Study on Overburden Structure Characteristics and Fracture Evolution Law in Upward Mining at Kuangou Coal Mine

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Abstract: The development of vertical fractures in the overburden rock below after upward mining of a coal seam can influence the safe mining of both this seam and the seams above. This paper employs the method of physical similarity simulation to experimentally study the overburden structure and fracture evolution law during upward mining of the No. 4 coal seam in Kuangou Coal Mine. The study reveals that the overburden rock of the lower No. 4 coal seam after mining exhibits a typical "three-zone" characteristic, with the caved zone overburden showing a distinct cantilever beam-hinged structure, and the overburden structure of the bending and sinking zone is relatively intact. In the experiment, no significant vertical through-layer fractures were observed during the first five periodic pressures. However, during the 6th to 11th periodic pressure periods, when mining pressure became intense, a total of six vertical through-layer fractures appeared near the coal wall of the working face. These fractures, aligned with the caving angle direction, extended upwards through the No. 3 coal seam located 60m above the No. 4 seam. The overall fracture evolution showed opening during intense mining pressure and gradual closing after the pressure subsided. Two of these vertical through-layer fractures had a larger extension range, eventually reaching the surface. During the upward mining process, the appearance of vertical through-layer fractures did not lead to sliding instability or rapid sinking of the overburden roof. The working face could thus continuously advance. This research has implications for the safe upward mining in similar mines.

Keywords: Upward Mining; Physical Similarity Simulation; Vertical Through-Layer Fracture; Overburden Structure

1. Introduction

Downward mining is the general method used in coal mine extraction of coal seam groups. However, in special circumstances such as the recovery of residual coal resources and limitations in construction conditions, it's possible to first mine the lower coal seams and then the upper ones, adopting an upward mining approach [1]. Upward mining began in the 1920s and 1930s. Poland in the Silesian coalfields, the former Soviet Union in the Donbas coalfields, and the United States in Colorado, Pennsylvania, and Virginia have all conducted research on upward mining, accumulating some successful mining experiences [2,3]. In China, the practice of upward mining began in the 1970s, and numerous scholars and engineering technicians have achieved certain theoretical and on-site application results in upward mining research [4-6]. After years of practice and research, it is preliminarily believed [7-9] that if only one coal seam is mined in the lower part and the influence multiple of mining $Q > 7.5$, the upper coal seam can be mined normally.

However, previous research on upward mining has mainly focused on demonstrating the feasibility of upward mining in a specific mine. Studies on the evolution process of overburden during upward mining and the development law of vertical fractures have been rare [10]. Especially in some regions where coal seams are generally shallow, if upward mining is adopted, vertical through-layer fractures that penetrate the upper coal seams and reach the surface may form during the intense periodic pressure in the mining process of the lower coal seams, directly affecting the safe mining of both the seam in question and the upper seams. Therefore, it is necessary to study the evolution law of overburden fractures in such regions during upward mining. This paper will use the method of physical similarity simulation to experimentally study the fracture evolution law of overburden during upward mining in Kuangou Coal Mine.

2. Mine Overview

Kuangou Coal Mine is located in the northern plateau of the Zhundong mining area. The mine's resources include the No. 2 and No. 4 coal seams. Before the integration of resources in the Kuangou mining field, the remaining recoverable reserves of the No. 2 coal seam were 6.562 million tons. After integration, with further clarification of the situation of the goaf in the No. 2 seam and the setting of coal pillars, there is a possibility of upward mining of the No. 2 seam after the completion of mining in the No. 4 seam. The No. 2 and No. 4 coal seams involved in upward mining have an average minable thickness of 2.91m and 5.89m, respectively, with burial depths of 113-189m (average 178m) for the No. 4 seam, and 66.5-121.3m (average 71.46m) for the No. 2 seam. The average interlayer spacing between these two seams is 60m.

3. Model Establishment

The experimental design model is 3.0m in length, 2.0m in height, and 0.2m in width. The geometric similarity ratio for the physical similarity model is set at 1:100. The simulation is based on the comprehensive columnar diagram of the No. 4 coal seam, as shown in Table 1. The model's geometric similarity constant is 100, the density similarity constant is 1.55, and the stress similarity constant is 155. The model material consists of river sand as aggregate and a mixture of gypsum, white powder, and water as binding materials, proportionally mixed and layered in the model frame.

4. Simulation of Overburden Fracture Evolution in the No. 4 Coal Seam Mining

In the simulation, the thickness of the No. 4 coal seam is 3m and that of the No. 2 coal seam is 6m, with a spacing of 60m between them. The open cut is located 20m from the model's left boundary and has a width of 6m.

Table 1. Model Layer Thickness and Loading Ratio

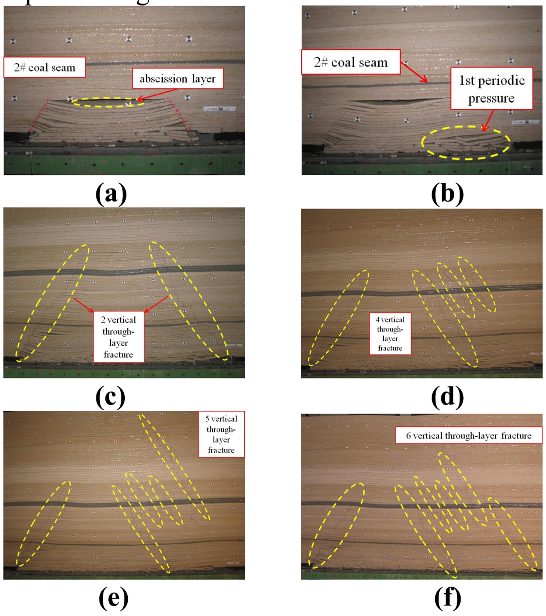
Number	Lithology	Layer Thickness (m)	Model Layer Thickness (cm)	Ratio
1	Loess	50.37	49	819
2	Fine Sandstone	6.63	6	837
3	Muddy Sandstone	4.42	5	737
4	Carbonaceous Mudstone	5.05	4	828
5	No. 2 Coal Seam	5.89	6	2.1（coal ash）
6	Carbonaceous Mudstone	0.31	2	828
7	Fine-grained Sandstone	3.87	3	837
8	Medium-grained Sandstone	6.21	6.5	746
9	Muddy Sandstone	1.17	1.5	737
10	Medium-grained Sandstone	5.3	4.5	746
11	Carbonaceous Mudstone	3.68	3.5	828
12	No. 3 Coal Seam	0.71	0.7	2.1（coal ash）
13	Medium-grained Sandstone	13.13	13	746
14	Sandy Mudstone	2.04	2	828
15	Medium-grained Sandstone	4.71	5	746
16	Siltstone	2.49	3	737
17	Carbonaceous Mudstone	4.23	4	828
18	Fine-grained Sandstone	2.36	2.5	837
19	Carbonaceous Mudstone	3.71	3.5	828
20	Sandy Mudstone	2.58	2	828
21	Fine-grained Sandstone	2.88	3	837
22	Carbonaceous Mudstone	0.87	1	828
23	No. 4 Coal Seam	2.91	3	2.1（coal ash）

When the working face advanced to 55m, a wide range of collapse occurred in the old roof rock layer (Figure 1(a)), leading to the first pressure step at the working face, determined to be around 55m. The collapse height of the rock layer was 12m above the coal seam roof, forming a flat-arch shape with a span of 35m. The collapse angle on the open cut side was 55 degrees, and on the coal wall side, it was 60 degrees. The maximum vertical gap between the collapsed rock mass and the flat arch was 2.3m. After the collapse of the old roof rock layer, it fractured into rock blocks of varying lengths, forming a certain hinge structure between the blocks and the unbroken rock layer near the open cut and coal wall. At a working face advance of 66m, the first periodic pressure occurred (Figure 1(b)), with a pressure step of 12m. The total thickness of the old roof rock layer was observed to be 18m, consisting of 3.5m thick fine-grained sandstone, 5.6m thick medium-grained sandstone, and 8m of medium-grained sandstone. In the first five periodic pressures, no vertical fractures impacting the No. 2 coal seam were observed.

However, when the working face advanced to 140m, two distinct vertical through-layer fractures occurred near the open cut coal wall and the working face coal wall. These fractures extended horizontally along the No. 2 coal seam over a distance of 61m. The horizontal fractures between rock layers below the No. 2 coal seam showed a clear closing trend. At this point, the sixth periodic pressure appeared at the working face (Figure 1(c)), with a pressure step of 11m, and the rock layer collapse height was 71m from the coal seam roof, with vertical fractures extending to 112m above the coal seam roof. The No. 2 coal seam experienced overall subsidence, with a maximum subsidence of 2.2m. The opened vertical through-layer fractures began to close as the working face advanced to 155m.

As the working face advanced to 171m, the old roof experienced its 8th periodic pressure (Figure 1(d)), with a pressure step of 15m. The collapse angle on the open cut side was 63 degrees, and on the coal wall side, it was 61 degrees. An upward fracture developing along the collapse angle direction near the coal wall of the working face, after passing through the No. 3-2 coal seams, formed the 4th vertical through-layer fracture crossing the No. 2 coal seam, 13m horizontally apart from the 3rd vertical through-layer fracture. At this point, a total of 4 upward fractures crossing the No. 2 coal seam were formed in the roof rock layer as the working face reached 171m; one near the open cut coal wall and three near the coal wall side of the working face during periodic pressure. The 2nd and 3rd vertical through-layer fractures showed a closing tendency. Given the brittle failure characteristics of the rock, the closed vertical through-layer fractures still possessed certain water conductivity.

In the range of 180-220m advance of the working face, the last two vertical through-layer fractures appeared. At 183m, the 5th vertical through-layer fracture crossing the No. 2 coal seam formed near the coal wall of the working face, coinciding with the 9th periodic pressure (Figure 1(e)) at a pressure step of 13m. At 211m, the 6th vertical through-layer fracture formed near the coal wall of the working face, 15m horizontally apart from the 5th fracture, coinciding with the 11th periodic pressure (Figure 1(f)) at a pressure step of 14m. The 5th fracture connected with the surface, and after the surface was damaged, the shallow interlayer fractures became pronounced, but there was no rapid sinking of the roof.



(a) (b)

(c) (d)

(e) (f)

Figure 1. Development of Overburden Fractures in No. 4 Coal Seam Mining: (a) 1st Pressure Step on Old Roof; (b) 1st Periodic Pressure; (c) 2 Through-Layer Fractures; (d) 4 Through-Layer Fractures; (e) 5 Through-Layer Fractures; (f) 6 Through-Layer Fractures

During the advancement of the working face in the No. 4 coal seam to 211m, a total of six vertical through-layer fractures crossing the No. 2 coal seam were formed in the overlying rock layer (see Table 2). Of these, one vertical through-layer fracture was formed near the open cut coal wall, and five were formed near the coal wall side of the working face during periodic pressures. Among the five vertical through-layer fractures formed during periodic pressures and crossing the No. 2 coal seam, all but the one at the 211m mining stop showed a gradual closing trend. The top boundary of the fracture zone was determined to be about 72m from the top of the No. 4 coal seam, approximately 24 times the mining height, and the horizontal fractures between rock layers in the fracture zone were essentially closed. Although the No. 2 coal seam was located within the rock layer of the fracture zone, it maintained good overall continuity after subsidence, with no rapid sinking of the roof. The rock layer above 72m from the top of the coal seam, with mainly mudstone, sub-sand soil, and sub-clay lithology, showed good closure of horizontal and vertical fractures, identifying it as part of the bending and sinking zone.

This indicates that the mechanism of disaster caused by overburden fracture is due to the breakage and collapse of its cantilever structure formed by the rock layers. As the rock layers are influenced by multiple mining disturbances, the cantilever structure formed due to back mining will gradually increase the overburden load. When the lower working face advances over the mined-out area of the upper working face, the failure mode of the cantilever structure will gradually transform from shear failure to tensile failure until the tensile stress exceeds the load-bearing limit of the cantilever structure. During this dynamic instability process, the overburden above the hard interlayer rock is prone to overall subsidence. The fracture of the hard interlayer rock in the cantilever will release a large amount of elastic energy accumulated due to stress concentration and collide with the floor, which could be a cause of chain disasters.

Table 2. Development Situation of Crack Through Strata

Typical Features crack through strata	Fracture Direction	Surface Penetration	Fracture Status	Fracture Width (cm)	Water Conductivity
1st	Along the collapse angle direction of the open cut coal wall	Penetrates	Partially open	14	Strong water conduction
2nd	Along the collapse angle direction of the working face coal wall	Does not penetrate	Closed	-	No water conduction
3rd	Along the collapse angle direction of the working face coal wall	Does not penetrate	Closed	-	No water conduction
4th	Along the collapse angle direction of the working face coal wall	Does not penetrate	Closed	-	No water conduction
5th	Along the collapse angle direction of the working face coal wall	Penetrates	Partially open	2	Weak water conduction
6th	Along the collapse angle direction of the working face coal wall	Does not penetrate	Open	11	Strong water conduction

5. Simulation of The Evolution Process of Vertical Fractures in the Upper No. 2 Coal Seam Mining

The simulated thickness of the No. 2 coal seam is 6m. At this point, the floor rock layer of the No. 2 coal seam has stabilized. An open cut is made 21m away from the upward penetrating fracture near the open cut coal wall of the No. 4 coal seam (at the waterproof coal pillar), with a cut width of 6m. When the working face advances 28m, the roof rock layer fractures 14m away from the open cut coal wall, resulting in a separation with a gap of 1m.

As the working face advances 44m, the No. 2 coal seam experiences its first periodic pressure, with a pressure step of 8m. The collapse height is 20m from the top of the No. 2 coal seam, forming a flat-arch shape with a span of 28m. The collapse angle on the open cut side is 74 degrees, and on the coal wall side, it is 65 degrees, with a maximum separation gap of 2m. The working face smoothly passes through the vertical through-layer fractures formed during the 6th periodic pressure at 140m advancement of the No. 4 coal seam; during the advancement of 56m, it passes through the fractures formed during the 7th periodic pressure at 156m advancement; and at 92m advancement, it passes through the fractures formed during the 5th periodic pressure at 184m advancement. The overburden changes and damage situations during the 100m advancement of the No. 2 coal seam are shown in Fig.2.

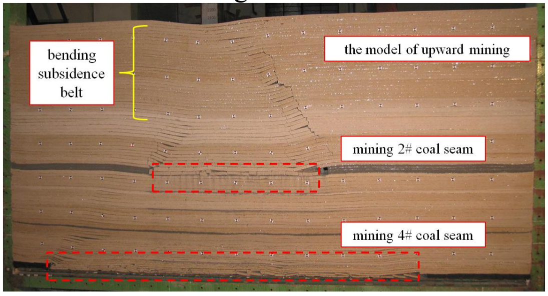


Figure 2. Overburden Movement in No. 2 Coal Seam Mining

During the 100m advancement of the No. 2 coal seam working face, the widths of the two through-layer fractures near the stopping point of the No. 2 coal seam working face (formed during the 5th periodic pressure at 184m and 6th periodic pressure at 211m advancement of the No. 4 coal seam) expanded to 15-20cm, while the other three closed through-layer fractures remained closed as the working face passed. There were no sliding instability or rapid sinking of the roof at the locations of the vertical through-layer fractures formed during the No. 4 coal seam mining. The continuous and progressive mining of the No. 2 coal seam can be ensured.

6. Conclusions

The Zhundong region, as a major energy base constructed under China's "Belt and Road" development plan and the 14th modern large-scale coal base, often contains more than one minable coal seam in most of its mining areas. The inability to implement upward mining in these areas would result in a significant waste of coal resources. Therefore, this paper conducts a physical similarity simulation experiment on upward mining in multi-coal seam conditions of the Zhundong mining area. The research findings are of great importance for the rational and effective utilization of coal resources and for promoting stable energy supply. The specific research outcomes are as follows:

(1) The development of vertical fractures following upward mining will impact the safe mining of both the seam in question and the seams above. In the Kuangou Coal Mine, the overburden of the No. 4 coal seam exhibited "three-zone" characteristics during a simulated advancement of 211m, forming a total of six upward fractures crossing the No. 2 coal seam. Of these, five were upward fractures formed near the coal wall side of the working face during periodic pressures. Except for the upward fracture at the 211m mining stop, which remained open, the other four fractures crossing the No. 2 seam did not penetrate the surface and showed a gradual closing trend as mining progressed.

(2) No sliding instability or rapid sinking of the roof was observed at the No. 2 coal seam working face when passing through the vertical through-layer fractures formed by the mining of the lower No. 4 coal seam. The mining of the No. 2 coal seam is secure from a rock layer control perspective. The upward fractures formed near the coal wall side of the working face along the collapse angle direction were more developed, and appropriate water prevention measures should be taken near the advancing coal wall.

Although this paper analyzes the difficulties and feasibility of upward mining from the perspective of overburden fracture and crack development, it does not further combine experimental results with actual mining conditions, which remains a limitation of this study. Furthermore, the paper does not delve into how upward mining conserves coal resources and the specific economic benefits it brings to the mine, which is an area for improvement.

With the development of science and technology, the application of more scientific techniques to mining is no longer a dream. The challenges of upward mining will inevitably become more convenient and effective methods of extraction as humanity progresses. The fractures induced by upward mining could, with the help of technology, be transformed from waste to treasure, potentially serving as channels for exploring underground resources and realizing underground energy storage. This is a hopeful outlook for the future, based on the research findings of this paper on upward mining.

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