

Article

Numerical Simulation of Grout Diffusion and Overlap Characteristics in Horizontal Curtain Grouting for Underground Mines Within 3D Discrete Fracture Networks

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Abstract

Deep metal mines face increasing risks of water and sand inrush under complex fracture network conditions, where the unclear mechanism of slurry diffusion limits the reliability of horizontal curtain grouting. Taking the Cuihongshan iron–polymetallic mine as a case study, this paper establishes a stochastic three-dimensional discrete fracture network model and adopts an orthogonal experimental design to systematically investigate the effects of key engineering parameters on grout diffusion behavior. The results reveal that grouting pressure acts as the dominant controlling factor, significantly expanding the diffusion range and promoting the formation of continuous high-fill zones within the fracture network. Conversely, slurry viscosity exhibits a negative correlation with diffusion performance, leading to reduced inter-borehole connectivity as viscosity increases. Compared with conventional macro-indicators, the inter-borehole overlap rate provides a more precise quantitative measure of curtain continuity. The study demonstrates that achieving a sufficiently high overlap rate is critical for transitioning from discontinuous filling to a reliable impermeable curtain. These findings offer a theoretical basis for optimizing grouting parameters and evaluating sealing effectiveness in deep mine construction.

Keywords: water and sand inrush; horizontal curtain grouting; 3D fracture network; diffusion law; grouting pressure

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1. Introduction

Metallic minerals serve as a cornerstone of the modern industrial system and national economic growth; consequently, their strategic value is intrinsically linked to national productivity advancement and energy security assurance [1–3]. However, constrained by the depletion of shallow mineral resources, China’s metal mining sector has entered a strategic phase characterized by deep excavation and westward expansion. This transition is accompanied by increasingly complex and severe engineering and hydrogeological conditions, where high in situ stress, elevated geothermal gradients, high karst

water pressures, and intense mining-induced disturbances are superimposed upon one another [4–6]. This transition has not only significantly altered the physico-mechanical properties of rock masses but also facilitated the connection of concealed water-sand channels, thereby directly elevating the risk of water and sand inrush disasters. Consequently, such phenomena have emerged as a critical bottleneck constraining safe production and efficient extraction in mines [7–9].

From the perspective of disaster occurrence, the continuous expansion of metal mining operations has precipitated a shift in water inrush and sand inrush incidents from sporadic events to prominent safety hazards across the industry [10–12]. Notable accidents, such as those at the Macheng iron mine and the Cuihongshan iron–polymetallic mine, have resulted in substantial economic losses and compromised safety, while also revealing the destructive nature of such disasters within the metal mining sector. Concurrent with these developments, numerous metal mines across multiple provinces in China continue to face persistent latent risks or remain under prolonged threat from such disasters, rendering the urgency of their governance increasingly prominent [13]. Unlike water inrush and sand bursting disasters in coal mines, those in metal mines are characterized by distinct metallogenic backgrounds, such as complex stratigraphic structures induced by magmatic intrusions, intricate fracture networks, and heterogeneous hydrogeological systems [14]. These factors endow metal mine disasters with greater suddenness, amplified destructive power, and heightened mitigation complexity. Moreover, occurring predominantly in dynamic hydrogeological settings, these incidents further complicate prevention and control efforts [15].

Extensive research has been conducted by scholars worldwide on mine water and sand inrush disasters, establishing a consensus that the occurrence of such hazards is contingent upon four core prerequisites: (i) abundant source materials; (ii) conduits capable of transmitting water-sand mixtures; (iii) a driving force sufficient to breach the aquifuge; and (iv) an accommodation space for the disaster to manifest [16]. Regarding mitigation technologies, conventional approaches primarily rely on dewatering coupled with pressure relief and grouting reinforcement. While the dewatering method retains limited applicability in shallow mining scenarios, it fails to meet the demands of deep excavation. As mining depth increases, the drainage volume escalates exponentially, leading not only to a surge in operational costs but also to ecological repercussions, such as the disruption of regional groundwater systems [17]. As a pivotal technique for strata reinforcement and water plugging, the efficacy of grouting technology hinges critically on the precise characterization of slurry diffusion patterns. Particularly within the complex void structures of fractured and collapsed bodies, the mechanisms governing slurry migration and diffusion remain incompletely understood [18–20]. Consequently, investigating the mechanisms governing slurry migration and diffusion within the voids of fractured and collapsed bodies, and elucidating the evolution laws of slurry penetration, filling, and consolidation under multi-factor coupling effects, holds considerable theoretical value and provides practical guidance for optimizing grouting parameters and enhancing the efficacy of strata reinforcement and water inrush control.

Furthermore, the unexpected exposure of concealed aquifer-bearing structures in deep mining, such as undetected faults and karstic erosion channels, often triggers sudden, large-scale water and sand inrush. Such unforeseen risks exponentially amplify the complexity and difficulty of disaster prevention and control [21–23]. Existing studies indicate that neither conventional water inrush prevention techniques for metal mines nor mitigation experience derived from coal mines can be directly adapted to the unique operational contexts of metal mining. The integration of new-generation information technologies within this domain remains largely exploratory. Notably, there is a paucity of

research coupling the characterization of slurry diffusion patterns with the fine-scale delineation of three-dimensional fracture networks. Consequently, the diffusion behavior of slurry within stochastic fracture networks has been insufficiently studied, thereby impeding the effective prediction of the continuity and integrity of curtain grouting bodies. In view of this, constructing stochastic three-dimensional fracture network models to systematically analyze the influence of grouting parameters on slurry diffusion patterns—thereby achieving a synergistic optimization of disaster prevention and on-site remediation—has emerged as a critical research frontier requiring urgent breakthroughs.

2. Materials and Methods

2.1. Case Study

2.1.1. Engineering Geological Conditions

The Cuihongshan iron–polymetallic mine is located in Xunke County, Heilongjiang Province, China, approximately 240 km southeast of Heihe City and 80 km north of Yichun City. In 2019, a caving-induced water inrush occurred at the northwestern side of an old goaf at the 310 m level during the mining operation of the Cuihongshan iron–polymetallic mine [24,25]. Following the incident, compaction backfilling was implemented to treat the surface subsidence zone. Exploratory drilling revealed that a substantial volume of loose sands, interbedded with minor fluvial gravels, is distributed at depths of 110–116 m within the collapse core zone. The disaster mitigation zone is characterized by highly active hydrodynamic conditions and extremely complex geological structures; consequently, a scientific approach is imperative to achieve the comprehensive remediation of the collapse and caving masses. The designed horizontal grout curtain has a total length of 913.58 m, with 126 grouting holes arranged along the alignment. The average hole depth is 122.05 m, resulting in a total drilling footage of 15,377.69 m and a total grouted length of approximately 14,072.69 m. Grouting is carried out following the principle of stage-wise densification. Each row of grouting holes is constructed in three sequences: the Stage I holes are drilled and grouted first, followed by the Stage II holes, and finally the Stage III holes, as shown in Figure 1. The total grout volume injected is 1623.41 m³, with a total cement mass of 934.48 t. The average grout consumption is 1.27 m³/m, and the average cement consumption is 0.697 t/m. The maximum grout intake occurred in borehole ZK62, where the cumulative grout volume reached 99.886 m³, corresponding to 8.241 m³/m and 4.633 t/m for unit grout and cement consumptions. These results indicate significant heterogeneity in the development of karst fractures and notable variability in grout uptake across the formation.



Figure 1. Site photographs of the horizontal grout curtain construction at the Cuihongshan iron–polymetallic mine.

2.1.2. Hydrogeological Conditions

The study area is situated in the northern segment of the Yichun–Yanshou geosynclinal fold system, within the eastern part of the Hinggan–Inner Mongolia geosynclinal fold region. The crystalline basement comprises metamorphic rocks of the Lower Paleoproterozoic Dongfengshan Group, ranging from high greenschist to low amphibolite facies, while the early sedimentary cover is composed of marine magnesian carbonates of the Qianshan Formation, Lower Cambrian Xilin Group. The district is characterized by multi-phase granitic intrusions, predominantly of the Middle Caledonian and Indosinian epochs, which are the most widespread. Paleozoic strata predominantly occur as xenoliths within these plutons, wherein the Qianshan Formation serves as the primary host horizon for mineralization. The regional geological framework and lithology govern the formation and evolution of the groundwater system, while meteorological, hydrological, and topographic factors further modulate the prevailing hydrogeological conditions. Groundwater in the study area is categorized into bedrock fissure water and Quaternary porous water. The former is subdivided into weathering fissure water and karst fissure water. Weathering fissure water exhibits low permeability and poor water abundance, with an aquifer thickness of 30–40 m, a single-well yield of less than 10 m³/h, and a hydrochemical type dominated by Ca–HCO₃ or Ca–Mg–HCO₃. Its permeability coefficient ranges from 0.01 to 0.04 m/d. Karst water strikes in a NE–SW-trending belt across the Cuigang, Hongchuan, and Hongqishan areas, as well as sporadic localities, covering an area of approximately 10 km². The lithology is dominated by crystalline limestone and dolomitic crystalline limestone. The aquifer thickness ranges from 70 to 120 m (locally up to 160 m), exhibiting high water abundance with a single-well yield exceeding 1000 m³/d and a permeability coefficient of 0.50–1.80 m/d. Quaternary porous water is primarily hosted within the high floodplains of the Ku’erbin River valley and its tributaries upstream of the mining area, as well as in modern alluvial sandy gravel layers. The valley width ranges from 200 to 1000 m, with an aquifer thickness of 10–20 m and a water table depth of 0.5–1.2 m. It is characterized by abundant yields, with single-well discharges ranging from 3000 to 5000 m³/d and a hydraulic conductivity of 20–50 m/d. The hydrochemical type is predominantly Ca–Na–HCO₃. Recharge is mainly derived from atmospheric precipitation and river leakage, while discharge occurs primarily through evaporation and subsurface runoff [26–28]. This system vertically infiltrates to replenish bedrock fissure water, thereby indirectly influencing the water inflow environment of the ore deposit.

2.2. Numerical Simulation Design for Curtain Grouting

Constructing a stochastic three-dimensional fracture network model that accurately captures the structural characteristics of subsurface rock masses constitutes the foundation for subsequent slurry diffusion simulations. In this study, COMSOL Multiphysics software (version 5.6) was employed to conduct a finite element simulation of the grouting process within three-dimensional fractured rock masses. The Discrete Fracture Network-3D (DFN-3D) module within this software operates on DFN theory, utilizing stochastic distribution functions and geometric parameterization to generate three-dimensional fractures. This process culminates in the formation of elliptical planar fracture networks that accurately reproduce the random distribution characteristics of fractures within rock masses. By solving the coupled partial differential equations governing multi-physics interactions, the software effectively simulates the mechanical and permeability characteristics of fractured rock masses, the seepage and diffusion behaviors of grout, and the associated grout solidification reactions.

In this methodology, the geometric parameters of the fractures—including the coordinates of the centroid, orientation, and size—are defined as random variables. Statistical

analysis of field-measured parameters was conducted to determine their underlying probability distribution functions. Subsequently, Monte Carlo random sampling was employed to generate a large population of virtual fractures conforming to these specific distributions, which were then assembled into a three-dimensional Discrete Fracture Network (DFN) model.

(1) Uniform Random Model for Fracture Locations:

$$f(x) = \begin{cases} \frac{1}{X_{\max} - X_{\min}}, & X_{\min} < x < X_{\max} \\ 0, & \text{else} \end{cases} \quad (1)$$

where $X_{\max}$ and $X_{\min}$ denote the maximum and minimum bounds of the location parameter within the respective dimension, respectively.

(2) Power-Law Random Model for Fracture Sizes:

$$f(x) = \frac{\alpha-1}{x_{\min}} \left(\frac{x}{x_{\min}} \right)^{-\alpha} \quad (2)$$

where α denotes the power-law distribution exponent (reflecting the characteristic power-law decay of the size distribution), and $x_{\min}$ represents the minimum measured fracture length.

(3) Fisher Random Model for Fracture Orientations:

$$f(\theta) = K \frac{\sin\theta \cdot e^{K\cos\theta}}{e^K - e^{-K}} \quad (3)$$

where θ is the angular deviation, K is the Fisher dispersion coefficient or Fisher constant.

The probability density function of the Fisher distribution describes the angular deviation (θ) from the mean orientation of the elliptical directions. The parameter K , referred to as the Fisher dispersion coefficient or Fisher constant, quantifies the degree of concentration of fracture orientations relative to the mean direction. A larger K value indicates a more tightly clustered directional distribution. Statistical analysis of borehole-measured joints and fractures identified three dominant discontinuity sets, with orientations of $75^\circ \angle 70.5^\circ$, $44.7^\circ \angle 73.1^\circ$, and $20.4^\circ \angle 80^\circ$. Based on these field-derived data, three corresponding structural plane models were subsequently established. The stochastic three-dimensional fracture network model generated in COMSOL is illustrated in Figure 2. The model has dimensions of 20 m in length, 6 m in width, and 15 m in height, and contains a total of 240 fractures. It should be noted that while the DFN was generated based on statistically calibrated field data, the simulation results presented in this study correspond to a single, representative realization containing 240 fractures. The numerical model preserves the statistical distributions of fracture geometry (orientation, aperture, density) obtained from the field investigation. Although the absolute length scale is reduced, the relative proportions and structural complexity remain consistent with the field conditions. Supplementary analysis involving 10 additional realizations for selected test cases yielded coefficients of variation of 8.7% and 6.2% for diffusion volume, respectively. This indicates that the selected realization provides a stable approximation of the fracture network's transport properties, sufficient for identifying the dominant controlling factors within the scope of this parametric study.

The hydraulic boundary condition was defined by a constant injection flux at the borehole inlets, corresponding to the specified grouting pressures. All external boundaries of the 20 m $\times$ 6 m $\times$ 15 m domain were set as impermeable walls to simulate the confined nature of the collapse mass. The fracture apertures were assumed to be constant to isolate the effects of the tested engineering parameters. A mesh independence study was conducted prior to the simulations; the results indicated that a further refinement beyond the selected element size changed the calculated diffusion volume by less than 5%, confirming

numerical stability. The simulations were considered converged when the relative error in the flow continuity equation fell below 10^{-6} .

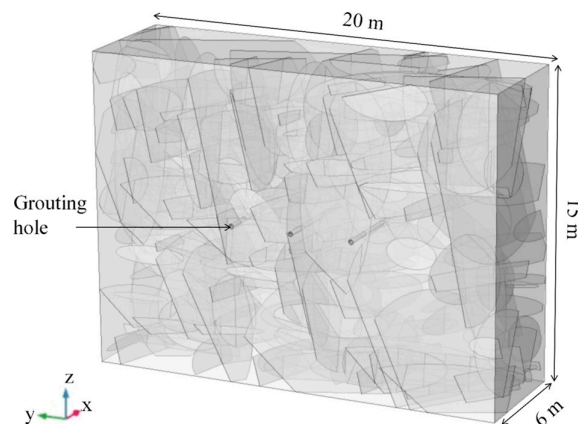


Figure 2. Stochastic three-dimensional fracture network.

In the practical construction of curtain grouting projects, a single row or multiple rows of grout holes are typically arranged at certain intervals, followed by sequential grouting performed either individually or in groups. For the grouting experiment within the 3D fracture network, a single row of three grout holes was deployed. An $L_{16}(4^4)$ orthogonal experimental design was adopted, investigating four factors: grouting pressure (A), hole spacing (B), initial grout viscosity (C), and hydrostatic pressure (D). Each factor was assigned four levels, which were determined based on practical engineering experience. The grouting design employed a cement grout. The initial viscosity of this grout is governed by the water–cement ratio, ambient temperature, and the slurry mix proportion. A higher viscosity results in greater seepage resistance, thereby increasing the difficulty of grout diffusion. Four cement grout with distinct initial viscosities (0.08, 0.10, 0.12, and 0.14 Pa·s) were selected as the injection slurries for this study. In accordance with the specifications of the mine curtain grouting design, a baseline hole spacing of 5 m was established. Accordingly, four distinct hole spacings (3 m, 4 m, 5 m, and 6 m) were selected for the comparative study. The design hole depth was set at 180 m, and four levels of hydrostatic pressure were selected for the experiments: 0.4 MPa, 0.6 MPa, 0.8 MPa, and 1.0 MPa. The grouting pressure for the mine curtain grouting must exceed the hydrostatic pressure, with specific values stipulated by the code to range from 1.6 to 3.0 times the magnitude of the hydrostatic pressure. These regulatory provisions, synthesized from extensive engineering practices and experimental data, are designed to ensure the impermeability effectiveness of the curtain and overall engineering safety. In practical applications, considering the relatively high viscosity and substantial flow resistance of the grout, the injection pressure must be moderately elevated to ensure adequate diffusion. Consequently, four specific pressure levels were selected for the experiments: 2 MPa, 3 MPa, 4 MPa, and 5 MPa. The factor levels and the orthogonal experimental design matrix are presented in Tables 1 and 2, respectively. Following the orthogonal array outlined in Table 2, a three-dimensional fracture network model was established, and 16 sets of simulated grouting tests were subsequently conducted on this model. Each simulation was run for a duration of 30 min, and the final effective diffusion volume of the grout was extracted for analysis. It should be noted that cement grout typically exhibits time-dependent rheological behavior due to progressive gelation. In this study, given the relatively short injection duration (30 min), the grout was simplified as a Newtonian fluid with a constant dynamic viscosity. The relationship between shear stress (τ) and shear rate (γ) is expressed as $\tau = \mu\gamma$, where

μ is the initial apparent viscosity of the grout, set as 0.08, 0.10, 0.12, and 0.14 Pa·s, corresponding to different mix proportions. Although this simplification neglects the gradual viscosity build-up during gelation, it is acceptable for analyzing the macroscopic diffusion range and overlap characteristics under varied engineering parameters [29–31]. The implementation of this rheological model was achieved via the Fluid Properties interface in COMSOL, where the viscosity was defined as a constant material parameter for each simulation case.

Table 1. Values of factors in orthogonal tests for grouting in 3D fracture networks.

Factors	Factor A: Grouting Pressure (MPa)	Factor B: Hole Spacing (m)	Factor C: Initial Grout Viscosity (Pa·s)	Factor D: Hydrostatic Pressure (MPa)
Level 1	2 (A1)	3 (B1)	0.08 (C1)	0.4 (D1)
Level 2	3 (A2)	4 (B2)	0.10 (C2)	0.6 (D2)
Level 3	4 (A3)	5 (B3)	0.12 (C3)	0.8 (D3)
Level 4	5 (A4)	6 (B4)	0.14 (C4)	1.0 (D4)

Table 2. Orthogonal test table for grouting in 3D fracture networks.

Test No.	Factor Levels	Factor A: Grouting Pressure (MPa)	Factor B: Hole Spacing (m)	Factor C: Initial Grout Viscosity (Pa·s)	Factor D: Hydrostatic Pressure (MPa)
1	A1B1C1D1	2	3	0.08	0.4
2	A1B2C2D2	2	4	0.1	0.6
3	A1B3C3D3	2	5	0.12	0.8
4	A1B4C4D4	2	6	0.14	1
5	A2B1C2D3	3	3	0.1	0.8
6	A2B2C1D4	3	4	0.08	1
7	A2B3C4D1	3	5	0.14	0.4
8	A2B4C3D2	3	6	0.12	0.6
9	A3B1C3D4	4	3	0.12	1
10	A3B2C4D3	4	4	0.14	0.8
11	A3B3C1D2	4	5	0.08	0.6
12	A3B4C2D1	4	6	0.1	0.4
13	A4B1C4D2	5	3	0.14	0.6
14	A4B2C3D1	5	4	0.12	0.4
15	A4B3C2D4	5	5	0.1	1
16	A4B4C1D3	5	6	0.08	0.8

3. Results

The diffusion behavior of the grout within the stochastic 3D fracture network exhibits pronounced non-uniformity and multi-factor coupling effects, wherein grouting pressure plays a particularly prominent role in controlling the diffusion range. To visually elucidate the distribution patterns of the effective grout diffusion volume under varying injection pressures, the 16 experimental tests were categorized into four groups based on the pressure levels (2, 3, 4, and 5 MPa). The effective diffusion volume here represents the total volume. Point-line graphs were subsequently plotted using the extracted 30 min effective diffusion volume data, as illustrated in Figures 3–6. Under identical grouting pressure conditions, the effective diffusion volume decreases as the initial grout viscosity increases. For instance, in the 4 MPa test group, the effective diffusion volume decreased as the grout viscosity increased. Analysis of the effective diffusion volume under various grouting pressures indicates a significant positive correlation between the injection pressure and the grout diffusion volume. For instance, in the 2 MPa test group, the effective

diffusion volume at 30 min ranged from 18.02 to 105.43 m³. In contrast, for the 5 MPa group, the volume ranged from 72.59 to 227.38 m³, indicating a substantial overall increase in the grout spread.

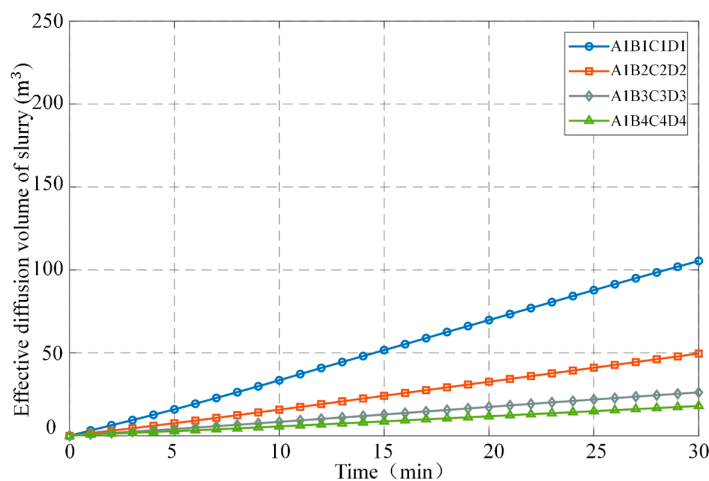


Figure 3. Distribution of the effective grout diffusion volume under a 2 MPa injection pressure.

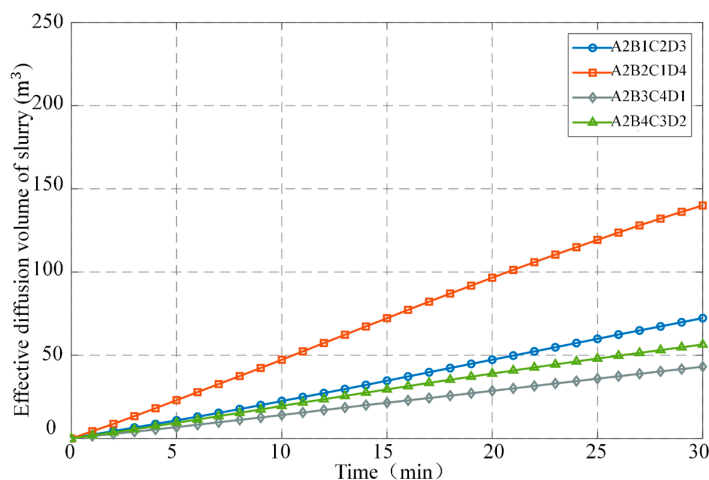


Figure 4. Distribution of the effective grout diffusion volume under a 3 MPa injection pressure.

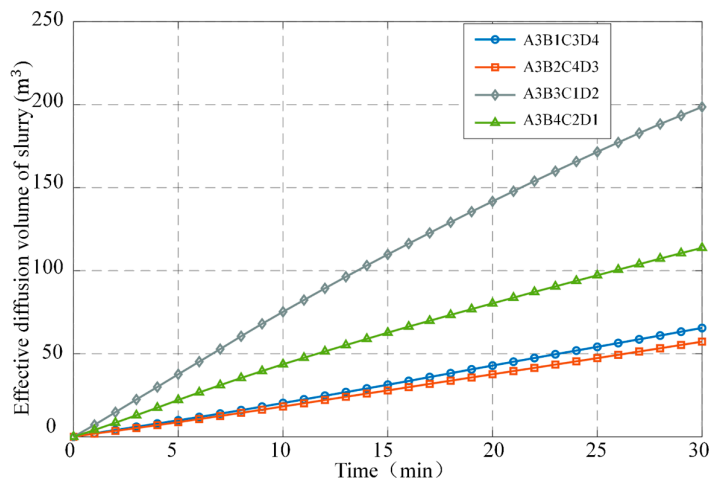


Figure 5. Distribution of the effective grout diffusion volume under a 4 MPa injection pressure.

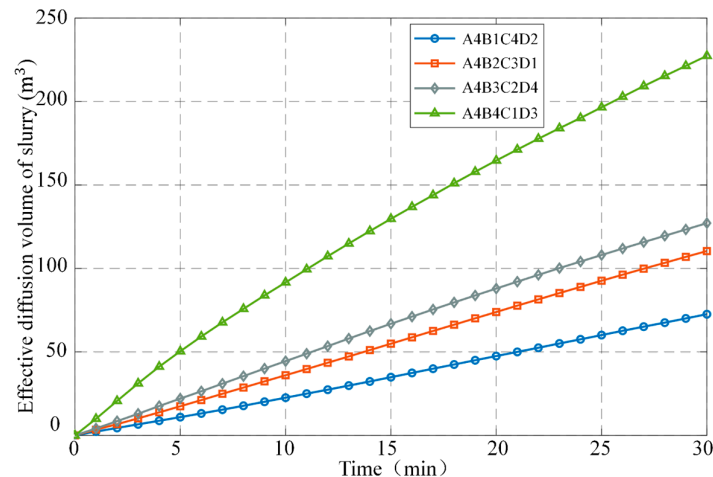


Figure 6. Distribution of the effective grout diffusion volume under a 5 MPa injection pressure.

Figures 7–10 illustrate the effective diffusion morphology of the grout within the stochastic 3D fracture network, based on the 16 sets of orthogonal experiments. The spatial distribution of the grout fill fraction is visually represented via a color map, where red-to-yellow regions correspond to highly filled, effective diffusion zones, while blue-to-white areas indicate low-fill diffusion regions. By comparing the diffusion contours across different test groups, the extent of grout spreading and interconnectivity under the coupled effects of grouting pressure, hole spacing, and grout viscosity can be systematically analyzed. Under low-pressure conditions (Figure 7), grout diffusion is confined by the local fracture network connectivity, with filling predominantly restricted to the vicinity of the injection boreholes, forming isolated pods. Consequently, distal fractures remain largely unfilled. With increasing grouting pressure, the enhanced kinetic energy of the grout enables it to overcome greater viscous resistance, significantly extending the diffusion range and markedly improving the continuity of high-fill regions (warm tones). Under high-pressure conditions (Figure 10), the grout demonstrates exceptional diffusivity, with the affected zone encompassing nearly the entire fracture network model and forming extensive, continuous filling domains (Figure 10d). This confirms the decisive role of high injection pressure in establishing a competent impermeable curtain.

It is noteworthy that the dominance of grouting pressure is not merely a statistical inference but a physically evident phenomenon. The 30 min effective diffusion volume exhibits an order-of-magnitude increase (from 18.02–105.43 m³ to 72.59–227.38 m³) as pressure rises from 2 MPa to 5 MPa. In contrast, variations in initial viscosity or hole spacing result in relatively marginal changes within the same pressure cohort. In addition, the range analysis (R value) results for the effective slurry diffusion volume reveal that the primary-secondary order of the influencing factors is: grouting pressure > slurry viscosity > borehole spacing > hydrostatic pressure. This quantitative disparity underscores that, within the context of deep horizontal curtain grouting, the energy input from pressure is the primary determinant governing the transition from discontinuous filling to full-network connectivity, thereby validating its role as the dominant controlling factor.

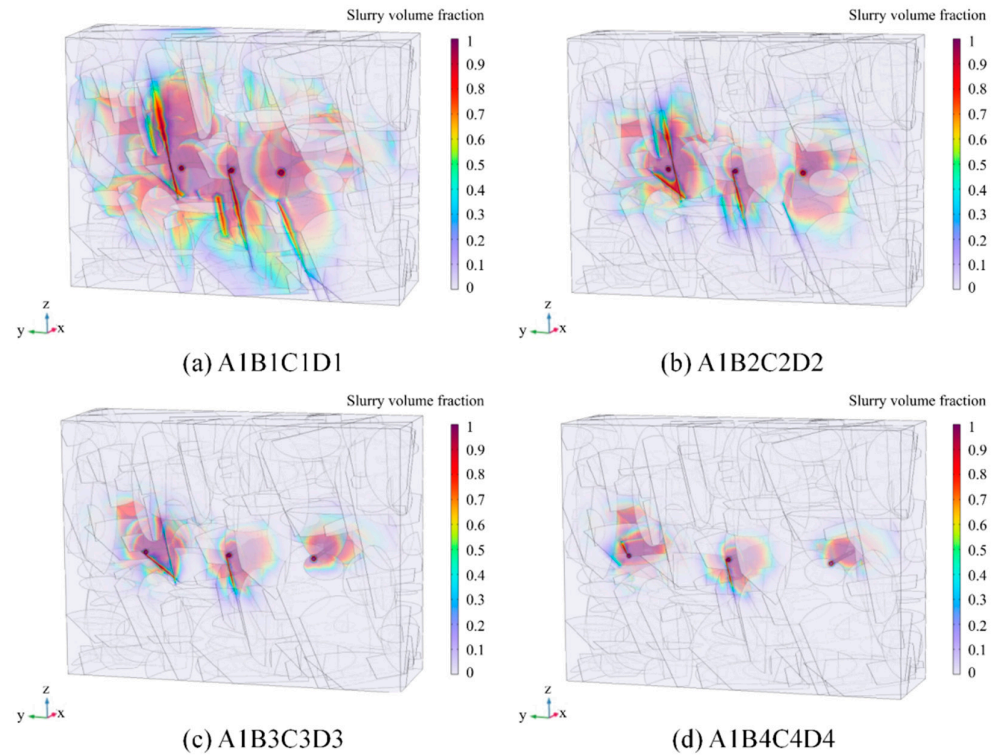


Figure 7. Morphology of the grout diffusion zone under a 2 MPa injection pressure.

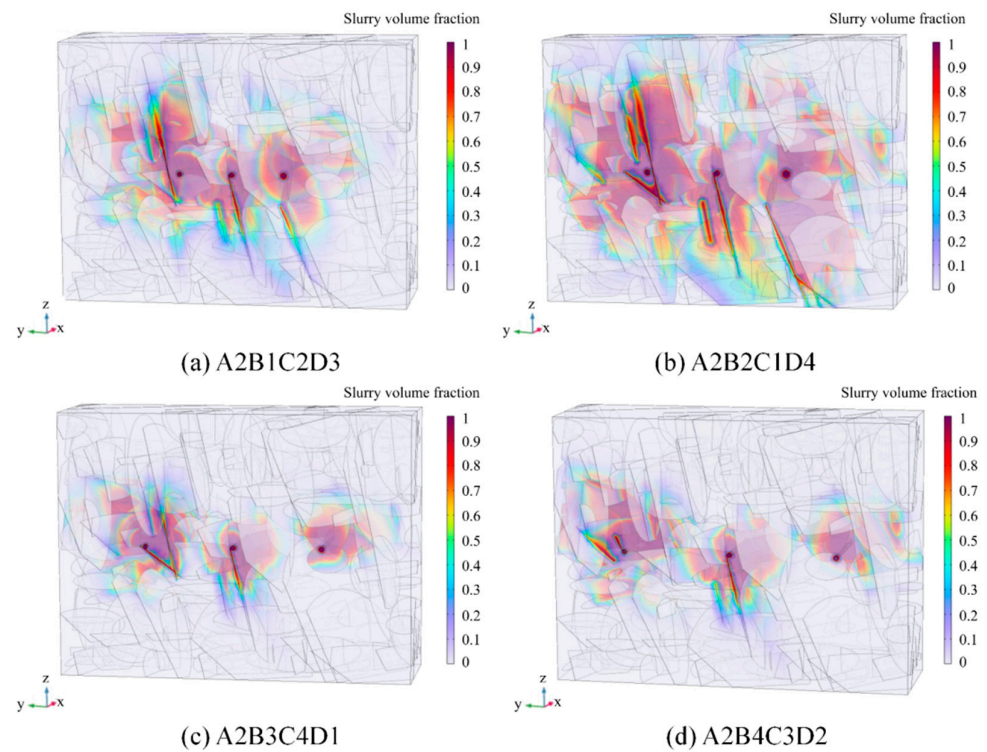


Figure 8. Morphology of the grout diffusion zone under a 3 MPa injection pressure.

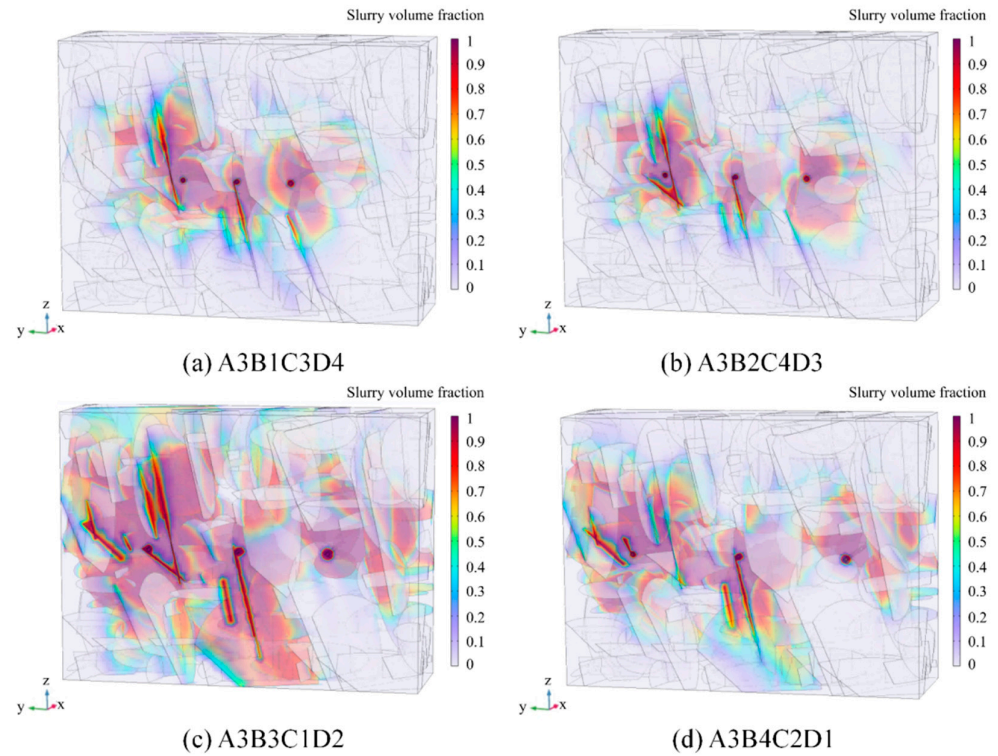


Figure 9. Morphology of the grout diffusion zone under a 4 MPa injection pressure.

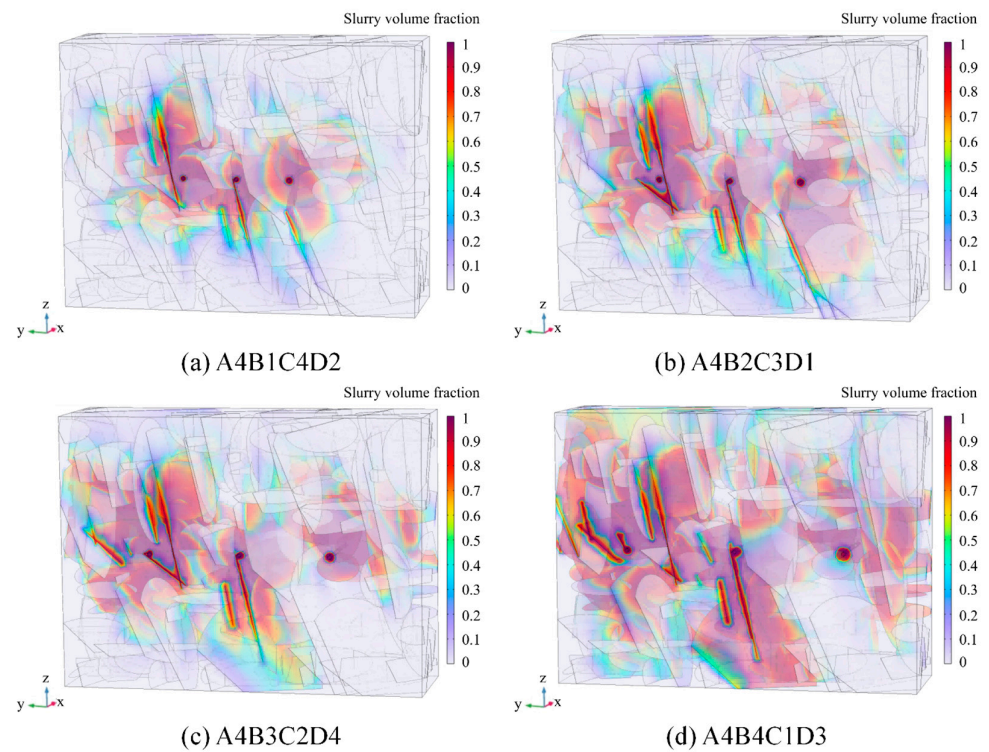


Figure 10. Morphology of the grout diffusion zone under a 5 MPa injection pressure.

4. Discussion

4.1. Model Validation

To verify the reliability of the 3D DFN-COMSOL grouting model, the simulation results were quantitatively compared with field monitoring data from the Cuihongshan iron–polymetallic mine. First, the simulated average grout consumption was 2.1 m³/m per borehole, which closely matches the field-measured average unit grout intake of 2.0 m³/m, corresponding to an average fracture porosity of 20% in the collapsed rock mass [32]. Second, the simulated post-grouting equivalent Lugeon value was reduced to below 10 Lu, consistent with packer test results from site inspection boreholes, confirming that the grout overlap effectively sealed the dominant flow channels. Third, the simulated reduction in water inflow reached approximately 71%, agreeing well with the observed decrease in mine discharge from 12,498 m³/d to 3600 m³/d after curtain grouting [32]. These comparisons demonstrate that the proposed stochastic DFN model, combined with the overlap-rate indicator, can reasonably reproduce the grout diffusion behavior and hydraulic sealing performance under real field conditions, thereby supporting its applicability for engineering practice.

4.2. Overlap Rate

In practical grouting engineering, the complexity of geological conditions and the lack of visual access constrain direct observation of the grout diffusion process. Consequently, indirect indicators—such as grouting time, pressure, grout take, and variations in water inrush volume—must serve as the primary criteria for determining grouting termination. However, these indicators only provide a macro-level reflection of the construction status and fail to precisely characterize the actual diffusion behavior and interconnectivity of the grout within the fracture network. While the core objectives of grouting engineering are surrounding rock reinforcement and curtain water blocking, the COMSOL numerical simulations enable direct visualization of the grout diffusion scope, morphology, and inter-borehole connectivity by adjusting the model transparency and transmissivity. In contrast to conventional indirect evaluation metrics, the interconnection rate directly quantifies the degree of grout overlap within the fracture network, offering a precise reflection of sealing efficacy. Consequently, this rate should be adopted as a core indicator for assessing grouting performance.

The overlap rate (η_v) refers to the degree to which the diffusion ranges of adjacent grouting holes overlap and connect with each other in the direction of the designed curtain thickness [33]. When the diffusion zone of the grout between two grouting holes fully overlaps or overlaps, the overlap rate is high, the curtain continuity is good, and it is conducive to forming a reliable anti-seepage system. On the contrary, if the diffusion range of the slurry is insufficient and there are unfilled gaps or weak areas between the holes, the overlap rate will be low, resulting in discontinuous curtains, which may cause problems such as leakage, water inrush, or decreased stability of the surrounding rock. The classification of overlapping effect levels is shown in Table 3 [34–37]. The formula for calculating the overlap rate (η_v) is:

$$\eta_v = \frac{\bar{V}_l}{\bar{V}_d} \times 100\% \quad (4)$$

where $\bar{V}_l$ is the average overlapping volume of the effective diffusion zone between two pores, and $\bar{V}_d$ is the average effective diffusion volume of a single pore.

Table 3. Classification of overlap rate.

Levels	η_v	Overlapping Effect
1	$30\% \leq \eta_v$	very good
2	$25\% \leq \eta_v < 30\%$	good
3	$15\% \leq \eta_v < 25\%$	general
4	$10\% \leq \eta_v < 15\%$	poor
5	$5\% \leq \eta_v < 10\%$	very poor
6	$\eta_v < 5\%$	failure

Extract the effective diffusion volume of the final slurry and the overlapping volume of the effective diffusion zone between the two grouting holes, calculate the overlap rate of each test group according to formula (4), and evaluate the overlap effect according to Table 3. The calculation results and overlap effects are shown in Table 4.

Table 4. Orthogonal test of grouting overlapping ratio and lap joint effectiveness.

Test No.	Factor Levels	$\bar{V}_l$ (m ³)	$\bar{V}_d$ (m ³)	η_v	Overlapping Effect
1	A1B1C1D1	4.49	35.14	12.79%	poor
2	A1B2C2D2	3.23	16.54	19.55%	general
3	A1B3C3D3	2.05	8.73	23.51%	general
4	A1B4C4D4	0.00	6.01	0.00%	failure
5	A2B1C2D3	4.72	24.12	19.58%	general
6	A2B2C1D4	3.48	46.66	7.45%	very poor
7	A2B3C4D1	3.17	14.38	22.05%	general
8	A2B4C3D2	1.95	18.83	10.36%	poor
9	A3B1C3D4	4.76	21.84	21.79%	general
10	A3B2C4D3	3.33	19.09	17.42%	general
11	A3B3C1D2	5.75	66.21	8.68%	very poor
12	A3B4C2D1	4.01	37.93	10.57%	poor
13	A4B1C4D2	4.66	24.20	19.27%	general
14	A4B2C3D1	3.44	36.81	9.34%	very poor
15	A4B3C2D4	1.25	42.38	2.95%	failure
16	A4B4C1D3	1.36	75.79	1.79%	failure

Based on the overlap rate data from 16 orthogonal experiments, it can be seen that there is a significant difference in the diffusion and overlap effects of the slurry in the random three-dimensional fracture network. Based on the aforementioned background, the diffusion behavior of slurry in a random three-dimensional fracture network exhibits significant spatial heterogeneity, which is mainly attributed to the random distribution characteristics of natural fracture geometry (attitude, aperture, roughness) [38–41]. In this heterogeneous medium, grouting pressure is not a single driving force, but plays the role of a “path selector”. Under high pressure conditions, the slurry tends to undergo viscous fingering and channeling along dominant fracture channels, resulting in significant anisotropy in the diffusion range and the formation of complex tree like or vein like networks, rather than ideal uniform ellipsoids. This dynamic evolution process dominated by pressure results in extremely uneven filling of the slurry in space: some areas have blind spots due to obstructed pressure transmission, while others experience excessive diffusion due to excessive pressure. Therefore, a deep understanding of the coupling mechanism between pressure field and fracture network structure is the key to revealing this spatial heterogeneity diffusion law.

4.3. Limitations and Future Research

Although the proposed overlap rate indicator effectively evaluates curtain continuity under various engineering parameters, several simplifications should be acknowledged. In this study, the cement grout was treated as a Newtonian fluid with constant viscosity, and the fracture network was assumed to be mechanically stable during grouting. These assumptions neglect the coupled effects of time-dependent rheological evolution, temperature variation, and in situ stress on slurry diffusion behavior. In particular, the gelation-induced viscosity buildup, thermal effects on fluid properties, and stress-dependent fracture aperture changes may significantly influence the filling pattern and sealing efficiency. Future research should incorporate multiphysics coupling, including time-varying rheology, temperature fields, and hydro-mechanical interactions, to better represent the complex slurry diffusion mechanisms within deep fractured rock masses. In addition, future studies should also transcend these parametric constraints by exploring intensified injection regimes and optimized borehole arrays to align numerical outcomes with the rigorous field standards required for a “very good” sealing performance. Simulation analysis on the scale of actual engineering projects is also an important direction. Such efforts are essential to bridge the gap between laboratory-scale simulations and the stringent demands of full-scale deep mine construction.

5. Conclusions

This study takes Cuihongshan Iron Mine as the geological background, aiming at the difficult problem of predicting the effective diffusion range of slurry in curtain grouting of deep mines. By constructing a random three-dimensional fracture network model, an L_{16} (4^4) orthogonal experiment was designed, and the influence of grouting parameters on the overlapping effect of slurry was systematically explored. The main conclusions are as follows:

- (1) A significant positive correlation exists between injection pressure and effective diffusion volume: when pressure increases from 2 MPa to 5 MPa, the 30 min effective diffusion volume rises from a range of 18.02–105.43 m³ to 72.59–227.38 m³. High pressure also enables slurry to overcome viscous resistance and fracture network constraints, expanding diffusion to cover nearly the entire model domain and forming continuous, high-fill zones critical for reliable impermeable curtains.
- (2) Within the same grouting pressure group, effective diffusion volume decreases progressively as viscosity increases from 0.08 Pa·s to 0.14 Pa·s. Higher viscosity amplifies seepage resistance, restricts slurry migration along fracture pathways, and reduces inter-borehole overlap rates—for example, the overlap rate drops from 12.79% to 0% under 2 MPa pressure when viscosity increases from 0.08 Pa·s to 0.14 Pa·s, shifting the overlapping effect from “poor” to “failure”.
- (3) Unlike indirect measures such as grouting pressure or grout take, the overlap rate quantitatively characterizes the connectivity of slurry-filled zones between adjacent boreholes, directly reflecting the continuity of the anti-seepage curtain. Simulation results show that overlap rates vary widely (0%–23.51%) across test groups, and only cases with overlap rates $\geq 30\%$ can achieve a “very good” sealing effect, providing a targeted quantitative basis for optimizing grouting parameter combinations in deep metal mine horizontal curtain construction.

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Data Availability Statement: The authors declare that the data supporting the findings of this study are available within the paper. Should any raw data files be needed in another format they are available from the corresponding author upon reasonable request.

Conflicts of Interest: Xuotong Gao, Guilei Han, Xiaofeng Xue, Dajin Liu and Zhiqi Wang were employed by North China Engineering Investigation Institute Co., Ltd. The remaining authors declare no conflicts of interest.

References

1. He, M.C.; Wang, Q.; Wu, Q.Y. Innovation and future of mining rock mechanics. *J. Rock Mech. Geotech.* **2021**, *13*, 1–21. <https://doi.org/10.1016/j.jrmge.2020.11.005>.
2. Gao, H.; Xie, H.P.; Zhang, Z.T.; Lu, J.; Zhang, D.M.; Zhang, R.; Wu, M.Y. True triaxial energy evolution characteristics and failure mechanism of deep rock subjected to mining-induced stress. *Int. J. Rock Mech. Min.* **2024**, *176*, 105724. <https://doi.org/10.1016/j.ijrmms.2024.105724>.
3. Yuan, S.C.; Han, G.L.; Liu, D.J.; Zhang, A.W. Multicriteria risk assessment of water inrush in underground mines with large-scale curtain grouting: A mine disaster risk reduction strategy. *Geomat. Nat. Haz. Risk* **2024**, *15*, 2409200. <https://doi.org/10.1080/19475705.2024.2409200>.
4. Yuan, S.C.; Han, G.L. Combined drilling methods to install grout curtains in a deep underground mine: A case study in Southwest China. *Mine Water Environ.* **2020**, *39*, 902–909. <https://doi.org/10.1007/s10230-020-00701-x>.
5. Wang, Z.; Liu, D.; Xue, X.; Han, G.; Gao, X.; Yuan, S. An investigation on the effectiveness of horizontal curtain grouting based on multi-method joint analysis: A case study of the Cuihongshan iron-polymetallic mine. *Water* **2026**, *18*, 613. <https://doi.org/10.3390/w18050613>.
6. Yang, Z.; Li, Y.; Xie, S. Water hazards prevention and control technology of non-coal mines under the new safety situation and development trend. *China Min. Mag.* **2025**, *34*, 298–307.
7. Wang, D.D.; Sui, W.H.; Ranville, J.F. Hazard identification and risk assessment of groundwater inrush from a coal mine: A review. *Bull. Eng. Geol. Environ.* **2022**, *81*, 421. <https://doi.org/10.1007/s10064-022-02925-3>.
8. Li, Q.; Sui, W.H.; Sun, B.T.; Li, D.L.; Yu, S.B. Application of TOPSIS water abundance comprehensive evaluation method for karst aquifers in a lead zinc mine, China. *Earth Sci. Inf.* **2022**, *15*, 397–411. <https://doi.org/10.1007/s12145-021-00730-2>.
9. Jones, B.R.; Van, R.J.L.; Mouton, D.J. Verifying the ground treatment as proposed by the Secondary Permeability Index during dam foundation grouting. *Bull. Eng. Geol. Environ.* **2019**, *78*, 1305–1326. <https://doi.org/10.1007/s10064-017-1219-9>.
10. Zhang, D.Y.; Liu, D.P. The effect of thermal-hydro-mechanical coupling on grouting in a single fracture under coalmine flowing water conditions. *Deep Undergr. Sci. Eng.* **2025**, *4*, 264–277. <https://doi.org/10.1002/dug2.12144>.
11. Li, S.; Liu, R.; Zhang, Q.; Zhang, X. Protection against water or mud inrush in tunnels by grouting: A review. *J. Rock Mech. Geotech.* **2016**, *8*, 753–766. <https://doi.org/10.1016/j.jrmge.2016.05.002>.
12. Guo, S.; Wang, H. Research on hydrogeological structural characteristics and water hazard control mode of Ningtiaota Coal Mine. *China Min. Mag.* **2024**, *33*, 190–200.
13. Qian, Z.; Jiang, Z.; Guan, Y.; Yue, N. Mechanism and remediation of water and sand mixture inrush induced in an inclined shaft by large-tonnage vehicles. *Mine Water Environ.* **2019**, *37*, 849–855. <https://doi.org/10.1007/s10230-018-0531-3>.
14. Liu, J.; Wu, G.; Liu, Z. Numerical study on fracture evolution and slurry diffusion laws of multistage large-diameter drilling boreholes. *China Min. Mag.* **2025**, *34*, 174–182.
15. Liu, J.; Sui, W.; Zhao, Q. Environmentally sustainable mining: A case study of intermittent cut-and-fill mining under sand aquifers. *Environ. Earth Sci.* **2017**, *76*, 562. <https://doi.org/10.1007/s12665-017-6892-2>.
16. Ma, D.; Duan, H.; Zhang, J.; Liu, X.; Li, Z. Numerical simulation of water-silt inrush hazard of fault rock: A three-phase flow model. *Rock Mech. Rock Eng.* **2022**, *55*, 5163–5182. <https://doi.org/10.1007/s00603-022-02878-9>.
17. Yuan, S.; Sun, B.; Han, G.; Duan, W.; Wang, Z. Application and prospect of curtain grouting technology in mine water safety management in China: A review. *Water* **2022**, *14*, 4093. <https://doi.org/10.3390/w14244093>.
18. Sui, W.; Liu, J.; Yang, S.; Chen, Z.; Hu, Y. Hydrogeological analysis and salvage of a deep coalmine after a groundwater inrush. *Environ. Earth Sci.* **2011**, *62*, 735–749. <https://doi.org/10.1007/s12665-010-0562-y>.

19. Atakhanova, Z.; Meirambayeva, M.; Baigaliyeva, M. Mine water use in Kazakhstan: Data issues, risks, and regulations. *Sustainability* **2024**, *16*, 2456. <https://doi.org/10.3390/su16062456>.
20. Xie, S.; Xu, L.; Yi, W. Exploration and control of tailings leakage in a tailings reservoir in karst area. *China Min. Mag.* **2024**, *33*, 101–108.
21. Sui, W. Active prevention and control of water-sand mixture inrush with high potential energy due to mining based on structural hydrogeology. *J. Eng. Geol.* **2022**, *30*, 101–109.
22. Liu, Y.; Wang, P.; Gojenko, B.; Yu, J.; Wei, L.; Luo, D.; Xiao, T. A review of water pollution arising from agriculture and mining activities in Central Asia: Facts, causes and effects. *Environ. Pollut.* **2021**, *291*, 118209. <https://doi.org/10.1016/j.envpol.2021.118209>.
23. He, J.; Li, W.; Qiao, W.; Yang, Z.; Wang, Q. Risk assessment of water inrushes from bed separations in Cretaceous strata corresponding to different excavation lengths during mining in the Ordos Basin. *Geomat. Nat. Haz. Risk* **2021**, *12*, 2300–2327. <https://doi.org/10.1080/19475705.2021.1950220>.
24. Chen, Y.; Sun, B.; Xu, M.; Li, D.; Hu, Y.; Xu, C.; Cui, Y.; Yuan, S. Design and implementation of an escape route planning system for deep mine water inrush based on graph structure. *China Min. Mag.* **2025**, *34*, 126–136.
25. Huang, G.; Zhou, G.; Sun, B. Treatment of water inrush in distribution chamber at 430 m middle level of Yiliang Maoping Lead Zinc Mine. *China Min. Mag.* **2025**, *34*, 237–245.
26. Yuan, S.; Han, G.; Liu, D.; Li, G.; Zhang, A.; Li, W. Analyzing water recharge mechanisms and predicting water inflow in deep mining based on hydrogeological structures: A case study. *Sci. Rep.* **2025**, *15*, 44764. <https://doi.org/10.1038/s41598-025-28821-w>.
27. Xu, Z.; Wang, Y.; Xiong, W.; Chai, J.; Cao, C. Experimental investigation on the sealing of flowing water by cement-sodium silicate slurry in rough single fracture. *Bull. Eng. Geol. Environ.* **2023**, *82*, 361. <https://doi.org/10.1007/s10064-023-03384-0>.
28. Liu, Y. Study on Metallogenesis of Cuihongshan Fe-Cu Polymetallic Deposit in Lesser Xing'an Range. Master's Thesis, Jilin University, Changchun, China, 2021.
29. Wang, Z.Y.; Zhe, Y.L.; Hou, K.P.; Cheng, Q.Z.; Liang, W. A depth-dependent framework for grouting parameter selection in anisotropic strata: From diffusion mechanism to pareto-optimal decision-making. *Res. Eng.* **2026**, *31*, 111568. <https://doi.org/10.1016/j.rineng.2026.111568>.
30. Chen, J.; Qin, Y.; Hu, F.; Xu, N.; Guo, Y.; Qin, J.; Ren, G. Microstructural evolution and mechanical properties of fly-ash-based grouting materials in different aqueous environments. *Water* **2025**, *17*, 1407. <https://doi.org/10.3390/w17101407>.
31. Li, C.; Lu, C.; Xu, J.; Zhang, K.; Liu, S.; Zhao, H. Diffusion mechanism of variable-rate grouting in water prevention and control of coal mine. *Water* **2024**, *16*, 2814. <https://doi.org/10.3390/w16192814>.
32. Wu, B. Prevention and Control of Water and Sand Mixture Inrush in a Metal Mine Under Flowing Water Conditions: A Case Study of the Cuihongshan Iron Polymetallic Mine. Master's Thesis, China University of Mining and Technology, Xuzhou, China, 2024.
33. Fan, G.; Ren, C.; Zhang, D.; Ma, Z.; Fan, Z.; Zhang, S.; Han, X.; Xu, G. Analysis on curtain slurry diffusion pattern and interception effect of inclined shafts in dynamic water sanding area. *Chin. J. Geotech. Eng.* **2026**, *48*, 157–167.
34. *DZ/T 0285–2015*; The Industry Standard Editorial Committee of the People's Republic of China. Specification of Mine Curtain Grouting. Geology Press: Beijing, China, 2015.
35. Lou, Q.N.; Shi, B.; Han, H.M.; Zhu, H.H.; Wei, G.Q.; Zhang, K. Research on mine curtain strain curve features for its grouting defects identification with ultra-weak fiber Bragg grating. *Measurement* **2025**, *244*, 116507. <https://doi.org/10.1016/j.measurement.2024.116507>.
36. Ashjari, J.; Soltani, F.; Rezai, M. Prediction of groundwater seepage caused by unclogging of fractures and grout curtain dimensions changes via numerical double-porosity model in the Karun IV River Basin (Iran). *Environ. Earth Sci.* **2019**, *78*, 85. <https://doi.org/10.1007/s12665-019-8054-1>.
37. Sui, W.; Qu, H.; Gao, Y. Modeling of grout propagation in transparent replica of rock fractures. *Geotech. Test. J.* **2015**, *38*, 765–773. <https://doi.org/10.1520/GTJ20140188>.
38. Qian, Z.; Huang, Z.; Song, J. A case study of water inrush incident through fault zone in China and the corresponding treatment measures. *Arab. J. Geosci.* **2018**, *11*, 381. <https://doi.org/10.1007/s12517-018-3727-8>.
39. Shi, W.; Yang, T.; Liu, H.; Yang, B. Numerical modeling of Non-Darcy flow behavior of groundwater outburst through fault using the forchheimer equation. *J. Hydrol. Eng.* **2018**, *23*, 04017062. [https://doi.org/10.1061/\(ASCE\)HE.1943-5584.0001617](https://doi.org/10.1061/(ASCE)HE.1943-5584.0001617).

40. Zhou, J.R.; Yang, T.H.; Zhang, P.H.; Xu, T.; Wei, J. Formation process and mechanism of seepage channels around grout curtain from microseismic monitoring: A case study of Zhangmatun iron mine, China. *Eng. Geol.* **2017**, *226*, 301–315. <https://doi.org/10.1016/j.enggeo.2017.07.002>.
41. Lavrov, A. Flow of non-newtonian fluids in single fractures and fracture networks: Current status, challenges, and knowledge gaps. *Eng. Geol.* **2023**, *321*, 107166. <https://doi.org/10.1016/j.enggeo.2023.107166>.

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