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Mechanism of Fault-Related Water Inrush during Roadway Excavation in Deep Phosphate Mines and Construction of a Predictive Model for the Safe Thickness of Water-Resistant Rock Mass

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Abstract

Fault-induced water inrush poses a major safety threat during roadway excavation in deep phosphate mines. To elucidate its evolution mechanism under excavation disturbance and accurately predict the critical safe rock thickness, the Yingping phosphate mine in central Guizhou served as the engineering background. Based on Biot's poroelasticity theory and the fluid – solid coupling principle, a three-dimensional numerical model was established in COMSOL Multiphysics to simulate the spatiotemporal evolution of the stress field, displacement field, plastic zone, and pore water pressure in surrounding rock during excavation, revealing the triggering conditions and controlling mechanisms of fault-induced water inrush. An $L_{25}(5^5)$ orthogonal design combined with multiple linear regression quantified the influence weights of fault dip angle, roadway size, fault water pressure, burial depth, and surrounding rock elastic modulus on the safe thickness, and developed a high-accuracy predictive model. Results show that the plastic zone expands wedge-shaped from the roadway periphery toward the fault, eventually connecting with the fault fracture zone to form a water-inrush pathway. Stress concentration, roof subsidence, floor heave, and a sharp drop in pore water pressure constitute the precursory characteristics of water inrush. The significance ranking is fault water pressure > elastic modulus > burial depth > roadway size > fault dip angle, with only fault water pressure being statistically significant. The regression model achieved $R^2 = 0.994$ and field validation accuracy of 85.25%, markedly superior to traditional empirical formulas for coal mines. The results provide theoretical and technical support for preventing fault-induced water inrush and designing waterproof rock pillars in deep phosphate mines.

Keywords: Fault-induced water inrush; Roadway excavation; Fluid – solid coupling; Numerical simulation; orthogonal experiment; Safe thickness prediction

Introduction

Phosphate rock is a strategic mineral resource that underpins both food security and the development of the phosphorus chemical industry. As shallow resources become increasingly depleted, phosphate mining has fully entered a deep mining stage characterized by high in situ stress, high water pressure, and complex geological structures, resulting in a sharply increased risk of water inrush during roadway excavation (Xie et al. 2019; Xue et al. 2023; Sun et al. 2022). As preferential pathways for groundwater migration and mechanically weak zones,

faults are prone to rock-mass damage, hydraulic fracturing, and eventual catastrophic water-inrush accidents under the coupled effects of excavation-induced unloading, stress redistribution, and high hydraulic head (Song and Liang 2021; Tu et al. 2024; Song and Zhang 2022), which poses a serious threat to the safety of underground personnel and the sustainable production of the mine.

Deep rock masses are subjected to strong coupling between the stress field and the seepage field. Excavation disturbance induces unloading damage, crack propagation, and abrupt permeability changes in the surrounding rock, which constitute the key triggers for fault activation and water inrush (Yang et al. 2025; Zeng et al. 2024). In recent years, extensive studies have been conducted worldwide on the seepage – stress coupling mechanism in fractured rock masses, the evolution of fault-controlled water-inrush pathways, and the identification of precursory signals of water inrush (Xue et al. 2019; Zhu et al. 2020; Wei et al. 2023; Chen et al. 2021; Meng et al. 2024). At the theoretical and experimental levels, (Zhang et al. 2023) revealed the relationship between permeability and stress path through unloading confining-pressure tests; (Yu et al. 2020) established a nonlinear seepage model to analyze the characteristics of fault water-inrush pathways; (Gao et al. 2025) characterized the evolution of damage and pore structure in coal rock based on fractal theory; and (Zhou et al. 2024) investigated the influence of confining pressure on seepage behavior in light of the hydraulic characteristics of fractures involved in engineering water-inrush events. (Zhou et al. 2018) combined uniaxial compression tests, triaxial seepage experiments, and a discrete element model to analyze the effects of stress and water pressure on the permeability of fractured sandstone under hydromechanical coupling. Regarding the evolution mechanism of fault-related water-inrush channels, many scholars have proposed various derivative dynamic water-inrush models and corresponding prevention and control frameworks (Cai et al. 2022; Gao et al. 2024; Wang et al. 2022; Sun et al. 2023). In terms of water-inrush mechanisms, (Zhai et al. 2017) based on the mining-induced stress characteristics of surrounding rock in key aquifers, employed similar simulation tests and numerical modeling to investigate the mechanism and dominant controlling factors of water inrush; (Ji et al. 2018) elucidated the mechanism of water inrush in coal seam floor through coupling analysis of seepage and stress; and (Du et al. 2021) demonstrated through numerical modeling the spatiotemporal patterns of water inrush induced by plastic zone extension. Regarding the mechanism of fault water inrush, (Gong et al. 2025) developed a spatiotemporal evolution model capturing the coupling characteristics of seepage and creep in fault rocks; similarly, (Yang et al. 2024) employed material simulation experiments and continuous discrete coupling numerical methods to elucidate the response mechanisms governing fault activation and crack evolution under mining stress; investigated the effects of various parameters on material deformation and failure in fault zones, further revealing the mechanism behind delayed groundwater fracture in these zones. At the numerical simulation level, (Li and Wu 2019) employed the Forchheimer non-Darcy flow model to analyze the multi-field coupling mechanisms of coal mine water inrush; (Shi et al. 2017) utilized COMSOL to visualize the dynamic process of fault-induced water inrush.

However, most existing studies have been conducted in the context of longwall coal mining, while targeted research on deep phosphate mines characterized by karst development, high water pressure, and layered backfill mining remains clearly insufficient. Phosphate deposits in central Guizhou occur within a karst – fault composite water-control system, where the rock mass is highly heterogeneous, and the hydrogeological conditions are complex. In addition, phosphate mine roadways generally have large cross-sections and are frequently affected by group-roadway disturbances. As a result, the unloading path and stress redistribution characteristics of the surrounding rock differ significantly from those in coal mines, and the water-inrush models and safe-thickness formulas established for coal mining cannot be directly applied. Therefore, there is an urgent need to systematically reveal the disaster-causing mechanism involving surrounding-rock failure, fault activation, and water inrush under excavation disturbance, and to establish an accurate and reliable method for predicting the safe thickness against water inrush under the specific engineering geological conditions of deep phosphate mines.

In this study, the F102 water-conducting fault in the Yingping phosphate mine was selected as the research object. By combining three-dimensional fluid – solid coupling numerical simulation with an orthogonal experimental design, the entire process of roadway excavation approaching the fault was dynamically reproduced. The spatiotemporal evolution of multiple physical fields was quantitatively analyzed, and the critical triggering conditions for water inrush were identified. Through range analysis and analysis of variance, the dominant controlling factors affecting the safe thickness against water inrush were determined, and a multiple linear regression prediction model was established and validated against field measurements and traditional code-based formulas. The results of this study can provide a scientific basis for the early warning of fault-induced water inrush and the optimal design of waterproof rock pillars in deep phosphate mines.

Engineering Geological Setting and Research Methods

Overview of the Study Area

The Yingping phosphate mine is located in Fuquan City, Guizhou Province, China, with geographic coordinates ranging from E107°21'32" to E107°22'27" and from N26°55'40" to N26°57'34". Geographical Map of the Mining Area Figure. 1. Tectonically, the study area is situated in the transitional zone between the northern Guizhou uplift and the southern Guizhou depression of the Yangtze Block. It is characterized by a monoclinic structure with well-developed faults predominantly striking in the north–south direction. The elevation of the mining area ranges from 1113 to 1412 m. The region is subject to a subtropical humid monsoon climate, with an annual precipitation of 1119.64 mm. Groundwater in the mining area is strongly recharged by atmospheric precipitation.

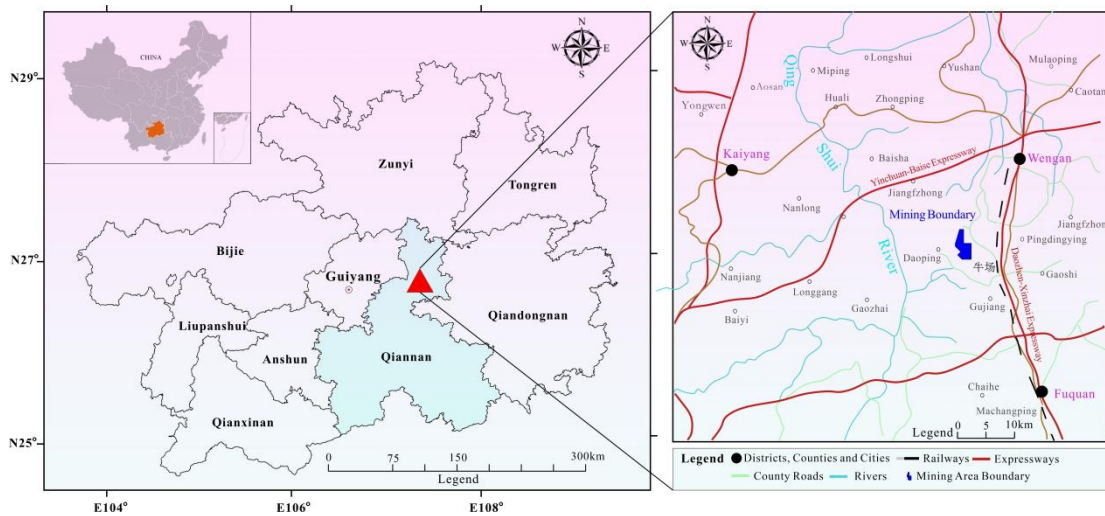


Fig. 1 Geographic location of the mining area

The strata in the mining area, from bottom to top, are as follows: the Qingbaikouan Qingshuijiang Formation (Qbq), the Nanhua Nantuo Formation (Nh_{2n}), the Sinian Doushantuo Formation (Z_{1d}¹⁻³), the upper Sinian to Cambrian Terreneuvian Dengying Formation (Z_{2dy}), the Cambrian Terreneuvian to Series 2 Niutitang Formation (Є1-2n), the Cambrian Series 2 Mingxinsi Formation (Є2m), the Cambrian Series 2 Jindingshan Formation (Є2j), and the Quaternary (Q). Among these units, the Doushantuo Formation is the principal phosphate-bearing stratum, whereas the Dengying Formation dolomite is characterized by well-developed karstification and strong water-bearing capacity, constituting the major regional aquifer.

Mudstone and tuffaceous sandstone in the Niutitang and Nantuo formations form regionally extensive relative aquitards, together defining a typical aquifer–aquitard association. A simplified stratigraphic column of the mining area is shown in Fig. 2.

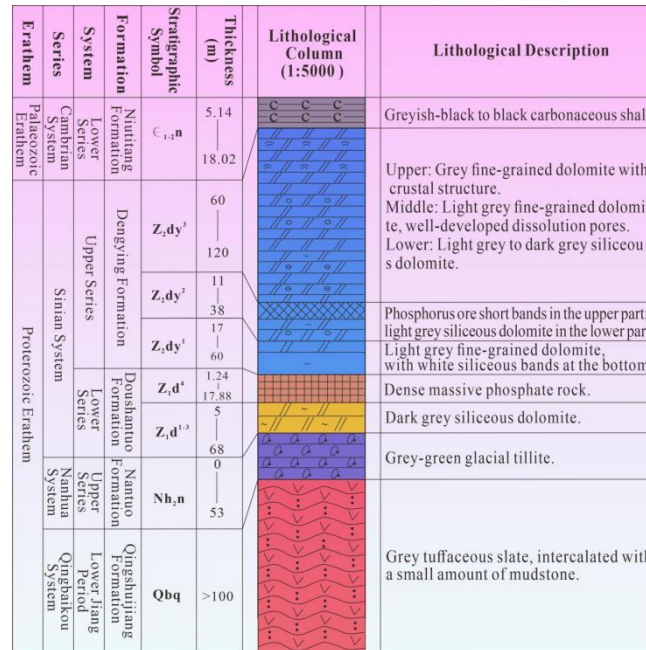


Fig. 2 Simplified stratigraphic column of the mining area

Faults are well developed in the mining area, among which the F102 fault is the most prominent. The faults generally have dip angles of 60°~85° and extension lengths of 0.6~3.5 km. The F102 fault strikes nearly north–south, dips toward the east to south-southeast, and has a dip angle of 60°~70°. The width of its fractured zone is approximately 5 m. Fractures and dissolution pores are well developed on both sides of the fault, resulting in strong hydraulic connectivity. It is therefore a typical water-conducting fault and was selected as the key object of this study. The investigated roadway is located in the crosscut at the 830 m level, with a cross-sectional size of 4.8 m × 5.2 m. The excavation direction is consistent with the strike of the strata, and the initial distance from the fault is approximately 20 m. The development of structural fractures and dissolution pores provides the essential conditions for the formation of a continuous fracture-dissolution pore-type aquifer and water-conducting medium zone, serving as the primary storage space and migration pathway for regional groundwater. Groundwater flows directionally laterally and through surface runoff along this water-conducting medium, continuously replenishing the fault fracture zone. As the region's main water-conducting structure, the fault fracture zone features interconnected fractured rock masses, fractures, and dissolution pores, significantly enhancing its water-conductivity. This results in concentrated groundwater runoff areas within the fracture zone, forming the core runoff channel of the groundwater system. The hydrogeological profile of the fault water inrush is shown in Fig. 3.

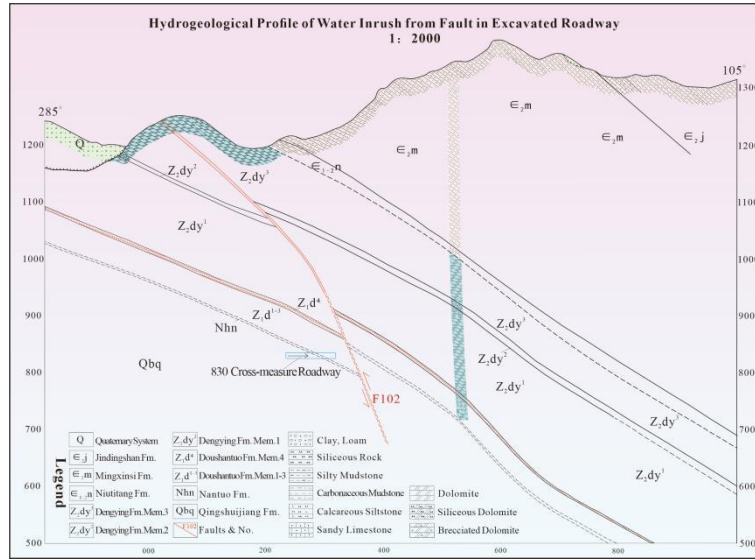


Fig. 3 Hydrogeological profile map of fault-related water inflow

Governing Equations for Numerical Simulation

Based on Biot's poroelasticity theory, the coupled governing equations for rock-mass deformation and groundwater seepage were established. The basic assumptions are as follows: (1) the rock mass is treated as an isotropic porous continuous medium; (2) the initial stress field considers only gravitational stress; (3) thermal effects are neglected; and (4) no macroscopic fractures are present in the initial state.

Equilibrium equation of solid mechanics:

$$\nabla \cdot \sigma + \rho_b g = 0 \quad (1)$$

where σ is the total stress tensor, ρ_b is the bulk density, and g is the gravitational acceleration. The total stress consists of the effective stress σ' and the pore water pressure, i.e., $\sigma = \sigma' - \alpha pI$, where α is the Biot coefficient.

Darcy seepage equation for porous media:

$$\frac{\partial}{\partial t}(\rho_f \phi) + \nabla \cdot (\rho_f u) = Q_m \quad (2)$$

$$u = -\frac{k}{\mu}(\nabla p + \rho_f g \nabla z) \quad (3)$$

where σ_f is the fluid density, ϕ is the porosity, u is the Darcy velocity, k is the permeability tensor, μ is the dynamic viscosity of the fluid, and is the source-sink term.

To characterize the nonlinear seepage behavior within the fault fracture zone, the Brinkman-Forchheimer equation was adopted:

$$\left\{ \begin{array}{l} \frac{\eta}{k} \cdot u = \nabla \cdot \left(-pI + \frac{\eta}{\varepsilon_p} (\nabla u + (\nabla u^T)) \right) - \frac{\rho \varepsilon_p C_f}{\sqrt{k}} u |u| \\ \nabla \cdot u = 0 \end{array} \right\} \quad (4)$$

$$C_f = \frac{1.75}{\sqrt{150 \varepsilon_p^3}} \quad (5)$$

$$\beta_F = \frac{\rho \varepsilon C_f}{\sqrt{k}} \quad (6)$$

where u is the seepage velocity vector, μ is the dynamic viscosity of the fluid, k is the permeability of the porous medium, p is the fluid pressure, I is the unit tensor, ε_p is the porosity of the porous medium, C_f is the Forchheimer form drag coefficient, and β_F is the Forchheimer inertial resistance coefficient.

Numerical Model Construction

A three-dimensional numerical model with dimensions of 150 m × 25 m × 150 m (length × width × height) was developed in COMSOL Multiphysics, as shown schematically in Fig. 4. The model comprises the F102 fault and the major stratigraphic units in the study area, including the Qingshuijiang slate, Nantuo diamictite, Doushantuo phosphorite, and Dengying dolomite. The mechanical and hydrogeological parameters were determined based on laboratory tests and engineering geological investigations. The lithological and mechanical parameters used in the model are summarized in Table 1.

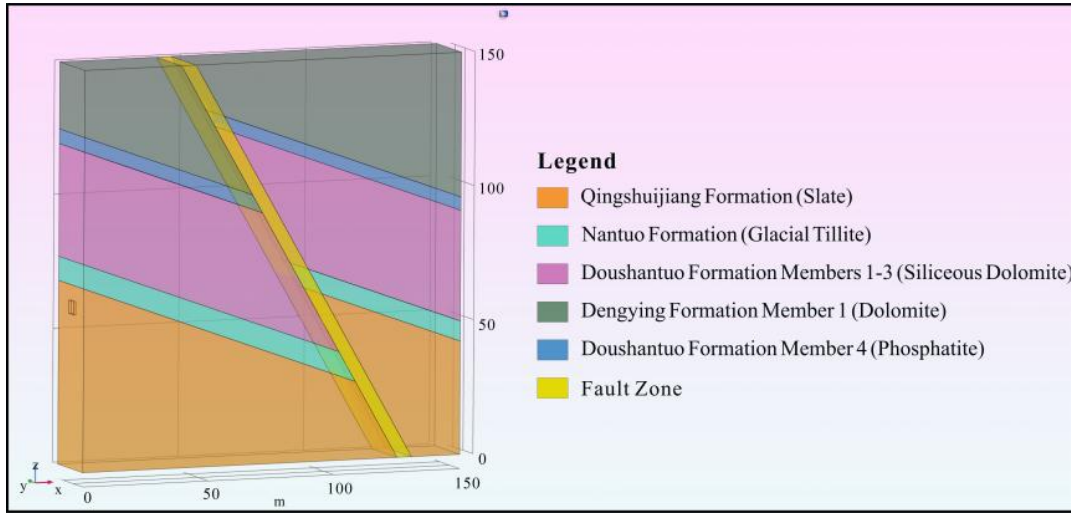


Fig. 4 Three-dimensional numerical model used for numerical simulation

Table 1 Lithology and Mechanical Parameters of Strata

Stratum	Lithology	Simulated Thickness (m)	Density (kg/m ³)	Elastic Modulus (GPa)	Tensile Strength (MPa)	Cohesion (MPa)	Internal Friction Angle (°)	Poisson's Ratio
Qingshuijiang Formation	Slate	60	2663	22.95	9	1.03	49.6	0.32

Nantuo Formation	Glacial Conglomerate	8	2600	19	8	1.25	45.4	0.32
Doushantuo Formation Members 1-3	Siliceous Dolomite	45	2720	24.18	10.32	1.5	55.8	0.29
Doushantuo Formation Member 4	Phosphorite	5	2720	28.52	11.15	1.43	52.5	0.2
Dengying Formation Member 1	Dolomite	32	2710	24.38	10.2	1.46	52.3	0.25

To better characterize the evolution of the stress-seepage coupling behavior during roadway excavation, monitoring lines were arranged along the roof, floor, and fault-zone regions of the roadway, and monitoring points were uniformly distributed along these lines. Specifically, monitoring points A1-A4 were installed along the floor monitoring line, and monitoring points B1-B4 were arranged along the roof monitoring line. In addition, monitoring point C4 was set within the water-resistant rock mass near the fault and was compared with points A4 and B4 on the floor and roof, respectively. Within the fault zone, monitoring points 1-18 were arranged along monitoring lines located on the left side, middle, and right side of the fault zone. This layout enabled comprehensive monitoring of the dynamic evolution of the physical fields in the roadway and in the vicinity of the fault. The arrangement of monitoring points for fault water inrush is shown in Fig 5.

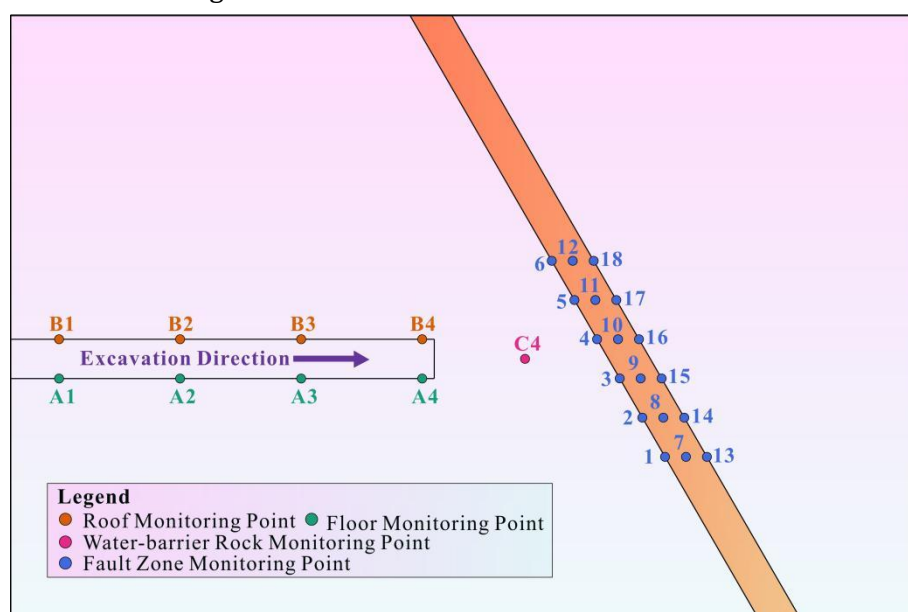


Figure. 5 The arrangement of monitoring points for fault water inrush

Boundary Conditions

Mechanical boundary conditions: Normal displacement constraints were applied to the four lateral boundaries of the model, and the bottom boundary was fully fixed. A vertical overburden stress of 4.78 MPa, representing the self-weight of the overlying strata, was applied to the top surface. The roadway walls and excavation face were treated as free boundaries, and the Drucker–Prager elastoplastic constitutive model was adopted.

Seepage boundary conditions: A water pressure of 1.4 MPa was applied at the top of the fault and 2.9 MPa at the bottom. The permeability coefficient of the fault fracture zone was set to $1.2 \times 10^{-10} \text{ m}^2/(\text{Pa}\cdot\text{s})$, and

the porosity was taken as 0.35. The pore water pressure at the roadway walls and excavation face was set to 0.

Excavation Scheme

For the roadway section far from the fault, excavation was carried out with a step length of 10 m for a total of six steps. When the excavation face approached the fault, the advance step was reduced to 4 m, and five excavation steps were performed. In total, the roadway excavation process was simulated in 11 steps. The detailed excavation simulation scheme is presented in Table 2.

Table 2 Excavation simulation scheme

Simulation stage	Excavation step	Excavation mode
Initial condition	0	Initial in situ stress under the combined effects of burial depth and fault water pressure
Far from the fault	1~5	10 m excavation per step
Approaching the fault	6~10	4 m excavation per step

Orthogonal Experimental Design

Considering the actual geological conditions of deep phosphate mines in central Guizhou, a generalized fault water-inrush model for an advancing roadway was established to numerically simulate the safe thickness of the water-resistant rock pillar against fault-induced water inrush. A schematic diagram of the prediction model for the safe thickness against fault water inrush is shown in Fig. 6. In this study, the factors influencing the thickness of the waterproof rock pillar were identified as follows: fault dip angle (θ), roadway size (H), fault water pressure (P), roadway burial depth (B), and elastic modulus (E). Based on field measurements and the parameter ranges reported in previous studies, each factor was assigned five levels. The levels of the influencing factors are listed in Table 3, and an L_{25} (5^5) orthogonal array was adopted to design the orthogonal experiment, ensuring uniform distribution of all factor levels without repeated combinations.

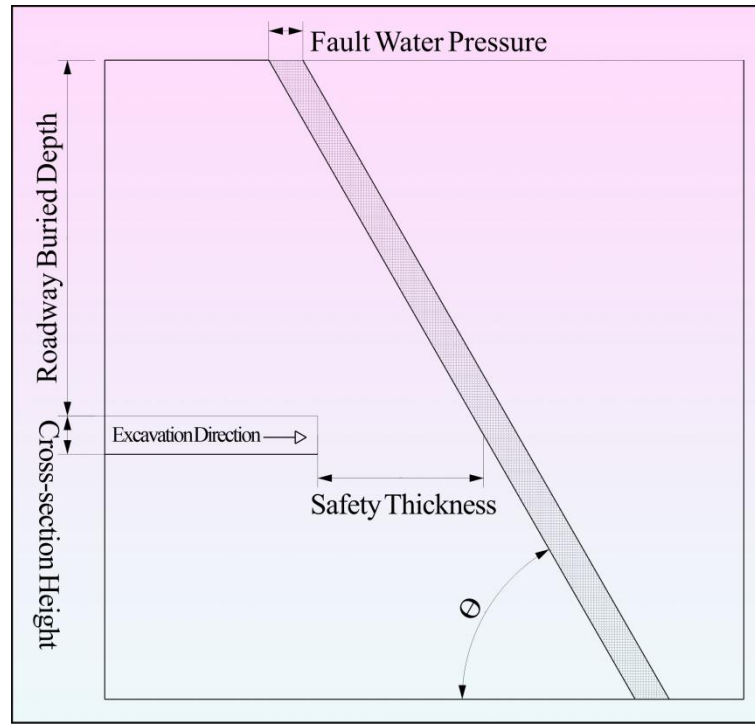


Fig. 6 Schematic diagram of the prediction model for the safe thickness against fault-induced water inrush

Table 3 Levels of the influencing factors

Fault dip angle, θ ($^{\circ}$)	Roadway size, H (m)	Fault water pressure (MPa)	Roadway burial depth, B (m)	Elastic modulus, E (GPa)
50	4	2	300	20
55	4.5	2.5	350	25
60	5	3	400	30
65	5.5	3.5	450	35
70	6	4	500	40

Numerical Simulation Results of the Multi-Physical Fields of Fault-Induced Water Inrush

Evolution Characteristics of the Plastic Zone

During roadway excavation, the plastic zone exhibits a stagewise expansion pattern, for specific changes, refer to Figs 7 and 8. When the excavation distance reaches 50 m, as shown in Figures 6(a) and 7(a), the working face remains far from the fault, and the excavation disturbance is mainly confined to the area surrounding the roadway. At this stage, the stress equilibrium of the fault fracture zone has not yet been disrupted. The plastic zone is limited to the shallow parts of the roof, floor, and two sidewalls of the roadway and does not extend to the fault. The rock mass is dominated by elastic deformation, remains relatively intact, and is in a stable state. When the excavation distance increases to 58-66 m, as shown in Figures 6(b), 6(c), 7(b), and 7(c), the excavation face gradually approaches the fault. The influence of excavation disturbance progressively extends toward the fault, and stress redistribution in the surrounding rock intensifies. The plastic zone enters a stage of rapid expansion. As the working face advances toward the fault, the plastic zone extends in a wedge-shaped manner. Meanwhile, cracks initiate

and propagate in the deeper surrounding rock, forming potential water-conducting pathways, and the risk of water inrush rises rapidly. When the excavation distance reaches 70 m, as shown in Figures 6(d) and 7(d), the working face enters the core zone affected by the fault. The plastic zone further expands into the fault zone and becomes fully connected with the fault fracture zone, forming a through-going water-conducting system of “roadway–damage zone–fault.” Under these conditions, the rock mass loses both its load-bearing and water-resisting capacities, and high-pressure groundwater rushes into the roadway through the connected pathway, ultimately triggering a water-inrush disaster.

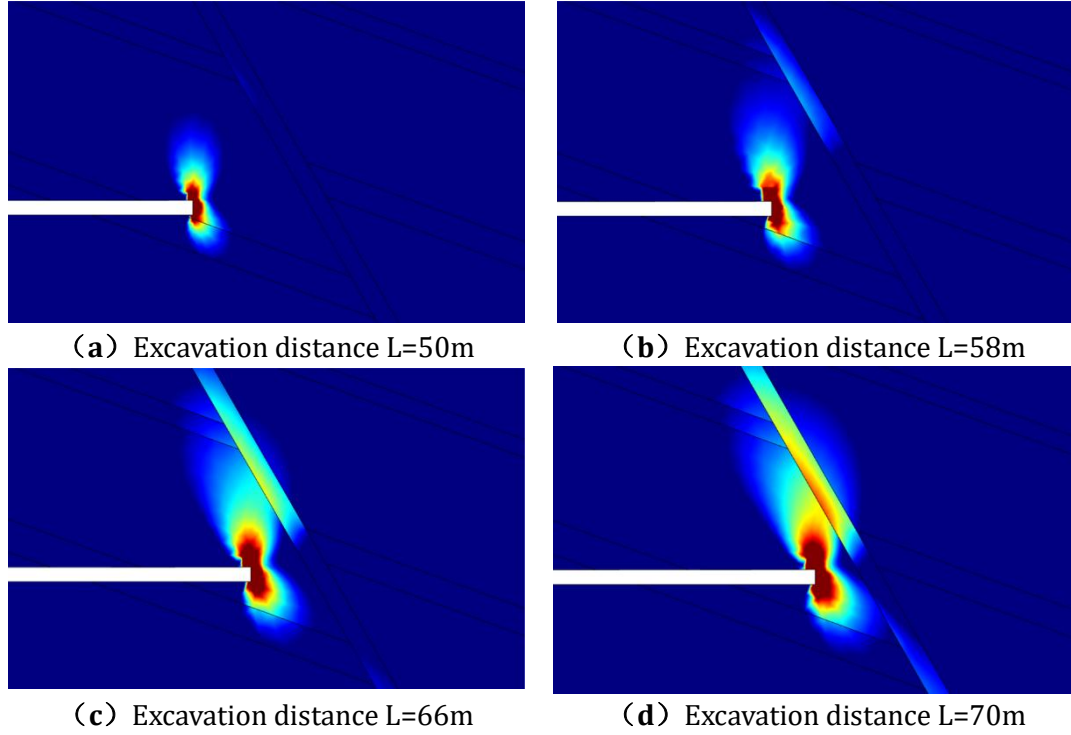
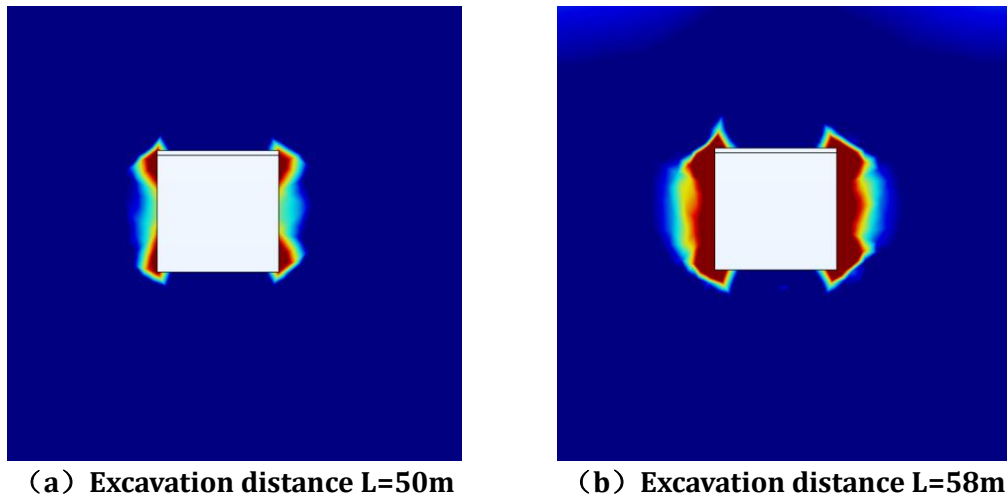


Fig. 7 Xz-sectional contours of the plastic zone in the surrounding rock during roadway excavation at different excavation distances



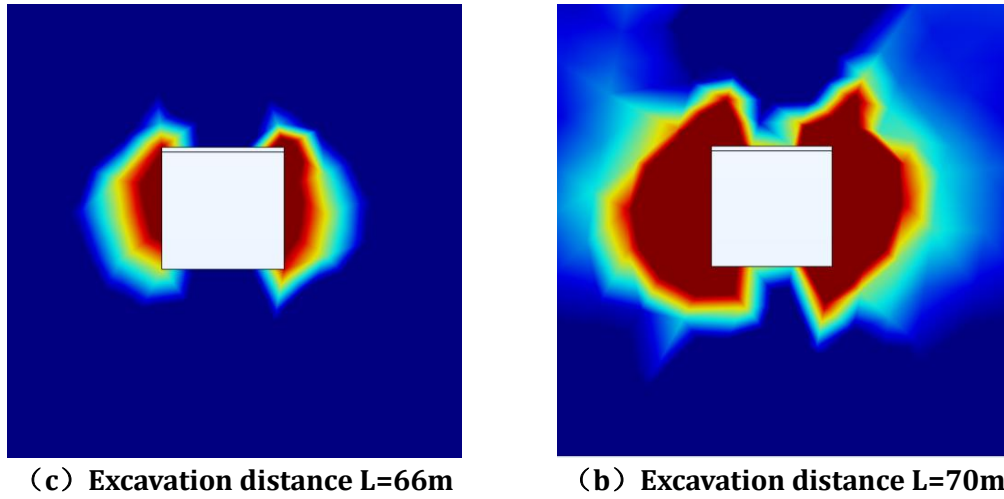


Fig. 8 Yz-sectional contour maps of the plastic zone in the surrounding rock at different excavation distances

Analysis of Stress Variation Characteristics

By plotting the stress variation curves at different monitoring points against excavation distance, the influence of roadway advancement on stress distribution was systematically analyzed. The stress evolution characteristics at each monitoring point are shown in Figs. 9 to 12. Roadway excavation induces unloading and stress redistribution in the surrounding rock, leading to the formation of unloading and pressure-relief zones in the roof and floor, and to the development of a stress concentration zone ahead of the excavation face. As excavation proceeds, the extent of stress concentration continuously expands and is progressively transferred toward the fault. The stresses at roof monitoring points B1-B4 and at floor monitoring points A1-A4 first increase slightly, then decrease sharply. Due to the superposition effect of stresses near the fault, the stress reduction at points A4 and B4, which are closer to the fault, is relatively smaller. The stresses at the monitoring points on both the left and right sides of the fault increase continuously with excavation progress, reaching their peak values when the excavation distance is 70 m. The superposition of the dual stress concentration effects significantly increases the probability of rock-mass instability. The magnitude of stress increase varies spatially along the fault: the closer a monitoring point is to the working face, the more pronounced the stress accumulation. In particular, the increase in stress at monitoring point 5 reaches 58.0%, providing a strong driving force for water inrush. These results indicate that, with continuous roadway excavation, the stress variation trends at the monitoring points on the right side of the fault are generally consistent, and the stresses at all these points increase to varying degrees. All monitoring points on the right side of the fault reach their maximum stress values at an excavation distance of 70 m, indicating intense stress concentration in the rock mass on the right side of the fault at this stage. Once superimposed with the stress concentration in the surrounding rock ahead of the roadway face, this condition is more likely to induce deformation, instability, and failure of the surrounding rock, thereby triggering water inrush.

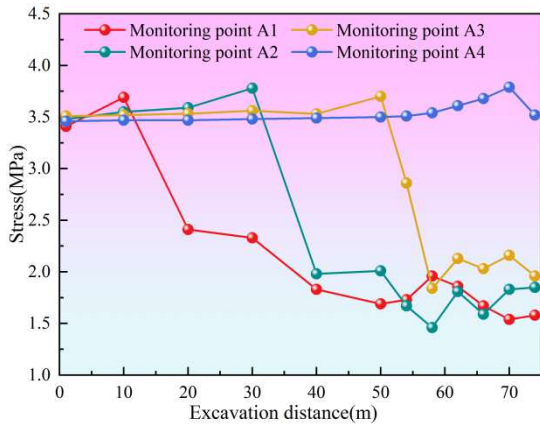


Fig. 9 Stress evolution at monitoring points in the roadway

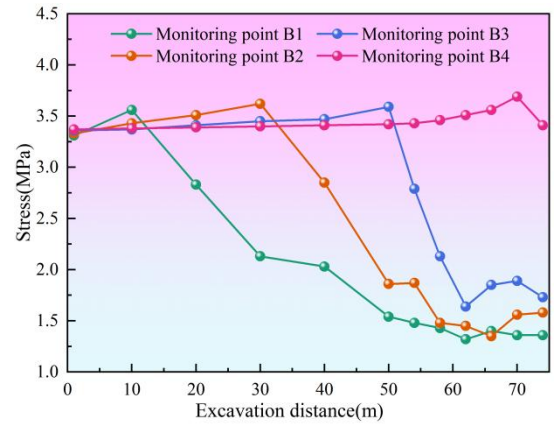


Fig. 10 Stress evolution at monitoring points in the roadway floor

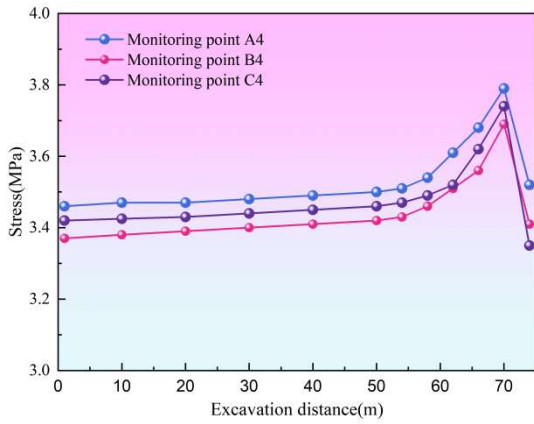


Fig. 11 Stress evolution of monitoring points in the water-resisting rock mass adjacent to the fault

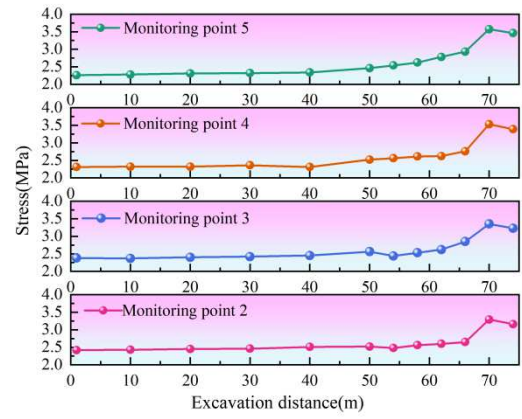


Fig. 12 Stress evolution of monitoring points on the right-hand side of the fault

Analysis of Displacement Variation Characteristics

To analyze the displacement variation characteristics during roadway excavation, numerical monitoring points were established within the numerical simulation model (not field-measured points). These monitoring points were selected at the roadway roof and floor, within the water-resisting rock mass near the fault, at the middle, left side, and right side of the fault zone, and in the area to the left outside the fault zone. Displacement variation curves for each monitoring point with respect to excavation distance were plotted for analysis, as shown in Figs. 13 to 16. The displacement field exhibits a spatially differentiated distribution. As the excavation face advances, the roof rock moves downward toward the roadway void (negative displacement) due to the lack of effective support after excavation. In contrast, the floor rock heaves upward (positive displacement) due to the loss of upper confinement. After the formation of the excavation free surface, the vertical displacement of the surrounding rock becomes significant, and the closer the rock mass is to the free surface, the more pronounced the displacement change. The roof is dominated by subsidence deformation, with a maximum settlement of 0.0443 m, while the floor is dominated by floor heave, with a maximum heave of 0.0206 m. The overall displacement magnitude of the floor is smaller than that of the roof. This is because the roof is subjected

to the combined effects of the self-weight of the overlying strata and the high in situ stress at depth, making the rock mass more susceptible to damage and larger subsidence. This evolution pattern is consistent with the results of the stress-field analysis. In addition, as the roadway advances toward the fault and the excavated void expands, the displacements of the roof and floor rock masses in different directions increase significantly. Although the fault zone and its surrounding rock are also dominated by negative vertical displacement, the displacement amplitudes are generally smaller than those observed in the core disturbance zone of the roadway roof and floor, indicating that the displacement disturbance effect of roadway excavation on the fault rock mass is relatively weaker. During roadway excavation, the vertical displacements at monitoring points in the roof and floor show clear evolutionary characteristics. The roof monitoring points mainly exhibit negative displacement as excavation proceeds; as the roadway approaches the fault, this displacement increases to a peak and then tends to stabilize. The vertical displacements at all roof and floor monitoring points remain essentially stable after peaking, with no obvious fluctuations. Meanwhile, the increase in vertical displacement at the roof monitoring points is significantly greater than at the floor monitoring points, indicating that the surrounding rock at the roof is more prone to subsidence deformation during roadway excavation. As the excavation face approaches the fault, water inrush is more likely to occur at the roof.

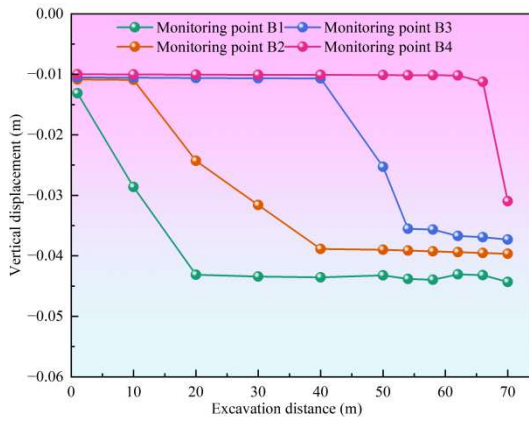


Fig. 13 Displacement evolution at monitoring points in the roadway roof

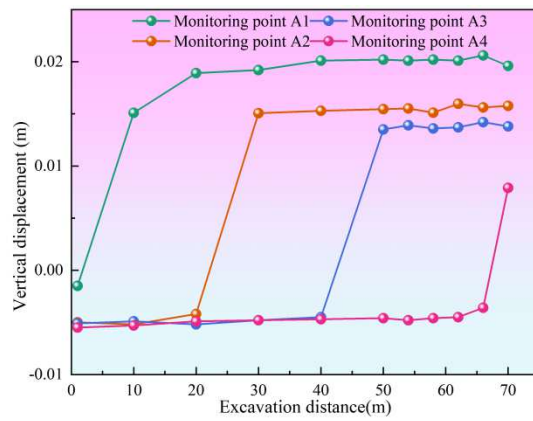


Fig. 14 Displacement evolution at monitoring points in the roadway floor

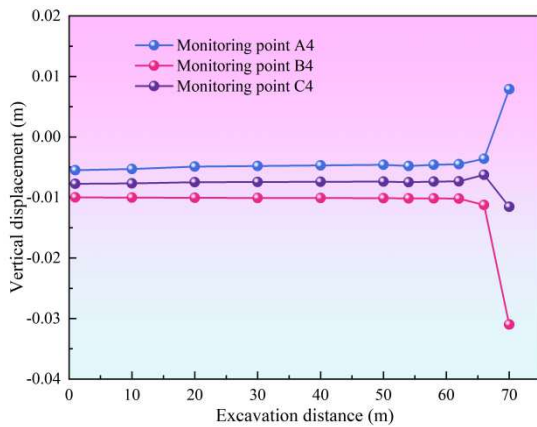


Fig. 15 Displacement evolution at monitoring points in the water-resisting

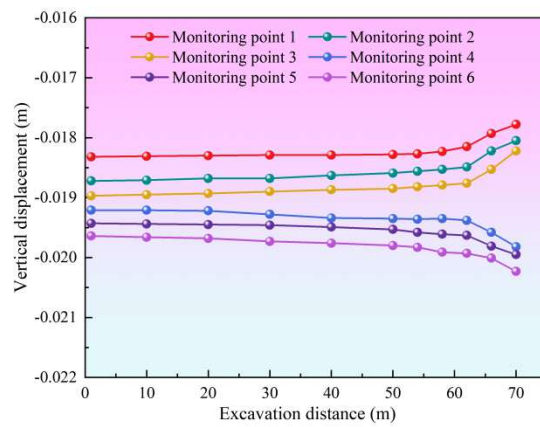


Fig. 16 Vertical displacement evolution at monitoring points

Analysis of Pore Water Pressure Variation Characteristics

Taking monitoring points 4, 9, 10, and 16 as examples, the variation in pore water pressure with excavation distance is shown in Fig. 17. Overall, the initial pore water pressure within the fault fracture zone exhibits a stratified distribution and generally increases with depth. When the excavation distance reaches 54 m, roadway excavation disturbance causes only instantaneous changes in pore water pressure within a local area. At this stage, when the excavation face is still far from the fault, the overall pore water pressure distribution remains essentially unaffected. As the roadway gradually advances toward the fault, the variation in pore water pressure becomes increasingly pronounced when the excavation distance reaches 62-70 m. Once the excavation-induced void and mining-induced stress begin to affect the pore water pressure within the fault, a marked decrease in pore water pressure is observed. When the excavation distance reaches 70 m, the pore water pressure drops sharply. At this stage, unloading further intensifies water flow along the fault plane or fracture surfaces toward the roadway, resulting in a rapid local release of water pressure. This strongly suggests water inrush, consistent with the through-going connection of the plastic failure zone observed at an excavation distance of 70 m. Specifically, the pore water pressure at monitoring point 4 decreases from 2.32 MPa at the initial excavation stage to 1.10 MPa at an excavation distance of 70 m, representing a 53% reduction. At monitoring point 9, the pore water pressure decreases from 2.36 MPa to 1.24 MPa, with a reduction of 47%; at monitoring point 10, it decreases from 2.29 MPa to 1.16 MPa, corresponding to a reduction of 49%; and at monitoring point 16, it decreases from 2.26 MPa to 1.21 MPa, with a reduction of 46%. Among these points, monitoring point 4 exhibits the greatest decrease in pore water pressure. A comparison of the stable stage in the early excavation period further shows that monitoring point 4, which is located closer to the excavation face, is more sensitive to excavation disturbance, and its pore water pressure begins to decline significantly at 58 m. Monitoring points 9 and 10, located in the middle of the fault zone, begin to show an obvious decrease at 62 m. In contrast, monitoring point 16, located on the right side of the fault zone, does not show a clear decline until the excavation distance reaches 66 m. These results indicate that, within the fault zone, rock masses closer to the roadway are affected earlier by excavation disturbance, leading to an earlier reduction in pore water pressure and making them more susceptible to failure under the coupled action of mining disturbance and water pressure. In contrast, rock masses farther from the roadway exhibit a pronounced lag in deformation and failure. It can therefore be concluded that as the excavation roadway approaches the fault, the pore water pressure within the fault progressively decreases, increasing the hydraulic gradient. According to Darcy's law, both seepage velocity and seepage hydraulic pressure increase accordingly, making groundwater more likely to flow into the roadway along fractures generated by excavation disturbance. This process causes softening of the surrounding rock and deterioration of its mechanical properties, thereby affecting its deformation behavior and structural stability. As a result, instability and failure of the rock mass within the fault fracture zone are further aggravated, eventually forming a water-inrush pathway and triggering a fault-induced water-inrush disaster.

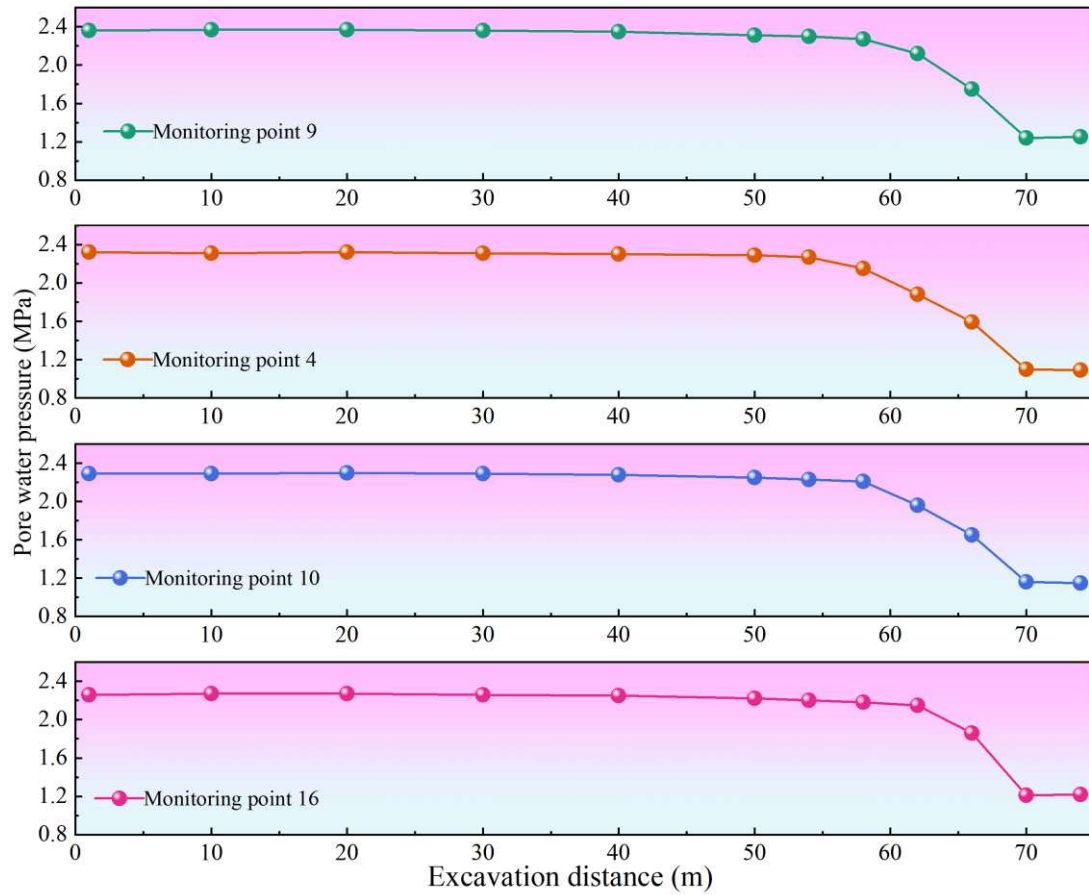


Fig. 17 Evolution of pore water pressure at different monitoring points with excavation distance

Influencing Factors of the Safe Thickness against Water Inrush and Construction of the Prediction Model

Orthogonal Experimental Results and Sensitivity Analysis

Based on the orthogonal experimental design, numerical simulations were conducted to assess the effect of waterproof rock pillar thickness on fault-induced water inrush under different factor combinations and levels, yielding the corresponding simulation results. For example, the simulated thicknesses of the waterproof rock pillar at different fault dip angles were selected for analysis. The experimental data for different levels of all influencing factors are listed in Table 4.

Table 4 Experimental results of the waterproof rock-pillar thickness against fault-induced water inrush during roadway excavation

Orthogonal test No.	Fault dip angle	Roadway section height	Fault water pressure	Roadway burial depth	Elastic modulus	Waterproof rock-pillar thickness
	θ	H	P	B	E	D
1	50	4.0	2.0	300	20	10.9
2	50	4.5	2.5	350	25	14.0
3	50	5.0	3.5	400	30	16.9
4	50	5.5	4.0	450	35	19.1

5	50	6.0	2.0	500	40	22.1
6	55	4.0	2.5	400	35	13.3
7	55	4.5	3.0	450	40	15.7
8	55	5.0	3.5	500	20	20.6
9	55	5.5	4.0	300	25	21.2
10	55	6.0	2.0	350	30	11.0
11	60	4.0	3.0	500	25	17.2
12	60	4.5	3.5	300	30	18.0
13	60	5.0	4.0	350	35	20.6
14	60	5.5	2.0	400	40	10.2
15	60	6.0	2.5	450	20	15.2
16	65	4.0	3.5	350	40	17.1
17	65	4.5	4.0	400	20	21.6
18	65	5.0	2.0	450	25	11.7
19	65	5.5	2.5	500	30	14.5
20	65	6.0	3.0	300	35	15.3
21	70	4.0	4.0	450	30	21.2
22	70	4.5	2.0	500	35	10.7
23	70	5.0	2.5	300	40	11.6
24	70	5.5	3.0	350	20	16.8
25	70	6.0	3.5	400	25	19.5

Range analysis was performed on the orthogonal experimental results to determine the relative importance of each influencing factor. The results of the range analysis are presented in Table 5.

Table 5 Range analysis of factors affecting the safe thickness against water inrush

Factor ID	Fault dip angle θ	Roadway size H	Fault water pressure P	Roadway burial depth B	Elastic modulus E
K ₁	82.87	79.68	54.42	77.05	85.02
K ₂	81.79	79.99	68.51	79.57	83.61
K ₃	81.30	81.40	81.80	81.40	81.60
K ₄	80.20	81.76	94.34	82.77	78.94
K ₅	79.71	83.05	106.81	85.08	76.71
k ₁	16.57	15.94	10.88	15.41	17.00
k ₂	16.36	16.00	13.70	15.91	16.72
k ₃	16.26	16.28	16.36	16.28	16.32
k ₄	16.04	16.35	18.87	16.55	15.79
k ₅	15.94	16.61	21.36	17.02	15.34
Range R	0.63	0.67	10.48	1.61	1.66

Through a range analysis of experimental results on the safe thickness for fault-induced water inrush during roadway excavation, the following relationship is obtained. Based on the magnitude of the range R, the order of importance of the influencing factors on the thickness of the water-resistant rock pillar is $P > E > B > H > \theta$, that is, fault water pressure > elastic modulus > roadway burial depth > roadway size > fault dip angle.

To further investigate the effects of different factors on the thickness of the water-resistant rock pillar against fault-induced water inrush, an analysis of variance was conducted. The results are presented in Table 6.

Table 6 Analysis of variance for factors affecting the thickness of the water-resistant rock pillar

Source of variance	Sum of squares	Degrees of freedom	Mean square	F value	Significance
θ	1.266	4	0.317	0.031	Not significant
H	1.490	4	0.373	0.037	Not significant
P	341.379	4	85.345	8.364	significant
B	4.520	4	1.130	0.111	Not significant
E	13.687	4	3.422	0.335	Not significant
Error e	40.804	4	10.201		

It is found that the critical value is $F_{0.05}(4,4)=6.388$. Since $F_{\theta}<F_H<F_B<F_E<F_{0.05}(4,4)$, fault dip angle, roadway size, roadway burial depth, and elastic modulus have no significant effect on the experimental results. In contrast, because $F_P>F_{0.05}(4,4)$, fault water pressure has a significant effect on the results at the given significance level of $\alpha = 0.05$. Accordingly, the significance ranking of the influencing factors on the thickness of the fault water-resistant rock pillar is $P > E > B > H > \theta$, which is consistent with the range analysis and thus verifies the reliability of the experimental results.

Influence of Different Factors on the Thickness of the Fault Water-Resistant Rock Pillar

According to the above range analysis and analysis of variance, the effects of different factors on the thickness of the fault water-resistant rock pillar differ to varying degrees. Based on the variation trends in the thickness of the fault water-resistant rock pillar under different influencing factors, as shown in Fig. 18, the following conclusions can be drawn. As the fault dip angle increases, the required thickness of the water-resistant rock pillar decreases, because a steeper fault reduces the normal component of water pressure acting on the fault plane and shortens the water-inrush pathway. As the roadway cross-sectional size increases, the required thickness of the water-resistant rock pillar also increases, attributable to the enlargement of the excavation disturbance zone and the further development of the plastic zone. As fault water pressure increases, the required thickness of the water-resistant rock pillar increases correspondingly, because higher water pressure enhances hydraulic fracturing stress and reduces effective stress. As roadway burial depth increases, the required thickness of the water-resistant rock pillar also increases, owing to the intensified stress release and the further propagation of surrounding-rock failure under high in situ stress. In contrast, as the elastic modulus increases, the required thickness of the water-resistant rock pillar decreases, reflecting improved rock-mass integrity, fewer fractures, and lower permeability. Among all factors, fault water pressure is the primary controlling factor for water inrush, as it determines the energy available for water to break through the rock mass and therefore exerts the greatest influence on the required thickness of the water-resistant rock pillar. The elastic modulus mainly reflects the intrinsic stiffness characteristics of the rock mass. It influences its failure mode, whereas roadway burial depth controls the degree of stress release and the deformation and failure characteristics of the surrounding rock during roadway excavation under high in situ stress. However, the effects of elastic modulus and roadway burial depth on the thickness of the water-resistant rock pillar are weaker than that of fault water pressure, although they remain important controlling factors. By contrast, roadway size and fault dip angle mainly affect the local stress state and the geometric conditions of the water-inrush pathway, and therefore have relatively smaller influences on the required thickness of the water-resistant rock pillar.

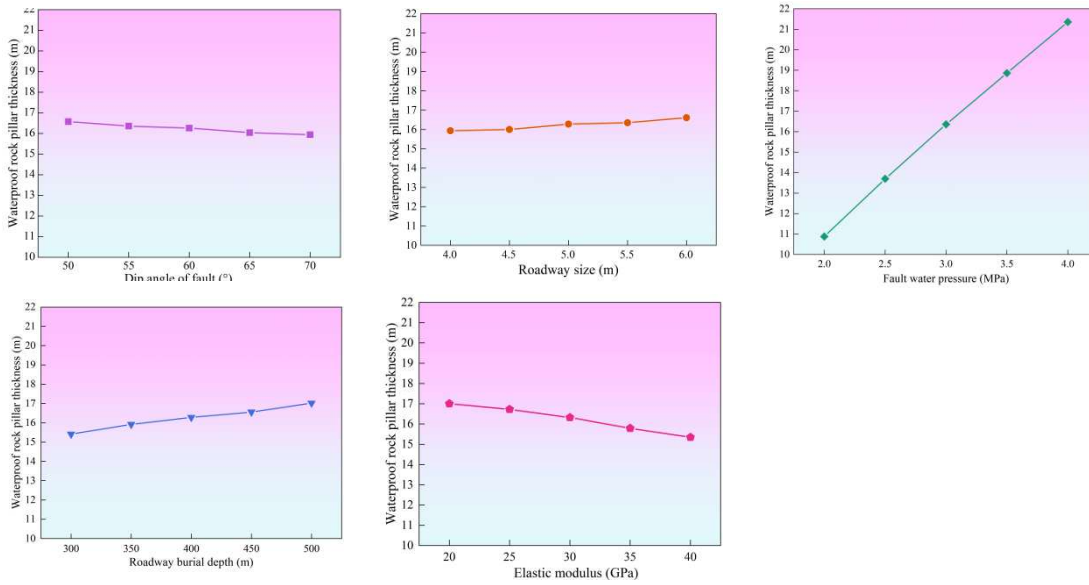


Figure. 18 Variation trends of the thickness of the fault water-resistant rock pillar with different influencing factors

Prediction Model for the Thickness of the Water-Resistant Rock Pillar against Fault-Induced Water Inrush during Roadway Excavation

Multiple linear regression was employed to investigate the linear relationship between one continuous dependent variable and multiple independent variables. This method allows multiple confounding factors to be incorporated and controlled simultaneously, thereby enabling estimation of the independent effect of each variable. The parameter estimates (regression coefficients) have intuitive quantitative interpretability, and the statistical significance of each variable can be evaluated through hypothesis testing. In addition, the model is computationally efficient and highly reproducible. The average values of the thickness of the water-resistant rock pillar against fault-induced water inrush obtained from the orthogonal experiments were regressed against fault dip angle θ , roadway size H , fault water pressure P , roadway burial depth B , and the elastic modulus of the surrounding rock E . The thickness of the water-resistant rock pillar against fault-induced water inrush, denoted by T , was taken as the dependent variable. At the same time, the above factors were treated as independent variables. Correlation analysis was then conducted to establish the regression relationship between T and the influencing factors. Accordingly, a calculation model for the thickness of the water-resistant rock pillar against fault-induced water inrush during roadway excavation was proposed. It was assumed that a linear relationship exists between T and $T(\theta)$, $T(H)$, $T(P)$, $T(B)$, and $T(E)$, which can be expressed as

$$T = \mu_1 T(\theta) + \mu_2 T(H) + \mu_3 T(P) + \mu_4 T(B) + \mu_5 T(E) + \xi \quad (7)$$

where T is the minimum safe thickness, and μ_i and ξ are undetermined coefficients. By solving these coefficients through multiple linear regression, the final prediction formula for the thickness of the water-resistant rock pillar against fault-induced water inrush during roadway excavation was obtained as

$$T = -0.0307\theta + 0.3308H + 5.0691P + 0.0075B - 0.0501E + 0.6995 \quad (8)$$

The coefficient of determination for this equation is $R^2 = 0.994$, indicating that the multiple linear regression model provides an excellent fit. A comparison between the measured values and the predicted

values is shown in Fig. 19.

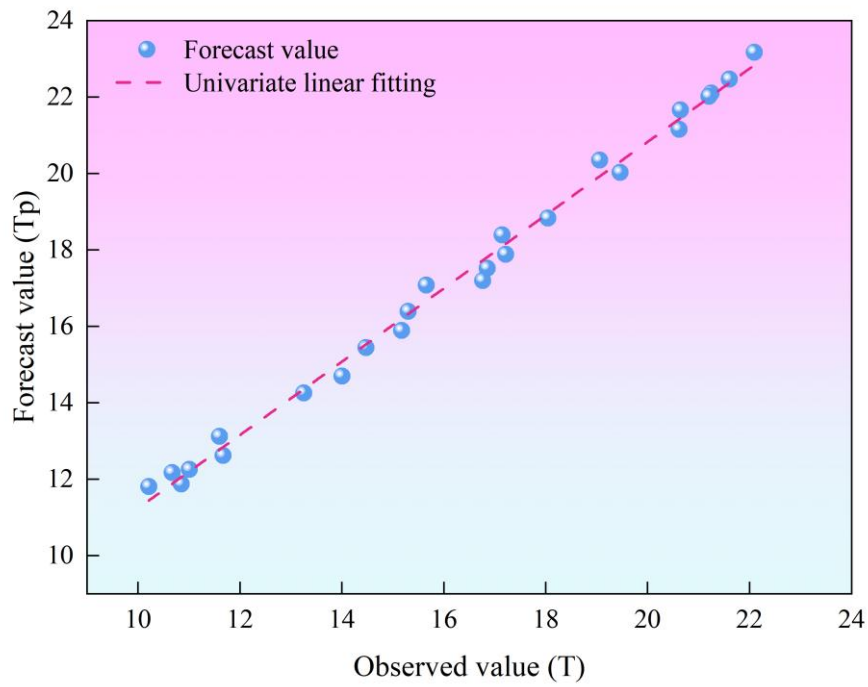


Figure. 19. Comparison between measured and predicted values of the thickness of the water-resistant rock pillar

A significance test was further performed on the above fitting results, and the results are presented in Table 7.

Table 7 Analysis of variance for the fitted formula of the thickness of the water-resistant rock pillar against fault-induced water inrush

Source of variance	Sum of squares	Degrees of freedom	Mean square	F value	Significance
Regression	333.91	5	66.78	47.69	Significant
Residual	26.59	19	1.40		
Total	360.50	24			

The F statistic follows an F-distribution with degrees of freedom (5,19). For the given significance level of $\alpha=0.01$, the critical value is $F_{0.01}(5,19)=4.17$. Since the calculated value $F = 47.69$ is much greater than $F_{0.01}(5, 19) = 4.17$, a highly significant linear relationship exists between T and θ , H, P, B, and E. This result confirms the validity of the assumptions underlying the fitted formula.

Validation and Comparison of the Prediction Model for the Safe Thickness against Water Inrush

To validate the theoretical assessment in a specific field case, the F102 fault at the 830 m level crosscut of the Yingping phosphate mine was selected as a demonstration site. For the case considered in this study, the F102 fault has a dip angle of 60° , the roadway size is 5 m, the burial depth is 400 m, the fault water pressure is 2.9 MPa, and the elastic modulus of the surrounding rock is 23.2 GPa. Substituting these parameters into the prediction model yields a water-resistant rock pillar thickness of $T = 17.05$ m. During excavation, the advance distance was measured by a total station, and the pore water pressure in the fault

zone was continuously monitored by three borehole piezometers. The inrush event was identified by a rapid increase in water inflow at the working face and a simultaneous abrupt drop in piezometric pressure. According to the field monitoring data and geophysical exploration results, water inrush occurred when the roadway excavation distance reached 70 m. At this stage, the distance from the center of the roadway face to the fault was approximately 20 m, and the corresponding thickness of the water-resistant rock pillar against fault-induced water inrush is denoted as $T_w = 20$ m.

According to the Detailed Rules for Mine Water Prevention and Control in Coal Mines, when water inrush in the advancing direction of a roadway face is considered, and a water-bearing or water-conducting fault is present, the required thickness of the water-resistant stratum can be calculated using the following formula:

$$T_0 = 0.5KM \sqrt{\frac{3P}{\sigma_t}} \quad (9)$$

where T_0 is the required thickness of the water-resistant stratum, M is the working-face height, P is the hydrostatic pressure, and σ_t is the tensile strength of the water-resistant rock stratum. According to the specification, the safety factor is taken as $K = 3$. Substitution into the formula gives $T_0 = 6.89$ m.

After calibrating the numerical model with the measured in situ stress and piezometric data, the previous numerical simulation results also indicate that water inrush occurred when the excavation distance reached 70 m. At this point, the distance from the center of the roadway face to the fault was likewise about 20 m, and the corresponding thickness of the water-resistant rock pillar is denoted as $T_s = 20$ m.

A comparison among the actual water-inrush thickness from field observation T_w , the numerical simulation result T_s , the thickness predicted by the multiple linear regression model T , and the safe thickness derived from the Detailed Rules for Mine Water Prevention and Control in Coal Mines T_0 gives: $T_s = T_w > T > T_0$. The identical values of T_s and T_w verify the scientific validity of the parameter selection and the restoration of working conditions in both the physical investigation and numerical simulation, indicating that the test data can realistically reflect the actual requirement for rock-pillar thickness under fault-induced water inrush conditions in deep phosphate mines. Furthermore, the field-measured critical thickness $T_w = 20$ m provides direct field data to back up the model prediction: the relative error between the predicted $T = 17.05$ m and the observed critical thickness is 14.75%, i.e., the model achieves 85.25% accuracy. Meanwhile, the proposed model achieves 85.25% prediction accuracy, indicating that multiple linear regression is relatively accurate and can be applied to determining the required thickness of water-resistant rock pillars for roadway excavation under complex geological conditions.

Discussion

By integrating coupled numerical simulation with an orthogonal experimental design, this study systematically revealed the multi-field coupled mechanical mechanism underlying fault-induced water inrush during roadway excavation in deep phosphate mines and, on this basis, established an empirically constrained prediction model for the minimum thickness of the water-resistant rock pillar. The numerical simulation results clearly show that excavation disturbance induces intense stress redistribution in the rock mass surrounding the fault zone. The macroscopic responses manifest as progressive expansion of

the plastic zone, pronounced stress concentrations, accumulation of displacement, and dynamic evolution of pore water pressure. These interrelated hydro-mechanical coupling phenomena strongly demonstrate that fault-induced water inrush is not a simple process driven by a single factor, but rather a catastrophic result arising from the nonlinear interaction among multiple variables, including fault geometry, hydrogeological conditions, engineering parameters, and the mechanical properties of the rock mass. The orthogonal sensitivity analysis quantitatively clarified the relative importance of the influencing factors, indicating that fault water pressure and roadway burial depth are the dominant controlling factors, followed by fault dip angle and the elastic modulus of the surrounding rock. It provides a solid physical basis for prioritizing monitoring and prevention measures in high-risk zones.

The prediction model for safe thickness against water inrush, based on the above mechanistic understanding, achieved 85.25% prediction accuracy during validation, which is significantly superior to the empirical formula T_0 recommended in the Detailed Rules for Mine Water Prevention and Control in Coal Mines. Comparative analysis reveals that the T_0 formula substantially underestimates the required thickness of the water-resistant rock pillar under the complex geological conditions of deep mining, characterized by coupled high in situ stress and high water pressure. This systematic deviation highlights the fundamental limitation of the existing code-based formula: its theoretical basis is rooted in shallow coal-mining practice. It therefore cannot effectively characterize the high in situ stress environment, complex fault-structure networks, and persistent high hydraulic-head gradients unique to deep phosphate mine systems. Accordingly, the model proposed in this study is not merely a new calculation tool but also represents a paradigm shift from “empirical application” to a “mechanism-driven, scenario-adaptive” approach, thereby providing a critical bridge to narrow the gap between existing safety regulations and the practical realities of deep mining.

Conclusions

Taking fault-induced water inrush during roadway excavation in a phosphate mine as the engineering background, this study systematically investigated the water-inrush mechanism during roadway advance toward a fault. It established a prediction model for the safe thickness of the water-resistant rock pillar by integrating COMSOL numerical simulation, orthogonal experimental design, and multiple linear regression. The main conclusions are as follows.

(1) Under excavation disturbance, fault-induced water inrush exhibits a clear multi-physical-field coupled evolution pattern. Excavation-induced unloading and stress redistribution in the surrounding rock lead to the formation of a stress concentration zone ahead of the excavation face, and the coupled effect of excavation disturbance and fault water pressure is the key trigger for water inrush. The evolution of the plastic zone is strongly stage-dependent, expanding from a shallow distribution toward the fault in a wedge-shaped manner and ultimately connecting with the fault fracture zone to form a water-conducting pathway. Pore water pressure along the excavation direction undergoes a three-stage evolution, namely, stable fluctuation, gradual decline and rapid drop. High-pressure groundwater then flows preferentially along the path of “fault–plastic failure zone–roadway”, and the hydraulic gradient provides the key hydrodynamic condition for water inrush.

(2) Based on a five-factor, five-level orthogonal experiment and range–variance analysis, the significance ranking of the factors affecting the safe thickness of the water-resistant rock pillar was determined as

follows: fault water pressure > elastic modulus > roadway burial depth > roadway size > fault dip angle. Among these factors, fault water pressure is the most significant controlling factor, further confirming the central role of hydraulic conditions in preventing and controlling fault-induced water inrush. The empirical prediction formula for safe thickness, established by regression analysis ($R^2=0.994$), achieved a validation accuracy of 85.25% using field data. Moreover, the predicted value falls between the measured critical thickness for water inrush and the value calculated using the code-based formula, indicating that the proposed model is applicable and has practical engineering value under pressure-bearing excavation conditions in deep phosphate mines.

(3) This study still has several limitations that warrant further improvement. First, the numerical model is necessarily simplified relative to the actual hydrogeological conditions, and the strong nonlinearity of fluid–solid coupling may lead to convergence difficulties in computation. Future studies should therefore further refine the modeling of hydrogeological structures. Second, the influence of initial rock fractures on mechanical behavior and seepage characteristics was not considered. However, fractures play an important controlling role in the deformation and failure of the surrounding rock. In future work, three-dimensional fracture reconstruction techniques may be introduced to establish a more realistic coupled fracture–seepage–stress model. Third, the selection of influencing factors for the safe thickness against water inrush remains incomplete, and the interaction effects among factors have not been revealed. Subsequent studies should incorporate a more comprehensive set of control variables and conduct interaction analyses to further improve the theoretical framework for prediction.

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Declarations

Data availability

The datasets generated and analyzed during the current study are not publicly available due to confidentiality agreements with the participating mining enterprise. The raw data contain sensitive operational parameters of the mining site, which could compromise commercial interests if disclosed. However, processed data supporting the findings of this study, including the geological parameters, rock mechanical properties, and the construction of the predictive model for safe thickness of water-resistant rock mass, are available from the corresponding author upon reasonable request, subject to approval from the collaborating mining company.

Ethics approval and consent to participate

This study did not involve human participants, human data, or animal subjects. All experimental

data, including geological surveys, mining records, and rock mechanics test results, were collected from operational deep phosphate mines under the authorization of the mine owner. The research was conducted in compliance with applicable institutional and national safety regulations for underground mining operations. Therefore, ethics approval and consent to participate are not applicable to this work.

References

- Cai, W. Y., Y. Wang, and F. J. He. 2022. "The Seepage-Destruction Mechanism of Water Inrush Channel of Sandstone Fault Filling Using the EDEM-Fluent Method." *Advances in Civil Engineering*. 2022 (1): 3313013.
- Chen, H. Z., Z. S. Shao, and D. D. Jin. 2021. "A Numerical Investigation into the Effect of Homogeneity on the Time-Dependent Behavior of Brittle Rock." *Materials*. 14 (22): 6818.
- Du, Y. H., W. T. Liu, and X. X. Meng. 2021. "Effect of Crack Propagation on Mining-Induced Delayed Water Inrush Hazard of Hidden Fault." *Geofluids*. 2021 (1): 6557578.
- Gao, X. H., F. Gao, and H. M. Chen. 2025. "Numerical Simulation of Stress and Permeability Evolution in Damaged Coal." *International Journal of Non-Linear Mechanics*. 168: 104953.
- Gao, Z. Z., X. Q. Yang, and Z. H. Li. 2024. "Evolution Mechanism of Water-Conducting Fractures in Overburden Under the Influence of Water-Rich Fault in Underground Coal Mining." *Scientific Reports*. 14 (1): 5081.
- Gong, X. F., Y. Liu, and Q. Li. 2025. "Experimental and Numerical Study on Seepage-Creep Coupling Characteristics of Fault Rocks." *Frontiers in Earth Science*. 13: 1566556.
- Ji, Z. Q., H. Tian, and Z. N. Yang. 2018. "Mechanism of Water Inrush from Coal Seam Floor Based on Coupling Mechanism of Seepage and Stress." *Journal of Intelligent*. 34 (2): 965–74.
- Li, Bo., and Q. Wu. 2019. "Catastrophic Evolution of Water Inrush from a Water-Rich Fault in Front of Roadway Development: A Case Study of the Hongcai Coal Mine." *Mine Water and the Environment*. 38 (2): 421–30.
- Meng, S. H., Q. Wu, and Y. F. Zeng. 2024. "Enhancing Mine Groundwater System Prediction: Full-Process Simulation of Mining-Induced Spatio-Temporal Variations in Hydraulic Conductivities via Modularized Modeling." *International Journal of Mining Science and Technology*. 34 (12): 1625–42.
- Shi, W. H., T. H. Yang, and Q. L. Yu. 2017. "A Study of Water-Inrush Mechanisms Based on Geo-Mechanical Analysis and an in-Situ Groundwater Investigation in the Zhongguan Iron Mine, China." *Mine Water and the Environment*. 36 (3): 409–17.
- Song, W. C., and Z. Z. Liang. 2021. "Theoretical and Numerical Investigations on Mining-Induced Fault Activation and Groundwater Outburst of Coal Seam Floor." *Bulletin of Engineering Geology and the Environment*. 80 (7): 5757–68.
- Song, Z. L., and Z. G. Zhang. 2022. "Experimental Study on the Influence of Hydrostatic Stress on the Lode Angle Effect of Porous Rock." *International Journal of Mining Science and Technology*. 32 (4): 727–35.
- Sun, D. D., X. G. Hou, and T. H. Yang. 2022. "Calibration of Water Inrush Channel and Numerical Simulation of Water Inrush Process in Coal Mine Roof." *Frontiers in Earth Science*. 10: 931508.

- Sun, Y. J., J. P. Zuo, and C. N. Mi. 2023. "Investigation on Fault Activation-Induced Floor Water Inrush and Its Pressure Relief Control in a 1000-m Depth Coal Mine." *Bulletin of Engineering Geology and the Environment*. 82 (6): 222.
- Tu, W. F., L. P. Li, and C. S. Shang. 2024. "Comprehensive Risk Assessment and Engineering Application of Mine Water Inrush Based on Normal Cloud Model and Local Variable Weightr." *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*. 46 (1): 4298–313.
- Wang, Y. C., N. Zhao, and W. Jiang. 2022. "Investigation on the Evolution Mechanism of Water and Mud Inrush Disaster in Fractured Rock Mass of Mountain Tunnel." *Geomatics, Natural Hazards and Risk*. 13 (1): 1780–804.
- Wei, L. D., Z. N. Lin, and H. F. Long. 2023. "Experimental Study on Permeability Evolution of Sandstone During Triaxial Compression Damage." *Applied Sciences*. 13 (20): 11579.
- Xie, H. P., M. Z. Gao, and R. Zhang. 2019. "Study on the Mechanical Properties and Mechanical Response of Coal Mining at 1000 m or Deeper." *Rock Mechanics and Rock Engineering*. 52 (5): 1475–90.
- Xue, Y. L., J. R. Chai, and J. Liu. 2023. "Effect of Water-Cooling Shock on Fracture Initiation and Morphology of High-Temperature Granite: Application of Hydraulic Fracturing to Enhanced Geothermal Systems." *Applied Energy*. 337: 120858.
- Xue, Y., Y. Liu, and F. Dang. 2019. "Assessment of the Nonlinear Flow Characteristic of Water Inrush Based on the Brinkman and Forchheimer Seepage Model." *Water*. 11 (4): 855.
- Yang, S., J. G. Wang, and J. Chen. 2024. "Study on the Response Mechanism Characteristics of Fault Activation Under the Mining Effect of Thick Coal Seam." *Journal of Applied Geophysics*, 105954.
- Yang, W. H., Y. F. Zeng, and H. Bao. 2025. "Development of Cement-Based Grouting Material Containing High Polymer and High-Water Resistance." *Construction and Building Materials*. 470: 140660.
- Yu, H., S. Y. Zhu, and H. D. Xie. 2020. "Numerical Simulation of Water Inrush in Fault Zone Considering Seepage Paths." *Natural Hazards*. 104 (2): 1763–79.
- Zeng, Y. F., A. S. Mei, and Q. Wu. 2024. "Double Verification and Quantitative Traceability: A Solution for Mixed Mine Water Sources." *Journal of Hydrology*. 630: 130725.
- Zhai, X. R., Z. S. Dou, and K. Huang. 2017. "Water Inrush Mechanism Caused by Fault Activation Based on Stress Evolution of Surrounding Rock of Key Aquifer." *Journal of Engineering Science and Technology Review*. 10 (6): 179–85.
- Zhang, D., Z. Q. Wang, and M. Li. 2023. "Crack Propagation Behavior in Sandstone During Unloading Confining Pressure Under Different Seepage Pressures." *Journal of Central South University*. 30 (8): 2657–70.
- Zhou, P., H. C. Ma, and J. P. Wang. 2024. "Experimental and Theoretical Study of Seepage Models Under Confining Pressure for a Single Rock Fracture." *KSCE Journal of Civil Engineering*. 28 (5): 1799–808.
- Zhou, S., D. S. Zhang, and Z. Wang. 2018. "Influence of Stress and Water Pressure on the Permeability of Fissured Sandstone Under Hydromechanical Coupling." *Mine Water and the Environment*. 37 (4): 774–85.
- Zhu, Z. D., Z. H. Niu, and X. C. Que. 2020. "Study on Permeability Characteristics of Rocks with Filling Fractures

Under Coupled Stress and Seepage Fields." Water. 12 (10): 2782.

