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Research on the Mechanism and Evolution Law of Delayed Water Inrush Caused by Fault Activation with Mining

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Abstract: Confined water inrush caused by fault activation is the main form of water disaster in deep mining. With theoretical analysis and similar simulation tests, the mechanism and evolution law of delayed water inrush caused by fault activation are revealed. At the theoretical level, the expansion and extension of the internal microstructure in the fault zone under the action of the mining stress field and seepage field are the essential causes of fault activation. Overlying strata movement and surrounding rock creep failure are the basic reasons for delayed water inrush caused by fault activation, and delayed time caused by surrounding rock creep failure is much longer than that of overlying strata movement. A similar simulation test was carried out with self-development solid–liquid coupling with similar simulation materials; the results show that delayed water inrush caused by fault activation with mining includes three stages. Micro-activation stage: Water inrush weakness point is formed because of the expansion and extension of the micro-fissure and structure at the bottom of the fault zone. Macro-activation stage: With the change in the stress of the waterproof coal pillar and surrounding rock, the micro-fissures and structures in the stress relief area and tension area of the fault zone expand and extend sharply; meanwhile, water intrudes into the interlayer stratification of the floor in the stress relief area, forming a strong laminar flow phenomenon, and cracks in the floor form and expand; finally, water-conducting channels in the fault zone and floor are formed. Water inrush stage: The waterproof coal pillar and water-resisting layer fail and are destroyed, and the first confined water inrush point is located at the junction of the waterproof coal pillar and gob floor.

Keywords: fault activation; delayed water inrush; surrounding rock creep failure; similar simulation test; water-conducting channel

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1. Introduction

With resources becoming exhausted and an increase in mining depth, high ground stress, high ground temperature, high confined water pressure, and strong mining disturbance are the main threats to deep resource mining [1,2]. In particular, the confined water inrush disaster in deep mining has become a major problem in the field of mining engineering all over the world. Coal will be the main energy resource in China for a long time in the future. However, coal reserves above confined water take up as much as 95 billion tons in central and eastern deep mining areas, and the pressure of confined water is as high as 10 MPa, which induces many major accidents and disasters. Accident and disaster statistics show that more than 80% of confined water inrush accidents are caused by fault structures, and the main form is non-water-conducting fault activation which causes water inrush with a significant delay in time. Hidden, sudden, delayed and strong harms are the typical characteristics of water inrush caused by fault activation, which causes a huge threat to coal and other resources in mining above confined water [3].

Aiming at water inrush disaster prevention and control caused by fault activation, a large number of scholars around the world have carried out a great deal of research work to ensure the safe exploitation of resources. In relation to theory: Lu et al. [4] derived the water pressure expression of the floor considering fault structure and analyzed the influencing law of the distance to fault zone, advancing direction, and lateral pressure coefficient of the critical pressure of water inrush. Mechanical mechanisms of fault self-locking, activation criterion, and stability control measures were established by Lin et al. [5]. Zhang et al. [6], based on the rock mass limit equilibrium theory on the floor, established the mechanical model of mining stress under the influence of fault and the fault activation criterion, and obtained the evolution law of water inrush channel formation. However, the mechanism of delayed water inrush caused by fault activation is still unclear. Through experiments and tests: Zhu et al. [7], based on the self-developed solid–liquid coupling with similar simulation materials, revealed the evolution law of confined water rising along the fault zone and failure of overlying strata with a similar simulation test. The water inrush mechanism, evolution law, the characteristics, and the whole process of buried fault structure under the coal seam floor above confined water were studied by Sun and Chen et al. [8,9]. Ma et al. [10] carried out an experiment on pore structure characterization and the nonlinear seepage characteristics of rock mass in the fault zone. Liu et al. [11] analyzed water inrush accidents in mining engineering to research delayed water inrush by fault activation and the time effect. At present, there are few large-scale similar simulation tests on delayed water inrush caused by fault activation. In numerical simulation calculation: Lu et al. [12] analyzed the influence mechanisms of multiple factors on fault activation, the solid–liquid coupling of water inrush, and the distribution and evolution law of multi-fields, with FLAC, RFPA, and COMSOL. Aiming to study delayed water inrush caused by fault activation, Li et al. [13] carried out a large work of numerical simulation calculations and obtained many conclusions and achievements. In prediction and prevention: Zhu et al. [14], according to an unascertained mathematical theory, and based on analyzing factors affecting delayed water inrush caused by fault activation, established an assessment system of water inrush. Yuan et al. [15] revealed fault activation characteristics, an evolution law of water inrush channel formation with micro-seismic monitoring technology, and established a monitoring technology system and integrated platform. Shi et al. [16], based on different mathematical methods and evaluation principles, established many evaluation models and methods of water inrush caused by fault activation. The multi-field evolution law of fault activation inducing water inrush is relatively clear, and the prevention and control technologies have obtained certain field effects. Numerous other scholars, aiming at water inrush of confined water, carried out numerous studies to guide in resource mining safety [17–20].

In summary, a lot of research work and numerous achievements were carried out and obtained in the field of water inrush caused by fault activation, which plays an important guiding role in the prevention and control of confined water. However, the mechanism of delayed water inrush caused by fault activation needs to be thoroughly studied. In this work, we investigate this issue using theoretical analysis and similar simulation tests to research the delayed water inrush mechanism caused by fault activation.

2. Theoretical Mechanism of Delayed Water Inrush Caused by Fault Activation

2.1. Expand and Extend Mechanism of Microstructures in Fault Zone

Under the combined effect of the mining stress field and seepage field, microstructures expand and extend in the non-water-conducting fault zone, which causes water-conducting channels to form as time passes; this is the essential reason for delayed water inrush, that is, the expansion and extension mechanism and time effect of rock mass microstructures in the fault zones under multi-field action [21].

In the mechanical property, microstructures in the fault zone are divided into five basic forms: tensile, compressive, torsional, tensile–torsional, and compressive–torsional. Field engineering geological surveys and laboratory experiment results show that the more delayed the fault structure formation, the easier it is to expand, activate, and conduct water inrush under the mining effect. During the formation of large fault structures, a large number of tensile and shear joints and secondary fault structures are derivative on both sides of the main fault structure because of the dislocation and slip of two fault plates. The effect of mining activities on the fault structure are mainly in two aspects: (1) the original cemented and closed microstructures are re-opened by shear stress and (2) the accompanied joints and fractures are secondarily expanded and extended by tensile stress, which causes the continuity and conductivity of faults to greatly increase. By comparison, the accompanied joints, fractures, and secondary fault structures ease activation and conductivity [22,23]. The expand and extend mechanisms of microstructures in the fault zone is shown in Figure 1.

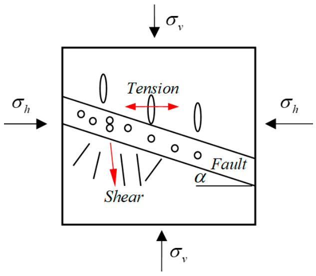


Figure 1. Expand and extend mechanisms of microstructures in the fault zone.

The root cause of delayed water inrush is the time effect for the expansion, extension, and penetration of microstructures in the fault zone. In engineering, microstructure expansion in the fault zone is prevented to a certain extent and range for the reserved fault waterproofing coal pillar. However, the activation and breaking of microstructures in the fault zone continues to occur quickly or slowly to form a water-conducting channel and to conduct water inrush because of the secondary movement of the overlying strata with coal seam mining in the footwall or the action of high mining stress. Thus, there are two basic forms of delayed water inrush caused by fault activation: (1) when the overburden structure variation and the change in stress field cause cracks to expand and extend, causing fault activation and water inrush with coal seam mining in the footwall, and (2) when the long-term creep of surrounding rock in the fault zone induces the continuous expansion and failure of microstructures, causing fault activation and water inrush with high mining stress. Moreover, the delayed time effect of the surrounding rock creep failure is more obvious than that of the overlying strata movement.

2.2. Delayed Water Inrush Caused by Fault Activation with Overlying Strata Movement

After mining the face in the hanging wall mining of a normal fault, a large width B_1 of the waterproof coal pillar is left. The movement and fracture of the overlying strata are insufficient for supporting and controlling the effect of the waterproof coal pillar and in forming a cantilever beam structure. The peak abutment pressure on the fault waterproof coal pillar is $K_0\gamma H$, and it gradually decreases the primary rock stress toward the fault zone side. During this period, the waterproof coal pillar prevents the fault activation process, and the surrounding rock around the fault is in a stable state.

During the footwall mining of the face, the width of the waterproof coal pillar is generally smaller than or equal to that in the hanging wall face, which is $B_2 \leq B_1$. By comparison, the overlying strata movement is more violent than that during the hanging wall face mining, and the relationship of abutment pressure peak is $K_1\gamma H > K_0\gamma H$. The depth inside the waterproof coal pillar is $t_1 > t_0$, and the abutment pressure of waterproof coal pillar next to the fault zone is greater than the primary rock stress γH. Meanwhile, the overlying strata in the hanging wall are secondary movement, rotation and settlement, and the abutment pressure on the waterproof coal pillar in the hanging wall's sudden changes. At this moment, the peak abutment pressure is $K_2\gamma H > K_1\gamma H > K_0\gamma H$, the depth inside the waterproof coal pillar is $t_2 > t_1 > t_0$, and the stress of surrounding rock next to the fault zone is much higher than the primary rock stress γH.

The state change of the overlying strata movement causes the abutment pressure change of the waterproof coal pillar, which induces the stress field sudden change of surrounding rock in the fault zone [24,25]. Meanwhile, the expansion and extension criterion of microstructures of the surrounding rock in the fault zone are satisfied quickly, inducing microstructure development to form a continuous water-conducting channel and a rapid delayed water inrush disaster. The overlying strata movement is generally short and intense, and the time effect of delayed water inrush caused by fault activation with the overlying strata movement is also generally short. It usually occurs during coal seam mining in the footwall, as shown in Figure 2.

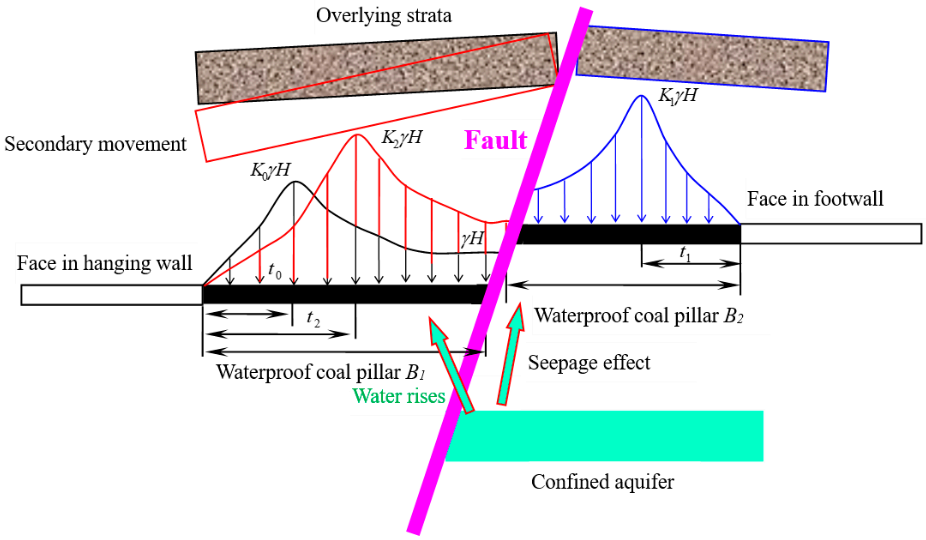


Figure 2. Delayed water inrush caused by fault activation with overlying strata movement.

2.3. Delayed Water Inrush Caused by Fault Activation with Surrounding Rock Creep Failure

Creep is an inherent characteristic of rock mass under long-term stress [26,27]. When the waterproof coal pillar is small, the stress of the surrounding rock in the fault zone caused by coal mining is higher than the primary rock stress, but less than the rock failure strength. Under the long-term stress, surrounding rock in the fault zone is creeping all the time; meanwhile, the confined water makes a certain hydraulic effect on the surrounding rock, which eventually induces gradual compression and deformation of the waterproof coal pillar and the slow settlement of the overlying strata. The subsidence of the overlying strata and the compression of the waterproof coal pillar result in the further increase in abutment pressure, creep, and hydraulic action. The cycle of the above process eventually leads to the expansion and extension of microstructures and cracks in the fault zone, forming a water-conducting channel and a delayed water inrush disaster. The time of rock creep failure is extremely longer, so the time effect of delayed water inrush caused by fault activation with the surrounding rock creep failure is generally much longer than that of the overlying strata movement, which may take several years or even decades, as shown in Figure 3.

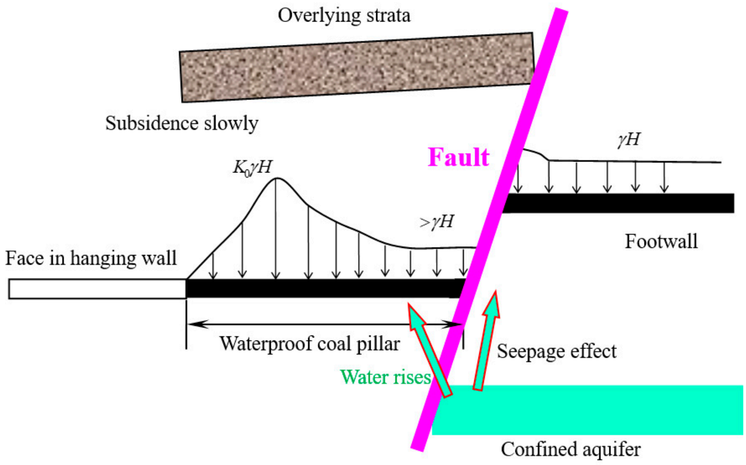


Figure 3. Delayed water inrush caused by fault activation with surrounding rock creep failure.

3. Similar Simulation Test of Delayed Water Inrush Caused by Fault Activation

3.1. Engineering Background

Wugou coal mine is located in Huaibei coalfield, Anhui Province, China. There are many huge fault structures and small faults in the mining areas, and the fault zone is mostly filled with sand and mud. The field drilling works show that there is no water leakage in the fault structures, which belong to non-water-conducting fault structures. At present, 10# coal seam is the main mining coal seam, the buried depth is 400~500 m, and the average thickness of the coal seam is 4 m. The roofs are mainly of medium sand and siltstone. The average distance between coal seam floor and confined aquifer of Taiyuan Formation is 42 m, the floors are mainly siltstone and sand–mudstone interlayers, with a good water resistance property. The confined water pressure measured on the site is up to 9 MPa. With the development of fault structures, coal seam mining is seriously threatened by the confined water. A similar simulation test of delayed water inrush caused by fault activation will be carried out according to the above geological conditions.

3.2. Solid–Liquid Coupling with Similar Simulation Materials

The reasonability and feasibility of the solid–liquid coupling with similar simulation materials are the key to the success of delayed water inrush caused by fault activation simulation tests [28,29]. For this reason, solid–liquid coupling with similar simulation materials of a water-resisting layer, water-bearing layer, and fault zone were developed, and the relevant parameters such as strength, water absorption, and permeability were measured.

River sand, gypsum, and calcium carbonate are used as the basic materials to develop solid–liquid coupling with similar simulation materials. Paraffin and Vaseline are as additive, hydraulic oil is as a blender to develop water-resisting-layer solid–liquid coupling materials [30]. Relevant parameters are as follows: the uniaxial compressive strength is 0.045~0.165 MPa, the saturated water absorption is 1.54~3.45%, and the permeability coefficient is 4.35×10^{-7}~15.9×10^{-6} cm/s, which meet the requirements of poor hydrophilicity and low permeability. With poplar sawdust as an additive to develop a water-bearing layer for solid–liquid coupling materials, the main parameters are as follows: the uniaxial compressive strength is 0.235~0.625 MPa; the water absorption is 18.5~34.5%, with quick saturation and no disintegration damage occurred; and the permeability coefficient is 5.75×10^{-4}~1.24×10^{-3} cm/s; which meet the requirements of strong water permeability and high integrity. Taking coconut shell powder and coarse salt as additives and hydraulic oil as a blender to develop fault zone solid–liquid coupling materials, the parameters are as follows: the uniaxial compressive strength is 0.0275~0.055 MPa; the water absorption is 39.5~50.5%, with damage and failure within 0.5 h; the permeability coefficient is 1.59×10^{-3}~4.55×10^{-3} cm/s, which satisfies the characteristics of strong water permeability, expansion softening and mineral dissolution.

3.3. Test Equipment

Test equipment mainly relies on the visualization test platform for the floor water inrush evolution process of coal seam mining in the State Key Laboratory of Mining Disaster Prevention and Control, which was cofounded by Shandong Province and the Ministry of Science and Technology in Shandong University of Science and Technology. The test platform is shown in Figure 4.

(**a**) (**b**) (**c**) (**d**)

Figure 4. Visualization test platform for water inrush. (**a**) Testing platform; (**b**) electrohydraulic servo loading system; (**c**) water pressure loading control system; and (**d**) intelligent monitoring system.

The water inrush testing system consists of four subsystems: testing platform, electro-hydraulic servo loading system, water pressure loading control system, and an intelligent monitoring system. The maximum size of the model that can be laid on the testing platform is 900 × 500 × 800 mm (length, width, and height). The loading system includes two modes, load, and displacement: the maximum lateral and vertical loading load is 300 kN, and the loading rate is 0.01 kN/s~100 kN/s; the maximum lateral displacement loading is 200 mm and vertical is 400 mm; and the loading rate is 0.01 mm/min~100 mm/min. The maximum water injection pressure of water pressure loading control system is 1.5 MPa, which can realize continuous linear regulation and control. Intelligent monitoring system includes water pressure and mining stress monitoring: the water pressure is monitored by arranging 96 sensors at the water outlet at the bottom of the model; DH3816N static strain test and an analysis system are used for mining stress monitoring, which realize the monitoring and collecting of experimental data in real time.

3.4. Test Scheme

According to the engineering background of Wugou coal mine, a similar simulation test of delayed water inrush caused by fault activation was carried out, based on the solid–liquid coupling with similar simulation materials and test equipment. The specific testing parameters are as follows: the similarity ratio is 1:150, the laying size of the model is 900 × 500 × 730 mm, and the thickness of coal seam is 3 cm. The parameters of the fault: the dip angle is 70°, the width of the fault zone is 2 cm, and the fault throw is 11 cm. On both sides of the fault zone, 4 cm small waterproof coal pillars are reserved to simulate the failure process of the waterproof coal pillars on site, and 3 cm coal pillars are left at the boundaries of both sides of the model to eliminate boundary effect. The lengths of the face in the hanging wall and the footwall are both 38 cm, which is larger than the first fractured step of the overlying strata. A total of 11 stress sensors are arranged on the waterproof coal pillar, roof, and floor in the fault zone to monitor the change in mining stress in real time. The specific test scheme is shown in Figure 5.

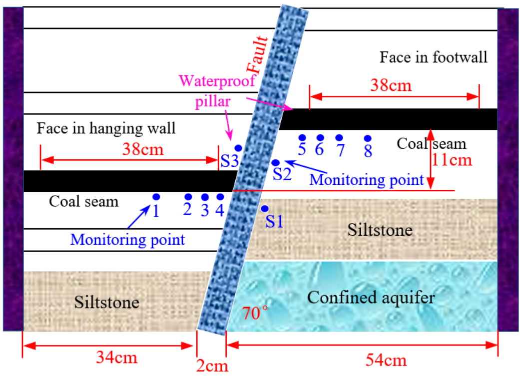


Figure 5. The testing parameters of delayed water inrush caused by fault activation.

3.5. Test Procedures

During the laying of the test model, the similar simulation materials of the water-resisting layer must be mixed and heated, and laid layer by layer. The temperature of materials should be higher than the melting point of paraffin wax (not less than 60 °C) to ensure that paraffin, Vaseline, hydraulic oil, and solid materials are fully mixed. The laying process is shown in Figure 6.

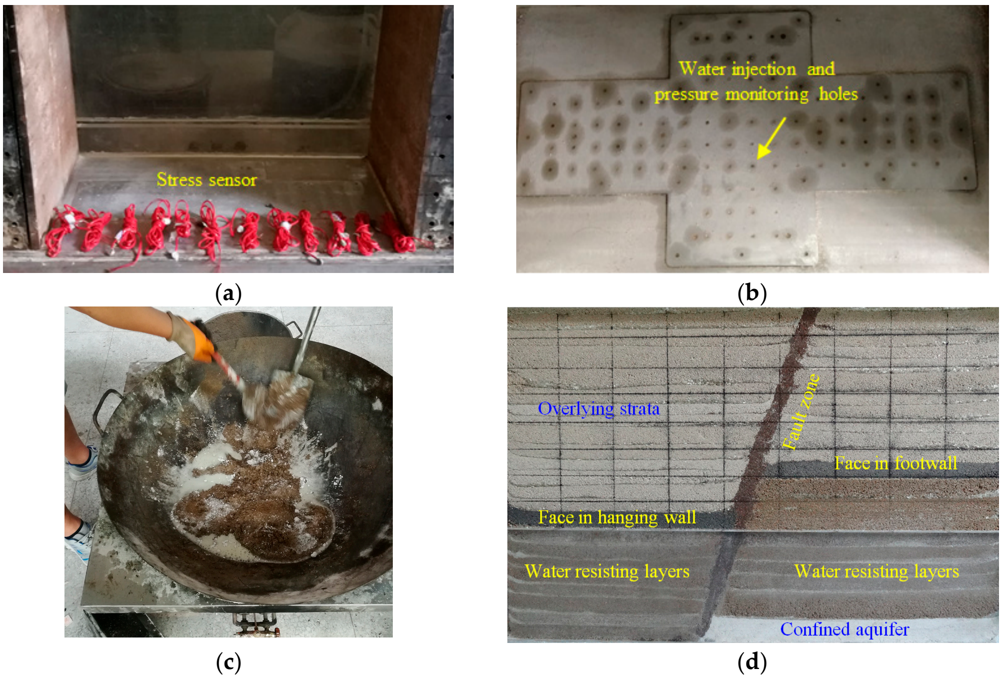


Figure 6. Testing process and similar simulation model. (**a**) Stress sensor; (**b**) confined water injection and monitoring hole; (**c**) materials mixed and heated; and (**d**) testing model.

After the test model is cured and dried, the loading mode adopts the load control. According to the in situ stress testing and the similarity ratio, the vertical and horizontal loads of 30 kN (0.07 MPa) are applied to simulate the primary rock stress field. The water injection pressure is 0.06 MPa, and ink is added to the water in order to observe the rise in the confined water. The mining sequence begins with the face in the hanging wall first, then the face in the footwall. The damage, fracture, and failure of the roof, floor, and waterproof coal pillar, fault zone expansion and extension, mining stress change, especially the stress evolution law of the waterproof pillar, water conduction, and water burst in the fault zone will be recorded during the coal seam mining in real time.

4. Evolution Law of Delayed Water Inrush Caused by Fault Activation

According to the phenomenon shown in the test, including the stress change, surrounding rock failure, and water inrush process, especially the development of the water-conducting channel, the delayed water inrush caused by fault activation is divided into three distinct stages: the micro-activation stage of crack development, the macro-activation stage of water-conducting channel formation, and the confined water burst stage of the waterproof coal pillar and the floor failure.

4.1. Micro-Activation Stage of Crack Development

After the primary confined water pressure is applied, the floor of limestone quickly absorbs water and becomes confined aquifer, which forms an obvious water–layer interface between the water-resisting layer and limestone. Due to the direct perfusion of confined water and the infiltration of the confined aquifer, the bottom of the fault zone is rapidly saturated with the confined water, and it rises to a height of 14 cm along the fault zone. The interlayer stratification of the floor is a natural weak plane structure, and the confined water intrusion length is 4 cm. Meanwhile, minerals at the bottom of the fault zone absorb water, soluble matters dissolve, and voids and cracks develop. If the confined water pressure is kept at a constant, the above process tends to gradually stabilize before coal seam mining, as shown in Figure 7.

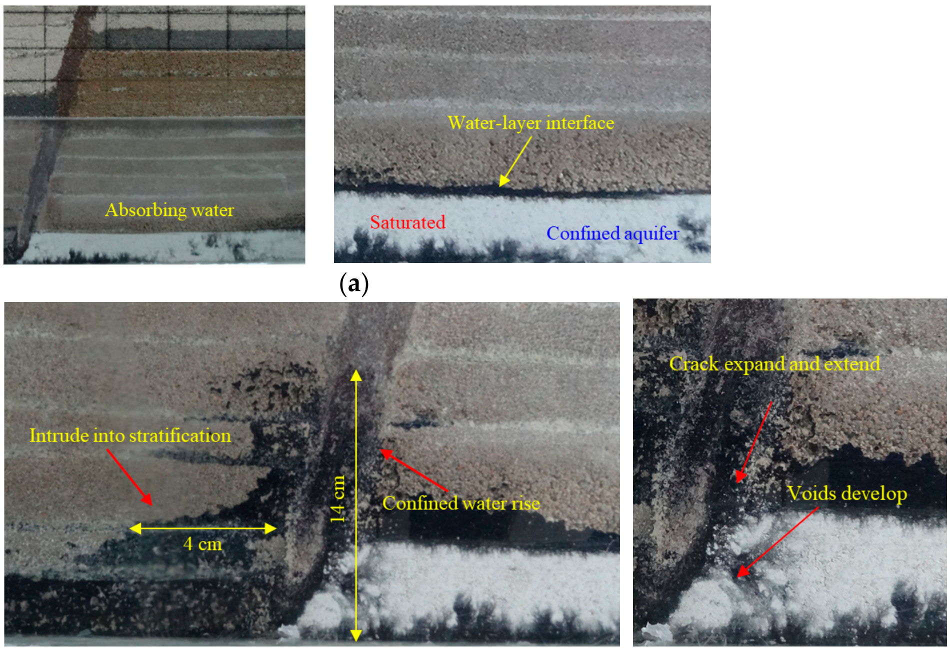


Figure 7. Micro-activation stage of crack development. (**a**) Confined aquifer formation process; (**b**) voids and cracks develop and expand.

4.2. Macro-Activation Stage of Water-Conducting Channel Formation

4.2.1. Evolution Law of Overlying Strata Fracture and Movement

During the hanging wall mining of the face, the overlying strata fractured, and the movement formed a hanging roof on the side of the waterproof coal pillar and produced longitudinal cracks along the coal wall. During the footwall mining of the face, the overlying strata movement is similar to that in the hanging wall. Meanwhile, the overlying strata on the hanging wall is a secondary movement, and a thick short cantilever beam structure is formed above the fault waterproof coal pillar; the waterproof coal pillar next to the hanging wall is obviously compressed, as shown in Figure 8.

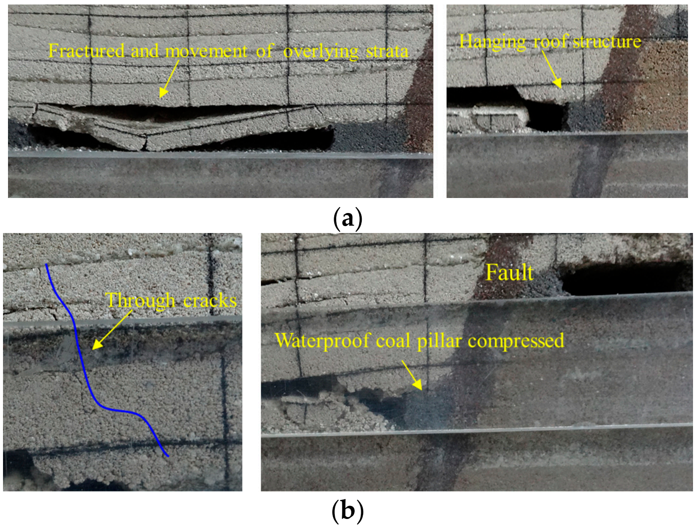


Figure 8. Fracture and movement of overlying strata. (**a**) Hanging roof structure during hanging wall mining and (**b**) thick short cantilever beam structure during footwall mining.

4.2.2. Stress Evolution Law of Waterproof Coal Pillar

The stability of the fault waterproofing coal pillar is the key to prevent fault activation and water inrush disaster. During the hanging wall mining, the coal pillar stress gradually increases, the maximum stress is 0.055 MPa (stress monitoring point 2) but does not exceed its ultimate strength, and the coal pillar compression is small and remains stable. On the contrary, during footwall mining, the stress increases sharply to 0.095 MPa (stress monitoring point 5) and the compression amount of the waterproof coal pillar increases rapidly to 1.2 cm, which is accompanied with serious compression molding and side-falling. The short thick cantilever beam structure above the coal pillar rotates, which generates tensile stress in the fault zone between two plates of the waterproof coal pillar (stress monitoring point S3 becomes negative) and causes crack development and expansion in the fault zone. Meanwhile, waterproof coal pillar on the hanging wall squeezes into the fault zone, forming a compression zone under the side. Pressure relief occurs on the floor next to the waterproof coal pillar, and as an effect with the confined water, a tension zone is formed, which is proven by the change in the stress values of the stress monitoring points 2 and 3 into negative values. The stress state and changing law are shown in Figure 9.

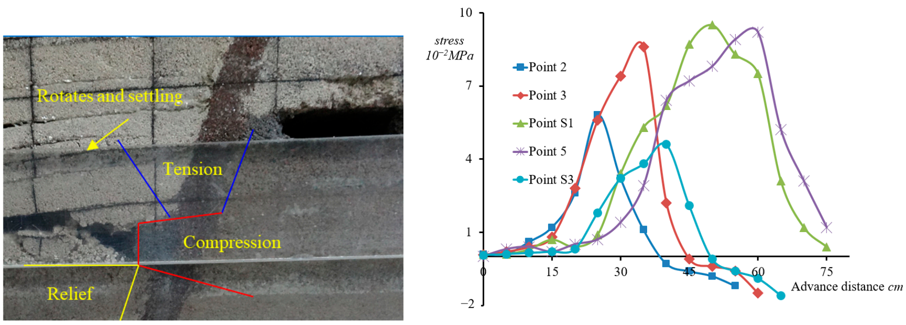
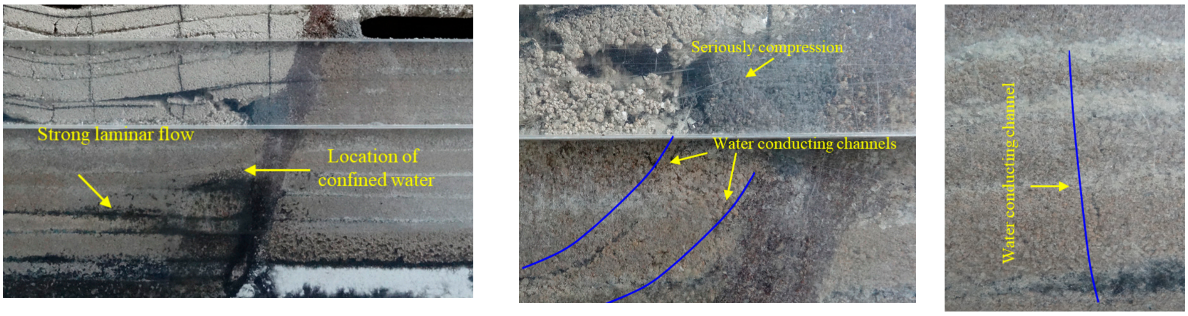


Figure 9. Stress state and changing law of the waterproof coal pillar.

4.2.3. Formation Process of Water-Conducting Channels

The difference in stress states and distribution near the waterproof coal pillar and the fault zone makes it easier for confined water to intrude into the tension zone and induce a large number of tension cracks near the fault zone next to the waterproof coal pillar, which gradually forms through water-conducting channels. At the same time, the confined water further intrudes the interlayer stratifications of the floor strata, inducing a strong laminar flow phenomenon and tension stress. The cracks on the floor are generated by tension stress and gradually expand and extend to form through water-conducting channels, as shown in Figure 10.



(**a**) (**b**) (**c**)

Figure 10. Formation process of water-conducting channels. (**a**) Confined water rises rapidly and a strong laminar flow phenomenon occurs; (**b**) water-conducting channels next to coal pillar; and (**c**) water-conducting channel in the floor.

4.3. Confined Water Burst Stage of Coal Pillar and Floor Failure

With the expansion and extension of the water-conducting channels, the infiltration effect of the confined water is strengthened, and the waterproof coal pillar gradually fails. The junction between the waterproof coal pillar and the gob floor is the most obvious, and the confined water first breaks and bursts here. At this moment, the working face of the footwall advances to 26 cm, as shown in Figure 11.

Figure 11. The location of the confined water bursting.

5. Conclusions

Based on similar self-development simulation materials, with the use of theoretical analysis and a similar simulation test, the mechanism of delayed water inrush caused by fault activation was studied. The main conclusions are as follows:

(1) The expansion and time effect of rock mass microstructures around the fault zone are the essential reasons for fault activation and delayed water inrush disaster, which includes two basic forms: overlying strata movement and long-term creep failure of surrounding rock. By comparison, fault activation and water inrush caused by the surrounding rock creep failure have a long time effect, which can reach several years or even decades.

(2) The solid–liquid coupling with similar simulation materials developed for the water-resisting layer, water-bearing layer, and fault zone are proven to be reasonable and feasible via the similar simulation test of delayed water inrush caused by fault activation. They can be applied in the geotechnical and architectural engineering fields.

(3) Delayed water inrush caused by fault activation can be divided into three stages. The micro-activation stage of crack development: with the effect of mining activities and confined water, microstructures develop, expand, and extend to form natural water

inrush weakness points. The macro-activation stage of water-conducting channel formation: cracks expand and extend rapidly to form water-conducting channels because of stress state and the changing amount of the waterproof coal pillar and the fault zone with coal seam mining in the footwall. The confined water burst stage of coal pillar and floor failure: the waterproof coal pillar failure and cracks through the floor cause a water inrush disaster, and the first bursting point is located at the junction between the waterproof coal pillar and the gob floor.

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