Research Article

The Spatio-Temporal Evolution of Overlying Rock Structure and Mine Pressure Behavior in a Short-Distance Coal Seam Face

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This research is aimed at exploring the evolution of overlying strata structure and the ground pressure in the working face mining of close-distance coal seams. By taking the Xiashijie Coal Mine as an example, the direct relationship between the rotation angle of key blocks of overlying strata and the subsidence of key blocks and the length of rock blocks was deduced using theoretical analysis and similar simulation experiments, and the critical criterion of basic overlying strata breaking was formed. Through the real-time monitoring of the characteristics of overlying strata and its pressure, the evolution of overlying strata structure and the ground pressure in the working face mining of close-distance coal seams could be clarified. The results show that the main factors that affect the turning angle of key blocks are the subsidence of key blocks and the length of rock blocks. When the subsidence and turning angle of rock blocks are larger and the length is smaller, the rock blocks are prone to rotational deformation and instability. The lower coal mining of the nearby coal seam group is more difficult due to the overlying strata caving in upper coal mining, and the damage height is about 335 mm higher than that in the upper coal. When mining over the same distance between the upper and lower coal seams of the close-distance coal seam group, fewer weightings are generated when mining the lower coal seam working face, the average weighting step is longer, and the average single weighting value is high. The research results provide a basis for the safe mining of close coal seams.

1. Introduction

Coal mining has a very important impact on the mining area; the integrity of the overlying rock is destroyed after underground coal mining, and the development of cracks in the upper part of the overlying rock will cause surface subsidence [1–3]. Compared with single coal seam mining, the surface movement and deformation of close-distance coal seam mining is more severe than that of single mining. Close-distance coal seam mining also affects the integrity of overburden structure [4–9]. It makes any dynamic disaster caused by overlying rock fracture in working face more prominent, making it necessary to study the evolution of overlying rock structure and the pressure distribution in short-distance coal seam mining to ensure the efficient and safe production of the mine [10–12].

Through the study of the development of strata movement from bottom to top, Xu et al. found the cumulative effect of unloading expansion of mining overlying strata and its mechanism of influence on strata movement [13]. Based on the basic experiment of coal and rock mass in shallow-buried deep stopes, Ren and Li conducted similar material simulation experiments of roof cutting failure in a shallow-buried deep stope based on time series characteristics and obtained the cutting failure mechanism of shallow-buried deep roof [14]. Ning et al. revealed the mechanical
mechanism of overlying strata fragmentation and fracture development in short-distance coal seam group mining [15]. Wang et al. used the methods of theoretical analysis and field measurement to study the influence of gangue compression effect in goaf on the structural stability of overlying rock in stope, and to reveal the effect of changes in pressure behavior and control in fully mechanized mining face [16]. Shi et al. conducted an in-depth study on the pressure-relief-induced failure of the floor in the compaction stress adjustment stage wherein the pressure-relief range of the floor is larger than that in the mined-out area of the stope, and the pressure-relief value of the floor changes constantly, endowing the more stable stage with particular characteristics [17]. Through the simulation study of the Caragana Tower Coal Mine, Huang and Han revealed the crack expansion conditions and mechanism of evolution of repeated mining under an overburden stratum [18]. Zheng et al. investigated the roof failure characteristics and overburden movement of short-distance coal seams under conditions of repeated mining, which allowed the safe advancing of the working face. The research results provide a theoretical basis for coal seam mining under similar conditions [19].

At present, most scholars have studied the mining failure mechanism [20–22]. The research on coal seam mining under repeated mining is mainly focused on clarifying trends in surface movement [23], overlying rock fracture development [24, 25], and instability [26]. In the present work, the Shijie Coal Mine was used as an example and through theoretical analysis and similar simulation experiment. The failure of overlying rock structure after short-distance coal seam mining was explored, and the stability and pressure behavior of overlying rock structures in short-distance coal seams were analyzed. The results provide a basis for safe mining of short-distance coal seam groups.

2. Theoretical Analysis of Overburden Stability

2.1. Mechanical Model of Overburden Structure in Short-Distance Coal Seams. There is a great difference in the overburden structure between the short-distance coal seam and the single coal seam, and it is greatly influenced by the overburden and the rock structure between the coal seams. The basic top fracture mechanical model of the lower coal mining is shown in Figure 1; the block structure of short-distance coal seam mining is unstable, resulting in a “double masonry beam” structure distributed up and down between coal seam groups. When the mining of the upper coal seam is finished, there is a multilayer hard basic roof structure between the two coal seams, and the periodic pressure is induced with the continuous mining of the lower coal seam. The pressure behavior characteristics of the lower coal seam face are affected not only by the structural movement of the upper key layer but also by the movement of the basic roof structure of the coal seam.

For the lower coal seam with basic roof structure between the two coal layers, when the working face of the upper coal seam ends, the overburden structure and movement characteristics of the lower coal seam are much more complex than those of the upper coal seam mining. In the process of lower coal seam mining, the mine pressure intensity will change due to the distribution and stable state of the key strata of the upper coal seam, the mining height of the lower coal seam, the basic roof breaking form between the coal seams, and so on. When mining the lower coal seam, the basic roof of the lower coal seam will break regularly with the continuous advancing of the working face, thus forming a stable “masonry beam” structure. On the other hand, the masonry beam structure formed by the broken key strata of the overlying strata of the upper coal seam will suffer from structural instability, thus affecting the pressure on the working face, and the further from the lower coal seam, the smaller the effect on the pressure on the lower coal.

Based on the key layer theory, after the first pressure of the working face, the fracture rock block will undergo “stability-instability-re-stabilizing” behavior, thus forming the periodic pressure of the working face. The basic top fracture position is generally located on the inside of the coal wall, and the fracture rock block is supported by coal wall, support, direct roof, and goaf gangue, forming a masonry beam structure as shown in Figure 2. In the figure, $T$ is the horizontal thrust, $Q_A$ and $Q_C$ are the shear forces, $A$ is the hinge point, $B$ and $C$ are two rock blocks, and $P_1$ and $P_2$ are the loads acting on the rock blocks.

The two rock blocks in the simplified masonry beam model become the key blocks (Figure 3), and their stability determines the structural stability of the whole masonry beam. $\theta_1$ and $\theta_2$ are the angles between two rock blocks and the horizontal direction, and $l$ is the horizontal length of the rock blocks. The subsidence of block $B$ in the goaf $w_1$ is related to the total thickness of the direct roof $\sum h$, the mining height $M$, and the loose rock coefficient $K_p$ after the failure of the overlying rock [27], that is

$$w_1 = M - \sum h(K_p - 1).$$

According to the contact geometric relationship of rock mass after rotation,

$$a = \frac{1}{2}(h - l \sin \theta_1).$$

Contact between two rock blocks forms a plastic hinge, so the left and right points of horizontal thrust $T$ are located at $a/2$.

According to the analysis of a full masonry beam, $R = q$, where $R$ is the bearing force. For two rock blocks $\sum M_A = \sum M_B = 0$, so

$$T = \frac{ql^2}{2(h + w_2 - 2w_1 - a)},$$

$$Q_C = \frac{ql(w_2 - w_1)}{2(h + w_2 - 2w_1 - a)}.$$
2.2. Critical Criterion of Basic Overburden Fracture. When the fracture line is just exposed above the coal wall in the stope, it is most likely to slip and lose stability. Therefore, the value of $\theta_1$ determines the stiffness of the coal wall. If the stiffness is larger, the value of $\theta_1$ tends to zero, then the blockiness $i$ is less than 0.3, and if the stiffness is smaller, $\theta_1$ is generally only about 3°, then $i$ should be less than 0.34. Therefore, the degree of fracturing $i$ of the bearing layer of the masonry beam should be less than 0.34. The relationship between horizontal thrust $T$ and angle of rotation $\theta_1$ can be obtained from Equation (5), and the nonlinear characteristics of the relationship between $T$ and $\theta_1$ are derived from Figure 4, which shows that this structure is geometrically nonlinear.

Bringing Equations (5) and (7) into the sliding instability condition:

$$i \leq \tan \varphi + \frac{3}{4} \sin \theta_1,$$

where $\varphi$ is the internal friction angle of the rock block, and $\tan \varphi$ is 0.3. According to Equation (8), the relationship between degree of fracturing $i$ and $\theta_1$ is shown in Figure 5. In the shadow area, the structure is stable, and the smaller the height-length ratio of the rock block, the less likely the structure is to slip and lose stability.

With the rotation of the second rock block, the horizontal thrust $T$ will become larger and larger, which may cause the rock block at the corner to crush, leading to instability, thus while maintaining the stable condition of the structure:

$$\frac{T}{\alpha} = \eta \sigma_c,$$

where $T/\alpha$ represents the average extrusion stress on the contact surface; $\eta \sigma_c$ represents the compressive strength at the corner end. In view of the special conditions at the corner, $\eta$ is 0.3.

Equation (8) is brought into Equation (9), and the limiting angle of rotation $\theta$ for a stable structure is

$$\theta \leq \arcsin \left( \frac{3}{2} t - \sqrt{\frac{i^2}{4} + \frac{40 \gamma (h + h_1) l^2}{3 \sigma_c}} \right).$$

According to Equation (10), the relationship between the rotation and the structural bearing thickness $(h + h_1)$ under different degrees of fracturing is determined. Taking the bulk density $\gamma$ of 25 kN/m$^3$, the compressive strengths of two bearing layers with different sizes are selected. As shown in Figure 6, the part below the curve represents the stable area.

Limiting subsidence $w$:

$$w \leq \frac{3}{2} h - \sqrt{\frac{h^2}{4} + \frac{40 \gamma (h + h_1) l^2}{3 \sigma_c}}.$$

Because the lower part of the key block is a collapsed rock block, the maximum subsidence of the key block is $w_{\max}$.
According to Equation (11), the curves of the relationship between different maximum subsidence \( w \) and structural bearing thickness \( (h + h_1) \) are obtained, as shown in Figure 7.

The research shows that a cantilever beam structure is formed on the basic roof of close-distance coal seams due to repeated mining disturbance. The reason is that the rotation \( \theta \) of the broken block exceeds the maximum rotation angle that can maintain its structural stability, so that the structure at the hinge has no bearing function, and the relationship between the rock blocks has lost the lateral thrust, which leads to the block breaking without supporting function. Therefore, judging whether the basic roof presents the structural form of a cantilever beam can be used to assess the change of the rotation of the fault block.

The factors influencing the rotation of key blocks in overlying strata are the sinkage \( w \) of key blocks and the length \( l \) of the rock blocks. When the sinkage of the rock blocks is large, and the length of the rock blocks is small, the rotation of the rock blocks is large, making them prone to the rotational instability; however, the maximum subsidence of a rock block is related to the crushing and expansion coefficient of caving gangue. The larger the crushing and expansion coefficient of caving gangue in the upper coal seam, the smaller the subsidence \( w \) of the broken block. However, the lower coal has a lower crushing expansion coefficient than the upper coal, so the subsidence of the block increases when mining the lower coal. Combined with Equations (11) and (12), the critical criterion of basic overburden rock fracture is formed, that is, when Equation (13) is satisfied, the basic roof will be in the caving zone after periodic fracture, showing a cantilever beam structure. For thick coal seam working face, the greater the mining height of the working face is, the lower the stratum the basic roof is, and the easier it is to form the cantilever beam structure of the basic roof.

\[
w \leq \frac{3}{2} h - \sqrt{\frac{h^2}{4} + \frac{40\gamma(h + h_1)^2}{3\sigma_c}}. \tag{12}
\]

\[
M - \sum h(K_p - 1) > \frac{3}{2} h - \sqrt{\frac{h^2}{4} + \frac{40\gamma(h + h_1)^2}{3\sigma_c}}. \tag{13}
\]

3. Engineering Background and Model Design

3.1. Geology. The Xiashijie Coal Mine is 4.0 km long, 3.3 km wide, and has a coal-bearing area covering some 13.2 km². The Jurassic 4-2 coal seam is mainly used, and its thickness is generally 10.0 to 12.0 m. The main coal seams in the Xiashijie Coal Mine are the 3-2 coal seams and 4-2 coal seams. Among them, the 3-2 coal seam is currently mining at the 2301 working face, with an inclined length of 210 m and a mining thickness of 4.5 m. The overall coal seam dip angle of this working face is 3° to 8° (generally about 5°), and some coal seams are near-horizontal. The 4-2 coal seam is currently mining the 222 working face, with an inclined length of 170.0 m and a mining thickness of 10.0 m. Its two wings are relatively gentle, with an inclination of 40° to 80° in the west wing and 30° to 50° in the east wing. Small fluctuations can be developed locally, belonging to the Zhiluo Group of
Middle Jurassic and Yan’an Group of Lower Jurassic strata. The interval between the 3-2 coal seam and 4-2 coal seam is 3.7 to 38.4 m, with an average of 21.8 m.

3.2. Pattern Plan. To study the evolution of overlying strata structure and the ground pressure behavior in the Xiashijie coal seam working face, a strike physical similarity simulation experimental model was established. The 2301 working face, the 222 working face, roof, and floor at the lower stone section were built as the engineering background. Physical and mechanical parameters of the rock strata are listed in Table 1. The plane strain model frame with the overall dimensions (length × width × height) of 3.0 × 0.2 × 1.6 m was used in the experiment, and the model design is shown in Figure 8. The geometric similarity ratio \( r_M = \frac{l_H}{l_M} \) of the simulation experiment is determined to be 1:400; according to the similarity theorem, the time similarity ratio \( \alpha_t = \sqrt{r_M} \) is 0.05, bulk density, Poisson’s ratio, and the internal friction angle similarity ratio are 1, the stress similarity ratio \( \alpha_p = \frac{r_H}{r_M} \) is 0.06, the pressure similarity ratio \( \alpha_p = \frac{r_H}{r_M} \) is 9.6 × 10^{-8}, and model paving size (length × width × height) is 3.0 × 0.2 × 1.6 m.

In this physical similarity simulation experiment, a support pressure sensor and floor pressure sensor are used to monitor the changes in the pressure around the working face in the process of model mining in real time. Among them, the support pressure sensor is CL-YB-141 force sensor produced by Hanzhong Precision Measuring Electric Appliance Co., Ltd, and the rated working resistance of the sensor is 32.0 MPa, which is used to monitor the change in the pressure on the working face when the overlying strata collapse. A total of 69 floor pressure sensors which are laboratory force sensors are installed. The floor pressure sensors are installed side by side at the bottom of the simulated rock stratum and are installed before the model is paved. The rated working resistance of the sensors is 35.0 MPa, which is used to monitor the floor pressure changes of the mined-out area and the solid coal on both sides of the working face after coal seam mining. By analyzing the support pressure and floor pressure, the distribution of roof weighting in the mining face of the model and the pressure in the mined-out area and the working face ahead of the floor are found.

4. Evolution of Overlying Strata in Close-Distance Working Face Mining

4.1. Structural Evolution Characteristics of Upper Coal Overburden. After the mining of the upper coal seam 3-2, the evolution of the upper strata underwent the first collapse of the direct roof, the first collapse of the main roof, and the gradual breaking of the upper strata. Therefore, the evolution of overlying strata in the working face mining of close-distance coal seams was analyzed through physical simulation experiment, and its size was expressed by actual simulation.

The evolution characteristics of different overburden cavities in mining 2301 working face are shown in Figure 9. With the advancing of the working face, cracks are constantly formed, developed, and propagated, eventually reaching the surface. As the face advances, there are 32 periodic weighting events, and when the 22nd periodic weighting occurs, the fracture first develops to the surface. At the end of mining in the 2301 working face, the roof of the working face collapses, the upper strata of the mined-out area are severely damaged, and there is significant bending deformation. The cracks in the overlying strata of the mined-out area expand upward, which makes the water-conducting fracture zone develop upwards, and the height of the water-conducting fracture zone after mining is in the range of 255 to 380 mm. At the end of mining in the 2301 working face, the crack field in the roof strata expands upwards, and the concentrated distribution area of crack field presents a laddered distribution, and the deformation area of rock strata is mainly concentrated in the range of model length of 925 to 1275 mm and height of 150 to 550 mm.

Affected by the mining of working face, the stress in the original environment redistributes, the overlying strata of coal seam migrate, and the overlying strata collapse, bend, and sink, which gradually spread to the surface from bottom to top, forming a sinking basin on the surface. Cutting off the hole 200 mm from the left frame of the model, we advance to the right in turn. When the local surface sinks by 15 mm each time, the dial indicator data are recorded after the model is stabilized. Figure 10 shows the subsidence characteristics of the top of the model at different mining distances. The dial indicators before mining are all set to their maximum range of 30.0 mm, so the initial surface subsidence line is quasilinear; when the working face is advanced to 960 mm, the top of the model begins to show signs of subsidence, but the subsidence is small, and the spread is small. When the working face is advanced to 1770 mm, the overlying strata completely collapse and spread to the surface, forming an obvious bending subsidence zone. Meanwhile, the surface bending subsidence occurs, and the surface subsidence basin begins to form, with the maximum subsidence being 4.081 mm.

With the increasing mining distance, the sinking basin gradually widens, the sinking curve gradually moves towards...
the working face, and the strata above the working face move more obviously, while the strata above the goaf move slowly, and the strata tend to be stable. After mining over 2190 mm, the strata collapse, affecting the surface settlement. A large curved subsidence area is formed on the surface, and the subsidence basin keeps increasing in size. The maximum subsidence point in the center of the subsidence basin is 950 mm from the open cut, and the subsidence exceeds 7.575 mm. The maximum subsidence point does not appear in the middle of the goaf but further back. Since then, there is no obvious rock stratum failure when advancing the working face, so the surface subsidence changes little, and the maximum subsidence also changes little. For example, at 2505 mm and 2600 mm, the maximum subsidence is 8.579 mm and 9.353 mm, respectively, and the hysteresis of the maximum subsidence point can also be found.

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Figure 8: Design of similar simulation experiment model.

Figure 9: The 2301 working face is opened until the end of mining. (a) The 2301 working face for the first weighting. (b) The 2301 working face for the 7th weighting. (c) The 2301 working face for the 19th weighting. (d) End of mining in the 2301 working face.
When the coal seam is mined, the overlying strata structure will be broken continuously with the occurrence of periodic weighting, and the broken blocks will be compacted and mined out continuously, as shown in Figure 11, wherein the evolution of overlying strata structure in the 3-2 coal seam can be seen. When mining to 705 mm (the seventh periodic weighting), the main roof was periodically broken, and the caving angle of overlying strata on the left side of the periodic model is 40°; the caving angle of overlying strata on the right side of the model is 28°, and the caving height of overlying strata is 150 mm. When mining to 1560 mm (the 19th periodic weighting), the caving height of overlying strata reaches the maximum, the development height is 762.5 mm, the caving angle of overlying strata on the left side of the model is 63°, and that on the right side of the model is 66°. When the mining of the 2301 working face is finished, the upper coal is fully mined, and the left side of the goaf has a breaking angle of 70°, and the right side has a breaking angle of 68°. At this time, the upper coal goaf is compacted by the blocks of collapsed rock.

4.2. Structural Evolution Characteristics of Lower Coal Overburden. After the mining of the upper coal seam, the overlying strata experience a mining failure, the direct roof collapses irregularly, and the arrangement in the goaf is irregular. The basic roof is broken and arranged neatly. The overlying strata evolution characteristics of the mining ending tendency model of the lower coal seam 222 working face are shown in Figure 12. It is found that when the 222 working face first comes under pressure, the roof of the working face fully collapses, the upper strata of the goaf are damaged, with significant bending deformation, the cracks expanded upwards, and the height of the water-conducting fracture zone ranges between 502.5 mm and 540 mm. When the eighth periodic weighting of the 222 working face occurs, the fracture field of roof strata expands upward, and the concentrated distribution area of fracture field is laddered. The deformation area of rock strata is mainly concentrated in the range of model lengths of 950 to 1350 mm and heights of 75 to 550 mm, and the maximum height of water-conducting fracture zone is 489 mm.

When the 12th periodic weighting of the 222 working face occurs, the subsidence of the roof in the goaf of the 2301 working face above is maximized, and the vertical displacement above the 2301 working face is such that the displacement of strata near the goaf gradually decreases to the ground away from the goaf, while the vertical displacement below the 2301 working face is largely unchanged. After the lower coal is mined, the left breaking angle becomes larger, and the right breaking angle remains unchanged, which shows that the lower coal seam mining causes the greater disturbance to the working face.

There are two stages from aquifer migration to water inrush in the mining process of single coal seam or multilayer coal: in the first stage, when the coal seam is first mined, the connectivity of overlying strata fissures is enhanced, forming connected fissures, and aquifer water moves down along the water-conducting fissures and slowly enters the goaf, which is defined as the initial water outlet stage; in the second stage, microcracks gradually develop into large cracks until the rock mass structure is destroyed and completely collapsed. At this time, the aquifer collapses into the goaf in a large area, leading to the formation of water-conducting channels.

The observation of surface subsidence in the 222 working face mining is basically the same as that in the 2301 working face. A hole 200 mm from the left border of the model is cut and advanced to the right in turn in excavation increments of 10 mm, and each time the local surface undergoes obvious subsidence, the dial indicator data are recorded after the model has stabilized. Figure 13 shows the subsidence characteristics of the top of the model at different mining distances.

Because the coal seam continues to be mined after the mining of the upper coal seam ends, its surface subsidence also continues to sink after the mining of the upper coal seam ends to form a surface subsidence basin. The deformation and failure process of the overlying strata during mining is similar to that of the upper coal seam, and its subsidence curve is similar to that of the upper coal seam, but because the lower coal seam is 25 mm thick, the upper coal seam is 11.25 mm thick, and the lower coal seam is more than twice as thick as the upper coal seam; the surface subsidence caused by lower coal mining is larger than that caused by upper coal mining. As can be seen from the figure, the maximum surface subsidence caused by mining of the 222 working face is from 950 to 1050 mm from the open cut in the center of the subsidence basin, which is further back than the 1500 mm in the middle of the model, exhibiting significant lag. The maximum surface subsidence value reached about 29.0 mm after the end of the working face mining.

The evolution characteristics of overlying strata structure of the 4-2 coal seam are shown in Figure 14. When mining the 4-2 coal seam, due to the mining influence of the upper coal, the caving rock mass in goaf is more broken at the working face, and the overlying stratal damage is more severe. When mining to 64.0 mm (the eighth periodic weighting), the lower roof of overlying strata falls periodically, further
increasing the caving height of the overlying strata. The caving height is 370 cm, and the breaking angle on the left side of goaf is 66°, and the breaking angle on the right side is 54°. With the advancing of the working face, when the mining is 1470 mm (the 15th periodic weighting), the caving height of overlying strata is maximized, the development height is 1082.5 mm, and the breaking angle on the left side of the goaf is 80°, and the breaking angle on the right side is 72°.
5. Stress Recovery in Mined-Out Area and Ground Pressure Behavior

5.1. Characteristics of Stress Recovery Time in Goaf. After the underground coal seam is mined out, a certain mined-out space is formed underground, which is first filled by the collapsed broken rock mass, and a large number of voids are formed therein, then the upper strata begin to break, bend, and sink, and some voids in the collapsed broken rock mass are transferred to the upper part in the form of cracks and surface subsidence. The structural evolution of the fractured rock mass in overlying strata after mining determines its permeability and stability, and the stress recovery of fractured rock mass in overlying strata after mining is the main factor of structural evolution law. When the coal seams with different thicknesses are mined, the influence on goaf is also different. Seventy-nine floor pressure sensors are set under the coal seam to monitor the change in the mining stress during coal seam mining in real time, and the positions of five measuring points are selected as shown in Figure 15.

When mining the 2301 working face, five floor pressure sensors (No. 15 (403 mm), No. 30 (935 mm), No. 45 (1468 mm), No. 60 (2035 mm), and No. 78 (2965 mm)) were taken from the open cut as examples to collect and analyze the floor pressure values during mining (Figure 16). The pressure curve trend of each floor pressure gauge is similar (except No. 78). The pressure at the four measuring points goes through four stages: initial equilibrium zone, stress increasing zone, stress decreasing zone, and stress recovery zone. With the advancing of the working face, the goaf is compacted, and the stress gradually recovers.

The No. 78 floor pressure sensor is under the boundary coal pillar; the stress curve is relatively stable, which is different from the stress changes at the first four pressure sensors. When in the stress-reduction zone, the lowest stress value from the No. 15 floor pressure sensor to the No. 60 floor pressure sensor shows a downward trend and approaches zero. When the stress peak value from the No. 15 floor pressure sensor to the No. 60 floor pressure sensor is gradually increasing, it shows that with the advancing mining face’s abutment pressure gradually increasing, periodic weighting occurs more frequently in the later period, and weighting step is gradually shortened. Therefore, it is necessary to prevent and control the occurrence of rockburst in the actual mining face, and make prediction, allowing advanced implementation of control and countermeasures. After the goaf is gradually compacted and stabilized, it can be restored to three-fifths of the initial pressure before mining, and the peak pressure is found some 25.0 to 117.5 mm ahead of the working face.

When the working face 222 is mined, the above five floor pressure sensors are also monitored in real time. The stress curve is shown in Figure 17. As the working face advances, parts of the mined-out areas are fully enriched, resulting in that part of the floor stress becoming irrecoverable. When the mining of the upper coal is finished, the stress is redistributed. The initial pressure of the lower coal is different from that of the upper coal roof. The peak stress is 57.5 to 215.0 mm ahead of the working face, and the peak stress is 1.5 times that of the upper coal. The stress curve at the No. 15 floor pressure sensor is different from the stress trend of other measuring points due to incomplete enrichment of the goaf, and the stress redistributes. After the initial stress equilibrium is disturbed, the stress increases for a long time until the stress tends to stabilize. The trends in the stress at the No. 30, No. 45, and No. 60 floor pressure sensors are quite consistent with that of the upper coal, and they all go through four stages. At the end of mining, the stress at the No. 30 measuring point returns to one-third of the initial stress balance. The stress at measuring point 45 is restored to five-thirds of the initial stress in the period of equilibrium at the end of mining. At the end of mining, the stress at the No. 60 measuring point recovered to three times the initial equilibrium stress.

5.2. Characteristics of Stress Recovery Time in Goaf. When the 2301 working face is mined, stress concentration develops in the coal walls on both sides of the goaf, and the collapse of roof overlying strata will lead to the generation of strong ground pressure in the working face. In the previous process of roof cutting, the floor pressure will gradually increase with the advancing of the working face, and
the real-time stress in the goaf will gradually decrease. The change in coal seam advance abutment pressure can reflect the formation and development of roof caving accidents. In addition, the weighting of the upper layer coal is intense, and the weighting step is large.

When the working face 222 is mined, because the working face 2301 has been mined out, the roof collapses, and a compacted area is formed in the goaf. When the working face 222 is mined, the goaf fails to enrich the goaf fully, which leads to the systematic improvement of the next goaf. Due to the mining, the mined-out area of the lower coal layer is partially deformed by elastic energy recovery; because of this deformation, the stress recovery time of the lower coal layer under the influence of repeated mining is slower than that of the upper coal layer.

5.3. Changes in the Magnitude and Position of Support Pressure. In the initial mining stage of the working face, the distance from the position of support pressure to the coal wall increases slowly with the advancing of the working face, and the support pressure reaches two peaks at the end of mining. Figure 18 shows the characteristic relationship between model support pressure and stress concentration coefficient during the advancing of the 2301 working face, which reflects the changing support pressure with overlying strata movement therein. Before the working face advances to 1470 mm, the support pressure increases continuously with the advancing of the working face, the maximum is about 54.55 MPa, and the average stress concentration coefficient is 1.56. When the working face advances to 1470 to 1830 mm, the pressure on the model floor decreases, and
the stress concentration coefficient decreases to 1.92. When the working face advances to 2025 mm, the floor pressure in the model reaches its peak value again, and the floor pressure is 58.37 MPa. Until the end of mining, the support pressure starts to decrease from the peak value.

The characteristic relationship between support pressure and stress concentration coefficient in the advancing process of the 222 working face of the 3-2 coal seam is shown in Figure 19. When the working face advances to 640 mm, the support pressure reaches the first peak value of 57.81 MPa,
and the average stress concentration coefficient is 1.63. When the working face advances to 640 to 1470 mm, the pressure on the floor of the working face model continues to increase and reaches the peak again, with a maximum of 57.81 MPa and the stress concentration coefficient increasing to 2.3. When the working face is advanced to 1470 mm, the support pressure is continuously reduced. Roof caving will cause a high ground pressure to appear in the working face, and in the previous roof caving process, the support pressure will gradually increase with the advancing of the working face, and then gradually decreases after the leading abutment pressure reaches the second peak value.

According to the trend in the support pressure and weighting step during mining of the 2301 and 222 working faces, the periodic weighting rule of the short-distance coal seam group mining is shown in Figure 20. The first weighting step of the coal seam mining under the close-distance coal seam group is larger than that of the upper coal seam mining. In the same distance mining process of the upper and lower coal seams, the weighting times generated in the mining process of the lower coal seam working face are less, the average weighting step is long, and the average single weighting value is high. Taking the mining of close-distance coal seams in the Xiashijie Coal Mine as an example, 32 weighting events occurred during mining of the 2301 working face and its upper coal seam, with an average weighting of 43.02 MPa and the average interval between periodic weighting events of 73 mm; during the mining of the No. 222 face and its lower...
coal seam, 22 weighting events occurred, with the average weighting being 47.01 MPa and the average interval between weightings being 88 mm. The average weighting value and average weighting step of the lower coal seam are about 8.49% and 16.60% higher than those during mining of the upper coal seam, respectively.

6. Conclusion

(i) By studying the mechanical model after basic roof fracture, the structural stability of key blocks in close-distance coal seams was theoretically investigated, and the direct relationship between the rotation of key blocks of overlying strata and the subsidence of key blocks and the length of rock blocks was deduced, thus forming the critical criterion for basic roof fracture. The results indicated that the main factors affecting the rotation of key blocks are the subsidence of key blocks and their length; when the subsidence and the angle of rotation of the rock blocks are large and the lengths of the rock blocks are small, rotation and instability are more likely to occur.

(ii) The repeated disturbance effect of close-distance coal seams was estimated by similar material simulation experiment. The fracture angle of the goaf in the 222 face is much greater than that in the 2301 face in its upper coal seam. The caving and compaction of the upper coal roof can lead to the dynamic pressure in the lower coal seam area, resulting in the overburden collapse of the lower coal mining being more severe than that during upper coal mining, and the failure height is about 134 m higher than that during upper coal mining. Therefore, it is necessary to strengthen the stability control-measures implemented along the lower coal working face to prevent dangerous accidents.

(iii) The first weighting step of coal seam mining under the close-distance coal seam group is larger than that of the upper coal seam mining. In the same distance mining process of the upper and lower coal seams, the number of weighting events generated in the mining of the lower coal seam working face is smaller, the average weighting step is long, and the average single weighting value is high. Taking the mining of the close-distance coal seams in the Xiashijie Coal Mine as an example, 22 weighting events occur during the mining of the 222 working face of the lower coal seam, with an average weighting of 47.01 MPa and the average interval between periodic weightings of 88 mm (these are about 8.49% and 16.60% higher than those when mining the upper coal seam, respectively)

Data Availability

The test data used to support the findings of this study are included within the article. Readers can obtain data supporting the research results from the test data table in the paper.

Disclosure

I would like to declare on behalf of my coauthors that the work described was an original research that has not been published previously and not under consideration for publication elsewhere, in whole or in part.
Conflicts of Interest
The authors declare no conflict of interest.

Authors’ Contributions
The manuscript is approved by all authors for publication. All the authors listed have approved the manuscript that is enclosed.

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