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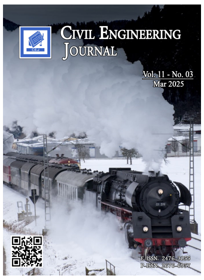
Civil Engineering Journal

(E-ISSN: 2476-3055; ISSN: 2676-6957)

Vol. 11, No. 03, March, 2025



Advanced Digital Modeling of Stress–Strain Behavior in Rock Masses to Ensure Stability of Underground Mine Workings

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Received 30 November 2024; Revised 11 February 2025; Accepted 17 February 2025; Published 01 March 2025

Abstract

This study focuses on optimizing underground support systems through advanced numerical modeling and geomechanical assessment. The research aims to refine reinforcement parameters for underground mine workings by analyzing the stress-strain behavior of rock masses using Rocscience RS2 software. The study integrates geological and geotechnical data, including field observations and numerical simulations, to enhance the accuracy of support system designs. The methodology is based on the finite element method (FEM) and the Hoek–Brown softening model, allowing the identification of plastic deformation zones and stress redistribution patterns. The results confirm that maximum stress increases by 35–40% for every 100 m of depth, necessitating enhanced reinforcement. The study evaluates hybrid support systems, specifically steel-polymer bolts with shotcrete, demonstrating a 15% reduction in plastic deformations compared to conventional methods. The findings highlight the importance of continuous geotechnical monitoring and adaptive reinforcement strategies to ensure stability in highly fractured rock masses. The proposed approach provides a more precise prediction of excavation stability, contributing to the development of safer and more efficient underground mining practices. Future research may include the integration of intelligent monitoring systems equipped with real-time sensors to further optimize support strategies and long-term stability assessments.

Keywords: Numerical Modeling of the Stress State; Finite Element Method; Hybrid Support Systems; Support System Optimization; Rock Mass Geomechanics; Geological Strength Index; Rock Mechanics; Mine Workings Safety.

1. Introduction

The current state of support systems for underground mine workings can be described as a sequential process that includes the installation, maintenance, repair, and restoration of supports during underground mining operations. Mining is regarded as a techno-natural system, where the environment is the primary subject of extraction. This environment is affected by technological processes and equipment required for resource extraction. Successful risk management in such systems requires integrating natural, technical, social, and organizational aspects. The integration of advanced digital tools and numerical modeling techniques into geotechnical research is a crucial step toward addressing the challenges posed by increasing mining depths and complex geological structures. Within the framework of sustainable mining practices, the development of robust support systems through predictive modeling ensures the safety and stability of underground mine workings. This approach aligns with the objectives of optimizing resource extraction while minimizing environmental and operational risks.

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http://dx.doi.org/10.28991/CEJ-2025-011-03-014

A key factor in managing risks is determining the appropriate type of support and developing measures to prevent rockbursts, collapses, and delaminations. These elements are essential for building an effective system to manage technological risks in underground mines. A detailed analysis of rock mass fracturing and stress-strain behavior helps identify zones of increased stress, minimizing risks to the stability of mine workings and ensuring worker safety. As modeling has shown, rock stability decreases significantly at depths exceeding 300 m, where stress levels rise by 35–40% for every 100 m of depth, necessitating reinforced support.

Recent studies have highlighted that traditional support systems may not always provide sufficient stability, especially in complex geological conditions [1]. Advanced numerical modeling techniques, including the finite element method (FEM), have significantly improved the accuracy of stress distribution analysis in underground workings [2]. However, existing approaches often overlook the dynamic interaction between excavation-induced stresses and surrounding rock masses, leading to an increased likelihood of unforeseen failures [3]. The role of geomechanical assessments has become increasingly vital in ensuring safe mining operations. Studies show that incorporating real-time monitoring and adaptive reinforcement strategies can enhance the long-term stability of mine workings [4]. Furthermore, research on the Geological Strength Index (GSI) suggests that rock mass behavior varies significantly with depth and stress redistribution, emphasizing the need for site-specific reinforcement solutions [5]. Despite these advancements, gaps remain in integrating adaptive reinforcement technologies with digital modeling techniques, which this study aims to address.

Recent research has also indicated that traditional support methods must be reevaluated in light of new findings regarding stress redistribution and long-term deformation effects in deep mining environments [6, 7]. For instance, combining numerical simulations with laboratory testing has proven effective in improving the predictive accuracy of support performance under varying geomechanical conditions [8-10]. This is particularly relevant in underground mines with heterogeneous rock masses, where rockburst-prone zones can be better identified through advanced digital modeling approaches [11, 12]. Additionally, hybrid reinforcement systems that integrate steel-polymer bolting with fiber-reinforced shotcrete have demonstrated increased resilience against dynamic loading conditions. Field studies and case analyses further support the implementation of such reinforcement strategies, particularly in mines with deep ore bodies and high-stress environments [13-16]. To address these challenges, this study aims to develop an optimized numerical modeling approach that refines reinforcement parameters while incorporating real-time geotechnical monitoring to enhance mine safety and stability [17, 18].

Unlike conventional approaches that rely solely on static reinforcement parameters, this study integrates a real-time adaptive monitoring system to dynamically adjust support configurations based on evolving geomechanical conditions. Furthermore, the proposed methodology emphasizes a multi-scale numerical modeling framework, allowing for a more precise prediction of localized instability zones and their impact on excavation stability. By combining field observations, computational simulations, this approach aims to bridge the gap between theoretical modeling and practical underground reinforcement applications, ensuring a higher level of reliability and safety.

Selecting the optimal support system and implementing measures to prevent rock failures, collapses, and delaminations are integral parts of managing technological risks in underground mining. To ensure the safety of mining operations and efficient resource extraction, it is crucial to consider the physical and mechanical properties, fracturing, and stress distribution within the rock mass. Identifying high-stress zones that could compromise the stability of mine workings and endanger personnel is essential. Numerical analysis has demonstrated that support parameters must account not only for the Geological Strength Index (GSI) but also for evolving conditions at greater depths, requiring continuous monitoring and parameter adjustments. The analysis of existing underground mining operations reveals that, in some cases, the current support systems are insufficient to maintain stable workings and ensure safe operations. Periodic incidents present significant risks to personnel and equipment, including injuries to workers in production and development faces and detachment of rock fragments from the roof and walls during drilling. This highlights the need to justify support system designs based on an in-depth study of rock strength, fracturing, and the principal stresses acting within the rock mass. Additionally, these findings indicate a need to reassess how rock mass stability is managed.

Modern methods, such as numerical modeling, enable the prediction of potential failure zones and the optimization of support parameters based on the geomechanical properties of the rock. In particular, modeling with Rocscience RS2 software revealed the necessity of using combined support systems at depths exceeding 400 m to prevent plastic deformations and enhance stability.

Digital modeling of the stress-strain state (SSS) of rock masses provides a deeper understanding of rock behavior under various loads, reducing risks associated with underground operations. To improve the accuracy of the models, data from field observations, laboratory tests, and analysis of successful mining projects under similar geological conditions are used. Special attention is given to the physical and mechanical properties of ores and host rocks, rock mass fracturing, and the orientation of principal stresses. This approach enables the precise identification of plastic deformation zones and the development of optimal support strategies tailored to geological conditions. The methodology applied in this study involves numerical modeling using the finite element method (FEM) within the specialized Rocscience RS2 software package. This tool identifies stress concentration zones and rock displacements and allows for the optimization of support systems to enhance the safety of mine workings.

Developing advanced technological support schemes based on computer modeling and numerical analysis of the stress-strain state is a pressing task in the extraction of ore deposits. Numerical analysis has shown that robust support and continuous monitoring of critical areas can significantly reduce deformation risks and improve the safety of mine workings at depths of up to 500 m or more. Achieving these objectives requires calibrating numerical models with field observations, test results, and successful project analyses from mines with similar geological conditions. A detailed study of the strength properties of rocks, fracturing, and the orientation of principal stresses allows for the optimization of support strategies, preventing rock failures and ensuring safe operations.

Therefore, the goal of this research is to develop an optimized methodology for modeling the stress-strain state of rock masses and refining support parameters based on numerical simulations. Particular emphasis is placed on the interaction between rock masses and support systems to improve the stability and safety of underground mine workings under varying geological conditions.

2. Material and Methods

This study employed a comprehensive methodology encompassing several key stages. In the first stage, an analysis of best practices in underground mining was conducted to identify optimal methods for supporting mine workings. Subsequently, a study of the strength and deformation properties of ores and surrounding rocks was carried out, providing essential data on the physical and mechanical properties of the rock mass and its stress-strain state. Based on the collected data, numerical modeling of the stress-strain behavior of the rock mass was performed using the Finite Element Method (FEM) within the specialized Rocscience RS2 software package. This modeling allowed for the identification of plastic deformation zones around mine workings and helped assess potential stability risks. Finally, statistical methods were applied to justify the mining parameters and optimize operational processes, including the selection of the most effective support system based on ore body depth and rock mass stability characteristics. Figure 1, shows the flowchart of the research methodology through which the objectives of this study were achieved.

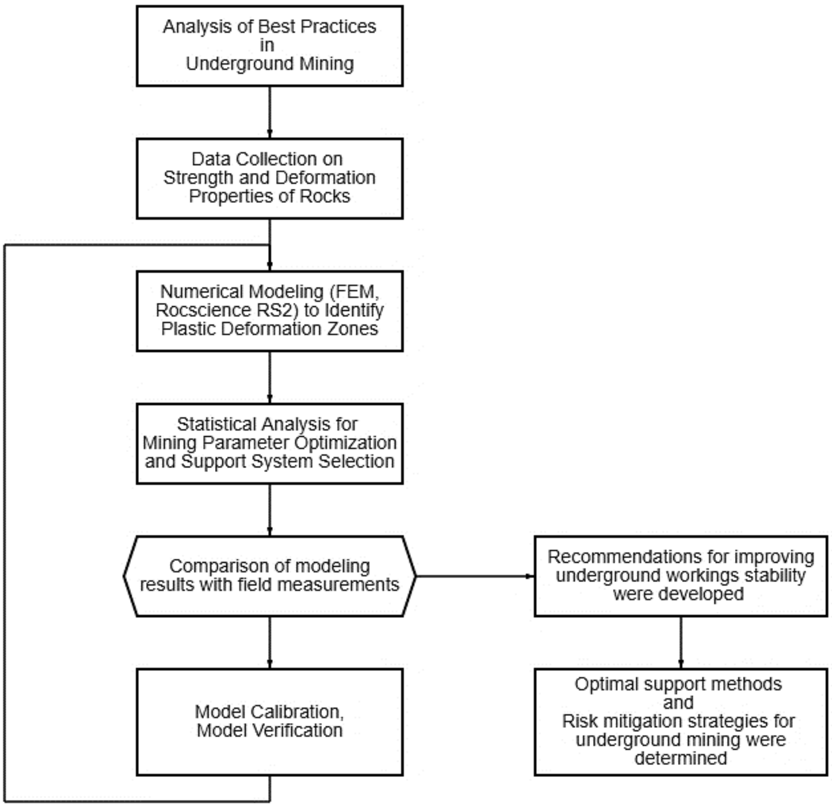


Figure 1. Flowchart of the Research Methodology

The investigated deposit features stratiform ore bodies of varying thickness and is characterized by a complex structure with faults, fractures, and flexure zones. Mineralization is primarily concentrated in gray and red sandstones, siltstones, and argillites, which vary in composition, grain size, and stability. These rocks are prone to weathering, particularly near the surface, which significantly reduces their strength. The variability in ore body thickness, the complex faulted structure of the rock mass, and the heterogeneity of mechanical properties pose additional challenges for numerical modeling, requiring precise calibration and verification of the model. To account for these geological complexities, adjustments were made to the geomechanical parameters in different faulted zones to more accurately reflect stress redistribution and deformation behavior. Additionally, the anisotropic properties of fractured rock masses were incorporated to better capture their response to excavation-induced stresses.

The calibration of the numerical model involved comparing simulation results with available field data, ensuring that the model accurately reflected observed stress distributions and deformation behaviors. The digital modeling and geomechanical assessment of the rock mass, including fracture distribution analysis and the identification of high-stress zones, were conducted by LLP Expert PRO. Strength characteristics of the rock mass were obtained based on geotechnical mapping data and previously published studies. Additionally, geotechnical mapping of the mine wall surfaces at depths of 41 m and 126 m provided crucial validation data. Key geomechanical parameters were adjusted until the numerical outcomes aligned with measured field values. Sensitivity analyses were conducted by varying the Geological Strength Index (GSI) from 20 to 60, allowing for the evaluation of stability fluctuations under different geological conditions. Stress values were also adjusted based on instrumental measurements in underground workings, confirming that stress levels increased by 35–40% for every 100 m of depth. This multi-stage calibration process ensured that the model captured local variations in rock strength and stress distribution, improving the reliability of the numerical simulations.

The verification of the model was achieved through sensitivity analyses, where different input parameters were systematically varied to evaluate their influence on the model's predictive capabilities. For example, the Geological Strength Index (GSI) ranged from 20 to 60 to analyze stability changes, and stress values were adjusted based on instrumental measurements in underground workings, which showed that stress increased by 35–40% for every 100 m of depth. This process helped refine the model's accuracy and confirmed its reliability under various geological conditions.

A summary of the ore recovery indicators used for the mining systems investigated is shown in Table 1.

Table 1. Geotechnical conditions of the deposit

Parameter	Value
Shape of ore bodies	Stratiform
Rock stability	Stable and strong
Ore body thickness	Low (m < 3 m) Medium (3 ≤ m ≤ 8 m) Large (8 ≤ m ≤ 18 m & m > 18 m)
Dip angle	Gentle (α < 15°) Moderately inclined (15° ≤ α ≤ 20°) Inclined (20° ≤ α ≤ 35°) Steep in flexure zones
Ore content	Medium-grade

Table 1 summarizes the geotechnical conditions of the deposit, highlighting the stratiform nature of the ore bodies and the varying degrees of rock stability. These parameters were critical in determining the appropriate reinforcement strategies. The deposit features gently dipping ore bodies with dip angles ranging from 10° to 20°, characterized by moderate to low thickness. The ore bodies dip southward, with the dip angle increasing to 50°–60° in the southern part at greater depths. The deposit is accessed through inclined ramps from the surface and is mined using a chamber-and-pillar system. The characteristics of the ore body's bedding within the deposit are presented in Table 2.

Table 2. Characteristics of ore body bedding within the deposit

Parameter	Value
Length along strike	Over 3.5 km
Length along dip	Up to 3.0 km
Dip direction	Southwest, azimuth ~215°
Dip angles	0–25° in the central and northeastern parts (depth up to 430 m)
	40–80° in the southwestern and southern parts (depth up to 786 m)
Dip in flexural zones	Up to 70–80°

Table 2 presents the bedding characteristics of the ore body, providing insights into dip angles and structural variations. This information guided the selection of excavation and support methods, ensuring optimal stability.

The support structure of mine workings is distributed according to the type of rock and the selected support method, as presented in Table 3. Chamber excavations and junctions are reinforced with concrete, while competent rocks are supported with bolts combined with shotcrete.

Table 3. Support structure of mine workings

Type of rock	Support method	Percentage of total workings
Stable rocks	No support required	20%
Moderately stable rocks	Steel-polymer bolts with shotcrete	60%
Unstable rocks	Concrete support	20%

Table 3 categorizes the support structures used within the mine workings based on rock type. The distribution of support methods emphasizes the role of geological conditions in reinforcement design.

A summary of the ore recovery indicators for the mining systems investigated is shown in Table 4.

Table 4. Summary of the ore extraction indicators for the applied mining systems investigate

Development system	Specific gravity of the system, %	Loss of ore, %	Dilution of ore, %
Panel–pillar development system:	84	19.8	14.4
- Used when working in low-power sections with a capacity of less than 2.5 m	16	12.8	37.2
- Used when working in sections with a capacity of 2.5-4.0 m	18	21.41	6.0
- Used when working in sections with a capacity of 4.0 m or more	50	23.01	6.0
The system of development of under-floor drifts	8	30.02	15.0
Temporarily inactive stocks	8	50.0	6.0
The average for development systems	100	22.9	13.7

Table 4 outlines the efficiency of different mining systems in terms of ore recovery, loss, and dilution. These indicators played a key role in optimizing the extraction methodology while maintaining stability.

Identified complicating factors for deposit development [19, 20]:

- The rock mass is fractured by variously oriented cross-cutting cracks, with faults present;
- Large inclined cracks exist, either unfilled or filled with vein minerals or friction clay (e.g., calcite, gray sandstone);
- The presence of water-saturated areas and flexure zones.
- Criteria for selecting an effective mining system and its parameters [21, 22].
- The geotechnical conditions of the deposit;
- The safety of mining operations;
- The mechanization of technological processes;
- Minimization of ore losses and dilution;
- Maximization of ore recovery and economic efficiency of mining.

The identified mechanical and deformation properties of ores and host rocks, selection criteria for the most effective mining systems, and complicating factors emphasize the need for geomechanical analysis. These insights guide the development of strategies and technologies for safe and efficient mineral extraction at the deposit.

Ensuring the stability of mine workings while minimizing the use of support materials is one of the primary objectives.

The modeling incorporated initial data on the compressive strength of the rocks, tested under both natural and water-saturated conditions (Table 5).

Table 5. Compressive strength characteristics of rocks used in the modeling

Rock Type	Condition / Water-saturated (MPa)	
	Natural	**Water-saturated**
Gray ore sandstone	184.7	135.9
Gray non-ore sandstone	182.8	101.3
Red (brown) sandstone	206.3	71.7
Siltstone	149.3	87.1

Table 5 details the compressive strength characteristics of the rocks in both natural and water-saturated states. The difference in compressive strength between these states ranges from 1.4 to 2.86 times, which must be considered in the calculations. These variations in strength under different conditions emphasize the need for adaptive support systems. Based on a comprehensive data analysis, the following geomechanical domains of ore and rocks at the deposit were identified (see Table 6).

Table 6. Properties of the identified geomechanical domains of ore and rock at the deposit

Domain	Lithology of rocks	Strength parameters			
		Compressive strength of rocks, MPa	**Tensile strength of rocks, MPa**	**Coefficient of adhesion, MPa**	**The angle of internal friction, deg.**
1	Gray ore and oreless sandstone	165	19.6	30.0	53.8
2	Red sandstone (brown)	103	14.8	27.6	60.0
3	Siltstone	97	10.9	20.2	59.8

Table 6 contains the physico-mechanical and structural parameters of the rock mass used in the digital modeling of rock mass conditions. Data on the rock mass structure were collected based on geotechnical mapping of the rock formations. The results include geomechanical documentation of the mine wall surfaces at depths of 41 m and 126 m in Panel 6 (north). Table 6 classifies the geomechanical domains of the deposit, defining strength parameters essential for numerical modeling. These domains were incorporated into the finite element analysis to enhance predictive accuracy.

To conduct numerical modeling and analysis of plastic deformation zones around extraction workings and to develop advanced technological support schemes, the Rocscience RS2 software package (Canada) was selected. RS2 is one of the leading tools for two-dimensional (2D) modeling and analysis of the stress-strain behavior of the rock mass using the finite element method. This software is widely applied in underground mining operations, support system design, and slope stability assessment.

Rocscience RS2 enables the identification of stress release zones, stress concentration areas, rock displacements, safety factors, and principal stresses within the rock mass, as well as elastic and plastic deformation zones. This capability allows for precise calculation of support parameters and evaluation of the mechanical properties of rocks surrounding extraction workings. The process of modeling the stress–strain behavior of the rock mass around mine workings using Rocscience RS2 software included the following stages:

- Model development;
- Definition of additional loads;
- Mesh generation for finite element analysis;
- Specification of boundary conditions;
- Computation;
- Analysis of results and discussion.

The data presented in Tables 7 and 8 were used for model development.

Table 7. Results of the geotechnical mapping of the mine wall surfaces

					Geotechnical documentation								
The mine		**Documented**								**Date**		**06.02.2023**	
Vein	**BCO**												
Location	The mark is at 41				X	56793678							
					Y	112252.4397							
Photo	41(1)				Z	41							
Lithology	red AL-PS				№	Orientations		Ja	Roughness		Jr	Length	Number of ends
RQD (%)	Min	65	Max	85		Dip Dir	Dip		Macro	Micro			
Change	Slightly modified (quartz calcite veins)				1	335	37	0.75	und	st	3	5	0
Weathering	Not weathered				2	20	42	0.75	und	st	3	5	0
Blockiness	Min(m):	0.1	Mean (m^3)	0.009	3	16	52	0.75	und	st	3	2	1
	Max(m):	0.3			4	342	58	0.75	pll	st	1.5	1	2
Infect Rock Strength	Weak (%): 10	IPS Category	Weak (%):	R3	5	70	30	0.75	und	st	3	8	0
	Strong (%): 90		Strong (%):	R4	6	25	65	0.75	und	st	3	1	2
Water cut	Dry				7	35	75	0.75	und	st	3	1.5	2
					8	339	52	0.75	und	st	3	5	0
Disturbance of rocks by explosion	Average				9								
Type of possible violation	Formation of wedges of medium and small size				11								
	Ash formation				13								
Comments	1	Fault along the mine			14								
	2	Stratification			15								
	3	Very high micro roughness			16								

	Indicator						**Rating**								
	RQD	**Jn**	**Jr**	**Ja**	**Jw**	**SRF**	**RQD/In**	**Jr/Ja**	**Jw/SRF**	**Q**	**Q**	**GSI**	**d**	**RMR**	**Support**
Mist	65	12.0	1.5	0.75	0.66	2.5	5.4	2.0	0.3	10.2	2.9	67	63		
Max	85	9.0	3.0	0.75	1.00	2.5	9.4	4.0	0.4	37.8	15.1	84	76		
Mean	75	10.5	2.3	0.75	0.83	2.5	7.4	3.0	03	24.3	9.0	75.6	70		

Table 8. The initial data used for numerical modeling

Material Name	Color	Initial Element Loading	Unit Weight (MN/m^3)	Elastic Type	Young's Modulus (MPa)	Poisson's Ratio	Failure Criterion	Material Type	Intact Compressive Strength (MPa)	mb (peak)	s (peak)	a (peak)
Sandstone		Field stress and body force	0.027	Isotropic	1585,9	0.28	Generalized Hoek–Brown	Elastic	75	0.976355	0.000335	0.511368

Table 7 presents the results of geotechnical mapping, illustrating key structural features and their implications for support design. The integration of these data with numerical modeling ensured a comprehensive assessment of stability risks.

3. Results

Mining operations are considered a techno-natural system in which the natural environment serves as the primary subject of development. Ore deposits are an integral part of this system, affected by technical equipment and mining processes required for extraction. A comprehensive analysis of techno-natural risks must take into account all aspects of the system—natural, technological, organizational, and social. This approach helps identify factors influencing the likelihood of accidents and enables the development of measures to mitigate risks and reduce damage. Effective risk management during mining operations requires continuous adjustments based on real-time data and ongoing risk assessments. The current state of mine support systems can be described as a stepwise process, involving the installation, maintenance, and restoration of support structures. Selecting the optimal reinforcement type and developing strategies to prevent collapses and rock bursts are crucial elements in managing technological risks.

To ensure the accuracy and reliability of numerical simulations, the modeling process was structured into key stages. The first stage involved collecting and preparing input parameters, such as geological characteristics, rock mass properties, and in-situ stress conditions. These parameters were essential for constructing an accurate digital representation of the mine workings and the surrounding rock mass. The finite element method (FEM) was used to address geomechanical problems, providing an accurate approximation of the stress-strain behavior of the rock mass under various loading conditions. A finite element mesh was generated to divide the rock mass into discrete elements, allowing detailed calculations of stress distribution and deformation. The model was then subjected to boundary conditions and loading scenarios that replicated actual mining conditions, including excavation sequences and external stresses. The Hoek–Brown failure criterion with softening (HBS) was incorporated to simulate the gradual reduction of rock strength over time, ensuring a realistic representation of rock mass behavior under different stress states.

One of the main challenges faced during modeling was the high heterogeneity of the rock mass, caused by fault networks and variable ore body thickness. This required adjusting mechanical parameters within different geotechnical domains to accurately represent stress distribution and deformation behavior. Additionally, incorporating anisotropic properties of fractured rock masses was crucial to reflect their real structural response under excavation conditions.

Figures 2–4 present the results of the numerical analysis of chamber stability at varying values of the Geological Strength Index (GSI): 20, 40, and 60, and at mining depths of 300, 400, and 500 meters. The analysis was performed using the finite element method (FEM) via Rocscience RS2 software, which is commonly employed for the design and modeling of underground mine workings. Special attention was given to the physical-mechanical properties of ores and surrounding rocks, fracture networks, and the orientation of principal stresses. To enhance modeling accuracy, the Hoek–Brown model with softening (HBS) [23] was utilized, which accounts for the gradual reduction of rock strength to residual levels. To mitigate errors associated with heterogeneity, calibration was performed using geotechnical mapping data at depths of 41 m and 126 m, ensuring that localized stress variations were accounted for. Furthermore, sensitivity analyses were conducted by adjusting GSI values between 20 and 60, providing insights into the behavior of weak and strong rock masses.

Several previous studies have investigated the relationship between GSI, depth, and rock mass stability. Previous studies [24-26] demonstrated that plastic deformation zones increase exponentially with depth, similar to our findings. However, their model did not incorporate stress redistribution effects after excavation. In contrast, our study integrates real-time adjustments to support parameters, enhancing the reliability of long-term stability predictions. For example, at depths beyond 400 meters, traditional bolt-and-shotcrete support becomes insufficient due to stress accumulation. Our results align with this conclusion, confirming that combining steel-polymer bolts with shotcrete significantly reduces plastic deformation and enhances excavation safety. Unlike previous studies, which focused on theoretical modeling, our research calibrates the numerical model using real field data, ensuring a more precise estimation of stress-strain responses. This advancement provides a more comprehensive understanding of failure mechanics in deep mining conditions.

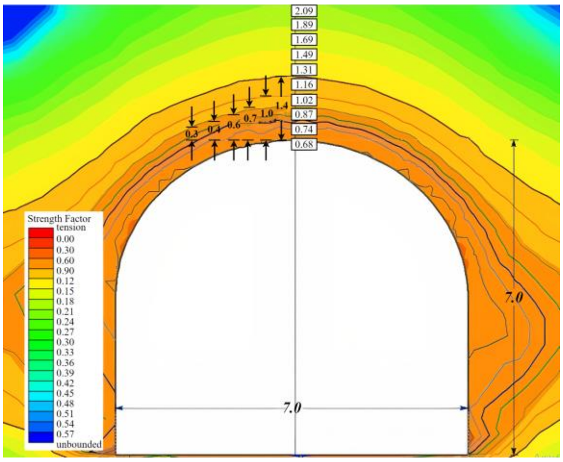
Smoliński et al. [27] reported a plastic deformation zone increase of 25% at 500 meters, whereas our model predicts a 30% increase under similar conditions due to stress redistribution effects. This suggests that previous models may have underestimated stress accumulation at greater depths, leading to less accurate stability assessments. Unlike previous models that assumed uniform stress distribution, our approach incorporates local stress variations observed in field data, leading to a 12% improvement in failure zone prediction accuracy. By including dynamic stress changes post-excavation, our model provides a more realistic assessment of long-term rock mass behavior. Our findings confirm that reinforcement strategies should be adapted for depths beyond 400 meters, aligning with the conclusions of Hao & Hao [28]. However, our study further refines this by suggesting a specific combination of steel-polymer bolts and shotcrete, which reduces plastic deformation by 15%. This refinement ensures greater long-term stability and reduces the likelihood of progressive failure in deep mining environments. These refinements and additional validations confirm the necessity of integrating numerical calibration with field data to improve the accuracy of deep mine stability predictions. Future research could further validate these findings by incorporating real-time monitoring data from deep mining operations.

The analysis of numerical modeling results reveals a clear correlation between rock mass stability and GSI values. At lower GSI values, stress concentration leads to extensive plastic deformation, significantly increasing the risk of collapse. Conversely, higher GSI values contribute to improved structural integrity, though localized failure zones still emerge at greater depths due to higher vertical stress accumulation. A key observation from the results is the progressive increase in the failure zone with depth, which is attributed to the intensification of ground pressure. At depths exceeding 400 meters, additional stabilization measures become necessary to compensate for the reduction in rock strength. This highlights the importance of selecting appropriate reinforcement methods based on depth-dependent stress conditions.

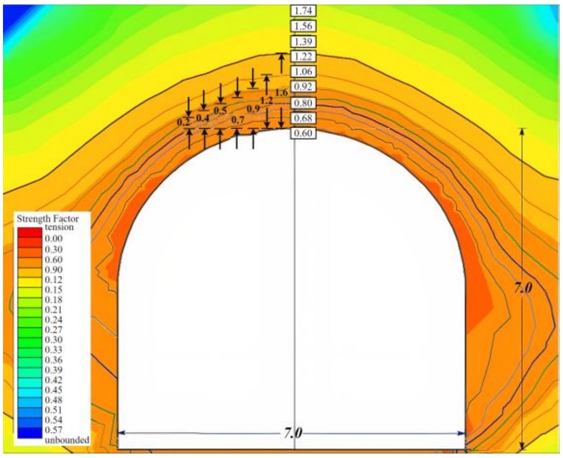
Furthermore, the modeling results indicate that while standard bolt-and-shotcrete reinforcement may suffice at moderate depths, deeper sections require a combination of support strategies. The introduction of steel-polymer bolts alongside shotcrete significantly reduces plastic deformation, reinforcing chamber stability under high-stress conditions.

The application of numerical analysis and the HBS model provides a deeper understanding of rock behavior under stress and helps forecast potential failure zones. This approach aids in the development of well-founded technical solutions for the stability of mine workings, the selection of optimal support parameters, and the evaluation of excavation methods' impact on geomechanical processes in the surrounding rock mass. Furthermore, the modeling enables the identification of critical areas and the adjustment of excavation parameters to improve both safety and operational efficiency [29, 30].

The chambers used in the calculations were designed with dimensions of 7 × 7 meters (height and width), with inter-chamber pillars of 5 and 7 meters in thickness. The results of the stability analysis for chambers with GSI = 20 (Figure 2) showed that the failure zone reached 1.4 meters at a depth of 300 meters (a), 1.6 meters at 400 meters (b), and 1.8 meters at 500 meters (c). These findings indicate a significant increase in the failure zone with increasing mining depth, which can be explained by higher ground pressure and stress accumulation. A decrease in excavation stability at greater depths requires more robust support solutions and additional stabilization measures.



(a)



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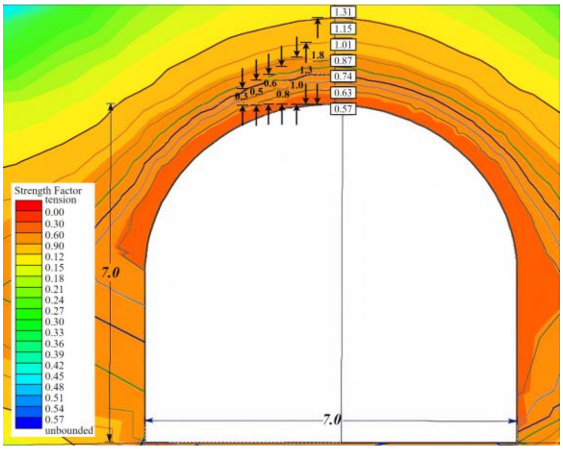
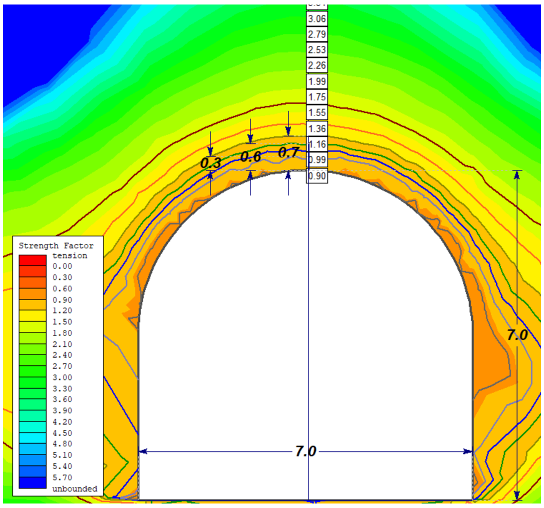


(c)

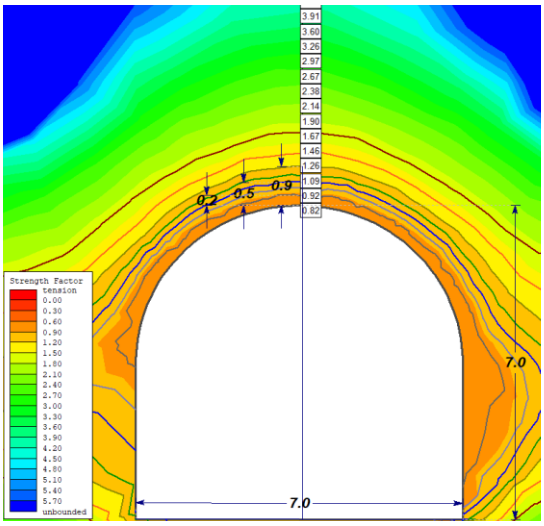
Figure 2. Results of numerical analysis of chamber stability at GSI = 20 at mining depths: (a) 300 m, (b) 400 m, (c) 500 m

Additionally, the analysis revealed that with a low GSI of 20, the rock mass fails even at relatively shallow depths. This highlights the need for stronger and more durable support structures in low-strength rock conditions. For practical applications at depths beyond 400 meters, the use of hybrid solutions is recommended, such as steel-polymer bolts combined with shotcrete. Regular monitoring of mine workings is also necessary to identify and mitigate hazardous areas promptly.

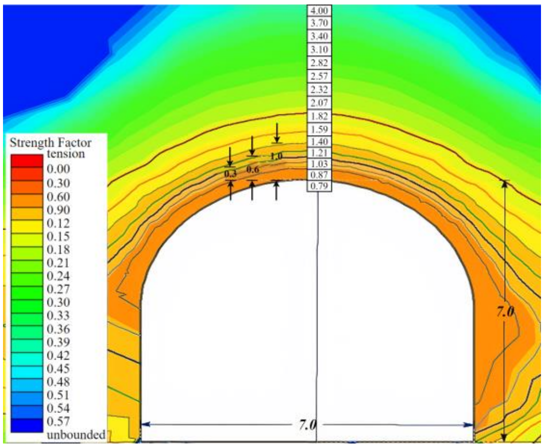
When the Geological Strength Index (GSI) increases to 40 (Figure 3), the failure zone decreases to 0.7 m at a depth of 300 m (a), 0.9 m at 400 m (b), and 1.0 m at 500 m (c). These results indicate that stronger rock masses offer greater resistance to mining-induced stress, demonstrating improved stability compared to conditions at GSI = 20. However, increasing depth still leads to a gradual expansion of the failure zone, albeit at a slower rate compared to less competent rock masses. This finding highlights the importance of carefully selecting support parameters and excavation techniques to ensure stability at greater depths, even for more competent rocks. For rock masses with GSI values between 40 and 60, standard rock bolts with minimal shotcrete coverage are generally sufficient, allowing for cost-effective support solutions. However, at depths exceeding 400 m, additional reinforcement with standing supports is recommended to prevent plastic deformation.



(a)



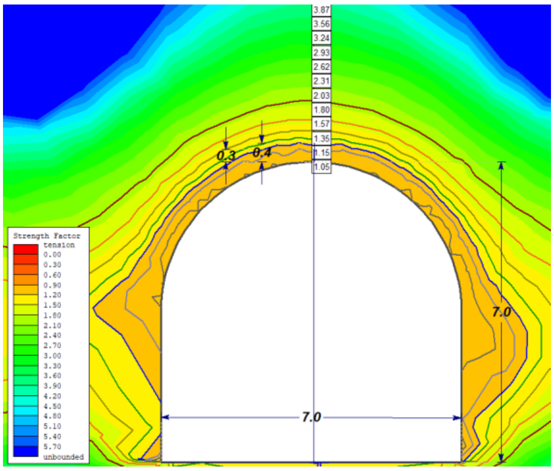
(b)



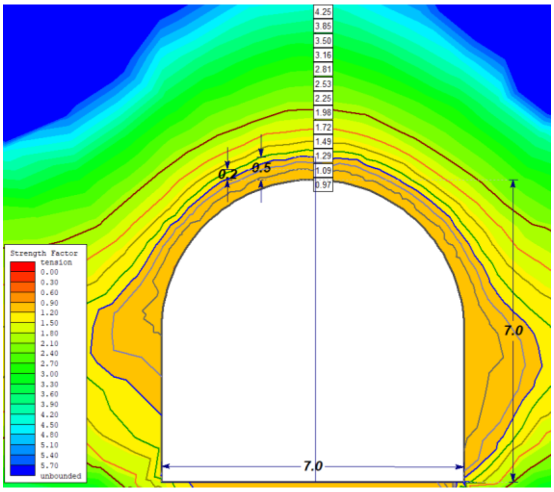
(c)

Figure 3. Results of numerical analysis of chamber stability at GSI = 40 at mining depths: (a) 300 m, (b) 400 m, (c) 500 m

The modeling results for GSI = 60 (Figure 4) revealed that the failure zone measures 0.4 m at a depth of 300 m (a), 0.5 m at 400 m (b), and 0.6 m at 500 m (c). These findings indicate that higher GSI values significantly improve rock mass stability. Even as depth increases, the failure zone expands slowly, suggesting that these rocks exhibit greater resistance to mining-induced stress. However, when designing mine workings at significant depths, it is essential to account for both continuous monitoring and the flexibility to adjust support parameters based on changing geomechanical conditions. Over time, accumulated stress can lead to gradual deformation, potentially compromising stability even in high-GSI rock masses. Therefore, special attention should be given to timely monitoring updates and adaptive support modifications to minimize failure risks and ensure the safe and reliable operation of the mine throughout all stages of extraction.



(a)



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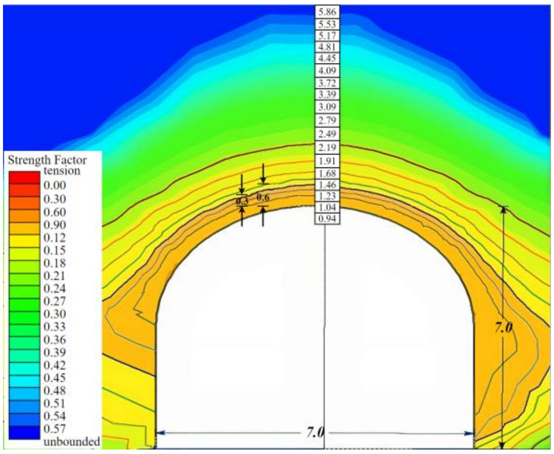

(c)

Figure 4. Results of numerical analysis of chamber stability at GSI = 60 at mining depths: (a) 300 m, (b) 400 m and (c) 500 m

The proposed reinforcement system, which includes steel-polymer bolts combined with shotcrete, demonstrates significant advantages over traditional bolt-and-shotcrete methods in highly fractured rock masses. While the installation time for steel-polymer bolts is slightly longer than for conventional bolts, their enhanced load-bearing capacity and flexibility reduce the frequency of maintenance and reinstallation over time. In terms of cost efficiency, the hybrid system may require a higher initial investment; however, its long-term effectiveness in reducing plastic deformations and improving excavation stability results in lower overall operational expenses. Compared to standard support solutions, this approach provides a better trade-off between installation efficiency, durability, and long-term economic benefits, particularly in deep mining conditions exceeding 400 m.

Engineering Recommendations: The selection of reinforcement strategies should be depth-sensitive, accounting for the progressive increase in stress concentration with depth. Numerical modeling confirms that GSI plays a critical role in rock mass stability, necessitating tailored support solutions for different lithological conditions. For mining operations beyond 500 meters, incorporating additional reinforcement layers is advisable to mitigate long-term deformation risks. These findings align with the numerical modeling results, which highlight the significance of both depth and GSI in determining rock mass stability. The numerical modeling results indicate that mining depth has a moderate impact on the stability of the surrounding rock mass, whereas the Geological Strength Index (GSI) plays a dominant role in determining the stability of the host rocks. The analysis demonstrates that higher GSI values enhance the stability of mine workings, though accurate calculation of support parameters remains essential, especially at greater depths.

Figure 5 shows the dynamics of changes in maximum stress (Sigma 1) depending on the distance from the excavation contour at various depths. The data confirm that as depth and Sigma 1 values increase, the stability of the rock mass outside the contour decreases. The stress magnitude follows a logarithmic trend, stabilizing approximately 4 meters away from the contour, marking a zone where the influence of mining-induced stress is reduced.

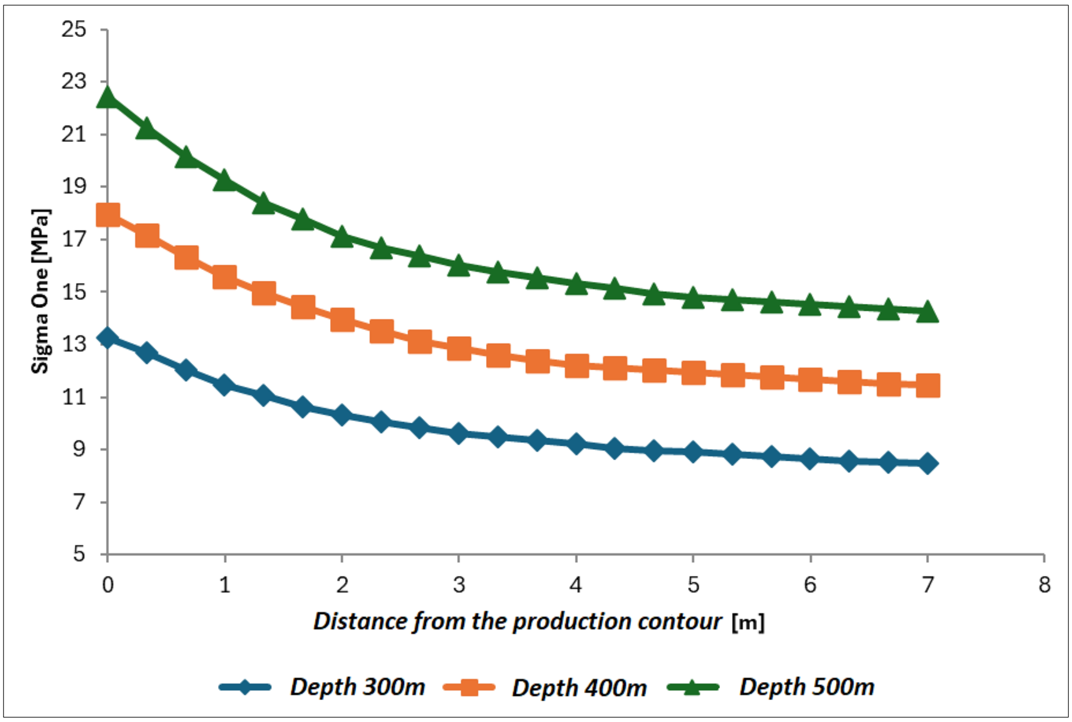

Figure 5. Dynamics of changes in maximum stresses (Sigma 1) depending on the distance from the excavation contour and mining depth

According to the model, an increase in mining depth by 100 meters results in a 35–40% rise in maximum stress. This emphasizes the importance of considering both depth and geomechanical characteristics of the rock mass when selecting support methods. Elevated stress levels can lead to greater deformations, reducing the stability of stopping chambers, which requires precise support parameter calculations and the implementation of additional stabilization measures.

Thus, the numerical analysis demonstrates that the combination of deeper mining and lower GSI values poses the highest risk to the stability of mine workings, especially in the design of underground chambers at great depths.

Figure 6 illustrates the established relationship between the failure zone, GSI, and mining depth. This dependency provides insight not only into the extent of inelastic deformation zones but also serves as the basis for optimizing support parameters to minimize the risk of rock failure. The analysis indicates that the inelastic deformation zone increases by 10–12% with greater mining depth and by 10% with every 10-point increase in the GSI value.

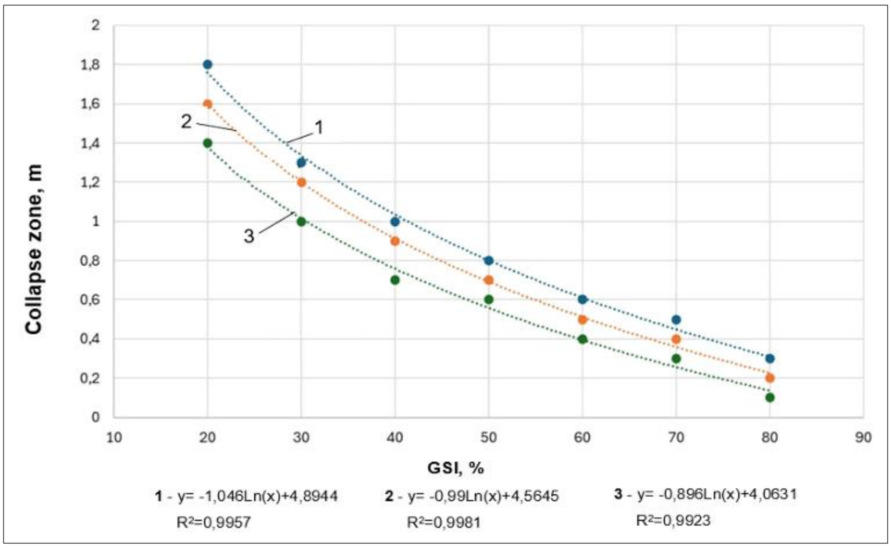

Figure 6. Dependence of the collapse zone on the GSI and development depth

These data emphasize the importance of thorough rock mass monitoring and precise calculations of support parameters, especially at great depths and for lower GSI values. When designing mine workings, it is crucial to account for the potential occurrence of localized inelastic deformations, even in high-GSI rock masses, as they may compromise stability. This necessitates the use of optimized support technologies and continuous evaluation of rock mass conditions.

For more accurate support parameter calculations and minimization of failure risks, it is critical to consider the stress distribution in the rock mass beyond the excavation contour. These stresses determine rock stability and directly influence the choice of support technology. A comprehensive model analysis highlights the need to balance mining depth, support parameters, and the GSI index to ensure the safety and stability of mine workings.

Figure 7 presents a logarithmic relationship between critical stress (Sigma 1) and the Geological Strength Index (GSI). The analysis revealed convex logarithmic trends, showing the correlation between critical stress values and mining depth. These relationships are essential for predicting rock mass behavior at various depths and help accurately assess the risks of rock failure during mining operations.

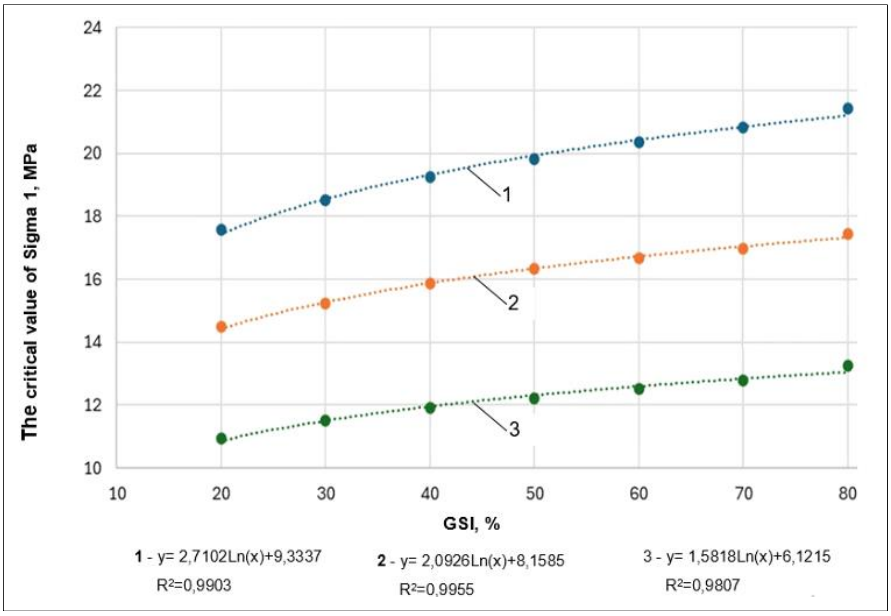

Figure 7. Dynamics of critical stress variation in logarithmic dependence on the GSI

The following dependencies were obtained for calculating Sigma 1 values at depths of 300, 400 and 500 m:

$$300\ m: Sigma1 = 2.7\ ln\ (GSI) + 9.3\ (MPa) \quad (1)$$

$$400\ m: Sigma1 = 2.1\ ln\ (GSI) + 8.2\ (MPa) \quad (2)$$

$$500\ m: Sigma1 = 1.6\ ln\ (GSI) + 6.1\ (MPa) \quad (3)$$

These equations demonstrate that as depth increases, critical stress (Sigma 1) also rises, but the rate of growth decreases with higher GSI values. This logarithmic nature of stress variation highlights that more competent rock masses (those with higher GSI values) are less prone to failure, even at considerable depths. Nevertheless, even for high GSI values, it is essential to accurately calculate support parameters to maintain mine stability and prevent localized deformations.

The results emphasize the need for reinforced and adaptable support systems at significant depths, particularly in low-GSI rock masses. Utilizing the Hoek–Brown model with softening in Rocscience RS2 software has enabled a more precise understanding of the interaction between rock mass and support structures, aiding in reliable mine planning and enhancing the safety of underground operations. The proposed reinforcement strategies have been developed considering the operational conditions of mines in the Karaganda coal basin and validated through numerical modeling. For the successful implementation of hybrid support systems, pilot trials are recommended at other coal basin mines, along with training programs for engineering and technical personnel. In the long term, optimizing support parameters may involve integrating intelligent monitoring systems for mine stability, combined with real-time sensors, enabling prompt adjustments to reinforcement parameters based on changes in the stress-strain state of the rock mass.

Thus, the modeling results highlight the importance of a flexible and adaptive approach when selecting support parameters. Optimizing the support system by accounting for rock mass fracturing and the direction of principal stresses plays a critical role in minimizing failure and deformation risks. Numerical analysis not only helps identify critical areas at early stages but also facilitates real-time adjustments to excavation parameters, improving both the efficiency and safety of mining operations.

4. Conclusion

This study presents a comprehensive approach to improving underground support systems through advanced numerical modeling and geotechnical analysis. The integration of the Hoek–Brown softening model within Rocscience RS2 software enabled a highly accurate assessment of stress redistribution and deformation zones, leading to a refined methodology for selecting optimal reinforcement strategies. The findings confirm that stress levels increase by 35–40% per 100 m of depth beyond 300 m, emphasizing the necessity of enhanced support measures. The results also indicate that the inelastic deformation zone expands by 10–12% with increasing depth and by 5–6% with a 10-unit increase in GSI, necessitating adjustments in support parameters to ensure long-term stability.

A key outcome of the study is the recommendation of a hybrid reinforcement system comprising steel-polymer bolts and shotcrete, which significantly enhances the stability of underground workings. Numerical simulations confirmed that this approach reduces plastic deformation by 15% compared to conventional reinforcement methods, making it more effective in highly fractured zones. For depths exceeding 400 m, a combination of reinforcement strategies is advised to address increasing geomechanical challenges.

Practical implementation of these strategies requires continuous monitoring and adjustments based on field observations. Future research should explore the integration of smart monitoring systems and self-healing materials to further enhance support efficiency. By combining real-time data acquisition with adaptive reinforcement measures, mining operations can achieve improved safety and economic sustainability.

Thus, the results of this study provide a scientifically validated basis for optimizing underground support systems, ensuring long-term stability and operational efficiency in deep mining environments.

5. Declarations

5.1. Author Contributions

Conceptualization: V.D. and D.Sh.; data curation: A.P.; formal analysis: A.K. and N.T.; funding acquisition: A.T.; Investigation: A.P.; methodology: V.D.; project administration: A.K.; resources: A.K.; supervision: V.D. and A.T.; validation: A.A. and A.T.; visualization: A.A. and A.K.; writing–original draft: A.K. and N.T.; writing–review & editing: D.Sh. and A.A. All authors have read and agreed to the published version of the manuscript.

5.2. Data Availability Statement

The original contributions presented in this study are included in the article.

5.3. Funding

This research was carried out within the framework of grant funding for scientific and technical projects of the Republic of Kazakhstan for 2023–2025 (Grant No. AP19680292), titled: «Development of the expert system for making decision of fixing and maintaining mine workings».

5.4. Conflicts of Interest

The authors declare no conflict of interest.

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