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The Formation of The "Upper Three Belts" in The Collapse of Rock Formations and Water Inrush Studies

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Abstract

In order to study the formation of the "upper three belts" by the collapse of the overlying rock layer in coal mining and communicate the influence of the overlying aquifer on the water inrush of the working face, the process of the overlying rock layer crossing to form a complete "upper three belts" and the occurrence of roof water inrush occurred was simulated based on FLAC3D software. The development law of water conduction fracture channel and the change law of permeability coefficient of roof rock mass and the water inflow of roof rock mass were studied by numerical simulation method. The results show that: (1) The disturbance of coal seam mining activities leads to the collapse of the overlying rock layer, which makes the overlying rock layer form the distribution characteristics of "upper three belts"; (2) The development form of the water conduction fracture zone after the working face is advanced by 140m is "saddle-shaped". Four dominant water fracture zones from left to right are formed in the "curved zone", which are located at 15m, 70m, 100m and 150m respectively in the model. The "fracture zone" and "falling zone" formed four dominant water fracture zones at 20m, 80m, 140m and 158m of the working face. A separation zone is formed between the "bending zone" and the "fracture zone", and the maximum development height of the separation zone is 2.3m, and the average height is 0.8m; (3) The detection points on the roof showed that the maximum water inrush was located at the monitoring points with coordinates of (78,2) to (78,8) and (80,2) to (80,8), and the maximum water inrush at the monitoring points was 1.024m^3/h. After the seepage simulation started, the maximum water inrush from the roof was 54.9m^3/h.

Keywords

Upper three belts; delayered development; zones of water-conducting fractures; numerical simulation; water inrush.

1. Introduction

During coal seam mining and the advancement of the working face, the overlying rock strata undergo regular caving, fracturing, and subsidence due to mining-induced disturbances. Based on the intensity and extent of rock layer failure, the overlying strata are divided, from bottom to top, into the caved zone, fractured zone, and bending subsidence zone, collectively referred to as the "upper three zones." The caved zone and fractured zone together are termed the water-conducting fracture zone. When the development height of the water-conducting fracture zone reaches the overlying aquifer, a water-conducting channel is formed, which can easily lead to roof water inrush accidents, posing serious risks to the safe production of coal mines[1-3].

Once the water-conducting fracture zone in the overlying rock strata extends to the aquifer above the coal seam, water from the aquifer can flow or burst into the underground workings, leading to mine water disasters. [4-6].

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Regarding the seepage evolution mechanism of the water-conducting fracture zone, scholars have conducted extensive research from the perspectives of theoretical analysis, model experiments, and numerical simulations. In terms of theoretical analysis, Li Liping [7] summarized four mechanical mechanisms of water inrush failure in fractured rock masses under the influence of karst water and water pressure, and proposed a formula for calculating the minimum rock thickness to prevent water inrush. Li Shucai[8] proposed the conditions, criteria, and safety thickness analysis methods for different tunnel water inrush disasters. In the area of model experiments, Liu Gang[9] conducted similarity simulation experiments based on the three laws of similarity theory, considering different lithological combinations of the roof and varying coal seam burial depths. A digital photogrammetry system was used to analyze the experimental results. Under conditions where the integrity of the roof rock layers was relatively good, the morphology of the water-conducting fracture zone in all models exhibited a trapezoidal shape. Specifically, the water-conducting fracture zone in the hard rock roof model showed a regular trapezoidal shape. The study also analyzed the connectivity of fractures in the model based on the theory of plastic hinges, revealing that the plastic zone morphology obtained from the strain-softening model in the three-dimensional numerical simulation presented a stepped trapezoidal shape. Wang Deming[10] established a three-dimensional geological model test system, which effectively revealed the evolution laws of displacement, seepage pressure, and the mass of ejected materials during tunnel water and mud inrush under the influence of fault fracture zones.

For the prediction and analysis of roof water inrush, the key factors lie in the distribution of aquifers and the developmental characteristics of the water-conducting fracture zone. In this study, a numerical model was established using the simulation software FLAC^{3D}. Under the condition of an overlying aquifer above the coal seam, as the working face advanced a certain distance during coal mining, large-scale failure occurred in the overlying rock strata due to excavation-induced disturbances. This led to the formation of a water-conducting fracture zone that connected to the aquifer, thereby creating a water-conducting channel and triggering roof water inrush. The simulation software demonstrated the development of the water-conducting fracture zone in the overlying rock strata, the variation in roof water inrush, and the volume of inrush water. The results provide valuable insights for preventing roof water inrush during safe coal mining operations.

2. Engineering Background

The Sima Coalfield is bounded to the south by the Jingfang Coal Mine and to the north by the Nanzhai Coal Mine of Sanyuan Coal Industry Co., Ltd. The Jingfang Coal Mine, operated by Changzhi County, currently extracts Coal Seam No. 3 through a pair of inclined shafts using the longwall mining method with full caving for comprehensive extraction. The immediate roof of the coal seam consists of carbonaceous mudstone with a thickness of 0–0.16 m, while the direct roof is composed of mudstone with a thickness of 2.5-3.0 m. The main roof is sandstone. The mine has a drainage volume of 50-62.5 m^3/h and a relative gas emission rate of 1.19 m^3/t. It is classified as a low-gas mine, and no incidents of spontaneous coal combustion have been reported. The current annual production is 3 million tons. Based on the data from the surrounding areas of the 1303 working face, the roof and floor strata of the coal seam were reasonably simplified and consolidated to establish a physical and mechanical model of the rock strata, as shown in Figure 1.

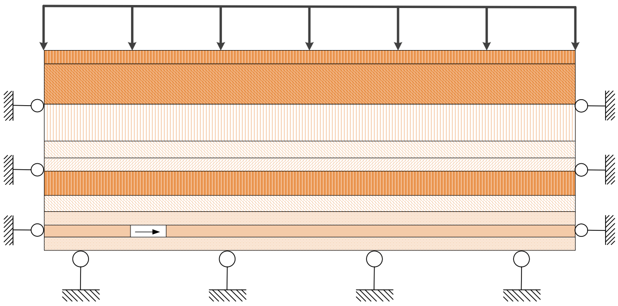
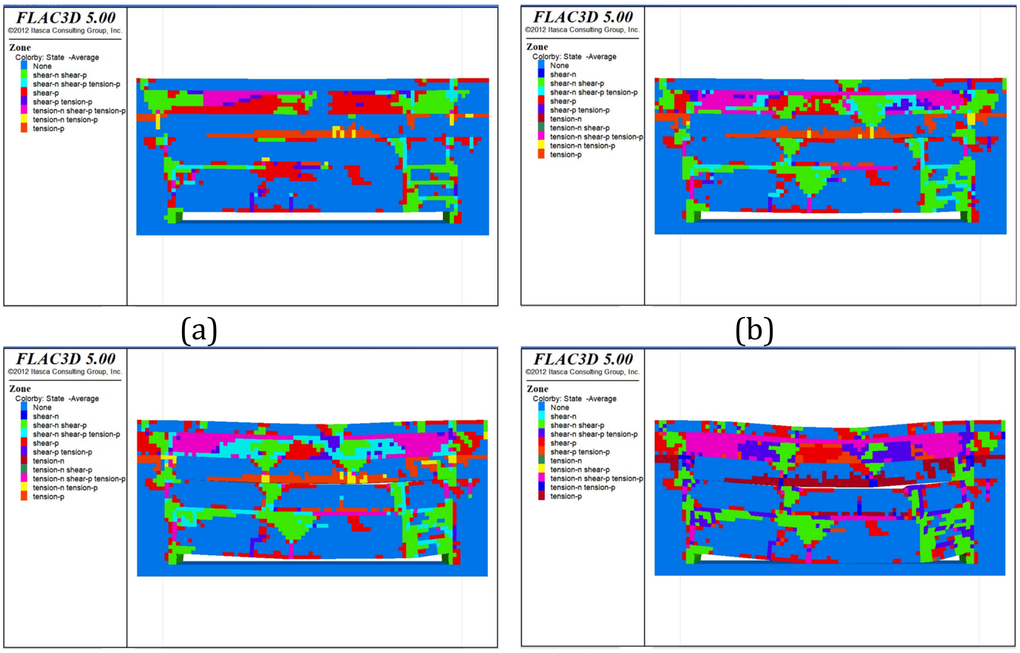


Figure 1. Physical Model

3. The Development of Water-Conducting Fracture Zone and Separation Zone

3.1. The development of the main water flowing fractured zone

Figure 2 presents the cloud diagram of the development of the water-conducting fracture zone after the working face has advanced 140 meters. The overall morphology of the water-conducting fracture zone exhibits a "saddle shape." Between the 40-meter and 140-meter sections of the working face, the development pattern of the water-conducting fracture zone approximates a trapezoidal shape.



(a) (b)

(c) (d)

Figure 2. Development cloud of the pilot fracture zone after the working face was advanced by 140m

During the advancement of the working face, the immediate roof completely collapses, while the main roof forms a cantilever beam structure. Due to the presence of the sub-key stratum (fractured zone), the development of the water-conducting fracture zone does not continue upward indefinitely; instead, it stagnates below the sub-key stratum. After the sub-key stratum fractures, the overlying rock layers simultaneously undergo fracturing, causing the water-conducting fracture zone to rapidly extend upward. When the working face advances to 140 meters, the water-conducting fracture zone in the coal seam roof develops up to the main key

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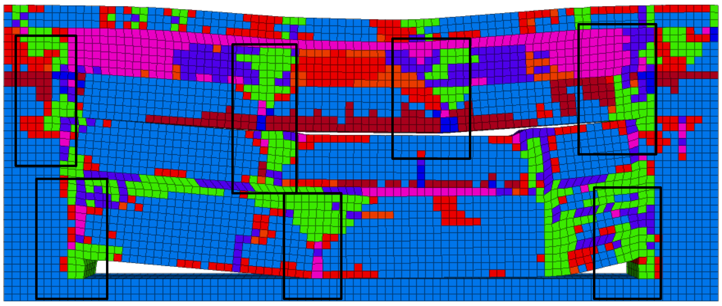
stratum (bending zone), and its height stabilizes, forming an approximately trapezoidal developmental morphology.

Due to the cantilever beam structure formed by the "bending zone," under the pressure of the overlying rock strata, the deformation of the "bending zone" leads to the formation of four main water-conducting fracture zones from left to right within the model, located at 15 meters, 70 meters, 100 meters, and 150 meters, respectively.

Meanwhile, the failure and collapse of the "fractured zone" and "caved zone" result in the formation of four main water-conducting fracture zones at 20 meters, 80 meters, 140 meters, and 158 meters in the model, as shown in Figure 3.



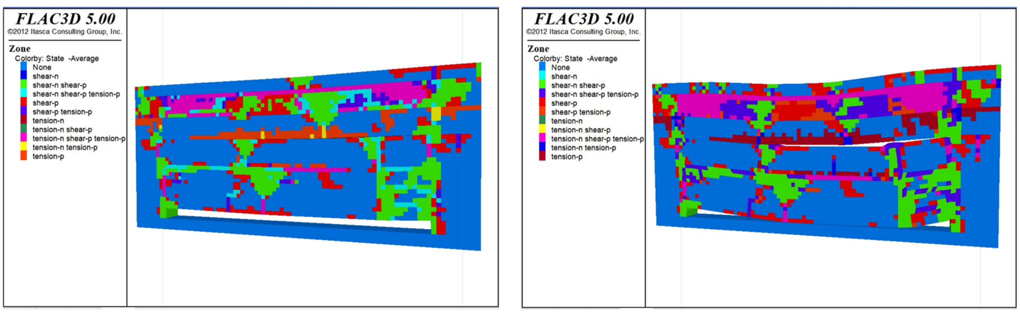
water-conducting fracture zone

Figure 3. Dominant fissure zone development conglomerate

3.2. Separation zone development

As shown in Figure 4 below, the main key stratum (bending zone) bears the weight of the overlying rock strata above it without reaching its fracture strength. The main key stratum deforms in coordination with the upper rock layers but exhibits non-coordinated deformation with the lower rock layers, resulting in the formation of a separation zone between the key stratum and the top of the water-conducting fracture zone. Due to the load-bearing effect of the sub-key stratum, the upper rock layers near the working face do not collapse to the developmental height of the water-conducting fracture zone but instead support the weight of the overlying rock layers in a cantilever beam structure.

With the continuous development of the water-conducting fracture zone, the lower rock layers (fractured zone and caved zone) continuously subside, causing the height of the separation zone to increase until the "caved zone" completely collapses, at which point the development of the separation zone ceases. The maximum developmental height of the separation zone is 2.3 meters, with an average height of 0.8 meters.



(a) (b)

Figure 4. Destratogenetic contour map

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4. Roof Water Inrush Quantity

4.1. Analysis of water pressure of surrounding rock

After the water-conducting fracture zone connects to the overlying aquifer, water from the aquifer flows into the working face through the water-conducting fracture zone under the influence of gravity and the hydraulic pressure of the aquifer.

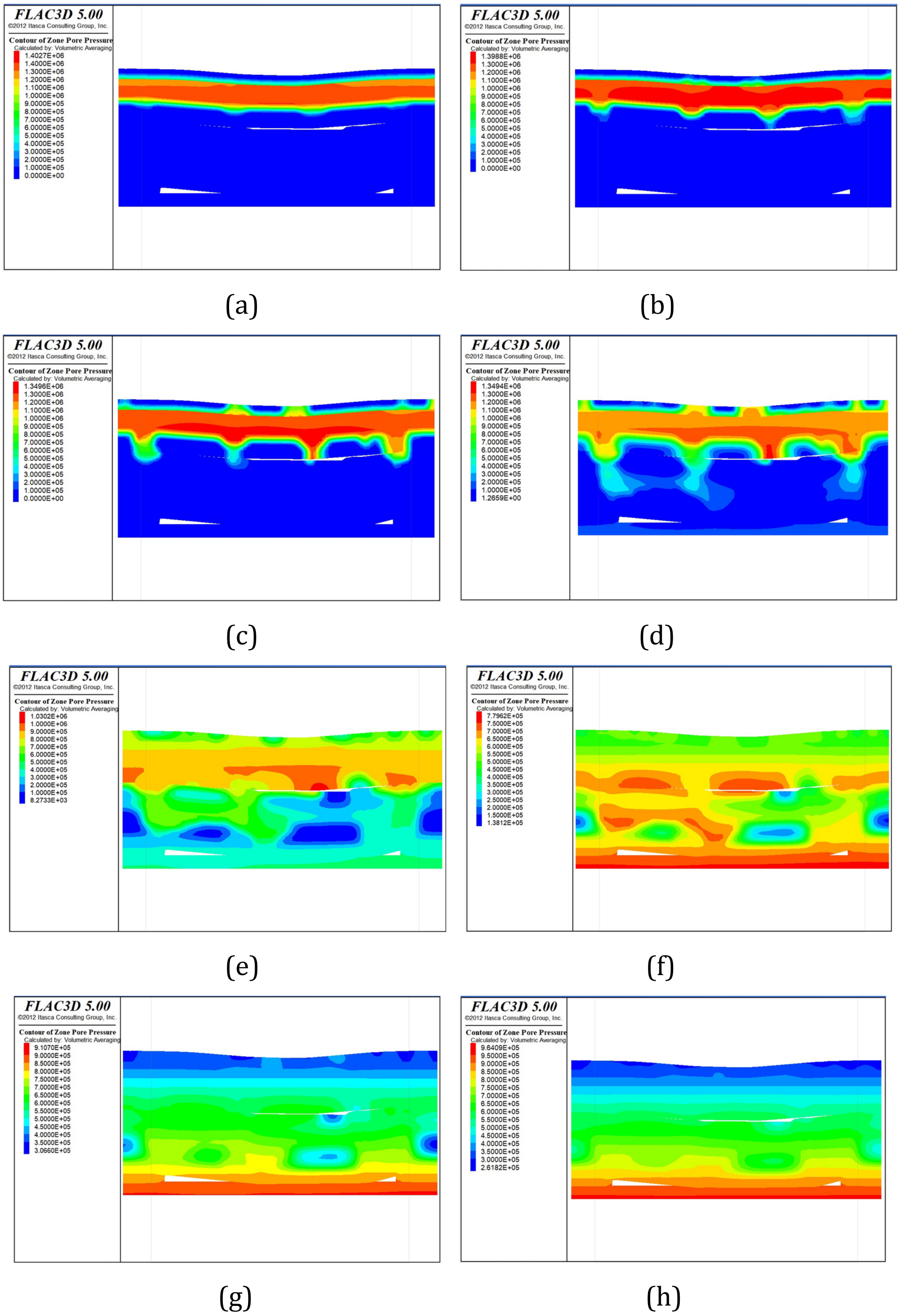

Figure 5. Contour of water pressure change in numerical model

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From the beginning of the seepage simulation, the changes in water pressure within the model are illustrated in Figures 5-(a) and 5-(c). Water from the aquifer initially begins to seep through the four water-conducting fracture zones located at both ends of the working face and the "bending zone" above the two ends of the saddle-shaped water-conducting fracture zone, consistent with the developmental pattern of the water-conducting fracture zone in the "bending zone."

As shown in Figures 5-(d) to 5-(h), once the water breaks through the "bending zone" and enters the separation space, it begins to fill the separation space and continues to seep downward along the main water-conducting fracture zones in the "fractured zone and caved zone" until it connects with the working face. At this point, water inrush begins at the roof of the working face and continues until the water stabilizes under the influence of gravity. The main water inrush points in the working face correspond to the locations of the dominant water-conducting fracture zones in the roof.

4.2. Statistical analysis of roof water inrush

The volume of water inflow directly influences the risk level of water inrush disasters. Once water inrush occurs, the greater the water inflow, the more severe the disaster. Therefore, water inflow is one of the primary indicators for early warning of water inrush disasters. To study the variation in water inflow in roadways, the node variables built into FLAC3D were used to investigate the patterns of water inflow changes during the excavation of deep roadways. To monitor the water inrush volume from the roof in detail, monitoring points were set at each node of the roof, totaling 426 points.

As the four water-conducting fracture zones in the "bending zone" connect to the overlying aquifer, water seeps into the separation zone under the influence of gravity and the hydraulic pressure of the aquifer. It then flows downward through the water-conducting fracture zones in the "fractured zone" and "caved zone" toward the working face.

Along the Y-direction, the maximum water inrush from the roof occurs at approximately 80 meters of the working face excavation, with a peak value of 5.12 m^3/h. This indicates the presence of a dominant water-conducting fracture zone at this location, consistent with the distribution of dominant water-conducting fracture zones in the "fractured zone" and "caved zone."

The cloud diagram of water inrush volume at the roof monitoring points is shown in Figure 6. The maximum water inrush occurs at monitoring points located between coordinates (78, 2) to (78, 8) and (80, 2) to (80, 8), with a peak water inrush volume of 1.024 m^3/h. The locations of the monitoring points with the maximum water inrush correspond to the positions of the dominant water-conducting fracture zones in the roof.

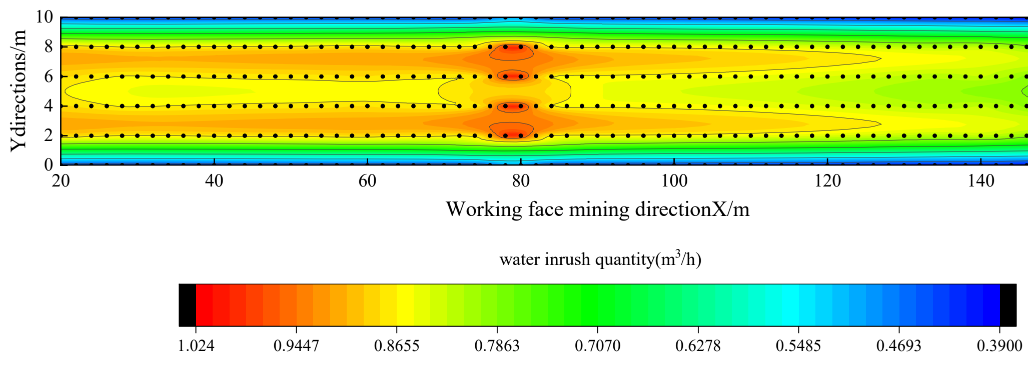

Figure 6. Water inrush contour map of roof detection point

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5. Conclusion

In this study, a numerical simulation model of coal seam mining was constructed using the FLAC^{3D} software to simulate the collapse of overlying rock strata caused by mining activities, resulting in the formation of the "upper three zones" distribution characteristics in the overlying strata. The distribution patterns of the "upper three zones," the development of water-conducting fracture zones connecting to the overlying aquifer due to rock mass failure, and the seepage patterns of aquifer water through the water-conducting fracture zones toward the working face were investigated. The following conclusions were drawn:

(1) After the working face advanced 140 meters, the overall developmental morphology of the water-conducting fracture zone exhibited a "saddle shape." The deformation of the "bending zone" led to the formation of four main water-conducting fracture zones from left to right, located at 15 meters, 70 meters, 100 meters, and 150 meters in the model, respectively. Meanwhile, the failure and collapse of the "fractured zone" and "caved zone" formed four main water-conducting fracture zones at 20 meters, 80 meters, 140 meters, and 158 meters along the working face. A separation zone formed between the "bending zone" and the "fractured zone," with a maximum developmental height of 2.3 meters and an average height of 0.8 meters.

(2) The main water inrush point on the roof was located at approximately 80 meters of the working face excavation, where the maximum water inrush volume reached 5.12 m^3/h. Based on the monitoring points on the roof, the maximum water inrush occurred at coordinates (78, 2) to (78, 8) and (80, 2) to (80, 8), with a peak water inrush volume of 1.024 m^3/h at the monitoring points. Statistical analysis revealed that the maximum water inrush volume from the roof was 54.9 m^3/h.

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