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Stability analysis of surrounding rock and dam body of underground reservoir under the influence of faults

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Abstract: In order to explore the dynamic evolution process of underground reservoir constructed by coal mine goaf under the influence of faults and the evolution mechanism of water storage space in goaf of underground reservoir with dam stability under the influence of faults, this paper takes the stress and water pressure change in fault mining area as the main research object, and comprehensively uses the method of combining theoretical analysis, numerical simulation and engineering verification. Combined with the classical seepage mechanics equation, a numerical model of ' stress-pore water pressure ' in line with the geological conditions of the mining area is constructed. FLAC3D is used to simulate the stress change of roadway through fault and working face during mining, the evolution of water storage space of underground reservoir and the stability characteristics of dam body, and the influence of stress transfer difference between hanging wall and footwall of fault on water storage space of underground reservoir under mining action is analyzed. The results show that : (1) When the hanging wall is mined, part of the load is transmitted through the fault, and the stability of the surrounding rock of the water storage space of the underground reservoir is better ; when the footwall is mined, the stress at the fault is concentrated, and the surrounding rock of the water storage space is prone to deformation and collapse. When the width of coal pillar decreases, the stress concentration factor of footwall load is larger, which further aggravates the instability risk of surrounding rock in water storage space. (2) With the advance of the working face, the stress concentration coefficient near the fault increases, the plastic zone is characterized by stage development, and the pore water continues to rise along the fault. At the same time, a water storage space with fissures as the carrier is formed in the goaf, and its volume and connectivity change dynamically with the mining process. Under the continuous influence of tunnel mining disturbance, the damage range of surrounding rock in water storage space is expanded, and the pore water pressure of surrounding rock is more prone to step mutation, which may lead to seepage instability of surrounding rock in underground reservoir. Through the control of bolt and anchor cable, the strength of surrounding rock at fault is improved, and then the shear strength is improved. The expansion of plastic zone of surrounding rock is significantly inhibited, the range of plastic zone is reduced, the stress concentration degree of surrounding rock is effectively reduced, and the stress concentration coefficient is reduced, which plays a good role in controlling the vertical displacement of surrounding rock. The study reveals the water-rock coupling evolution law and dam stability control mechanism of underground reservoirs in goaf under the influence of faults, and provides theoretical support for the location, optimization design and safe operation of underground reservoir water storage space.

Key words: Fault ; Stress evolution ; Pore water pressure ; Water-rock coupling ; Dam stability

China is rich in coal resources, but with the continuous increase in coal mining intensity, long-term large-scale mining has led to the formation of a large number of goafs (Hou. 2019). According to incomplete statistics, the cumulative mined-out area in China has exceeded millions of hectares. These mined-out areas not only occupy a large amount of land resources, but may also cause a series of ecological and environmental problems, such as surface subsidence, which will bring serious challenges to the sustainable development of mining areas (Zhu et al. 2016). To alleviate the shortage of water resources in the mining area and realize the coordinated development of ' coal-water symbiosis ', the goaf is transformed into an underground reservoir, which can effectively store water resources such as groundwater and mine water, meet the water demand of production, life, and ecological restoration in the mining area, and has significant economic, social, and ecological benefits (Jha et al. 2014).

The development and utilization of water storage space in the goaf face many difficulties, among which the influence of the fault structure is particularly prominent (Wang et al. 2023; Ma A et al. 2022, Karatela et al. 2018, Munoz et al. 2016). Statistics show that approximately 70 % of coal mine water disaster accidents in China are closely related to fault structure, and faults are also the core factor restricting the stability of water storage space in the goaf. As a weak structural plane in a rock mass, the existence of faults significantly changes the distribution law of the stress field and seepage field around

the goaf (Wang et al. 2003). On the one hand, the additional stress field caused by mining activities can easily lead to fault slip instability and destroy the integrity of the surrounding rock in the goaf, resulting in deformation of the water storage space; on the other hand, fault activation aggravates fracture development and connectivity, changes the groundwater seepage path, may cause water inrush disaster, and also affects the sealing and water retention capacity of the water storage space (Cathy et al. 2002). In addition, the structural characteristics, physical and mechanical parameters of the rock mass and fillings on both sides of the fault (Qian et al. 1996, Miao et al. 1995), as well as the magnitude, direction, and evolution process of the slope stress, will directly affect the fault activation and nonlinear slip motion, which will lead to changes in the volume, connectivity and stability of the water storage space (Li et al. 1996; Wei et al. 2019, Ju et al. 2011). The change in the surrounding environment of the fault has a key control effect on the progressive failure process, energy release law, and instability risk of the water-storage space.

In recent years, scholars at home and abroad have conducted extensive research on the interaction between mining and faults. Some researchers have analyzed the influence of weak surfaces on the deformation and shear deformation of the surrounding rock in a goaf by means of physical and numerical simulations (Zhao et al. 2018; Zhao et al. 2014, Liu et al. 2010); and Jiang et al. (Jiang et al. 2015; Du et al. 2019) discussed the distribution characteristics of the stress field and abutment pressure during mining near reverse faults. Jiang et al. (Jiang et al. 2013) used the Coulomb shear contact surface model to analyze the temporal and spatial evolution of the normal stress and shear stress of the fault plane under different mining relative positions and directions, and their correlation with the movement of the two walls of the fault. Wang (Wang et al. 2022) revealed the barrier effect of faults on vertical stress, horizontal stress and shear stress. In the study of water inrush mechanism of fault activation, Shi et al (Shi et al. 2005), based on the theory of mine pressure, pointed out that the closer the distance between the fault plane and the mining face, the more significant the mining influence and the greater the probability of water inrush. The PANDAS software developed by Xing et al (Xing et al. 2000; Xing et al. 2020). simulated the dynamic characteristics of a fault system using the nonlinear finite element method, and revealed the bond-slip state and stress accumulation-release law of the fault contact surface (Li et al. 2003; Li et al. 2012). In addition, scholars have also found that an increase in fracture opening and connectivity at the fault under the action of mining stress will lead to an increase in permeability; however, at the same time, the increase in fracture spacing may also reduce the overall permeability of coal and rock mass (Li et al. 2013; Li et al. 2009); and the change in ground stress caused by mining activities will further affect the permeability of the floor rock mass. Under the dual action of mining stress and high confined water, the water body in small faults easily moves along the penetrating cracks, which accelerates the erosion and expansion of the crack wall, ultimately affecting the integrity of the floor aquiclude and water retention performance of the water storage space (Li et al. 2011).

Although some progress has been made in existing research, there are still some shortcomings in the systematic study of the water storage space in a goaf under the influence of faults. First, the existing achievements mostly focus on the single dimension of the fault water inrush mechanism and goaf stress evolution, and lack in-depth discussion on the coupling mechanism of ' stress-pore water pressure-water storage space ', which makes it difficult to reveal the full-cycle evolution law of water storage space from formation to stability. Second, the stage division of the evolution of the water storage space in the goaf is not clear, especially the lack of the mutation mechanism of the water storage space during the superimposed mining of multiple working faces, and the cognition of the synergistic deformation mechanism of the supporting structure and the water storage space under the long-term mining effect, which can not provide accurate theoretical support for the stability control of the water storage space.

Based on this, this study combines the seepage mechanics coupling equation to construct the FLAC3D numerical model, simulates the stress change in the process of roadway crossing fault and working face mining, the evolution and stability characteristics of underground reservoir water storage space, and quantifies the evolution and stability characteristics of underground reservoir water storage space under the coupling of ' stress-pore water pressure-water storage space.' The influence of the support parameters on the stress, plastic zone expansion, and displacement of the surrounding rock in the water storage space is systematically analyzed, and the relationship between the support parameters and mechanical properties of the rock mass is established. The correlation between the failure range of the surrounding rock and the risk of instability in the water storage space during the superposition mining of multiple working faces is clarified, which provides a scientific basis and technical support for site selection optimization, stability control, and safe operation of the underground reservoir water storage space in the goaf of the fault-affected area.

1 Fluid-Solid Coupling Analysis Of Mining Fault Zone

1.1 Fluid-Solid Coupled Model

The stress concentration factor refers to the ratio of the maximum principal stress or vertical stress of a certain point of the surrounding rock to the original in-situ stress under the influence of mining, which is used to quantify the stress concentration caused by mining. Based on the stress monitoring data of the monitoring points in the FLAC3D numerical simulation, the characteristic stress points near the surrounding rock and fault around the goaf were selected, the maximum vertical stress value of each advancing stage was extracted, and the ratio calculation was carried out with the original in-situ stress applied at the beginning of the model.

The fluid-solid coupling calculation adopts the classical Biot seepage mechanics coupling equation, which includes : equilibrium, geometric, constitutive, and seepage equations.

Balance equation:

$$\frac{\partial \sigma_{ij}}{\partial x_{ij}} + \rho X_j = 0 (i, j = 1, 2, 3) \quad (1)$$

where: ρ is the density, kg/m³; σ_{ij} is the total stress, and Pa

Geometrical equation:

$$\varepsilon_{ij} = \frac{1}{2} (\mu_{i,j} + \mu_{j,i}), \quad \varepsilon_{\pi} = \varepsilon_{11} + \varepsilon_{22} + \varepsilon_{33} \quad (2)$$

Constitutive equation:

$$\sigma_{ij} = \sigma_{ij} - Ep \delta_{ij} = Y \delta_{ij} \varepsilon_v + 2T \varepsilon_{ij} \quad (3)$$

$$\Delta t = \frac{p}{Q} - E \varepsilon_v = \frac{p}{H} - \frac{\sigma_{ii}}{3H} \quad (4)$$

where: σ_{ij} is the effective stress, Pa; ε_{ij} is the total strain; δ_{ij} is the Kronecker constant; p is the pore water pressure, Pa; $R(Q, E)$ is the Biot constant; E is the pore water pressure coefficient; T is the shear modulus, Pa; Y is the Lamé coefficient.

Flow equation:

$$k_{ij} \nabla^2 p = \frac{1}{Q} \frac{\partial p}{\partial t} - E \frac{\partial \varepsilon_v}{\partial t} \quad (5)$$

where: k_{ij} is the permeability coefficient, m/d; and the relationship among H , Q , R , H and E is:

$$E = \frac{E'}{K} \quad (6)$$

$$\frac{1}{R} = \frac{1}{Q} + \frac{E}{H} \quad (7)$$

where: K' is bulk modulus, Pa

2 Mechanical analysis of water storage space stability under the influence of fault

2.1 Engineering Background

Based on the hydrogeological conditions of a working face in a mining area, the mechanism of the fault water storage space was studied. The thickness of the coal seam in the recoverable range was 0.60 ~ 2.60 m, with an average thickness of 1.89 m. Mining mainly occurred through the exposed F1 and F2 faults. The main mechanical parameters of the fault and coal seam roof and floor are listed in Table 1 (Flesch et al. 2018; Peng et al. 2025, Zhao et al. 2025).

Table 1 Main rock mechanics parameters of coal seam roof and floor

rock formation	bulk modulus /GPa	shear modulus /GPa	force of cohesion /MPa	tensile strength /MPa	angle of internal friction/°	Density kg/m ³
fault	0.73	0.32	4.10	6.50	34	2400
sandstone	8.34	4.52	6.0	6.40	34	2700
siltstone	6.57	6.93	4.30	5.43	34	2265
fine sandstone	4.65	1.95	4.06	4.14	34	2720
medium grained sandstone	7.94	4.12	4.37	5.56	32	2700
fine sandstone	4.65	1.95	4.06	4.14	34	2720
sandy mudstone	7.53	4.37	6.17	3.20	37	2730
coal	3.29	2.17	2.50	1.10	24	1500
sandstone	8.34	4.52	6.0	6.40	34	2700
impermeable layer	8.34	4.52	6.0	6.40	34	2700
fine sandstone	4.65	1.95	4.06	4.14	34	2720

2.2 Numerical Model And Boundary Conditions

Considering the actual requirements of the calculation, the size of the model was determined to be 600 m long, 400 m wide, and 300 m high. Horizontal displacement constraints were imposed on the front, rear, left, and right sides of the model, and vertical displacement constraints were imposed on the bottom boundary. 17.5 MPa uniform load is applied to the top of the model to equate the stress of the unmodeled overlying strata. A water pressure of 9 MPa was set in the aquifer to simulate the effect of water pressure of the Ordovician limestone aquifer on the model. Through FLAC3D built-in modeling, a three-dimensional contour model of an oblique fault was generated, and the meshing work was completed. The model diagram is shown in Figure 1.

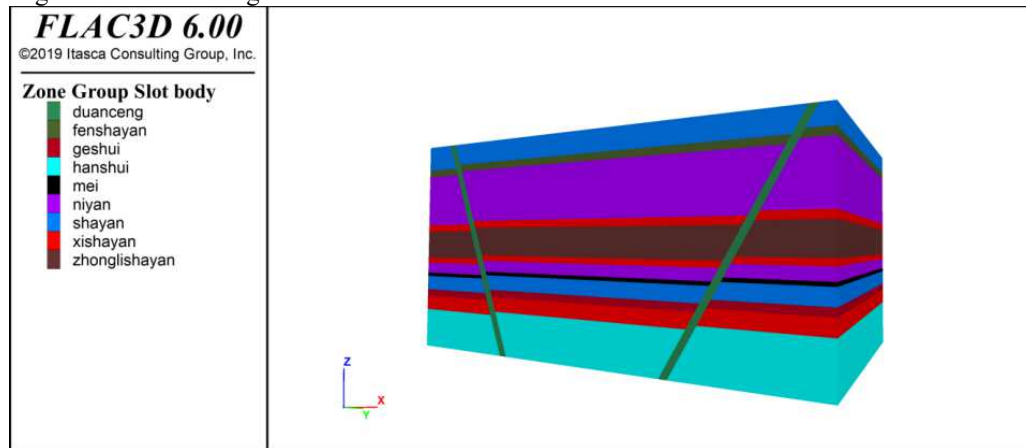


Figure.1 Numerical model diagram

3 Analysis Of Numerical Results

3.1 The Stress Change In The Process Of Roadway Excavation

In the setting of the model coordinate system, the advancing direction of the working face is selected as the Y axis, and the two working faces of the model are called working faces A and B, respectively. The left working face is the working face, and the right working face is the B working face. First, three roadways with dimensions of 5 m × 5 m (width × height) were dug in the coal seam, as shown in Figure 2. The roadway was pushed along the positive direction of the Y-axis, 80 m each time, five times in total.

During roadway excavation, the fault has a significant barrier effect on the vertical stress in front of the working face, and the stress release accumulated when the fault is excavated increases the risk of excavation construction. The vertical stress of the excavation face obtained from the simulation is shown in Figure 3. During roadway advancement, the original stress balance is broken, resulting in a stress redistribution. When the roadway was advanced to 80 m, the stress on the rock surrounding the roadway was released. As a weak surface, the fault zone hinders the transmission of stress, and a stress barrier appears at the fault plane. This phenomenon is more evident when the roadway is advanced to 160 m. When the roadway was advanced to 240 m, the heading face intersected the fault plane. Owing to the barrier effect of the fault zone, stress cannot be transmitted along the fault to the footwall rock mass, and the stress change of the floor is relatively low. When mining reaches 320 m, the roadway is excavated to the fault, the strength of the surrounding rock drops sharply, and the original high stress is quickly released.

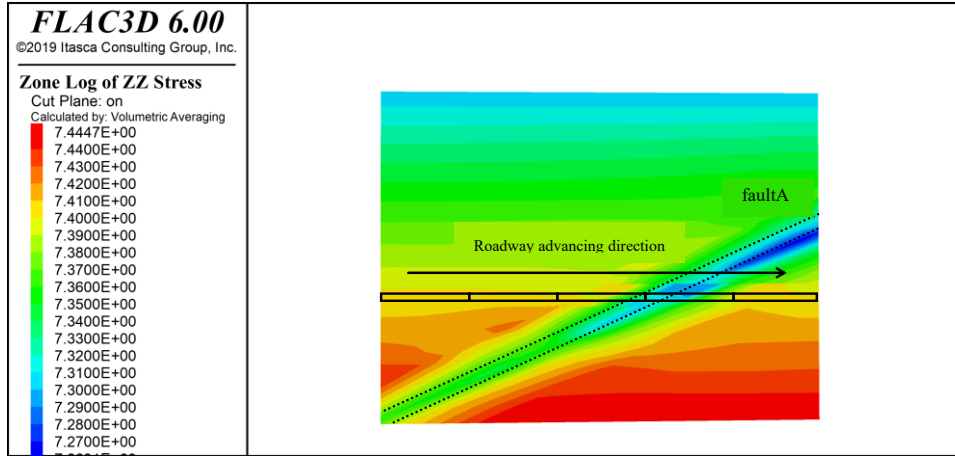


Figure.2 Variation characteristics of roadway advancing direction

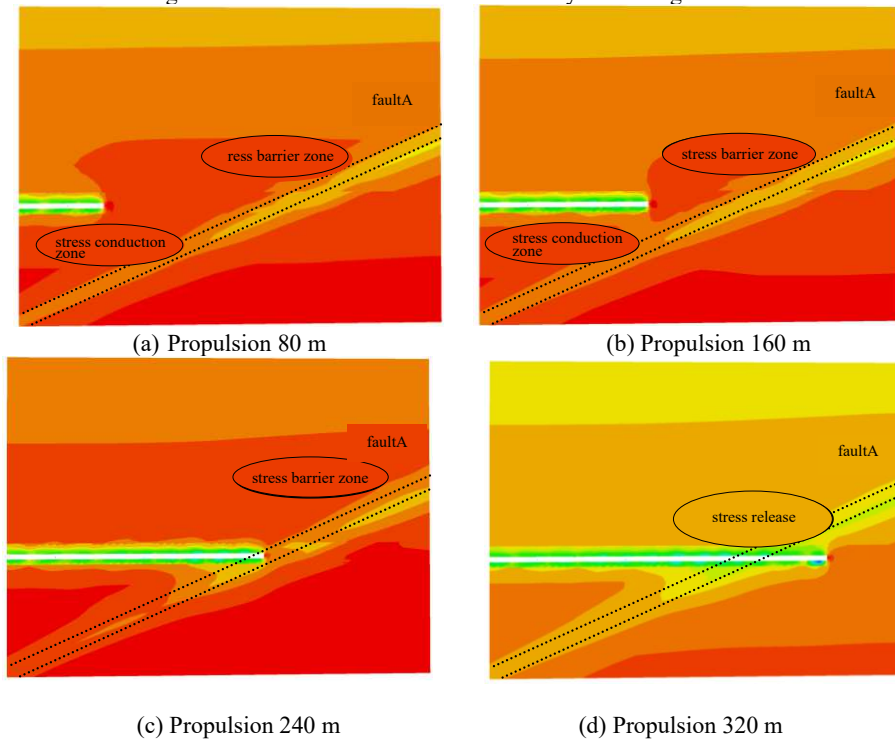


Figure.3 Variation characteristics of vertical stress of advancing strata in left roadway

3.2 Analysis Of Advancing Stress Evolution Of Left Working Face A

(1) Stress evolution analysis

Working face A advances along the Y direction, advancing 40 m each time and advancing five times, as shown in Figure 4. As working face A continues to advance along the Y-direction, the stress of the surrounding rock changes continuously. In the initial stage of advancement, the vertical stress did not change significantly because the working face was far from the monitoring surface, and the stress concentration factor was 1.59, as shown in Figure 5 (a). When it is pushed to 120 m, coal seam mining at the cross-section is completed. At this time, the stress distribution state exhibited an arch structure, and the stress concentration factor was 2.4, as shown in Figure 5 (b). When advancing to 200 m, the arch expanded further, and the stress concentration factor increased to 3.6, as shown in Figure 5 (c). The existence of a fault structure has an important influence on the propagation and distribution of stress in the advancing process of working face A. As a weak structural plane in a rock mass, the mechanical properties of the faults are significantly different from those of the surrounding intact rock mass. The stress was concentrated near the fault, and this stress concentration effect was more evident when the working face was mined to the fault. Because the displacement and deformation of the rock mass on both sides of the fault are not coordinated, the stress value near the fault sharply increases.

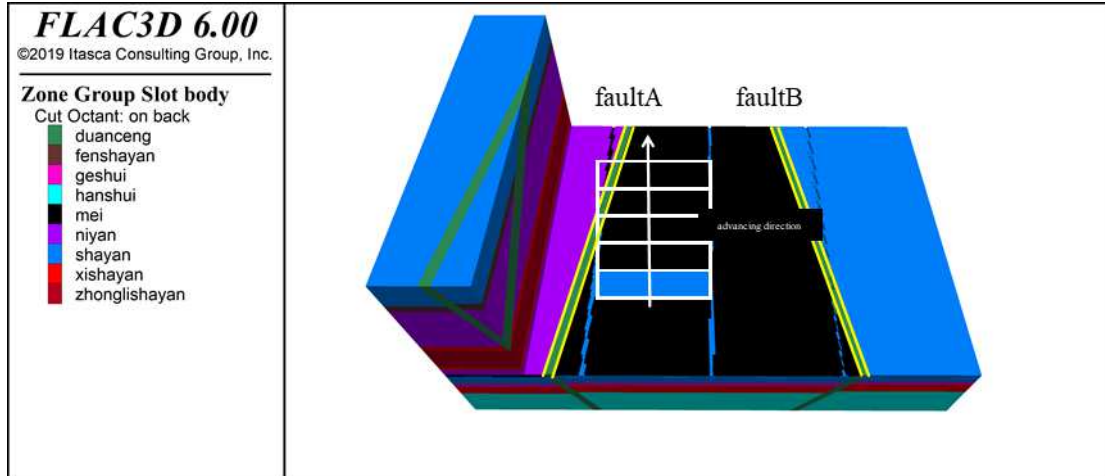


Figure.4 A working face advancing process

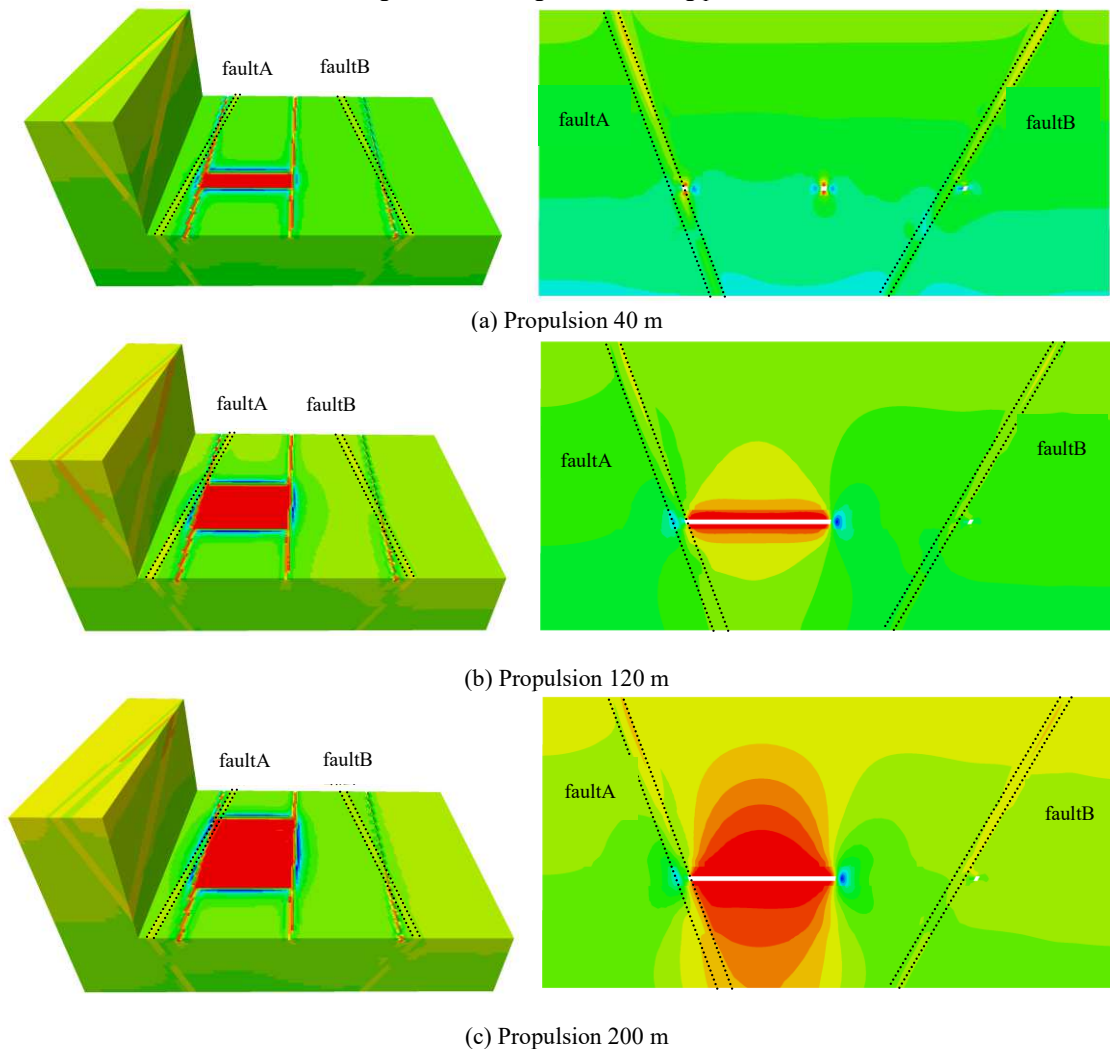


Figure.5 Variation characteristics of vertical stress of advancing strata in left roadway

During the mining process of a working face, the development of the plastic zone shows an obvious stage and expansibility. When the thrust was 40 m, the maximum plastic zone depth of the vertical surface of the floor was 2 m, and the plastic zone was mainly concentrated in the small range of the fault and the bottom of the mining area, as shown in Figure 6 (a). When advancing to 120 m, the depth of the maximum plastic zone in the vertical plane of the bottom plate increased to 9 m, and the range of the plastic zone expanded significantly, as shown in Figure 6 (b). When advancing 200 m, the development area of the plastic zone of the roof and floor of the coal seam increased significantly, and the plastic zone of the floor fault area expanded further, as shown in Figure 6 (c).

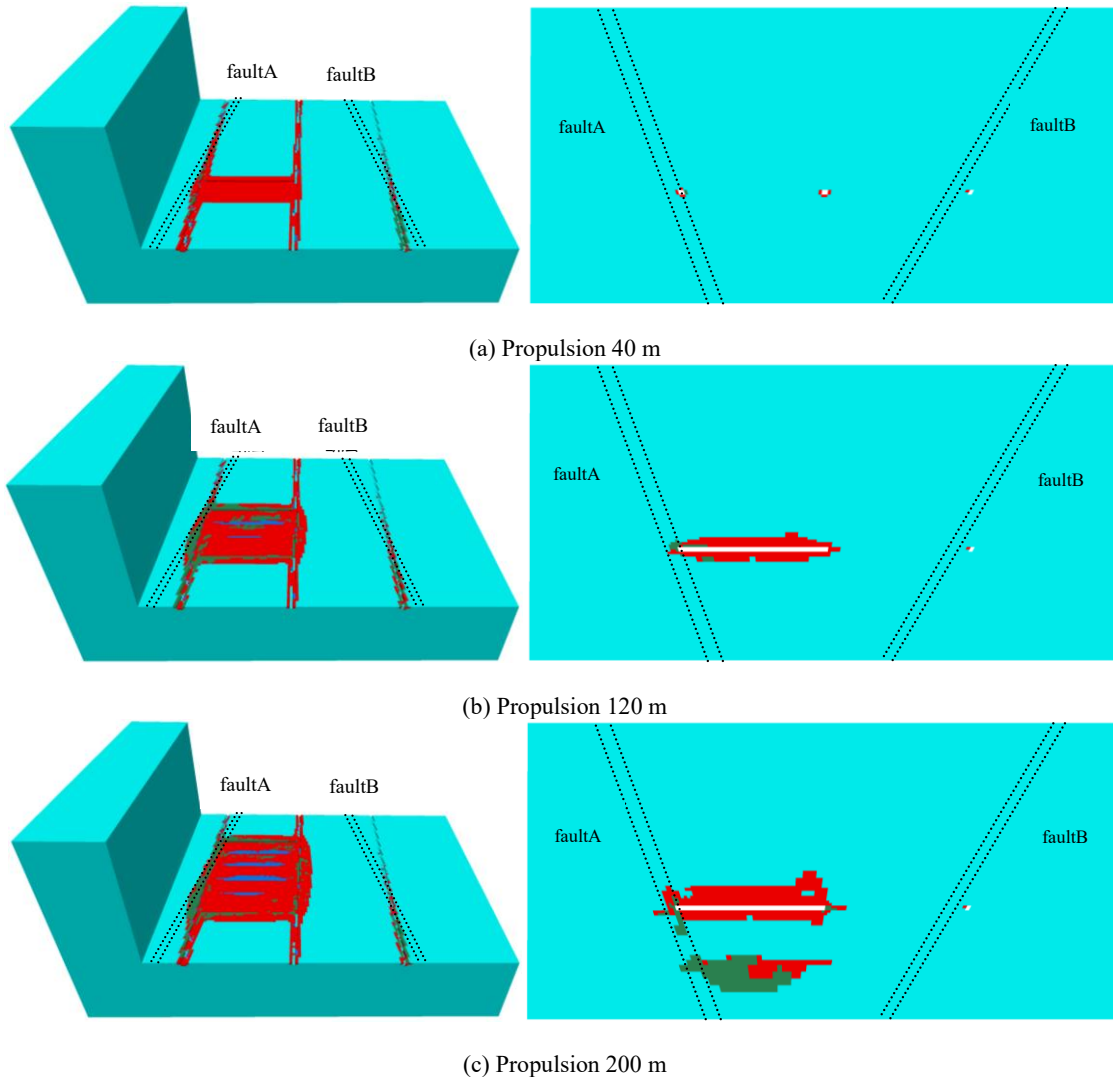
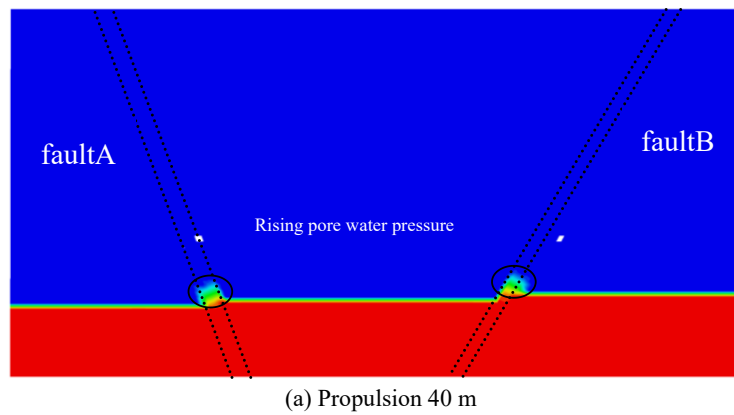


Figure 6 A working face mining plastic zone

(2) Evolution analysis of pore water pressure

Figure 7 shows the evolution process of the pore water pressure with the advancing distance. When the advancing distance was 40 m, the pore water pressure began to rise near faults A and B. Owing to the short advancing distance, the disturbance range of mining activities on the formation is limited, and the initial change in pore water pressure occurs only in a small area near the fault.



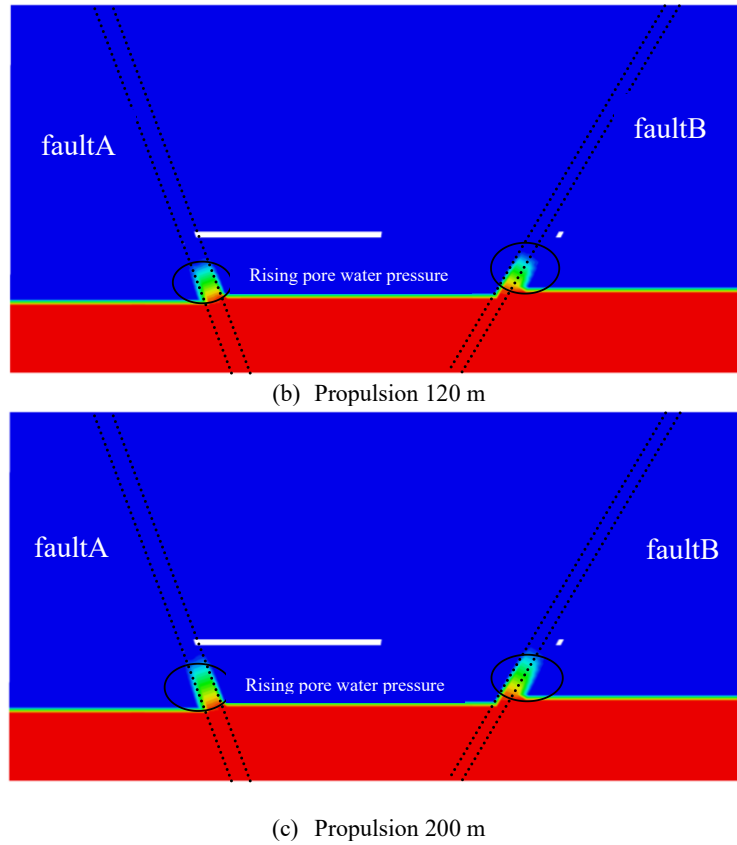


Figure.7 A working face mining pore water pressure diagram

With the increase of the advancing distance to 120 m, the area where the pore water pressure rises at the fault is obviously expanded, and the pore water conductivity rise trend is more significant. At this time, due to the influence of mining, the disturbance of the stratum is further intensified, and the stress of the fault and surrounding rock is released and adjusted, so that the pore water pressure rises in a larger range. There is an accelerated nonlinear change between the height of the guide lift and the influence of mining. With the increase of the advancing distance, the rate of increase of the pore water pressure is gradually accelerated, and the expansion speed of the rising area is also accelerated, which reflects that the influence of the mining disturbance on the pore water pressure shows an increasing nonlinear effect. The curve of the relationship between the mining distance and the height of the guide lift is shown in Figure 8.

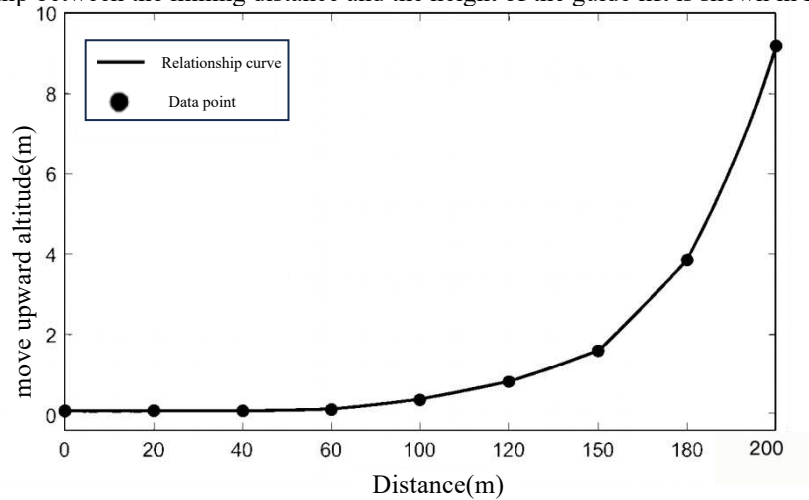


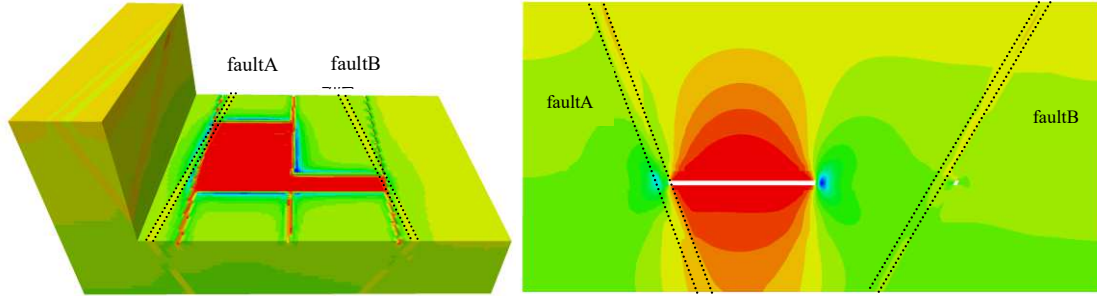
Figure.8 The relationship curve between mining distance and lifting height

3.3 Analysis Of Superposition Effect Of Working Face B Advancing

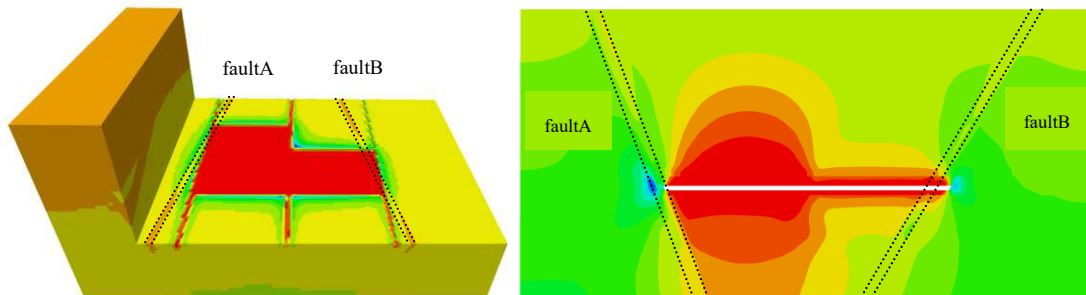
(1) Analysis of the stress superposition evolution

After mining working face A, mining work of working face B was carried out, and the advancing parameters were consistent with those of working face A on the left side. The same advance was 40 m each time and 5 times were advanced.

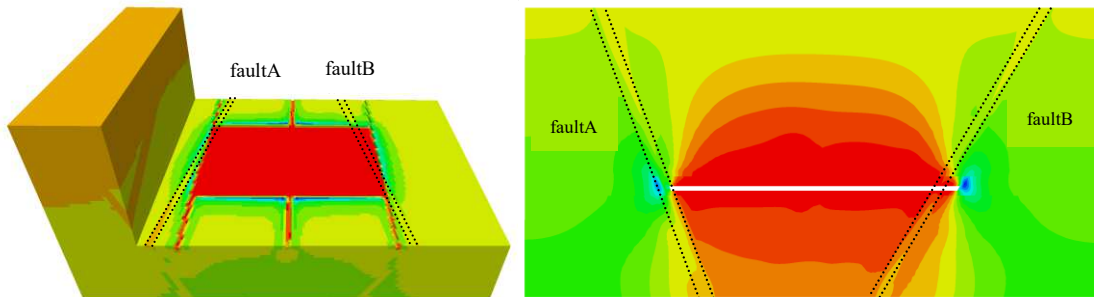
When working face B was advanced to 40 m, the stress concentration area was mainly distributed near the excavated coal seam on the left side, and the stress concentration factor was 3.5, as shown in Figure 9 (a).When advancing to 120 m, more than half of the right coal seam was mined, the stress concentration range expanded to the footwall of the fault, and the stress concentration factor decreased to 2.7, as shown in Figure 9 (b). When advancing to 200 m, the stress concentration factor increases to 3.4, as shown in Figure 9 (c).



(a) Propulsion 40 m



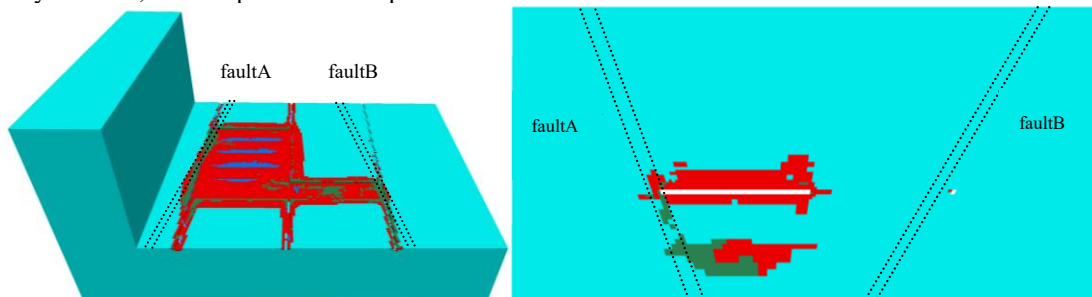
(b) Propulsion 120 m



(c) Propulsion 200 m

Figure.9 B working face advancing strata vertical stress variation characteristics

The plastic zone induced by mining in working face B shows the characteristics of ' progressive expansion-local penetration ', as shown in Figure 10. The maximum plastic zone of the bottom plate was further expanded under the influence of the completion of working surface A. When advancing to 120 m, the plastic zone extended in the fault direction. The plastic failure range of surrounding rock in water storage space is expanded. When advancing to 200 m, the plastic zone of the roof and floor of the coal seam is connected, forming a continuous failure zone along the fault plane. The surrounding rock failure zone of the water storage space is interconnected with the plastic zone, and the stability is significantly deteriorated. Under the influence of a working face, the damage range of working face B is larger than that of a single working face. Simultaneously, owing to the existence of a fault zone, the strength of the surrounding rock is significantly reduced, and the plastic failure process is accelerated.



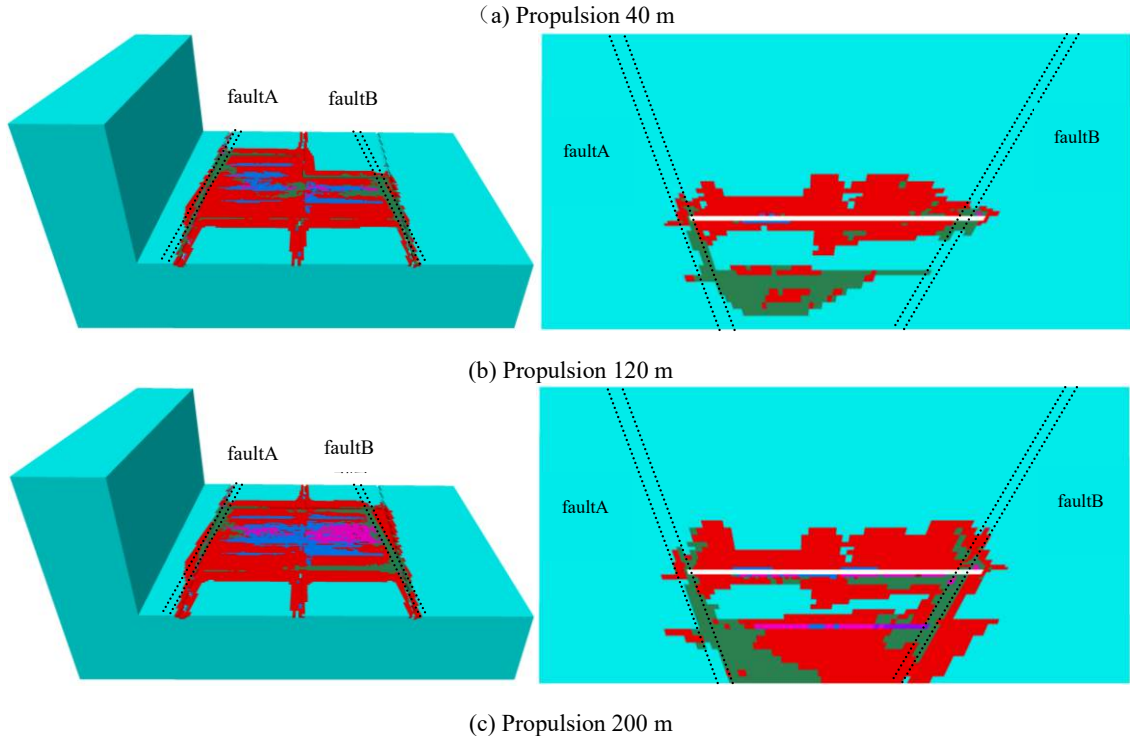
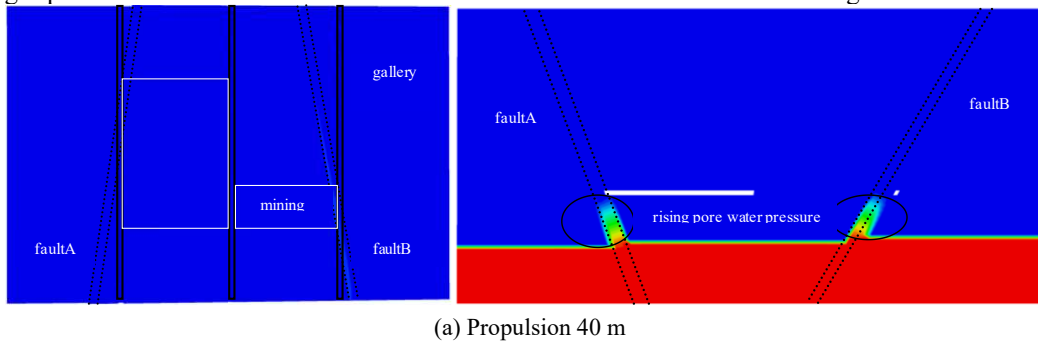


Figure 10 B working face mining plastic zone

After the mining of working face A is completed, the mining of working face B leads to a sudden increase in the pore water pressure, as shown in Figure 11. When advancing 40 m, the height of pore water conduction does not change significantly compared with that of a working face, and the stability of the surrounding rock in the new water storage space. When the mining reaches 120 m, owing to the further expansion of the plastic zone, a water channel is formed, the pore water lift height rises rapidly, the pore water rises rapidly along the height of the fault, and the water flow increases along the fault to the water storage space, but the stability of the surrounding rock in the water storage space decreases. When mining reached 200 m, the pore water pressure in the roof increased. At this time, the confined water led to the bottom of the coal seam, and further led to the roof of the coal seam along the fault, and the water inflow at the bottom increased abruptly.

According to the comparison, when the double working face is mined, compared with the single working face, the pore water pressure exhibits a more obvious change trend with an increase in the advancing distance. Under the influence of double working face mining, the degree of disturbance of the strata is significantly enhanced, which intensifies the change in pore water pressure. The rate and range of pressure rise show more obvious accelerated nonlinear characteristics, which greatly increase the risk of surrounding rock instability in the water storage space. To ensure the safety of mining operations, support measures must be further strengthened. The evolution process of the plastic zone of the fault zone was controlled, and the uplift of the pore water was strictly controlled to reduce the risk of surrounding rock instability in the water storage space and to create a safe and stable construction environment for the mining of the double working face.



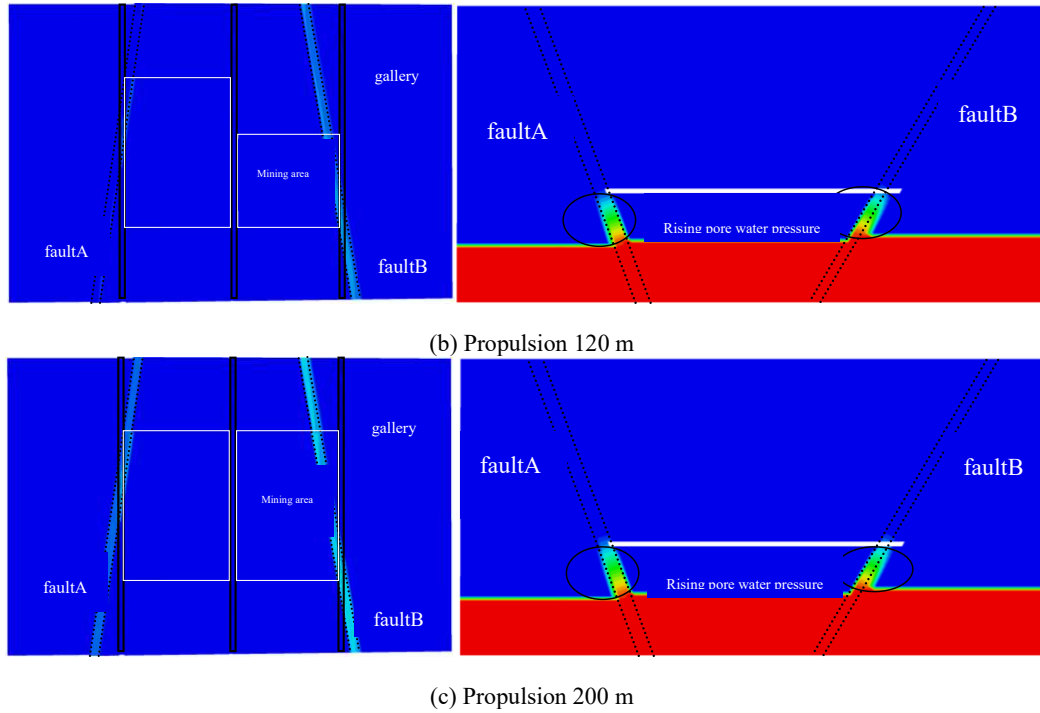


Figure.11 B working face mining pore water pressure diagram

4 Analysis Of The Influence Of Fault Zone Support Structure Under The Influence Of Mining

In the process of roadway excavation, anchor bolts and anchor cables were set up to simulate the control effect of the supporting structure on fault activation. The anchor rod is 2.4 m long, the row spacing between the anchor rods is $1\text{ m} \times 1\text{ m}$, the length of the anchor cable is 6.2 m, the spacing of the anchor cables is 2 m, and the preload is set to 152 kN, as shown in Figure 12. The parameters of the anchor bolt and cable are listed in Table 2.

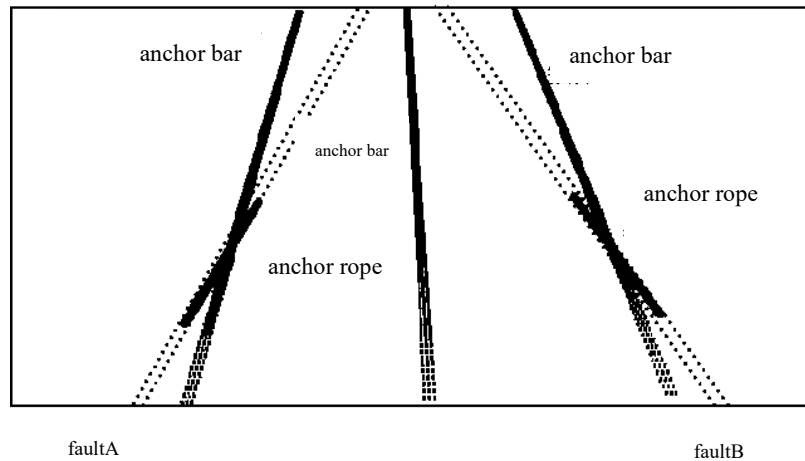
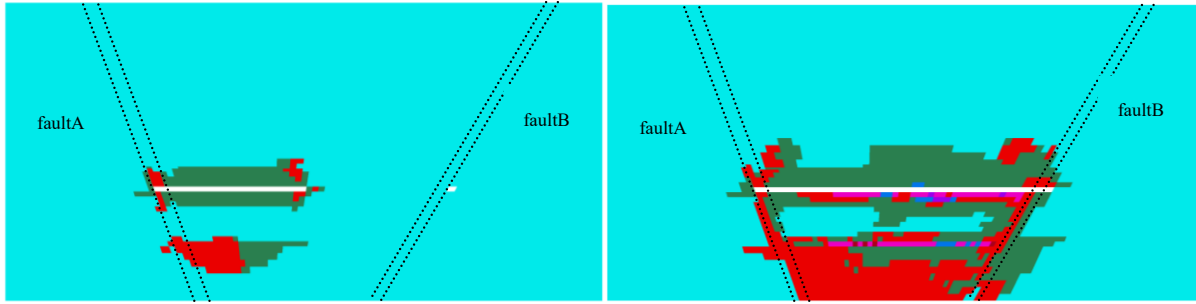


Figure.12 Arrangement diagram of anchor bolt and anchor cable

The numerical simulation shows that the grouting anchor cable support significantly inhibits the expansion of the plastic zone of the surrounding rock under the mining stress field through a triple mechanism of interface bonding enhancement, prestressed active bearing and stiffness synergistic deformation. Under the condition of no support, when the working face advances to 200 m, the depth of plastic zone is 9 m, and the fault zone presents continuous shear failure. The volume of plastic zone of surrounding rock in water storage space increases further, and the stability of surrounding rock decreases. After the support, the plastic zone was reduced by 55.6 %, and the maximum depth of the vertical surface of the bottom plate was controlled at 3 m ~ 5 m. The strength of the surrounding rock and fault is strengthened by the grouting body, and the shear strength of the interface is increased by 30 % ~ 50 %. The plastic zone of the mining after bolt support is shown in Figure 13.



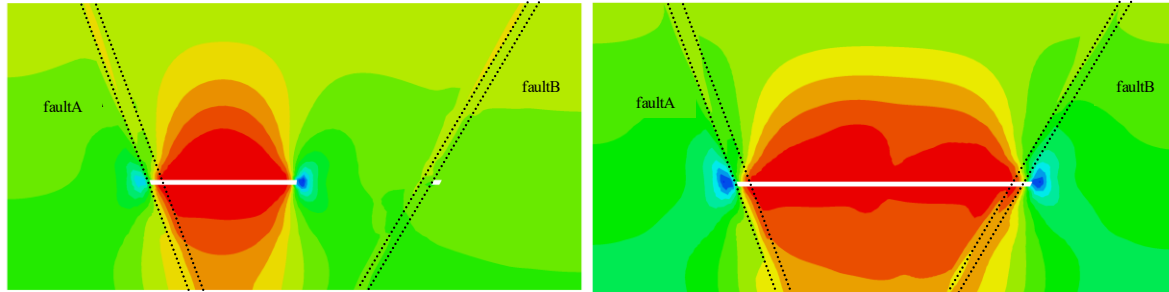
(a) The left coal seam propulsion is completed (b) The right coal seam propulsion is completed

Figure.13 Mining plastic zone after bolt support

The numerical simulation results of the stress distribution of the surrounding rock under the grouting anchor cable support in the mining stress field show that the stress concentration coefficient is 3.6 when the support measures are not taken. After grouting the anchor cable support, the stress concentration factor of the left working face A decreases to 2.7 from 80 MPa to 60 MPa after mining. The stress concentration factor decreases from 3.4 to 2.5 after full mining, and the stress value decreases from 75 MPa to 55 MPa. The vertical stress diagram after the bolt support is shown in Figure 14. The stress concentration factor of the rock mass around the water storage space is reduced, and the stability of the surrounding rock is enhanced.

Table 2 Parameter table of bolt and anchor cable

name	elastic modulus/Gpa	compressive strength/MPa	tensile strength /MPa	cross-section area /mm ²
anchor bar	2.05	15.34	1.00	/
anchor rope	2.05	15.34	1.00	1384



(a) The left coal seam propulsion is completed (b) The right coal seam propulsion is completed

Figure.14 Vertical stress diagram after bolt support

The vertical displacement, vertical stress and water pressure of the roof under different conditions were monitored by setting the roof displacement monitoring line. A horizontal distance of 140 m ~ 145 m is the fault. The horizontal monitoring line of the coal seam roof is shown in Figure 15. It can be observed that with the completion of working face A, the vertical stress increases obviously as a whole, and the stress at the fault zone rises sharply to form a stress concentration area. The stress at the remaining positions decreased, and the vertical stresses before and after the bolt support are shown in Figure 16. A comparison of the vertical displacement after the bolt support is shown in Figure 17. Because the anchor cable shares part of the stress, the stress in the stress concentration area and displacement of the roof are reduced accordingly. At the same time, because of the action of the grouting anchor cable and bolt, the lateral stress is increased, the strength of the rock surrounding the fault is enhanced, and the permeability of the fault is reduced, thus reducing the possibility of water conduction through the plastic zone near the working face and the plastic zone of the rock surrounding the fault. The pore water pressure at the monitoring line is significantly reduced. The water pressures before and after bolt support are shown in Figure 18.

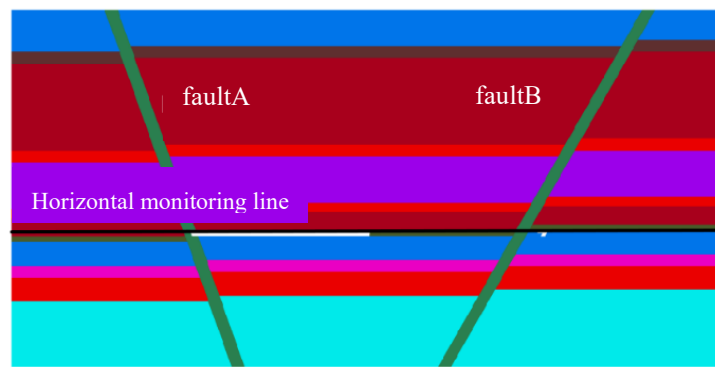


Figure 15 Vertical displacement diagram after bolt support

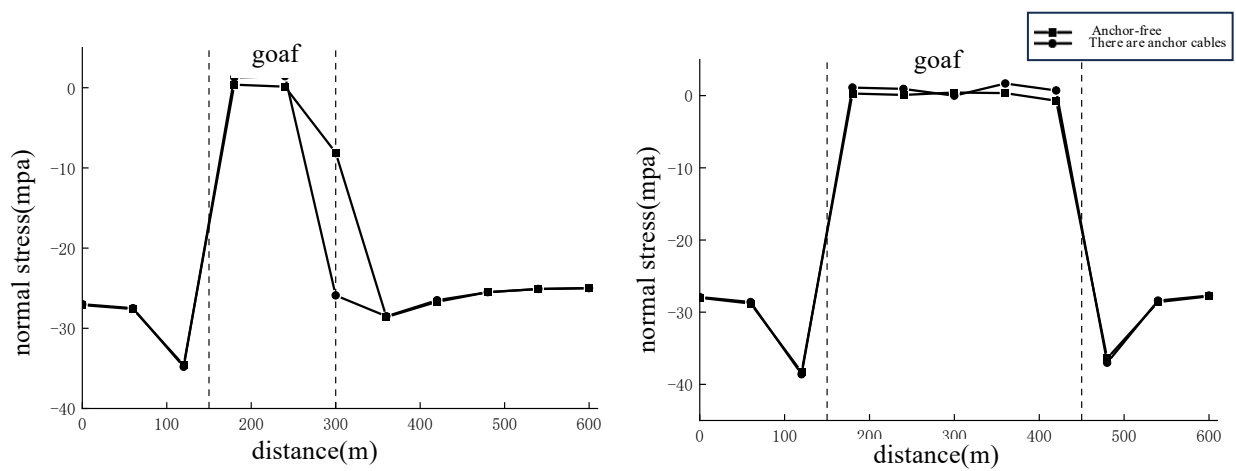
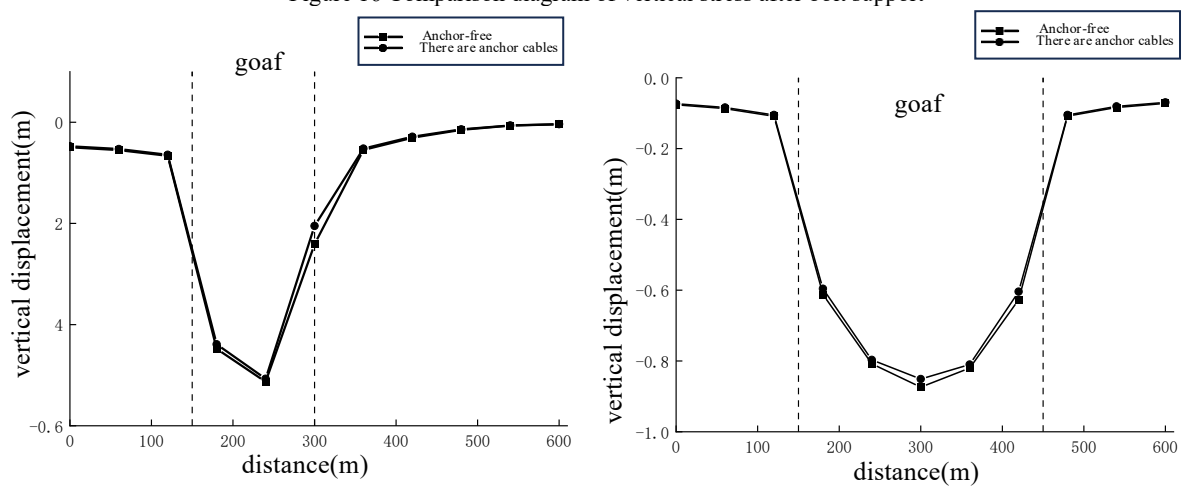


Figure 16 Comparison diagram of vertical stress after bolt support



(a) A working face advancement is completed

(b) B working face advancement is completed

Figure 17 Comparison of vertical displacement before and after bolt support

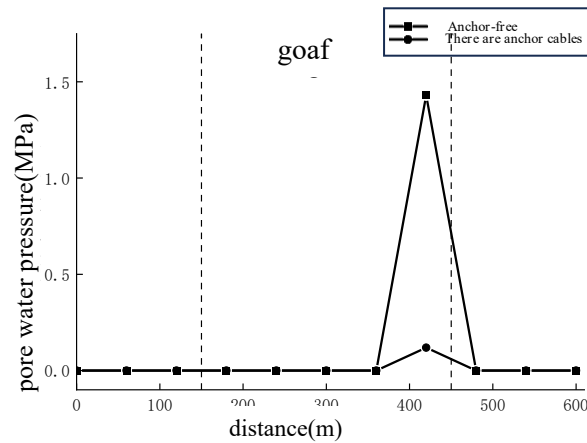


Figure 18 Comparison diagram of water pressure before and after bolting support

By arranging the survey line on the roof in the horizontal direction of the fault, the vertical stress and vertical displacement before and after the support were monitored during the propulsion process, and the support effect of the anchor cable on the fault and surrounding rock under the influence of mining is analyzed. The position of the monitoring line was shown in Figure 19.

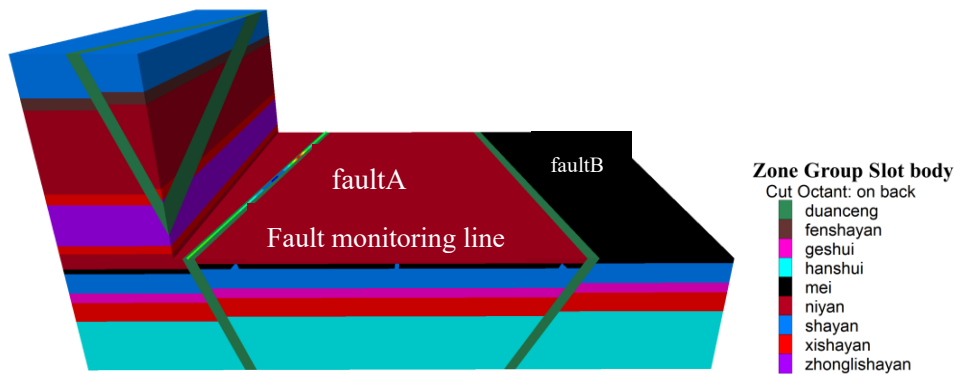
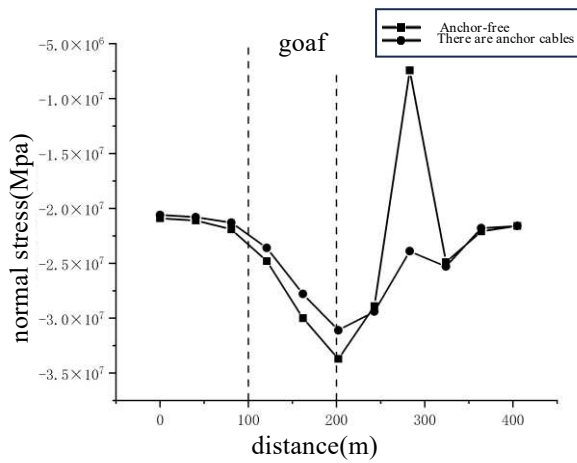
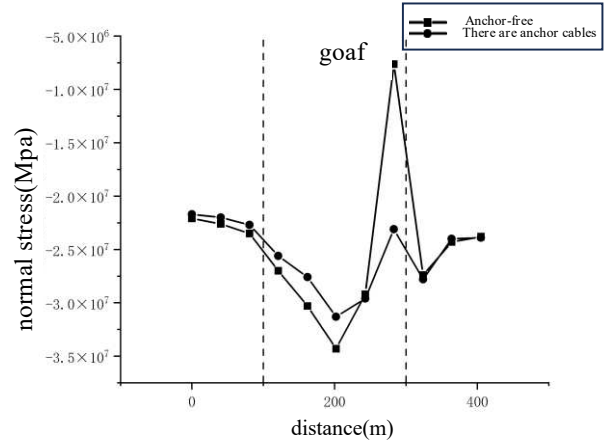


Figure.19 Vertical displacement diagram after bolt support

The vertical displacement and stress after bolting are shown in Figure 20 and 21, respectively. As the working face continues to advance, the vertical stress and vertical displacement increase, and are mainly concentrated on both sides of the goaf. Owing to the existence of the faults, the vertical displacement was significantly higher than that of the intact surrounding rock. Because the weak structure of the fault is more likely to produce plastic failure, the lateral stress is reduced, and the formation of the water channel is induced. Owing to the action of the grouting anchor cable, the lateral stress is increased, the strength and lateral stress of the surrounding rock are enhanced, and the degree of stress concentration of the surrounding rock is reduced, which limits the development of the plastic zone and water channel. The pore water pressure is reduced from 1.8 MPa to 1.5 MPa, which has a good effect on controlling seepage instability in underground reservoir water storage space. The pore water pressure at the monitoring line after the bolt support is shown in Figure 22. The results show that support structures such as bolts and anchor cables can effectively control seepage instability in underground reservoir water storage spaces by controlling fault activation and fault stress transfer.

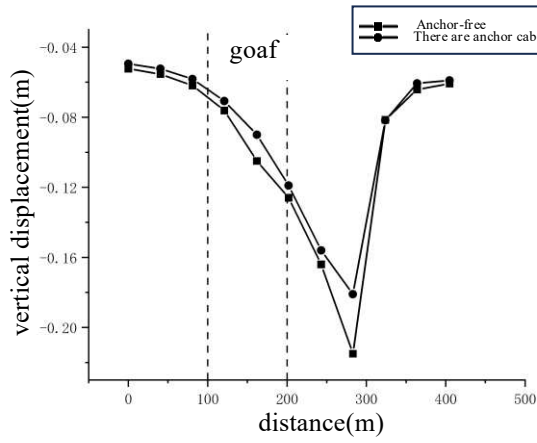


(a) A working face advancement is completed

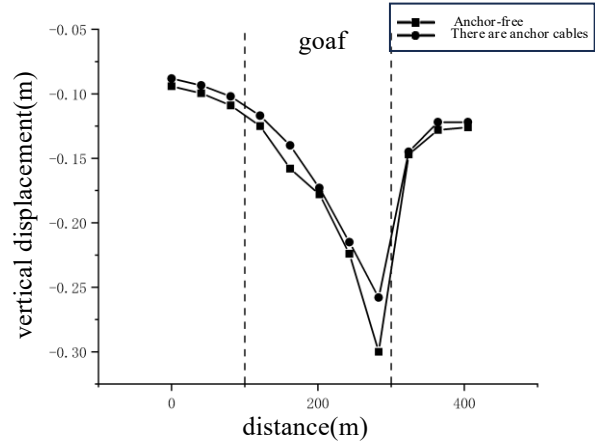


(b) B working face advancement is completed

Figure.20 Comparison diagram of vertical stress after bolt support



(a) A working face advancement is completed



(b) B working face advancement is completed

Figure.21 Comparison of vertical displacement before and after bolt support

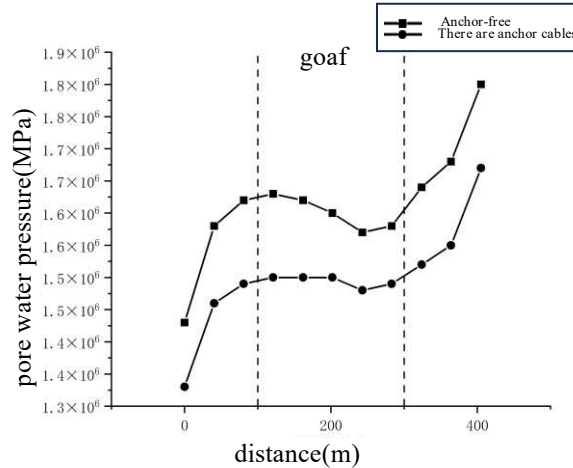


Figure.22 Comparison diagram of water pressure before and after bolting support

5 Conclusion

Through the stress state of the surrounding rock, the expansion range of the plastic zone, and the change in vertical displacement, the transformation characteristics of rock mass from shear slip-crack expansion sudden failure to progressive controllable deformation were analyzed, and the synergistic deformation mechanism of the grouting anchor cable and surrounding rock of the underground reservoir water storage space was obtained. The main conclusions are as follows :

(1) In this study, a FLAC3D numerical model of the dynamic coupling of ' stress-pore water pressure-water storage space ' under the influence of faults was constructed to simulate the stress changes in the process of roadway passing through faults and working face mining. The evolution and stability characteristics of the underground reservoir water storage space, and the stage characteristics of the ' initial inoculation-rapid expansion-stable development ' of fault activation were analyzed. By simulating the collaborative mining process of adjacent multi-working faces, the dynamic evolution law and stability control mechanism of underground reservoir water storage space in a goaf under the influence of faults are clarified, which provides theoretical support for site selection, optimization design and safe operation of underground reservoir water storage space.

(2) The relationship between the support parameters and mechanical properties of the rock mass was studied by introducing support parameters, such as grouting bolts. By analyzing the influence of stress, plastic zone, and displacement of the surrounding rock, the synergistic deformation mechanism of the grouting bolt and rock mass was obtained, and the influence of the stress transfer difference between the hanging wall and footwall of the fault on the water storage space of the underground reservoir under mining action was verified.

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7 Author contributions statement

Min Li: Funding acquisition, Methodology, Data management, Conceptualization, Manuscript review and editing, Form analysis.

Yi Yang: Formal analysis, Funding acquisition, Conceptualization.

Shoubiao Li: Conceptualization.

Jinhai Zhao: Form analysis, Data verification, Document revision.

Huiwen Sun: Experimental design, Data curation.

Hailong Ma: Form analysis, Document revision.

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9 Conflict of interest statement

All authors declare that there are no relevant financial or non-financial competing interests that could have influenced the work reported in this paper.

10 Data availability

The datasets generated or analysed during the current study are available from the corresponding author upon reasonable request.

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