Research Article

Effect of Crack Propagation on Mining-Induced Delayer Water Inrush Hazard of Hidden Fault

Yanhui Du ^{1,2} **Weitao Liu** ^{1,2} **Xiangxi Meng** ^{1,2} **Lifu Pang**¹ and **Mengke Han**²

¹State Key Laboratory of Mine Disaster Prevention and Control, Shandong University of Science and Technology, Qingdao 266590, China

²College of Safety and Environmental Engineering, Shandong University of Science and Technology, Qingdao 266590, China

Correspondence should be addressed to Weitao Liu; wliu@sdust.edu.cn and Xiangxi Meng; skdmxx1990@sdust.edu.cn

Received 28 April 2021; Revised 29 June 2021; Accepted 15 July 2021; Published 11 August 2021

Academic Editor: Hamed Lamei Ramandi

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Hidden faults in deep coal seam floor threaten the exploitation of coal resources. Under the influence of mining and water confined in the floor, the cemented filler in the hidden fault will be eroded by water flow, in order to investigate the fracture characteristics and water inrush risk of hidden faults in floors above confined aquifer. Using the 27305 working face as geological background, the influence of the seepage scouring filler on the mechanism of water inrush from hidden faults was assessed by developing a stress-seepage coupling model and employing the finite difference method to simulate the seepage process of hidden faults under the combined action of high ground stress and high confined water. The evolution of seepage, shear stress, and plastic zone was also assessed. The influence of the hydraulic pressure of the aquifer and the thickness of a waterproof rock floor on the formation of the water inrush pathway was analyzed. Results indicate that (1) under the influence of mining, the hidden fault experienced the change process of stress stability, stress concentration, and stress release. The shear stress increases first and then decreases. The compressive stress decreases gradually due to stress release. (2) Water inrush disaster will not occur immediately when the working face is above the hidden fault. The delayed water inrush occurs in the mined-out area when the working face advances to 160 m, the floor failure zone is connected with the hidden fault failure zone, and the delayed water inrush channel is formed. (3) With the mining advances, the water pressure of aquifer is the same. The larger-angle fault leads to the thinner thickness of floor aquifer. The greater the influence of hidden fault on coal seam mining, the higher the danger of water inrush.

1. Introduction

Water inrush in coal mine is one of the major disasters in mine safety production [1]. With the increasing year by year of mining depth and coal output in China, more and more coal reserves are threatened by water inrush, and many mines have entered the stage of deep mining [2]. During the mining process will inevitable be affected by the complex mechanical environment of high crustal stress, high geotemperature, high confined water, and strong mining disturbance, resulting in a series of disasters accidents [3–5]. According to the statistics of relevant departments in China, water disasters are second only to gas explosions in grave accidents in coal mines [6]. About 3% of coal mine safety accidents from 2005 to 2019 were caused by water inrush [7] (see Figure 1). Com-

pared with other types of accidents, water disasters have caused in a number of deaths and huge economic losses [8, 9]. It is more and more important to effectively prevent and control these disasters [10].

Water inrush from mine floor is a phenomenon of local instability in the mining process, especially the water inrush from fault structure is the most serious [11, 12]. Under the influence of mining activities, the hydrogeology condition of coal floor changes and the impermeable layer is destroyed, which causes the confined water under the floor to flow into the working face through faults and tectonic fissure, causing water inrush from the coal floor to cause safety problems [13–15]. In addition, water inrush disasters also lead to environmental damage, such as surface collapse and groundwater contamination [16, 17]. For a long time, the water inrush

FIGURE 1: Water disaster accidents from 2005 to 2019.

from hidden fault has been one of the important topics in rock and hydraulic mechanics studies [18–20].

In recent years, many researchers have conducted a large number studies on the water inrush mechanism of the hidden fault in the floor from different research directions. At present, a number of mechanism for the formation of water inrush, including floor relative water resisting layer thickness, Hoek-Brown improvement [21], lower three zone theory [22], in situ tensile fracture and failure at zero position [23], key stratum theory [24], nonlinear catastrophic model [25], critical water outburst coefficient [26], and other water inrush criteria and theory, have been studied. These achievements have played a positive guiding role in preventing water inrush from the coal floor. However, there are still obviously insufficient in the study mechanism of fault-induced water inrush. For some water inrush accidents induced by hidden fault, it is obviously no longer applicable to use the previous theory for prediction and analysis. In the study of delayed water inrush from hidden fault in floor, the occurrence of floor water invasion can be days, weeks, or longer [27]. This is closely related to the fault structure, the fracture development, and the confined water. Therefore, it is very important to study the water inrush law of hidden fault from the interaction of stress field and seepage field, and it will be more consistent with reality [28, 29].

Numerical simulation and laboratory test are important means to predict the risk of fault water inrush and formulate corresponding prevention measures. Shi and Yang [30] analyzed the evolution of particle migration and seepage properties of the water inrush through broken rock mass by a numerical case. Guo et al. [31] used the Comsol Multiphysics software to study the fault water inrush and current flow

mechanism under the effect of stress and water pressure. Based on the theory of fluid-structure coupling mechanics and multitechnical means, the formation characteristics of water inrush channel damaged by mining rock strata, the precursor information of microseismic activity of water inrush rock strata, and the numerical simulation results of parallel seepage coupling are comprehensively inversed [32, 33]. Zhang et al. [34] used the FLAC^{3D} fluid-solid coupling model and variable parameter rheological model, the influencing factors and mechanism of delayed ground-water inrush induced by hidden fault coal seam are studied, and the influencing factors of permeability of hidden fault are analyzed.

Many researchers at home and abroad have made a body of researches and have gained great achievements on mechanism of the water inrush from coal floor comprehension studies [35–37]. There are few studies on mechanics model of water inrush from mining fault and risk criterion of water inrush from fault activation in coal floor. In this paper, a damage evolution mechanics model of coal seam floor with hidden fault in confined water is established. This paper conducts FLAC^{3D} to simulate the temporal and spatial distribution characteristics of the hidden fault activation, and the change of confined water is obtained. Analyze the process of the delayed evolution of the hidden fault floor in the confined water from new perspective.

2. Stress-Seepage Coupling Model

2.1. Equilibrium Equation of Saturated Porous Media. The equilibrium equation of saturated porous media is suitable for the parameters derived from the macro scale of the mass

and momentum conservation equation of the hidden fault. The hidden fault can be regarded as kind of “porous media,” and is finely meshed by the finite element method. The basic equilibrium equations for rock strata and hidden faults are the same, but their constitutive equations are different. The macroscopic analysis assumes that the porous medium can be regarded as the continuous medium, and the volume change of porous media in time t is equivalent to the volume change of the fluid [38, 39].

$$\frac{\partial \xi}{\partial t} = \frac{1}{N} \frac{\partial p}{\partial t} + \alpha \frac{\partial \varepsilon}{\partial t}, \quad (1)$$

where ξ is the volume change of fluid in pores of a unit volume, α is Biot's coefficient, ε is the volume strain of porous media, N is the Biot modulus, and p is the pore pressure.

2.2. Strength Criteria of Hidden Fault. To investigate the evolution law of stress field, seepage field and failure range of roof and floor during the mining process, the local grid of deformation and failure of roof and floor refined. For hidden fault and surrounding rock materials in this paper, Mohr–Coulomb criterion [40, 41] is used and the shear strength criterion f'_c and the tensile strength criterion f'_t are expressed as:

$$\begin{aligned} f'_c &= \sigma_1 - \sigma_3 \frac{1 + \sin \theta}{1 - \sin \theta} + 2c \frac{\cos \theta}{1 - \sin \theta}, \\ f'_t &= \sigma_3 - \sigma_t \end{aligned} \quad (2)$$

where σ_1 and σ_3 are the maximum and minimum principal stress, c is the cohesive force, θ is the internal friction angle, and σ_t is the tensile strength. When $f'_t = 0$, the rock mass will undergo tension failure, and when $f'_c = 0$, the rock mass will undergo shear failure.

2.3. Flow and Fine Particle Migration Equations. The constitutive relation for groundwater fluid flow can be expressed by Darcy's law [42] as follows:

$$q_w = -\frac{k}{\mu_w} (\nabla p + \rho_w g \nabla z), \quad (3)$$

where q_w is the velocity of fluid flow, k is the permeability coefficient, ρ_w is the density of water, g is gravitational acceleration, and μ_w is the viscosity of the water. Substitution of Equation (3) into the conservation equation of fluid results in [43, 44],

$$c_1 \frac{\partial \varepsilon_v}{\partial t} + c_3 \frac{\partial p}{\partial t} = \nabla \cdot \left[\frac{k}{\mu_w} (\nabla p + \rho_l g \nabla z) \right], \quad (4)$$

where

$$\begin{aligned} c_1 &= 1 - \frac{K'}{K_s}, \\ c_3 &= \frac{\varphi}{\beta_l} + \frac{1 - \varphi}{K_s}, \end{aligned} \quad (5)$$

where φ is porosity, β_l denotes the bulk modulus of fluid, ν_u is undrained Poisson's ratio of porous medium, and K_s is the effective bulk modulus of the solid constituent.

To investigate the mechanism of particle migration, by referring to the theoretical work of solid particle erosion in hidden faults. According to a generalized Exner equation, sediment mass balance can be described [45] as follows:

$$\frac{\partial \eta}{\partial t} = -\frac{1}{\varepsilon_0} \nabla \cdot q_s + \sigma, \quad (6)$$

where ε_0 can also be expressed as $(1 - \lambda_p)$, λ_p equals the bed porosity, q_s is the negative divergence solid particle, and σ is positive with an increase in elevation over time and is negative with a decrease in elevation over time.

2.4. Permeability Evolution Equation. According to the permeability test of rock in the deformation and failure process, the expression formula between permeability and volumetric strain for relatively complete rock can be written as follows:

$$k = \begin{cases} k_0 \exp(\beta_1 \varepsilon_r), \\ k_0 \ln(-\beta_2 \varepsilon_r), \end{cases} \quad (7)$$

where β_1 and β_2 are two coefficients reflecting the permeability before and after peak value under compaction and damage, respectively, and ε_r is the volumetric strain in the rock expansion stage.

For the granular rock mass inside the hidden fault, the relation between permeability and volume strain is as follows:

$$k = k_0 \left(\frac{\varphi}{\varphi_0} \right) \exp(\xi_1 \varepsilon). \quad (8)$$

Since the Carman–Kozeny equation can investigate granular rocks accurately [46], it is used to model the relationship between permeability and porosity of hidden fault as follows:

$$k = k_f \frac{\phi^3}{(1 - \phi)^2}, \quad (9)$$

where k_f is a parameter related to rock properties of hidden fault, which can be determined experimentally.

3. Numerical Simulations on Hidden Fault Delayer Water Inrush

3.1. Engineering Background. Take the 27305 working face of mine as research background, with the ground elevation +33.5 m~+34 m and the working face elevation -1110 m~-1090 m. The designed strike length of coal seam is 960 m, the average width is 160 m, the average thickness of coal seam is 4.5 m, and the dip angle of coal seam is 4~9°. According to the exposure of excavation face, there is no obvious fold structure in the coal seam of 27305 working face, but the geophysical prospecting results show that there are hidden faults in the coal seam floor, which poses a certain threat to the

FIGURE 2: Typical geological log profile of No. 27305 face and its overlying and underlying strata.

FIGURE 3: Schematic diagram during mining of coal seam with hidden fault above confined aquifers.

mining of the working face. The geological conditions related to the 27305 working face of the coal seam are shown in Figure 2.

When the hidden fault existing in the coal seam floor connects the Ordovician limestone aquifer, under the infiltration of confined water, the upward developed water flowing fracture occurs at the top interface of the aquifer, and the uplift height of confined water caused by structure is usually small. In the process of working face mining, the front coal seam floor strata produce compression deformation under the condition of advanced support pressure and floor stress redistribution, which causes the development and expansion of floor cracks. When the working face continues to advance, the floor rock expands and deforms under the stress release state, and the floor damage cracks further develop to form the floor failure zone with water conductivity. As shown in Figure 3, the rock around the hidden fault in the floor is easily activated by mining, and the fissures expand and develop along the fault to form fault failure zones. Under the syner-

gistic effect of vertical stress of floor and Ordovician limestone water pressure, the confined water body rises further along the original confined water conduction zone and hidden fault failure zone and then forms confined water heads with different conduction heights. During the advancing process of the working face, the floor rock of the floor failure zone of the working face is compressed and destroyed by the advance support pressure. After unloading, it will expand and deform and eventually form a floor rock failure zone. The hidden fault and its surrounding rock are activated and destructed by shear force and then the confined water-conducting zone. When the coal seam floor failure zone is connected with the water diversion zone of the hidden fault, the water inrush channel is formed, which causes the water inrush of the hidden fault.

3.2. Numerical Simulation of the Depth of Floor Mining Failure Zone. Itasca Consulting Group Inc. has developed a three-dimensional fast Lagrangian analysis program

FIGURE 4: Schematic of using $\text{FLAC}^{3\text{D}}$ for a loop calculation about basic explicit.

FIGURE 5: A mechanical model of coal seam mining with hidden fault.

($\text{FLAC}^{3\text{D}}$), which can simulate the mechanical behavior of failure plastic flow of geological materials when they reach the strength limit. It is especially suitable for analyzing progressive failure and instability and simulating large deformation, and is very accurate in simulating plastic failure and flow of materials.

The explicit Lagrangian method is a new numerical analytical method different from the implicit difference method. It divides the computational domain into several quadrilateral elements, each of which is endowed with physical-mechanical properties, and simulates the three-dimensional mechanical behavior of rock or other materials. In the simulation, the grid cell can be deformed with the deformation of the material [47]. This algorithm is very suitable for simulating large deformation for rock. Figure 4 shows such a specific loop calculation relationship. This relation first calls the equation of motion to derive new velocities and displacements from stresses and external forces. The strain rate is derived from the velocity, and new stresses are derived from the strain rate. For each cycle of the cycle, we use a time step.

3.3. Simplified Geological Model of Mining-Activated Water Inrush from Hidden Fault in Coal Floor. As shown in Figure 5, a simplified mechanical model is established in line with the engineering geological conditions of hidden fault. The model is $250\text{ m} \times 200\text{ m} \times 200\text{ m}$ in volume, with a total of 126600 units and 133496 nodes. The coal seam is approximately horizontal distribution with the width of 4.5 m. There are hidden faults in the coal seam floor which rise to sandstone and descend to the aquifer. The width and height of hidden fault are 4 m and 25 m, respectively. According to the geological conditions of the study area and the actual size of the working face, the mining physical model of 27305 working face was constructed, and the $\text{FLAC}^{3\text{D}}$ numerical

model was established based on the column diagram of stratum and the physical mechanical properties (see Figure 6).

The boundary of the model is constrained in X and Y directions; the full constraint is applied to the bottom of the model; the vertical equivalent uniform load of 10 MPa is applied to the top boundary of the model. At the same time, in order to better simulate the fluid-solid coupling between seepage of high confined water along hidden fault and floor failure, the pore water pressure in the aquifer under the initial condition is 4 MPa and that of the remaining strata is 0 MPa.

Two monitoring lines along and perpendicular to the hidden fault direction are arranged on the coal seam floor of the model ($Y = 100\text{ m}$), with a total of 5 monitoring points (see Figure 6). The thickness of waterproof layer of coal seam floor is 50 m. In the process of numerical simulated calculating, elastic-plastic constitutive model and Mohr-Coulomb failure criterion are used to calculate the mining failure characteristics of coal seam floor.

According to the actual process of the numerical model, the excavation should be used to realize, waiting for the model to reach the preequilibrium. Through the excavation calculation of the model stopping space, the mining thickness of the coal seam is 4.5 m, and the excavation step is 10 m in the quality calculation; the stress field, displacement field, and seepage field are calculated once every 10 m excavation. After finishing the face mining, the seepage field is calculated by 2000 steps. At this time, the maximum unbalanced force of the model tends to 0, and then, the failure range of the impermeable layer in the coal floor tends to be stable.

In the calculation process, the structural stress of the rock formation is ignored, and parameters are set as follows: the model is divided into eleven layers in line with the actual situation, the coal seam is in the fifth layer, and the floor is in the sixth to eighth layers. Table 1 shows mechanical parameters of each rock layer.

4. Results and Discussion

This study addressed the main concerns described in Introduction, which are the evolution of large deformation, stress field, and seepage field near hidden fault caused by mining and the height range of floor failure zone and confined water flowing fractured zone. For successional and complete analysis, the numerical simulation examples for coal seam mining process with hidden fault and the simulation calculations were carried out according to the method proposed above. In the following numerical examples, a dynamic numerical simulation model of coal seam mining was established with

FIGURE 6: Numerical simulation model.

TABLE 1: Geological and geomechanical properties of rock strata and hidden fault.

Lithology	Young's modulus (GPa)	Tensile strength (MPa)	Poisson's ratio	Density ($\text{kg}\cdot\text{m}^{-3}$)	Friction angle ($^{\circ}$)	Cohesion (MPa)	Porosity
Coarse-grained sandstone	28	4.5	0.27	2800	30	3.4	0.15
Fine sandstone	22	3.7	0.23	2550	28	2.0	0.13
Medium-grained sandstone	22	3	0.22	2700	28	2.0	0.13
Mudstone	18	2.6	0.28	2650	34	2.4	0.11
Coal seam 3	10	2	0.30	2500	29	1.4	0.12
Mudstone	18	2.6	0.28	2400	34	2.4	0.13
Siltstone	24	3.4	0.23	2500	26	2.8	0.1
Sandstone	22	3.1	0.26	2650	30	2.8	0.15
Coarse-grained sandstone	28	2.5	0.22	2700	28	2.5	0.12
Limestone	24	2.8	0.21	2650	32	2.8	0.13
Aquifer	25	6	0.27	2400	30	7	0.25
Fault	12	1.2	0.29	1900	20	1.65	0.11

FLAC^{3D} program, and the material parameters are applied to the numerical model to determine the development and distribution of the plastic zone of mining-induced fissure and the evolution of stress field and seepage field.

4.1. Evolution of Plastic Zone and Seepage Flow Field during Mining Advances. Plastic cloud pictures of the floor along the strike were selected to reflect the time-space evolution process from floor failure to passage formation can be reflected by the change of failure range in plastic zone, and analyze the failure characteristics of coal seam floor. The failure characteristics along the strike are generally consistent with those of normal faults. The plastic zone of the working face and the seepage vector diagram of the hidden fault at 80 m, 120 m, 140 m, 150 m, and 160 m are shown in Figure 7.

- (1) The activation stage of the hidden fault is caused by the interaction of the mining stress and the pore pressure of floor. When mining had advanced 80 m, the hidden fault was activated and the influence range at the bottom of the fault was increased. The internal

failure at the bottom of the hidden fault causes the upwelling of groundwater and indicating that the hidden fault is in the activation stage, which also provides the necessary conditions for the formation of the water inrush channel

- (2) *Expansion Stage of Hidden Fault Activation Area.* When mining had advanced 120 m, the failure of the original stress field is intensified due to the large mining stress, and the surrounding of the pinch-out of the fault is subjected to tensile and shear forces, which is in the extended state, and the active fissures of the hidden fault gradually develop to working face. When mining had advanced 140 m, the hidden fault is directly below the working face, the mining stress and the confined water pressure of the floor are more intense, the damage is more obvious, and the hidden fault is in a stable state of damage accumulation.
- (3) *Formation Stage of Water Flow Channel of Hidden Fault.* When mining had advanced 150 m, the activation area of hidden fault fissures is further expanded,

FIGURE 7: Evolution of the plastic zone and seepage field during mining advancing. (a) 80 m, (b) 120 m, (c) 140 m, (d) 150 m, and (e) 160 m.

the failure and destruction of the impermeable layer between the plastic zone of the floor and the active expansion of hidden fault are continuously reduced, and the water-conducting fissure zone is continuously expanded and developed. When mining had advanced 160 m, the water flow channel is formally formed and the failure mode is shear failure. At this time, the coal seam floor has completely lost its water-blocking capacity.

4.2. Analysis of the Vertical Stress State of Fractured Floor Rock Mass. The vertical stress cloud pictures of the corresponding floor in the mining process are shown in Figure 8. The vertical stress change process of the floor can reflect the stress change trend of the hidden fault, especially the influence of vertical stress change on the plastic zone damage of the bottom plate near the hidden fault.

With the advancement of working face, the initial stress redistributes due to the stress unloading effect, and the influence range of the vertical stress of the floor is gradually increasing. The stress concentration appears on both sides of working face, and the initial stress field around the hidden fault is gradually increasing due to the influence of the vertical stress of the floor. The vertical stress plays an important role in the initiation, expansion, and development of fissures in hidden faults.

When mining had advanced 80 m, it can be seen that the vertical stress in the hidden fault and surrounding rock is accumulated. The stress concentration area first occurs at the bottom of the hidden fault, which is mainly affected by the vertical stress of the floor and the pore pressure of the aquifer. At the same time, the roof and floor fissure zone increases with the roof caving and ground heave, and the influence range of the stress relaxation area expands accordingly. The hidden fault fracture zone and surrounding rock mass will produce initial activated fissures under the action of vertical stress. When mining had advanced 120 m or 140 m (when the working face is above the hidden fault), the vertical stress around the hidden fault gradually tends to be unified from the bottom stress concentration to the overall stress. The hidden fault and the floor impermeable layer are in the stage of fissure expansion and development and accumulate stress energy. At the same time, the floor and the hidden collapse column are also easily affected by the failure of the goaf ground heave. When mining had advanced 150 m or 160 m, combined with the failure characteristics of the plastic zone, it is found that the vertical stress distribution near the hidden fault tends to be stable due to the influence of the mining work, which indicates that the hidden fault and surrounding rock are damaged, and the surrounding rock and its internal stress energy release. The water inrush

FIGURE 8: Vertical stress evolutions during mining advancing. (a) 80 m, (b) 120 m, (c) 140 m, (d) 150 m, and (e) 160 m.

channel is formed by the connection between the floor failure zone and the internal fracture of the hidden fault.

4.3. Analysis of the Shear Stress State of Floor Rock Mass. The shear stress cloud pictures of the corresponding floor in the mining process are shown in Figure 9. Usually, after the coal is extracted, the floor stress released and forms a relief area under the goaf, and the roof above the goaf is affected by stress concentration and forms a pressurized area. Affected by the concentration and release of shear stress, the pressure relief area and pressurized area are formed in front of working face and the roof and floor of coal seam. The change of shear stress affects the fracture propagation and activation failure of rock mass in hidden faults.

With the advancement of working face, the influence area range of the shear stress gradually increases, and the stress concentration in front of working face has stronger influence on the hidden fault. The shear stress field around the hidden fault gradually increases, and the maximum shear stress reaches -6 MPa. The shear stress plays a leading role in the activation, development, and destruction of hidden fault during mining.

When mining had advanced 80 m, the shear stress field inside the hidden fault and the surrounding rock began to increase, indicating that the hidden fault and the surrounding rock mass began to be activated and deformed, and partial failure occurs to release the shear stress. Meanwhile, the stress accumulation began in the middle and upper of the hidden fault and the surrounding rock. The influence range of the roof and floor fissured zone and the stress relaxation zone reached the maximum with the advancement of working face. When mining had advanced 120 m or 140 m (when the working face is above the hidden fault), the stress on the floor impermeable layer between the working face and the hidden fault is relatively concentrated, and the hidden fault and the floor impermeable layer are rapid deformation stage. Meanwhile, the hidden fault is easily damaged by shear stress. When mining had advanced 150 m or 160 m, the mined-out area floor continues to develop and destroy, and the influence range of shear stress field of the hidden fault little changes, indicating that the hidden fault interior and the surrounding rock have been completely destroyed, the shear stress is released, and the water inrush channel is formed.

FIGURE 9: Shear stress evolutions during mining advancing. (a) 80 m, (b) 120 m, (c) 140 m, (d) 150 m, and (e) 160 m.

FIGURE 10: The relationship between stress evolution of monitoring point during mining advancing. (a) ZX-stress and b ZZ-stress.

FIGURE 11: Failure area and seepage vector diagram for excavation of 160 m under different dip angle of hidden fault conditions. Dip angles: (a) 45°, (b) 60°, and (c) 75°.

4.4. Analysis of the Stress Evolution of Floor Rock Mass. Figure 10 shows the relationship between vertical stress and shear stress at each measuring point as the advancing distance changes. The following results can be obtained:

When excavation is 0 m to 60 m, the compressive stress and shear stress of the monitoring point are fixed load, and the stress of the monitoring point does not change. When excavation is 60 m to 140 m, the shear stress of the monitoring points in the hidden fault gradually increases, while the vertical stress gradually decreases. The compressive stress of monitoring points 4 and 5 increases at first then decreases. The stress redistribution will reverse increased in the initial stage of shear stress, and the stress redistribution will increase the circumferential stress and decrease the radial stress, and then, the stress recovered and reached the maximum shear stress at 130 m and 140 m, respectively. When excavation is 140 m to 160 m, due to the failure deformation of the surrounding rock and the hidden fault, the release stress leads to the compressive stress and shear stress corresponding to the monitoring point that gradually decreases.

4.5. Effect of Dip Angle of Hidden Fault on Water Inrush. Different dip angles of hidden fault directly change the thickness of water-resisting layer of floor and then affect the formation of water inrush channel. According to the above analysis, when 160 m is excavated, the floor failure zone is connected with the hidden fault failure zone, reaching the critical state of delayer water inrush. To explore influencing factors of water inrush from hidden fault floor, this section simulates the working condition of 160 m excavation under different dip angles of fault. The simulated dip angles of hidden fault floor are 45°, 60°, and 75°, respectively. Figure 11 shows the failure area diagram and the seepage vector diagram of the hidden fault.

In the process of mining, hidden fault will be activated and destroyed under the action of shear stress, when the fissure will occur. Meanwhile, the confined water in the aquifer softens and erodes the fault, which leads to the failure of the faults cut into the aquifer. Under the same other geological

conditions, hidden faults with large angle are easy to destroy the failure zone of connected floor. When the dip angle of the hidden fault is 60° or 75° and mining had advanced 160 m, the hidden fault and the surrounding rock failure zone are connected with the floor failure zone. Combined with the expansion of seepage vector and path distribution of hidden fault, it can be seen that floor delayer water inrush has occurred at this time. When the dip angle of the hidden fault is 45, the failure area of the hidden fault cannot be connected with the failure zone of the mining floor, and the seepage vector around the hidden fault is small, so the hysteresis water inrush disaster will not occur.

5. Conclusions

A numerical model of underground mining with a hidden fault was developed to analyze the mechanism of water inrush due to hidden fault activation in the mining process. The evolution of stress field, seepage field, and plastic zone around the hidden fault during the advancing process was simulated. The influence of the thickness of the aquifer and its water pressure on the water inrush was analyzed, reaching the following conclusions:

- (1) The working face has a great influence on the distribution of the shear stress in the hidden fault. The shear stress increases first and then decreases, while the compressive stress decreases gradually due to the release of stress energy in the mined-out area. When the working face is excavated above the hidden fault, the shear stress inside the fault and surrounding rock reaches its peak value and the critical state of failure
- (2) With the advancement of the working face, the hidden fault gradually deforms, and the shear failure tends to occur at the extension of the dip angle of the hidden fault. When the excavation is 150 m, a water inrush channel is potentially developed between the floor

failure zone and the hidden fault. The delayed water inrush in the mined-out area occurs when mining had advanced 160 m, the floor failure zone is connected with the hidden fault failure zone, and the delayed water inrush channel is formed

- (3) When the working face advances above the hidden fault, the stability of the floor of the impermeable layer decreases, and the large-angle hidden fault easily produces fissures that penetrate the coal seam floor and aquifer. The dominant seepage channel is formed by the fractures, and seepage is mainly concentrated under the working face. When the water pressure of aquifer is the same, the larger-angle fault leads to the thinner thickness of the floor of the aquifer. In addition, the greater the influence of the hidden fault on coal seam mining, the higher the danger of water inrush

Data Availability

The data used to support the findings of this study are included in the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Acknowledgments

This research was funded by the National Natural Science Foundation of China (grant 51874192 and 42007172), the Shandong Province Natural Science Foundation (grant ZR2019MEE084 and ZR2020QE126), and the SDUST Research Fund (grant 2018TDJH102).

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