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A Novel Approach to Selecting Rational Supports for Underground Mining Workings

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Abstract

The goal of this study is to examine the stress-strain state and stability of rock massifs to select a rational type of support for underground workings in challenging mining and geological conditions. The primary aims include increasing the speed of mine workings, reducing capital expenditure, and enhancing safety. Established and novel theoretical methods for mining, geomechanics, and rock massif management were employed. These methods involve analyzing factors affecting the mine working speed, studying the physical and mechanical properties of rocks, developing stratigraphic profiles, and assessing the stress-strain state and stability using Bieniawski's Rock Mass Rating (RMR), Barton's Q-rating, and construction norms and rules. Numerical modeling with the Rocscience RS2/RS3 software was utilized to identify failure-prone areas and determine rational support types and parameters. This study provides comprehensive insights into the stress-strain state of the massif, identifying high-risk zones, and recommending suitable support types. The findings contribute to accelerating the progress of underground work, enhancing safety, and reducing construction costs. The developed support systems for challenging mining and geological conditions were designed to increase the speed, safety, and profitability of underground workings. Additionally, this research emphasizes the significance of selecting appropriate support systems to ensure the longevity and stability of underground structures, thereby optimizing operational efficiency and cost-effectiveness.

Keywords: Underground Mine Workings; Conducting and Supporting Mine Workings; Stress-Strain State; Rock Massif; Massif Stability Category; Support Design.

1. Introduction

The sustainable economic growth of a country is closely linked to the efficient utilization of its natural resources. At present, mineral extraction is primarily limited to ore reserves located at depths of up to 1,200 meters. However, the future of the mining industry requires the exploration and extraction of deep-lying mineral deposits through the implementation of safe and advanced technologies. To facilitate this, extensive mine construction is essential, including the establishment of new mining enterprises and the expansion of existing operations to access deeper horizons. This approach aims to enhance the annual production rates and expedite the construction and commissioning of underground mine workings. Achieving these objectives requires substantial capital investments and extensive preparatory mine development. Underground mine workings serve critical functions, including personnel movement, ore transportation, and the integration of essential infrastructure, such as compressed air, ventilation, water supply, and electrical systems. Consequently, mine workings represent complex underground engineering structures that are fundamental to modern mining operations.

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The study of factors influencing the speed of mine workings and the quality of their support under complex mining and geological conditions requires a comprehensive approach. This is because of the influence of multiple variables, which depend on both natural factors and the technologies used. The primary factors determining the mine working rate include mining and geological conditions, as well as technological, economic, environmental, and social aspects. Under complex conditions, progress may be slowed by the need for additional wall reinforcement, enhanced monitoring of rock stability, and application of specialized methods. Furthermore, the implementation of modern technologies, such as mechanized supports and advanced drilling rigs, can significantly accelerate the process but requires substantial investment and highly qualified specialists [1, 2].

Underground mine workings must retain their designed shape and dimensions throughout the operational lifespan of the mine to ensure long-term structural stability. This necessitates prevention of collapse over extended periods. Therefore, selecting an optimal support system and enhancing its design by studying the physical and mechanical properties of the rock mass, as well as its geomechanical conditions, is a critical task in modern mining engineering [3, 4]. For instance, the scientific works of Protodyakonov focused on the study of rock properties, rock pressure issues, support systems for mine workings, and the management of rock mass stability. He developed an original theory of rock pressure and was the first to derive a formula for its calculation [5–8].

An outstanding Soviet and Kazakh scientist in the field of mining science and mechanics –Erzhanov– made a significant contribution to the development of the mechanics of natural and technogenic processes related to human activities on the Earth's subsurface. He developed the theory of rock creep, which has been widely applied in mining. His research encompasses methods for calculating the strength, deformability, and seismic resistance of underground structures for various purposes [3, 4]. A classification system based on rock mass characteristics was developed by Bieniawski and is known as the Rock Mass Rating (RMR) method. In this approach, specific parameters are assessed using a table compiled by Bieniawski, in which each parameter is assigned a certain number of points based on its value. The total score determined the stability category of the rock mass. The evaluated parameters include the uniaxial compressive strength of intact rock, rock quality designation (RQD), spacing of discontinuities, condition of discontinuities, hydrogeological conditions, and an adjustment factor for unfavorable orientations of the rock interface [9].

As a result of analyzing a large number of real examples of underground mine workings, Barton proposed using the tunnelling (mine workings) quality index Q, which is expressed as $Q = \frac{RQD}{J_n} \times \frac{J_r}{J_a} \times \frac{J_w}{SRF}$. In his research, Y. Zaslavsky developed support systems with enhanced load-bearing capacity and lightweight designs for underground mine workings and structures, considering the characteristics of rock massifs. Furthermore, Makarov conducted a comprehensive study on the patterns of rock pressure formation in underground workings using laboratory experiments, theoretical analysis, and statistical methods. By applying modern mathematical modeling techniques, he achieved significant results in understanding and predicting rock pressure behavior.

In the concept of anchoring design, the research presented in Elrawy et al. [10] is particularly noteworthy because it employs mechanical calculations to evaluate tunnel stability by considering strength coefficients, collapse zones, and rock mass displacements. Despite the thorough investigation of this topic, the study remains limited to the application of anchor supports exclusively for tunnels, without considering the conditions of solid mineral development. Foreign studies have also made significant contributions to research on rock mass stability [11, 12]. For example, mines in Shanxi Province, China, have developed a mechanistic model to analyze the stability of coal massifs by incorporating field monitoring and identifying key instability factors. While these results have proven to be highly effective for coal deposits, their applicability to solid minerals and complex tectonic conditions requires further refinement.

Modern research on rock mass state assessment employs various empirical and analytical methods to enhance the accuracy of stability predictions and optimize anchorage systems. In particular, Abramkin et al. [12] proposed a comprehensive methodology that integrates structural evaluation using the Deere Rock Quality Designation (RQD) method, application of the Rock Mass Rating (RMR) system to determine the deformation modulus, and geomechanical classification based on the Q-system. This approach enables a comparative analysis of rock masses under different mining and geological conditions, identifies the strengths and limitations of each method, and emphasizes the need for their combined application. However, its scope is restricted to relatively simple geological conditions as it does not account for complex geological and mining environments, thereby limiting its applicability to rock masses affected by tectonic disturbances [13]. This study examined the effects of drilling and blasting, including analyses of rock impacts, displacements at significant depths, and recommendations for massif consolidation. While the findings are highly relevant, these studies primarily focus on conditions influenced by anthropogenic factors, without accounting for the effects of tectonic faults or the complexities of challenging mining and geological conditions [14–17].

Studies conducted in the East Sary-Oba field (Kazakhstan) [18], including an analysis of the natural stress state of the rock mass, provide valuable data for selecting appropriate support systems for mine workings in complex geological conditions. The evaluation of the stress distribution and the application of 2D measurements in horizontal and vertical boreholes serve as crucial tools for assessing the stress-strain state of the rock mass in support system design. The obtained results, which are essential for enhancing the safety and efficiency of mining operations, facilitate the informed selection of anchorage systems by considering the local mining, geomechanical, and hydrogeological conditions necessary for ensuring the stability of underground workings [19].

Elbialy et al. [20] examined the deformation state and stability of quarry slopes in Ukraine. As part of this research, the stress-strain state of the rock mass and the interaction between quarry rocks and filling materials were analyzed. These studies provide a deeper understanding of the impact of these processes on the stability of underground workings, which is a critical factor for ensuring their reliability and safety [21].

The analysis of the impact of existing fractures on rock stability under seismic action using numerical methods, such as ABAQUS and XFEM, enhances the understanding of the effects of seismic forces on rock mass stability. Studying fracture propagation under seismic loads is particularly relevant for deposits in which seismic activity or other dynamic factors pose potential threats to rock stability. Establishing the relationship between crack geometry, rock mechanical properties, and seismic activity enables the optimization of support system designs capable of withstanding dynamic loads, thereby ensuring the structural integrity and safety of underground mine workings. This area of research plays a crucial role in developing innovative support designs that enhance the stability of mine workings under dynamic impacts and minimize failure risk [22–24].

Research on the selection of construction materials, particularly concrete mixtures modified with microsilica and superplasticizers, provides valuable insights for improving the quality of underground mine workings. Studies have confirmed that high-strength concrete can be produced using locally available raw materials, which is especially relevant for the Beskempir deposit. Given that mining operations are primarily conducted in remote areas, the rational selection of concrete mix components based on available materials helps reduce economic costs, enhance operational efficiency, and improve the durability of support structures, particularly in challenging mining and geological conditions. The incorporation of specialized additives to enhance the strength and workability of concrete is a promising approach that can be effectively applied in the design and construction of mine support systems at this site [20, 25].

In Demin et al. [26], the stress-strain state of rocks in hollow coal seams and the impact of mining engineering factors on the zones of underground working were studied. This research identified stress dependencies and their effect on the stability of mine workings, which is crucial for support system design. Empirical relationships were established to demonstrate how the mining method, depth, and rock strength influence the stability of mine workings. These findings enable the prediction of mine behavior at various developmental stages. Under complex mining conditions, anchoring is recommended to enhance the stability and safety of underground workings [27]. All researchers emphasize in their scientific works that the consolidation of underground mine workings and the management of rock pressure exhibit unique characteristics and natural regularities due to the varying mining and geological conditions of each deposit. Even within the same mine, the rock mass properties can change significantly, necessitating a detailed study of the rock mass at each horizon. In addition, the service life of mine workings must be considered when selecting support types.

Global mining practices have historically shown that capital and preparatory mine workings have been supported using a single type of fastening along their entire length, regardless of frequent changes in mining and geological conditions. However, with modern mine workings extending for kilometers, the strength and deformation properties of the rock mass may vary significantly, even within the same lithological unit, leading to nonuniform displacement along the workings. These irregularities can reach considerable magnitudes and affect the stability of underground structures.

Despite extensive studies on the mining, geological, and geomechanical conditions of deposits, few studies have systematically addressed the selection of rational support types in relation to rock-mass stability indicators. To bridge this gap, we propose a comprehensive methodology for evaluating the stability parameters and selecting rational support types based on these assessments. Underground mine workings in rock masses affected by tectonic faults present additional challenges for excavation and support installation. Therefore, a thorough analysis of rock stability along the entire length of the mine workings is essential, considering the influence of fault zones. Identifying zones of unstable rock prone to fracturing and classifying them into distinct sections along the workings will allow for the implementation of differentiated support systems tailored to the specific stability conditions of each section, making this a highly relevant issue in underground mine workings.

The new approach to mine excavation and support systems emphasizes the implementation of rational technologies and the application of various support designs along the length of underground workings tailored to the specific geomechanical conditions of each section. Due to variations in rock stability and stress-strain characteristics within the surrounding mass, certain sections may exhibit favorable load-bearing capacities, allowing for the use of lighter, cost-effective, and technologically efficient support structures. By utilizing innovative research methods, it is possible to segment the rock mass along the longitudinal axis of underground workings based on specific geomechanical conditions and accordingly apply distinct support types. This targeted approach enhances the technical and economic efficiency of mine workings and improves labor productivity. The proposed support methods have broad applicability in the mining industry and offer a practical solution for optimizing underground stability.

2. Study Area

2.1. Brief Mining and Geological Characteristics of the Beskempir Deposit

The Beskempirskoye deposit serves as a prime example of complex geological conditions where studies have identified an irregularly layered structure intersected by disjunctive fractures. The presence of tectonic faults results in rock mass stability classifications ranging from category I to category IV according to construction norms and regulations. Similarly, the Akzhal and Khromtau deposits exhibit intricate geological and geomechanical mining conditions, yet their underground workings have largely been designed with uniform support types, which may not fully account for site-specific variations in stability. The Beskempir deposit is situated in the northern part of South Kazakhstan within the Zhambyl region, approximately 300 km southwest of Balkhash. Geographically, these deposits lie within the Chu-Balkhash watershed (Figure 1). The region features relatively smooth relief with shallow sandstone formations. The absolute surface elevations reach 500 m, with relative height differences of 3–5 m. The area was not seismically active. The primary valuable mineral extracted from the deposit is gold, with silver and sulfide sulfur as associated components.

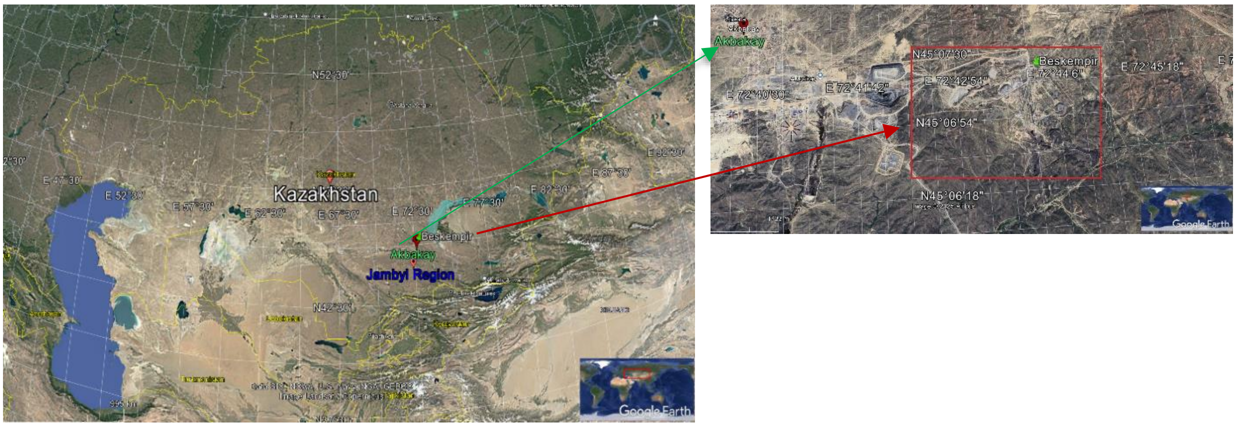


Figure 1. Geographical location of the Beskempir deposit

Given the geological complexity of these deposits, the conventional uniform support systems may not provide rational stability. This highlights the necessity to implement adaptive support designs tailored to specific geomechanical conditions to ensure safer and more efficient underground mining operations. An example is the Beskempirskoye deposit, in which studies have revealed an irregularly layered structure with disjunctive fractures. The presence of tectonic faults causes the stability of the rock mass to range from category I to category IV according to construction norms and regulations. Similarly, the mining geological and geomechanical conditions at the Akzhal and Khromtau deposits are characterized by complex geological structures. Underground mine workings at these sites were predominantly designed using uniform support types.

This study provides a comprehensive examination of the mining, geological, geomechanical, and mining engineering characteristics of the Beskempir Deposit. This research specifically focuses on the geomechanical conditions of the deposit, which is classified as a moderate gold-quartz sulfide formation within Kazakhstan's gold deposits. Alongside gold, the deposit contains associated components such as silver and sulfide sulfur. The Beskempir deposit is characterized by shallow and relatively flat relief, with absolute elevations ranging from +465 to +490 m. The region experiences a sharply continental and arid climate with strong northeastern winds. Summers are dry and hot, while winters are snowy, with frequent thaws. Stable snow cover, typically 0.3–0.4 meters thick, lasts from December to February. The average annual temperature varies between +5°C and +6°C. The area recorded a seismicity level at six points.

The most significant ore-controlling structures in the deposit are spearheading fractures that result from chipping or detachment. These fractures extend up to 2–3 km in length, with multidirectional dips varying from 40° to 45° to 60°–85°. In addition, dikes play a crucial role in influencing the positioning of ore bodies, further shaping the geomechanical conditions of the deposit. Understanding these geological features is essential for optimizing mining strategies and ensuring the stability and safety of underground workings. The morphology of ore bodies in the Beskempir deposit is highly complex, with multiple geological faults shearing the ore bodies both vertically and horizontally and varying in displacement from 1 to 25 m.

The hydrogeological conditions of the deposits are relatively simple. No significant water-bearing horizons were present within or near the ore field, eliminating the risk of sudden water inflow into the underground workings. The existing groundwater is of the fracture type, with an actual inflow into underground workings of 10–15 m^3/h. However, groundwater exhibits aggressive properties toward concrete made with non-sulfur-resistant cement, although it does not contain carbonic acid-aggressive waters. The Beskempir Au deposit lies in an intense tectonic zone at the fault intersection. The maximum rock disturbance was observed in the western part of the deposit. The ore field of the Beskempir deposit is complicated by numerous differently oriented faults ranging from regional faults of ancient emplacement (Kengirsky) and long-lived faults of the second order (Beskempirsky, Dolinniy, etc.) to leading faults, fractures, spalling, and fracture structures [4-6].

This study examined the stress-strain state of the rock mass surrounding the transport drift along the Surprise vein, located at the +150 m horizon of the Beskempir deposit. The initial field data required for this research, including the geological and geomechanical parameters, are summarized in Table 1.

Table 1. Initial data required for research and development activities

No.	Name of indicators	Values
1	Mine workings	Transport drifts along the Surprise vein
2	Cross-sectional area of the mine workings, m^2	10.9
3	**The strength of the host rocks according to the scale of Prof. M. Protodyakonov:**	
	- Host rocks	11-14
	- Ores	16-17
4	Loosening coefficient	1.6
5	**Average compressive strength ($\sigma_{сж}$), MPa:**	
	- Granodiorites	135.33
	- Orgovician sandstones	159.45
	- Quartz ores	166.71
6	Berezites	125.32
	Lamprophyres	90
7	**Volume density, t/m^3:**	
	- Host rocks	2.7
	- Ores	2.73

The planned total length of the mine workings is L_{drift} =1200 m, of which approximately 30% of the mine workings cross deformed rock massifs with medium stability prone to destruction, and the rest of the length of the transport drift (70%) is more stable.

The mine workings have a vaulted shape, the cross-sectional area is S=10.9 m^2 (L=3400 mm, H=3450 mm, R=2350 mm, r=890 mm). The analysis of mining geological and engineering conditions revealed that the stress-strain state of rocks around the transport drift is distinctively complex. The complexity of this task is owing to the variety of rock properties along the length of the transport drift. Beskempir ore bodies are represented by quartz veins with berezite solbands in the granodiorites.

3. Research Methodology

In this study, both established and novel theoretical and analytical research methods were employed, utilizing specialized software and critical experimental analyses. Through theoretical and analytical investigations, key factors influencing the rate of mine development under complex mining and geological conditions were identified. Based on the analysis of specific geological data, the stress-strain state of the rock mass and the physical-mechanical properties of the rocks were examined. Stratigraphic columns of the studied rock mass were developed, and the lithological characteristics of the deposit were identified. Rock mass stability was assessed using multiple approaches, including the official methodology outlined in construction norms and regulations (Building Codes and Regulations), the Bieniawski rock mass rating (RMR) and E-Hook diagram, as well as the empirical Q-rating method by Barton (Figure 2). Using numerical modeling with advanced software programs, such as Rocscience RS2/RS3, the boundaries of zones prone to failure within the rock mass intersected by underground horizontal mine workings were identified. The study involved segmenting these areas based on rock mass stability, providing a more precise justification for the stress-strain state of the massif. For each identified section of the mine workings, optimal support types were selected, their structural designs were determined and substantiated, and the key support parameters were recommended. Additionally, research has been conducted on support installation technologies for underground mine workings (Figure 3).

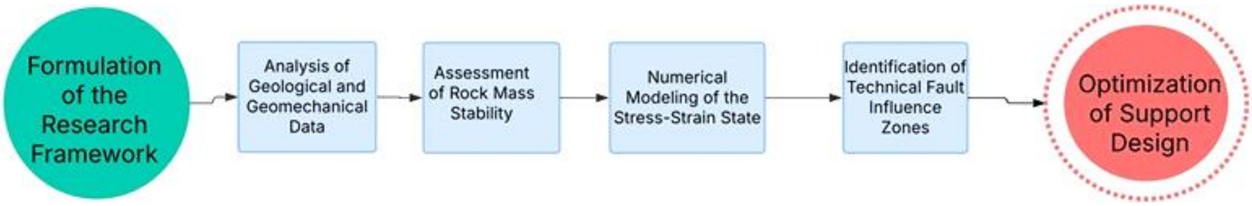


Figure 2. Generalized methodological algorithm for selecting a rational type of support in mine workings

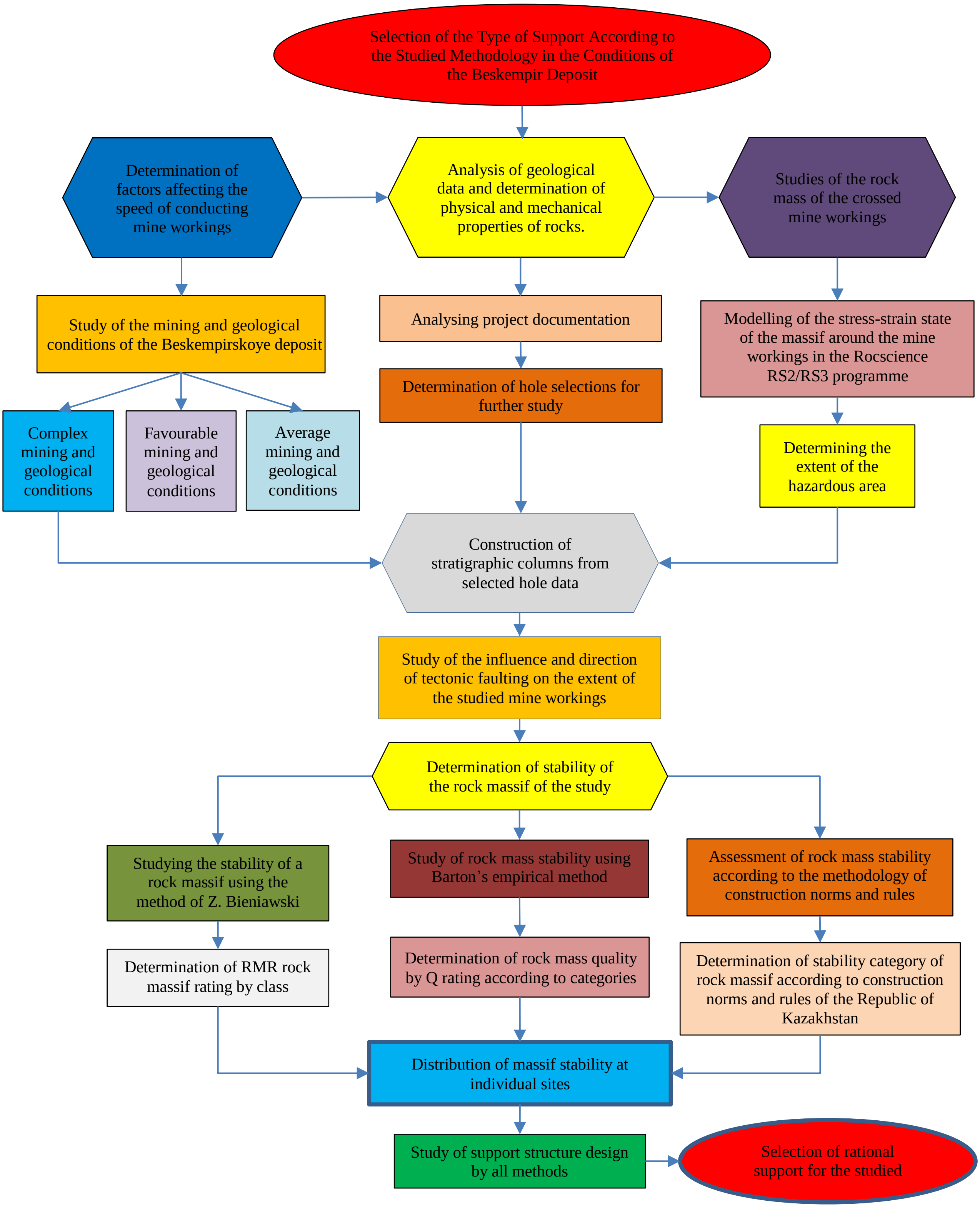


Figure 3. Detailed structural and logical scheme of the algorithm for selecting rational support for mine workings in complex mining and geological conditions

4. Results of the Study

4.1. Study of the Formation of Stratigraphic Columns of the Rock Massif and Lithological Features of the Deposit

Stratigraphic characterization of a deposit plays a crucial role in evaluating the overall condition of the rock mass, including the properties of the surrounding formations above and below the mining horizon. The geological age of the rocks directly influences their physical and mechanical properties. In this study, profiles XL-XL and XLVIII-XLVIII, which exhibited frequent tectonic faults along the deposit, were analyzed.

The mine workings (drift) were developed at the +150 m horizon, with a total length of 1,200 m, following the Surprise orebody. Of this length, 48% is located within a tectonic fault zone, while the remaining 42% lies within a stable rock massif [5]. During the investigation, it was determined that a significant portion of mine workings (L = 580 m) developed within a fractured rock massif affected by tectonic faults. Given the instability in this zone, it is essential to select a rational and durable support system. To achieve this, samples and cores extracted from boreholes near the unstable rock mass were comprehensively analyzed to assess the geomechanical properties of the hazardous sections (Figure 4).

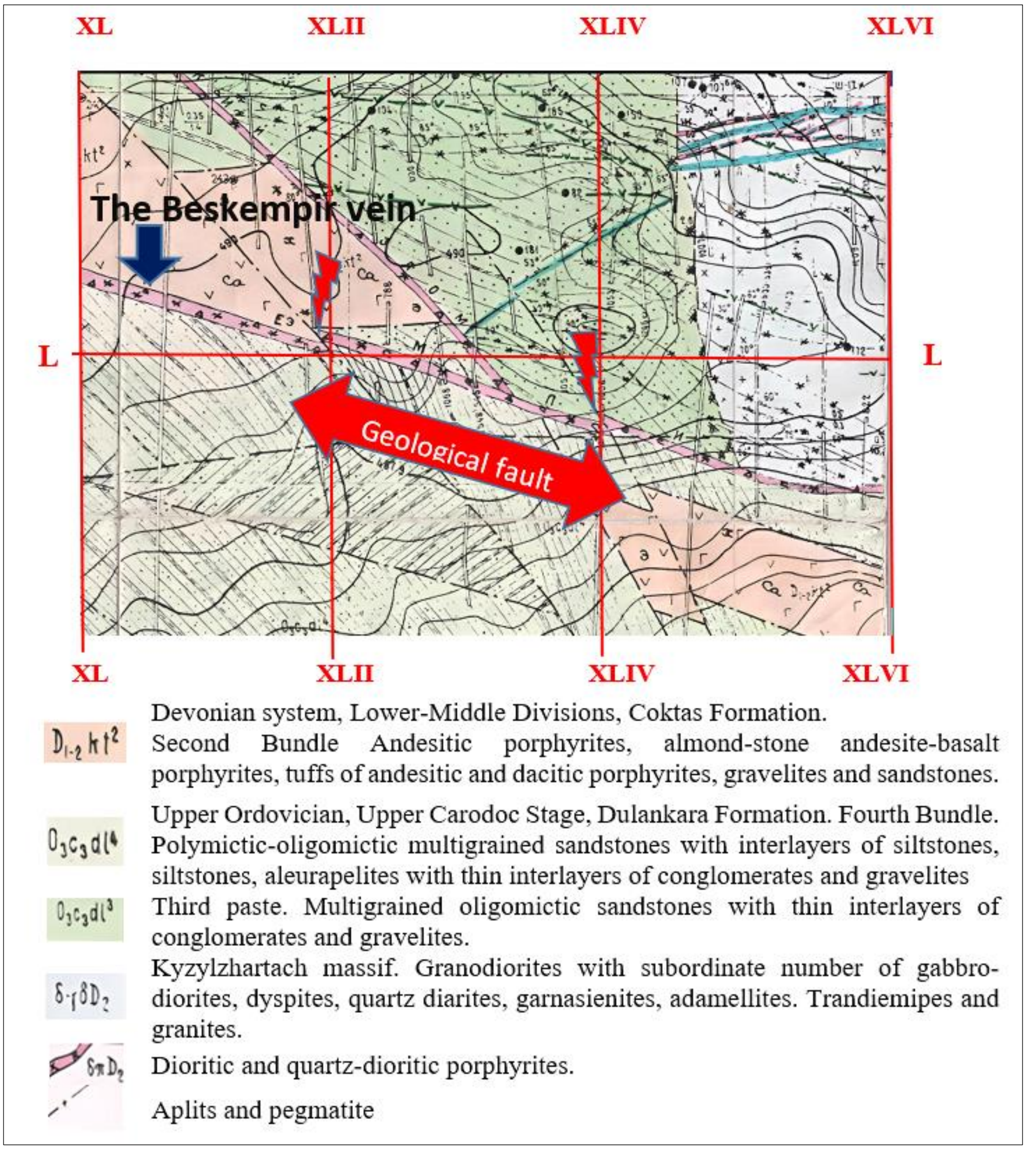


Figure 4. Geological map of the Beskempir field (Western part)

During this research, the area containing tectonic faults was identified using a general geological map of the Akbakai field (Beskempir section). Based on the selected map (Figure 1), geological cross-sections were analyzed for XL-XL, XLII-XLII, XLIV-XLIV, and XLVI-XLVI, with one geological section of a hazardous zone presented as an example (Figure 5).

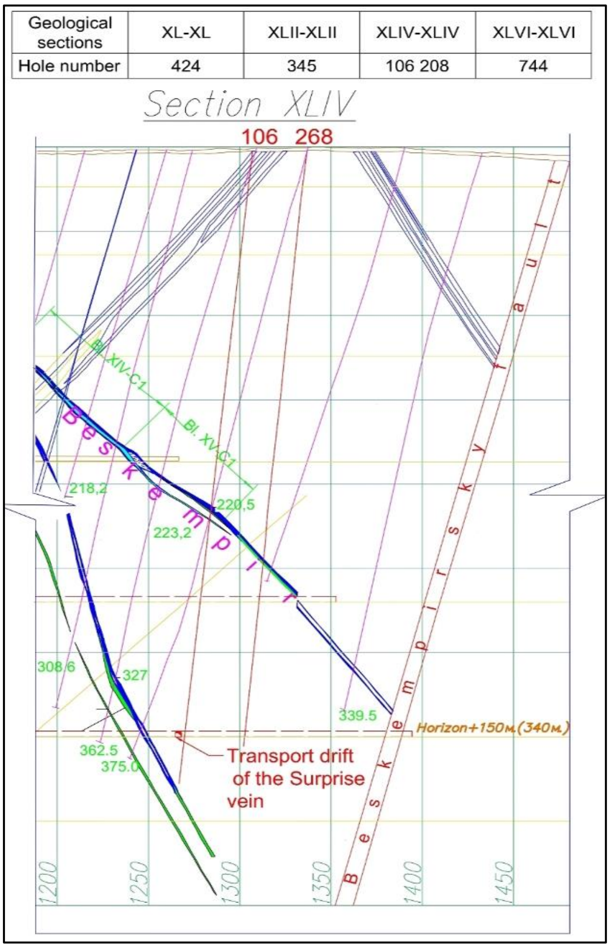


Figure 5. Geological section along profile XLIV-XLIV

For a detailed assessment, boreholes with diameters of 70–85 mm drilled along the cross sections of each profile were considered. The analyzed holes included no. 57 (depth 350 m), no. 424 (depth 590 m), no. 345 (depth 450 m), no. 268 (depth 700 m), no. 245 (depth 520 m), no. 313 (depth 480 m), no. 106 (depth 170 m), no. 268 (depth 510 m), no. 744 (depth 410 m), no. 86 (depth 350 m), and no. 66 (depth 100 m). The study was conducted using data from selected holes [5].

Laboratory studies were conducted to determine the physical and mechanical properties of the core and rock samples taken from the rock massif surrounding the mine workings at a horizon of +150 m in the Beskempir field. These studies were carried out at the laboratory of the Kazakh National Research Technical University, named after K.I. Satbayev (Figure 6). The physical and mechanical properties of the core samples were assessed using a specialized Pilot-4 press. Additionally, research findings from the VNIICVETMET Institute, the Zhetisu Geological and Geophysical Expedition, and Altynalmas JSC were considered in the analysis [2, 5].

The analysis of theoretical, analytical, and experimental studies indicates the presence of tectonic faults in distinct submeridional sections along with smaller fractures in the same direction within the Beskempir deposit. The ore field is structurally complex and intersected by multiple faults of varying orientations, including regional faults of ancient emplacement (Kengirsky), long-lived second-order faults (Beskempirsky, Dolinniy, etc.), and leading faults, fractures, spalling, and other fracture structures. The primary ore-controlling structures are spearheading fractures of chipping or detachment, with lengths reaching 2–3 km and dips varying from 40–45° to 60–85°. Dikes significantly influence the positioning of orebodies. The ores exhibited no tendency toward caking, soaking, bloating, or spontaneous combustion. However, with a free silica content of 30–40%, they are classified as silica-prone. The natural radioactivity of rocks remains within background values, ranging from 10 to 15 μr/h in diorite porphyrites, 25–31 μr/h in granodiorites, and 20–30 μr/h in ore bodies. The bulk density of ores is 2.73 t/m³, while that of host rocks is 2.7 t/m³, with a loosening coefficient of 1.6 for both.

Hardness of the host rocks on the scale of Professor M. Protodyakonov 11-14, ore 16-17. The volume densities of the ores and rocks were 2.73 t/m^3. Loosening coefficient of 1.6. The average compressive strength of granodiorites is as follows $\boldsymbol{\sigma_c}$=1380 kg/cm^2, in orgovician sandstones σ_c=16290 kg/cm^2, at quartz ores σ_c=1700 kg/cm^2, berezits σ_c=1278 kg/cm^2, in lamprophyres σ_c=918 kg/cm^2. The fracture coefficient was in the range 0.011–0.008.

The impact of water-bearing properties on the stability of rock massifs in tectonically fractured zones was analyzed. The natural moisture content of ores and rocks does not exceed 1.5%, while water inflow into underground workings during mining operations ranges from 1.5 to 4.5 m³/hour. Underground water is aggressive toward concrete made with non-sulfate-resistant cement, but does not exhibit carbonic aggression. Water mineralization varies between 0.7 and 7.6 g/L, depending on rainfall. Rock fractures in tectonic fault zones demonstrate high water permeability, and water infiltration into these fractures contributes to rock displacement, ultimately increasing rock pressure.

Taking these factors into account, the impact of tectonic fault orientation on the length of the studied mine workings was analyzed. It was established that the tectonic faults influence the mine workings in four distinct directions (Figure 7). These fracture orientations will be considered in future studies for selecting appropriate support systems, incorporating modeling results obtained using RS software.

Figure 6. Photos of the core samples

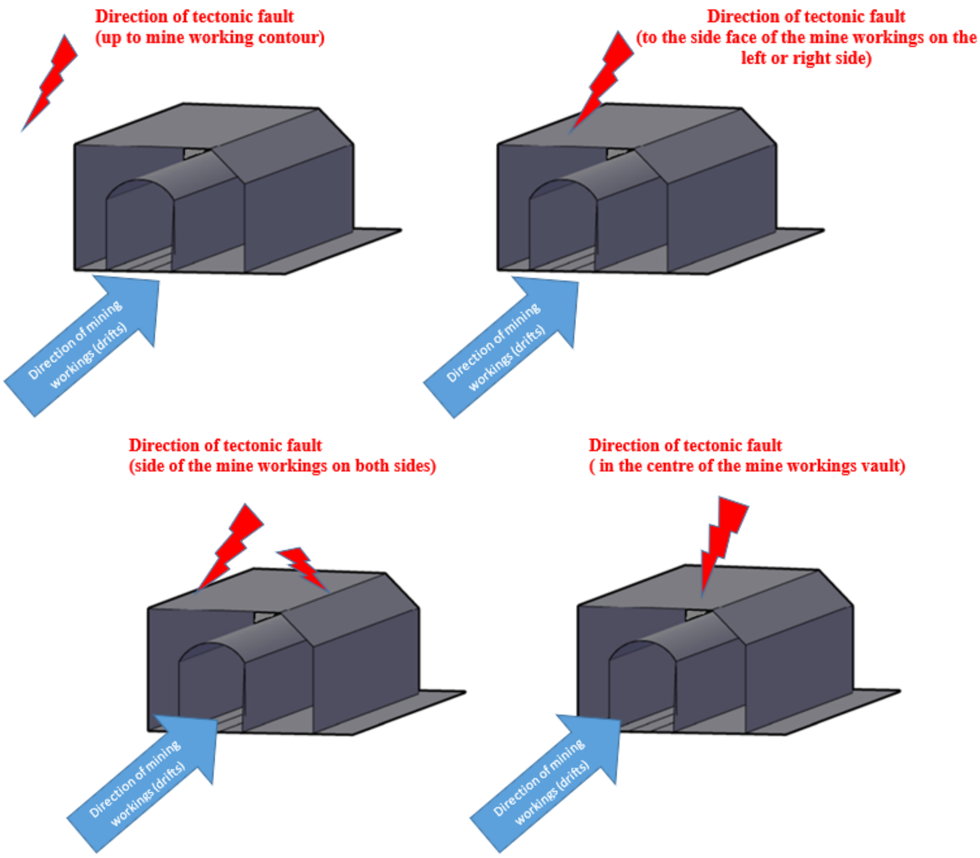


Figure 7. Influence of tectonic fault direction on the length of the investigation of mine workings

The stability, tectonics, stratigraphy, and geological age of the rocks through which underground mine workings pass vary, depending on the properties of the rock layers. For the construction of stratigraphic columns selected from geological sections on XL-XL, XLII-XLII, XLIV-XLIV, and XLVI-XLVI (1:10000), data from wells 424, 345, 106, 268, and 744 were studied (Figure 8).

Engineering-geological column of hole 268 based on sections VI-VI

Engineering geological element	Density, g/cm3	hardness	Depth, m
1 layer Loamy loam	1,81	6,5	0 - 8
2 layer Siltstones	2,71	8,3	8 - 25
Layer 3 Aquartz sandstones	2,70	5,2	25 - 70
Layer 4 Fine-grained sandstones	2,75	5,2	70 - 100
5 layer Arkozovski sandstone	2,64	3,9	100 - 120
6 layer Siltstones raslantsic	2,73	4,5	120 - 180
7 layer Siltstones quartzed	2,75	4,7	180 - 200
8 layer Brecciated siltstones	2,74	5,4	200 - 230

Engineering-geological column of hole 106 based on sections VI-VI

Engineering geological element	Density, g/cm3	hardness	Depth, m
1 layer Crushed stone loam	2.73		0 - 5
Layer 2 Granodiorites	2.7	16	5 - 20
3 layer Orgovik	2.7	12	20 - 70
Layer 4 Quartz ores	2.73	18	70 - 120
5 layer Berezites	2.73	14	120 - 200
Layer 6 Lamprophyres	2.73	12	200 - 230

Engineering-geological column of hole 744 based on sections VIII-VIII

Engineering geological element	Density, g/cm3	hardness	Depth, m
1 layer Crushed stone loam	2.73		0 - 5
2 layer Granodiorites (water-bearing rocks)	2.70	12.7	5 - 13
Layer 3 Dykes (Metho) Lamprophyre	2.77	7.4	13 - 70
Layer 4 Granodiorites	2.69	10.5	70 - 230

Figure 8. Stratigraphic columns of wells No. 268, No. 106, No. 744 and physical and mechanical properties of rocks

In particular, the general picture of geological faults is clearly visible from profiles XLII-XLII and XLVI-XLVI profiles. Therefore, stratigraphic columns along each well were constructed based on data from each profile.

Analyzing the results of the stratigraphic columns formed along the specified profiles (Figures 1-4), where tectonic faults numbered 2, 4, 7, 12, and the main "Beskempir" fault are located, it is evident that the strength properties of the rock massif undergo significant changes (Figure 9).

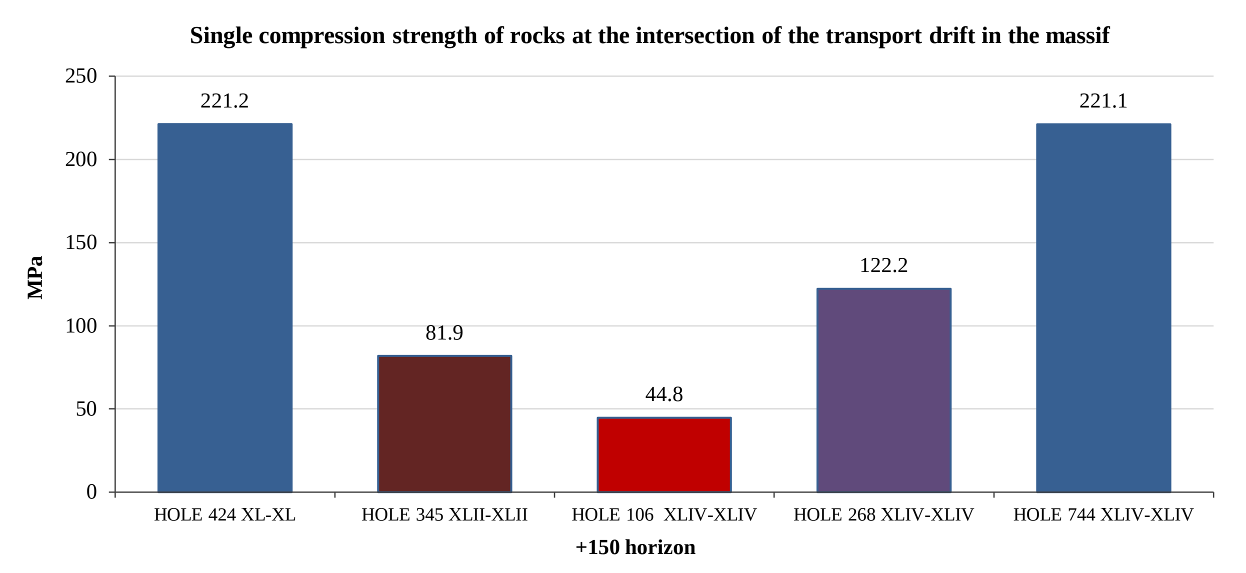


Figure 9. Uniaxial compressive strength of rocks intersected by underground mine workings

Figure 9 illustrates a significant variation in rock strength under uniaxial compression, ranging from 221.2 MPa to 44.8 MPa. This indicates that the stress-strain state of the rock massif within the tectonic fault zone is highly complex, leading to considerable changes in the potential rock shear and rock pressure affecting underground mine workings. Consequently, an in-depth study of the rock mass stability in this hazardous zone is essential.

5. Analyzing the Results of the Studies

To justify the selection of a rational support type for the transportation drift at the +150 m horizon in the "Surprise" vein of the Beskempirskoye deposit, a comprehensive analysis of the stress-strain state of the rock massif is conducted. This study employed three distinct methods: Z. Bieniawski's RMR classification, Barton's Q-method, and numerical modeling, along with a traditional approach based on building codes and regulations. The use of these methods was necessitated by the complex geological conditions, particularly the presence of fault zones, which required a comparative analysis to identify the most effective support system. The detailed results of each method are provided in the respective sections, with a summarized analysis presented at the end of this section and the conclusion.

5.1. Investigation of Rock Mass Stability Using Z. Bieniawski Method (Rock Mass Rating RMR)

To predict and assess the stability of the rock massif surrounding unconfined mine workings, the Rock Mass Rating (RMR) system proposed by Bieniawski was used. This method evaluates the potential for rockfall and delamination in the roofs of mine workings based on six key parameters. Each parameter is assigned a specific gradation corresponding to the characteristics of the assessed rock mass. A rating scale in points was applied to each gradation, allowing for a comprehensive assessment of mine working stability and the identification of necessary support measures [27, 28].

Samples were taken from boreholes No. 424, 345, 106, 268, and 744, which were located along the route of the mine workings. Based on the RMR rating, the stability classification of the rock mass according to Bieniawski was determined within a score range of 0–100. The obtained results are summarized in Tables 2 and 3 and illustrated in Figure 10.

Table 2. Results of the study of rock massif stability by the method of Z. Bieniawski

Parameters	No. 424 L_1=198	No. 345 L_2=50	No. 106 L_3=138	No. 268 L_4=50	No. 744 L_5=52
Rock uniaxial compressive strength, MPa	221	81.9	44.8	122.1	221.1
Strength coefficient	16	8	5.4	10.5	16
J_{A1}	12	7	4	9	12
J_{A2}	18	13	3	13	18
J_{A3}	15	10	6	8	15
J_{A4}	20	13	3	15	20
J_{A5}	14	13	5	13	14
J_B	0	0	0	0	0
RMR Massif Rating	79	56	21	58	79
Category of sustainability	Resistant rocks	Breeds of medium resistance	Very unstable rocks	Breeds of medium resistance	Resistant rocks
Massif class	II	III	V	III	II
Cohesion in the massif, MPa	0.3-0.4	0.2-0.3	< 0.1	0.2-0.3	0.3-0.4

Table 3. Stability and class of the rock massif

No. 424 L_1=198m	No. 345 L_2=50m	No. 106 L_3=138m	No. 268 L_4=50m	No. 744 L_5=52m
RMR =79	RMR =56	RMR =21	RMR =58	RMR =79
Resilient breeds	Medium resilient breeds	Very resilient breeds	Medium resilient breeds	Resilient breeds
II class	III class	V class	III class	II class

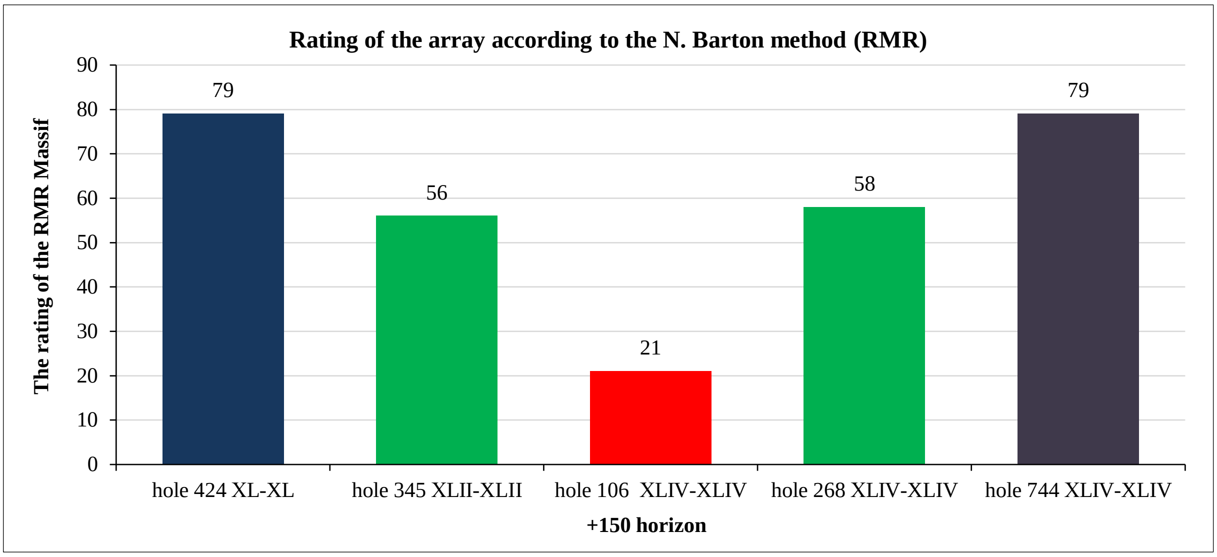


Figure 10. Results of rock mass stability research using Z. Bieniawski method

It has been established that the stability indicators of the rock massif where the mining drift is excavated fall into several categories according to the RMR rating of Z. Bieniawski. This means that, after analyzing the stability indicators of the rock massif at the +150 m horizon, where the "Drift" mine workings will be located, the area can be divided into three sections, each requiring a specific type of support construction adapted to its stability conditions.

In the same mine workings, two types of rock stability loss can be simultaneously observed: rock fallout along the weakened slopes of the massif and rock destruction due to high-acting stresses in the concentration zones. These forms of stability loss are not mutually exclusive and can occur simultaneously, further complicating the selection of appropriate support measures. Taking this factor into account, Hoek proposed a diagram (Figure 11) for selecting the type of fastening using two key parameters: the Rock Mass Rating (RMR) and the ratio of the maximum stress (σ_{max}) acting on the mine working contour to the compressive strength of the rock mass (σ_m).

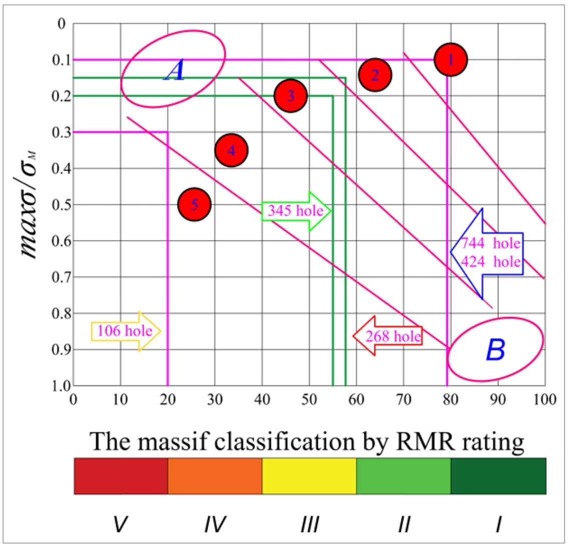


Figure 11. Hook's recommendations on the selection of the type of fastening depending on the RMR rating of the massif and the value of the maximum acting stresses on the mine workings contour: 1 - without fastening; 2 - light fastening; 3 - medium fastening (combined with metal mesh); 4 - heavy fastening (metal frame, monolithic concrete, reinforced concrete); 5 - maintenance of permanent mine workings are inexpedient; I, III, IIII, IIV, V - classes of massifs in terms of stability respectively very stable, stable, medium stable, unstable, very unstable. Areas of values in which the loss of rock stability in mine workings occurs in the form of A - slumps, delaminations, collapses on weakening slopes under the action of own weight, and B - destruction of rocks in stress concentration zones.

The ratio of RMR and σ_{max} / σ_M determines the form of rock stability loss in the mine workings. In unstable rocks (RMR up to 40 points) with a low level of acting stresses on the contour ($\sigma_{max}/\sigma_M \leq 0.3$), rock stability loss occurs in the form of block collapses of fractured, unstable rocks under their own weight. In contrast, in stable rocks (RMR above 60 points), stability loss occurs due to rock crushing along the contour under the influence of high acting stresses ($\sigma_{max}/\sigma_M \geq 0.7$).

According to the results obtained during the study (Table 4), the recommended types of support were determined using a graph (Figure 11), taking into account the degree of displacement of the rock massif (Figure 12).

Table 4. Results of the RMR rock mass stability study and recommended types of support construction

Hole number Length of separate section, m	No. 424 L_1=198	No. 345 L_2=50	No. 106 L_3=138	No. 268 L_4=50	No. 744 L_5=52
σ_{max} / σ_c	0.1	0.2	0.3	0.14	0.1
Sustainability category	Resistant rocks	Breeds of medium resistance	Very unstable rocks	Breeds of medium resistance	Resistant rocks
Fastener types recommended by the RMR rating	1-without bracing or 2-light bracing (2-3 cm thick shotcrete).	3-Medium strength (combined with metal mesh).	4-Heavy fasten (metal frame, monolithic concrete, reinforced concrete).	3-Medium strength (combined with metal mesh).	1-without bracing or 2-light bracing (2-3 cm thick sprayed concrete).

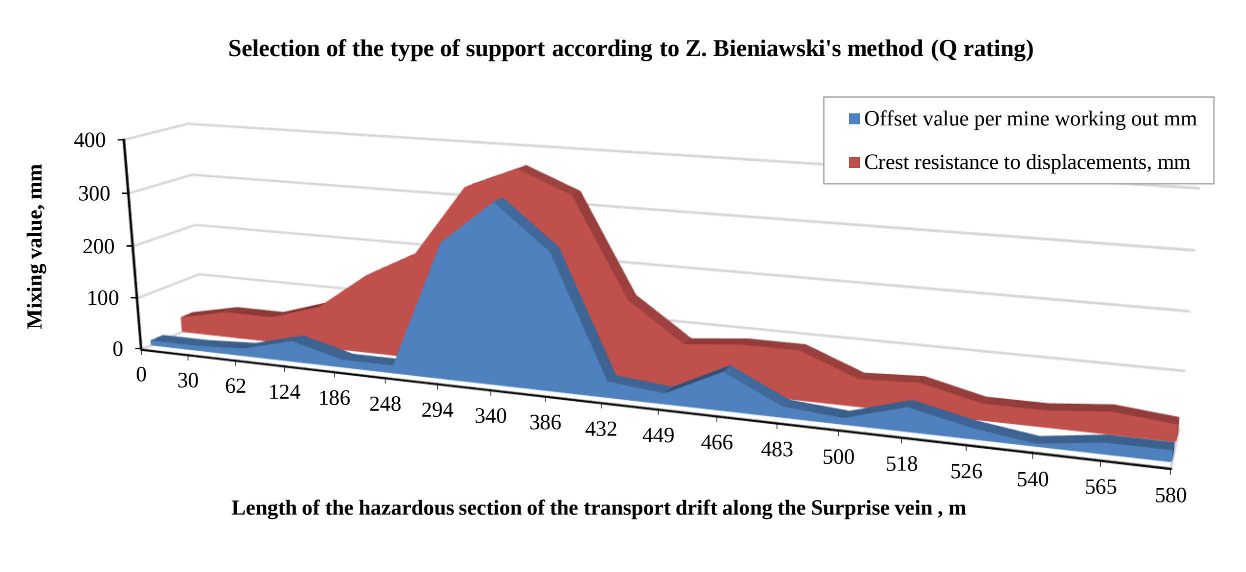


Figure 12. Dynamics of displacement of the dangerous section of the transport drift according to Bieniawski methodology

5.2. Assessment of Rock Mass Stability Using Bartons Empirical Method (Q-rating)

Barton's empirical method (Q-rating) assesses the impact of factors such as rock strength and quality, mining depth, cross-section of mine workings, stress state in the surrounding massif, and number and condition of fractures, including their degree of alteration. The rock stability rating Q was determined based on six key indicators. Consequently, stability indicators of the rock massif were established and appropriate methods for supporting and reinforcing mine workings were identified [29]. The compliance of the rock stability system, as defined by the Q rating interval indicator, with the current official technical operating rules (TOR) is presented in Table 5.

Table 5. Results of rock mass stability assessment study (Q-rating) using Barton's method

Number of holes Length of separate section, m	No. 424 L_1=198	No. 345 L_2=50	No. 106 L_3=138	No. 268 L_4=50	No. 744 L_5=52
Strength factor	16	8	5,4	10,5	16
Rock uniaxial compressive strength, MPa	221	81.9	44.8	122.1	221.1
RQD	80	60	30	70	80
Jn	0.8	3	4	3	0,8
Jr	3	1	1.5	1	3
Ja	0.75	2	3	2	0.75
Jw	1	0.5	0.5	0.5	1
SRF	1	5	7.5	5	1
Q	400	1	0.3	1.17	400
Class of rock massif	A (ext good)	D (poor)	E (very poor)	D (poor)	A (ext good)

The study determined the quality of array Q, an index that considers the main parameters of the massif, RQD, which characterizes the quality of the massif (structural disturbance), Jn is the number of crack systems, Jr is the crack surface roughness, J_a is the weathered and fracture state changes, J_w is the watered massif and fractures, and SRF is the stress state of the massif.

$$Q = \frac{RQD}{Jn} \times \frac{Jr}{Ja} \times \frac{Jw}{SRF} \quad (1)$$

The obtained pair parameters characterize the three main factors determining the stability of mine workings: RQD/J_n – c degree of massif disturbance (relative size of the structural block); J_r/ J_a the relative frictional resistance along cracks; J_r/ SRF – acting stress (considering the influence of water and disturbance).

The quality of the rock massif (structural disturbance) was assessed by determining the *RQD* both on outcrops of mine workings outside the area of cleaning operations and based on core material analysis.

RQD was calculated according to formula:

$$RQD = \frac{L_\Sigma}{L_v} \cdot 100\%, \quad (2)$$

where L_Σ is sum of lengths of distances between natural cracks in the investigated outcrop section with length more than 10 cm, m; and L_v is total length of the investigated section, m.

The results of the rock mass stability assessment using Barton's Q-rating method are presented in Table 5 and illustrated in Figures 13 to 16.

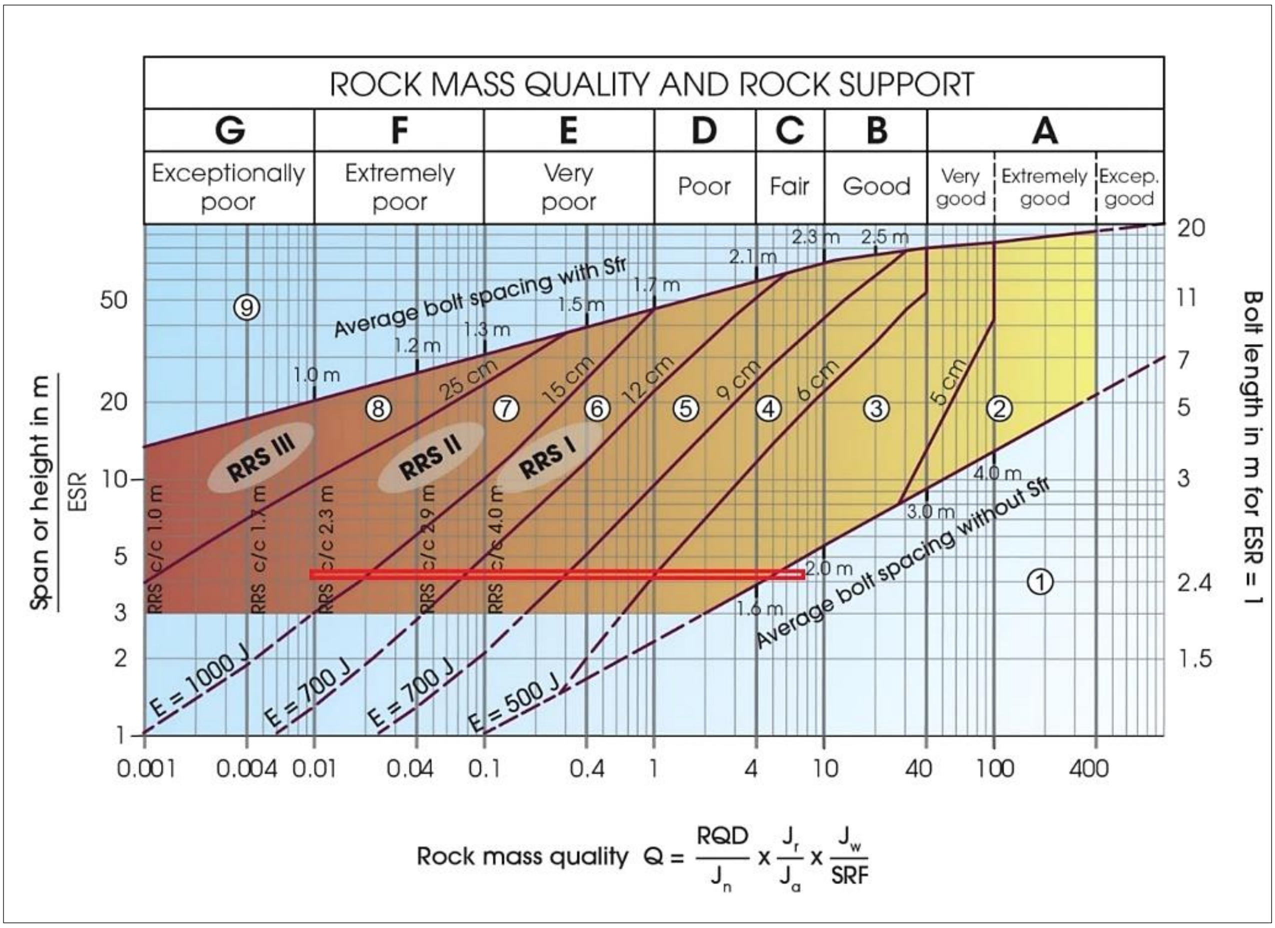


Figure 13. Diagram for determining the type of support for mine workings using Barton's method: 1- without fixing; 2- local fixing with anchors; 3- fixing with anchors; 4- support with anchors and 30–90 mm thick sprayed concrete; 5-fixing with anchors and 50–90 mm thick fiber-reinforced concrete; 6- anchoring with anchors and fibre reinforced concrete 90–120 mm thick; 7- anchoring with anchors and fibre reinforced concrete 120–150 mm thick; 8- anchoring with anchors, shotcrete, and metal arch bracing; 9- monolithic concrete bracing.

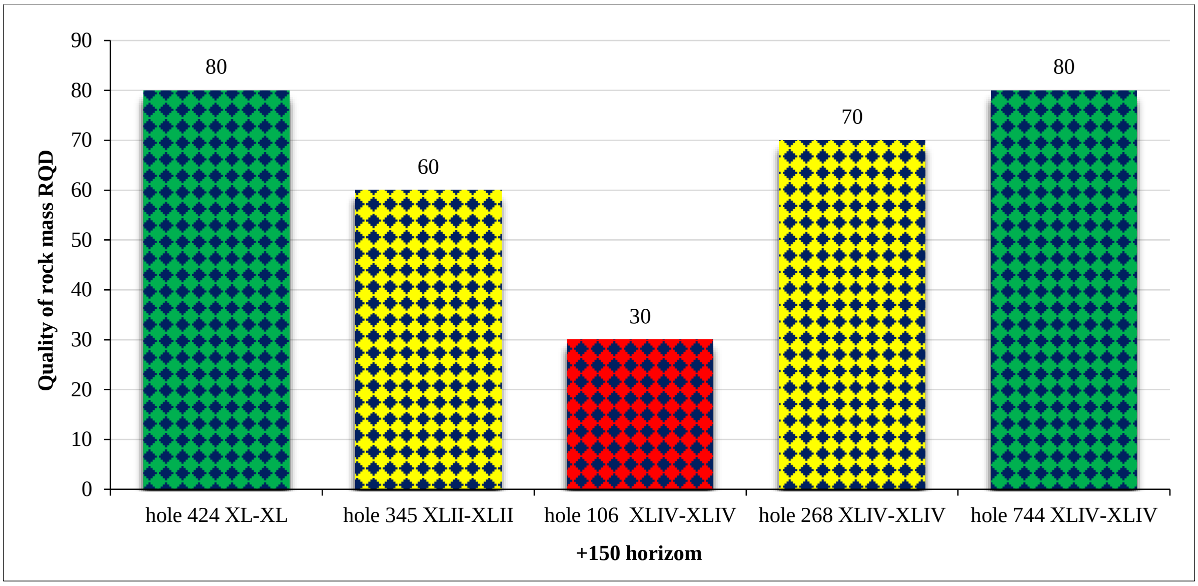


Figure 14. Quality of rock massif by Q rating

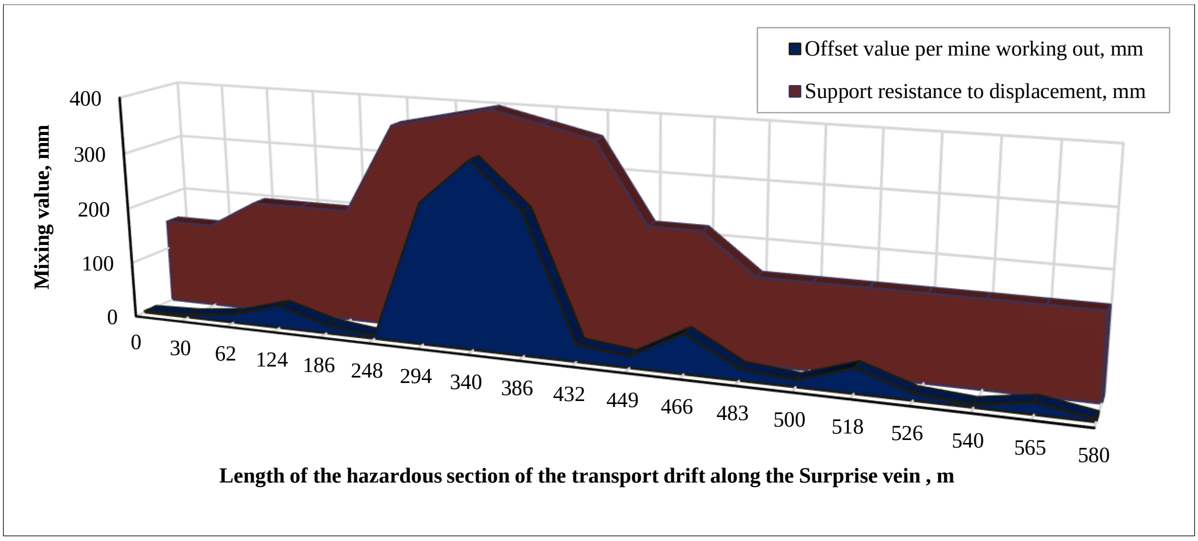


Figure 15. Dynamics of rock mass displacement at the dangerous section of the transport drift according to N. Barton's methodology

Hole, m	324 hole 198 m	245 hole 50 m	106 hole 138 m	268 hole 50 m	744 hole 52 m
Category	**A (ext. good)**	**D (poor)**	**E (very poor)**	**D (poor)**	**A (ext. good)**
Q rating	**400**	**1**	**0.3**	**1.17**	**400**

Figure 16. Rock massif class according to the RQD method

As shown in Figure 15, according to Barton's method, the design value of displacement (as per the Building Codes and Regulations) ranges from 5 mm to 380 mm, which was also considered when selecting the fastening methods.

Based on the evaluation of Q of the rock massif using the Barton method, the stability of the rock massif was classified into three different categories along the length of the mine workings: RQD = 80–90 corresponds to category A (extremely good) with more stable rocks, RQD = 60–80 corresponds to category D (poor) with medium stability, and RQD = 20–40 corresponds to category E (very poor) with unstable rocks (Figure 16).

Based on the analysis of rock mass stability using Barton's method (Q-rating), the rock massifs were classified into three categories (Figure 12). Therefore, a 3 cm thick sprayed concrete reinforcement is proposed for category A, anchoring with anchors and 5–9 cm thick sprayed concrete is recommended for category D, and a combined reinforcement system, including anchors, a metal mesh (5 cm × 5 cm), and 12–15 cm thick sprayed concrete, is recommended for category E.

5.3. Assessment of Stability of Rock Massif and Choice of Type of Support According to the Method of Construction Norms of the Republic of Kazakhstan

The selection of the type and calculation of parameters for horizontal and inclined mine workings should be based on the category of rock stability, considering the degree of impact from cleaning operations and other mine workings. As a criterion for determining rock stability categories, the displacement value (U) at the contour of the mine working cross section over its entire lifespan without support should be considered. The classification of mine workings into stability categories should be based on the absolute maximum displacement values of rocks at the cross-sectional contour, determined separately for the roof, floor, and sides of the mine workings [30].

The results of the studies on the assessment of rock mass stability and the selection of support types based on the methodology of construction norms and rules are presented in Table 6 and Figures 17 to 19.

Table 6. Recommended support according to the Construction norms of the Republic of Kazakhstan methodology

Category of rock mass stability	Recommended support
I category	In rocks of the I category of stability - anchor or poured-in-place concrete fasten with a thickness of not less than 30 mm. In monolithic, low-cracked rocks it is allowed to leave the mine workings without bracing.
II category	In rocks of II category of stability - monolithic concrete fasten, combined from poured concrete with thickness not less than S0 mm with anchors and metal mesh or without it, frame fasten from reinforced concrete posts with metal tops, prefabricated tubing, metal flexible fastens (supports) without a back vault, anchor-metal, metal arch fastens with poured concrete coating and tamping of the consolidation space.
III and IV categories	In rocks of III and IV stability categories prefabricated tubing and block, and with appropriate justification metal-concrete, metal malleable and anchor-metal support, while in soil rocks of I and II stability categories in the support of these types of back vaulting is not provided. In sedimentary rocks of soil of stability categories III and IV and in eruptive rocks of stability category IV, support should generally be back vaulted. In the rocks of III and IV stability categories, support without a back vault is allowed, but with the mandatory implementation of measures to reduce ground displacements by hardening the rocks by cementation, anchoring or unloading the massif.

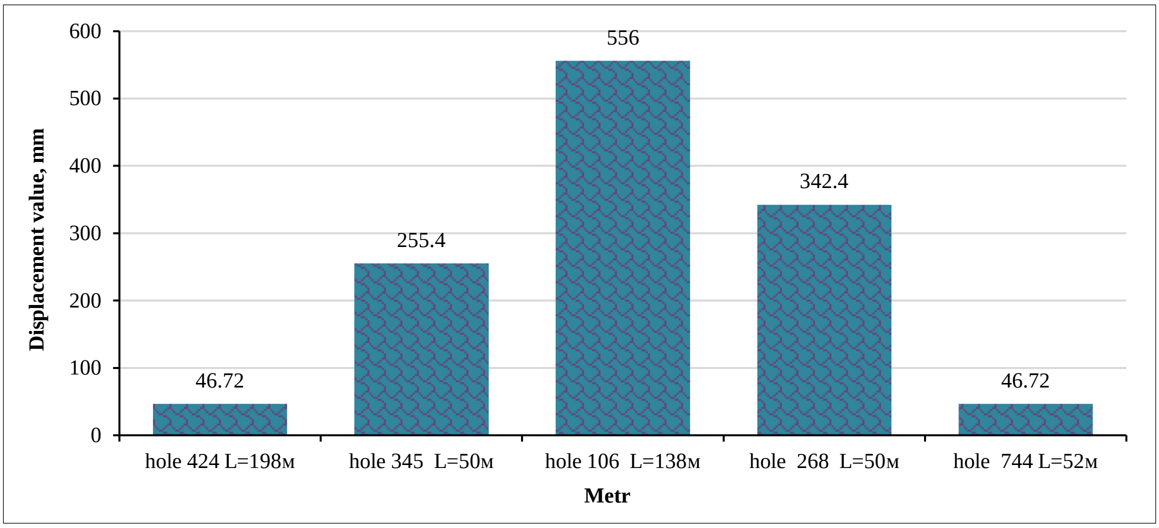


Figure 17. Displacement of rocks in the roofs along the length of the mine workings

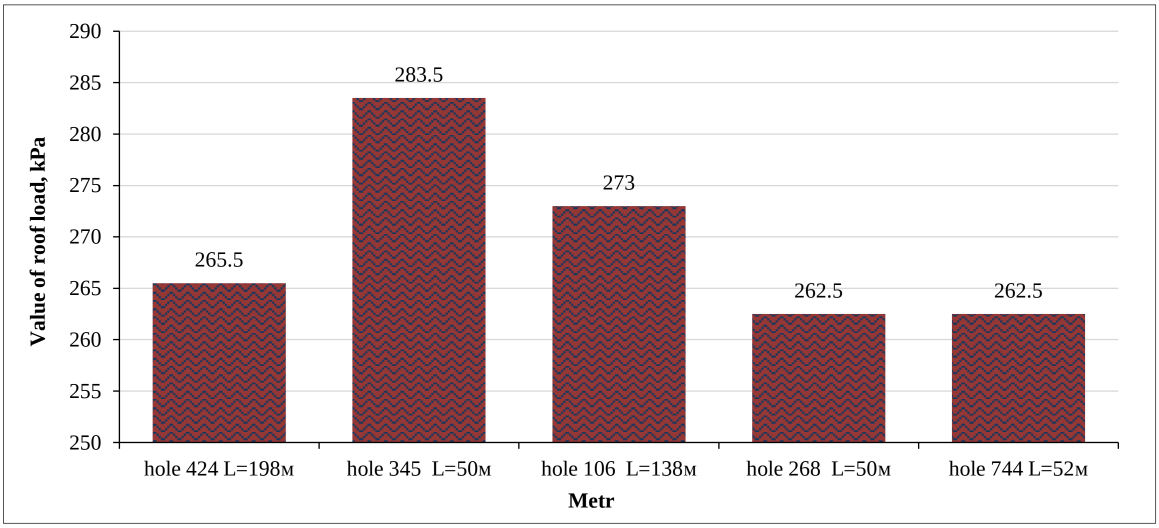


Figure 18. Estimated load on the transport drift fasten according to the methodology of Construction norms of the Republic of Kazakhstan

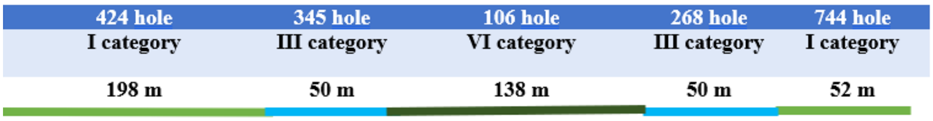


Figure 19. Categories of rock mass stability in the longitudinal conditions of mine workings

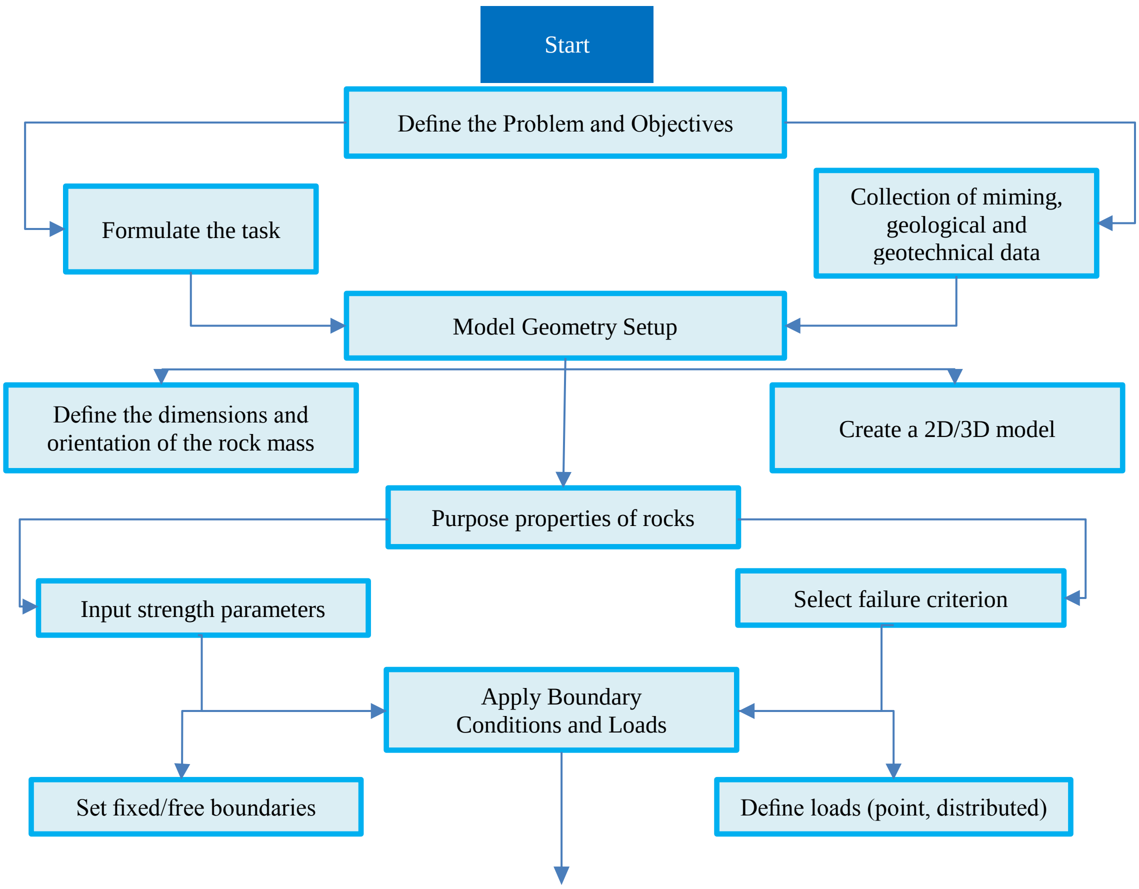
5.4. Estimation of Rock Mass Stability and Selection of the Type of Fasten by Means of Numerical Modelling Using Rocscience RS2/RS3 (Examine 2D/3D) Software Packages

The interaction between the support and rock massif, particularly when rock properties change rapidly along the length of the mine workings, presents a complex geomechanical challenge. Standard analytical methods are often unsuitable or highly labor-intensive. In such cases, mathematical modeling provides a more efficient approach for solving these problems. Therefore, numerical modeling studies have been conducted using Rocscience RS2/RS3 and Examine 2D software to analyze stability and support effectiveness [31-33].

Modeling the stress-strain state (STS) of a rock massif enables the assessment of stability variations along the route of underground mine workings. This approach not only helps identify zones prone to failure, but also allows for a detailed classification of the massif into sections based on their stability [19, 34].

For the numerical simulation of the stress-strain state (SS) of a rock massif using Rocscience RS2/RS3 software, a multi-stage approach is recommended, focusing on stability analysis and massif behavior prediction for each site, considering tectonic faulting. The first step involves defining the modeling problem, which may include evaluating the stability of mine workings, identifying stress concentration zones, or predicting massif failure. This is followed by the collection of geological and mining data, including rock properties, fault presence, and complex geomechanical conditions. Based on these inputs, a numerical model is developed that incorporates the boundary conditions, massif orientation, and configuration of the investigated mine workings.

In the subsequent modeling stage, key mine working parameters and rock mechanical properties, including the Young's modulus, Poisson's ratio, cohesion, internal friction angle, and tensile strength, were incorporated. The fixed and free boundaries of the model were established, and external loads, such as distributed stresses, point loads, and rock pressure, were applied. A mesh model was then generated to ensure calculation accuracy. The Shear Strength Reduction (SSR) method was employed to determine the stability factor, and the stress and displacement isolines were plotted to identify failure-prone zones. The final stage involves defining the stability assessment criteria and forming the basis for selecting an optimal support system. These results enhanced the accuracy of predicting rational support choices for the studied object. The flowchart in Figure 20 illustrates the complete step-by-step modeling process.



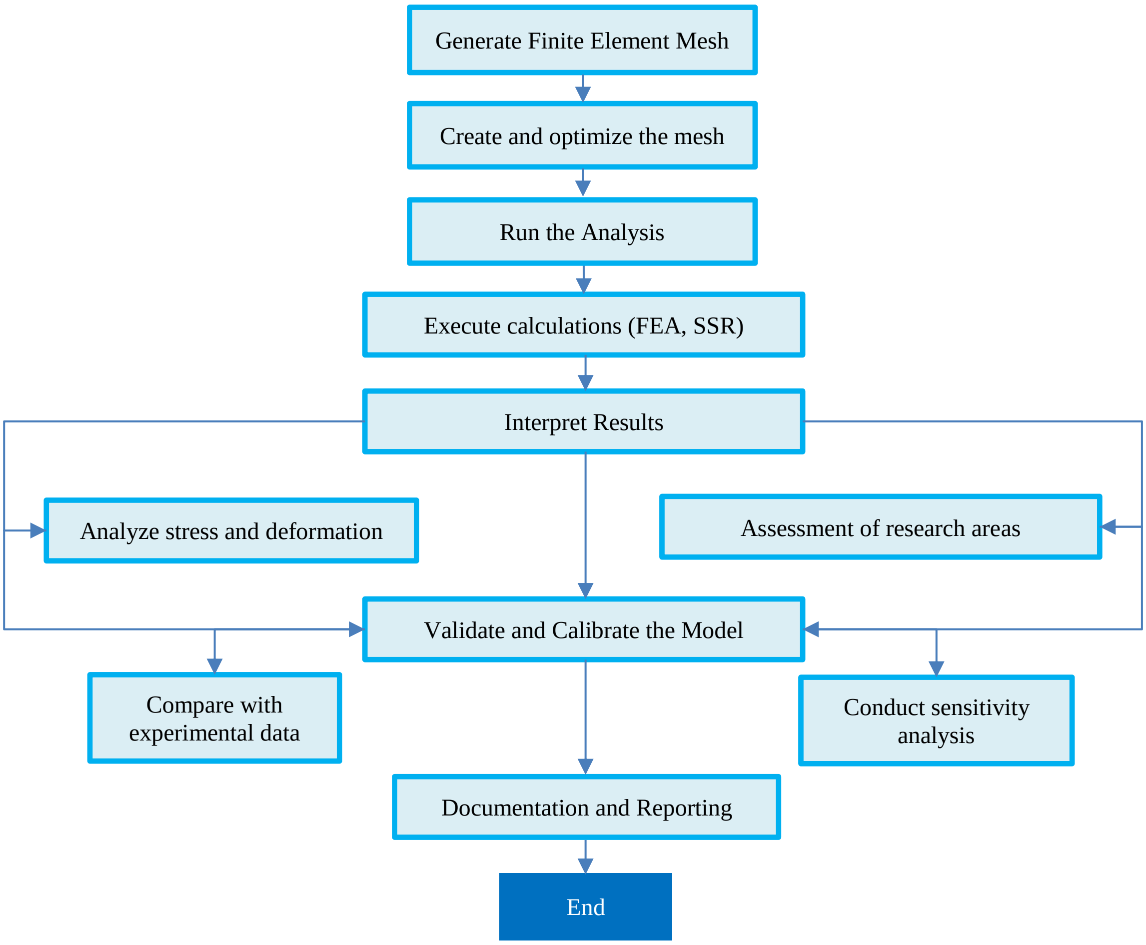
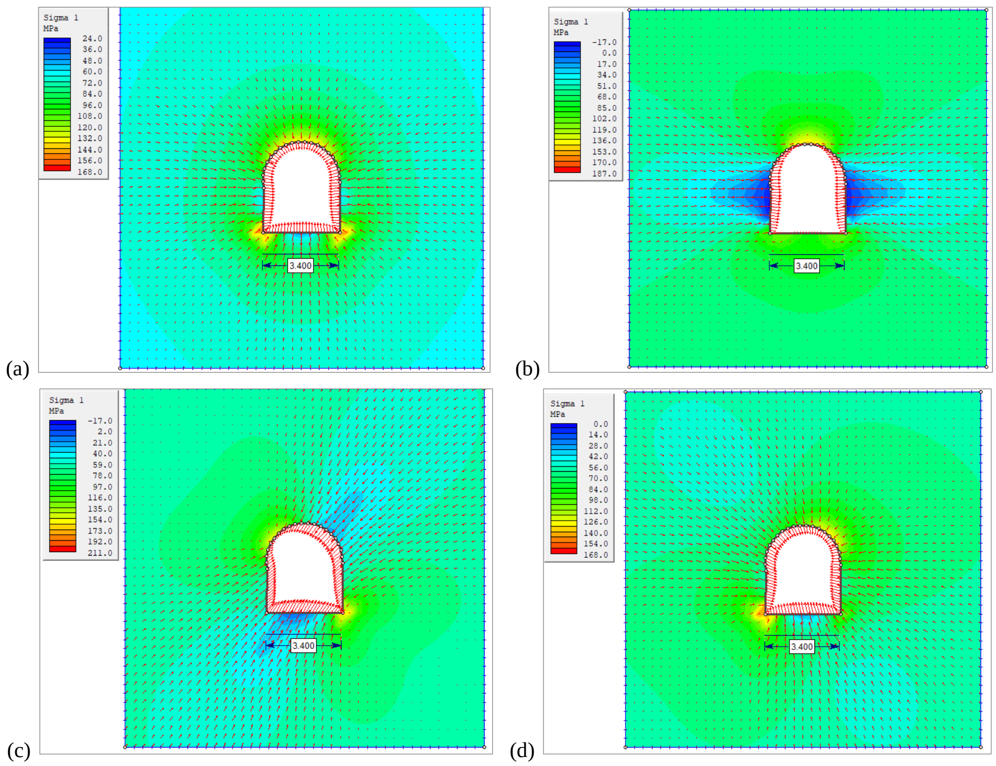
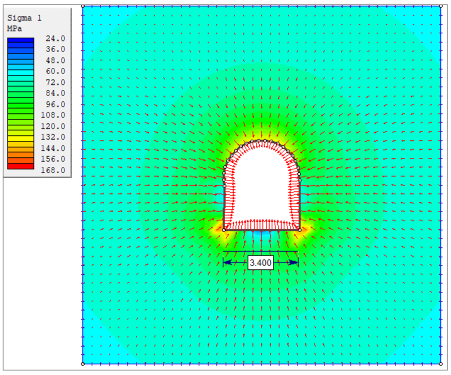


Figure 20. Block diagram of step-by-step modeling of stress-strain state of rock massif in Rocscience RS2 and RS3

In the Examine 2D program, a stress-strain state (STS) model of the transport drift was developed, incorporating the specified conditions for wells No. 424, 345, 106, 268, and 744. This model facilitates the identification of potential fracture zones and classifies rock massifs based on stability levels. Such an approach enhances mining safety and enables the development of effective strategies for managing rock-mass conditions. The results of this analysis are shown in Figure 21.





(e)

Figure 21. Model of the stress-strain state of the rock massif near the drift mine workings: (a) Stress-strain state of the massif around hole No. 424 along cross-section XL-XL (b) Stress-strain state of the massif around hole No. 345 in cross-section XLII-XLII (c) Stress-strain state of the massif around hole No. 106 (angle of incidence of tectonic fracture 57 degrees) in cross-section XLIV-XLIV (d) Stress-strain state of the massif around hole No. 268 (angle of incidence of tectonic fracture 57 degrees) in cross-section XLIV-XLIV (e) Stress-strain state of the massif around hole No. 744 in cross-sections XLVI-XLVI.

The raw data and input values used for the simulations in Rocscience RS2/RS3 and Examine 2D integrated programs are presented in Table 7.

Table 7. Input data and values entered the Rocscience RS2/RS3, Examine 2D integrated programme

Number of holes	Rock strength according to M. Protodyakonov's scale	Density, g/cm^3	Rock uniaxial compressive strength, MPa		Poisson's ratio	Parameters of mine workings
			dry	wet		
424	8-19	2.53-2.85	394-1660			Width, 3400 mm;
345	3.9-8.3	1.81-2.75	385-832	235-602	0.25-0.33	Height, 3450 mm
106	12-18	2.70-2.73	918-1629			Rectangular-vaulted shape
268	12-18	1.81-2.73	1390-1530		0.31	Mine workings cross-sectional area, 10.9 m^2
744	7.4-12.7	2.69-2.77	744-1660	938-2710	0.18-0.28	Type of mine workings – drifts

Studies on 1235odelling the stress-strain state (STS) of a rock massif using Rocscience RS2/RS3 and Examine 2D/3D complex programs have demonstrated that the design loads on the bracing primarily affect the right side of the roof (348 kPa) and the two lateral sides (275 kPa) of the mine workings. The 1235odelling process followed a structured approach: first, the unstable zones of the rock massif were identified, taking into account the dimensions of the tectonic fault "Beskempir" and the fracturing along the length of the mine workings. The distributions of the stable and unstable sections of the rock massif were then determined. As a result, the deformation propagation zones around the mine working contours were identified, enabling the tracking of rock behavior in the fault zone. This research established three main categories of rock stability based on the STS propagation model of the investigated massif. Figure 22 specifically highlights the fault influence zone (488 m), whereas the remaining 712 m of the mine workings are located in a stable rock massif of the 1st category, free of fractures.

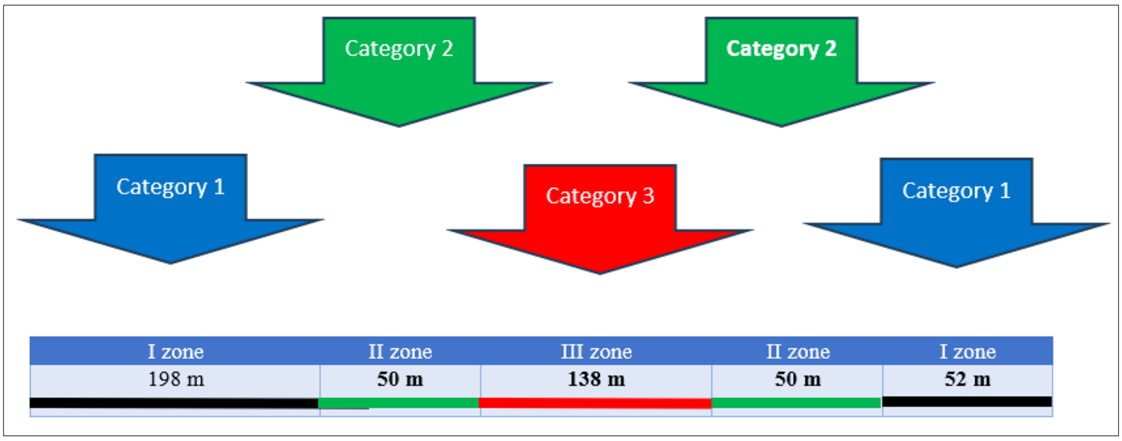


Figure 22. Separated categories of stable and unstable rock mass sections along the length of the mine workings (defined in Rocscience RS2/RS3 (Examine 2D/3D)

This study provides a rationale for the application of appropriate support systems for underground mine workings based on rock stability categories.

- Table rocks of the first category without fractures, no support is required, whereas for those with cracks, a 2–3 cm layer of sprayed concrete is recommended;
- Moderately resistant rocks of the second category require combined bracing consisting of anchors, a metal mesh, and a 5–10 cm layer of sprayed concrete;
- For unstable rocks in the third category, monolithic concrete supports with a thickness of up to 300 mm are necessary to ensure stability and safety in mine workings.

5.5. Comparative Analysis of Traditional and Proposed New Innovative Methods

According to the traditional method regulated by construction norms, a monolithic concrete support with a thickness of 0.3 m is recommended for the 1200 m long transportation drift. However, this approach involves high labor intensity and significant economic costs. In contrast, the results obtained using the Bieniawski and Barton Q-rating methods suggest that a more efficient solution would be the use of combined bracing systems, which better reflect the actual stability of the rock massif. This alternative approach optimizes both the safety and cost-effectiveness.

Analysis of the stress-strain state of the massif revealed varying degrees of rock stability along the drift. To ensure rational selection of support, a numerical modeling assessment was conducted using the Rocscience RS2/RS3 software package. The modeling process enabled the differentiation of stable and unstable sections of the massif, allowing for the application of appropriate support types based on the specific stability conditions of each section.

The research findings indicate that out of the 1200 m of mine workings, 488 m fall into the category of unstable sections. To ensure stability, a combined support system comprising anchoring and sprayed concrete (nabryzgcrete) is recommended, offering a rational balance between reliability and economic efficiency. A comparative analysis of the traditional monolithic concrete support versus the proposed combined system (nabryzgcrete + anchor), considering economic aspects (Table 8, Figure 23), confirmed the rationality of this approach.

Table 8. Techno-economic comparative analysis indicators

Indicators	Traditional existing Building Codes and Regulations reinforcement (monolithic concrete reinforcement)	Recommended rational support (fasteners) using combined fasteners (new method)
Cross-sectional area of mine workings in sinking, m^2	14.2	14.2
The cross-sectional area of the mine workings in clear view (after the construction of fasteners), m^2	12.5	13.3
Length of mine workings, L, m	1200	1200
Cost of 1 m^3 of concrete mix, dollar, ($)	41.4 $	-
Volume of sprayed concrete mixture used for 1200 m long mine workings using the traditional method, (m^3)	2040	-
Total cost of materials for (support) fixing a 1200 m long mine workings by conventional method with monolithic concrete support, US dollar ($)	844 560	-
Cost of 1 m^3 of sprayed concrete mix, dollar, ($)	-	40.4
Volume of sprayed concrete mixture used for 1200 m long mine workings according to the new method, (m^3)	-	779.4
Consumption of sprayed concrete mix for 1200 m long mine workings, dollar, ($)	-	31176
Cost of anchor 1 piece, dollar, ($)	-	17.3
Total consumption of anchorages, pieces	-	1320
Consumption of anchorages used per 1200 m mine workings, dollar, ($)	-	22836
Cost of 1 m^2 of metal mesh, dollar, ($)	-	0.9
Total consumption of metal mesh, for 1200 m long mine workings (metal mesh is used only for fixing (fastening) the roof and upper side of mine workings), (m^2)	-	1071
Metal mesh consumption per 1200 m mine workings, dollar, ($)	-	963.9
Total consumption of materials for fixing a 1200 m long mine workings using a new method of combined fixing (anchors with metal mesh and sprayed concrete), US dollar ($)	-	55 000

Note: Conversion from tenge to dollars is calculated on 24.01.2025.

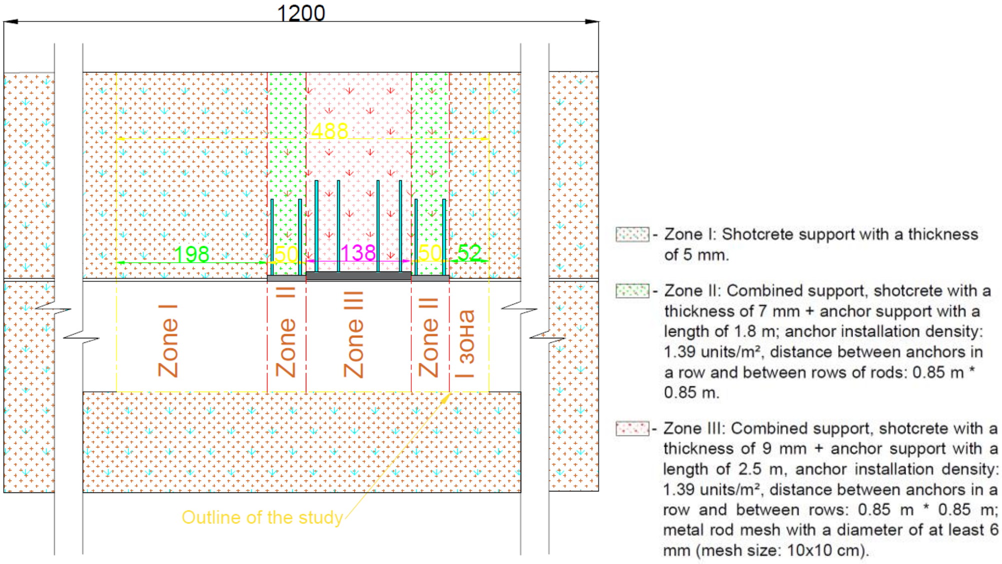


Figure 23. Design of the recommended support (new method)

Thus, the results of the conducted studies demonstrate that the implementation of the recommended support designs enhances the stability of mine workings, ensures operational safety, and reduces construction costs, making this method a rational choice for given mining and geological conditions. The results of the study are recommended and approved for implementation in underground mine workings of the Beskempirskoye deposit (Kazakhstan). Currently, the proposed combined support systems have been successfully introduced and are actively used in mine workings.

6. Discussion

Hazardous areas were identified and classified into three sections. Currently, the Beskempir deposit employs monolithic concrete support in accordance with Building Codes and Regulations for the entire 1200 m length of the mine workings (Figure 24). Although this support system is highly reliable and stable, its construction requires significant labor at all stages, including preparation, formwork installation, reinforcement, concreting, and maintenance. Additionally, the cost of monolithic concrete supports is considerably higher than that of recommended combined support systems.

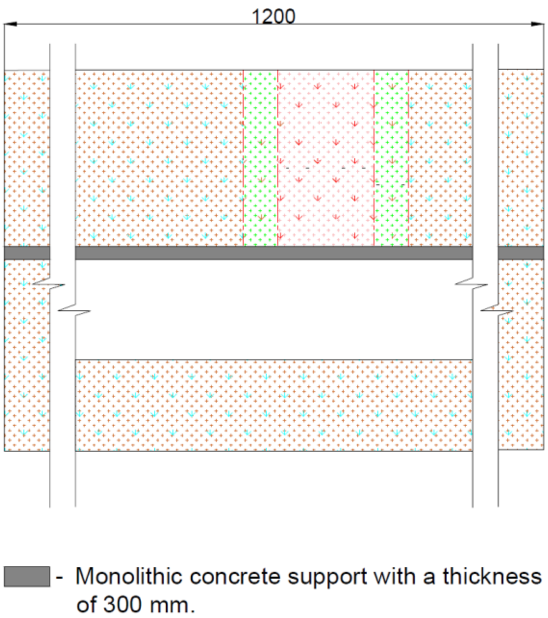


Figure 24. Design of the existing monolithic concrete support structure

Figure 23 illustrates the recommended design of the combined support, which is optimally suited to the current loads. This design ensures reliability while being more cost-effective and less labor-intensive than monolithic concrete supports.

Further studies should focus on evaluating the economic efficiency of the proposed support structures. A comparative analysis was conducted by calculating the material consumption of both types of supports. The results presented in Table 1 confirm that the recommended combined support system is not only highly reliable but also economically advantageous (Figure 25).

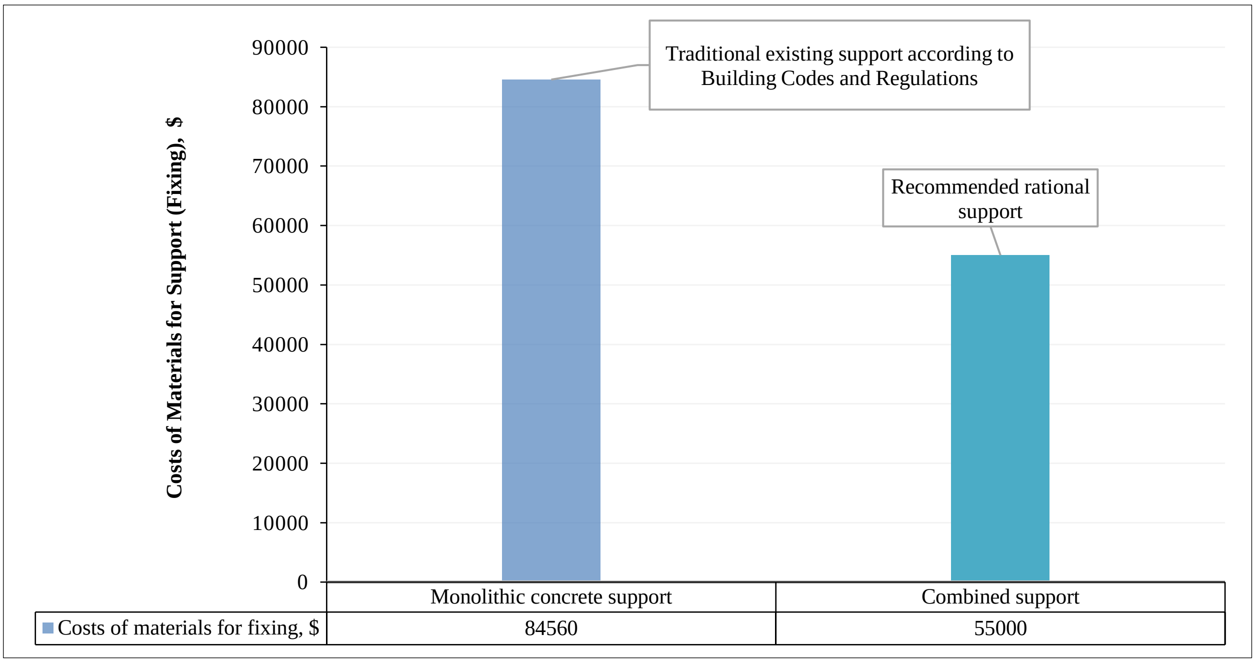


Figure 25. Diagram of comparative technical and economic indicators of materials used for supports

The results of this study propose a novel approach for selecting a rational, load-regulated support system designed to effectively stabilize horizontal mine workings. These findings confirm the advantages of the recommended support design, which enhances reliability and is more cost-effective, thereby contributing to the optimization of deposit development. It has been established that using adjustable resistance supports, compared to traditional monolithic concrete supports, accelerates the rate of mine workings by 1.4 times and reduces costs by a factor of 1.5.

7. Conclusions

7.1. Research Novelty

The scientific novelty of this study lies in the development of optimized support solutions for mine workings operating under complex mining and geological conditions. This study introduces a new approach for selecting support structures based on a detailed analysis of the stress-strain state of a rock massif. The proposed method enhances the rate of mine working penetration by 1.4 times, reduces capital expenditures on support by a factor of 1.5, and improves mining safety, making a significant contribution to both the theoretical and practical aspects of mining engineering.

7.2. Theoretical Contribution

The study of rock mass stability and support selection was conducted using three different methods, allowing for a more precise assessment of rock stability under various mining, geological, and engineering conditions. The application of the Bieniawski, Barton, and building codes enabled the classification of rock mass into multiple stability categories, leading to the recommendation of appropriate support designs for each zone. These methods optimize the selection of support types based on the geomechanical characteristics of the rocks, increasing the penetration rate by 1.4 times and reducing support costs by a factor of 1.5. Furthermore, numerical modeling of the stress-strain state using Rocscience RS2/RS3 software enhanced the understanding of rock-support interaction, providing a foundation for future research and improvements in underground support design methodologies.

7.3. Practical Significance

The practical significance of this study lies in the development of methods and technologies that ensure effective and safe support of mine workings under complex mining and geological conditions. The recommendations for selecting support structures based on geomechanical analysis of rock massifs enhance both the safety and economic efficiency of mining operations. This contributes to the overall improvement of mining enterprises by reducing material and labor costs while increasing productivity.

7.4. Research Limitations

The results of this research on selecting support systems for mine workings under complex mining and geological conditions can be widely applied in the design and construction of support structures for mining enterprises specializing in solid mineral deposits. However, their practical application must consider the specific mining geological, hydrogeological, and geomechanical conditions of each deposit, as these factors can influence the choice and effectiveness of support systems. Additionally, when applying this research methodology to layered coal massifs, it is crucial to account for gas dynamic conditions, including gas release from the massif, because these factors can significantly impact the stress-strain state of rocks and the stability of mine workings.

7.5. Future Research Directions

A detailed study of the rational parameters of support structures for underground mine workings is essential for enhancing their efficiency and reliability under complex mining and geological conditions. A promising direction for future research is the development of innovative support types, introduction of new high-strength and adaptive support materials, and improvement of construction technologies. These advancements contribute to optimizing support systems, increasing mine safety, and reducing operational costs.

Future research should focus on developing concrete compositions with high resistance to aggressive underground environments, particularly under conditions of high-water inflow, significant rock pressure, and chemical influences. Enhancing the adhesion and bonding properties of concrete is crucial for ensuring a reliable interaction with the rock massif. By improving these characteristics, support structures can be made more durable and effective, ultimately enhancing the stability and safety of underground mine working.

To achieve this goal, a comprehensive approach is necessary, involving the optimization of concrete mix compositions, selection of effective chemical and mineral additives, and in-depth study of the adhesive interaction mechanisms with various rock types. The implementation of such advanced materials will enhance the stability and durability of mine support structures, minimize the risks of deformation and failure, and significantly improve the safety of underground operations in complex mining and geological conditions

8. Declarations

8.1. Author Contributions

Conceptualization, T.A., R.Z., M.S., and D.S.; methodology, T.A., R.Z., M.S., and D.S; software, T.A. and R.Z.; validation, T.A. and R.Z.; formal analysis, T.A. and R.Z.; investigation, T.A. and R.Z.; resources, T.A. and R.Z.; data curation, T.A. and R.Z.; writing—original draft preparation, T.A., R.Z., M.D., and DM.S.; writing—review and editing, T.A., R.Z., M.D., and DM.S.; visualization, T.A. and R.Z.; supervision, T.A. and R.Z.; project administration, T.A. and R.Z.; funding acquisition, T.A. and R.Z. All authors have read and agreed to the published version of the manuscript.

8.2. Data Availability Statement

The data presented in this study are available in the article.

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8.4. Conflicts of Interest

The authors declare no conflict of interest.

9. References

[1] Makhanov B. (2022). Sustainability Report "Golden Prospects for a Sustainable Future 2022" Joint Stock Company "AK Altynalmas", p. 114. Available online: https://www.altynalmas.kz/inform/reports (accessed on February 2025).

[2] Begalinov, A., Almenov, T., Zhanakova, R., & Bektur, B. (2020). Analysis of the stress deformed state of rocks around the haulage roadway of the beskempir field (Kazakhstan). Mining of Mineral Deposits, 14(3), 28–36. doi:10.33271/mining14.03.028.

[3] Bakhramov, B., Begalinov, A., & Almenov et al. (2015). Method of development of steeply falling vein deposits. Patent No. 30460 for Invention of the Republic of Kazakhstan, Astana, Kazakhstan.

[4] Begalinov, A., Serdaliev, E., Almenov, T., Iskakov, E., Amanzholov, D., & Bahramov, B. (2012). Improvement of mining of gold-bearing ores of Akbakai ore field. Mining Journal of Kazakhstan, 12, 4–8.

[5] AK Altynalmas JSC (ALMS). (2020). Stripping and development of reserves of Beskempir and Aksakal deposits. Kazakhstan Stock Exchange JSC, Almaty, Republic of Kazakhstan.

[6] Korchak, S. A., Abaturova, I. V., Savintsev, I. A., & Storozhenko, L. A. (2021). Methodology for Studying the Fracturing of Rock Massifs at Different Stages of the study of Mineral Deposits. Engineering and Mining Geophysics 2021, 1–11. doi:10.3997/2214-4609.202152066.

[7] Makhanov B. (2023). Sustainability Report "Golden Prospects for a Sustainable Future 2023" Joint Stock Company "AK Altynalmas", p. 114. Available online: https://www.altynalmas.kz/inform/reports (accessed on February 2025).

[8] Matayev, A., Abdiev, A., Kydrashov, A., Musin, A., Khvatina, N., & Kaumetova, D. (2021). Research into technology of fastening the mine workings in the conditions of unstable masses. Mining of Mineral Deposits, 15(3), 78–86. doi:10.33271/MINING15.03.078.

[9] Yu, M., Zuo, J., Sun, Y., Mi, C., & Li, Z. (2022). Investigation on fracture models and ground pressure distribution of thick hard rock strata including weak interlayer. International Journal of Mining Science and Technology, 32(1), 137–153. doi:10.1016/j.ijmst.2021.10.009.

[10] Elrawy, W. R., Abdelhaffez, G. S., & Saleem, H. A. (2020). Stability assessment of underground openings using different rock support systems. Mining Geology and Petroleum Journal, 35(1), 49–64. doi:10.17794/rgn.2020.1.5.

[11] Feng, G., & Wang, P. (2020). Simulation of recovery of upper remnant coal pillar while mining the ultra-close lower panel using longwall top coal caving. International Journal of Mining Science and Technology, 30(1), 55–61. doi:10.1016/j.ijmst.2019.12.017.

[12] Abramkin, N. I., Mansurov, P. A., & Kuzina, A. V. (2024). Rationale for underground coal combustion. AIP Conference Proceedings, 3183, 080001. doi:10.1063/5.0244068.

[13] Ligotsky, D. N., & Argimbaeva, K. V. (2023). Effect of grain size distribution of tailings during the formation of technogenic deposit on the fragmentation index. Sustainable Development of Mountain Territories, 15(2), 275–282. doi:10.21177/1998-4502-2023-15-2-275-282.

[14] Waqar, M. F., Guo, S., & Qi, S. (2023). A Comprehensive Review of Mechanisms, Predictive Techniques, and Control Strategies of Rockburst. Applied Sciences (Switzerland), 13(6), 3950. doi:10.3390/app13063950.

[15] Yu, X., Lv, S., Luo, Y., Liu, P., Fu, H., & Zhou, Y. (2024). Research on Support Technology for Unstable Roof Roadway Under Abandoned Roadways in Ultra-Thick Coal Seam. Processes, 12(12), 2886. doi:10.3390/pr12122886.

[16] Ren, H., Dai, L., Pan, Y., Wang, A., & Xiao, Y. (2025). Instability mechanism of composite structure involved coal pillar and key strata induced by multi-face mining. Geomatics, Natural Hazards and Risk, 16(1), 2453085. doi:10.1080/19475705.2025.2453085.

[17] Zhang, L. (2004). Drilled shafts in rock: analysis and design. CRC Press, London, United Kingdom. doi:10.1201/9780203024423.

[18] Yussupov, K., Aben, E., Akhmetkanov, D., Aben, K., & Yussupova, S. (2023). Investigation of the solid oxidizer effect on the metal geotechnology efficiency. Mining of Mineral Deposits, 17(4), 12–17. doi:10.33271/mining17.04.012.

[19] Petlovanyi, M., Sai, K., Khalymendyk, O., Borysovska, O., & Sherstiuk, Y. (2023). Analytical research of the parameters and characteristics of new "quarry cavities – backfill material" systems: Case study of Ukraine. Mining of Mineral Deposits, 17(3), 126–139. doi:10.33271/mining17.03.126.

[20] Elbialy, S., Elfarnsawy, M., Salah, M., Abdel-Aziz, A., & Ibrahim, W. (2025). An Experimental Study on Steel Fiber Effects in High-Strength Concrete Slabs. Civil Engineering Journal (Iran), 11(1), 215–229. doi:10.28991/CEJ-2025-011-01-013.

[21] Akpanbayeva, A., & Issabek, T. (2023). Assessing a natural field of rock mass stress by means of in-situ measurements within Vostochnaya Sary-Oba deposit in Kazakhstan. Mining of Mineral Deposits, 17(3), 56–66. doi:10.33271/mining17.03.056.

[22] Izotova, V., Pankratova, K., & Pospehov, G. (2019). Analysis of the Vibration Impact on the Soils of Vasilyevsky Island of St. Petersburg. Akustika, 32, 332–334. doi:10.36336/akustika201932332.

[23] Akishev, K. M., Aryngazin, K. S., Tleulessov, K., Bulyga, L. L., & Stanevich, V. T. (2024). The Use of Simulation Modeling in Calculating the Productivity of the Technological System for the Production of Building Products with Fillers from Man-Made Waste. News of the National Academy of Sciences of the Republic of Kazakhstan, Series of Geology and Technical Sciences, 2024(4), 22–32. doi:10.32014/2024.2518-170X.422.

[24] Al-Fasih, M. Y. M., Edris, W. F., Elbialy, S., Marsono, A. K., & Al Sayed, A. A. K. A. (2024). Lateral Displacement Behavior of IBS Precast Concrete Elements Reinforced with Dual System. Civil Engineering Journal (Iran), 10(1), 317–335. doi:10.28991/CEJ-2024-010-01-020.

[25] Mnzool, M., Al-Mukhtar, A., Majeed, A. J., Arafat, A., & Gomaa, E. (2024). Simulation and performance characteristics of rock with borehole using Visual Finite Element Analysis. Mining of Mineral Deposits, 18(3), 33–41. doi:10.33271/mining18.03.033.

[26] Demin, V., Khalikova, E., Rabatuly, M., Amanzholov, Z., Zhumabekova, A., Syzdykbaeva, D., Bakhmagambetova, G., & Yelzhanov, Y. (2024). Research into mine working fastening technology in the zones of increased rock pressure behind the longwall face to ensure safe mining operations. Mining of Mineral Deposits, 18(1), 27–36. doi:10.33271/mining18.01.027.

[27] Imashev, A., Suimbayeva, A., Zhunusbekova, G., Adoko, A. C., & Issakov, B. (2024). Assessing stability of mine workings driven in stratified rock mass. Mining of Mineral Deposits, 18(1), 82–88. doi:10.33271/mining18.01.082.

[28] Cheremisina, O. V., Vasiliev, R. E., Netrusov, A. O., & Ter-Oganesyants, A. K. (2024). Hot Curing and Lime Boiling of High-Arsenic Copper Concentrate Pressure Oxidation Product and Their Effect on Precious Metals Recovery During Subsequent Cyanidation. Tsvetnye Metally, 2024(2), 19–26. doi:10.17580/tsm.2024.02.02.

[29] Burtan, Z., & Chlebowski, D. (2022). The Effect of Mining Remnants on Elastic Strain Energy Arising in the Tremor-Inducing Layer. Energies, 15(16), 6031. doi:10.3390/en15166031.

[30] SN RK 2.03-04-2020. (2020). Construction norms and rules. Underground Mine Workings, Republic of Kazakhstan, Astana, Kazakhstan.

[31] Rocscience Inc. (2021). User Manual for modelling and analysis of slopes, surface and underground mine workings, groundwater filtration, consolidation. Rocscience Inc., Toronto, Canada.

[32] Rocscience RS2 11.0. (2020). RS2 Version 11.0 - Finite Element Analysis for Excavations and Slopes. Rocscience Inc., Toronto, Canada.

[33] Van Kien, D., Anh, D. N., & Thai, D. N. (2022). Numerical Simulation of the Stability of Rock Mass around Large Underground Cavern. Civil Engineering Journal (Iran), 8(1), 81–91. doi:10.28991/CEJ-2022-08-01-06.

[34] Matayev, A. K., Lozynskyi, V. H., Musin, A., Abdrashev, R. M., Kuantay, A. S., & Kuandykova, A. N. (2021). Substantiating the optimal type of mine working fastening based on mathematical modeling of the stress condition of underground structures. Scientific Bulletin of the National Mining University, 2021(3), 57–63. doi:10.33271/nvngu/2021-3/057.