Mechanism of Support Optimization and Confined Blasting of Thick and Hard Rock with a Wedge-Structure Immediate Roof: A Case Study

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Based on the occurrence conditions of a thick and hard main roof and wedge-structure immediate roof in the Zhuxianzhuang Coal Mine, the fracture characteristics and instability migration law of a thick and hard roof (THR) were examined via physical simulations. Mining zones were divided with respect to the strata behaviors and roof control difficulties, and the principles and methods of zonal control under THR were put forward. This study proposed a coordinated control strategy of using confined blasting in water-filled deep holes, and reasonable support optimization, which could effectively reduce the roof fracture size, increases the supporting intensity and eliminate roof-control disasters. The length of confined blasting blocks and supporting intensity were calculated using a mechanical model for roof control in the strong strata behavior zone and less-strong strata behavior zone. These key parameters were determined as 20–25 m and 1.15–1.28 MPa, respectively, and the mining strategy was successfully applied in working face 880, performing high security and reasonable economical efficiency.

1. Introduction

In China, coal seams with a thick and hard roof (THR) are more than 1/3 of the total active coal mines [1, 2]; furthermore, roof accidents have been ranked the highest among coal mining accidents over the last decade for its frequency and fatality [3]. Fundamentally, THR is hard to control owing to its high strength, large thickness, and strong integrity [4]. Strong strata behaviors have been observed during mining, whose fracture instability has potentially led to frequent serious support crushing accidents. Therefore, THR control has been considered as the main principle for safe and efficient coal mining. The working faces 8218 and 8212 of the Jinhuaogong Coal Mine led to the damage of 111 hydraulic support posts accompanied by 8 roof accidents. With the immediate roof thickness being decreased to 0, THR came in direct contact with the coal seam; the subsidence space, fracture location, and size of the broken blocks differed from those with thick immediate roof, so was the mining response [5]. Under the conditions of a thick and hard main roof and thin or even lacking immediate roof, the precontrol of THR was a prerequisite for roof safety rather than support optimization in the conventional control strategy [6, 7].
Currently, high-positioned THR with a distance of more than 50 m between the THR and coal seam were taken as the background in extant studies, mainly on the fracture instability and control technologies [8, 9]. The elastic energy stored in the THR which is absorbed by the thick collapsed immediate roof could alleviate the disturbance of THR instability to the working face. Given the intrusion, the immediate roof exhibited a significantly smaller thickness. This implied that THR was at a close distance with the immediate roof. As a typical case, some part of the THR was in direct contact with the 8# extrathick coal seam in a relatively lower position at the Zhuxianzhuang Coal Mine. The mining of this coal seam led to the formation of a stope condition of a thick and hard main roof with a wedge-structure immediate roof—large goaf. Hence, the variability of overlying strata and complexity of roof control requires a more detailed examination.

By considering the THR at a close distance of the north-wing mining area in the Zhuxianzhuang Coal Mine, the present study aimed at exploring the fracture characteristics and control technology of THR by implementing a block stability mechanical model within the framework of physical simulation and theoretical analysis. Finally, a collaborative control test was performed on the 880 working face, and the confined blasting in water-filled deep holes presplit and hydraulic support optimization were applied for effective examination.

2. Experimental Methods and Procedures

2.1. Geological Conditions. The target coal mine (Zhuxianzhuang Mine) is located in Anhui province, China. Currently, 8# coal seam, with an average thickness of 10.03 m, is being mined at depths of 500 m with the long wall fully mechanized top coal caving technology. The overlying strata in the north-wing mine area are composed of hard roofs, with conglomerate as the main ingredient. As shown in Figure 1, a compressive strength of 67.79 MPa and an average thickness of 60 m make it the most typical and representative of a thick hard roof, whose instability presents strong strata behaviors during the mining.

The immediate roof is comprised of mudstone, sandstone, and sandy mudstone. With the erosion of conglomerate, multiple layers became thinner or disappeared; the thickness varied from 0 to 40 m. Along the advancing direction, the angle between the immediate roof and horizontal line is approximately 5°, which indicates the continuation of immediate roof thickness to the mount, forming a wedge-structure. This leads to a complicated and changeable behavior in the coal seam, immediate roof, and main roof. To clearly describe the relationship between the immediate roof thickness and the strata behaviors [10], the ratio of the immediate roof thickness \( \theta \) to the coal seam mining height \( \phi \) was determined as the immediate roof filling coefficient.

2.2. Physical Simulation System. The fracture structural characteristics and instability migration rules in a stope model of extrathick coal seam, wedge-structure immediate roof, and thick and hard main roof were analyzed via physical simulation. According to the histogram, coal seam (9.60 m thick), mudstone (6.36 m thick), sandstone (4.20 m thick), and mudstone (1.20 m thick) were constructed in the model. The angle between the immediate roof and horizontal line was approximately 5°, which simulated the variation in the thickness of the immediate roof, and accorded with the field rock strata.

The model was developed on a plane stress platform (2.5 m long × 2.0 m high × 0.2 m wide) in accordance with the histogram in Figure 2, and the principles of the parameters and ratios were determined and listed in Table 1 [11]. Physical–mechanical parameters of the coal and similar material proportions were presented in Table 2.

A loading system consisting of the air pump with a stress of 0.02929 MPa was applied in the model [12, 13], in which the self-weight of the other 250 m rock strata was loaded. With the completion of the model, cutting height, excavation footage, and boundary pillars (actual width of 36 m) were set as 80 mm, 50, and 300 mm, separately. After the monitoring system was set, the mining stage was commenced.

3. Results and Discussion

3.1. THR Structural Characteristics during the Mining Process. As shown on Figure 3, in the process of the working face which is advancing 126 m away from the setup entry, a series of initial cracks in the immediate roof caused the total collapse of the goaf, with a periodic weighting distance of 10–12 m. At this distance instance, the THR exhibited good stability without noticeable fracture or collapse. As the immediate roof thickness increased along the advancing direction, the filling degree of the collapsed rock in the goaf continuously increased and the subsidence space of THR continued to decrease.

The first fracture and collapse of THR occurred when the working face advanced to 132 m, which indicates that the first weighting distance is set to be 132 m (Figure 3(b)). The collapsed immediate roof failed and basically filled the goaf with a gradual filling degree, leading to a significant rotation sliding during the collapse of the fractured main roof. The THR blocks rapidly subsided and squeezed the gangue after the initial fracture, and consequently, strong strata behaviors occurred in the stope.

With a distance of 180 m from the setup entry, the THR experienced the second periodic failure, which was defined as the first periodic weighting with a respective distance of 48 m from the setup entry. The whole-layer conglomerate fractured into a parallelogram-shaped block. During the sliding instability of the roof toward the coal wall, it was squeezed and hinged with adjacent rock blocks to form a stable structure, which made the horizontal restraint between the larger and self-stabilized fractured rock masses, so the ground pressure appeared to be more alleviated.

A wedge-structure immediate roof with a varied thickness characteristic collapsed and exhibited the zonal filling of partial filling-complete filling-compaction filling along the advancing direction. This led to the initial fracture of THR, forming an entire trapezoid-shaped layer block, which rotated and slid to the goaf in an unstable manner.
The zonal filling of the collapsed immediate roof formed an asymmetric constraint effect on the deformation, damage, and migration of THR. This in turn led to obvious imbalance in the failure and instability of the surrounding rocks and thereby significantly affected the strata behaviors. As the immediate roof filling increased, it became easier for the fractured THR to rotate and became unstable. The horizontal constraint between the surrounding rock masses was large with a strong self-stabilizing ability, and thus, the strata behaviors were eased during the weighting. As the immediate
roof filling decreased, it became easier for the roof to shear, slip, and lose stability. The horizontal constraint between the surrounding rock masses was small with a weak self-stabilizing ability, and thus, the strata behaviors were strong during the weighting.

Therefore, under the condition with an immediate roof filling coefficient of \(N = 0\) and the THR in direct contact with the coal seam, huge blocks were formed owing to the fracture of the main roof, leading to substantial destabilization in the blocks. This in turn significantly increased the working resistance, causing the load on the support to reach out a critical value. At this stage, the working face was in the most dangerous state, which statistically leads to the crushing accidents.

3.2. Control Zones and Zonal Control Principles of THR.

According to the fracture characteristics and displacement evolution of different mining zones in physical simulation, the mining area of the 880 working face was classified into zones with strong strata behaviors, less-strong strata behaviors, and strata behaviors mitigation, as shown in Figure 4. The zonal control principles of THR were put forward depending on the strata behaviors and roof control difficulty in different mining zones.

3.2.1. Zone I. The immediate roof thickness was low or even missing (\(N < 2\)) wherein the distance between THR and coal seam was low, and thus, parts of the roof were in direct contact with the 8\# coal seam. By combining the parameters of the Zhuxianzhuang Coal Mine, the working face range in zone I corresponded to 0–230 m and the distance between THR and coal seam was less than 20 m.

During mining in zone I, the minimum subsidence space of the main roof was more than 4 m and the overhang, breakage, and collapse migration of THR exhibited a strong impact on the working face [14, 15]. This mining range was defined as the strong strata behavior zone.

3.2.2. Zone II. The immediate roof thickness was large. However, it could not effectively fill the goaf after collapse (\(2 < N < 5\)). By considering the parameters of the Zhuxianzhuang Coal Mine, the working face range in zone II corresponded to 230–580 m and the distance between THR and coal seam was 20–50 m.

The fractured and collapsed THR was supported by the gangue. The main roof instability exhibited an evident effect on the working face, and this mining range was defined as the less-strong strata behaviors zone.

3.2.3. Zone III. The thick immediate roof could completely fill the goaf after collapse. Given the parameters of the Zhuxianzhuang Coal Mine, the strike length was higher than 580 m and the distance between THR and coal seam was higher than 50 m.

The goaf was completely filled after mining, and THR was strongly supported by gangue with almost no subsidence space. The main roof did not fracture, and its instability exhibited no clear effect on the working face. This mining range was defined as the strata behavior mitigation zone.

Based on the fracture instability characteristics of THR in different mining zones, the following zonal control principles were proposed [16, 17].

(i) The control scope of THR mainly corresponded to the strong strata behavior zone and less-strong strata behaviors zone. Thus, increases in the working resistance could not fundamentally affect the THR safety control

(ii) Efficient auxiliary control measures should be considered for precontrolling the THR to realize the timely cutoff, collapse, and filling of the middle–low-positioned THR and reducing the subsidence space and load that acted on the hydraulic support. This was an effective means for decreasing the rock pressure

(iii) To realize zonal control, a coordinated control method with the central premise of confined blasting in water-filled deep holes of THR with reasonable support optimization is proposed

3.3. Mechanical Model of Precontrol of THR and Determination of Working Resistance. The confined blasting in water-filled deep hole presplit technology was applied to break THR into small blocks, which filled the goaf sufficiently, and this provided powerful support towards high-positioned THR. Thus, by releasing the strata behaviors acted on the hydraulic support, its optimization could be realized. Figure 5 showed the roof structure after presplitting.
The parameters depicted in Figure 5 are as follows: $M$ denotes the coal seam thickness (m), $h_1$ denotes the top coal thickness (m), $h$ denotes the immediate roof thickness (m), $h_2$ denotes the stratification thickness of THR after presplit (m), $h_3$ denotes the thickness of the high-position THR without presplit (m), $\beta$ denotes the fracture angle (°), and the presplit length of the THR corresponded to $L = L_1 + L_2$.

The fractured THR block, immediate roof block, top coal wall, and hydraulic support were separated, and the mechanical model of the “presplit-THR-block–immediate-roof-block–top-coal-wall–hydraulic-support” system was established. As shown in Figure 6, the blasting crack line is considered as the fulcrum by the fractured block. This can lead to rotary instability near the goaf and consequent deformation and subsidence of the immediate roof.

Under the interaction of self-weight of hanging $G_1$, additional force near the blasting crack line $G_2$, and weight of immediate roof $G_0$, the block rotated and sank. Therefore,
the hydraulic support should prevent the step convergence and rotation of the fractured block on the working face when the fracture line just enters the upper coal wall while maintaining the working resistance $P_0$ on the immediate roof. Thus,

$$P_0 = G_0 + G_1 + G_2. \quad (1)$$

By simplifying $P_0$ to the concentrated force, $L_K$ denotes the horizontal distance between the action position and coal wall, which is the roof control distance (m) and the moment equilibrium of point $O$ can be obtained in equations (2) and (3) as follows:

$$G_2L_K = G_1 \left[ L_1 + \frac{L_2}{2} + \frac{1}{2} (h + h_2) \cot \beta - L_K \right] + G_0 \left( \frac{L_1}{2} - L_K \right), \quad (2)$$

$$G_2 = G_1 \left[ 2L_1 + L_2 + (h + h_2) \cot \beta - 1 \right] + G_0 \left( \frac{L_1}{2L_K} - 1 \right), \quad (3)$$

where $G_0$ denotes the self-weight of the immediate roof, $G_0 = lh \gamma_1$; $l$ denotes the periodic weighting interval (m); $h$ denotes the immediate roof height (m); $\gamma_1$ denotes the immediate roof bulk density (kN/m$^3$); $\beta$ denotes the fracture angle (65°); $G_1$ denotes the self-weight of the hanging THR block, $G_1 = L_2 h_2 \gamma_2$; $h_2$ denotes the presplit THR block thickness (m); $\gamma_2$ denotes the THR block bulk density (kN/m$^3$); and $L_2$ denotes the hanging THR block length (m).
In equations (2) and (3), $L_1$ denotes the distance from the joint operating point to the coal wall (m), which is required to satisfy $L_2/L_3 = (h_2/h)$. By substituting equation (3) in equation (1), the following expression is yielded:

$$P_0 = lh_1 + L_2 h_2 y_1 + lh_1 B A + L_2 h_2 y_2 \left( \frac{C}{A} - 1 \right),$$  \quad (4)

where $A = 2L_K, B = l - 2L_K,$ and $C = 2L_1 + L_2 + (h + h_2) \cot \beta$. In Equation (4), $P_0$ is obtained from the hydraulic support via the top coal. The top coal does not exhibit any supporting capacity. Thus, the hydraulic support is required to withstand $P_0$ and the gravity due to the top coal $G_3 (G_3 = L_K h_1 y_0)$. Thus, the working resistance $P$ is obtained as follows:

$$P = G_0 + G_1 + G_2 + G_3,$$

$$P = P_0 + G_3 = L_K h_1 y_0 + lh_1 y_1 + L_2 h_2 y_2 + lh_1 B A + L_2 h_2 y_2 \left( \frac{C}{A} - 1 \right),$$  \quad (5)

where $h_1$ denotes the caving top coal thickness (m) and $y_0$ denotes the top coal bulk density (kN/m$^3$).

Based on equations (6), the relationship between the length and thickness of presplit THR block and the working resistance can be obtained by combining the parameters of working face 880, as shown in Figure 7. Analysis of the working resistance after the presplitting of THR in close distance reveals that as the presplit blasting block length increases, the working resistance increases exponentially, as shown in Figure 7(a). When the presplit block length increases in the range of 10–25 m, the working resistance exhibits a small increase. However, in the range of 25–40 m, the working resistance increases sharply. In
Figure 7(b), the working resistance increases linearly as the presplitting block thickness increases. When the presplitting block thickness is increased in the range of 10–25 m, the working resistance slightly fluctuates. Furthermore, in the range of 25–40 m, the working resistance increases significantly.

Based on above analysis, the working resistance is sensitive to the presplit blasting THR length. This implies that the working resistance promptly responds to the adjustment of block length. When the length and thickness of presplit block were in the range of 10–25 m, the working resistance exhibited small fluctuations and remained at a low value. This can be used as an important basis for optimizing the presplit blasting block size.

By using equation (6), Figure 7, and the engineering geological conditions of the 880 working face, the relationship between the supporting intensity and presplit block length and that between the supporting intensity and manufacturing cost are obtained [18], as shown in Figure 8.

As shown in Figure 8, as the length of the presplit blasting block increased, the load on the support increased and higher supporting intensity was required. However, as the supporting intensity increased, the manufacturing cost increased. When the supporting intensity exceeded 1.28 MPa, the manufacturing cost increased sharply. As the length of the presplit blasting block increased, the size of the blasting hole decreased, which in turn decreased the amount of explosives. Thus, the blasting cost decreased. Therefore, the presplit blasting block length, blasting cost, supporting intensity, manufacturing cost, and working face safety were comprehensively analyzed. The analysis revealed that a length of presplit blasting block in the range of 20–25 m and supporting intensity in the range of 1.15–1.28 MPa can economically satisfy the roof control requirements during mining.

Under the geological and technical conditions of the 880 working face, the results indicated a working resistance (P) of 12260.59 kN for the following components: \( L_1 = 5.5 \text{ m}, h_1 = 7 \text{ m}, b = 1.75 \text{ m}, \beta = 65^\circ, \gamma_0 = 13 \text{ kN/m}^3, \gamma_1 = 18.2 \text{ kN/m}^3, \gamma_2 = 25 \text{ kN/m}^3, h = 10 \text{ m}, h_2 = 20 \text{ m}, L_2 = 0.67L_1, \) and \( l = 14 \text{ m}. \)

Therefore, for a THR in the Zhuxianzhuang Coal Mine, a presplit blasting block length of 20 m and supporting intensity exceeding 1.15 MPa were obtained. Additionally, the length of the 880 working face was 165 m, strike length was 400 m, average coal seam thickness was 9.6 m, and average dip angle was 5°. Thus, it was observed that a fully mechanized coal caving technology with a cutting height of 3.0 m, caving height of 6.6 m, and mining and caving ratio of 1:2.2 was successfully adopted.

According to the calculation results of working resistance, in the condition of presplit THR, the hydraulic

| Name | Confined filled water | Coefficient of explosive amount | Explosive charge | Horizontal angle of blasting drilling | Charge hole distance | Diameter of large pore guidance hole |
|------|----------------------|-------------------------------|-----------------|-----------------------------------|---------------------|------------------------------------|
| Parameter | 2.0 MPa              | 0.3                           | 32 kg           | 15°, 20°                          | 7.0 m               | 100 mm                             |

Figure 9: Deep hole confined blasting drilling arrangement of THR in working face 880 of the Zhuxianzhuang Coal Mine.
support can be optimized as follows: (i) 87 pieces of ZF13000/21/40 chock-shield hydraulic supports with a maximum working resistance of 13000 kN, setting load of 10132 kN, center distance of 1750 mm, minimum and maximum support heights of 2.1 m and 4 m, respectively, and pumping station pressure of 31.5 MPa were selected; (ii) 7 pieces of ZFG13000/24/40 chock-shield transition supports with a setting load of 10132 kN (31.5 MPa), working resistance of 13000 kN (40.43 MPa), support height of 2.4–4.0 m, and supporting intensity of 1.25 MPa were selected.

3.4. THR Precontrol Technology

3.4.1. Application Object ONE: The Immediate Roof and Low-Positioned THR. Presplit blasting was adopted for them to collapse timely and fill the goaf sufficiently.

3.4.2. Application Object TWO: The Middle-Positioned THR. The truncation and layered presplit blasting shortened the size of fractured blocks, which acted on the hydraulic support and reduced the load [19].

The presplitting preparation was completed according to the drilling layout and parameters shown in Table 3 and Figure 9. The detailed process was as follows:

The construction scheme can be described as follows: (1) after the installation of the KHYD75 rock drilling machine (Jining Zhuoli Mining Equipment Co. Ltd.), blasting drilling was conducted to the predesignated position [20], (2) next is installing the explosives into the drilling holes, connection and debug of the explosive leads, the hole-sealing device, and the high-pressure pump—opening the pressure test device, injecting of water before starting the monitoring instrument, increasing the water pressure slowly, and...
stopping the pumping when the pressure reaches 2 MPa as shown in Figure 10, and (3) finalizing the placement of safety device and monitoring system and initiating and completing the blasting were done (Figure 11) [21, 22].

The on-site test was conducted in July 2019 to check the application effect of the collaborative control technology under the condition of the thick and hard main roof, wedge-structure immediate roof. Monitors (KJ110-J1 mine pressure collecting substation, XI’AN XIKE Measurement Controlling Equipment Co. Ltd., Xi’an City, Shaanxi Province, China) were set on the 880 working face in the Zhuxianzhuang Coal Mine to observe the weakening effect of THR and applicability of the hydraulic support. The support pressure decreased from 45.4 MPa to 36.3 MPa after the confined blasting, as shown in Figure 12. Given the large scope of the coal rock collapse, the support rear was completely filled by the gangue in time, and thus, no strong strata behaviors were observed in the working face.

4. Conclusions

The application of confined blasting in water-filled deep holes and hydraulic support optimization for THR management were studied in the paper. The effect of coordinated control was observed and monitored through on-site test, and the following conclusions were determined by virtue of the testing results:

(1) The wedge-structure immediate roof collapsed and exhibited zonal filling characteristics and imbalanced supporting, leading to easy rotation and sliding instability of THR blocks.

(2) The fracture characteristics and instability mechanism of THR with a wedge-structure immediate roof were researched. The confined blasting in water-filled deep holes was applied to the hard rock, shortening the size of fractured blocks. Redistribution of stress around the “presplit-THR-block–immediate-roof-top-block–top-coal-wall–hydraulic-support” system reduced the excessive load on the hydraulic support and thus played a key role in protecting the working face.

(3) On the basis of the mining zone division and zonal principles, collaborative control techniques were applied in the 880 working face. During the on-site tests, the main roof collapsed timely and filled the goaf, which reduced the resistance force and guaranteed the smooth operation of the hydraulic supports.

Data Availability

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

Conflicts of Interest

The authors declare that there are no conflicts of interest including any financial, personal, or other relationships with other people or organizations.

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