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Research Article

Study on the Migration Law of Overlying Strata on the Working Surface of Large Mining Height in Y.C.W Coal Mine

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The migration law of overlying strata on working face is of great significance for safe mining of working face. In this paper, theoretical calculation, numerical simulation, and similar simulation are used to study the distribution characteristics, migration, and fracture law of key strata in the overlying strata of 130204 working face of Y.C.W coal mine and the relationship between the development height of water flowing fractured zone and the spatial position of weak aquifer. The theoretical calculation results show that there are "one main two sub" key strata in the overlying strata of 130204 working face, which play an important role in controlling rock movement. Numerical simulation and similar simulation results show that the first weighting step distance of the direct roof of 130204 working face is about 30-40 m. The initial weighting interval of the basic roof of the working face is about 70-80 m, and the periodic weighting interval is about 23.5-25 m. After the first weighting and multiple periodic weighting of the basic roof of the working face, the first subcritical layer is located in the caving zone, the second subcritical layer is located in the fracture zone, and the main key layer is finally located in the bending subsidence zone. The final height of the caving zone of the overlying strata is about 24 m, and the height of the water flowing fractured zone is about 130 m. Since the water-conducting fractured zone is connected and passes through the second subcritical layer with weak water-bearing property, it is possible for the water permeability accident of the working face. Therefore, in order to ensure the safety of the working face, the water should be detected and released in advance during the mining of the working face.

1. Introduction

Coal plays an important role in the development of national economy and society. Fully mechanized caving mining technology with large mining height in thick coal seam has been rapidly popularized and applied for its advantages of high recovery rate, high mechanization degree, safety, and high efficiency [1, 2]. Generally, the fully mechanized mining with mining height of 3.5~5.0 m is called large mining height, and the fully mechanized mining with mining height of more than 5.0 m is called extralarge mining height [3, 4]. At the same time, large mining height mining has more problems than normal mining height workings, such as the greater thickness of mining, the greater collapse height of the overlying strata after coal mining, and the stronger pressure on the roof of the working face. In order to study the stability and control technology of the surrounding rock under the conditions of large mining height, it is necessary to study the transport and failure law of the overlying rock layer on the large mining height working face.

Many domestic scholars have carried out constructive research work on the moving rule of roof and overburden structure characteristics of large mining height working face. Gong and Jin [5] and Peilin and Zhongming [6] applied the key stratum theory, and according to different strata structures of the immediate roof, the immediate roof of the large mining height is divided into three types, namely I, II, and III. Wen et al. [7] pointed out that accurately determining the position, thickness, and possible maximum ceiling span of overburden strata is the key to the roof control design and support selection calculation of large mining height mining face. Hao et al. [8] concluded that there is a balance structure in the overburden layer on the large mining height fully mechanized working face, which is higher than that of the upper rock layer but similar to that of the layered extraction, and the activity of this structure is a gradual change process.

Huang and Zhou [9, 10] and Huang and Tang [11] proposed that the immediate roof "short cantilever beam" structure and the basic roof key strata "high oblique step beam" structure model for the roof of large mining height working face revealed the mechanism of pressure coming from the large mining face. Fu et al. [12] concluded that the height of the roof caving zone and fracture zone showed a stepwise rise by similar simulation tests on the 5.5 m high working face of Shangwan coal mine in Shandong mining area. Yang and Liu [13] and Yang [14] obtained that the reason why the mining pressure is more intense than that of the ordinary mining height working face is that the mining intensity of the working face is high and the roof activity is violent, which leads to the single structure of the key layer, low occurrence layer, easy to slip and instability, and the overall breakage of the overlying roof. It is concluded that Yin [15] proposed a structural model of " cutting block " of overlying rock layer in shallow buried super-high working face and believed that the overburden layer of shallow buried coal seam is cut down and broken as a whole, forming an articulated structure mainly by slipping and destabilization. Pang et al. [16] considered that the peak stress, differential stress, and strength-stress ratio of sandstone in different horizons had very great difference and proposed the structure and stability control technology of "cantilever beam+masonry beam" for the roof rock fracture of ultra large mining height working face.

Xiang et al. [17] established the dynamic distribution equation of caving zone in different mining stages in the case of structural rock strata and no structure in the direct roof, revealing that the caving zone in overburden goaf of large mining height working face presents obvious dynamic change characteristics. Sun [18] obtained the progressive fall characteristics of overburden from bottom to top in the western weakly cemented strata and revealed the mechanism of overburden fracture eruption-development-penetration. Zhao et al. [19] divided the overlying strata of the stope into six regions according to the fracture development pattern after fully mining in the working face with 8.8 m ultralarge mining height. The fitting formula of fracture development height, mining height, and working face advancing distance was obtained by numerical simulation. Jin et al. [20] believed that the distribution law of advanced abutment pressure in front of the coal wall in deep working face with large mining height was not related to the mining depth but mainly depended on the mining face height and the composition structure of roof strata. Liang et al. [21] concluded that there are two structural patterns and six moving types of the key stratum in a fully mechanized mining face with large mining height, gave and verified the formation conditions of each structural form and movement pattern, and revealed the influence law of the six key layer movement types on the mine pressure in the mining site. Hu and Jin [22] established a mechanical model of large mining height working face through field mine pressure observation and made a preliminary study on the classification of the working face roof and the rationality of bracket selection. Sun et al. [23] used three technical methods, including loses of drilling fluid measuring, borehole wall observing by color TV, and transient electromagnetic method (TEM) geophysical exploration, to detect the height of "two zone" of the overlying rock layer in the goaf of large mining face. Wu [24] concluded that the overburden structure of large mining face in thick coal seam is "composite cantilever structure-nonarticulated roof structure-articulated roof structure." Yan et al. [25] and Yu et al. [26] pointed out that the frequency and energy of microseismic events have obvious periodicity and concluded that the roof of fully mechanized caving working face with large mining height is a structure of "cantilever beam and articulated rock beam."

Liu et al. [27, 28] studied the stress distribution law of bottom suction roadway and the reasonable position of bottom suction roadway and working face in Zhaogu No.2 mine; this provides theoretical guidance for preventing the occurrence of bottom water seepage accident in working face and at the same time presents a detailed comprehensive case study of strata movement in extraction of a long wall top coal caving panel of a composite coal seam with partings in the Baozigou coal mine. The caved zone and fractured zone development were captured through physical modeling by incorporating the digital image correlation method (DICM), universal distinct element code (UDEC) numerical modeling, and field observation with the method of high-pressure water injection. Zhang et al. [29] established a three-dimensional discrete element numerical model of soft overburden in high-intensity mining and analyzed that the maximum height of "two zones" of soft overburden in high-intensity mining increases with the increase of mining thickness, but it has no obvious relationship with the dip length and advance speed of high-intensity mining face. By using 3DEC discrete element numerical simulation software, Yu et al. [30] determined the key strata parameters and their control effects under the condition of fully mechanized caving with large mining depth. Li et al. [31] conducted similar simulation, numerical simulation, and theoretical research on the dynamic movement law of the roof in fully mechanized caving mining of steeply inclined extrathick coal seam and revealed that the roof in goaf will have regular alternate movement of "squeezing, sliding, and turning" in space with the advance of the working face.

To sum up, the domestic scholars use a variety of research methods of large mining height in upper strata in mining process of different forms of structure and movement; the "two belts" of overburden rock height were studied, which has achieved good results, but for large mining height under the condition of mining rock weak aquifer and water flowing fractured zone height between the spatial evolution, the law research is relatively small. After the mining of Yangchangwan coal mine with 130204 high mining height, there is a possibility that water gushing accident may occur in the working face due to the connection of water-conducting fracture zone with weak aquifer in overlying strata. Based on this, the author conducted in-depth research on the migration and breaking rule of overlying strata in the mining of 130204 high mining height working face, and the development height of water-conducting fracture zone.

2. Engineering Background and Determination of the Location of the Key Layer

Y.C.W coal mine is located in Ningdong Town, Lingwu City, Ningxia Hui Autonomous Region, with a north-south direction length of about 12.8 km and an east-west inclination width of about 9.8 km. The No. 2 coal seam mined in 130204 fully mechanized coal mining face with large mining height is a stable coal seam that can be mined in the whole region. The average buried depth of the working face is 508.9 m, the average dip angle of the coal seam is 9°, and the average thickness of the coal seam is 8 m. The comprehensive column diagram of the coal seam at the face is shown in Figure 1. The mining method of 130204 working face is large mining height and full height toward the long wall comprehensive mechanized backward caving mining method. Above 130202 working face mined-out area, the coal pillar of 35 m is left in the transportation groove with 130202. The lower part is the original coal seam without mining, so there is no mining activity affecting the mining of the working face. The geological data of working face tunneling show two normal faults, DF12 branches cross 130204 working face. The layout of fully mechanized working face is shown in Figure 2, in which the strike length of working face is 2531 m and the inclination length is 290 m.

The first task to study the breakage and transport law of overburden rock in the mining process of Y.C.W coal mine large mining face is to determine the location of the key strata in the overburden rock layer. Bay will be collected at the site of sheep field of roof overburden theory for the physical and mechanical parameters of the calculation; it is concluded that 130204 working face strata exist in the "one main and two subcritical layers," that is, one main key layer and two subkey layers as shown in Table 1, respectively, located in the 5 m above the roof of coal seam thickness of medium sandstone in 15 m for the subcritical layer. The coarse sandstone with a thickness of 51 m at 24 m away from the top of the roof is the second subkey layer, and the medium sandstone with a thickness of 48 m at 133 m above the roof of the coal seam is the main critical layer. Due to the distance between the main and inferior key strata, the second fault of the inferior key strata will cause a large range of migration of the overlying strata, and the fault distance of the main key strata will be greatly affected by the migration of the lower strata. The mining height of large mining face is relatively large. Therefore, the collapse range of the overlying rock layer is much larger than the collapse range during normal mining height. In addition, there is a possibility of forming an articulated link balance structure, and the

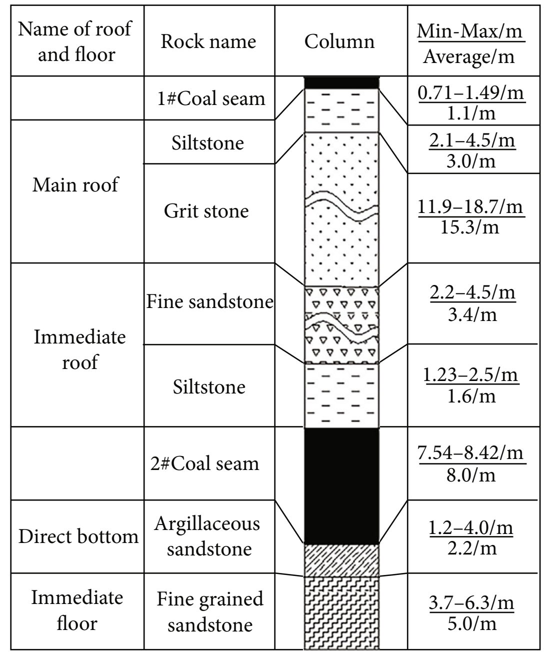

Figure 1: 130204 comprehensive column diagram of coal and strata in working face.

stable "masonry beam" structure may also have the structural form of "cantilever beam" and rotary collapse deformation due to excessive rotary volume, affected by the increase of mining height at the working face. The "masonry beam" structure is more likely to be formed in the higher rock seam above the coal seam.

Xu et al. proposed a height prediction method of water-conducting fracture zone based on the location of key layers [32], which is as follows: the specific methods and steps are as follows: first, according to the calculated location of the key stratum and the height of the mining coal seam, the identification of the key stratum broken fractures through. If the location of the key stratum is more than 7-10 M away from the height of the mining coal seam, the fracture fracture of the key stratum is not connected. If the location of the key stratum is less than 7-10 M from the height of the mining coal seam, the fracture fractures of the key stratum are connected, and the fracture fractures of the overlying strata controlled by the key stratum are also connected. Determine the height of the water-conducting fracture zone. When the main key stratum of overburden is within the critical height (7-10) M, the water-conducting fracture will develop to the top of bedrock, and the height of water-conducting fracture zone is equal to or greater than the thickness of bedrock. When the main key stratum of overburden is located beyond the critical height (7-10) M, the water-conducting fracture will develop to the bottom of the nearest key stratum above the critical height (7-10) M, and the height of the water-conducting fracture zone is equal to the height of the key stratum from the mining coal seam.

Based on the above theory and calculation method, further combined with the borehole bar chart of Y.C.W 130204 working face with large mining height and the determined key layer and location, it is concluded that the

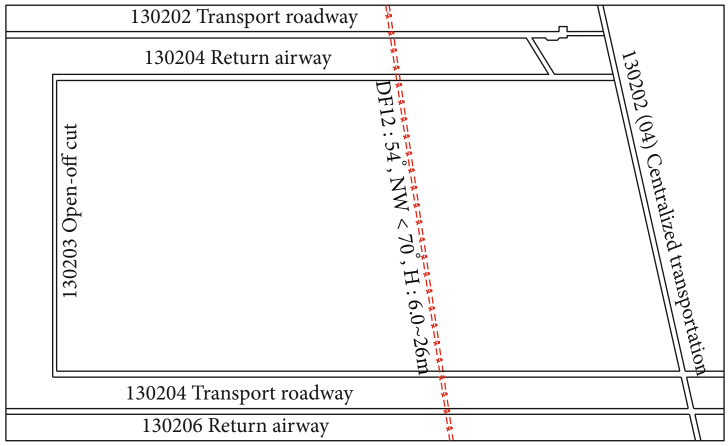

Figure 2: 130204 fully mechanized mining face layout.

Table 1: Mechanical parameters of overlying rock of working face and identification of key horizon.

No.	Rock name	Tensile strength (MPa)	Elastic modulus (GPa)	Poisson ratio	Cohesion (MPa)	Angle of internal friction (°)	Density (kg/m^3)	Thickness (m)	Depth (m)	Key strata location
1	Silty mudstone	2.64	1.14	0.22	4.27	39.2	2200	27	309	
2	Siltstone	2.4	1.39	0.22	9	42	2600	4	313	
3	Medium sandstone	3.12	0.85	0.22	7	39.2	2500	48	361	Main key stratum
4	Mudstone	1.5	0.78	0.34	6.89	24.7	2350	15	376	
5	Fine sandstone	3.86	1.44	0.23	4.83	52.4	2350	7	383	
6	Mudstone	1.15	0.56	0.34	6.89	24.7	2350	6	389	
7	Fine sandstone	3.51	1.52	0.23	4.83	52.4	2350	6	395	
8	Silty mudstone	2.64	1.14	0.22	4.27	39.2	2200	22	417	
9	Medium sandstone	3.12	0.82	0.23	7	39.7	2500	2	419	
10	Grit stone (with water)	3.27	1.46	0.23	4.66	46.7	2350	51	470	Inferior key strata II
11	1# coal seam	1.32	0.67	0.25	0.75	40.2	1500			
12	Siltstone	2.4	1.39	0.22	9	42	2600	1	471	
13	Medium sandstone	3.05	1.82	0.23	7	39.7	2500	3	474	
14	Fine sandstone	3.79	1.22	0.23	4.83	52.4	2350	15	489	Inferior key strata I
15	Siltstone	2.35	1.28	0.22	9	42	2600	3	492	
16	2# coal seam	1.35	0.71	0.25	0.75	40.2	1500	2	494	
17	Mudstone	1.57	0.68	0.34	6.89	24.7	2350	8	502	

fracture fracture of subkey layer 2 will be penetrated, while the fracture fracture of main key layer will not. The final development height of the water-conducting fracture zone is no more than 133 m. Therefore, the water-conducting fracture zone will run through the weak water-bearing strata above the working face. In order to ensure safe mining, water exploration and release work should be carried out in advance.

3. Numerical Simulation of Overlying Strata Migration Law on Working Face with Large Mining Height

3.1. Establishment of Numerical Model and Layout of Measuring Line. Based on geological conditions of 130204 working face with large mining height in Y.C.W coal mine and rock mechanical parameters measured in laboratory,

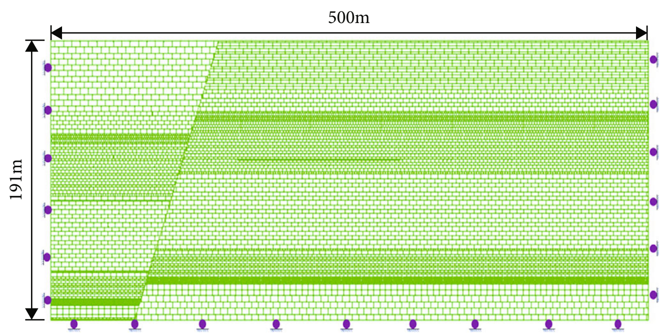

Figure 3: UDEC numerical model diagram of large mining height working face in Y.C.W coal mine.

considering the occurrence effect of DF12 fault, on the basis of reasonable simplification, the UDEC numerical model of Y.C.W coal mine working face with large mining height is established in two parts, as shown in Figure 3.

The size of the model is $X \times Y = 500\,\mathrm{m} \times 191\,\mathrm{m}$, the strike length of the model is 500 m, and the boundary influence area on both sides is 50 m. The left and right boundary is fixed by limiting the velocity and displacement in X and Y directions; thus, the boundary effect of the left and right models should be eliminated. The upper boundary of the model was fixed by applying 8.4 MPa overburden load in Y direction and setting stress gradient.

The model was calculated using the Coulomb criterion, and its physical and mechanical parameters are shown in Table 1. In 130204 working face, survey line 1 is arranged at the bottom of the direct roof of 2# coal seam; side line 2 is arranged at the boundary of the central strata of the direct roof 5 m above 2# coal seam; side line 3 is arranged at the bottom of the basic roof 20 m away from 2# coal seam roof. The model uses the method of multiple excavation, each excavation 5 m, continuous excavation 2 times, and recording data; namely, excavation of 10 m records a measuring point displacement and stress change data.

3.2. Numerical Simulation Analysis of Overlying Strata Migration Law. In the stress state of overlying strata in 130204 working faces of Y.C.W coal mine from 10 m excavation to 300 m advance, as shown in Figure 4, after the open-off cut, the overlying strata have a small bending due to the suspension. When the working face is pushed forward to 10 m (Figure 4(a)), the direct roof above the coal seam has the trend of subsidence, and the separation between the top and the basic top is formed. As the working face continues to advance to 30 m (Figure 4(b)), the distance between the direct roof and the basic roof increases gradually. The direct roof at the position of 30 m reaches the limit span, and the first collapse occurs. The collapse length is about 15 m and the height is 5 m. The first collapse of the direct roof falls behind with the advance of the working face, and the length of the basic roof is gradually increasing.

When the working face advances to 70 m (Figure 4(c)), a large area of collapse occurs after the basic roof reaches the ultimate breaking distance. The length of collapse is about 65 m and the height is about 20 m. The pressure of the working face is intense, and the strata above the basic roof also produce obvious cracks. When the working face advances to 95 m (Figure 4(d)), the basic roof breaks again. However, due to the support of the collapsed and broken rock strata to the overlying rock strata, the second subcritical layer after the broken rock blocks occluded each other to form a relatively stable articulated structure, which controlled the upper rock strata to sink obviously and produce a large separation layer. At this time, the basic roof breaking is periodic pressure, and the interval of periodic pressure step is 25 m. The analysis shows that the height of caving zone is about 24 m and the height of water flowing fractured zone is about 67 m.

When the working face advances to 120 m (Figure 4(e)), the third periodic fracture occurs on the main roof, and the periodic weighting step is 25 m. Because the caving broken rock strata fill the goaf sufficiently, the cracks formed above the goaf with the compaction of the overlying rock strata during the second cycle compaction of the coarse sandstone layer of the subkey 2 are closed. However, the water flowing fractured zone is further developed in the direction of the fracture angle of the strata before and after the mined-out area. At this time, the height of the caving zone is 24 m and the water flowing fractured zone is 98 m. When the working face advances to 300 m (Figure 4(f)), the overlying strata have undergone multiple periodic fractures. The periodic weighting step of the basic roof is about 25 m, and the maximum caving height is 24 m. At this time, the sandstone layer in the main key layer of the working face has been bent and sunk, and the development height of the water flowing fractured zone is 121 m. Compared with the results of the front mining, it is found that the development height of the water flowing fractured zone is no longer increasing with the expansion of the mined-out area, and the working face has entered the stage of full mining.

The measuring line 3 is placed in the basic roof 20 m away from the roadway roof, and 10 measuring points are arranged on the measuring line. From the cutting side, the measuring points are 10 to 1 along the mining direction, and the interval is 50 m. After extracting the data of the measuring points, the vertical displacement curve with the advancing process of the working face is obtained, as shown in Figure 5. With the mining face advancing to 30 m, the vertical displacement of monitoring point 9 and monitoring point 10 has changed obviously, and the direct roof of the working face has first collapsed. When the working face is mined to 70 m, the monitoring point 8 sank sharply, and the maximum subsidence

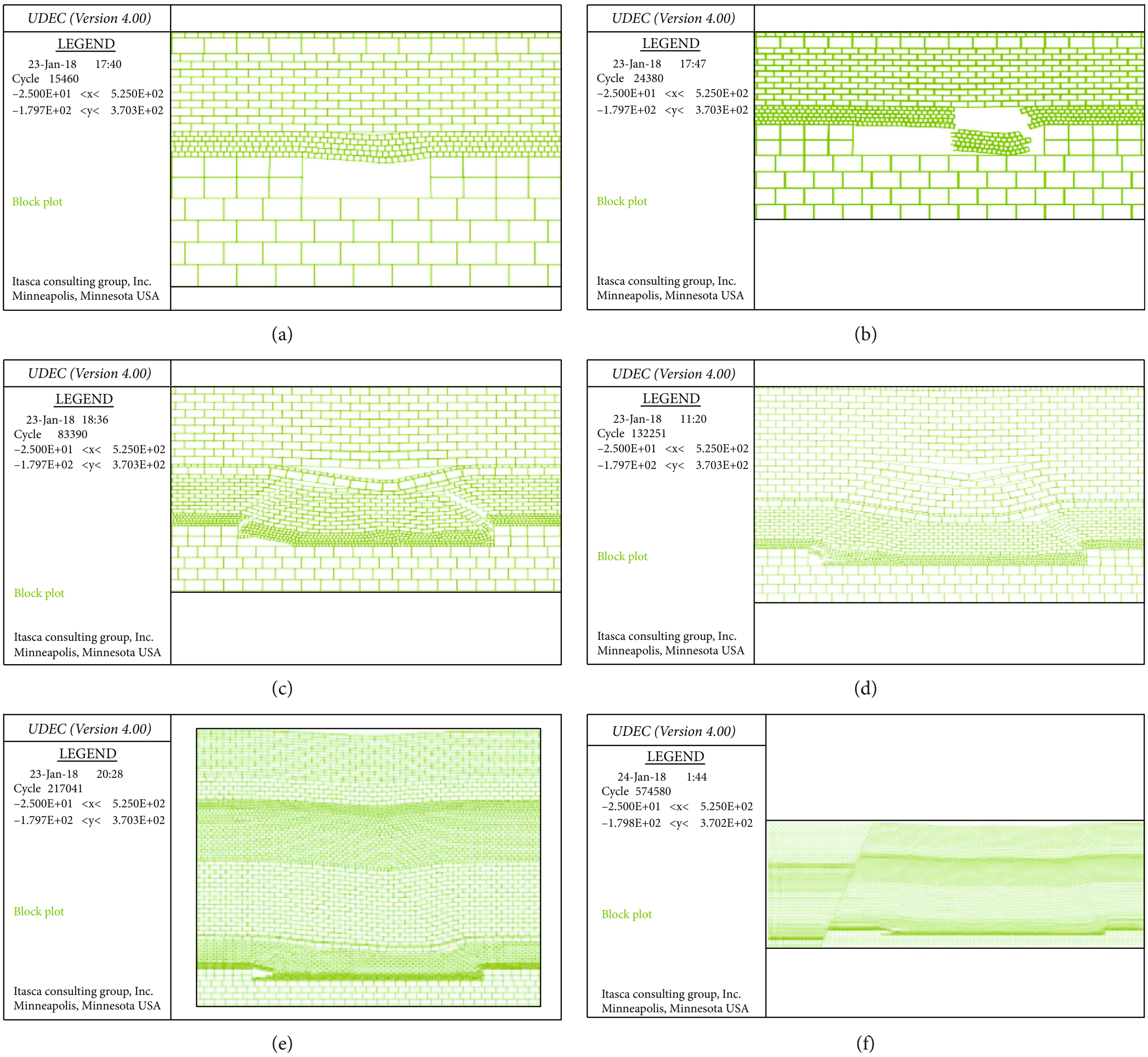

Figure 4: The migration change map of overlying strata under different distances of working face advancing, including (a) 10 m, (b) 30 m, (c) 70 m, (d) 95 m, (e) 120 m, and (f) 300 m.

reached 2.44 m. At this time, the primary roof collapsed and the roof collapsed in a large range. When the working face continues to stop at 95 m, the vertical displacement of monitoring point 7 continues to increase, and the maximum displacement increases to 3.49 m, and the vertical displacement of monitoring point 8 increases more. Therefore, the second periodic collapse of the basic roof of the working face occurred. By analyzing the maximum vertical displacement of 10 monitoring points in the mining process of the working face, when the vertical displacement of each monitoring point tends to be stable, the fully mining is achieved.

From Figure 6(a), it can be seen that the overlying strata on the working face have not broken and collapsed when the working face has not been mined after the opening and cutting of the working face, and the direct roof above the coal seam has subsided, but the subsidence is not large, but the shape of triangle-like cracks is produced in the interior of the direct roof and the bottom of the basic roof, and the height of the water-induced fracture zone is 9 m.

With the continuous advancement of the working face, the immediate roof above the mined-out area behind the working face continues to bend and sink, and a relatively obvious separation phenomenon occurs. The water flowing fractured zone continues to develop upward in a triangle shape. When advancing to 30 m, the direct roof breaks down for the first time, and the water-induced fracture zone rises further. At this time, the water-induced fracture zone develops to 33 m and develops into the weak aquifer of the second coarse sandstone in the subcritical layer. When the working face advances to 70 m and 95 m, the development heights of water flowing fractured zones are 45 m and 67 m. When the working face advances to 95 m, the longitudinal fractures develop upward in the shape of trapezoid. When the working face advances to 120 m, the basic roof

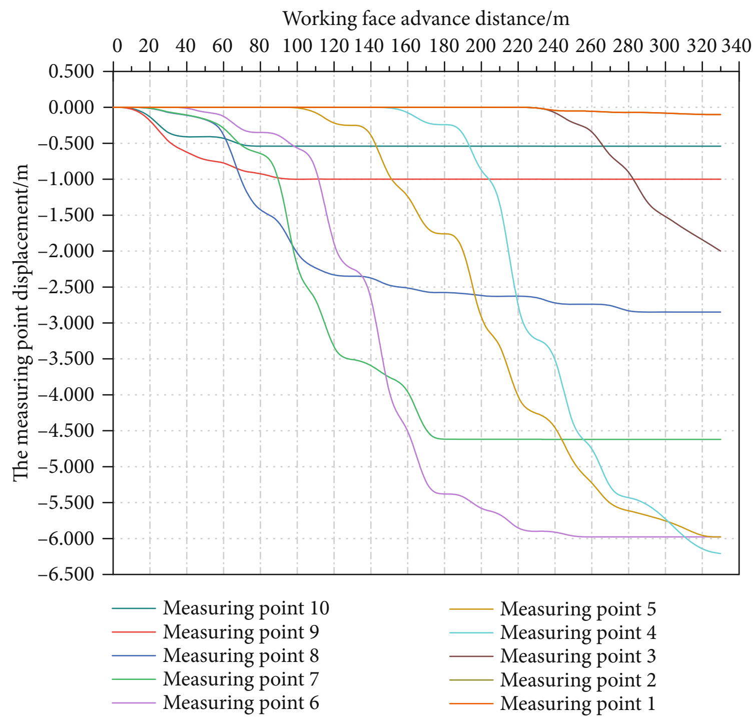

Figure 5: Measuring line 3 vertical displacement curve of each measuring point.

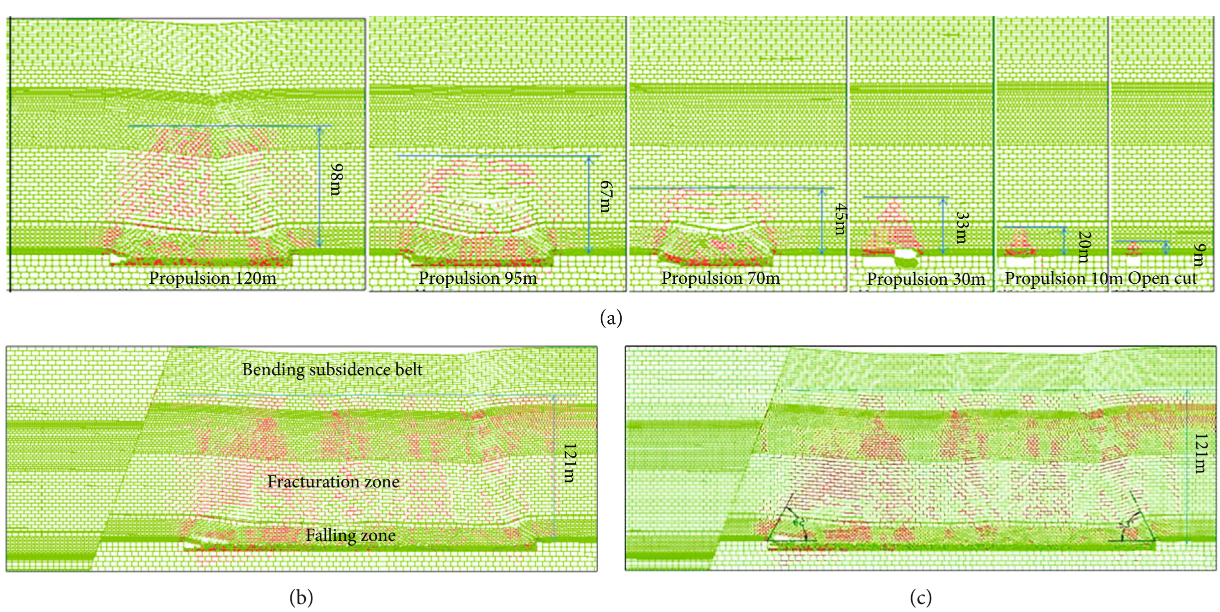

Figure 6: Variation of height of water flowing fractured zone with advancing distance of working face, including (a) 0, 10, 30, 70, 95, and 120 m and (b) 300 m and (c) stop mining line.

falls for the second time, and the water flowing fractured zone is still developed in a shape similar to the trapezoid with a development height of about 98 m.

When the working face advances to 300 m (Figure 6(b)), the overlying strata have reached full mining. At this time, the maximum development height of the water flowing fractured zone is 121 m. The fracture development is obvious in the overlying strata of the coal wall of 20 m in front of the working face, and a small range of longitudinal fractures also appear near the fault.

At the stop coal line position (Figure 6(c)), the height of the water flowing fractured zone did not continue to increase upward, still maintained at 121 m, but the fault activation was further obvious, and the cracks near the fault were further developed but did not connect with the water flowing fractured zone formed above the mined-out area, because

Table 2: Material ratio table of similar simulation test of Y.C.W mine 130204 working face.

Number right	Lithology	Model bulk density (g/cm^3)	Compressive strength of model (MPa)	Total thickness (cm)	Material ratio number	Total layered weight (kg)
16	Siltstone	1.63	0.07	4	855	1.97
15	Medium sandstone	1.56	0.06	21.5	755	10.14
14	Claystone	1.38	0.11	7.5	755	9.99
13	Fine sandstone	1.47	0.12	3.5	755	11.51
12	Claystone	1.38	0.11	3	755	10.05
11	Fine sandstone	1.47	0.12	3	855	10.25
10	Silty claystone	1.38	0.11	11	755	10.02
9	Medium sandstone	1.56	0.06	1	855	3.92
8	Grit sandstone (water)	1.47	0.08	25.5	755	14.86
7	One layer coal	0.94	0.04	0.5	873	2.09
6	Siltstone	1.63	0.07	1.5	855	6.3
5	Medium-grained sandstone	1.56	0.06	7.5	855	10.54
4	Fine sandstone	1.47	0.12	2	755	8.59
3	Siltstone	1.63	0.07	1	855	4.3
2	Two-layer coal	0.94	0.04	4	873	8.64
1	Silty claystone	1.38	0.11	7.5	755	10.85

Note: The material ratio number 873 indicates that the aggregate (sand) of the material accounts for 80%, the cement material accounts for 20%, and the cement material accounts for 70% lime and 30% gypsum.

it can be considered that the 40 m protective coal pillar left by the fault is reasonable, and the rock breaking angle at the cut is 63°, and the rock breaking angle at the stop mining of the working face is 62°.

4. Similar Simulation Study on Overburden Migration Law in Large Mining Height Working Face

4.1. Establishing Similar Simulation Model and Arranging Displacement Monitoring. Similarity simulation experiment has been widely used in the research of mining and rock mechanics because of its advantages such as easy to control, short test period, high efficiency, visual test results, and repeatable experiment process. On the basis of reasonable simplification, the similarity ratio between Y.C.W coal mine site and model is determined, which includes geometric similarity ratio 200 : 1, bulk density similarity ratio 1.6 : 1, and stress similarity ratio 320. At the same time, the motion of all corresponding points in the simulation is required to be similar to that of the entity; that is, the velocity, acceleration, and motion time of each corresponding point are required to be in a certain proportion, which is 14.1. The materials for similar simulation experiments are divided into aggregate and cementing material, in which fine sand is used for aggregate and lime and gypsum are used for cementing material, and the ingredients for each rock layer are finally obtained after several experiments and comparisons. The rock batching of similar simulation test of Y.C.W mine face 130204 is shown in Table 2. This experiment uses a laboratory table with dimensions of 1800 mm × 160 mm × 1300 mm. Since the second coal seam is a near horizontal coal seam, the dip angle of the coal seam is not considered too much in the lay-up experimental model, and the final completed lay-up model is shown in Figure 7.

The retraction channel was excavated in advance at 15 cm from the fault, and the open-off cut was excavated in advance at 15 cm from the right boundary. The mining height of the model was 4 cm, the model was retrieved every 14 minutes, and the mining length of the model was 140 cm. Since the theoretical calculation of the protective coal pillar of the fault is 40 m, the working face is pushed to stop mining at 40 m from the fault.

4.2. Analysis of the Overlying Rock Collapse Pattern of the Working Face Strike. The initial collapse process of the immediate roof is analyzed, as shown in Figure 8. When the advancing distance of the working face is less than 40 m (Figure 8(a)), there is no caving in the immediate roof. When the working face is pushed to 40 m, 60 m, and 78 m, the first collapse (Figure 8(b)), the second collapse, and the third collapse (Figure 8(c)) occur on the immediate roof, and the collapse lengths are 35 m, 18 m, and 15 m, respectively. Due to the relatively small bulking factor of the immediate roof, the broken rock between the goaf and the basic roof cannot fill the whole space. At this time, there are cracks between the basic roof strata and obvious bed separation phenomenon, and the lower layer is curved and deformed with obvious caving tendency. The lower layer is bent and deformed with obvious caving tendency. When the working face continues to advance to 80 m, the basic roof reaches the ultimate collapse distance (Figure 8(d)). The first weighting occurs with the pressure step of 80 m and the caving height of 5 m. The basic roof does not form a masonry beam structure after the first weighting fracture but forms a cantilever

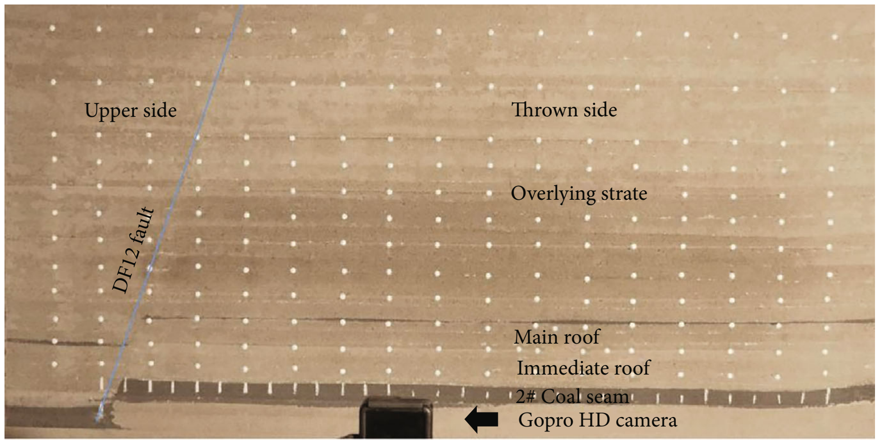

Figure 7: Similar simulation experiment layout.

beam structure. The caving height is 14 m, and the fracture development height is 4 m. The pressure of the working face is intense.

As the working face continued to excavate, the upper layer of the basic roof is broken and collapsed. Finally, when the working face is advanced to 105 m, the basic roof is completely collapsed (Figure 9(a)). The first weighting of the basic roof and the pressure step distance are 24 m, and the caving height is 17 m. The basic roof is separated from the overlying strata, and the longitudinal fracture development height is 26 m. However, the first periodic weighting of the basic roof is different from the first weighting breaking form. In the first weighting, the rock arch of the basic roof is an asymmetric rock arch structure. The thickness of the rock stratum at the right arch angle is thinner than that at the left side, and the bearing capacity is weak and the damage is serious. At this time, a relatively stable masonry beam structure is formed after the basic roof is weighting. The two ends of the beam are hinged on the rock strata that have not collapsed. The bending subsidence in the middle is the largest and acts on the caving zone. The broken rock in the caving zone is further compacted. At this time, the coarse sandstone 24 m above the coal seam is bending and sinking above the mining area, and longitudinal tension fissures are produced at the bottom of the seam, and off-layer fissures are also produced inside the seam, and the fissure zone development height is 28 m.

When the working face is advanced to 145 m (Figure 9(b)), the third periodic weighting of the basic roof and the pressure step distance are 20 m and the caving height is 22 m. The overlying strata continue to bend and sink. As the goaf is gradually filled, the overlying strata form a stable masonry beam structure under the support of the caving rock in the goaf. The maximum separation layer is located above the goaf 110 m behind the working face, and the height of the fracture zone is 62 m. As the working face continues to move forward to 175 m (Figure 9(c)), the fourth periodic weighting of the basic roof is 30 m, and the caving height is 19.5 m. However, the development height of the separation fracture and the longitudinal fracture does not change, and the development height of the fracture zone is 106 m at this time. When the working face is advanced to 185 m (Figure 9(d)), the working face is 60 m from the fault DF12, the fifth periodic weighting of the basic roof and the pressure step distance is 10 m, and the height of the caving zone is 14 m. There is no obvious migration change in the overlying strata, and the height of the fracture zone is still 106 m. When the working face advances to 195 m (Figure 9(e)), the working face is 50 m away from the fault DF12, the sixth periodic weighting of the basic roof and the pressure step distance is 10 m, the basic roof is cut off in large areas, and the caving height reaches 35 m. The overlying strata have undergone dramatic changes, resulting in a large number of separation fractures and longitudinal fractures. The maximum separation fracture develops to 125 m from the roof of the coal seam, and the height of the longitudinal fracture zone reaches 128 m.

When the working face advances to 205 m (Figure 9(f)), the working face is 40 m away from the fault DF12. Since the goaf is almost filled at this time, the extrusion between the rock seams is obvious, the overlying strata separation and longitudinal fracture zone continue to develop upward to 130 m above the roof of the coal seam, and many irregularly shaped fissure development areas appear. At this time, the breaking angle of the overburden at the open-off cut is 68°, and the breaking angle of the overburden at the stopping point of the working face is about 62°. It can be concluded from the collapse and fracture form of overburden roof in the whole process of working face that the goaf space of working face has relatively great influence on the collapse height of overburden roof. Because was not gob caving rock filling in time, so the permission of the overburden subsidence of space more than the limit between the broken blocks allow subsidence, resulting in in general can be formed under the condition of mining height are broken roof hinged structure breakage form, but due to mining under the condition of large mining height are broken down space is too large, lead to rupture rock cannot form the extrusion pressure. Finally, nonarticulated roof structure is applied to caving broken rock mass in goaf. Therefore, the overlying roof strata on the working face of 130204 large mining height in Y.C.W coal mine show the failure characteristics of “nonhinged roof structure-cantilever beam structure-hinged roof structure.” In the process of working

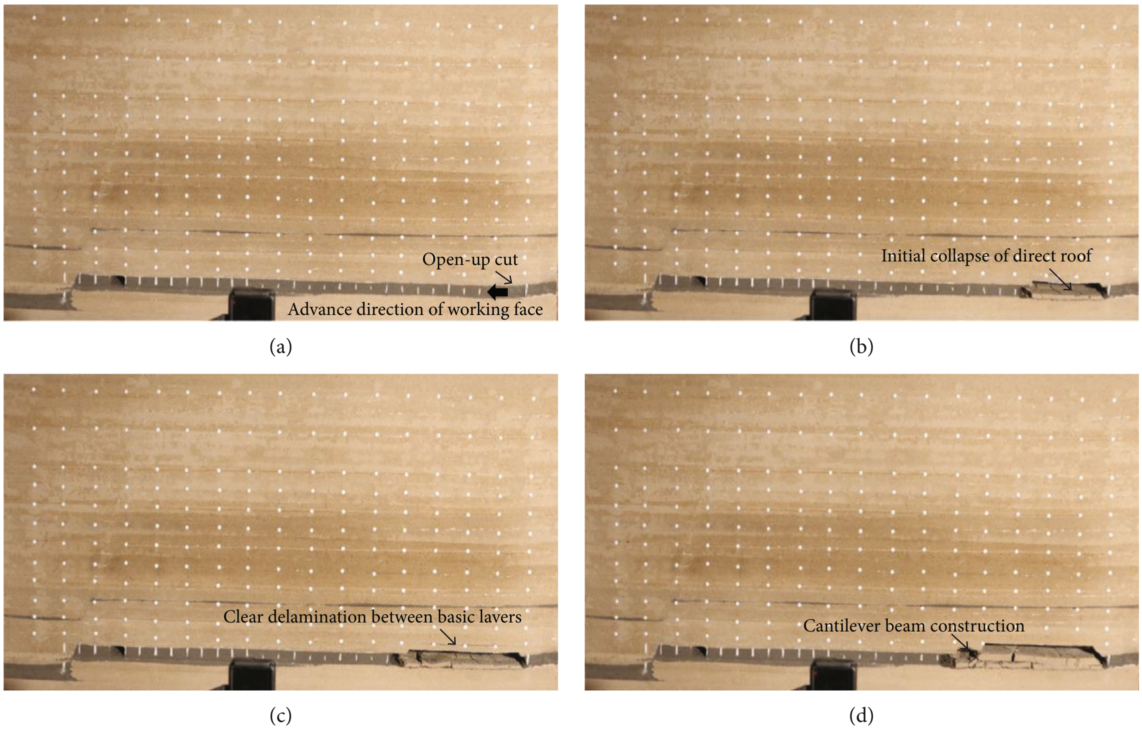

Figure 8: Immediate roof collapse diagram when the working face is advanced at different distances: (a) 0 m, (b) 40 m, (c) 78 m, (d) 80 m.

face advancing from the cut to DF12 fault, the periodic weighting interval of the main roof decreases from an average of 23.5 m to 10 m.

The relevant literature [33–37] shows that the macroscopic visible cracks in the model can be regarded as developed cracks. Therefore, based on the macroscopic visible cracks in the similar simulation experiment, the fracture development and distribution law of the overlying strata are studied. The variation curve of the development height of the water flowing fractured zone with the advance of the working face is shown in Figure 10.

It can be seen from the diagram that with the continuous advancement of the working face, the height of the caving zone increases first and then decreases, but the water flowing fractured zone is on the rise. When the working face advances to 125 m-180 m, the height of water flowing fractured zone develops fastest and reaches the maximum 130 m after the working face advances to the stop line.

Due to the large mining height of the working face, the stable hinge structure is not formed after the subcritical layer 1 reaches the limit breaking distance and enters the caving zone. Therefore, the height of the caving zone increases to 14 m after the first weighting of the basic roof, and the fracture zone also develops 4 m upward, which is shown as the first inflection point of the caving zone and the water flowing fracture zone in the figure. When the working face advances to 105 m, the basic roof continues to break in the form of a cantilever beam, and the overlying strata also break. At this time, the height of the caving zone further increases to 17 m, and the growth is small. The height of the water flowing fractured zone develops to 28 m, and the growth is large. When the working face advances to 125 m, the original hinge structure formed by the subcritical layer one has rotary deformation instability, which leads to its direct collapse, so the height of the caving zone increases rapidly. However, due to the existence of the subcritical layer two, the height of the water flowing fractured zone does not increase significantly, which is the second inflection point of the caving zone and the water flowing fractured zone in the diagram.

In the process of advancing the working face, the subcritical layer one enters the caving zone in the form of cantilever beam and masonry beam alternately, and the goaf space becomes smaller. The height of the caving zone is basically maintained at about 24 m. The bending and breaking subsidence of the subcritical layer two occurs, but due to the support of the broken rock in the goaf, it only enters the fracture zone. When the working face advances to 145 m and 165 m, the rock strata controlled above the bending fracture of the second subcritical layer also move downward, resulting in the development and penetration of internal fractures, and the height of water flowing fractured zone increases rapidly. The second subcritical layer and the overlying strata continue to move downwards, resulting in the formation of a stable masonry beam structure between the strata, which plays a supporting role in the main key layer above. The space under the main key layer is shrinking, and because the main key layer is thicker and stronger, in the process of advancing the working face to the stop line, only bending subsidence occurs, and the internal cracks are not penetrated. Therefore, when the working face reaches the stop line, the height of the water flowing fractured zone only develops to the bottom of the main key layer, and the final development height is 130 m.

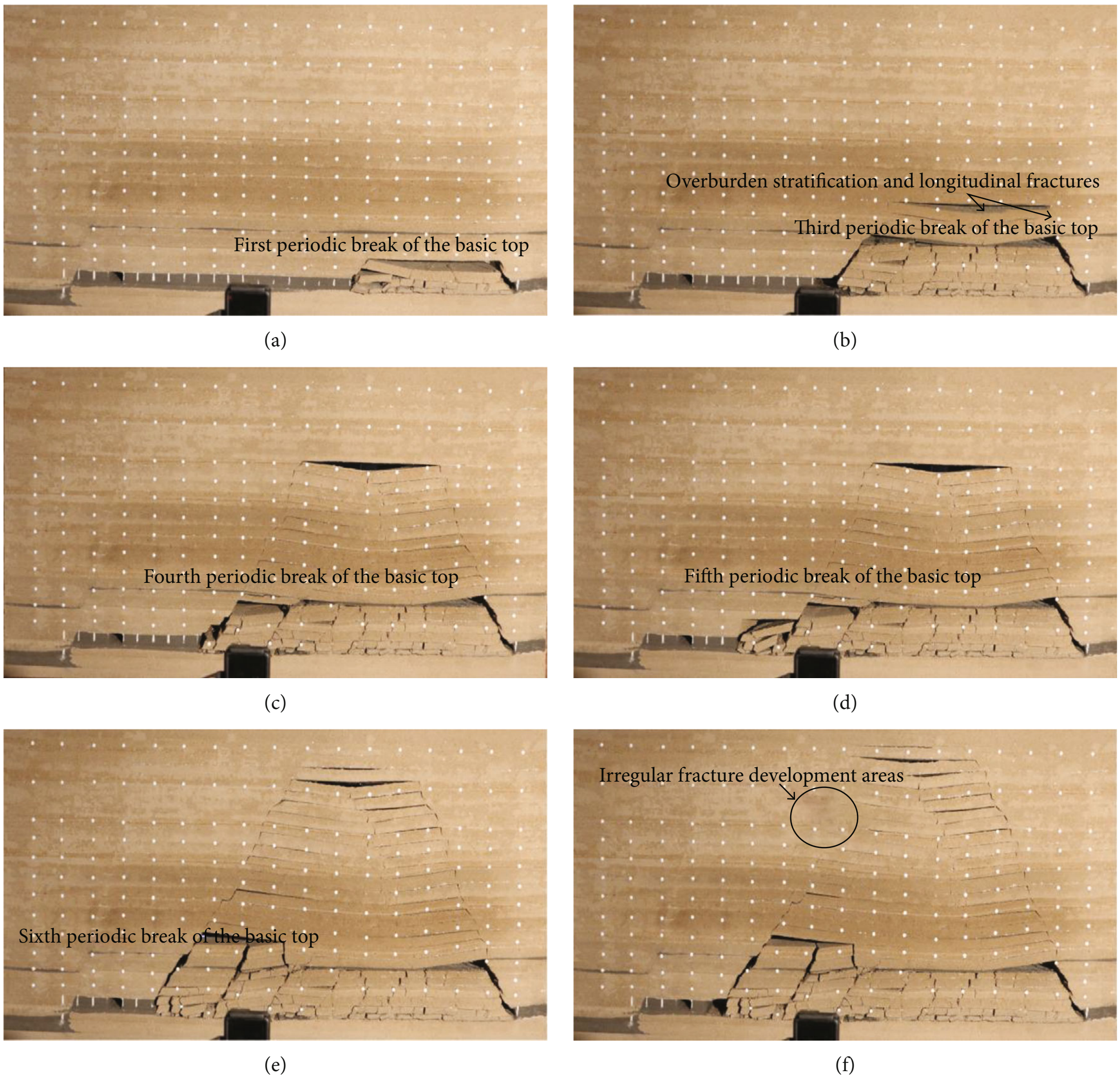

Figure 9: Periodic fracture diagram of basic roof under different distances of working face advancing, including (a) 105 m, (b) 145 m, (c) 175 m, (d) 185 m, (e) 195 m, and (f) 205 m.

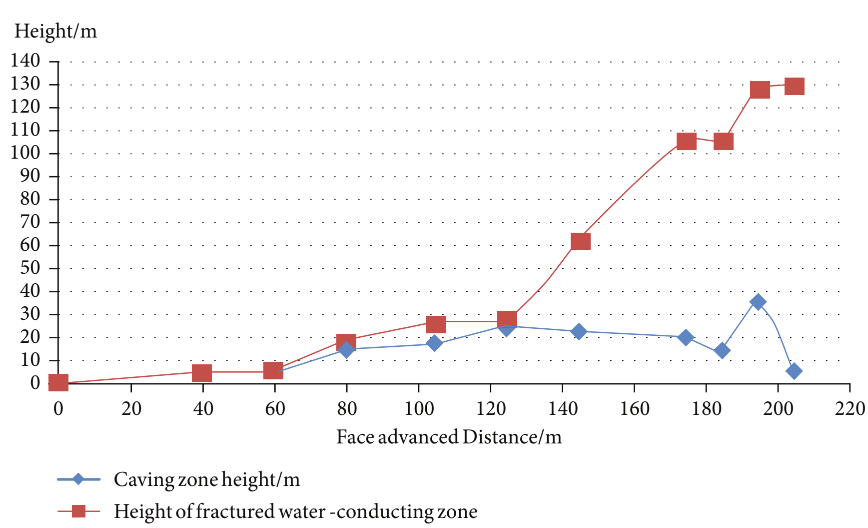

Figure 10: Curves of development height of water flowing fractured zone with working face advancing.

5. Conclusion

By means of theoretical analysis, similarity simulation, and numerical simulation, the migration law of overlying strata on the working face of large mining height in Y.C.W coal mine was studied. It is found that there are some deviations in the results obtained by the three research methods, but they are in line with the error range of engineering practice. Therefore, the maximum and minimum intervals of the three results are taken as the final conclusion. The main conclusions are as follows:

(1) The theoretical analysis results show that there are two subcritical strata and one main key strata in the strata above the direct roof, which are the subcritical strata of medium-grained sandstone with a thickness of 15 m above the coal seam roof. Coarse sandstone subcritical layer 2 with thickness of 51 m above the roof of coal seam is weak aquifer. Middle sandstone main key layer has a thickness of 48 m at 133 m above coal seam roof

(2) The roof of overlying strata on the working face of large mining height shows the failure characteristics of "nonhinged roof structure-cantilever beam structure-hinged roof structure." The initial caving step distance of the direct roof of the working face is about 30-40 m, and the initial caving step distance of the basic roof is about 70-80 m. When the working face is pushed to the DF12 fault greater than 60 m, the periodic weighting step distance is about 23.5-25 m. When the working face is pushed to the stop line position, the breaking angle of the overburden at the cutting hole is 63°-68°, and the breaking angle of the overburden at the stop line is about 62°

(3) With the working face continuous advancement, the overlying rock fractures continue to develop and the height of the water flowing fractured zone generally shows an upward trend. The development shape gradually changes from the initial triangle-like to trapezoid-like, and the final development height of the water flowing fractured zone is about 121-133 m. At the end of the mining, the height of the caving zone is developed to about 24 m. The water flowing fractured zone will lead to the overlying rock of the coarse sandstone weak aquifer above the working face, and the water should be detected and released in advance in the mining of the working face to ensure the safe and efficient mining of the working face

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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