance to ensure the efficiency and accuracy of core sampling under complex geological conditions [38]-[40].

During the description process, the rock mass quality index (RQD) was determined, the orientations of structural disturbances (azimuth and dip angle) were measured, the degree of filling of joints with mineralized inclusions was assessed, and the surfaces roughness was visually determined using the ISRM scale [41]-[43]. All structural disturbances were documented with reference to depth, classified according to type and morphology.

Stereographic processing of geological data and analysis of fracturing systems were performed using Dips software. The results of this stage provided a reliable basis for further geomechanical calculations and the development of scenarios for probabilistic stability analysis of underground mine workings [44].

At the second stage of the research, a detailed structural analysis of the rock mass was performed based on the description of oriented cores selected during geotechnical drilling. The parameters of fracturing were studied, including orientation, frequency, opening, roughness, and filling of joints. For spatial data processing and joint system identification, Dips software was used, which allows the mass to be classified according to indicative criteria with a high degree of accuracy.

During processing, the values of the number of joint systems (J_n) were determined, the quality of the rock mass was assessed using RQD, the spatial joint frequency was calculated, and histograms of J_r and J_a values were constructed, characterizing the roughness and filling of joints, respectively. Particular attention was paid to the analysis of the Fisher Contour Distribution [45], [46], which clearly reflects the density of joint orientations and allows the dominant directions in the rock mass to be identified. This distribution is important for further probabilistic stability analysis, as it provides information about the degree of anisotropy of the rock mass and the orientation of potential shear surfaces.

Based on the processed data, the rock mass quality index Q' was determined. Unlike the full form of the Q'-system, which takes into account water saturation (J_w) and the stress state factor of the mass (SRF), this research uses a simplified Q' index, which includes only reliably determined parameters: RQD, number of joint systems (J_n), roughness (J_r) and the degree of joint filling (J_a). This simplified formula minimizes uncertainties at an early stage of analysis, especially when there is insufficient information about the hydrogeology and stress state of the rock mass [47].

The use of Q' at this stage allows for an objective assessment of the rock mass state based on direct geotechnical observations. The mass quality index Q' is calculated using the Formula:

$$Q' = \left(\frac{RQD}{J_n} \right) \cdot \left(\frac{J_r}{J_a} \right), \tag{1}$$

where:

RQD (Rock Quality Designation) – core quality index;

J_n – number of joint systems;

J_r – joint roughness coefficient;

J_a – joint filling coefficient.

At the next research stage, a probabilistic analysis of the stability of mine workings was conducted using the Unwedge software package, developed to assess the risk of wedge formation in fractured rock masses. This stage is important for conditions where the rock mass is characterized by the presence of several intersecting joint systems and high variability in their parameters, especially in seismically active regions.

The analysis was performed based on the geometry of the intersections of joint systems identified at the previous stage using Dips. Stereographic information on the spatial position of joints (dip and strike angles), their number (J_n), length, pattern of closure, roughness (J_r) and degree of filling (J_a) were integrated into the Unwedge model. The rock mass was considered as a set of potentially unstable wedges formed by intersecting structural planes and interacting with the mine working contour [48].

The analysis of wedge stability in conditions of intersecting joint systems, performed using the Unwedge software package, plays a special role in the research. This makes it possible to assess the impact of the direction of drifting on the risk of formation of unstable geological structures, especially in fractured and seismically active rock masses.

The mutual relationship between the orientation of the mine-working front and the joint systems is considered, which is critical for determining possible wedges. As shown by the research presented in [46], the ratio between the azimuth of tunneling and the orientations of joints has a significant influence on the probability of formation of wedge blocks and their mobility. The model takes this into account by varying the azimuth of tunneling and by fixing the angles causing the most probable separation planes (planar, wedge-shaped and convergent forms of destruction).

In addition, the modeling uses a spectrum of pseudo-static coefficients (from 0.01 to 0.5), simulating the dynamic impact of seismic events. This allows for the reliable consideration of equivalent horizontal and vertical loads arising during earthquakes and the assessment of their impact on the stability of potential wedges [49].

The analysis generates statistics on the factor of safety (FS), taking into account the probability distribution of parameters and dynamic effects. The data allows identifying the most vulnerable configurations and determining recommendations for the orientation and support parameters of mine workings to minimize the risk of failure.

Thus, this stage not only allows for a quantitative assessment of the rock mass reliability, but also serves as a scientific basis for the transition to the design of support, taking into account the probabilistic risks and geomechanical peculiarities of the studied rock mass.

At the final research stage, based on the probabilistic analysis results, recommendations were formulated for optimizing the parameters for supporting underground mine workings in fractured and seismically active rock masses. Combined support schemes are proposed, including roof-bolt support and shotcrete, which provide for the effective stabilization of wedges and reduce the risk of failure under dynamic loads. This approach allows for both geomechanical uncertainty and scenarios of external dynamic impacts to be taken into account, ensuring that design solutions are adapted to difficult natural conditions and increasing the level of industrial safety.

3. Results and discussion

3.1. Structural analysis of the mass based on the description of oriented cores selected during geotechnical drilling

Structural analysis of rock mass was a key stage in assessing the geomechanical state in the projected zone of underground operations. As part of this research, a systematic description of oriented cores sampled during geotechnical drilling was performed with the aim of quantitatively and qualitatively characterizing fracturing. The main focus was on determining the spatial orientation of joints, their frequency, opening, filling and roughness as the main factors influencing the stability of the rock mass. The data obtained formed the basis for subsequent stereographic analysis, modeling of possible shear surfaces and probabilistic assessment of the stability of mine workings in fractured and seismically active rock mass conditions (Fig. 1).

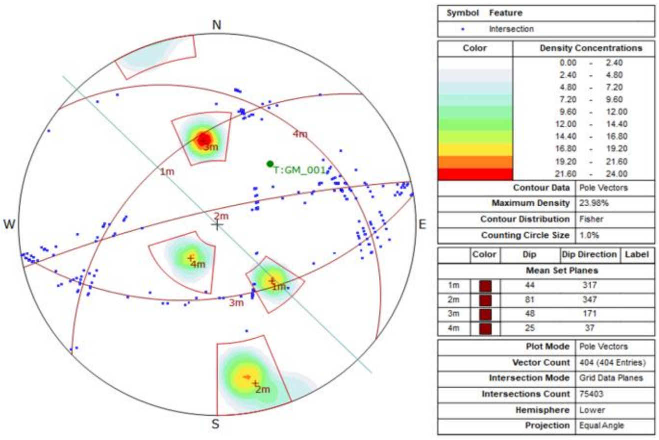

Figure 1. Stereographic projection with analysis of dominant joint systems based on geotechnical drilling data

Figure 1 shows a stereographic projection displaying the poles of joints identified based on geotechnical drilling data. Using the Fisher Contour Distribution, four dominant joint systems (1-4 m) have been determined, each characterized by its own dip azimuth and dip angle parameters. The maximum density of directions is 23.98%, which indicates a pronounced orientation of fracturing.

This analysis allows classifying joints, determining the parameter J_n, constructing histograms of frequency and distances between joints, and also serves as a basis for further geomechanical calculations, including assessment of rock mass quality Q' and probabilistic modeling of mine working stability.

Figure 2 shows a histogram of True Joint Spacing distribution, constructed based on the geotechnical mapping data analysis.

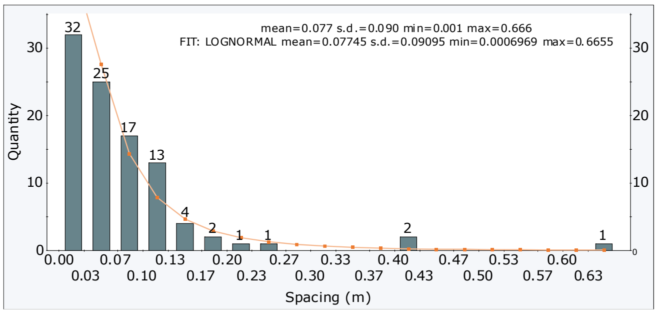

Figure 2. Histogram of True Joint Spacing with lognormal distribution

The distribution is described by a lognormal function, which is typical for natural fracturing. The average distance between joints is 0.077 m, with a standard deviation of 0.090 m. Most joints are located at intervals of less than 0.1 m, indicating a high concentration of fracturing in the rock mass. These data are used to calculate the frequency and density of joints, and are also key in statistical modeling and classification of the mass according to the Q'-system.

The graph (Fig. 3) shows the RQD distribution along the entire length of the core. The RQD index is used to quantitatively assess the degree of fracturing in the rock mass. The values range from 38 to 100%, with an average value of 90.3% and a standard deviation of 11.6%, indicating that the rock mass is generally of good quality with local intense fracturing zones.

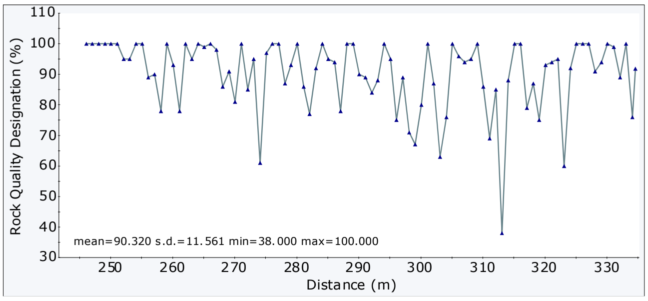

Figure 3. Graph of changes in RQD index along the well

Areas with reduced RQD indicate possible weakened zones that require additional attention when designing support and selecting mine working parameters. The obtained RQD values are used in calculating the rock mass quality index Q' and are key to classifying rocks according to stability.

The graph (Fig. 4) shows the distribution of joint frequency along the core length, expressed as the number of joints per meter. Values range from 0 to 14 joints/m, with an average value of 4.49 joints/m and a standard deviation of 2.39.

The analysis shows marked heterogeneity in the mass in terms of fracturing frequency. High frequency areas indicate potentially weakened rock mass zones that are susceptible to reduced stability, especially under seismic loads, which is a key parameter in calculating the Q'-system (J_n) and is used further for modeling.

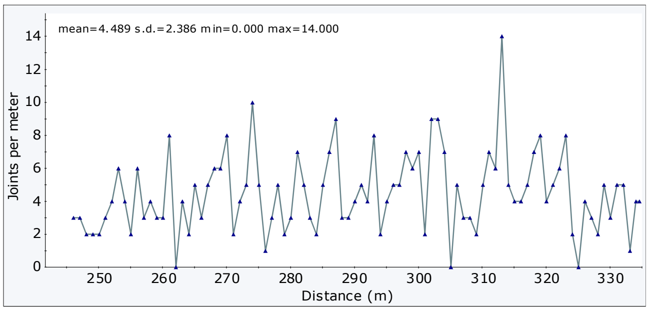

Figure 4. Graph of changes in joint frequency along the well

The histogram (Fig. 5) shows the distribution of J_a parameter values, reflecting the degree of joint filling, according to the NGI (Norwegian Geotechnical Institute) classification. This parameter is included in the formula for calculating the rock mass quality index Q' and directly affects the assessment of the strength characteristics of contact surfaces.

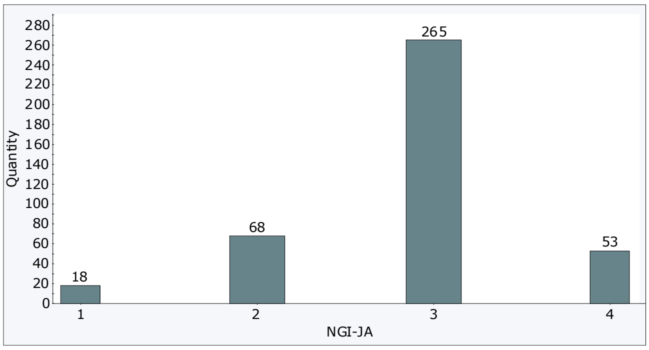

Figure 5. Histogram of the distribution of joint filling coefficient (J_a) values

Most joints (265) belong to category 3, indicating moderate or weak filling without significant strength reduction. Data are important for assessing the adhesion between mass blocks and calculating stability in numerical and probabilistic models.

The histogram (Fig. 6) shows the J_r parameter distribution, reflecting the degree of roughness of joint surfaces, according to the NGI classification. The J_r parameter characterizes the ability of joints to resist shear and is taken into account when calculating the rock mass quality index Q'.

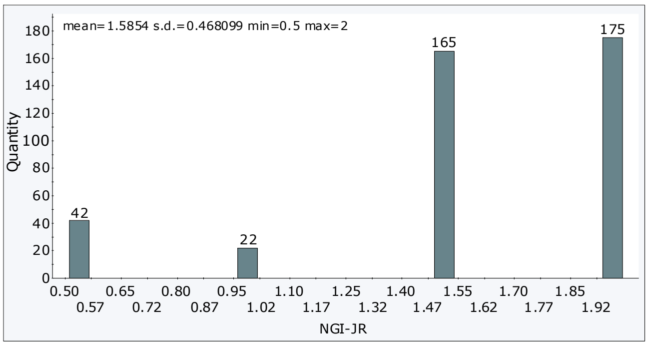

Figure 6. Histogram of the distribution of joint roughness coefficient (J_r) values

Most observations are concentrated in the range $J_r = 1.5\text{-}2.0$, which corresponds to well-defined natural joint roughness and indicates satisfactory adhesion between blocks. A small number of values are in the $J_r < 1.0$ range, which may indicate that there are smoothed or polished surfaces potentially prone to shear. The data obtained serve as a basis for assessing the stability of fractured rock mass and determining parameters in computational and modeling geomechanical systems.

The following parameters were used to calculate the mass rating according to the Q'-system: RQD = 90.32; $J_n = 12$; $J_r = 1.59$ and $J_a = 3$. The values were obtained as a result of geotechnical analysis using Dips software. Thus, the value of $Q' \approx 3.76$ determined by Formula (1) corresponds to the category of poor rock mass according to the classification of Barton et al. [50], which indicates the need to use engineering measures to strengthen the support when tunneling underground mine workings.

The value of $Q' \approx 3.76$, obtained based on comprehensive processing of geotechnical information, indicates poor rock mass quality according to the Barton classification. Core analysis using Dips software has identified four dominant joint systems characterized by varying degrees of filling and roughness, as reflected in stereographic projections, J_r and J_a coefficient distribution histograms, and spatial frequency diagrams. This combination of parameters indicates the presence of significant structural heterogeneity in the rock mass, which reduces its load-bearing capacity and requires a special approach when designing mine workings. The identified characteristics of the rock masses emphasize the need to use adaptive supporting methods and to substantiate parameters based on probabilistic analysis, especially when conducting underground operations in conditions of fracturing and potential seismic impact. Thus, the completed research stage provides a reliable engineering-geological basis for subsequent modeling and calculation of stability parameters of mine workings [51], [52].

3.2. Numerical modeling based on probabilistic stability analysis of wedges

This subsection presents the results of numerical modeling performed using the Unwedge software package to probabilistically assess the stability of wedges in underground mine workings. The analysis was conducted for various tunneling directions relative to fracturing systems determined based on the results of structural analysis of cores. Dynamic impacts, including seismic loads, were taken into account. Scenarios without supporting, as well as with the use of roof-bolt and combined support, were considered. Particular attention was paid to identifying critical directions for mine working and optimizing support parameters to ensure stability in fractured and seismically active rock mass. Figure 7 shows the scheme of failure (PoF) probability distribution along the contour of the underground mine working, obtained from the results of a probabilistic analysis using Unwedge software.

Each mark on the roof and upper sections of the side walls shows the calculated probability of an unstable wedge formation. PoF values range from 0 (no probability of failure) to 1 (100% probability of failure). The highest failure probability values (around 0.72-0.74) are concentrated in the central part of the roof, indicating a high probability of forming unstable wedges in this zone. Near the junction of the roof and walls, the failure probability is significantly reduced (to values of 0.003-0.027), indicating a relatively stable state of these areas.

Figure 8 shows the results of a probabilistic stability analysis of wedges in the Unwedge software. The left part of the figure shows a histogram of the factor of safety (FS) distribution generated by random sampling of the source data across the entire perimeter.

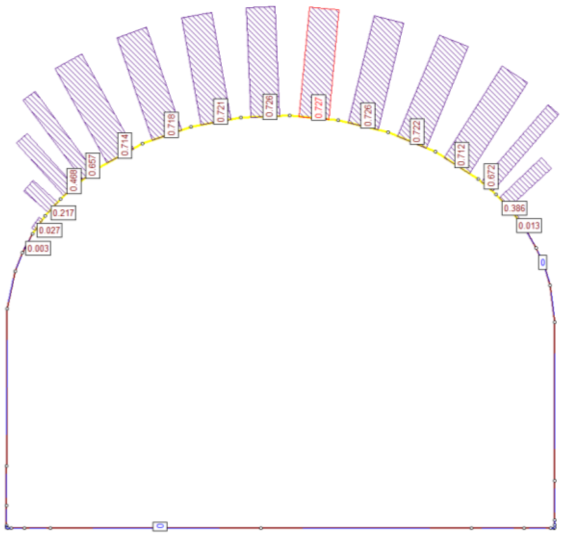

Figure 7. Distribution of failure probability along the mine working contour

Most implementations are concentrated in the range of low FS values, with a significant proportion of them being less than 1.0, which indicates a high risk of wedge stability loss at the specified parameters.

The right side of the figure illustrates a typical wedge with the lowest FS value in various projections. Wedge parameters: volume 1.821 m^3, mass 0.49 MN, wedge height 1.47 m, required maintaining pressure 0.024 MPa. These results confirm the necessity of designing the support taking into account the probabilistic nature of the formation of unstable wedges and possible scenarios for their failure.

Figure 9 shows a 3D diagram of the maximum required support pressure distribution to achieve FS = 1.5, depending on the direction and dip angle of the mine working. The diagram is based on the results of a probabilistic analysis in Unwedge software and shows how the spatial orientation of joints influences the required maintenance pressure.

The maximum pressure values correspond to certain combinations of wedge orientations that form the most unstable configurations relative to the mine working contour.

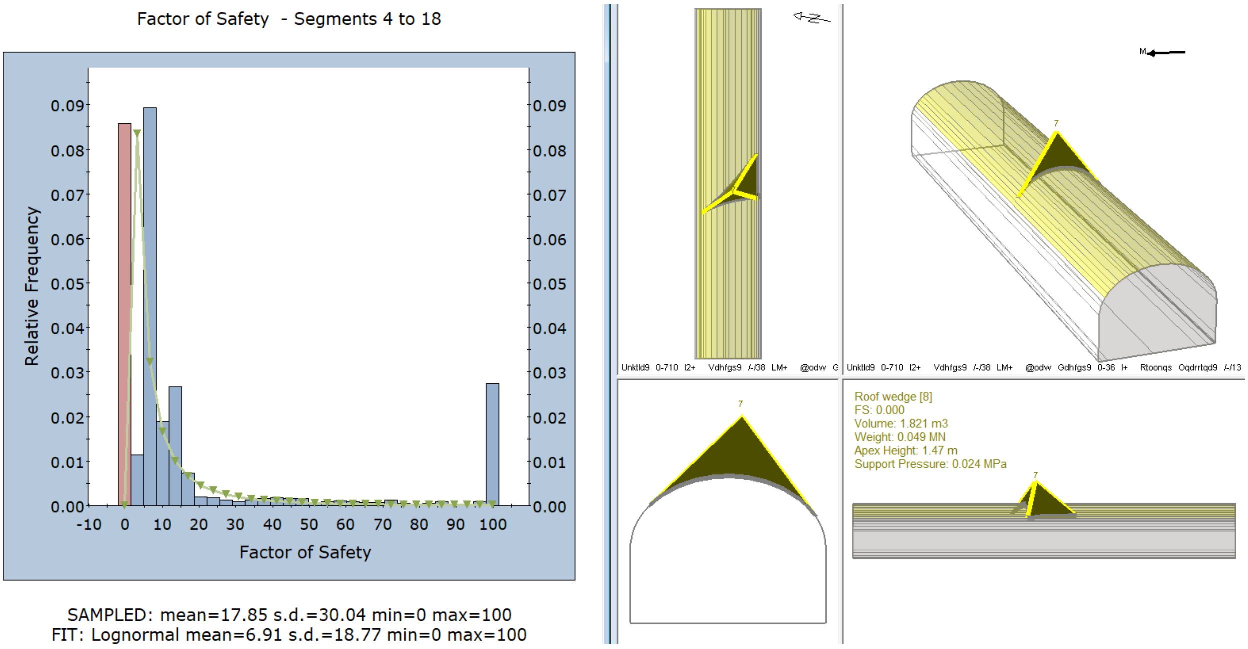

Figure 8. Results of probabilistic stability analysis of wedges: distribution of the factor of safety and wedge geometry

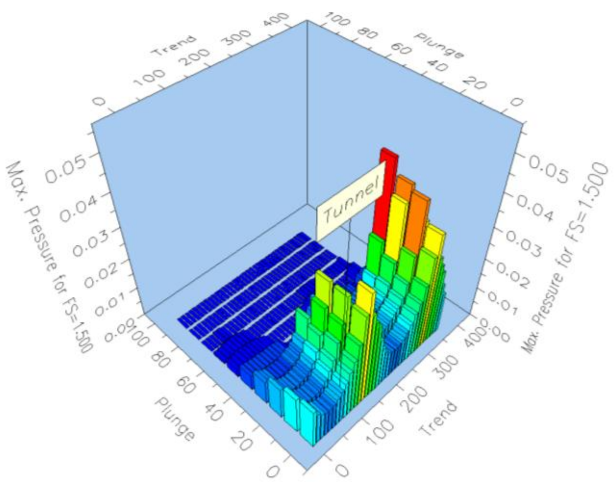

Figure 9. Spatial support pressure distribution depending on the joint orientation

These results make it possible to substantiate the parameters of roof-bolt support and shotcrete for effectively ensuring the boundary mass stability.

Figure 10 shows the maximum support pressure dependence (to achieve FS = 1.5) on the azimuth of the mine working axis direction (Tunnel Axis Trend). Graph demonstrates the influence of the mine working orientation relative to the joint systems on the required support pressure. It can be seen that at certain mine working axis directions (around 130 and 310°), maximum pressure (up to 0.037 MPa) is required to ensure stability, which is associated with the formation of the most unstable wedges. These results allow optimizing the tunneling direction and support scheme to minimize the risk of failure.

Figure 11 shows the probabilistic stability analysis results, reflecting the FS dependence on the azimuth of the mine working direction in the range of 90-170° without the use of support. The calculations include seismic impact with seismicity coefficients from 0.1 to 0.4.

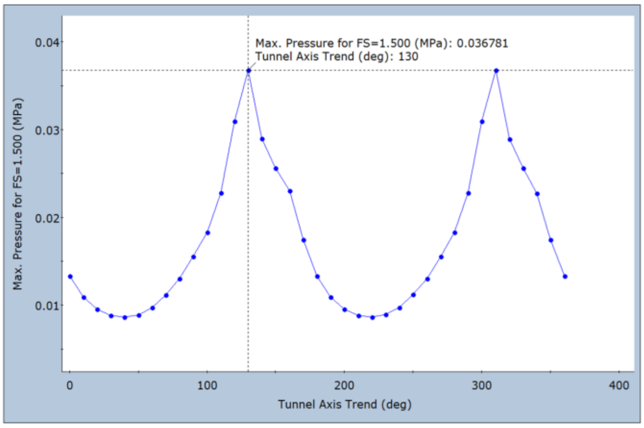

Figure 10. Dependence of the maximum required support pressure on the mine working axis orientation

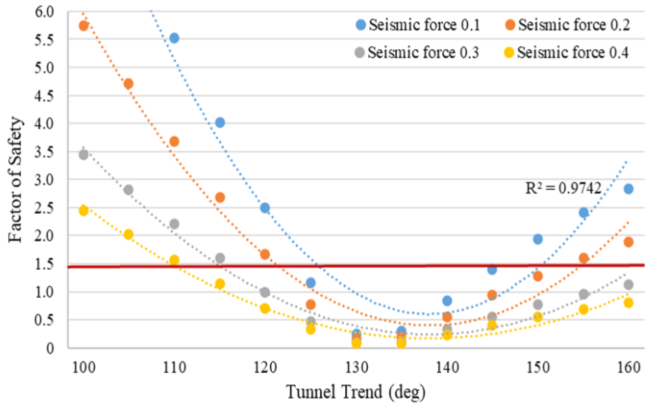

Figure 11. FS dependence on the tunneling azimuth in the absence of support

The red horizontal line at FS = 1.5 indicates the minimum permissible stability level according to industrial safety standards. It can be seen that as the seismicity coefficient increases, the FS values decrease significantly, and for unfavorable mine working direction (around 130°), the most critical situation is observed – FS drops below 1.5 even with minimal seismic impacts. This indicates a high probability of stability loss in this direction without the use of support.

Figure 12 shows the results of a similar analysis, but taking into account the use of combined support (roof-bolt + shotcrete). Support parameters: roof-bolt spacing 1.0×1.0 m, roof bolt length 2.4 m, load-bearing capacity of one roof-bolt 10 tons. The modeling is performed taking into account the seismic impact and for a critical azimuth of 130° mine working direction. The use of support significantly improves the stability of mine working: FS values exceed 1.5 in almost all directions and seismic load levels, including during unfavorable scenarios.

Figure 13 shows the results of modeling the stability of mine working wedges in three variants. The parameters of the wedges are specified for each variant: factor of safety (FS), volume, weight and height of the wedge. In the variant without support, a complete loss of the roof wedge stability (FS = 0) is observed, which indicates a high probability of failure.

The use of roof-bolt support (spacing 1.0×1.0 m, roof bolt length 2.4 m, load-bearing capacity of one roof-bolt 10 tons) made it possible to increase the stability of the wedges. However, the factor of safety for the roof wedge remains insufficient (FS = 0.501) to guarantee safe operation.

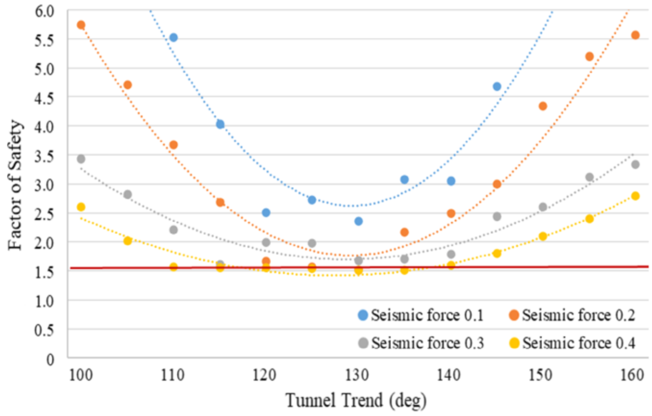

Figure 12. Dependence of FS on the azimuth of tunneling in combined support

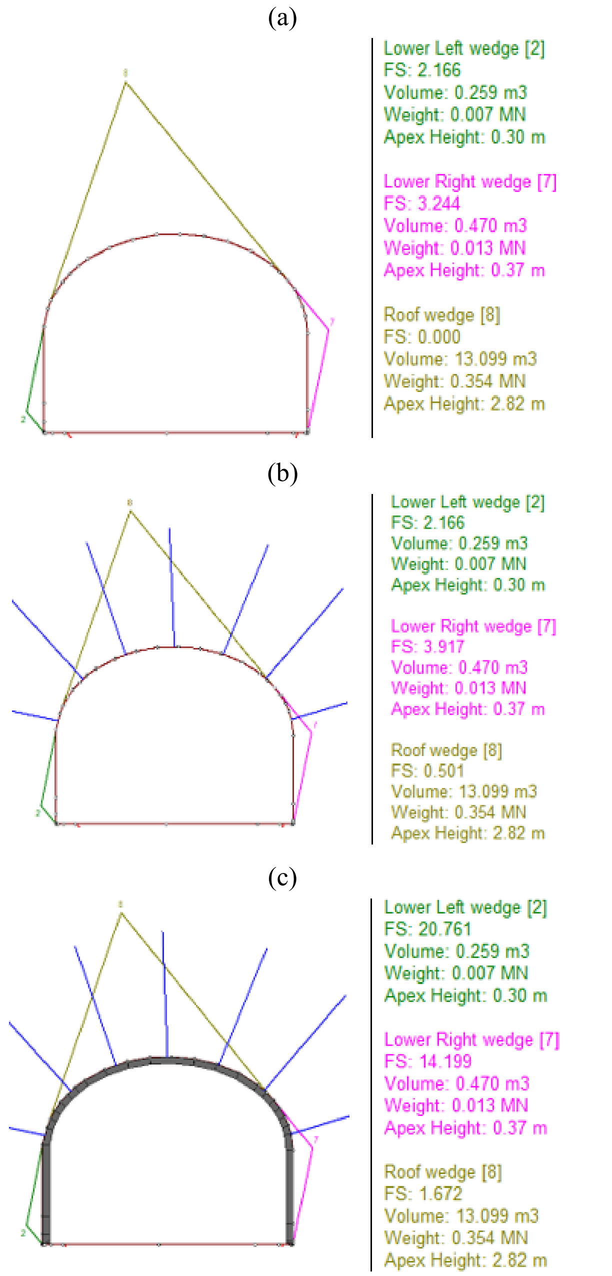

Figure 13. Comparative assessment of wedge stability with different types of support: (a) without support; (b) with roof-bolt support; (c) combined support (roof-bolt + shotcrete)

The most reliable stabilization is provided by a combined support, namely the combination of roof-bolting with 10 cm-thick shotcrete, where the factors of safety are significantly increased, including for the roof wedge (FS = 1.672), which meets the requirements of safe mining operations. The modeling performed for the most unfavorable azimuth of the mine working direction – 130° and with a seismicity coefficient of 0.3 makes it possible to take into account the influence of dynamic loads and mine working orientation relative to the joint systems.

The analysis conducted demonstrates the need to use support in conditions of high seismic activity and unfavorable orientation of the mine working relative to fracturing systems. The use of combined support ensures the design stability level (FS ≥ 1.5) even at high seismicity coefficients, thereby minimizing the risk of failure in underground mine workings.

4. Conclusions

In the course of the research, a comprehensive substantiation of the parameters for supporting underground mine workings in the conditions of fractured and seismically active masses has been performed on the basis of integration of field observations, geological-structural analysis and probabilistic modeling. The conducted analysis of oriented cores made it possible to quantitatively characterize the rock mass fracturing, identify the dominant joint systems, and determine the key geomechanical parameters, on the basis of which the rock mass quality index ($Q' \approx 3.76$) was calculated. Given this value, the mass was classified as poor, indicating the need for engineering measures to improve stability.

Numerical modeling using the Unwedge software package showed that, in the absence of support, wedges are formed in the mine workings with a high probability of loss of stability. This is particularly evident when the azimuth of mine working tunnelling is along critical directions relative to joint systems and when the seismicity coefficient is 0.3 or higher. The factors of safety (FS) in such conditions do not reach the permissible level specified in the project (FS ≥ 1.5), and the probability of failure in certain zones of the roof and sides is close to 100%.

The use of roof-bolt support partially increases stability, but only a combined support, namely roof-bolts and shotcrete combination, ensures that the FS standard is achieved and exceeded, even in the most unfavourable scenarios. Modeling confirmed that the combined support scheme most effectively stabilizes wedge formations, limits the development of unstable blocks and compensates for the dynamic impact of seismic activity.

Thus, the research confirmed that the stability of underground mine workings in fractured and seismically active rock masses cannot be guaranteed without the use of engineering-based support. The presented methodology of calculations and substantiation of support proves its efficiency and can be used in the design and operation of mine workings in similar mining-geological conditions.

This paper emphasizes the importance of integrating field analysis, numerical modeling and probabilistic methods to develop reliable solutions for ensuring the safety of underground mining operations. This approach forms the basis for practical application in the mining industry and for further scientific research in the field of geomechanics.

Author contributions

Conceptualization: AiM; Data curation: AI; Formal analysis: AzM; Funding acquisition: AiM; Investigation: AiM; Methodology: AiM; Project administration: AI; Resources: AzM; Software: RA; Supervision: AI; Validation: BK; Visualization: RA; Writing – original draft: AiM, AI; Writing – review & editing: AzM, BK, RA. All authors have read and agreed to the published version of the manuscript.

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Conflicts of interest

The authors declare no conflict of interest.

Data availability statement

The original contributions presented in the study are included in the article, further inquiries can be directed to the corresponding author.

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Застосування ймовірнісного аналізу для обґрунтування параметрів кріплення в сейсмічно активних і тріщинуватих гірських масивах

А. Мусін, А. Імашев, А. Матаєв, Б. Хусан, Р. Абдрашев

Мета. Обґрунтування параметрів кріплення підземних гірничих виробок в умовах тріщинуватих і сейсмічно активних масивів із використанням ймовірнісного аналізу стійкості.

Методика. Дослідження ґрунтується на інтеграції польових інженерно-геологічних спостережень, геолого-структурного аналізу, чисельного моделювання та ймовірнісних методів оцінки стійкості. На основі геотехнічного опису орієнтованих кернів визначено параметри тріщинуватості масиву (RQD, J_n, J_r, J_a), виконано стереографічний аналіз із використанням програмного забезпечення Dips та розрахований індекс якості масиву Q'. Ймовірнісний аналіз стійкості клинів проведено у програмному комплексі Unwedge з урахуванням динамічних впливів і сейсмічних коефіцієнтів до 0.4. Розглянуто сценарії без кріплення, з анкерним та комбінованим кріпленням.

Результати. Встановлено, що при несприятливій орієнтації виробки та високих сейсмічних навантаженнях без застосування кріплення коефіцієнт запасу стійкості (FS) не досягає проєктних значень (FS ≥ 1.5), що зумовлює необхідність застосування комбінованих схем кріплення.

Наукова новизна. Полягає в комплексному застосуванні ймовірнісного аналізу стійкості з урахуванням реальних геометричних і механічних характеристик тріщинуватості, сейсмічного впливу та просторової анізотропії масиву. Вперше для конкретних інженерно-геологічних умов об'єднані польові дані, індекс Q' та моделювання в програмі Unwedge для обґрунтування параметрів комбінованого кріплення, адаптованого до сейсмічно активних тріщинуватих масивів.

Практична значимість. Розроблена методика може бути адаптована до різних гірничотехнічних умов та сприяє підвищенню надійності проєктних рішень при будівництві та експлуатації підземних споруд у складних геологічних і сейсмічно активних районах.

Ключові слова: *тріщинуватість, підземні виробки, кріплення, ймовірнісний аналіз, сейсмічна активність, чисельне моделювання*

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