Fracture Characteristics and Disaster-Causing Mechanism of Rock Strata Based on Arch Mechanical Model of Plane Contact Block

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The 52307 working face with large mining height in Daliuta coal mine is chosen as the research background, where there is the special mining condition in the overburden structure with a buried depth of more than 150 m and only one layer of key structure in Shendong mining area. Using the methods of similarity simulation experiment and theoretical analysis, the overburden movement law based on the arch mechanical model of plane contact block is systematically researched. The research results indicate that before the initial weight, the main key layer appears layered fracture in the mining process, and its lower rock layer becomes a part of the collapse zone. Before the initial weight, the upper key layer forms a “fixed supported beam” structure. When the beam reaches the limit length, shear failure occurs in the middle position; during the periodic weight, the upper key layer breaks into the plane contact block arch structure close to the same size. Relying on the friction between the contact planes, it has a certain displacement but does not collapse completely. The load transmitted from overburden is transmitted to the rear of the gob through the semiarch characteristics of the structure; the sliding instability and rotary deformation instability of the plane contact block arch structure are analyzed. The fracture of the key layer lags behind the mining position of the working face by a certain distance, due to the influence of the fracture angle of collapse zone in the advancing process of working face. The research results provide an important guiding significance for prediction and prevention for dynamic disaster of rock strata in working face with large mining height.

1. Introduction

As the western part of China is rich in coal resource reserves and has a simple geological structure suitable for the construction of modern large mines, some scholars have proposed the strategic layout of the Jin-Shan-Meng-Ning-Gan area as key development zones in China [1, 2]. The rock stratum which plays a decisive role in all rock strata activities is named as the main key stratum, which plays a controlling role in a series of ground pressure behavior laws [3, 4]. With the mining of thick coal seams of the lower group in the Shendong mining area, there are some shallow buried quarries with a single giant thick key seam structure, and such mining conditions are different from those of shallow buried coal seams and near shallow buried coal seams [5, 6]. Taking the 52307 working face in Daliuta coal mine as an example, the initial weight distance is large after employing blasting technology to precrack the roof. In practice, it is found that the mine pressure at the working face does not appear to be abnormally strong in the form of cut-down mine pressure [7].
Zhang et al. [8] put forward the concept of “full-thickness cut-and-fall” topping pressure based on the compaction measurements in Dalitula coal mine and the mechanism of topping pressure on thin bedrock near horizontal coal seam with thick loose layer. Based on the theory of “masonry beam,” Huang et al. [9, 10] established the structural models of “asymmetric three-hinged arch” in initial weight and “step rock beam” in periodic weight of shallow buried coal seam, and the basic structures of “short masonry beam” and “step rock beam” of top period pressure were proposed, and the stability of the top structure was analyzed. Ju et al. [11] used similarity simulation tests to analyze the influence of the “cantilever beam” structure of the key layer on the mineral pressure manifestation; the “cantilevered beam-masonry beam” structure alternately collapses during the advance of working face, which enriched the content of the critical layer theory in the quarry. Jin et al. [12] proposed the existence of an arch or semiarch form in the process of releasing thick top coal, through a large number of field observations and theoretical verification. Zhang et al. [13, 14] proposed a semiarch or arch-shaped quarry structure combining the “semiarch” structure and the “masonry beam” of the quarry. Xu et al. [15] conducted a detailed study on the relationship between the breaking movement of the key seam and the bracket crush during shallow buried coal seam mining and proposed corresponding prevention and control measures, guiding the prevention and control practice of shallow buried coal seam crush hazard in Shendong mining area. Based on the deformation and damage characteristics of the key layer of the roof of the shallowly buried coal seam, the initial postbuckling theory was applied to explore the postbuckling behavior of the key layer of the roof during mining by Yang and Yu [16], and the calculation formula for the fracture sinking of the old roof of the quarry in initial weight was derived, and the criterion for the step sinking after the roof break was established, and the amount of step sinking was obtained.

Many scholars have done a lot of research on overburden structure morphology, the key layer breakage form, overburden structure destabilization mechanism, and prevention technology in shallow buried coal seam mining [17–19]. However, it is not fully suitable for the mining conditions where the depth of burial is greater than 150 m and only one layer of key structure exists in the overburden structure of the mine. This paper intends to study the problem of overburden movement under these special mining conditions based on previous research achievements, by means of similar simulation and theoretical analysis, focusing on the overburden breaking law for long working face, large mining height, and rapid advancement, to study the breaking law of overburden movement and establish the structural mechanics model of rock seam breaking, which provides an important reference for coal seam mining in Shendong mining area.

2. Project Background

2.1. Project Overview. The 5-2# coal seam of 52307 working face with large mining height is buried at a depth of 179.33 m in Dalitula coal mine. The working face has a strike length of 4462.6 m and a tendency length of 301 m and is mined back along the strike direction of the coal seam. The average thickness of the coal seam is 7.2 m, and the actual mining height is 6.8 m, and the inclination of the coal seam is 1–3°. The ZFY18000/25/39D hydraulic support is selected for the working face, with an initial bracing force of 9800 KN and a rated working resistance of 18000 KN.

In order to accurately study the rock movement during the mining process of the 52307 working face, coring boreholes are arranged in the middle of the working face and the basic mechanical properties of each layer are tested in the chamber. According to the borehole column data, the coal seam at this working face is buried at a depth of 179.33 m, of which the thickness of the surface loose layer is 21.9 m and the thickness of the overlying bedrock is 157.43 m. According to the key layer identification method [16–18], the fine sandstone with a thickness of 30.87 m at 3.71 m from the top of the coal seam is the main key layer. Based on the results of the field coring, it is obvious that there are soft and weak structural facets within the thick and hard main key layer, and there are fine grain laminations developed in the fine-grained sandstone of the key layer, which is grey-black in colour and filled with charcoal chips. These laminae are weak, and the sandstone tends to break along the laminae filled with charcoal chips, making it easy for the thick and hard main key layer to break in layers during the recovery process under the influence of mining. 52307 working face layout and drill log are shown in Figure 1.

2.2. Weighting Pattern of Working Face. In order to grasp the law of mining pressure appearing in the working face under the condition of large mining height and huge thick single key layer, the PM32 elector-hydraulic control system, which comes with the hydraulic support of 52307 working face, is employed to collect the pressure change data of the support in real time, and the weight law of the roof and the law of overburden breaking are analyzed. Taking the No. 75 bracket in the middle of the working face as an example, the end resistance variation curve of the bracket is obtained, shown in Figure 2.

It is important to note that the periodic weight distance L is from the end of the previous cycle to the end of the next cycle. It consists of the significant movement step $L_u$ (duration of pressure) and the relative stability step $L_b$ (duration of nonpressure) $L = L_u + L_b$.

1. The initial weight at 52307 working face is abnormal. The initial weight distance is still 94.5 m after the blast is employed to cut the roof at the site, much greater than the traditional theoretical estimate, and the periodic weight distance is also as high as 20–30 m

2. The initial weight is abrupt. There is no obvious foreshadowing before the initial weight, and the weight strength is much lower than the theoretical calculation value. Before the initial weight on the working face, the working resistance of the bracket is about 1100 KN, and it is basically in the initial bracing state; when the initial weight on the working face comes, the working resistance of the bracket increases rapidly, and the maximum pressure
<table>
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<tr>
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<tr>
<td>Sandy mudstone</td>
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<td>2.8</td>
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<tr>
<td>Siltite</td>
<td>3.6</td>
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Figure 1: 52307 working face layout and drill log.

![52307 working face layout and drill log]

Figure 2: Law of the end resistance variation curve.

![Law of the end resistance variation curve]
reaches 18722 KN when the pressure comes, and most of the hydraulic valves is open.

(3) The overtopping influence of the working face is small, and the plastic zone is extremely small in scope. Due to the high strength of the coal seam, the coal wall under the action of the roof weight, some areas of the coal body occurred point-like ejection phenomenon, and no major flake gang phenomenon occurs.

3. Breaking Pattern of Thick Key Layer at Large Mining Height

3.1. Similarity Simulation Scenarios. The experiment prototype is the 52307 large mining face at Daliuta coal mine, where the main mining face is 5-2# coal with a design mining height of 6.8 m, and the thickness of the coal seam mined in the test is 7 m. In order to visualize the breakage pattern of a single giant thick key seam in the overburden when mining the large mining face, a similarity material simulation experiment is employed to simulate it. A planar stress model under gravity conditions is selected for the experiments. The experimental frame is 400 cm long and 30 cm wide, with a 50 cm boundary coal pillar on each side. The geometric similarity ratio of the model is 1 : 100, the capacity similarity ratio is 1 : 1.5, and the time similarity ratio is 1 : 10. A simplified experimental model is employed to simplify each rock layer. The experimental model is shown in Figure 3.

The physical and mechanical parameters of the rock strata are determined according to similarity theory and Newton’s Second Law, and suitable ratios are selected from the similarity materials ratio table, shown in Table 1.

The materials are formulated with river sand (grain size less than 2 mm) as aggregate, gypsum and calcium carbonate as binder, borax as retarder, and a layer of mica at the rock junction to simulate the laminae of the rock layers. The overlying rock layer is loaded by means of iron block loading instead.

As the roof of the working face is precracked by blasting at the production site to a depth of 20 m above the roof, the roof is also precracked to a depth of 20 cm after the working face is advanced 15 m in the similarity simulation (equivalent to the working face cut-hole in the actual mining). In the mining process of the coal seam, the distance of each excavation is 15 cm, corresponding to the high-intensity mining conditions of 15 m of the working face excavation, and the interval between each excavation is 30 min. During the excavation process, the fracture movement of the overburden rock is recorded in real time, and the fracture phenomenon of the roof cladding during the excavation process is photographed and retained.

3.2. Experimental Result Analysis. The simulation results show that the direct roof emerges as it is mined and as the face advances the lower part of the key layer begins to collapse. When the initial weight occurs at the face, the upper part of the key layer collapses and the key layer is in the form of a “clamped beam.” As the workings continue to advance, the key layer collapses periodically, with the lower part of the key layer collapsing firstly and the upper part of the key layer breaking up. As the collapse zone below is already sufficiently filled, there is no “S-R” type of instability in this part, but rather a “plane contact block arch” formed by the back and forth extrusion of the key blocks. It is a plane contact block arch structure. In this working face, although the key layer is broken and unstable during the periodic weight, the front arch foot is located in the coal body in front and the rear arch foot is located on the collapsed gangue due to the large front and rear extrusion pressure. Due to the existence of this special structure, the pressure transmitted by the overlying rock layer is partly transmitted to the rear block and gangue through the key block, which does not cause a large weight impact on the quarry, and the working face does not have the phenomenon of cutting the roof and pressing the frame due to the breakage of a single main key layer. The graph of simulation results is shown in Figure 4.

(1) As the workings advance, the key layer breaks up in layers, thus verifying that the presence of weak structural planes in the borehole column at the site causes the key layer to break up in layers.

(2) Before the initial weight, the direct top and the lower key layer collapse as the working face advances, and the upper key layer forms a “solid support beam” structure. Before the initial weight of the working face, the support is basically in the initial support state; when the “solid support beam” reaches the limit length, shear damage occurs in the middle of the beam, when the initial weight occurs at the working face. Because of the large breakage length and thickness, the working resistance of the brace increases rapidly when the initial weight occurs.

(3) The simulations show that the lower key layer collapses and the upper key layer forms a “plane contact block arch” that influences the direction of the overall overlying load field during the period of the working face. The overlying rock layer transfers a large part of the load force to the hollow area horizontally through the “plane contact block arch” structure, and no roof-cutting and crushing phenomenon occurs at the working face due to the breakage of the single main key layer.

4. Structural Model of Overburden Fracture at Working Face

4.1. Overburden Fracture Structure. It is based on the formula for the thickness of direct top of the quarry in the following equation.

\[
\sum h = \frac{M}{K_p - 1},
\]

where \(h\) is the direct top thickness, m. \(M\) is the thickness of the mined coal seam. \(K_p\) is the initial crushing and swelling factor of the rock, 1.35 (empirical value).
It is calculated that the height of direct top required to fill the collapse zone is about 20 m, the thick key layer occurs as a stratified collapse phenomenon, and the lower part of its rock layer about 16 m turns into a direct top part of the collapse to the mining void. Numerical and similarity simulations show that the overburden breaking structure of the working face exists in the form of plane contact block contact, shown in Figure 5. The mechanical analysis model of the overburden structure of the quarry is established, shown in Figure 6.

The morphology of the contact structure at the face of the quarry is mechanically analyzed according to the morphology of the self-forming structure of the roof of the large mining face. Under the influence of coal seam mining, the overlying rock bed on the working face and the intact laminated rock body regularly break into blocks. These blocks are close to the same size, and the blocks are subjected to strong squeezing pressure between contact planes. The friction force generated to maintain its own weight and the load of overlying part of rock strata, and the semiarched-shaped balanced structure is called as “plane contact block structure.” The mechanical essence of structure is that it is capable of generating large horizontal thrusts under vertical loads and that it is capable of generating horizontal thrusts under vertical loads and transmits the combined forces in a curved line of action.

The schematic diagram of the model half arch structure is shown in Figure 7. A end is located in front of the working coal body, and B end is in the gangue side of the collapse and stability.

The structure of the rear gangue on the structure plays a large role in the role of the load above to provide the vertical direction of the reaction force and horizontal reaction force, and the structure of the combined force line of action is from the lower right corner of the fracture block above the support to the structure and gangue contact point of a curve. It is concluded that the plane contact block arch structure is essentially a horizontal thrust produced under the action of the vertical direction load, which in turn causes a huge frictional force and a strong squeezing force around the restraint. It can not only complete the self-support of the structure but also withstand certain loads from above. The force analysis of study object is shown in Figure 8.
(a) The working face advances at 45 m

(b) The working face advances at 80 m

(c) The working face advances at 95 m

**Figure 4**: Continued.
$A_1$ and $B_n$ are the two points of force on the overall structure; $X_{A1}$ and $Y_{A1}$ are the horizontal and vertical components of the integrated support force on the working face at the point $A_1$ of the plane contact block structure; $T$ and $Q$ are the horizontal and vertical components of the rear support force at the point $B_n$ of the plane contact block structure; $l$ is the length of the block, and $H$ is the thickness of the block.

A force analysis of the structure yields that

$$X_{A1} - T + nql \sin \beta = 0,$$  

(2)

$$Y_{A1} + Q - nql \cos \beta = 0,$$  

(3)

$$T \left[ H - \frac{ns}{\cos \beta} \right] + Qnl - nql \frac{l \cos \beta + H \sin \beta}{2} - ql(l \cos \beta - s \tan \beta) \sum_{n=1}^{N-1} N = 0.$$  

(4)

In the above equation, $n$ is the number of blocks in the structure; $\beta$ is the angle of rotation of the block; $q$ is the overlying load; $S$ is the relative vertical sinkage between adjacent blocks.

The most important aspect of the structure is the identification of the critical contact plane, where the sliding instability of a particular block along the critical contact plane results in the overall instability of the entire structure, with
**Figure 6**: Model for structural mechanical analysis of quarry overburden.

**Figure 7**: Schematic diagram of the model half arch structure.

**Figure 8**: The force analysis of study object.
a new plane contact structure forming as it advances. There is no strength damage to the rock, and the overall instability of the structure is due to slip along the face of the structure under the overlying load.

The analysis of the formation process and the overall movement characteristics of the structure show that the key contact plane of the structure is the left contact plane between blocks 2 and n. The contact plane between the second block and the first block and the third block and the second block is the critical contact plane.

A mechanical analysis of the critical contact planes yields the following equation.

\[ Q - (n-1)ql \cos \beta + (T - (n-1)ql) \sin \beta f_1 \geq 0. \]  

The critical state is

\[ Q - (n-1)ql \cos \beta + (T - (n-1)ql) \sin \beta f_1 = 0, \]  

where \( f_1 \) is the friction factor for the right-hand side of the first block of the plane contact block structure.

\[ T = \frac{(n-1)q[l - \frac{1}{2}nl \cos 2\beta \cos \Delta/2 \tan \beta - nl f_1 \sin \beta - H/2 \sin \beta]}{(H - \Delta) \cos \beta + nl (\tan \beta - f_1)}, \]

\[ Q = (n-1)ql(\cos \beta + f_1 \sin \beta) - \frac{(n-1)q[l - \frac{1}{2}nl \cos 2\beta \cos \Delta/2 \tan \beta - nl f_1 \sin \beta]}{(H - \Delta) \cos \beta + nl (\tan \beta - f_1)}. \]

This structure is characterized by the horizontal reaction of the rear to the structure, so that it is better able to bear its own loads and at the same time transfer the loads coming down from above to the rear of the extraction area through the semiarch characteristics of the structure. Therefore, the pressure on the supports is not particularly high and leads to the phenomenon of crushing the frame.

4.2. Instability Conditions of Fractured Overburden Structure.

According to the mechanical model of the plane contact block arch structure, it is known that the structure exists only when there is sufficient squeezing pressure between the blocks and the blocks do not slip along the contact plane. The mechanical analysis of key blocks is shown in Figure 9.

(1) Structural slip instability analysis

A "plane contact block arch" structure experiences slip instability at point \( A_1 \) and if slip instability does not occur at that point that it satisfies.

\[ X_{A1} \tan \phi \geq Y_{A1}. \]

Taking the two equations in equation (2) and equation (8) yields

\[ \Delta = ns + nl \sin \beta + H(1 - \cos \beta) \]

is the maximum gap between the direct top.

The combination of equation (2), equation (4), and equation (6) yields

\[ \Delta = \frac{ns + nl \sin \beta + H(1 - \cos \beta)}{2} \]

(2) Structural rotational deformation instability

Slewing instability occurs when the squeezing pressure between the blocks is large, which leads to the block being crushed and instability at the hinge. If the structure does not become unstable by rotational deformation, it is necessary to satisfy

\[ X_{A1} \geq a \sigma_c, \]
where \( a \) is the height of the end-foot extrusion contact plane.

\( \eta_\sigma \) is the end-angle crush strength of the rock mass (\( \eta \) is the end-angle crush factor, taking it as 0.3).

Taking the equation \( XA_1 - T + nql \sin \beta = 0 \) into equation (10) yields

\[
H - \Delta \geq \frac{ql[n \cos 2\beta - n^2 + n f_1 \sin 2\beta - i(n-1) \sin \beta]}{0.3\eta_\sigma(i - n \sin \beta)}
\]

\[
- n(\tan \beta - f_1)l \cos \beta.
\]

(11)

If sufficient friction exists on the key contact planes in this structure, and the gangue behind provides horizontal squeezing pressure, the slip instability and swing instability are less likely to occur. The plane contact block structure rotates sequentially as it advances until it falls completely on the gangue of the collapse zone. During the advance of the working face, the breakage of the key layer lags behind the mining position of the working face by a certain distance due to the breakage angle of the collapse zone. As the working face continues to advance, the key layer is periodically broken and unstable, and the plane contact block structure appears to be “stability-instability-stability” with the key layer breaking and sinking.

5. Conclusions

1. Due to the increase of buried depth, it is found for the first time that the buried depth in the overburden structure of Shandong mining area is greater than 150 m. There is only one layer of key structure mining conditions, and the thick and hard single key layer structure is close to the coal seam, and its overburden fracture law has certain particularity.

2. The near-field thick and hard single key layer structure leads to an abnormal increase in the weight distance. After adopting the blasting top cutting measures, the initial weight distance is as high as 94.5 m, and the periodic weight distance is also as high as 20-30 m. When the pressure is applied, the working resistance of the support reaches 18000 KN, which does not bear all loads overlying the key layer.

3. Before the initial weight, the main key stratum is stratified and broken in the mining process. The lower stratum becomes a part of the caving zone, and the upper stratum forms a “fixed beam” structure after breaking. When the beam length reaches the limit length, shear failure occurs in the middle position. During the periodic weight, the upper key layer breaks into the “plane contact block arch” structure.

4. The plane contact block arch structure depends on the friction between the contact planes. To a certain extent, the arch structure ensures the safe mining of the working face. As the working face continues to advance, the key layer periodically breaks and becomes unstable, and the key layer breaks and sinks in the structure of the plane contact block in the form of “stability-instability-stability”.

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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