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Study on the Mechanism and Control of Strong Rock Pressure in Thick Coal Seam Mining under the Goaf of Very Close Multiple Coal Seams

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Abstract: With the increasing proportion of close-distance coal seam mining in China, the problem of strong mining pressure during the mining of close-distance coal seams is becoming more and more severe. This article focuses on the complex stress environment and severe mining pressure encountered in the mining of thick coal seams under the multi-coal-seam goaf of Zhunnan Coal Mine. By using research methods, such as similar material simulation, theoretical analysis, and numerical simulation, it studies in depth the instability characteristics of the overlying rock structure of the W1701 working face, the inducing factors and mechanisms of strong mining pressure during the mining process, and control measures. The results show that the roof structure of the W1701 working face can be divided into "high-level key layer (hard rock)–giant thick soft and weak rock group–low-level key layer (hard rock)", and the law of mining pressure manifestation presents a small cycle formed by the instability of "masonry beam" structure and a main large cycle formed by the periodic penetration and step-down of the giant thick soft and weak rock group, with the load on the support during the large cycle up to 5.4 times the rated working resistance. In addition, this article proposes the strategy of using layered mining to control the manifestation of strong mining pressure under the "hard sandwiched soft" overlying rock condition of the Zhunnan Coal Mine, optimizes the thickness of the layered mining of the thick coal seam, and finally, determines the upper layer thickness of 2.8 m and the lower layer thickness of 4 m, inducing the giant thick soft and weak rock formation to undergo incremental damage and releasing the fracture energy incrementally, effectively controlling the manifestation threat of strong mining pressure in the mining of thick coal seams under the close-distance coal seam goaf. As the proportion of close-range coal seam mining increases in China, the problem of strong mining pressure during the mining of close-range coal seams becomes more severe. This article focuses on the complex stress environment and severe mining pressure in the mining of thick coal seams under multiple mined-out areas in the Zhunnan coal mine. Similar material simulation, theoretical analysis, and numerical simulation methods were used to conduct in-depth research on the unstable characteristics of the overlying rock structure of the W1701 working face, the causes and mechanisms of strong mining pressure during the mining process, and control measures. The results show that the roof structure of the W1701 working face can be divided into "high-level key layer (hard rock)–thick soft weak rock group–low-level key layer (hard rock)." The law of mining pressure manifestation presents small cycles of instability formed by "block beams" and main cycles of pressure formed by vertically cracked periodic penetration and step sinking of the thick soft weak rock group. Moreover, during the main cycle of pressure, the load-bearing capacity of the support is up to 5.4 times the rated working resistance. Furthermore, it is proposed to use hierarchical mining to control the manifestation of strong mining pressure in the "hard-inlaid soft" overlying rock condition of the Zhunnan coal mine and optimize the thickness of layered mining of thick coal seams. Ultimately, the upper layer thickness was determined as 2.8 m; the lower layer thickness was determined as 4 m, and the layered mining induced the thick soft weak rock group

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to undergo gradual damage and energy release, effectively controlling the threat of severe mining pressure during the mining of thick coal seams under the close-range coal seam mining.

Keywords: close-range coal seam group; strong rock pressure manifestation; layered mining; fracture energy

1. Introduction

The predicted coal reserves of Xinjiang are 2.19 trillion tons, accounting for more than 2/5 of the national coal resources [1,2]. The very close coal seams in each mining area in Jiangxi account for about 1/4 of the recoverable reserves and involve more than 100 mines. In the mining process of very close coal seam groups, disaster accidents caused by strong mine pressure appearing on the top plate, such as roofing sheeting and hydraulic bracket breakage, often occur. Many scholars have studied the mechanism of strong mine pressure in close coal seam mining. Huang et al. [3] concluded that mining of the lower coal seam in a close coal seam leads to the activation of the already stable roof structure of the upper coal seam, which, in turn, generates violent sinking motion and causes strong incoming pressure at the working face of the lower coal seam. Feng et al. [4] used field measurements and theoretical analysis to conclude that the middle thick key layer of the shallow buried close multi-seam coal seam collapses in a stratified manner and the lower thick. The mineral pressure anomaly phenomenon, the key layer structural instability, and the dynamic load mine pressure mechanism were studied in depth. Du Feng et al. [5] studied the mechanism of strong mine pressure in mining under the boundary coal column of shallowly buried close coal seam and concluded that the articulated structure of the key block above the coal column occurred in reverse rotary motion, which triggered strong dynamic pressure disaster. Yang Ke et al. [6] studied the evolution of the pressure stacking mechanism of comprehensive mining support under a large inclination thick coal seam in the close mining area and a proposed working face. He Fulian et al. [7] researched the support pressure evolution law in front of the repetitive mining workings in the close coal seam and determined the reasonable width of the stopping coal column in the close coal seam.

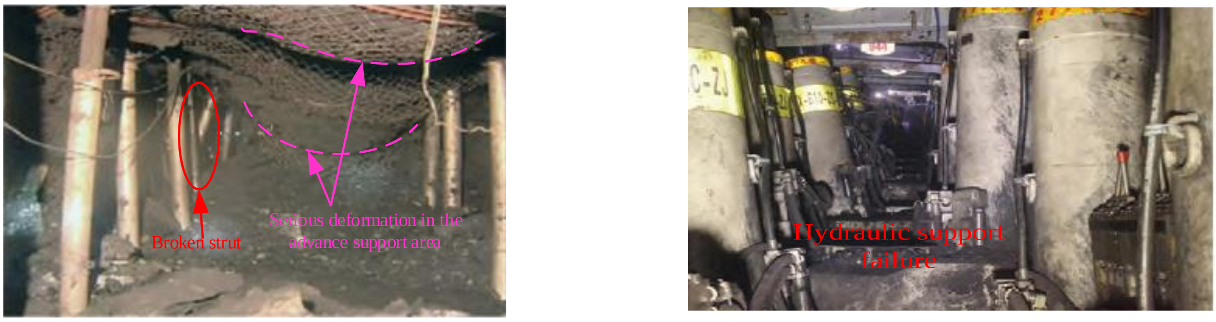
From the above scholars' research results, it can be seen that the causes of strong mine pressure induced by close coal seam group mining are closely related to the factors such as coal pillars left in the mining area above them, hard roof breakage, structural instability of key layers, and stress superposition of repeated mining. Based on this, some scholars proposed mine pressure control techniques such as coal pillar or hard roof unloading, roadway reinforcement support, and optimized working face design [8–13]; for example, Yang Junzhe et al. [14] proposed top cutting and pressure unloading and over-weakening management techniques for close coal seam group under a hard roof; Zhu Tao et al. [15] took the rock structure of close lower coal roof and working face stent load as the research objects, and derived through mechanical analysis. Hao Dengyun et al. [16] used high prestressing full anchor cable to strengthen the support for the back mining roadway under the near extra-thick coal seam, which effectively controlled the roadway deformation; Wang Longfei et al. [17] proposed a combined anchor and anchor cable support system based on the principle of "zoning support and source control" for the back mining roadway under the near coal seam group mining area in deep wells. Tu Shihao et al. [18], in response to the problem of large impact pressure on the overlying rocks, adopted the control measures of blasting the residual coal column to release the top and unload the pressure, injecting sand into the coal room and reasonably controlling the mining height to achieve the safe and efficient production of the working face in response to the problem that the mining under the room mining area of the working face of the shallowly buried coal seam is prone to unload the mine pressure and even the mine pressure. Xu Jingmin et al. [19] proposed the control measures of using blasting or other means to weaken the coal pillar of room mining in advance, slow down the advancing speed of the working face, and slurry filling in the coal pillar area of room mining in view of the vulnerability of mining under the room mining area of the shallowly buried coal seam, and other scholars put forward the control measures of optimizing the position of back mining tunnel under the near coal seam mining area [20–23], and joint and coordinated mining of near coal seam group [24–27], etc. The technical measures for mine pressure control are proposed.

The research results of the above scholars mainly focus on close coal seam mining, but not much research has been conducted on the mining pressure mechanism and control technology of the thick coal seam under the very close multi-seam mining void area with smaller layer spacing. In this paper, based on the research results of previous scholars, the strong mining pressure phenomenon on the roof plate of the W1701 working face under the very close multi-seam mining void area in Zhunnan coal mine is studied by using physical similar simulation experiments, theoretical analysis, and numerical simulation, etc., to investigate the mechanism of strong mining pressure induced by the roof plate and control countermeasures, which provides a reference for mining pressure control in similar coal seams.

2. Project Background

2.1. Overview of the Working Face

The main recoverable coal seam of the Zhunan coal mine is located in the Middle Jurassic Xishangyao Formation. Two coal seams have been formed in the middle and lower part of this section due to frequent alternation of water and land. The mine is currently mining the middle and upper B5~B7 coal seams, of which the B5 and B6 coal seams have all been retrieved; the average coal thickness of B5 and B6 is 2.6 m and 3.5 m; the average thickness of B7 coal seam is 6.8 m. The spacing between B5 and B6 coal seams is 4.5 m; the spacing between B6 and B7 coal seams is 4 m, and the dip angle of coal seams is 8~12°. In the process of W1701 back mining, strong mine pressure phenomenon continuously appeared in the quarry—the violent sinking of the top plate, breakage of the monolithic column of the roadway over support, and frequent opening of the safety valve of the hydraulic bracket at the working face, which seriously affected the safety of the working face (Figure 1).



(**a**) (**b**)

Figure 1. Site strong mineral pressure appears. (**a**) Over-supported monolithic column fracture. (**b**) The hydraulic support at the working face is crushed.

2.2. Preliminary Analysis of Strong Mine Pressure Triggers

The inducing factors of abnormal coal seam pressure at a very close distance are complex, but it is most affected by the residual coal column and overburden fault transport in the goaf area [28–31]. The W1701 working face belongs to the extremely close multi-seam mining area, and the working face is staggered under the B6 coal seam mining area (Figure 2), and there is a large horizontal staggering distance (20 m) from the overlying coal column, so it is less likely to be affected by the concentrated stress of the coal column left in the B6 coal seam mining area. The influence of concentrated stress is less likely, and the coal pillar left in the B5 coal seam mining area was destabilized and broken when the B6 coal seam was retrieved, which also had little influence on the W1701 working face; therefore, the W1701 working face is most likely to be affected by the strong mine pressure of the overlying rock structure movement during the retrieval process.

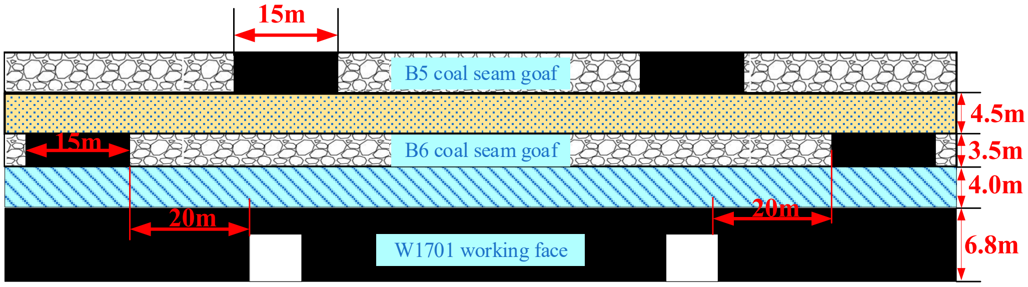
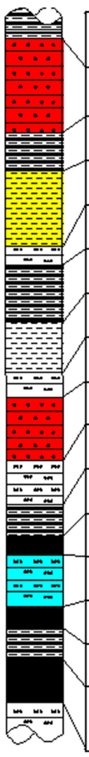


Figure 2. Schematic diagram of the location relationship of W1701 working face.

According to the comprehensive bar diagram of the coal seam geological drilling in Figure 3 and combined with the key layer theory [32,33], it can be seen that the overburden rock above the B7 coal seam is endowed with two key layers, among which the low key layer is coarse sandstone with a thickness of 10.3 m, the high key layer is coarse sandstone with a thickness of 15.8 m, and the rock layers between the key layers are mainly soft sandy mudstone, mudstone, and thin siltstone, with a total thickness of 44.5 m (Figure 3) On the whole, the overlying rocks of W1701 workings generally show the structure of "high key layer (hard rock)–giant thick soft rock group–low key layer (hard rock)", and the overlying rocks of "high key layer (hard rock)–giant thick soft rock group–low key layer (hard rock)" during the mining process of the very close coal seam. It is necessary to study the characteristics of the overlying "high key layer (hard rock)–huge soft rock group–low key layer (hard rock)" structure to grasp the incoming pressure law of the roof of the W1701 working face.



Lithology of rock formations	Rock strata	Average strata thickness(m)	Average buried depth(m)
Coarse sandstone	High critical strata	15.8	144.3
Sandy mudstone	Soft rock formations	6.4	151.8
Mudstone		12.3	164.1
Siltstone		3.5	167.6
Sandy mudstone		9.1	176.7
Mudstone		8.8	185.5
Siltstone		4.4	189.9
Coarse sandstone	Low critical strata	10.3	200.2
Siltstone	Main roof	4.9	205.1
Sandy mudstone	Immediate roof	3.2	208.3
B5 coal seam		2.6	210.9
Siltstone	Interbedded rock formations	4.5	215.4
B6 coal seam		3.5	218.9
Sandy mudstone	Interbedded rock formations	4.0	222.9
B7 coal seam		6.8	229.7

Figure 3. Coal seam-integrated bar graph.

3. Methodology

3.1. Physically Similar Simulation Experiments

In order to further analyze the law of pressure coming from the open roof of the W1701 working face, physical similarity simulation experiments were carried out to study the actual geological conditions of B5, B6, and B7 coal seams in the Zhunnan coal mine as the prototype.

3.2. Experimental Design

The physical similarity simulation experiment uses a plane stress model; the model geometric similarity ratio is $\alpha_L = 100$; the capacity similarity ratio is $\alpha_\gamma = 1.6$; the displacement similarity ratio is $\alpha_s = \alpha_L = 100$; the stress similarity ratio is $\sigma_r = \alpha_L \times \alpha_\gamma = 160$; the time similarity ratio $\alpha_t = 10$; the model length × width × height is 160 cm × 20 cm × 120 cm, and the top of the model is applied with 0.012 kN compensation load. The model was laid with pre-buried miniature pressure sensors at the top of each coal seam with a spacing of 5 cm. The model was mined in a downward direction, and each coal seam was mined at a full thickness in one step with 10 cm excavation. For the convenience of description, the experimental simulation data were converted to the prototype data. The coal rock mechanical parameters are shown in Table 1; the model similar material ratios are shown in Table 2, and the physically similar model and experimental equipment are shown in Figure 4. In order to eliminate the influence of boundary effects on simulation results, a cut-out was made on the right side of the model at a distance of 30 cm from the boundary. Then, the model was pushed from the right side to the left side, stopping the excavation at a distance of 30 cm from the left side boundary, with a total advance distance of 100 cm. After the completion of the excavation, stress monitoring was stopped when stress transmission became stable.

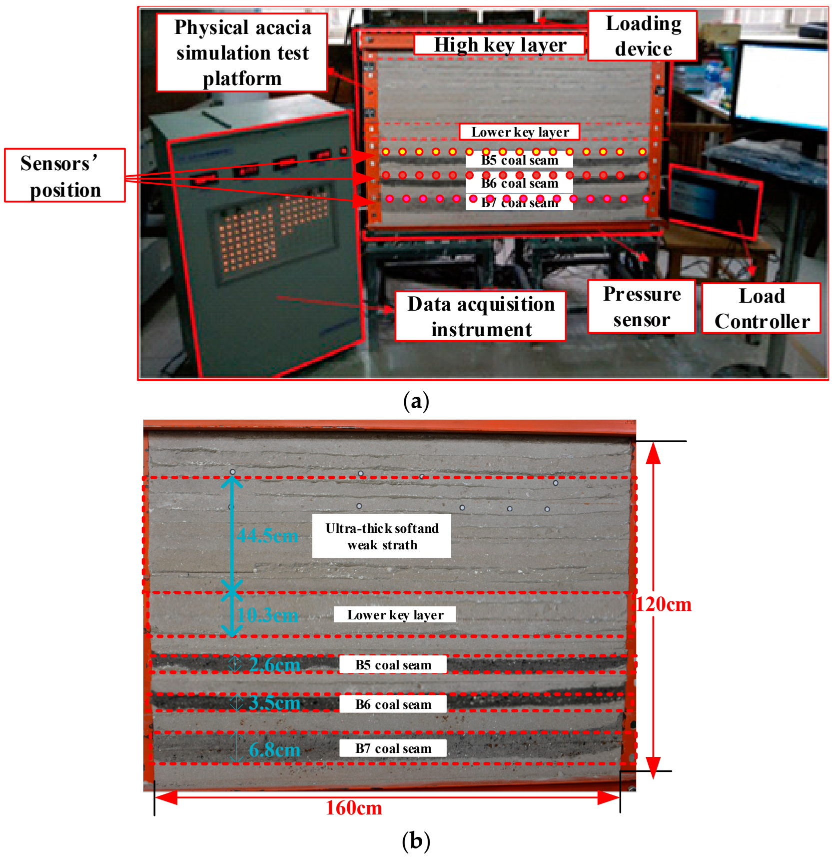


Figure 4. Similar material experimental model. (**a**) Experimental monitoring equipment. (**b**) Main parameter.

Table 1. Mechanical parameters of coal rock.

Name of Rock Layer	Capacity Weight (kN/m^3)	Tensile Strength (MPa)	Cohesion Force (MPa)	Internal Friction Angle (°)	Poisson's Ratio	Elasticity (GPa)
Coarse sandstone	25.4	6.2	10.2	31.7	0.21	8.5
Siltstone	26.3	3.7	5.4	30.4	0.23	5.1
Mudstone	26.8	0.9	1.6	27.5	0.35	4.4
Sandy mudstone	25.8	2.2	3.4	29.9	0.33	4.4
B5 coal seam	14.4	1.4	2.8	29.5	0.27	1.7
B6 coal seam	14.9	1.1	3.8	28.8	0.24	2.8
B7 coal seam	16.1	1.5	4.1	28.5	0.26	4.2

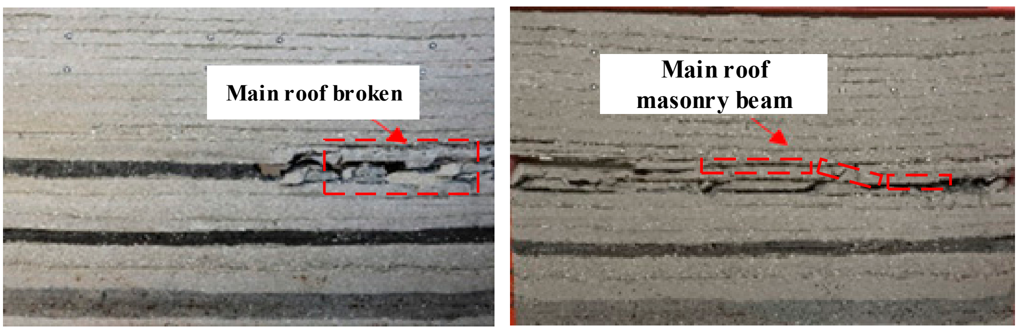
Table 2. Physical similarity simulation material ratios.

Serial No.	Name of Rock Layer	Rock Strata	Simulated Thickness /cm	Ratio Number (1:100)	Main Materials/kg		
					Fine Sand	Plaster	Lime
15	Coarse sandstone	High key layer	15.8	737	77.4	3.3	7.7
14	Sandy mudstone	Thick and weak rock formations	6.4	837	31.4	1.2	2.8
13	Mudstone		12.3	982	110.9	9.9	2.5
12	Siltstone		3.5	728	17.2	0.5	2.0
11	Sandy mudstone		9.1	837	44.6	1.7	4.0
10	Mudstone		8.8	737	43.1	3.9	1.0
9	Siltstone		4.4	728	21.6	0.6	2.5
8	Coarse sandstone	Low critical layer	10.3	737	50.5	2.2	5.0
7	Siltstone		6.9	728	33.8	1.0	3.9
6	Sandy mudstone		5.2	837	25.5	1.0	2.3
5	B5 coal seam		2.6	855	12.7	0.8	0.8
4	Siltstone		4.5	728	39.2	1.1	4.5
3	B6 coal seam		3.5	882	17.2	1.7	0.4
2	Sandy mudstone		4.0	837	24.5	0.9	2.2
1	B7 coal seam		6.8	874	33.3	3.0	1.7

3.3. Analysis of Experimental Results

3.3.1. Overburden-Breaking Characteristics

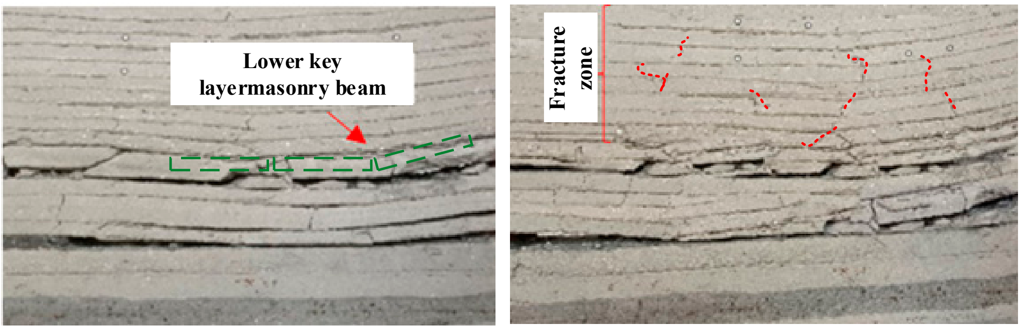
As shown in Figure 5, the overburden movement characteristics of B5 coal seam mining are similar to those of ordinary single coal seam; its direct top collapses with mining (Figure 5a); the basic top breaks periodically and is neatly arranged to form "masonry beam" structure, with 15~18 m pressure step of the cycle; after the end of back mining of B5 coal seam, visible fissures appear in the middle and lower part of the low-key seam. However, there was no breakage (Figure 5b).



(**a**) (**b**)

Figure 5. Overburden fracture characteristics of the B5 coal seam workings. (**a**) Main roof broken. (**b**) Retrieval completed.

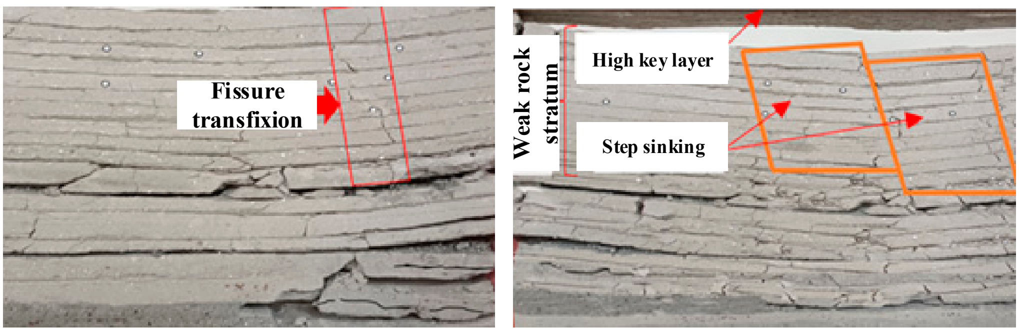
Figure 6 shows the characteristics of overlying rock failure during the mining process of the B6 coal seam. It can be seen from the analysis in Figure 6 that during the mining of the B6 coal seam, due to the presence of 4.5 m of siltstone between the B5 and B6 coal seams, although there is a certain strength when the working face advances 20 m, the thin layer of siltstone begins to fall, and the "masonry beam" structure on the basic roof of coal seam B5 is broken and unstable, losing its bearing capacity, and the rear goaf is connected with the roof caving zone of B5 Coal Seam. When the working face advances by 35 m, the low key layer structure of the roof undergoes initial fracture, and the B6 coal seam undergoes significant pressure. Later, as the B6 coal seam continues to advance, the low-key layer periodically fractures, and the broken rock blocks are arranged neatly (Figure 6a). The "masonry beam" structure is hinged and stable, and the weak rock group also sinks significantly. The crack development is obvious. After the B6 coal seam was mined, the height of the crack zone developed up to 35.5 m (Figure 6b).



(**a**) (**b**)

Figure 6. Overburden fracture characteristics of B6 coal seam working face mining. (**a**) Low key layer "masonry beam" structure. (**b**) Workface retrieval completed.

Figure 7 shows the characteristics of strata caving and fracturing during the mining of coal seam B7. Due to the large thickness of coal seam B7, the mining disturbance is more intense, providing ample space for the overlying roof to collapse and sink. The 4.0 m-thick sandy mudstone between coal seams B6 and B7 squeezed and burst out during mining, causing the previously stable lower key strata to continue to sink, creating small periodic pressure. When the working face advanced 40 m, the 44.5 m-thick weak rock group between the high and low key strata developed upward fractures continuously until a longitudinal through crack was formed in the high key strata (Figure 7a), accompanied by a relatively large separation space between the high key strata and the weak rock group. The weak rock group was sheared and fractured along the through crack, causing periodic stepwise sinking (Figure 7b), resulting in a large cyclic pressure with a step distance of about 40 m.



(**a**) (**b**)

Figure 7. Overburden fracture characteristics of the B7 coal seam working face mining. (**a**) Through fracture formation. (**b**) Step down.

3.3.2. Law of Incoming Pressure of the Roof Plate

As shown in Figure 8a–c, in the process of B5 seam mining, the peak pressure of the roof support is 6.48 MPa, 6.56 MPa, 6.67 MPa, 6.55 Mpa; the stress concentration coefficient is 1.08~1.11; the peak pressure of the support does not change much, and the mine pressure appears more moderate. In the process of opening the B6 seam, the peak bearing pressure is 8.25 MPa, 8.36 MPa, 8.24 MPa, and 8.47 Mpa, respectively, for the process of advancing the working face to 40 m, 60 m, 80 m, and 100 m, and the stress concentration coefficient is 1.37~1.41; compared with the B5 seam, the pressure of the working face increases significantly, but the peak pressure of the supporting pressure does not change much; the pressure of the roof is mainly affected by the secondary destabilization of the "masonry beam" structure formed after the basic roof breakage of the B5 seam and the periodic breakage of the low key layer. The peak bearing pressure of the roof is 12.86 MPa, 10.55 MPa, 13.92 MPa, and 11.15 Mpa, respectively, and the stress concentration coefficient is 1.76~2.21; the peak bearing pressure shows a jumping change with a significant difference.

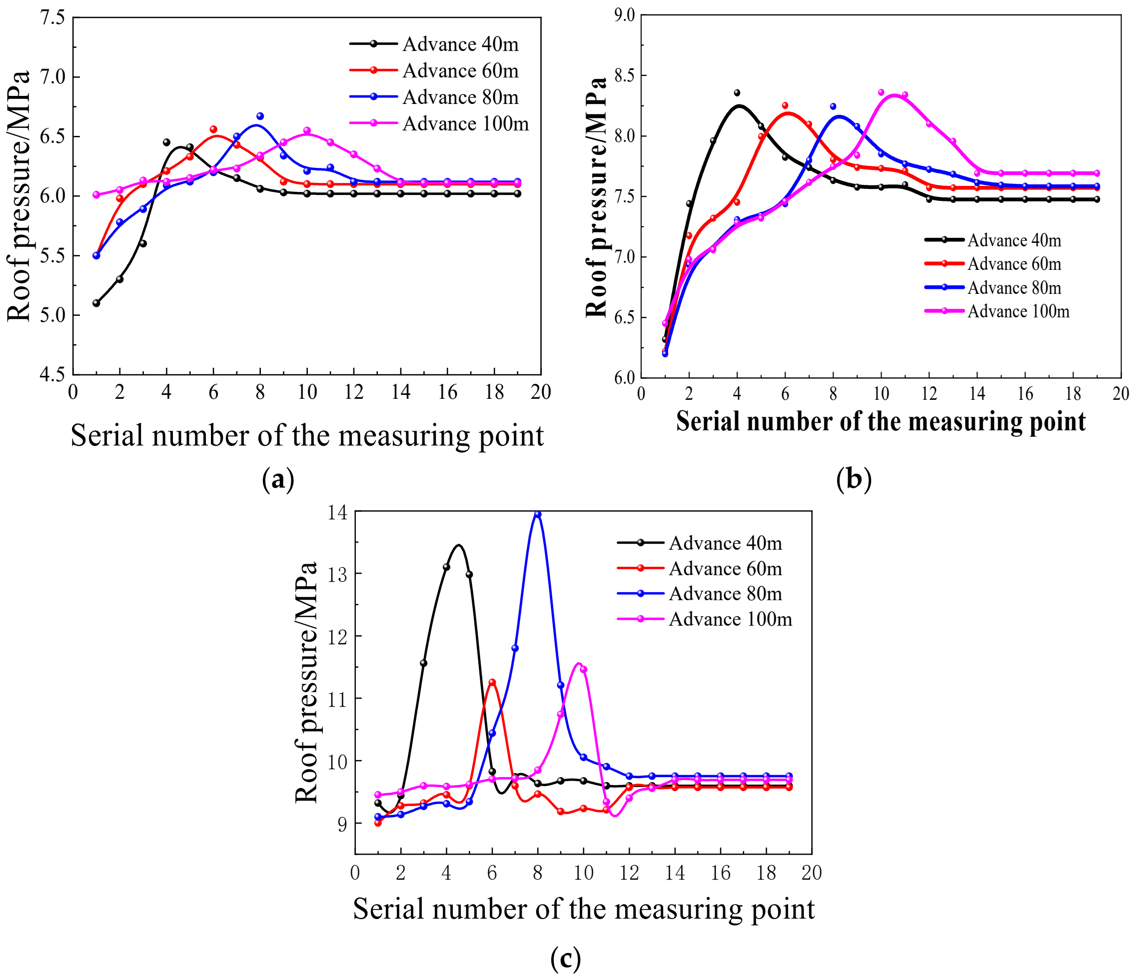


Figure 8. Top pressure variation curve of each coal seam retrieval working face. (**a**) B5 coal seam. (**b**) B6 coal seam. (**c**) B7 coal seam.

4. Mechanism of Strong Mine Pressure on the Roof and Control Measures

4.1. Mechanism of Strong Mine Pressure on the Roof

Through similar simulation experiments, it is known that the cause of strong mine pressure at the W1701 working face is closely related to the overburden structure and movement of "high key layer (hard rock)–huge thick soft rock group–low key layer (hard rock)" above it. After the destabilization of the structure, the "masonry beam" of the low-key layer, the huge thick weak rock group above it forms penetrating fissures, and shear breakage occurs as a whole, resulting in periodic step-down movement (Figure 8b), which causes the peak pressure of the roof support to jump and increase suddenly. This is the main reason for the strong mine pressure at the working face [34,35].

From the physically similar simulation experiments, it is easy to see that during the large periodic step-down motion, the brace load *Pm* on the W1701 working face is composed of the static load of the direct top, the interval layer that emerges with mining and the dynamic load of the step rock beam that produces the step-down motion (Figure 9), and the brace load *Pm* of the step rock beam is calculated by [21,29].

$$P_m = bl_k r_z \sum h + \frac{i - \sin\theta_{1\max} + \sin\theta_1 - 0.5}{i - 2\sin\theta_{1\max} + \sin\theta_1} bP_1 \tag{1}$$

$$\theta_{1\max} = \arcsin\frac{M - (K_p - 1)\sum h}{l} \tag{2}$$

where b is the width of the stand, m; l_k is the top control distance of the stand, m; $\sum h$ is the thickness of the direct top and interval seam with mining, m; r_z is the capacity of the direct top and interval seam with mining, kN/m^3; i is the block size of the step rock beam, the value of which is the ratio of the thickness of the step rock beam to the length of the structure block of the step rock beam; $\theta_{1\max}$ is the maximum rotation angle of the step rock beam, (°); θ_1 is the initial rotation angle of the step rock beam, (°); M is the mining height of coal seam, m; l is the length of the structural block of step rock beam, m; K_p is the coefficient of fragmentation and swelling of the riser seam; P_1 is the dynamic load of step rock beam, kN/m^3.

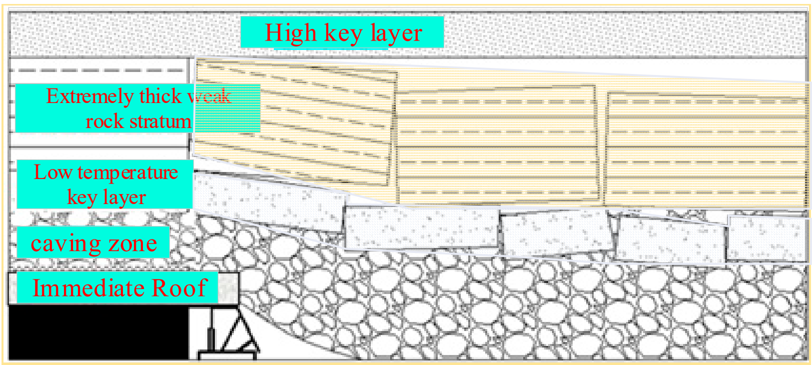


Figure 9. Step rock beam support load model.

P_1 consists of the weight P_G of the articulated rock block of the low-key seam and its upper load P_Z.

$$P_1 = P_G + P_Z \tag{3}$$

$$P_G = h_s r_s l \tag{4}$$

$$P_Z = K_G h_1 r_1 l \tag{5}$$

$$K_G = K_r K_t \tag{6}$$

$$K_r = \frac{l}{2h_1 a \tan\varphi} \tag{7}$$

where K_G is the load transfer coefficient; K_r is the load transfer lithology factor; K_t is the load transfer time factor, which is generally taken as 0.85 and 1 for a long time state; h_s

is the thickness of the articulated block of the low key layer, m; r_s is the capacity of the articulated block of the low key layer, kN/m^3; h_1 is the thickness of the load layer, m; r_1 is the average capacity of the load layer, kN/m^3; a is the lateral stress of the load layer coefficient, $a = 1 - \sin\varphi$, and φ is the internal friction angle of the load layer.

According to the results of the physical similarity simulation experiments of W1701 working face mining, the length of the step rock beam that produces the step-down motion is l = 40 m; the thickness of the load layer is h_1 = 44.5 m; K_P = 1.41; φ = 27°; $a = 1 - \sin\varphi = 0.65$; the average capacity of the load layer is r_1 = 18.5 kN/m^3; K_t is taken as 1; h_s = 10.3 m; r_s = 24 kN/m^3. The above parameters are substituted into Equations (1)–(7) to obtain the load of the bracket at W1701 working face during the period of large cycle pressure of the roof P_m = 96,768 kN, which is 5.4 times the rated working resistance of the bracket (18,000 kN). It can be seen that the rated working resistance of the working face bracket is much lower than the load transmitted by the rock layer above, which will surely lead to the whole working face bracket being crushed and then causing a major production safety accident.

4.2. Strong Mine Pressure Control Strategy for Very Close Range Coal Seam Group

The key to controlling the strong mine pressure in the W1701 working face is to avoid the formation of penetrating fissures in the "huge thick and weak rock group" and the occurrence of violent movement of the whole rotary sinking. According to related research, the overburden fracture height on the roof of the thick coal seam is much higher than the corresponding range when mining in layers; the thickness of the periodically broken rock blocks also increases, and there is no obvious separation between the rock layers; the rock layer breakage occurs along the fracture toward the coal wall of the quarry, causing the overburden rock layer of the quarry to sink sharply; the mining of thick coal seam in layers with limited thickness can make full use of the overburden structure disaster control mechanism, which makes the overburden fracture energy released in stages and avoids the occurrence of strong mine pressure accidents in the quarry. Obviously, the current use of full-thickness back mining in the W1701 working face at one time is not conducive to mine pressure control.

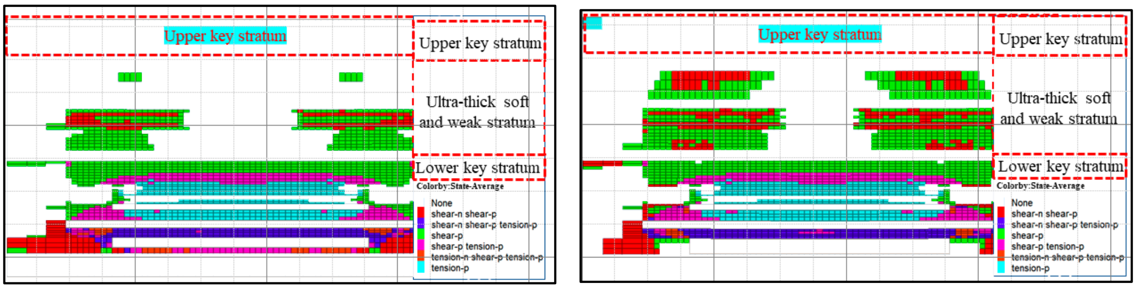
In order to verify the overburden fracture and mine pressure characteristics of stratified mining, a flac3D numerical model of stratified mining under a B7 thick coal seam in a multi-seam mining area is established, with the model of 500 m (length) × 200 m (width) × 110 m (height), coal rock mechanical parameters are shown in Table 1 of Section 2.1, and the model adopts Mohr–Coulomb Model criterion, the boundary around the model is simply supported, the bottom is fixed, and a uniformly distributed load of 8 MPa is applied at the top to simulate the self-weight load of the overlying rock layer. To eliminate edge effects, the model reserves 50 m coal pillars on both the left and right sides. The comparison plan for the difference in strong rock pressure behavior between the upper and lower layers during layered mining of the B7 coal seam is as follows.

Scheme 1: Upper stratification mining thickness 3.4 m, lower stratification mining thickness 3.4 m.

Scheme 2: Upper stratified mining thickness 2.8 m, lower stratified mining thickness 4.0 m.

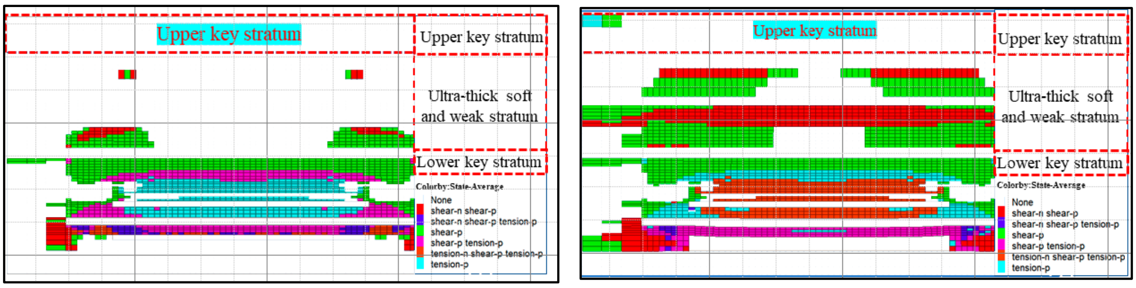
The development pattern of the plastic zone in the surrounding rock with different thicknesses of layered mining is shown in Figures 10 and 11. From the analysis of Figures 10 and 11, it can be seen that after adopting layered mining, the thick and weak rock formations between the high and low key layers have undergone staged damage, and the fracture energy of the "thick and weak rock formations" has been released in stages. When the thickness of the upper layer mining is 3.4 m (Scheme 1), after the upper layer coal seam mining is completed, the low-key layer undergoes plastic damage, and there are also some plastic zones developed in the thick and weak rock formations. After the current layer of coal seam mining is completed, the plastic zone further develops upwards, with a development height of up to 34 m. When the thickness of the upper layer mining is

2.8 m (Scheme 2), although the low key layer is also damaged after the coal seam mining is completed, the development height and range of the plastic zone are significantly smaller than in Scheme 1, with a development height of 30.5 m. By comparing the development cloud map of the full-thickness mining plastic zone in a single mining operation (Figure 12), it can be seen that when using a full-thickness operation to mine the B7 coal seam, not only the low-key layer and weak rock formations are damaged, but also the high key layer undergoes plastic damage. Moreover, the development range of the plastic zone is extremely wide, seriously threatening the production safety of the mining site. Therefore, in order to avoid strong rock pressure during the mining process of the B7 coal seam working face in the lower layer of the close-range coal seam group, layered mining should be selected, and the thickness of the upper and lower layered mining should be 2.8 m and 4 m, respectively.



(**a**) (**b**)

Figure 10. Scheme 1 stratified mining overburden plasticity zone cloud map. (**a**) Upper stratification (mining thickness 3.4 m). (**b**) Lower stratification (mining thickness 3.4 m).



(**a**) (**b**)

Figure 11. Cloud map of overburden plasticity zone for Option 2 stratified mining. (**a**) Upper stratification (mining thickness 2.8 m). (**b**) Lower stratification (mining thickness 4.0 m).

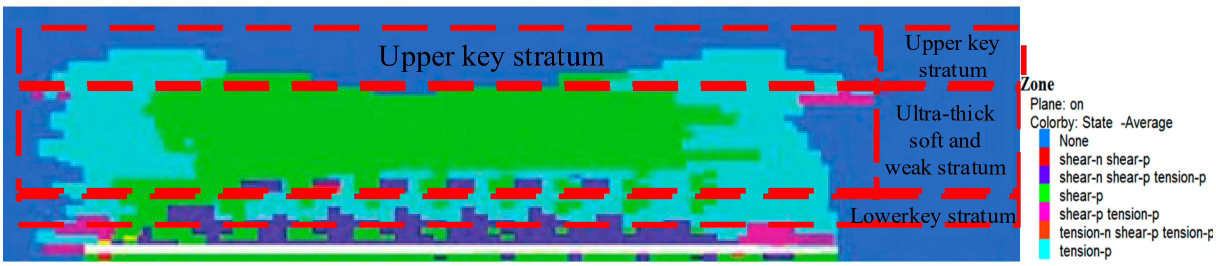


Figure 12. Cloud map of overburdened plastic zone of full-thickness mining.

According to Figure 13, when the entire thickness is mined in one pass, the peak value of the roof support pressure continuously moves forward with the advancement of the working face and gradually increases. Before the working face advances 150 m, there is little variation in the peak value of the support pressure. However, when the working face advances from 150 m to 200 m, the peak value of the support pressure jumps from

12.8 MPa to 13.9 MPa. This is because the thickness of the working face is large. After the working face is mined, it provides a large space for the roof to sink, and the weak rock strata undergo large displacement, which brings a great impact on the working face.

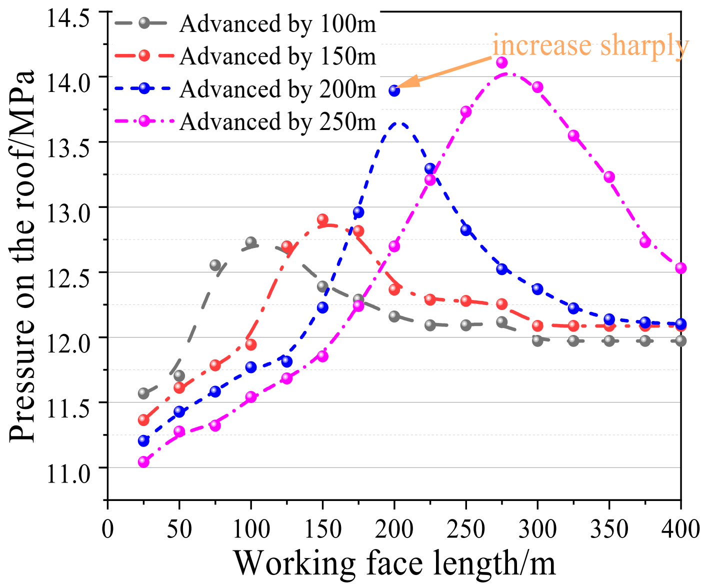


Figure 13. Full-thickness mining roof support pressure variation curve.

When the layered mining method is used, the curve of the roof support pressure changes, as shown in Figures 14 and 15. By comparing and analyzing Figures 14 and 15, it can be seen that the peak value of the roof support pressure did not undergo a sudden jump after using the layered mining method, and the top pressure on the working face was significantly reduced compared to the entire thickness mining method. The peak value of the support pressure for Option 2 is slightly smaller than that of Option 1, indicating that the change in support pressure is smaller and the impact load of roof movement on the working face is lower. Therefore, for extremely close coal seams and when mining thick coal seams under the goaf, the layered mining method should be used to avoid the occurrence of strong mining pressure, which can lead to accidents such as pillar damage or coal wall detachment.

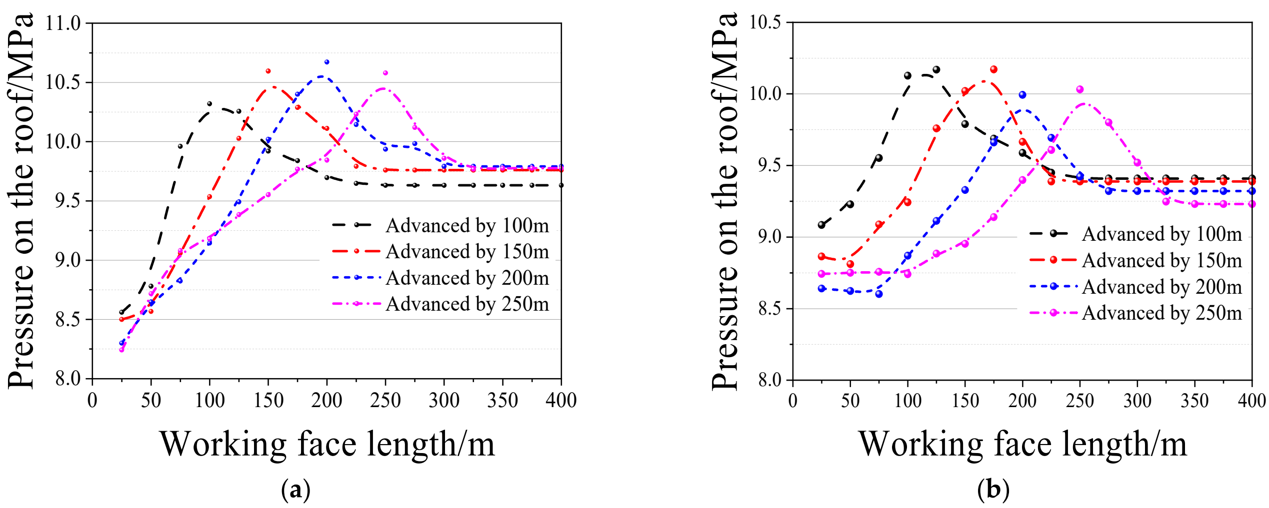


Figure 14. Scheme 1 stratified mining roof support pressure variation curve. (**a**) Upper stratification (mining thickness 3.4 m). (**b**) Lower stratification (mining thickness 3.4 m).

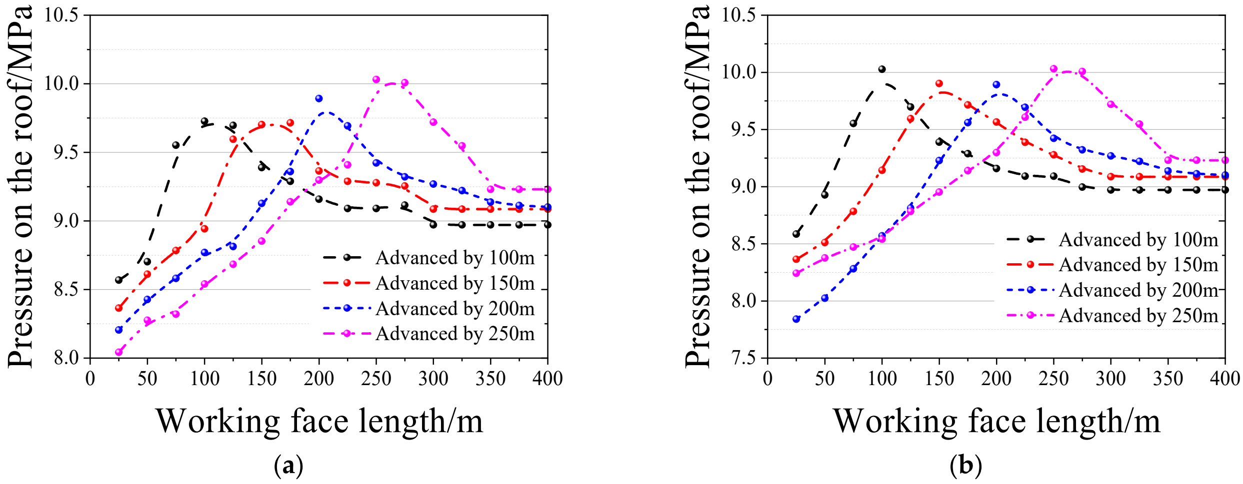


Figure 15. Scheme 2 stratified mining roof support pressure variation curve. (**a**) Upper stratification (mining thickness 2.8 m). (**b**) Lower stratification (mining thickness 4.0 m).

5. Conclusions and Discussion

(1) The W1701 working face rock structure is composed of a "high-level key layer (hard rock)–thick soft and weak rock group–low-level key layer (hard rock)" structure. During the working face mining period, there is a phenomenon of large and small cycle squeezing. The lower key layer's "masonry beam" structure becomes unstable, forming small cycle squeezing; the thick, soft, and weak rock group between the low-level and high-level key layers periodically passes through vertical cracks, causing step sinking and forming strong large cycle squeezing.

(2) In the extremely close distance coal mining area, the main cause for the manifestation of strong coal pressure is the sudden increase in roof support pressure, which causes the working resistance of the support to reach 5.4 times its rated working resistance, leading to support failure and easily inducing major safety accidents.

(3) The thick coal seams under the mined-out area of the Zhunnan Coal Mine, at an extremely close distance, should not be fully excavated in one pass. Instead, a layered excavation technique was proposed to control the occurrence of strong mining pressure. By analyzing and comparing the characteristics of mining pressure under different layer thicknesses, it was determined that the upper layer thickness should be 2.8 m and the lower layer thickness should be 4 m.

Layered excavation techniques for the thick coal seams under the mined-out area of the Zhunnan Coal Mine can cause sequential damage to the extremely thick and soft rock masses between high and low-key layers. The energy released by the fractures of the extremely thick and soft rock masses is released sequentially, effectively avoiding the sudden jump of the peak pressure in the top plate support, which can help prevent mining accidents related to strong mining pressure. The research results can provide theoretical guidance and technical reference for controlling the occurrence of strong mining pressure during coal seam mining under similar conditions.

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References

1. Xiong, Y.; Kong, D.; Cheng, Z.; Wen, Z.; Ma, Z.; Wu, G.; Liu, Y. Instability Control of Roadway Surrounding Rock in Close-Distance Coal Seam Groups under Repeated Mining. *Energies* **2021**, *14*, 5193. [CrossRef]
2. Cui, F.; Jia, C.; Lai, X.; Yang, Y.; Dong, S. Study on the Law of Fracture Evolution under Repeated Mining of Close-Distance Coal Seams. *Energies* **2020**, *13*, 6064. [CrossRef]
3. Huang, Q.; He, Y.; Luo, L.; Jian, C. Study on activation structure and support resistance of collapsed roof in shallow buried extremely close distance coal seam goaf area. *J. Min. Saf. Eng.* **2018**, *35*, 6–11. [CrossRef]
4. Feng, J.; Zhou, Y.; Zhang, K.; Xu, Y.; Li, H. Breaking characteristics of thick key layer and determination of working resistance of bracket in shallow buried close-range multi-coal seam goaf area. *J. Min. Saf. Eng.* **2018**, *35*, 7–12. [CrossRef]
5. Du, F.; Yuan, R.; Zheng, J. Abnormal ore pressure mechanism of mining under coal column in shallow buried near range coal seam. *J. China Coal Soc.* **2017**, *42* (Suppl. S1), 24–29. (In Chinese) [CrossRef]
6. Yang, K.; Kong, X.; Lu, W.; Liu, S. Study on mining pressure law of large dip thick coal seam under close goaf. *Chin. J. Rock Mech. Eng.* **2015**, *34* (Suppl. S2), 4278–4285. (In Chinese)
7. He, F.; Li, L.; Lv, K.; Qin, B.; Xu, X.; Ma, Q.; Chen, Y. Study on Evolution of Front Abutment Pressure at Working Face in Repeated Mining of Close-Distance Coal Seams. *Sustainability* **2022**, *14*, 12399. [CrossRef]
8. Cheng, Z.; Yong, Y.; Wen, W.; Zhong, C.; Sheng, W.; Zhong, H. Research on the "three shells" cooperative support technology of large-section chambers in deep mines. *Int. J. Min. Sci. Technol.* **2021**, *31*, 665–680. [CrossRef]
9. Wang, W.; Yuan, Y.; Liang, X.; Qin, Z.; Chen, Z.; Ding, K.; Xia, Y.; Yan, C. Experimental Study on Floor Damage and Slurry Material Ratio Optimization in Deep and High Confined Water Mining. *Processes* **2022**, *10*, 1806. [CrossRef]
10. Kai, L.; Fu, H.; Liang, L.; Xu, X.; Bin, Q. Field and simulation study of the rational retracement channel position and control strategy in close-distance coal seams. *Energy Sci. Eng.* **2022**, *10*, 2317–2332. [CrossRef]
11. Wang, Y.; Yuan, H.; Gao, M.; Li, M.; Sun, J. Fracture law of different overlying strata in mining of protective seam under close distance coal seam. *Energy Sci. Eng.* **2023**, *11*, 1336–1348. [CrossRef]
12. Qin, D.; Wang, X.; Zhang, D.; Guan, W.; Zhang, L.; Xu, M. Occurrence Characteristic and Mining Technology of Ultra-thick Coal Seam in Xinjiang, China. *Sustainability* **2019**, *11*, 6470. [CrossRef]
13. Wang, W.; Yuan, Y.; Chen, Z.; Zhu, C. Physical modeling of floor failure above confined water: A case study in China. *Environ. Earth Sci.* **2022**, *81*, 325. [CrossRef]
14. Yang, J.; Zheng, K.; Wang, Z.; Pang, N. Advanced weakening treatment technology of hard roof power disaster. *J. China Coal Soc.* **2020**, *45*, 3371–3379. [CrossRef]
15. Zhu, T.; Zhang, B.; Feng, G.; Zhang, X. Roof structure and control of coal stope in the lower layer of coal seam at very close range. *J. China Coal Soc.* **2010**, *35*, 4–8. [CrossRef]
16. Hao, D.; Wu, Y.; Chen, H.; Chu, X.; Li, Y. Instability mechanism and control of short-range extra thick coal seam recovery roadway under goaf. *J. China Coal Soc.* **2019**, *44*, 2682–2690.
17. Wang, L.; Chang, Z.; Yang, Z.; Wang, X.; Han, D. Joint support technology of underground mining roadway in goaf area of deep well close coal seam group. *J. Min. Saf. Eng.* **2018**, *35*, 686–692. [CrossRef]
18. Tu, S.; Dou, F.; Wan, Z.; Wang, F.; Yuan, Y. Control technology of roof plate of short-range coal seam comprehensive mining under shallow buried room column goaf area. *J. China Coal Soc.* **2011**, *36*, 366–370. [CrossRef]
19. Xu, J.; Zhu, W.; Ju, J. Dynamic load ore pressure mechanism of close range coal seam mining under shallow buried house mining area. *J. China Coal Soc.* **2017**, *42*, 500–509. [CrossRef]
20. Gao, R.; Yu, B.; Xia, H.; Duan, H. Reduction of Stress Acting on a Thick, Deep Coal Seam by Protective-Seam Mining. *Energies* **2017**, *10*, 1209. [CrossRef]
21. Zhang, W.; Guo, J.; Xie, K.; Wang, J.; Chen, L.; Hu, W.; Xu, J. Comprehensive technical support for safe mining in ultra-close coal seams: A case study. *Energy Explor. Exploit.* **2021**, *39*, 1195–1214. [CrossRef]
22. Zhang, J.; Yan, Y.; Dai, H.; Xu, L.; Li, J.; Xu, R. Hyperbolic Secant Subsidence Prediction Model under Thick Loose Layer Mining Area. *Minerals* **2022**, *12*, 1023. [CrossRef]
23. Wen, X.; Ge, Z.; Zhang, F.; Pang, R. Study On the Migration Law of Overlying Rock in the Upward Layered Continuous Mining Face of Thick Coal Seam with Paste Backfill Mining. *Math Probl. Eng.* **2022**. [CrossRef]
24. Guang, Q.; Jing, C.; Chao, W.; Shuo, W.; Ming, Z.; Xuan, D. Characteristics of Stratum Structure and Fracture Evolution in Stratified Mining of Shallow Buried High-Gas-Thick Coal Seam by Similarity Simulation. *Geofluids* **2021**. [CrossRef]
25. Wei, L.; Li, P.; Bai, X.; Xi, S. Study on overburden failure characteristics in deep thick loose seam and thick coal seam mining. *Geomat. Nat. Hazards Risk* **2020**, *11*, 632–653. [CrossRef]
26. Hua, L.; Zhan, C.; Fei, L. Study on the mechanism of a new fully mechanical mining method for extremely thick coal seam. *Int. J. Rock Mech. Min. Sci.* **2021**, *142*, 1365–1609. [CrossRef]

27. Liu, P.; Gao, L.; Zhang, P.; Wu, G.; Wang, Y.; Liu, P.; Kang, X.; Ma, Z.; Kong, D.; Han, S. Physical Similarity Simulation of Deformation and Failure Characteristics of Coal-Rock Rise under the Influence of Repeated Mining in Close Distance Coal Seams. *Energies* **2022**, *15*, 3503. [CrossRef]
28. Huo, B.; Fan, Z.; Xie, W.; Duan, Z.; Lu, X.; Jing, X. Stress field analysis and dynamic pressure mechanism under shallow buried close-range goaf. *Coal Sci. Technol.* **2019**, *47*, 179–186.
29. Wei, X.; Bai, H.; Rong, H.; Yang, J.; Zhang, B. Research on mining fracture of overburden in close distance multi-seam. *Procedia Earth Planet. Sci.* **2011**, *2*, 20–27. [CrossRef]
30. Shang, Y.; Kong, D.; Pu, S.; Xiong, Y.; Li, Q.; Cheng, Z. Study on Failure Characteristics and Control Technology of Roadway Surrounding Rock under Repeated Mining in Close-Distance Coal Seam. *Mathematics* **2022**, *10*, 2166. [CrossRef]
31. Li, Q.; Wu, G.; Kong, D.; Xin, L. Study On Stability of Stope Surrounding Rock Under Repeated Mining in Close-Distance Coal Seams. *Geofluids* **2022**. [CrossRef]
32. Han, J.; Zhang, H.; Gao, Z.; Rong, H.; Wang, J. Failure height of weak overburden by layered fully-mechanized mining in extremely thick coal seam. *J. Min. Saf. Eng.* **2016**, *33*, 226–230,237. [CrossRef]
33. An, Y.; Zhang, N.; Zhao, Y. Field and numerical investigation on roof failure and fracture control of thick coal seam roadway. *Eng. Fail. Anal.* **2021**, *128*, 105594. [CrossRef]
34. Bian, Z.; Lei, S. Research on environmental effects and protection strategies of coal resources development in Xinjiang. *Coal Sci. Technol.* **2020**, *48*, 43–51.
35. Hong, L.; Bo, Z.; Xue, L.; Cheng, L.; Cheng, W.; Feng, W.; De, C. Research on roof damage mechanism and control technology of gob-side entry retaining under close distance gob. *Eng. Fail. Anal.* **2022**, *138*, 1350–6307. [CrossRef]