Heliyon 10 (2024) e41023

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Study on the stability of waste rock filling in goaf based on dynamic comprehensive analysis method

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ARTICLE INFO

Keywords:
Underground mine goaf
Stability
Midas GTS/NX
Waste rock filling
Green mines

ABSTRACT

The restoration and treatment of underground voids have always posed significant challenges for constructing environmentally sustainable mines. To investigate the effectiveness of a combined approach involving waste rock filling and grouting roof filling as treatment methods to ensure safety and stability in mining voids, this study employed a comprehensive dynamic analysis approach. It specifically focused on an individual underground metal mine cavity by integrating numerical simulation analysis techniques with onsite displacement monitoring methods. By simulating stress-strain conditions during different stages of cavity formation and subsequent treatments while considering onsite displacement monitoring data, this study extensively analyzed how these treatments impact rock stress levels, strain conditions within rocks themselves, and the stability of the surface riverbed. The results show that: (1) "waste rock filling + cemented roof filling" can effectively reduce the stress of surrounding rock, significantly improve the structural stability of goaf, reduce surface displacement and deformation, and ensure the stability of surface riverbed; (2) In the process of mining and filling, the stress and strain sensitive points are mainly distributed in the roof, bottom and intercolumn of the stope; (3) When the goaf is backfilled from top to bottom, the stress-strain changes at each stage are uneven: the maximum principal stress changes slowly in the early stage, but greatly in the later stage; The change of displacement showed a trend of slowing down in the early stage and stabilizing in the later stage: (4) "waste rock filling + cemented filling" roof joint can realize the transformation of solid waste into treasure in mines, effectively promote the construction of green mines, and is an effective means of goaf treatment. It provides ideas and means for other similar complex problem analysis and prevention.

1. Introduction

Due to societal progressions and increasing resource requirements, the depletion of shallow mineral reserves is occurring at a concerning pace. To address this growing demand, mining activities are gradually transitioning towards deeper strata within the Earth's crust. However, areas subjected to subterranean extraction techniques currently face significant safety and environmental obstacles.The goafs resulting from mining activities currently cause various problems in both the mining area and its surrounding environment. These issues include risks like roof collapse [1], wall failure [2], and extensive collapses(As shown in Fig. 1 (a)(b)) [3].

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https://doi.org/10.1016/j.heliyon.2024.e41023
Received 25 June 2024; Received in revised form 4 December 2024; Accepted 5 December 2024

Additionally, they can lead to surface subsidence along with structural failures and cracks on land surfaces(As shown in Fig. 1 (b)(c)) [4,5]. Consequently, these factors significantly affect mine safety as well as the lives of residents in nearby areas [6]. Currently, the control of Goaf mainly includes grouting and filling technology, biological remediation technology, structural adjustment technology, and comprehensive monitoring technology. Among these technologies, grouting and filling control are widely used [7]. Especially in sustainable development strategies and green mine construction, grouting and filling control closely connect the comprehensive utilization of mine waste with green environmental protection [8].Waste rock filling and cemented filling have become research hotspots. These prevention and control measures can not only effectively reduce major safety hazards in the goaf but also significantly decrease goaf treatment costs by fully utilizing waste rock filling while effectively transforming solid mine waste into valuable resources [9].

Therefore, many scholars at home and abroad have conducted a series of studies on the filling and treatment of goaf. For example, AdachPawelus Karolina and Pawelus Daniel [10] used numerical simulation methods to study the improvement of stope geomechanical conditions and the reduction of rock burst risk in copper mine goaf. Suo, Y. et al. [11] used orthogonal design and variance analysis to study the influence of different proportions of cemented filling materials based on coal gasification slag on the filling effect. Skrzypkowski Krzysztof [12,13] used laboratory tests and spatial numerical simulation to study the stress-strain conditions of the cement paste backfill during strip excavation displacement and used laboratory tests to study the compressibility of backfill materials. Xia-yu and Lu-Aihong [14] analyzed the mechanical characteristics and failure characteristics of the filling body, to provide a basis for more effective prevention of surface subsidence and maintenance of stope stability. Anas Driouch et al. [15] used a two-dimensional numerical simulation method to study the mechanical characteristics of ore bodies and surrounding rock in backfill mining based on engineering examples. Long Quoc Nguyen et al. [16] proposed an artificial neural network model combined with field monitoring to predict the surface subsidence caused by underground goaf.

From these studies at home and abroad, it is found that waste rock filling and cemented filling are gradually enriched in continuous research and development, and many gratifying results have been achieved. There are more and more methods to study waste rock filling and cemented filling by using laboratory tests, numerical simulations, theoretical analysis field monitoring, etc. In the research, the problems related to filling material improvement, filling effect analysis, filling physical characteristics, filling body failure characteristics, and goaf deformation are gradually deepened [17–19]. However, there are relatively few analyses on the whole process of mined-out area filling, especially on the stress and strain analysis of the mined-out area filling process, which can not provide effective guidance for the waste rock filling and cemented filling process.

To overcome this limitation, this study takes the local goaf of a metal mine in the Qinling area of China as the research object and adopts the dynamic comprehensive analysis method combining numerical simulation and field monitoring based on the idea of dynamic analysis to study the stress and strain law, surface deformation and stability of each process of waste rock filling and cement filling in the mine goaf. To comprehensively display the stress and strain conditions in the filling process, the whole process of each stage from step-by-step mining to waste rock backfilling was simulated to analyze the changes of displacement and stress in each stage, to study the influence of waste rock backfilling in goaf on the stability of surrounding rock, and to analyze the influence of the implementation of "waste rock backfilling + cemented roof backfilling" in the goaf in this region on the surface river. This paper expounds on the effect of waste rock filling, a green environmental protection management measure, and puts forward the optimization of mining technology and filling strategy, to benefit the development of underground mining and waste rock filling.

2. Project overview and treatment process

2.1. Project overview

The mining area has rugged topography, characterized by steep slopes, gullies, and well-established hydrological systems. The terrain gradient ranges from 20° to 40°, often resulting in towering limestone cliffs with vertical walls reaching heights of 50–100 m. Within the mining area, there is a highly developed surface water system consisting of seasonal streams with limited discharge capacity. The mine's topography facilitates natural drainage for efficient runoff and discharge conditions; however, it should be noted that the riverbed is located above the goaf.

The mine utilizes three mining methods: the hole section empty field method, the short-hole shrinkage mining method, and the pre-controlled top blasting force moving house column method. The total length of the ore body is 3300m, the occurrence level is 1890-720m, the upper wall of the lead-zinc ore body is phyllite, and the lower wall is carbonated limestone. Currently, mining operations above a depth of 1400 m have been completed which resulted in the formation of several goaves. Most of these goaves experienced

(a) Empty area collapse (b) Surface subsidence (c) Surface cracks

Fig. 1. Disaster in the underground goaf.

natural collapse followed by filling; however, some were artificially filled with waste rock instead. Additionally, the goafs formed through thin orebody extraction on both sides were successfully sealed off without any significant incidents related to caving or ground pressure disasters occurring. Waste rocks generated from underground tunneling activities were utilized for partial backfilling at depths ranging from 1300 m to 1460 m based on engineering design considerations. This paper will focus on the part of the goaf area between line 145 and line 149. The specific study area is the design filling area (area A) as shown in Fig. 2.

The goaf is composed of a sequence of carbonate and clastic rocks. We obtained the mechanical parameters for the rock mass from laboratory experimental data on rock samples and made adjustments based on actual geological investigations and established engineering practices. We used relevant empirical formulas to enhance the reliability and authenticity of the mechanical parameters associated with the rock mass [20]. The physical and mechanical properties of the waste rock backfill material were determined through laboratory tests and adjusted according to applicable empirical formulas [21,22]. Following a comprehensive analysis of both the geological and engineering characteristics of the deposit, we identified four types of mechanical media for consideration. The geomechanical parameters along with filling physical properties are summarized in Table 1.

2.2. *Filling and treatment process*

To facilitate subsequent analysis, the relevant restoration and rehabilitation processes are outlined based on the characteristics of mineral deposit distribution, current mining status, and filling situation: (1) Solution for an abandoned mine area: Originally designed as security pillars, the A area are located approximately 180m below ground level and contain an underlying ore body. To prevent future development of water-conducting fractures that could connect to nearby rivers, waste rock filling is used as the primary treatment method at this abandoned mining site. Furthermore, cemented filling is employed to provide roof support. This approach effectively reduces the potential breakdown and displacement of rocks above while minimizing risks associated with the formation of water-conducting fractures. Additionally, this cemented structure acts as a waterproof barrier ensuring safety for deep-mined ore bodies. (2)The waste rock filling involves filling the cavity with waste rock. A waste rock inclined chute is excavated from the middle section along the vein transportation roadway, and the waste rock is transported to the filling cavity in the middle section of the goaf. Two waste rock inclined chutes are set in each goaf. (3) Bonded filling: Mobile equipment is used for bonded filling and roof support in underground operations. The chosen approach involves the use of a stir-pump-spray unit as mobile equipment for preparing and applying bonded fillings underground. Bagged cement and aggregate are transported from the surface to the underground, while the stir-pump-spray unit integrates various functions including loading sand and stone materials, mixing, pumping, and spraying mortar.

3. Research ideas and related theories

3.1. *Research ideas*

The current study examines the impact of "waste rock filling + grouting roof filling" on the stability of underground mining voids using a comprehensive dynamic analysis approach at every stage of the process. To thoroughly investigate void stability dynamics, we have divided the process into excavation and filling phases. By utilizing numerical simulation methods and in-situ monitoring techniques, we analyze displacements and deformations in both surface and underground voids from stress-strain perspectives throughout the excavation and filling processes. Fig. 3 illustrates our research thinking.

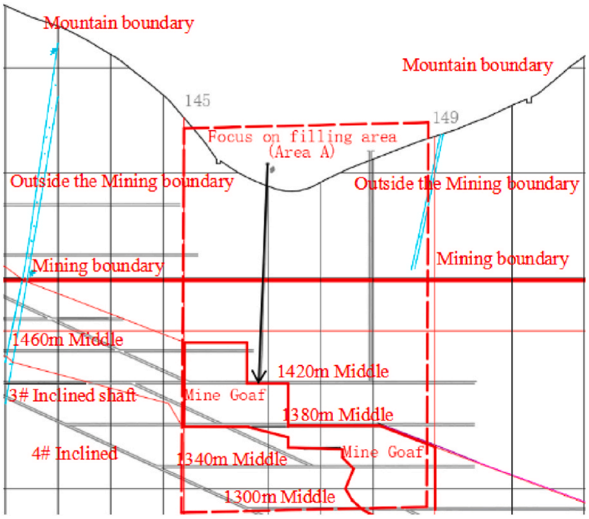


Fig. 2. Schematic diagram of the filling area.

Table 1
Physical and mechanical parameters of rock mass and filling mass.

Descriptions Items	Uniaxial-compressive-strength	Strength-extension	Modulus-deformation (E)	Cohesion (C)	Internal-friction angle (Φ)	Poisson Ratio (μ)
Epipelagic Phyllite	35.78 MPa	0.89 MPa	12400 MPa	11 MPa	32.40°	0.21
Lead-zinc Ore	54.11 MPa	7.47 MPa	14867 MPa	8.67 MPa	42.10°	0.19
Footwall Limestone	48.46 MPa	5.71 MPa	14933 MPa	7.00 MPa	38.56°	0.20
Waste-rock Filling	4.05 MPa	0.20 MPa	255 MPa	0.32 MPa	6.10°	0.24

3.2. Numerical simulation method

(1) MIDAS GTS NX

At present, finite element numerical simulation software has various types and functions. Considering that the numerical simulation needs to realize the study of the construction process in stages, to facilitate and concisely analyze the stress and strain conditions at each stage of the excavation and filling process, In this study, MIDAS GTS NX(2022-R1), an engineering software widely used in finite element geotechnical analysis, was used as a simulation calculation tool to build a three-dimensional numerical simulation solid calculation model to realize the whole process analysis of excavation and filling simulation in underground metal mines.

(2) Introduction of the basic theory

To improve the efficiency of our analysis, we have used the Mohr-Coulomb failure criterion in our numerical simulations. The resulting apply criterion equation and maximum tensile stress yield criterion function are presented as follows [23,24]:

$$\left.\begin{aligned} f_s &= \sigma_1 - \sigma_3\frac{1+\sin\varphi}{1-\sin\varphi} - 2c\sqrt{\frac{1+\sin\varphi}{1-\sin\varphi}} \\ f_t &= \sigma_3 - \sigma_t \end{aligned}\right\} \tag{1-1}$$

Where σ_1 represents the maximum principal stress, σ_3 represents the minimum principal stress, σ_t represents the tensile strength, φ represents the internal friction angle and c represents the cohesion in the rock mass.

The fundamental principle of numerical simulation using MIDAS GT/NX is the strength reduction method, which involves iteratively adjusting the reduction coefficient for trial calculations until the slope body reaches its limit state and experiences shear failure. The resulting reduction coefficient serves as a safety factor. In the finite element strength reduction method, a safety factor based on strength reserves is employed for calculation purposes. When determining the safety factor using MIDAS GT/NX, the basic principle of the strength reduction method formula can be summarized as follows [25]:

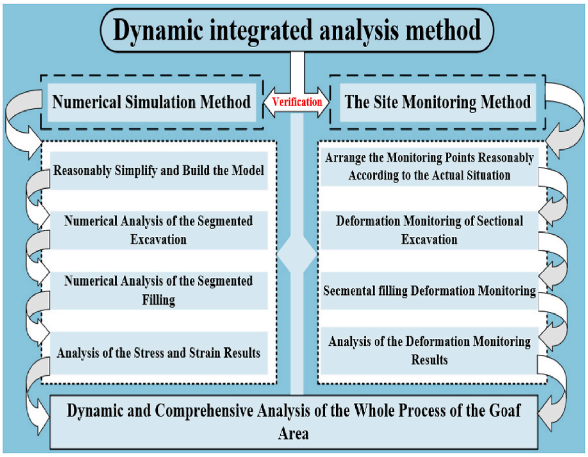


Fig. 3. Research ideas.

$$\left.\begin{aligned}\tan\varphi_F &= \frac{\tan\varphi}{F_s}\\ C_F &= \frac{C}{F_S}\end{aligned}\right\} \tag{1–2}$$

The formula includes C_F as the attenuating bonding force, φ_F as the reduced friction angle, and Fs as the reduction coefficient. In this study, MIDAS GTS NX(2022-R1) was used for numerical simulation. The failure criterion was the Mohr-Coulomb criterion, and the basic principle was shown in formula (1-1); the common strength reduction method was used for numerical simulation, and the basic principle was shown in Formula (1-2).

(2) Basic assumptions and boundary conditions of the calculation model

Basic Assumption: In order to facilitate the establishment of the model and ensure the scientific accuracy of the calculation, reasonable assumptions should be made based on engineering practice [26]: (1) Assuming the ore-rock body is an ideal elastoplastic material, the strength and volume of the material remain unchanged after reaching the yield point due to plastic deformation. (2) Assuming both the ore body and surrounding rock are locally homogeneous and isotropic materials, plastic deformation does not affect the isotropy of the material. (3) Assuming that the stability of ore-rock exhibits significant spatial randomness, geological phenomena such as fault structures in the ore-body have been taken into account to reduce rock mechanical parameters, eliminating their separate consideration during simulation.

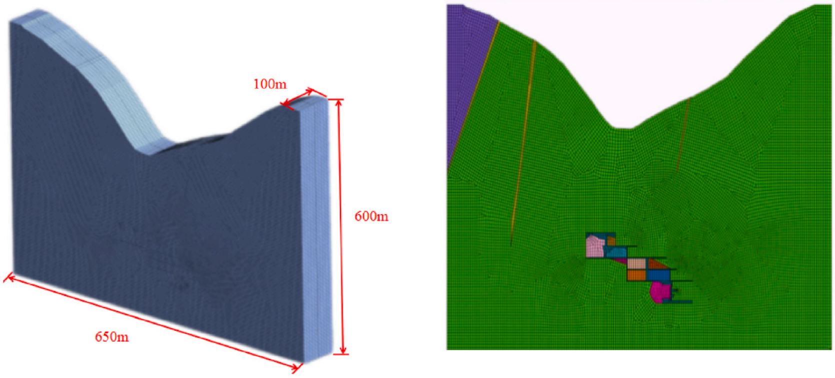
Border Conditions and Initial Stress [27,28]**:** In order to achieve the objective of computer simulation, it is crucial to impose reasonable constraints on the model, thereby transforming the established physical model into a corresponding geomechanical model. For the boundary conditions in this study, displacement constraints are employed: all nodes have limitations on displacements in three directions - X, Y, and Z at the bottom; for left and right boundaries, there are restrictions on displacements in the X and Y directions while Z remains unconstrained. Considering the characteristics and objectives of this numerical simulation, we have determined the initial stress field in our calculations based solely on the gravitational stress field of the rock mass due to a lack of actual in-situ stress test data. Specifically, vertical stresses are calculated by considering only the weight of the rock mass, while horizontal stresses are estimated by taking into account Poisson's effect.

(3) Numerical simulated experimental model

The reliability of numerical simulation is contingent upon the construction of the computational model. In this study, 3D finite element software MIDAS GT/NX was employed to conduct numerical simulation experiments in the A area of the mine, as depicted in Fig. 4(a). The establishment of a 3D computational model for numerical simulation was based on the section along exploration line 145, which is located at a lower position within the riverbed and represents an area closer to mining operations. This model aims to analyze stress and displacement variations in mineral bodies near the ground surface during mining activities adjacent to exploration line 145, as shown in Fig. 4(b).

3.3. Site monitoring method

The mine has established a relatively comprehensive safety monitoring platform, incorporating both surface and underground displacement change monitoring systems.However, their monitoring methods are different. (1)Surface monitoring: The monitoring benchmarks are established on the ground through regular observations using total stations, and a three-dimensional coordinate system is then created based on these benchmarks. These fixed points serve as references for measuring the three-dimensional



(a) The Computational Model (b) Distribution model of Empty Areas

Fig. 4. The numerical simulation model and research ideas.

coordinates (x, y, z) of monitoring points at various time intervals using total stations. Afterward, relative displacement and other parameters are calculated to analyze both the significance and pattern of deformation. This analysis allows us to determine how mining activities affect surface rock movement, as shown in Fig. 5. Three monitoring points are selected and designated as on-site subsidence monitoring points due to their spatial arrangement. (2)Underground monitoring: Ground deformation monitoring is conducted using differential resistance drill hole displacement meters, which convert deformation into electrical signals for remote monitoring purposes. The subsequent analysis of these electrical signals determines the displacement or strain of the original rock at each measurement point based on the calibration curve of the measuring head shown in Fig. 5. Three monitoring points are selected and designated as on-site subsidence monitoring points due to their spatial arrangement.(3) Monitoring frequency: Special personnel are responsible for on-site monitoring, surface deformation monitoring is recorded once a week, underground monitoring adopts a drilling displacement meter to collect and analyze data twice a week, and the specific situation is adjusted according to the project progress. The monitoring data in this study is selected according to the actual construction progress.

4. Numerical model and field monitoring results

4.1. Step-by-step simulation process

The excavation of rock masses during the mining process in underground mines disrupts the initial state of stress equilibrium within the rocks, resulting in the formation of void spaces and subsequent redistribution of stress, which leads to the development of a secondary stress field.However, the study of stress and strain analysis in rock masses plays a crucial role in managing surrounding rocks during mining operations, controlling surface subsidence, and mitigating associated disasters resulting from rock movement and mining pressure throughout the progress of a mine site. As excavation activities progress, there are ongoing changes in the dynamics of rock movements that require continual adjustment for an accurate assessment of stress distribution within adjacent geological formations. Therefore, investigating mining processes should be regarded as an ongoing research endeavor.

To investigate the stress and strain of surrounding rock in the goaf during the filling process, the numerical simulation primarily models the stress distribution and displacement area of surrounding rock in the goaf during mining and subsequent filling (using a top-down approach). The simulation procedure is presented in Table 2.

4.2. Numerical simulation of the experimental results

Simulated stress changes step by step: (1) Step 1: The initial step aims to simulate the stress distribution of the entire model before mining, ensuring a state of stress equilibrium. (2) Steps 2 to 4: These steps simulate the mining process for each stage of the ore body and analyze changes in surrounding rock stress within the void area, as depicted in Fig. 6. (3) Step 5: This step presents the current distribution of stress and displacement within the mined void area. (4) Steps 6 through 7: The final two steps involve simulating the gradual filling of the mined void area with waste rock, followed by an analysis of changes in surrounding rock stresses after filling. The distributions for maximum principal stresses and minimum principal stresses following void filling are illustrated in Fig. 7.

Simulate the displacement changes step by step: Steps 2 to 4 involve simulating the excavation of each stage of the ore body to analyze variations in intercolumn and surrounding rock displacement, as depicted in Fig. 8(a). Steps 5 to 7 encompass simulating the filling process for each stage of voids, further analyzing changes in intercolumn and surrounding rock displacement, while also evaluating the impact that filled voids have on the surface riverbed. The overall distribution of displacement after filling is illustrated in Fig. 8(b).

4.3. Results of on-site monitoring

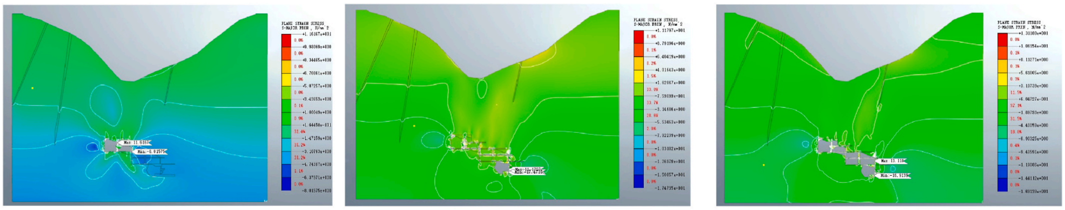
According to the monitoring situation obtained from the continuous monitoring of on-site displacement, the displacement and deformation results (data are preliminarily processed and converted into deformation amount) in the production and treatment process in area A of the mine are shown in Table 3 below.

(a) Surface observation spot (b) observation instrument (c) Empty area monitoring device

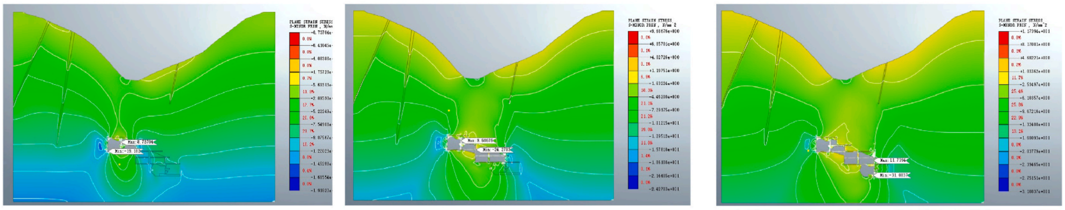
Fig. 5. Field displacement monitoring device.

Table 2
Step-by-step simulation process.

stage	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7
model	Initial model stress balance	Phase 1 ore body mining	Phase 2 ore body mining	Phase 3 ore body mining	Phase 1 Empty area backfill	Phase 2 Empty area backfill	Phase 2 Empty area backfill

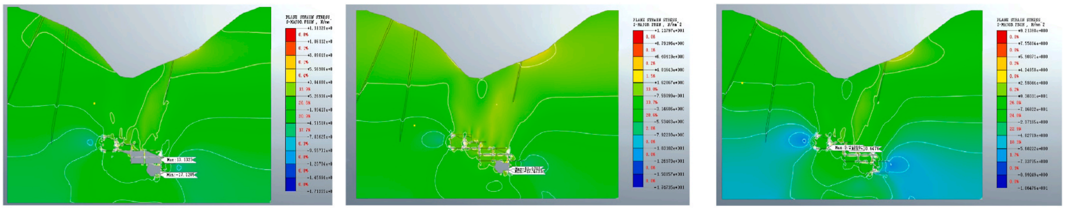

Step 2 Step 3 Step 4

(a) Maximum main stress diagram

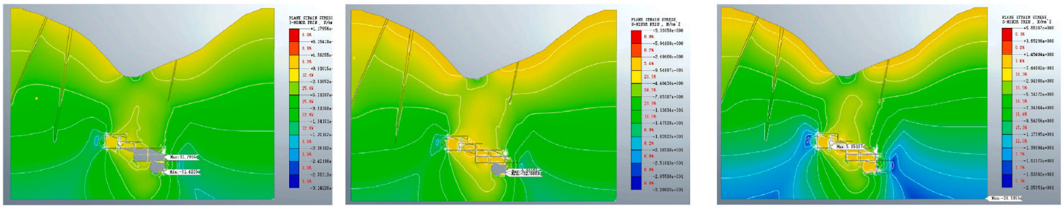

Step 2 Step 3 Step 4

(b) Minimum main stress diagram

Fig. 6. Main stress diagram of empty area in mining stage.


Step 5 Step 6 Step 7

(a) Maximum main stress diagram


Step 5 Step 6 Step 7

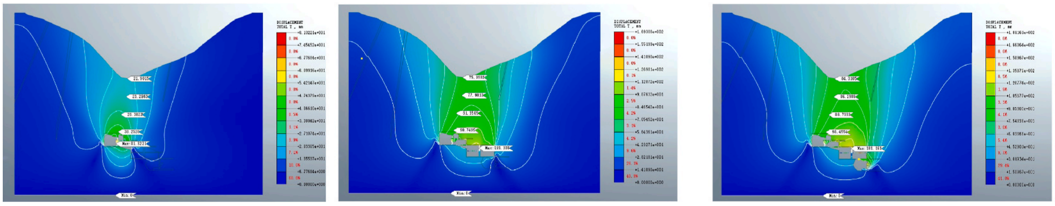
(b) Minimum main stress diagram

Fig. 7. Main stress distribution in the filling stage.

5. Results analysis

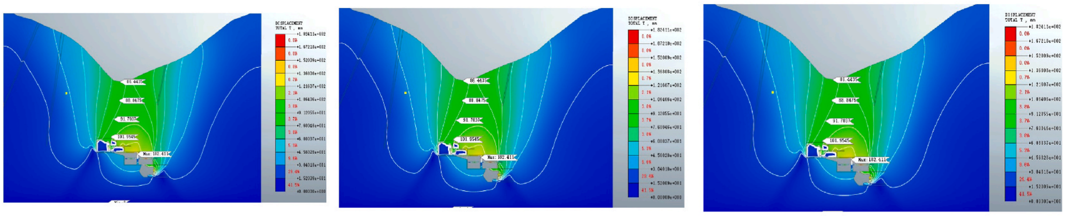
5.1. Data statistics

(1) Step-by step simulation mining stage



Step 2 Step 3 Step 4

(a) Displacement distribution diagram of the excavation stage



Step 5 Step 6 Step 7

(b)Displacement distribution map of the filling phase

Fig. 8. The overall displacement distribution of each stage in the empty area.

Table 3

Field monitoring of the displacement data.

Location	Number	Mining phase 1	Mining phase 2	Mining phase 3	Filling phase 2	Filling phase 2	Fill 3 stages
Surface-monitoring points	01	16 mm	66 mm	76 mm	81 mm	84 mm	86 mm
	02	19 mm	69 mm	79 mm	83 mm	86 mm	88 mm
	03	21 mm	72 mm	81 mm	84 mm	87 mm	89 mm
Emptyarea-monitoring point	01	63 mm	158 mm	167 mm	168 mm	172 mm	179 mm
	02	58 mm	153 mm	164 mm	166 mm	169 mm	171 mm
	03	79 mm	166 mm	178 mm	179 mm	184 mm	187 mm

The Stress Statistics: According to the numerical simulation results depicted in Fig. 6, the maximum values of the maximum principal stress following excavation of the ore body from top to bottom are recorded as 11.61 MPa, 11.63 MPa, and 13.11 MPa respectively; whereas the corresponding minimum values are recorded as −8.01 MPa, −13.97 MPa and −16.91 MPa respectively.The maximum values of the minimum principal stresses are as follows: 8.73 MPa, 9.68 MPa, and 11.73 MPa; while the corresponding minimum values are −19.18 MPa, −24.27 MPa and-31 .08 MPa.

The Displacement Statistics: According to the numerical simulation results shown in Fig. 8(a), displacement deformation of the goaf is primarily observed at the roof and extends from there to the surface when mining progresses gradually from top to bottom, with maximum deformations of 82 mm, 170 mm, and 182 mm respectively. The displacement gradually increases and is mainly observed at the intermediate pillar, with displacements extending to the surface measuring 22 mm, 76 mm, and 82 mm respectively.

(2) Step-by-step simulation and filling stage

The Stress Analysis: According to the numerical simulation results depicted in Fig. 7, the maximum values of the maximum principal stress following backfilling of the ore body from top to bottom are recorded as 13.13 MPa, 11.17 MPa, and 9.21 MPa respectively; whereas the corresponding minimum values are recorded as −17.12 MPa, −17.47 MPa and −10.64 MPa respectively.The maximum values of the minimum principal stresses are as follows: 11.79 MPa, 9.39 MPa, and 5.85 MPa; while the corresponding minimum values are −31.42 MPa, −32.00 MPa and −20.53 MPa.

The Displacement Analysis: According to the numerical simulation results depicted in Fig. 8(b), displacement deformation predominantly occurs at the roof and propagates towards the surface as the goaf gradually fills with waste rock. The maximum deformation values are successively measured as 183 mm, 188 mm, and 189 mm, while the displacement reaching the surface measures 86 mm, 89 mm, and 90 mm respectively.

(3) Field displacement monitoring

According to Table 3, according to monitoring data of the monitoring process of excavation and filling stages 3 of maximum displacement monitoring points is underground monitoring, each phase displacement of 79 mm, 166 mm, 178 mm, 179 mm, 184 mm, 187 mm. The ground monitoring process of excavation and filling stage 3 of maximum displacement monitoring points is underground monitoring, displacement at various stages of 21 mm, 72 mm, 81 mm, 84 mm, 87 mm, and 89 mm.

(4) Change the trend chart of stress, strain, and monitoring results

The numerical model simulated the stress and displacement changes after the excavation of the underground ore body in area A and the backfilling of the empty area, and the field monitoring monitored and recorded the displacements at each stage of the important points in the underground part and the above part of area A respectively. Based on the above simulation and monitoring, the maximum principal stress, minimum principal stress, displacement changes in the numerical simulation process, and field displacement monitoring were statistically analyzed, and the results are shown in Fig. 9.

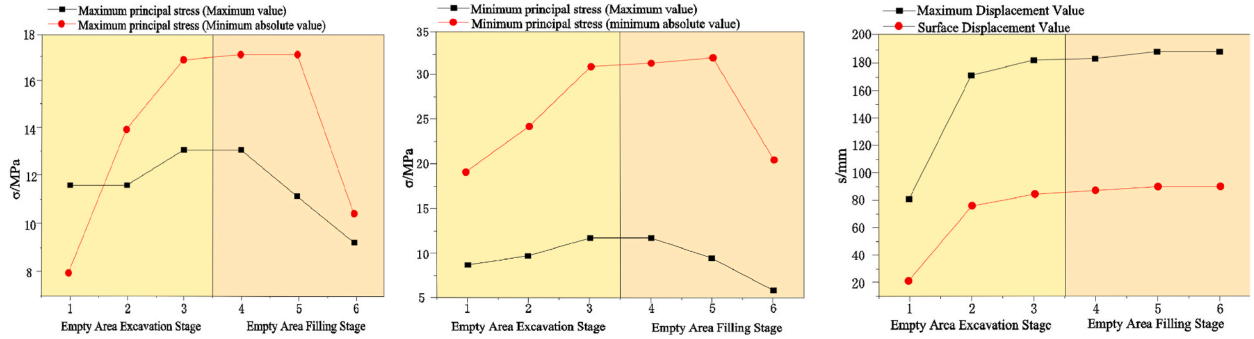
5.2. *Preliminary discussion*

According to the numerical simulation results, the in-situ displacement monitoring and the preliminary analysis of the changing trend, the stress-strain law, and the stability of the goaf in the mining process and filling process of area A are preliminaries analyzed:

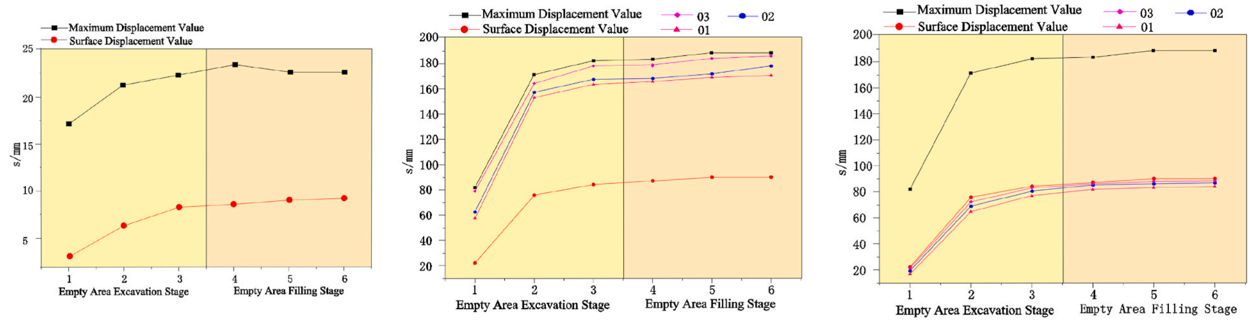
The Numerical simulation and analysis: According as shown in Fig. 9(a)(b)(c)(d) and Figs. 6–8 of numerical simulation displacement stress cloud, with the increase of mining depth of ore body, stress, and displacement is gradually increasing, in which stress is mostly concentrated in the top, bottom, and intercolumn of the stope, the increasing gradient of strain tends to increase, and the influence on the surface also increases in turn. With the waste rock filling in the goaf gradually, the stress is gradually reduced, especially in the stress concentration between the columns and the bottom floor, which indicates that the filling body plays a certain role in improving the stability of the goaf. As the displacement of waste rock filling in the goaf increases, the gradient amplitude slows down and tends to be stable due to the increase of displacement caused by the excavation of the ore body. Therefore, the use of waste rock filling has a better effect on the overall stability of the goaf.

The Monitoring and Analysis of the Empty Area: Based on an analysis of on-site monitoring data, Fig. 9 (e) reveals significant displacement deformation occurring in the goaf during excavation. Furthermore, progressive excavation leads to noticeable changes in the monitored displacements within this area. Particularly, during the waste rock filling + cement filling stages, a deceleration followed by stabilization of the rate of displacement change becomes apparent at these specific monitoring locations. This observed trend corresponds with the maximum predicted displacements derived from numerical simulations; however, actual field measurements exhibit lower magnitudes compared to those obtained through numerical simulations.

The Surface Monitoring and Analysis: The analysis and processing of field surface monitoring data reveal a significant increase in



(a)Maximum main stress map　(b)Minimum main stress map　(c) The overall deformation distribution



(d)Remove the deformation amount　(e) Monitoring displacement in empty area　(f) Surface monitoring of the displacement

Fig. 9. Statistical map of the main stress shift distribution.

surface displacement deformation during the excavation stage, as depicted in Fig. 9(f). However, the surface deformation stabilizes during the backfill stage. The observed phenomenon demonstrates that the filling process exerts a pronounced inhibitory influence on surface displacement.

The Validation of the numerical simulation results: According to the analysis of the changing trend of the field goaf monitoring and the surface monitoring, the changing trend of the field monitoring results and the numerical simulation results are consistent, which provides strong support for verifying the credibility of the numerical simulation results.

5.3. Comprehensive analysis of the results

According to data obtained from numerical simulations and on-site monitoring, there is a significant increase in both maximum and minimum principal stresses with increasing depth during the excavation process. After completion of backfilling, although there is a notable decrease in magnitudes of principal stress compared to pre-excavation levels, they still remain elevated. Throughout both the excavation and backfilling stages, both maximum displacement and surface displacement continuously increase; however, during the backfilling stage their rate of increase notably diminishes which indicates that backfilling has a pronounced influence on deformation within the mining area. Excavation followed by goaf's subsequent filling leads to reductions in both maximum principal stress as well as the absolute value of minimum principal stress; meanwhile, goaf displacement along with surface displacement tends towards stabilization.

During the filling process, the minimum principal stress gradually decreases during the construction stage but experiences a significant decrease after completing the filling of the roof. The maximum principal stress remains relatively constant, indicating non-uniformity in stress changes during filling. The strain is comparatively larger in the early stages of filling compared to later stages, indirectly illustrating how filling helps mitigate goaf deformation. During step-by-step mining, tensile stress occurs in most areas of surrounding rock while compressive stress concentrates and continues to increase within a small portion of that area. In the step-by-step filling process, as waste rock gradually fills the goaf, stress slightly increases and then decreases significantly. This effectively alleviates stress concentration in the surrounding rock and largely eliminates the risks of rock bursts and collapse after filling. The fill body plays an instrumental role in improving the stress condition and stability of the goaf.

According to the stress-strain calculated by numerical simulation and the displacement monitored in the field, it is found that the stress changes significantly between the floor, roof, and column during excavation and filling. In the excavation stage, the stress of the roof increases rapidly, and it is the most stress-sensitive part in the goaf area, and the deformation between columns is relatively obvious compared with other parts. In the filling stage, the stress of the floor decreases slowly, but the stress of the roof and the floor decreases rapidly, and the deformation and displacement increase during the filling process. In the initial stage of filling, the deformation of the hollow area of the pillar increases briefly, but the increasing gradient also decreases significantly, which fully shows that the effect of "waste rock filling + cemented roof filling" on maintaining the stability of the job is obvious.

In the step-by-step dynamic mining process, the maximum displacement occurs in the middle of the roof, pointing towards the goaf. As excavation progresses and enlarges it, there is a gradual increase in upper displacement with a significant gradient. During the step-by-step filling process, both values for maximum displacement and surface displacement exhibit an ascending trend; however, their rate of increase experiences a substantial reduction. This observation suggests that waste rock filling combined with cement filling can effectively mitigate surface deformation. The surface monitoring point 03 is located in close proximity to the riverbed, and its findings are consistent with the results obtained from numerical simulations. Furthermore, other field displacement monitoring outcomes also confirm a significant reduction in displacement increments during the filling process, effectively mitigating the impact on the river's surface.

5.4. Optimization recommendations

1. During the excavation of underground ore bodies in mines, when there is a river on the surface of the geological conditions in the upper part of the excavation area are complex, the monitoring of the roof stress in the excavation area should be strengthened, the deformation monitoring of the surrounding rock surrounding the excavation area should be strengthened, the daily inspection should be strengthened, and the displacement change information should be reported in time. Once there is a large movement, the underground operators should be evacuated immediately;
2. Filling can effectively alleviate the stress outburst in the goaf and reduce the deformation and displacement around the goaf and the surface, but the initial effect of filling is relatively not obvious. When the goaf roof is unstable and there is a large risk of caving, it is recommended to strengthen the underground and surface monitoring and early warning system in the early stage of filling, to prevent and control the safety risk of the goaf caused by large-scale disturbance in the early stage.
3. When filling the goaf in each middle section, the goaf should be filled as much as possible. When the waste stone filling is completed, the roof should be connected by cemented filling to ensure that the goaf is filled and the roof can be completely connected.

6. Conclusion

Based on a comprehensive analysis of numerical simulations and on-site monitoring results, the statistical analysis reveals the following conclusions regarding stress changes, displacement changes, as well as related stresses and strains at specific control points during the mining and filling processes in the goaf:The implementation of "waste rock filling + cement filling" for roofing effectively alleviates stress in the surrounding rock, ensuring stability on the surface's river in mining areas.

(1) As mining activities progress deeper into the mineral deposit, stress gradually accumulates and concentrates in the roof, floor, and pillars of the mining area. The displacement deformation of voids mainly manifests in the roof as it extends towards the surface with gradual increases in displacement. Therefore, deep mineral extraction results in an associated increase in surface impact, with significant stress and strain experienced by the roof.
(2) During top-to-bottom backfilling, as waste rock fills the goaf, the stress gradually decreases, thereby enhancing its stability. Displacement deformation mainly occurs in the roof and extends towards the surface. Although there is a slight increase in displacement caused by waste rock filling, this rate of increment slows down and approaches stability.
(3) The stress and strain changes exhibited non-uniformity at each stage of the backfilling process: gradual variations were observed in the maximum principal stress during the initial stage, while significant alterations occurred in subsequent stages; displacement changes initially decelerated before stabilizing. This observation implies that filling has a positive impact and can effectively guarantee cavity stability.
(4) The goaf treatment method of "waste rock filling + cemented roof filling" is adopted, and the filling material is an important guarantee for achieving the filling effect. In the process of designing waste rock filling, the selection of filling materials should be fully evaluated according to the actual mine, which can meet the requirements of the mining production on the filling process and the strength of the filling body, which is an important guarantee for achieving the excellent treatment effect of waste rock filling.
(5) The most prominent displacements and strains in the excavation and filling stage are at the top, bottom, and intercolumn of the stope, which provide references and references in the design, construction and monitoring and early warning, and provide effective guidance for the safety production of mines in the later stage.Based on comprehensive analysis, the subsequent research should study the stress-strain condition of the backfill body in the engineering practice during the field filling process, and further refine the distribution of stress-strain plastic zone in each stage of the filling process.
(6) The "waste rock filling + cemented filling" topping achieves the transformation of solid waste into treasure in mines, effectively promotes the construction of green mines, and is an effective means of goaf management.

CRediT authorship contribution statement

Gongyong Wu: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Xingxin Nie:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Linhai Zhao:** Project administration, Methodology, Data curation. **Zongli Li:** Project administration, Methodology, Data curation.

Data availability statement

Given the constraints of our data usage protocols, research data is not deposited in a publicly accessible repository. Data will be made available on request. The data that support the findings of this study are available from the corresponding author, WU-GY, upon reasonable request.

Declaration of funding issue

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Ethical statement

This study does not involve any human or animal subjects, and it is in accordance with research ethical standards.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

The authors thank all the individuals who participated in this study.

References

[1] Z. Haitao, X. Guangquan, Z. Yanxi, et al., Mechanical model and numerical simulation of the formation of karst collapse columns in the Huainan coalfield of Northern China, Energy Explor. Exploit. 41 (4) (2023) 1356–1373, https://doi.org/10.1177/01445987231168715.

[2] S. Guoshao, C. Yanxiang, J. Quan, et al., Spalling failure of deep hard rock caverns, J. Rock Mech. Geotech. Eng. 15 (8) (2023) 2083–2104, https://doi.org/10.1016/J.JRMGE.2022.11.021.

[3] R. M.G, M. Christopher, K. R.T, Massive pillar collapses in US underground limestone mines: 2015–2021, Mining, Metallurgy Exploration 40 (5) (2023) 1547–1556, https://doi.org/10.1007/S42461-023-00814-1.

[4] Z. Li, K. Hou, T. Li, et al., Numerical simulation of surface subsidence and fracture evolution caused by pulang copper mine mining, Appl. Sci. 14 (6) (2024), https://doi.org/10.3390/APP14062416.

[5] A. Akhil, S.P. Kumar, A.T. Kumar, et al., Subsidence analysis for old abandoned board and pillar coal mines using ANSYS and Monte Carlo simulation, J. Min. Sci. 59 (6) (2024) 938–948, https://doi.org/10.1134/S1062739123060078.

[6] G. Wu, X. Nie, X. Zhang, et al., Stability grade evaluation of slope with soft rock formation in open-pit mine based on modified cloud model, Sustainability 16 (11) (2024), https://doi.org/10.3390/SU16114706.

[7] L. Yu, L. Hui, S. Lijuan, et al., Developmental features, influencing factors, and formation mechanism of underground mining–induced ground fissure disasters in China: a review, Int. J. Environ. Res. Publ. Health 20 (4) (2023), https://doi.org/10.3390/IJERPH20043511, 3511-3511.

[8] N. Yao, T. Huang, G. Zhang, et al., Study on delamination characteristics and mechanical properties of cemented waste rock backfill with rubber aggregation, Construct. Build. Mater. (2024) 438137090, https://doi.org/10.1016/J.CONBUILDMAT.2024.137090, 137090.

[9] D. Luo, J. Huang, Y. Liang, et al., Comprehensive evaluation of green mine construction level considering fuzzy factors using intuitionistic fuzzy TOPSIS with kernel distance, Environ. Sci. Pollut. Res. Int. 31 (11) (2024) 16884–16898, https://doi.org/10.1007/S11356-023-31812-X.

[10] A. Karolina, P. Daniel, Application of hydraulic backfill for rockburst prevention in the mining field with remnant in the polish underground copper mines, Energies 14 (13) (2021), https://doi.org/10.3390/EN14133869, 3869-3869.

[11] S. Yonglu, Z. Caixin, L. Lang, et al., Proportion optimization and strength prediction of CGS backfill materials based on GA-ELM mode, Energy Sources,Part A: Recovery,Utilization,and Environmental Effects 45 (2) (2023) 5173–5189, https://doi.org/10.1080/15567036.2023.2205353.

[12] S. Krzysztof, Compressibility of materials and backfilling mixtures with addition of solid wastes from flue-gas treatment and fly ashes, E3S Web of Conferences (2018) 7100007, https://doi.org/10.1051/e3sconf/20187100007, 7.

[13] S. Krzysztof, 3D numerical modelling of the application of cemented paste backfill on displacements around strip excavations, Energies 14 (22) (2021), https://doi.org/10.3390/EN14227750, 7750-7750.

[14] Xia Yu, Aihong Lu, Analysis of dynamic characteristics and destruction characteristics of continuous graded high strength cementation, Journal of Mining and Rock Formation Control Engineering 5 (1) (2023) 55–66, https://doi.org/10.13532/j.jmsce.cn10-1638/td.20221212.002.

[15] A. Driouch, L. Ouadif, A. Lahmili, M.A. Belmi, K. Benjmel, Geotechnical modeling of the method for mining cobalt deposits at the Bou Azzer Mine, Morocco, Mining of Mineral Deposits 17 (1) (2023) 51–58, https://doi.org/10.33271/mining17.01.051.

[16] L.Q. Nguyen, T.T.T. Le, T.G. Nguyen, D.T. Tran, Prediction of underground mining-induced subsidence: artificial neural network based approach, Mining of Mineral Deposits 17 (4) (2023) 45–52, https://doi.org/10.33271/mining17.04.045.

[17] H. Wang, G. Feng, T. Qi, et al., Insight into the fracture mechanical properties of the interfacial transition zone of cemented coal gangue backfill under different stress angles by mesoscopic digital image correlation, Eng. Fract. Mech. (2024) 300109988, https://doi.org/10.1016/J.ENGFRACMECH.2024.109988.

[18] X. Zhang, Y. Ke, L. Liu, et al., Numerical simulation of heat-storage performance of filling body with uniformly mixed phase change paraffin, Therm. Sci. 27 (6A) (2023) 4609–4624, https://doi.org/10.2298/TSCI221231078Z.

[19] Y. Hu, Y. Ye, B. Zhang, et al., Distribution characterization and strength prediction of backfill in underhand drift stopes based on sparrow search algorithm-extreme learning machine and field experiments, Case Stud. Constr. Mater. (2024) e03784, https://doi.org/10.1016/J.CSCM.2024.E03784, 21e03784.

[20] Hong Chenjie, Huang Man, Xia Cai, Size effect study of anisotropic coefficient of variation in rock mass structure surface, Rock Soil Mech. 41 (6) (2020) 2098–2109, https://doi.org/10.16285/j.rsm.2019.1325.

[21] S. Krzysztof, K. Waldemar, M.P. Katarzyna, Binding capability of ashes and dusts from municipal solid waste incineration with salt brine and geotchnical parameters of the cemented samples, Arch. Min. Sci. 63 (4) (2018) 903–918, https://doi.org/10.24425/ams.2018.124983.

[22] W. Yuan, H. Tan, J. Niu, et al., A new criterion for defining the failure of a fractured rock mass slope based on the strength reduction method, Geomatics, Nat. Hazards Risk 11 (1) (2020) 1849–1863, https://doi.org/10.1080/19475705.2020.1814428.

[23] S. K.A, S. Atsushi, B. Thomas, et al., A conceptual three-dimensional frictional model to predict the effect of the intermediate principal stress based on the Mohr-Coulomb and Hoek-Brown failure criteria, Int. J. Rock Mech. Min. Sci. 172 (2023), https://doi.org/10.1016/J.IJRMMS.2023.105605.

[24] Xingxin Nie, Gongyong Wu, Xin Zhang, et al., Study on the "sitting-sliding" failure mode of weak rock strata group in high and steep complex slope of open-pit mine, Industrial Safety and Environmental Protection 50 (5) (2024) 40–44, https://doi.org/10.3969/j.issn.1001-425X.2024.05.008.

[25] J. Byungkyu, J. Hoyoung, C. Seungbeom, et al., Assessment of subsidence hazard in abandoned mine area using strength reduction method, KSCE J. Civ. Eng. 26 (10) (2022) 4338–4358, https://doi.org/10.1007/S12205-022-2408-Z.

[26] Xiongtian Zhang, Wenzhi Zhu, Research on the comprehensive technology of treating abandoned open pit and subsidence area in long-distance pipeline conveying mortar, Metal. Mine (2) (2022) 68–74, https://doi.org/10.19614/j.cnki.jsks.202202010.

[27] Kaige Zheng, Liang Yuan, Sen Yang, et al., Research on prevention and control of composite hard roof rock burst based on partition weakening, Journal of Mining and Safety Engineering 40 (2) (2023) 322–333, https://doi.org/10.13545/j.cnki.jmse.2022.0064.

[28] Gongyong Wu, Xingxin Nie, Xin Zhang, et al., Stability of high and steep slope of weak rock formation in open pit mine based on subjective and objective comprehensive weight-forward cloud model, Non-ferrous metal engineering 14 (9) (2024) 150–162, https://doi.org/10.3969/j.issn.2095-1744.2024.09.019.