INTRODUCTION

In China, due to the influence of economic, technical, and equipment factors in the past, many thick coal seams were mined by extensive methods.\textsuperscript{1-3} As a result, coal resources were wasted, and large number of abandoned roadways and other damaged areas were left in thick coal seam. Due to the existence of abandoned roadways, it is a basic problem for thick coal seam repeated mining face to pass through abandoned roadways during the mining process.\textsuperscript{4} Therefore, better control of the surrounding rock is of great significance for safe mining.\textsuperscript{5-8}
In recent years, many studies have been carried out on the working face passing through abandoned roadways, and the research results indicated that strong ground pressure would occur when the working face passed through the affected area of abandoned roadways. Xie et al. studied the ground pressure mechanism when the working face passed through the abandoned roadway and believed that the roof could be better controlled by supporting the abandoned roadway. Bai et al. and Zhao et al. established a mechanical model of the roof advanced breaking when the working face passed through the abandoned roadway and proposed the technique of filling the abandoned roadway with high water material to control the roof. Gong et al. analyzed the influencing factors of the roof advanced breaking when the working face passed through the abandoned roadway and calculated the maximum working resistance of the hydraulic support in the working face. Li et al. and Gu et al. studied the relationship between the support and surrounding rock when the working face passed through the abandoned roadway and proposed a method of adjusting the angle of the working face to pass through the abandoned roadway.

Through reviewing the current research on the working face passing through abandoned roadways, there were some deficiencies in the solutions adopted by the working face passing through abandoned roadways. Filling the abandoned roadway would cause the working face to cut the filling body or to bear the extra pressure brought by the filling body. Using high-resistance hydraulic support to replace the original one in the working face would greatly increase the mining cost. Adjusting the mining procedure in the working face would reduce the production efficiency. Therefore, it is very important to adopt a more reasonable solution when the working face passes through abandoned roadways.

Roof presplit is to break the roof in advance by artificial means, which can release and transfer the roof pressure in advance, and effectively reduce the ground pressure strength in the working face. Yu et al. proposed a technique of confined blasting in water-filled deep holes to prevent strong ground pressure of hard rock and coal. Liu et al. studied and determined the reasonable parameters of roof presplit, and well solved a series of mining problems such as large-scale hanging roof and strong ground pressure. Huang et al. believed that roof presplit can weaken the roof structure, form weak fracture plane favorable to roof caving, and reduce or eliminate roof hazards. Tu et al. used the LS-DYNA3D software to establish a roof presplit model of deep-hole blasting, revealed the roof control mechanism of blasting presplit, and optimized the blasting parameters. Zuo et al. proposed new roof blasting layouts of “triangular-fractal” and “deep-shallow-fractal,” which improved the explosive efficiency and enlarged the roof-blasting range.

In view of the advantages of roof presplit technique in ground pressure control, it is of great significance to study the application of roof presplit technique in the ground pressure control of the thick coal seam working face passing through the abandoned roadway. There were few studies on adopting roof presplit technique when the working face passed through abandoned roadways. In this paper, field practice, theoretical analysis, and numerical simulation were used to study the ground pressure reduction mechanism and effect of the working face passing through the abandoned roadway by roof presplit. It is helpful to provide technical guidance and theoretical support for the same type mines.

2 | ENGINEERING BACKGROUND

2.1 | Mining and geological conditions

The Huasheng Hufeng coal mine of Datong Coal Mine Group is a typical resource reorganization mine, which is in Hedong coalfield in Shanxi Province, China, as shown in Figure 1. At present, the 2# thick coal seam was the main mining layer, with an average thickness of 6.0 m, an average inclination angle of 8-14°, and an average burial depth of 290 m. The 2111 working face was the first repeated mining face. The width of the working face was 120 m, and the advancing length was 1120 m. According to the geological report, there were several abandoned roadways in the 2# thick coal seam. The width of the abandoned roadways was generally about 4.0 m, the height was about 2.5 m, and the axis direction of the abandoned roadways was basically parallel to the width direction of the repeated working face. The comprehensive mechanized top coal caving method was adopted in the working face, the mining caving ratio was 1:2, and the ZFS3100/16/26 standing shield hydraulic support was used to control the roof of the working face. The specific surrounding rock conditions of the working face are shown in Figure 2.

2.2 | Ground pressure characteristics

During the mining process of the 2111 working face, KJ533 mine online ground pressure monitoring system was installed on the hydraulic support to monitor the working resistance. Figure 3 shows the maximum working resistance of the hydraulic support when the working face passed through the abandoned roadway.

It can be seen obviously from Figure 3 that the existence of the abandoned roadway in the thick coal seam had a significant influence on the working resistance of the hydraulic support in the working face. When the working face passed through the affected area of the abandoned roadway, there were two sharp increase in the working resistance of the hydraulic support due to the roof violent movement. The working resistance of the hydraulic support was 3439 kN when the first strong ground pressure occurred, which was 10.91% higher than the rated working resistance of the hydraulic support. The working
resistance of the hydraulic support was 4043 kN when the second strong ground pressure occurred, which was 30.40% higher than the rated working resistance of the hydraulic support. The occurrence of strong ground pressure had seriously affected the working state of the hydraulic support.

3 | GROUND PRESSURE MECHANISM AND SOLUTION

In this section, the causes for the ground pressure characteristics when the working face passed through the abandoned roadway were analyzed, and the solution was proposed.

3.1 | Ground pressure mechanism

In order to analyze the ground pressure mechanism when the working face passed through the abandoned roadway, a corresponding mechanical model of roof breaking according to the relative position relationship between the working face and the abandoned roadway, as shown in Figure 4. In Figure 4, $q$ denotes the equivalent load on the main roof, MPa, $q = \gamma H$; $\gamma$ denotes the average volume-weight of the rock, kN/m$^3$; $H$ denotes the burial depth of 2# coal seam, m; $h$ denotes the immediate roof and main roof thickness, m; $M$ denotes the 2# coal seam thickness, m; $L$ denotes the abandoned roadway width, m; $B$ denotes the residual coal pillar width, m;
Lk denotes the control length of the hydraulic support, m; Lx denotes the length of the main roof hanging arch, m; Lz denotes the periodic fracture length of the main roof, m; and Pg denotes the support force of the falling gangue to roof, kN.

When the working face passed through the affected area of the abandoned roadway, once the width of the residual coal pillar $B$ reaches its critical width $B_0$, the roof would break at the position of the abandoned roadway. According to the Mohr-Coulomb failure criterion, the critical residual coal pillar width $B_0$ can be expressed as:

$$B_0 = \frac{A}{2 \tan \varphi} \left[ M_1 d_1 \ln \frac{C + K_1 \gamma H \tan \varphi}{C} + M_2 d_2 \ln \frac{C + K_2 \gamma H \tan \varphi}{C} \right]$$

(1)

where $A$ represents the side pressure coefficient; $M_2$ represents the abandoned roadway height, m; $d_1$ and $d_2$ represent the mining disturbance factor on both sides of the residual coal pillar; $K_1$ and $K_2$ represent the stress concentration factor on both sides of the residual coal pillar; $C$ represents the coal cohesion, MPa; and $\varphi$ represents the coal internal friction angle, °.
When the roof was broken at the abandoned roadway, the roof breaking length \( L_c \) can be expressed as:

\[
L_c = L + B_0 + L_x
\]  
(2)

Obviously, \( L_c \geq L_z \). Based on the material mechanics analysis, the roof periodic breaking length \( L_z \) meets the following equation:

\[
L_z = h_d \sqrt{K/\sigma_t/q_d}
\]  
(3)

where \( h_d \) is the roof equivalent load layer thickness, m; \( q_d \) is the roof equivalent load, MPa; \( \sigma_t \) is the tensile strength coefficient; and \( \sigma_t \) is the tensile strength of the main roof, MPa. The roof equivalent load layer thickness \( h_d \) can be obtained:

\[
h_d = 3\gamma L_z^2 / K \sigma_t
\]  
(4)

Through substituting Equations (2) into (5), the roof equivalent load layer thickness \( h_{dc} \) when the roof was broken at the abandoned roadway can be expressed as:

\[
h_{dc} = 3\gamma (L + B_0 + L_x) \sqrt{K/\sigma_t/q_d}
\]  
(5)

From Equations (2) to (5), when the roof was broken at the abandoned roadway, the roof breaking length and the roof equivalent load layer thickness both increase. Therefore, when the working face passed through the affected area of the abandoned roadway, the strong ground pressure would occur to affect the working resistance of the hydraulic support.

### 3.2 Roof presplit

Based on the roof breaking characteristics when the working face passes through the abandoned roadway, reducing the roof breaking length is an effective way to reduce the ground pressure in the working face. Therefore, it is proposed to use roof presplit for ground pressure control when the working face passes through the abandoned roadway. Figure 5 shows the mechanism of roof presplit. Considering the efficiency and cost factors of roof presplit, the roof presplit boreholes are arranged in the abandoned roadway. Compared with roof presplit in mining roadways or working face, it can not only reduce the length of presplit boreholes but also can not affect the production efficiency of the working face.

In order to reduce the secondary damage to the surrounding rock of the stope, the hydraulic fracturing is selected for the roof presplit. It is necessary to ensure good ventilation and stable roof in the abandoned roadway before the roof presplit.

When the distance between the working face and the abandoned roadway reaches a specified distance, the roof equivalent load layer thickness both increase.
presplit boreholes are arranged in the abandoned roadway and the roof is presplit. The initial support force of the hydraulic support in the working face should be appropriately increased when roof presplit. Through the roof presplit, the roof hanging length can be effectively reduced, and the roof equivalent load layer thickness is correspondingly reduced. The ground pressure can be released and transferred in advance and the ground pressure strength can be weakened in the working face.

4 | NUMERICAL ANALYSIS

In order to study the effect of the working face passing through the abandoned roadway by roof presplit, FLAC3D 5.0 numerical software was used to analyze. The roof vertical stress and vertical displacement characteristics were analyzed in detail to study the roof presplit effect with different presplit distance.

4.1 | Numerical model

The 2111 working face was taken to establish the FLAC3D numerical model. According to the actual existence conditions of the abandoned roadways in Hufeng coal mine, the parallel abandoned roadway was selected for study in this numerical simulation. It should be noted that the parallel abandoned roadway has the greatest influence on the ground pressure of the working face, and the study on the working face passing through the parallel abandoned roadway can provide better guidance for passing through other types of roadways.
abandoned roadways.\textsuperscript{5,22} Considering that the 2111 working face was a longwall mining face, the numerical model adopted the equivalent plane model.\textsuperscript{46} The size of the numerical model was 200 m (length) × 10 m (width) × 36.5 m (height), the left and right boundary was fixed in the X direction, the front and back boundary was fixed in the Y direction, the bottom boundary was fixed in the Z direction, and the upper boundary was subjected to an equivalent load of 6.8 MPa. The detailed physical and mechanical parameters of the coal and rock mass used in the numerical model are shown in Table \ref{table:1}, and the specific numerical model is shown in Figure \ref{fig:6}.

The numerical analysis was divided into the following steps: (a) establish the numerical model and calculate balance; (b) excavate the abandoned roadway in thick coal seam and calculate balance; (c) excavate the working face, presplit the roof in the abandoned roadway at a specified distance from the working face and calculate balance; and (d) extract and analyze the numerical results. Based on the Kang’s research\textsuperscript{24,25} and the previous field experience, the roof presplit boreholes angle was selected to be 45°, and the boreholes height was 2 m from the abandoned roadway floor. This would help to drill the roof presplit boreholes and reduce the presplit boreholes length. Figure \ref{fig:7} shows the detailed roof presplit scheme. The roof presplit distance (between the working face and the abandoned roadway) was selected as 30 m, 25 m, 20 m, 15 m, 10 m, and 0 m (without presplit), respectively.

### 4.2 Roof vertical stress characteristics

The roof vertical stress characteristics with different roof presplit distance are shown in Figure \ref{fig:8}. With the advancement of the working face, the shape of the roof vertical stress gradually changed from saddle to bell, and the larger the roof presplit distance, the earlier the shape of the roof vertical stress changed. When the roof presplit distance was 0 m (without presplit), the maximum vertical stress was 30.72 MPa, and the maximum vertical stress concentration factor was 4.21; when the roof presplit distance was 10 m, the maximum vertical stress was 28.85 MPa, and the maximum vertical stress concentration factor was 3.96; when the roof presplit distance was 15 m, the maximum vertical stress was 26.25 MPa, and the maximum vertical stress concentration factor was 3.60; when the roof presplit distance was 20 m, the maximum vertical stress was 27.49 MPa, and the maximum vertical stress concentration factor was 3.77; when the roof presplit distance was 25 m, the maximum vertical stress was 27.48 MPa, and the maximum vertical stress concentration factor was 3.74.

Roof presplit could effectively reduce the ground pressure strength of the working face. Figure \ref{fig:9} shows the characteristics of maximum stress concentration factor and maximum stress reduction rate with different roof presplit distance. For different roof presplit distance, the order of the maximum vertical stress in the working face was 0 m (without presplit) > 10 m > 20 m > 25 m > 30 m > 15 m. Here, the maximum stress reduction rate \(\eta\) was calculated using the equation \(\eta = \left(\frac{\sigma_i^0 - \sigma_i^1}{\sigma_i^0}\right) \times 100\%\), where \(\sigma_i^0\) represents the maximum vertical stress at different roof presplit distances and \(\sigma_i^1\) represents the maximum vertical stress without roof presplit. When the roof presplit distance was 15 m, the maximum vertical stress was minimum, and the maximum vertical stress reduction rate was maximum.

Figure \ref{fig:10} shows the variation characteristics of the maximum vertical stress with the advancement of the working face under different roof presplit distance. The maximum vertical stress increased first and then decreased with the advancement of the working face. When the roof presplit distance was 30 m, 25 m, and 20 m, the maximum vertical stress would increase after roof presplit, and the maximum vertical stress increasing distance was 12 m, 7 m, and 2 m. This indicated that the earlier roof presplit would cause the working face to be in a high vertical stress state earlier. When the roof presplit distance was 15 m, the maximum vertical stress would decrease after roof presplit, and the working face would be in a relatively low vertical stress state. When the roof presplit distance was 10 m, the maximum vertical stress was already at a high level before roof presplit, and the maximum vertical stress would drop sharply with a value of 15.30 MPa after roof presplit, which would give large impact load to the hydraulic support of the working face and affect the stability of the hydraulic support.

![Figure 7: Roof presplit scheme](image-url)
FIGURE 8 Roof vertical stress characteristics with different pre-split distance
4.3 Roof vertical displacement characteristics

Figure 11 shows the roof vertical displacement characteristics with different roof presplit distance. The roof presplit changed the maximum vertical displacement characteristics significantly during the advancement of the working face. The order of the maximum vertical displacement in the working face was 0 m (without presplit) > 10 m > 25 m > 30 m > 20 m > 15 m.

When the roof presplit distance was 0 m (without presplit), the maximum vertical displacement was 155.89 mm; when the roof presplit distance was 10 m, the maximum vertical displacement was 107.22 mm, and the maximum vertical displacement reduction rate was 31.22%; when the roof presplit distance was 15 m, the maximum vertical displacement was 97.42 mm, and the maximum vertical displacement reduction rate was 37.51%; when the roof presplit distance was 20 m, the maximum vertical displacement was 97.67 mm, and the maximum vertical displacement reduction rate was 37.35%; when the roof presplit distance was 25 m, the maximum vertical displacement was 99.94 mm, and the maximum vertical displacement reduction rate was 35.89%; and when the roof presplit
distance was 30 m, the maximum vertical displacement was 98.23 mm, and the maximum vertical displacement reduction rate was 36.99%. Here, the maximum vertical displacement reduction rate \( \lambda \) was calculated using the equation \( \lambda = \left| \frac{s_v^i - s_v^0}{s_v^0} \right| \times 100\% \), where \( s_v^i \) represents the maximum vertical displacement at different roof presplit distances and \( s_v^0 \) represents the maximum vertical displacement without roof presplit. When the roof presplit distance was 15 m, the maximum vertical displacement was minimum, and the maximum vertical displacement reduction rate was maximum.

5 | ENGINEERING APPLICATION

According to the geological conditions of Hufeng coal mine, the value of corresponding analysis parameters were taken...
as follows:  \( A = 0.45, M_L = 2.0 \text{ m}, M = 6.0 \text{ m}, d_1 = 1.5, d_2 = 2.0 \), \( K_1 = 2.5, K_2 = 3.5, \gamma = 25 \text{ kN/m}^3, H = 290 \text{ m}, C = 1.25 \text{ MPa} \), \( \varphi = 32^\circ, L_1 = 14.5 \text{ m}, L = 4.0 \text{ m}, K = 0.8, \) and \( \sigma_1 = 3.50 \text{ MPa} \). Through substituting the parameters into Equations (1)-(5), the critical residual coal pillar width \( B_0 = 13.80 \text{ m} \). When the working face was advanced to 15 m from the abandoned roadway, the roof overhanging length \( L_{c} = 4.8 \text{ m} \). So, when the roof was broken at the abandoned roadway, the roof breaking length \( L_r = 23.80 \text{ m} \) and the equivalent load layer thickness \( q_{w} = 15.17 \text{ m} \). Compared with the roof periodic breaking, the roof breaking length would increase by 64.12% and the equivalent load layer thickness would increase by 169.45%. This will inevitably cause strong ground pressure when the working face passes through the abandoned roadway.

Based on the presented solution, the roof presplit was used to reduce the ground pressure when the working face passed through the abandoned roadway. The roof presplit distance was determined to be 15 m by comparing the theoretical and numerical results. In order to ensure the safety of the roof presplit in abandoned roadway, it was necessary to use a local fan to reduce the gas concentration in the abandoned roadway in advance so that the gas concentration was lower than 1%. Moreover, the roof of the abandoned roadway was repaired in advance according to its stability, bolts support and single props were used to control the roof of the abandoned roadway. Figure 12 shows the maximum working resistance of the hydraulic support in the working face.

Seen from Figure 12, the ground pressure strength of the working face was obviously weakened, and the maximum working resistance of the hydraulic support in the working face was significantly reduced through roof presplit. The maximum working resistance of the hydraulic support was reduced by 35.86% after roof presplit. The maximum working resistance of the hydraulic support was 2641 kN, which accounted for 85.19% of the rated working resistance. The engineering application effect was good.

### 6 CONCLUSIONS

Based on the mining and geological conditions of Huasheng Hufeng coal mine, field practice, theoretical analysis, and numerical simulation were used to study the ground pressure reduction mechanism and effect of the working face passing through the abandoned roadway by roof presplit. The main conclusions are as follows:

1. When the thick coal seam working face passed through the abandoned roadway, the working resistance of the hydraulic support in the working face would be significantly increased because the roof was broken at the abandoned roadway. Roof breaking at the abandoned roadway would cause the roof breaking length and the roof equivalent thickness layer to increase.

2. Roof presplit can effectively reduce the ground pressure strength of the working face. When the roof presplit distance was 15 m, the maximum vertical stress and the maximum vertical displacement were both minimum. The maximum vertical stress was reduced by 14.55% and the maximum vertical displacement was reduced by 37.51% after roof presplit.

3. The research results were successfully applied to Huasheng Hufeng Coal Mine. Through roof presplit, the maximum working resistance of the hydraulic support in the working face was reduced by 35.68%, and the maximum working resistance of the hydraulic support was 2641 kN. The engineering application effect was good. The research results can provide reference for the mining of the same type mines.

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