Research Article

Evolution Mechanism of Water-Conducting Channel of Collapse Column in Karst Mining Area of Southwest China

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There are many karst collapse columns in coal seam roof in the southern coal field in China, which are different from those in coal seam floor in the northern coal field, due to the stratum characteristics. The karst collapse column in coal seam roof tends to reactivate and conduct water and induce the serious water inrush disaster, when the karst collapse column communicates with the overlying aquifer. In order to reveal the evolution mechanism of water-conducting channel of collapse column in karst mining area of southwest China, the aquifers and water inflow rule in 1908 working face in Qianjin coal mine are analyzed. Besides, the particle size distribution and mineral component of collapse column are researched by the X-ray diffraction test and the screening method, which are the basis for researching the water inrush mechanism in karst collapse column. On this basis, the water inrush of roof collapse column under the influence of mining is researched by establishing the numerical calculation model with the UDEC numerical software. The results show that the water flowing into the 1908 working face comes from the Changxing formation aquifer and Yulongshan formation aquifer above the coal seam, and the proportion of coarse particles and fine particles in collapse column is 89.86% and 10.14%, respectively. With the advance of working face, the water-conducting channel connected the working face with the aquifer, or the surface is formed by collapse pits, karst caves, and collapse column. The research results can be treated as an important basis for the water-preserved mining in southern coal field in China.

1. Introduction

Water inrush disaster is one of the major safety accidents in coal mine. According to statistics, the direct economic loss caused by water inrush disaster ranks first among all kinds of coal mine accidents [1]. More precisely, the water inrush of collapse column has the characteristics of concealment, abruptness, large water inrush value, and high harm, which is the hotspot and difficulty in the disaster-causing mechanism of water inrush in coal mine [2]. The geological structure of collapse column exists between the coal resource of Longtan formation and the aquifer of overlying Changxing formation, due to the overlap between late Permian coalfield and karst area in south China, especially with Guizhou province as the center, which is different from those in coal seam floor in the northern coal field [3]. The karst collapse column in coal seam roof tends to reactivate and conduct water in the mining process of working face and induce the serious water inrush disaster, when the karst collapse column communicates with the overlying aquifer, which poses a serious threat to safety production in coal mines [4]. For example, the water inrush disasters of roof collapse column occurred in working face in Qianjin coal mine and Xintian coal mine in Guizhou province, which greatly affected the safety mining [5, 6]. Therefore, it is of great significance to research the water-conducting channel of collapse column in karst mining areas, in order to ensure the safe mining of working face in southwest China.

The scholars at home and aboard have carried out lots of research on the water-conducting channel of collapse column. Wang et al. [7] conducted variable mass seepage experiments for broken mudstone considering particle migration, by using a modified variable mass seepage experiment system on broken rock and study the water inrush mechanism of karst collapse column in different depths with coupled underground
water pressure and compaction degree. Du et al. [8] studied the influence mechanisms of porosity of porous medium, the particle sizes of broken rock mass, and sand on water-sand inrush disaster, by using the self-developed porous medium two-phase water-sand flow testing system. Wu et al. [9] designed an experimental system for testing the seepage property of broken rock under the condition of mass loss and studied the effect of dissolution on the seepage property of broken rock. Based on the imagination between column pipeline of water inrush and thick wall canister, Yin et al. [10] generalized the former as column pipelines of uniform patterns and simulated with mechanical models of thick wall canisters. Song et al. [11] derived the criteria equation of elliptical cross section of thick cylinder collapse columns mechanical model in water inrush mode and predicted water inrush by karst collapse columns, by using complex function, elastic-plastic mechanics, and related theories. Li et al. [12] carried out the physical simulation experiment about mining effect on the activated collapse column, by the self-designed similar simulation experiment system, and observed the change laws of seepage field around collapse column and apparent resistivity. Yang et al. [13] researched the water inrush due to karst collapse columns, which is considered to be a coupled processes that can be characterized with Darcy equation in confined aquifer, Brinkman equation in fractured zone, and Navier-Stokes’s equation in tunnel. Zhu et al. [14] established the formulation of a damage-based hydromechanical model based on elastic damage theory, by understanding the mechanism of water inrushes controlled by geologic structures is of vital importance for adopting effective measures to prevent their occurrence. Yao et al. [15] presented a mechanical model for water outburst of karst collapse pillar involving the processes of solid deformation, water flow, particles erosion, and migration and obtained the variation of porosity, seepage velocity, water pressure, and particle concentration as well as water inflow volume as the time.

The above research results are focus on the water inrush mechanism of collapse column in north China, where the water resource is the Ordovician limestone aquifer in floor of coal seam [16, 17]. However, the water resource of collapse column in southwest China is the Yulongshan and Changxing limestone aquifer in roof of coal seam, which is different from the water inrush of collapse column in north China [18]. Besides, the particle size distribution and mineral component of collapse column are not researched intensively, which are the basis for the water inrush mechanism of karst collapse column [19]. The water-preserved mining in karst area in southwest China has not researched. Therefore, the evolution mechanism of water-conducting channel of collapse column in karst mining area of southwest China is researched systematically, on the basis of the 1908 working face in Qianjin coal mine in Guizhou province. The research results can be treated as an important basis for the prevention and treatment of water inrush disaster in southern coal field in China.

2. Overview of Trial Working Face

2.1. Mining Geological Condition. Karst landforms are well developed in Qianjin coal mine, which is located at Meidong-chang village, Jinpo township, Qianxi county, Bijie city, Guizhou province, such as peak cluster, depression, dissolving bucket, and karst cave [20, 21]. The 9# coal seam is the mining coal seam, and the thickness is basically stable, with an average thickness of 1.8 m and an average buried depth of 245 m. The trial engineering background is based on the 1908 working face in Qianjin coal mine. The strike length of 1908 working face is 403 m, and the cutting hole length is 104 m, and the dip angle of coal seam is 8°~14°, and the average dip angle is 10°. Because the dip angle of coal seam is gentle, the longwall mining method is employed to mining the coal seam, and the caving method is employed to manage the roof. Atmospheric precipitation is mostly concentrated in underground caves and underground rivers, while surface water resources are scarce [22, 23]. A collapse column exists at a distance of 235 m from the working face to the cutting hole. The length of long axis of the collapse column is 32 m, and the length of the short axis is 18 m.

2.2. Hydrological Geological Condition. There are two limestone aquifers exist above the 1908 working face, which are Changxing formation aquifer near the coal seam and Yulongshan formation aquifer far from the coal seam. The Yulongshan formation aquifer is exposed in the central and southern areas in the mine field, and the average limestone thickness is 130 m. Geomorphology is diversity, such as karst dissolution and underground karst cave. Besides, the depression is accompanied by falling-water holes, dissolving bucket, and vertical wells. Due to the strong development of surface karst fissure and underground karst pipeline, it is easy to collect a large amount of surface precipitation, which turns into karst fissure water and interlayer karst pipeline water. The Changxing formation aquifer is exposed in the north of the mine field, and the average thickness of limestone is 7 m. The limestone in outcrop area is strongly weathered, and the karst fissure is developed, which contains abundant karst fissure water. The gushing water at the 1908 working face comes from the Changxing formation aquifer and Yulongshan formation aquifer, conducted by the activated karst collapse column. According to the monitoring situation in 1908 working face in Qianjin coal, a large amount of water flow occurs in the working face, when the working face is 2 m away from the collapse column. Besides, the gushing water is affected by atmospheric precipitation. The water inflow in working face lags behind the atmospheric precipitation, and the water inflow begins to increase sharply in the rain after about two days.

3. Particle Distribution and Mineral Component of Collapse Column

The collapse column is the geological structure composed of fillings such as fine argillaceous and crushed rocks. The particle distribution and mineral component of collapse column are the basis for researching the water inrush mechanism of karst collapse column. The X-ray diffraction testing (XRD) and the screening method are carried out in this article, and the effect of particle distribution and mineral component on the seepage characteristic of collapse column is obtained.
3.1. Particle Distribution of Collapse Column. The dried particles of collapse column are screened by standard screens of different pore sizes and divided into different groups according to the particle size of standard screen diameters; then, the percentages of particle groups in the total amount are weighed and calculated. Specifically, a representative sample of dried collapse column weighed 500 g is poured into the standard screens. Then, vibrating the representative sample by the standard screens of different pore sizes, which is shown in Figure 1. Finally, the weight of particle remaining on each screen is weighed, and the particle size distribution of collapse column is obtained.

The particle size distribution of the collapse column is obtained through the standard screening test. These particles that cannot pass the minimum coarse screen (2 mm) are regarded as coarse particles (greater than 2 mm), while those that pass the minimum coarse screen are regarded as fine particles (less than 2 mm). The test result indicates that the proportion of coarse particles and fine particles is 89.86% and 10.14%, respectively. Besides, the particle size of 20-40 mm occupies the largest proportion (31.91%), followed by the particle size of 10-20 mm (21.08%). The mass loss of fine particles in collapse column in seepage accelerates the evolution and formation of water-conducting channel in karst mining area.

3.2. Mineral Component of Collapse Column. XRD (X-ray diffraction) is a diffraction pattern which is obtained by diffraction of X-rays in crystals [24, 25]. The mineral component of collapse column is measured by the X-ray diffraction test (XRD), which is shown in Figure 2. The XR test result indicates that the content of illite is 68%, and the content of quartz is 17%, and the content of pyrite is 11%, and the total content of sphalerite, calcite, zinccite, and anatase is 4%. The collapse column contains a large proportion of viscous minerals, such as illite, which are easy to transport along with water migration, causing the porosity expansion of collapse column, thereby triggering water inrush disaster of karst collapse column.

4. Numerical Simulation of Water Inrush of Roof Collapse Column

4.1. Numerical Calculation Model. UDEC (Universal Distinct Element Code) is the numerical calculation program based on the theory of discrete element method. The numerical calculation model is established, with reference to mining geological conditions of 1908 working face, which is shown in Figure 3. The length and the height of numerical model are 600 m and 245 m, respectively. Besides, the height of the collapse column is 186 m, and the upper boundary and lower boundary of the collapse column is 10 m and 30 m, respectively. There are two sinkholes in the surface and eight karst caves in limestone strata. The mining height and the mining depth of the coal seam are 2 m and 240 m, respectively.

The left and right boundary of the numerical calculation model is the velocity boundary condition, which are fixed horizontally, and the bottom boundary of the numerical calculation model is fixed vertically. Besides, the left boundary, right boundary, and bottom boundary of the numerical calculation model are set as impermeable boundary, while the top of the numerical calculation model is set as free permeable boundary. The water pressure of the aquifer in overlying limestone strata is 0.25 MPa. The mining step by step is adopted, and the mining length is 400 m. The material constitutive model is More-Coulomb model, and the joint constitutive model is coulomb slip model of surface contact. Besides, the physical parameters of rock mass are shown in Table 1, and the percolation mechanical parameters of joints are shown in Table 2.

4.2. Result Analysis. When the 1908 working face is mining to 140 m, the first weighting on the working face occurs. The distribution characteristics of mining-induced fracture field in overburden are shown in Figure 4, and the maximum opening of the fracture in overburden is 23.41 mm. The fractures in the roof of the working face are concentrated at the front and rear ends of the stope, and the fracture opening is greater than 5 mm. The fracture opening in floor is distributed at 0.1 mm-1 mm, and the fracture opening of the compacted rock mass in gob is distributed at 1 mm-5 mm. The first weighting on the working face has little effect on the collapse column. The first weighting in working face is the initial breakage of the basic roof, and the periodic weighting in working face is the periodic breakage of the basic roof.

When the 1908 working face is mining to 280 m, the distribution characteristics of mining-induced fracture field in overburden is shown in Figure 5, and the maximum opening of the fracture in overburden is 31.46 mm. The fractures in the roof of the working face are caused by periodic weighting in overburden, which are concentrated at the front and rear ends of the stope, and the fracture opening is greater than 5 mm. The fracture opening in floor is distributed at 0.1 mm-1 mm, and the fracture opening of the compacted rock mass in gob is distributed at 1 mm-5 mm.

The analysis of permeability characteristics of water-conducting channel in overburden is based on the fractures with the opening greater than 5 mm, since fractures with an opening greater than 5 mm belong to good water-conducting channels. From the transverse perspective, the fracture opening of collapse pits and karst caves above gob increases from 0.1 mm-1 mm to 1 mm-5 mm and greater.
than 5 mm, and the collapse column is connected with the collapse pit and karst cave through the mining-inducing fractures in the surrounding rock. From the vertical perspective, the collapse column is effected by the mining of working face, and the fracture opening of collapse column close to the working face increases from less than 0.1 mm and 0.1 mm-1 mm to 1 mm-5 mm and greater than 5 mm. Therefore, the water-conducting channel connected the surface with the working surface is formed by collapse pits, karst caves, and collapse column. The velocity diagram of water flow in the water-conducting channel can be obtained, as shown in Figure 6.

When the 1908 working face is mining to 300 m, the working face is in the center of collapse column. The distribution characteristics of mining-induced fracture field in overburden are shown in Figure 7, and the maximum opening of the fracture in overburden is 23.64 mm. The fractures in the roof of the working face are concentrated at the front and rear ends of the stope, and the fracture opening increases from less than 0.1 mm and 0.1 mm-1 mm to greater than 5 mm. The fracture opening in floor of working face is distributed at 1 mm-5 mm, and the fracture opening in floor of gob is distributed at 0.1 mm-1 mm. The fracture opening of the compacted rock mass in gob is distributed at 1 mm-
Table 1: The physical parameters of rock mass.

| Rock strata      | h/m  | K/GPa | G/GPa | d/N·m⁻³ | f° | C/MPa | t/MPa |
|------------------|------|-------|-------|---------|----|-------|-------|
| Limestone        | 138  | 26.6  | 21.9  | 2800    | 42 | 6.53  | 5.7   |
| Kern stone       | 4    | 21.3  | 16.7  | 2650    | 38 | 4.23  | 3.23  |
| Limestone        | 20   | 26.6  | 21.9  | 2800    | 42 | 6.53  | 5.7   |
| Siltstone        | 6    | 18.5  | 16.2  | 2800    | 37 | 3.64  | 2.25  |
| Silty mudstone   | 13   | 19.4  | 9.5   | 2840    | 33 | 2.65  | 2.1   |
| Fine sandstone   | 7    | 20.7  | 17.8  | 2800    | 37 | 3.64  | 2.25  |
| Silty mudstone   | 9    | 19.4  | 9.5   | 2840    | 33 | 2.65  | 2.1   |
| Fine sandstone   | 30   | 7     | 20.7  | 17.8   | 2800 | 37 | 3.64  | 2.1   |
| Silty mudstone   | 5    | 19.4  | 9.5   | 2840    | 37 | 2.65  | 2.1   |
| Fine sandstone   | 6    | 20.7  | 17.8  | 2800    | 37 | 3.64  | 2.25  |
| Coal seam        | 2    | 3.89  | 1.59  | 1600    | 40 | 1.50  | 1.2   |
| Argillaceous siltstone | 5 | 21.0  | 12.6  | 2770    | 35 | 3.15  | 2.31  |
| Collapse column  | 186  | 1.30  | 0.50  | 1300    | 35 | 0.5   | 0.5   |

Table 2: The percolation mechanical parameters of joints.

| Rock strata      | h/m  | jkn/GPa | jks/GPa | jfric/° | jperm/Pa⁻¹.s⁻¹ | ares/m | azero/m |
|------------------|------|---------|---------|---------|----------------|--------|---------|
| Limestone        | 138  | 8.06    | 6.39    | 10      | 246            | 0.003  | 0.02    |
| Kern stone       | 4    | 7.46    | 6.18    | 11      | 198            | 0.003  | 0.02    |
| Limestone        | 20   | 8.06    | 6.39    | 10      | 246            | 0.003  | 0.02    |
| Siltstone        | 6    | 4.58    | 2.73    | 8       | 128            | 0.003  | 0.02    |
| Silty mudstone   | 13   | 8.06    | 6.39    | 11      | 100            | 0.003  | 0.02    |
| Fine sandstone   | 7    | 4.58    | 2.73    | 10      | 143            | 0.003  | 0.02    |
| Silty mudstone   | 9    | 8.06    | 6.39    | 11      | 100            | 0.003  | 0.02    |
| Fine sandstone   | 30   | 4.58    | 2.73    | 10      | 143            | 0.003  | 0.02    |
| Silty mudstone   | 5    | 8.06    | 6.39    | 11      | 100            | 0.003  | 0.02    |
| Fine sandstone   | 6    | 4.58    | 2.73    | 10      | 143            | 0.003  | 0.02    |
| Coal seam        | 2    | 4.09    | 2.50    | 10      | 85             | 0.0003 | 0.003   |
| Argillaceous siltstone | 5 | 4.58    | 2.73    | 15      | 95             | 0.003  | 0.02    |
| Collapse column  | 186  | 3.46    | 2.20    | 14      | 330            | 0.010  | 0.08    |

Figure 4: The mining-induced fracture field (the mining distance is 140 m).
5 mm and greater than 5 mm. With the advance of the working face, the fracture opening of the basic roof formed by the periodic weighting decreases from greater than 5 mm to 1 mm-5 mm, due to the compaction effect.

When the 1908 working face is mining to 320 m, the collapse column lies behind the working face. The distribution characteristics of mining-induced fracture field in overburden are shown in Figure 8, and the maximum opening of the fracture in overburden is 29.46 mm. The fractures in the roof of the working face are concentrated at the front and rear ends of the stope, developed mostly in the area of collapse column. The fracture opening at the lower end of collapse column is greater than 5 mm, and the fractures of karst cave on the upper right of collapse column develop to the surface, connected with the upper end of collapse column. The fracture opening in floor of working face is distributed at 1 mm-

Figure 5: The mining-induced fracture field (the mining distance is 280 m).

Figure 6: The velocity diagram of water flow (the mining distance is 280 m).
5 mm, and the fracture opening in floor of gob is distributed at 0.1 mm-1 mm. The fracture opening of the compacted rock mass in gob is distributed at 1 mm-5 mm and greater than 5 mm. With the advance of the working face, the fracture opening of the basic roof formed by the periodic weighting decreases from greater than 5 mm to 1 mm-5 mm.

5. Conclusions

(1) The water flowing into the 1908 working face comes from the Changxing formation aquifer and Yulongshan formation aquifer above the coal seam, conducted by the activated karst collapse column. Besides, the water inrush quantity is affected by atmospheric precipitation, and the water inflow in working face lags behind the atmospheric precipitation; more precisely, the water inflow begins to increase sharply in the rain after about two days.

(2) The proportion of coarse particles and fine particles in collapse column is 89.86% and 10.14%, respectively. Besides, the particle size of 20-40 mm occupies the largest proportion (31.91%), followed by the particle size of 10-20 mm (21.08%). Besides, the collapse column contains a large proportion of viscous minerals, such as illite, which are easy to transport along with water migration, triggering water inrush disaster of karst collapse column.

(3) When the working face is in the center of collapse column, the maximum opening of the fracture is 23.64 mm. Besides, the collapse column is affected by the mining of working face, and the collapse column is connected with the collapse pit and karst cave through the mining-inducing fractures. Therefore, the water-conducting channel in overburden is formed, containing collapse pits in surface, karst caves, collapse column, and working face.
Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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