

## Research Article

# Surrounding Rock Control Technology When the Longwall Face Crosses Abandoned Roadways: A Case Study

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When a working face is crossing the abandoned roadways, problems such as roof subsidence, rock fracture, and instability will occur, resulting in widespread roof fall and rib spalling, which seriously affect safe and efficient mining on the working face. In this paper, the no. 23 coal pillar working face of Juji coal mine is taken as the engineering background, a mechanical model of crossing the abandoned roadways is constructed aimed at the problem of the working face crossing the abandoned roadway group, the collapse of the abandoned roadway roof is analyzed, a scheme of crossing the abandoned roadways is designed, and the development law of the stress and plastic zone after the reinforcement scheme is stimulated and analyzed. The results show that when the working face advances to the abandoned roadway, key block B crosses the abandoned roadway and the solid coal to form a “cross-roadway long key block.” It is calculated that the minimum support resistance required for the abandoned roadway is 6700 kN. Based on the results of numerical comparison, it is concluded that filling wood pile when the working face passes through the roof abandoned roadway and adding anchor cables for reinforcement support when the working face crosses the coal seam abandoned roadway effectively reduce the stress concentration of surrounding rocks, decrease the development of the plastic zone, and achieve safe and efficient mining when the working face crosses the abandoned roadways.

## 1. Introduction

In the process of coal mine production, in order to save coal resources and ensure smooth replacement of the working face, the reserved coal pillar is often recovered and mined. In the coal pillar mining, the coal pillar working face often passes through abandoned roadways, which are usually abandoned roadways that exist before the working face mining and lose their functions. As the mining of the coal pillar working face is subject to the goaf and the abandoned roadway, the movement law of the overburden strata on the working face is different from that of conventional coal mining [1–3]. The main problems faced in coal pillar mining include the following: (1) the occurrence conditions of the coal seam are complex, both sides of the coal pillar working face are goafs, and abandoned roadways can exist in the coal

seams. (2) Rock burst appears violent. The existence of abandoned roadways leads to roof fracture in the working face, to form a “cross-roadway long key block.” Therefore, the pressure strengthens. Affected by the abandoned roadways and the goafs, the surrounding rock stress on the working face is redistributed, and the periodic pressure is irregular. (3) The hydraulic support bears uneven stress and needs to bear the impact load caused by roof fracture.

A large number of studies have been made by scholars domestically and internationally on the safety guarantee technology of the working face passing through abandoned roadways. Bai and Hou [4] established a mechanical model of the working face through abandoned roadways and adopted the new technology of high water material filling to ensure the stability of the surrounding rocks of abandoned roadways. Feng et al. [5] developed the technology

of ultrahigh water material filling, which fills the abandoned roadways with high water materials and achieves the strength required in practical projects with different ratios. Zhou and Huang [6, 7] studied the instability mechanism of abandoned roadways and the law of the main roof fracture when the working face passes through the abandoned roadway group and put forward the scheme of the fully mechanized mining face quickly crossing the large-section abandoned roadway group, which can avoid roof fall accidents. Liu et al. [8] analyzed the failure mechanism of surrounding rocks on the fully mechanized mining face by multiple means and determined the support mode of filling the wood stack connection with coal powder and cement, which effectively ensures normal advancement of the fully mechanized mining face. Xu et al. [9] established a mechanical model of the main roof of an abandoned roadway, revealed the stability mechanism of the abandoned roadway roof, and determined the minimum support resistance to maintain the stability of the abandoned roadway roof. Yin et al. [10] applied catastrophe theory to analyze the instability mechanism of the coal pillar between the working face and the front abandoned roadway from the perspective of potential energy accumulation and applied the theory of elastic thin plate to study the stress state and fracture position of the main roof after the coal pillar loses stability. Zorkov et al. [11] studied the classification of the working face entering the predriven coal mining face (PDRR), simulated the process of the working face passing through abandoned roadways under the condition of a thick hard roof, and evaluated the load of the working face support. Tadolini et al. [12] applied the technology of fiber-reinforced shotcrete to roadway support, which helps alleviate the deformation and failure of the roadway caused by cyclic load. Esterhuizen et al. [13] monitored the rock mass displacement, rock support, and stress changes behind the working face and verified the numerical modeling program developed for evaluating the entry into the support system, based on the corresponding data of rock bolt in calibration modeling.

Based on the studies above, different support technologies for crossing abandoned roadways should be adopted in different mine geological environments and mining conditions. At present, the support technologies for crossing abandoned roadways mainly include [14–16] pseudoslope adjustment of the working face, strengthening roof management, concrete grouting, roof fall prevention by isobaric mining, and high water material filling. However, there are few relevant studies on the coal pillar working face crossing abandoned roadways in a deep well and a lack of similar experience of crossing abandoned roadways. Therefore, the abandoned roadway crossing mode should be reasonably selected in combination with the actual geological mining conditions in the technical study of the working face crossing abandoned roadways. In this paper, the no. 23 coal pillar working face in Juji coal mine is taken as the research background, with the methods of theoretical analysis, numerical simulation, and field measurement, the deformation control characteristics of surrounding rocks in the mining in the coal pillar working face in a deep well is studied, and the support scheme for crossing abandoned roadways and the

reinforcement support of the weak roof are designed, which ensures that the stope face crosses abandoned roadways smoothly.

## 2. Engineering Background

The no. 23 coal pillar working face of Juji coal mine is located at a level of -850 m, the ground elevation is +31.3 m to +32.5 m, the working face is 250 m wide, and the advancing length is about 270 m. The working face is located at the lower part of the north wing of the no. 23 mining area, with no. 2312, no. 2314, and no. 2316 goafs in the north, the protective coal pillar at the lower section of the no. 23 headentry in the south, the no. 23 middle water bunker and winch room in the west, and the no. 23 lower water bunker in the east. In the working face, there are many abandoned roadways, of which three are typical, namely, the track roadway, the headentry, and the return airway. The layout of the working face is shown in Figure 1.

The coal seam mined in the working face is the no. 2 coal seam, with a thickness of 2.0–4.1 m, an average thickness of 2.9 m, an inclination of 10–20°, and an average angle of 15°. Thus, it is a stable coal seam. The geological histogram of the no. 23 coal pillar working face is shown in Figure 2.

There will be some problems when the working face is passing through the abandoned roadways: sharp increase in the stress of the abandoned roadways, serious deformation of the surrounding rocks, roof sinking, and rib spalling. Therefore, the borehole peering instrument was used to detect the development of roadway fractures near the abandoned roadways, so as to analyze the impact of the abandoned roadway group on the gateway. The peering image of the vertical roof borehole near the abandoned roadway side is shown in Figure 3.

As observed, the fracture development at 0.8 m of the rock mass in the borehole is relatively obvious, the fracture area is large, and the fracture extends internally. The circumferential fracture development at 1.7–3.0 m is obvious. With the increase in depth, the degree of fracture decreases. When the depth exceeds 6.5 m, the internal structure is clear and complete, and almost no fracture development appears. From the peering result, near the abandoned roadway, the roof fracture can develop to 5.7 m, and some areas can run through the direct roof. Therefore, a mechanical model should be established to analyze the roof support conditions and structural change characteristics when the working face passes through abandoned roadways.

## 3. Analysis of Mechanical Characteristics When the Working Face Crosses the Abandoned Roadway

*3.1. Establishment of the Mechanical Model of the Working Face Crossing the Abandoned Roadway.* When the working face advances towards the abandoned roadway, the initial advancing working face is far from the abandoned roadway, the coal pillar stress is distributed along a saddle curve, and the stress is at a stable level. The breaking process is shown in Figure 4.

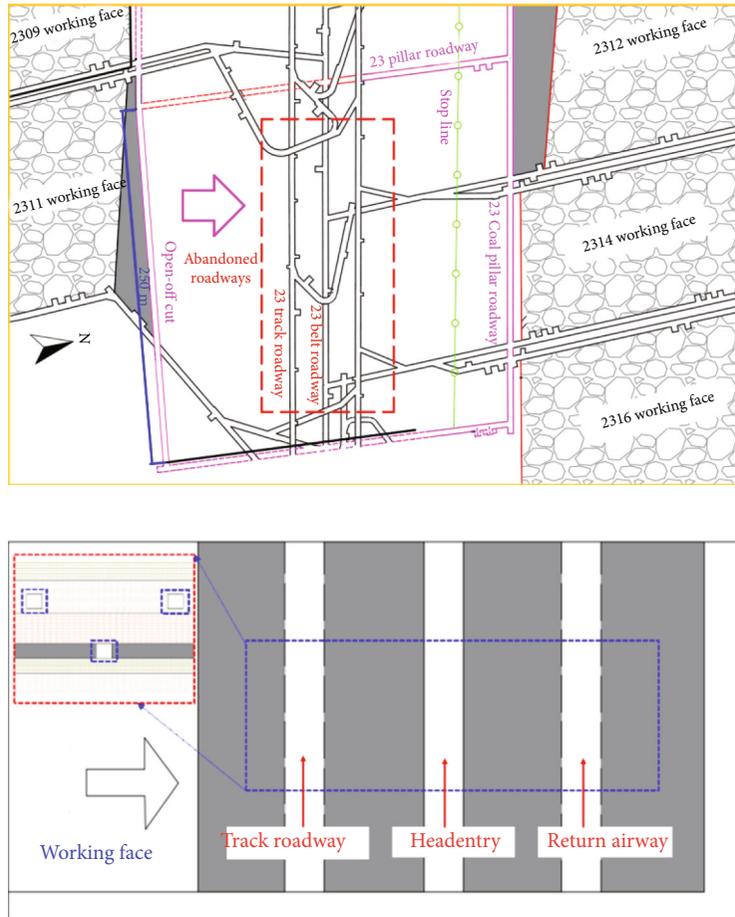


FIGURE 1: Layout of the no. 23 coal pillar working face.

Order	Histogram	Depth (m)	Thickness (m)	Rock structure	Lithology
1		721.60 m	2.90 m	Main roof	Fine grained sandstone
2		729.70 m	8.10 m		Sandy mudstone
3		730.42 m	0.72 m	Immediate roof	Carbonaceous mudstone
4		735.62 m	5.20 m		Siltstone
5		737.52 m	2.90 m	Coal seam	Coal
6		741.46 m	2.94 m	Immediate floor	Mudstone
7		750.06 m	8.60 m	Main floor	Fine grained sandstone
8		754.46 m	4.40 m		Sandy mudstone

FIGURE 2: Geological histogram.

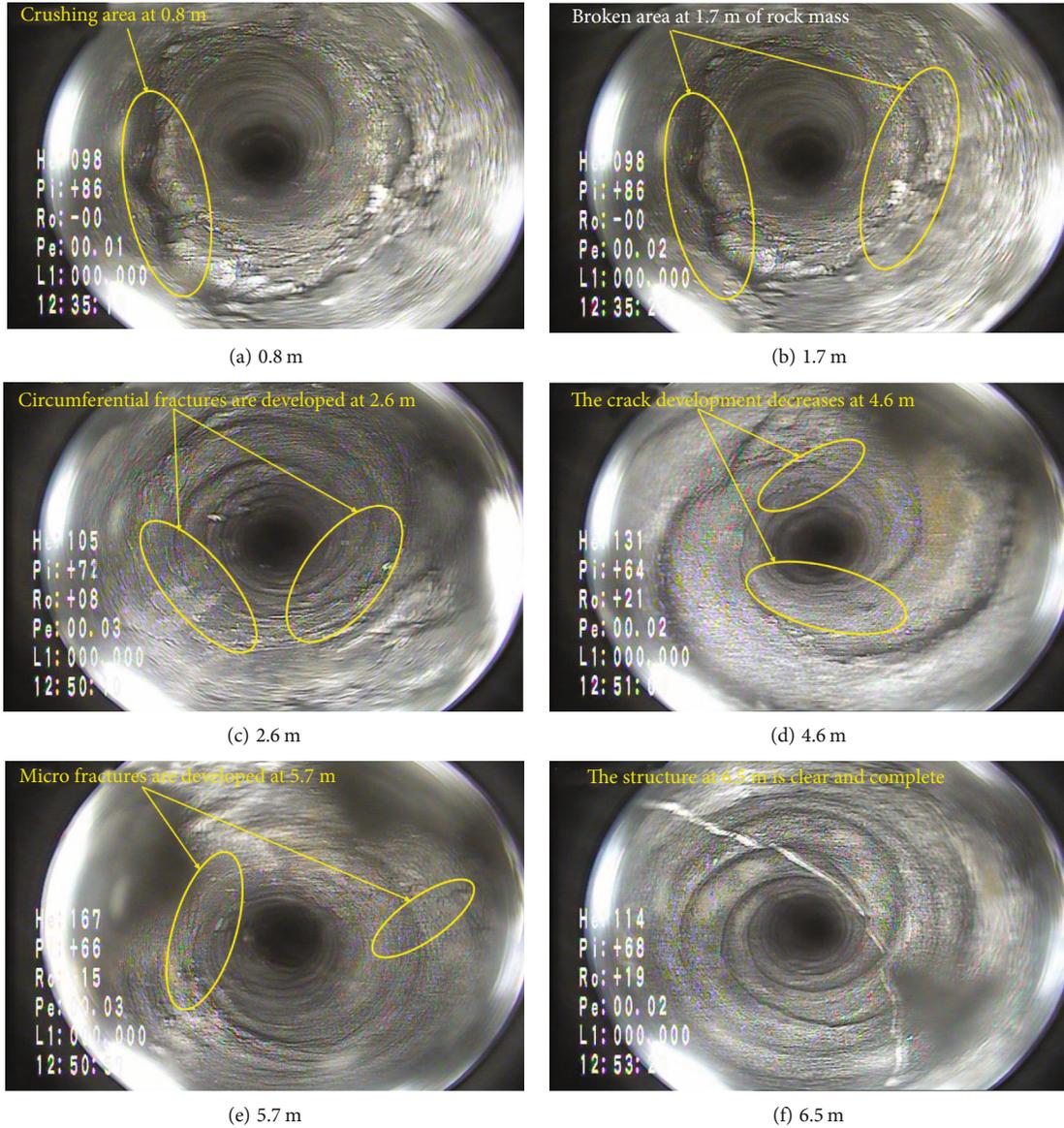


FIGURE 3: Peering image of the vertical roof borehole near the abandoned roadway side.

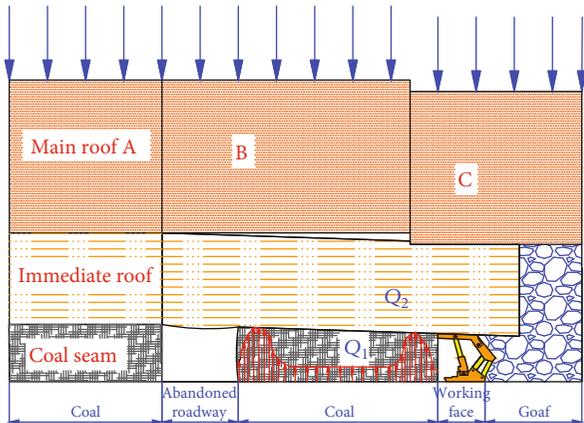


FIGURE 4: Schematic diagram of crossing the abandoned roadway during initial mining.

When advancement continues and affected by the abandoned roadway, the main roof breaks into key blocks, the coal pillar stress is distributed in double-saddle shape, and the bearing capacity of the coal pillar gradually decreases. The further breaking process is shown in Figure 5.

When the working face advances close to the abandoned roadway, the coal pillar before the abandoned roadway is broken and loses its stability and bearing capacity. The roof is broken into a masonry beam structure. The key block rotates in advance, and the stress of solid coal is redistributed. Key block B crosses the roadway and solid coal to form a “cross-roadway long key block” [17–21]. The block is broken in front of the abandoned roadway. The model diagram of crossing the abandoned roadway is shown in Figure 6.

The stress analysis of key blocks B and C when the working face passes through the abandoned roadway is shown in Figure 7.

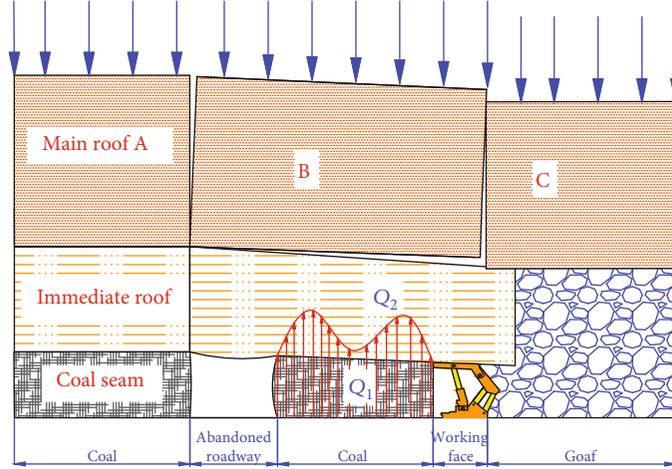


FIGURE 5: Schematic diagram of crossing the abandoned roadway during medium-term mining.

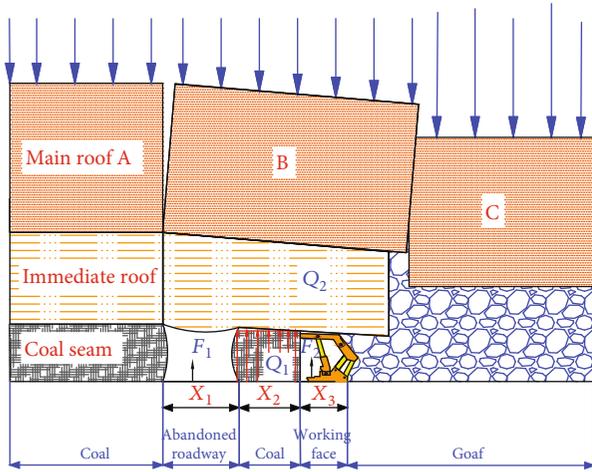


FIGURE 6: Schematic diagram of roadway crossing close to the abandoned roadway.

After analyzing the stress state of key blocks B and C, the balance equation is obtained:

$$\frac{2R_1(x_1 + x_2 + x_3)}{3 + T(h - \Delta - a) - (P_1 L \cos \theta_1)/2} = 0, \quad (1)$$

$$P_1 = R_1 + Q_A. \quad (2)$$

The simultaneous equation of (1) and (2) is

$$T = \frac{P_1 L \cos \theta_1}{2(h - \Delta - a)} - \frac{2R(x_1 + x_2 + x_3)}{3(h - \Delta - a)}. \quad (3)$$

To prevent the key block of the main roof from sliding and losing stability at point A', the following conditions shall be met:

$$T \tan \varphi \geq Q_{A'}. \quad (4)$$

By introducing formula (4) into (1)–(3), we can get

$$\begin{cases} R_1 \geq P_1 \left[ \frac{3L \cos \theta_1 \tan \varphi - 6(h - \Delta - a)}{4 \tan \varphi (x_1 + x_2 + x_3) - 6(h - \Delta - a)} \right], \\ P_1 = bL(q + h\gamma_2), \\ \theta_1 = \frac{\arcsin [M - (K_p - 1)\Sigma h]}{L}, \\ a = \frac{h - \Delta}{2}. \end{cases} \quad (5)$$

In the formula,  $T$  is the horizontal force on the key block (kN),  $a$  is the length of the contact surface pressed between key blocks B and C (m),  $R_1$  and  $R_2$  are the supporting forces of the immediate roof and the gangue on key blocks B and C (kN),  $Q_A$  and  $Q_B$  are the shear forces on the key blocks (kN),  $P_1$  and  $P_2$  are the self-weight and load borne of key blocks B and C (MPa),  $L$  and  $l$  are the lengths of key blocks B and C (m),  $\theta_1$  and  $\theta_2$  are the rotation angles of key blocks B and C ( $^\circ$ ),  $h$  is the thickness of key block B (m),  $\gamma_2$  is the unit weight of the immediate roof (kN/m<sup>3</sup>),  $\Delta$  and  $q$  are the rotation sinking value (m) and load borne of key block B (MPa),  $K_p$  is the rock dilatancy coefficient,  $b$  is the width of the hydraulic support (m), and  $\Sigma h$  is the thickness of the immediate roof (m).

Based on the above parameters,  $F_1$ , the critical support resistance of the abandoned roadway roof, is calculated:

$$\frac{F_1 x_1}{2} + F_2 \left( x_1 + x_2 + \frac{x_3}{3} \right) - \frac{2(Q + R_1)(x_1 + x_2 + x_3)}{3} = 0, \quad (6)$$

$$F_1 + F_2 = Q + R_1, \quad (7)$$

$$F_1 = \frac{2x_1 + 2x_2 - 2x_3}{3x_1 + 6x_2 + 2x_3} (Q + R_1). \quad (8)$$

The simultaneous equations (5)–(8) are obtained to substitute the relevant parameters of Juji coal mine: the main

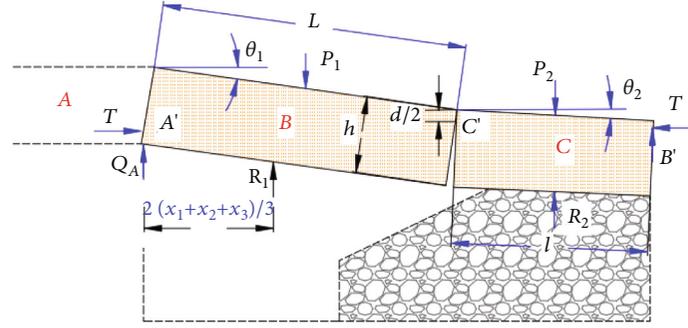


FIGURE 7: Stress state of key blocks B and C.

TABLE 1: Physical mechanical parameters of coal rock in the established model.

Lithology	Bulk modulus (GPa)	Shear modulus (GPa)	Internal friction angle ( $^{\circ}$ )	Cohesion (MPa)	Tensile strength (MPa)	Density ( $\text{kg}\cdot\text{m}^{-3}$ )
Main roof	3.2	1.8	33.82	7.27	5.66	2600
Immediate roof	4.3	2.6	34.99	10.79	8.41	2400
II2 coal	1.7	1.0	32.21	2.08	0.77	1400
Immediate floor	4.5	3.1	34.21	10.70	6.21	2400
Main floor	8.0	4.0	36.50	9.89	9.30	2500

roof thickness of the no. 23 coal pillar working face  $h = 11.0$  m, the immediate roof thickness  $\Sigma h = 5.92$  m, the internal friction angle in the rock stratum  $\varphi = 34^{\circ}$ , the unit weight of the rock stratum  $\gamma_2 = 26 \text{ kN/m}^3$ , the coal thickness  $M = 2.9$  m, the unit weight of coal seam  $\gamma_1 = 14 \text{ kN/m}^3$ , and the roof control distance  $x_3 = 3.51$  m. It is calculated that the minimum support resistance required for the abandoned roadway is  $F_1 = 6700$  kN.

However, the geological conditions of the no. 23 coal pillar working face are complex. There are many abandoned roadways located in the roof and coal seams, and around the coal pillar are goafs. Further analysis should be made on the distributions of the surrounding rock stress and plastic zone of the abandoned roadways in the mining process, to ensure that the working face passes through the abandoned roadways safely.

**3.2. Characteristics of Mining When the Working Face Crosses the Abandoned Roadways.** The FLAC3D software was applied to simulate and study the working face crossing the abandoned roadways, thus simulating and analyzing the maximum vertical stress and the development law of the plastic zone when the working face crosses the abandoned roadways. The Mohr-Coulomb failure criterion was adopted for the model. The  $x$ -axis represents the advancing direction of the working face. The  $x$ -axis is taken as 400 m, the  $y$ -axis is taken as 300 m, the  $z$ -axis is taken as 60 m, and the ground stress is taken as 20 MPa. The physical mechanical parameters of coal rock in the established model are shown in Table 1.

The model limits the lateral and bottom displacements, applies corresponding stress compensation on the upper boundary, and scales to a certain extent. The designed working face extends a length of 200 m and a width of 110 m.

Goafs were arranged on both sides of the working face. In the middle part of the working face, three abandoned roadways were arranged, namely, the track roadway, the headentry, and the return airway. The roadway widths were 4 m, the heights were 3 m, and the adjacent spacings were 20 m. The track roadway and the return airway were located at 5 m above the coal seam, and the headentry was located in the coal seam. The stress and the development law of the plastic zone when the stimulation working face passes through the three abandoned roadways are shown in the model in Figure 8.

The variation law of vertical stress distribution when the working face passes through the track roadway, the return airway, and the headentry is shown in Figure 9.

According to the results in Figure 9:

- (1) In the mining process from 50 m to 100 m in the working face, the peak stresses are 54.6, 55.3, 54.9, 21.3, 57.4, and 54.6 MPa, respectively. When the working face is mined to 75 m, there is only 5 m coal pillar between the working face and the headentry, and the coal pillar loses its bearing capacity
- (2) When the working face passes through the roof abandoned roadway, the leading stress peak shifts to the abandoned roadway and overlaps with the stress at the abandoned roadway. The stress peak increases continuously, and the stress intensively and gradually extends to the upper abandoned roadway, with a large degree of concentration
- (3) When the working face passes through the abandoned roadway of the coal seam, the peak stress gradually shifts to the abandoned roadway. As the working face advances, the width of the solid coal

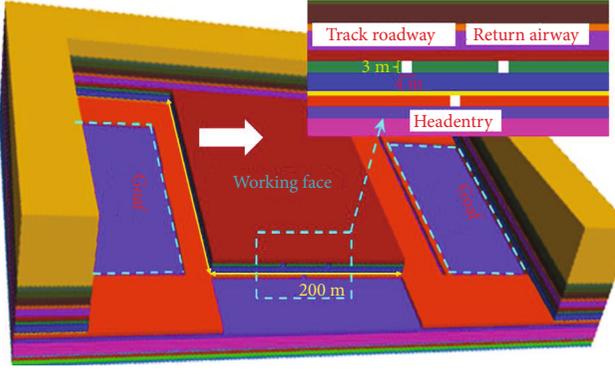


FIGURE 8: Numerical model of crossing the abandoned roadways.

pillar between the abandoned roadway and the working face decreases continuously, and its bearing capacity also decreases. When it is shortened to the limit width of the coal pillar, it will lose its bearing capacity and fully reach plastic failure

The development law of the coal seam and roadway plastic zone when the coal pillar working face passes through the track roadway, the return airway, and the headentry is shown in Figure 10.

As shown in Figure 10, the development law of the plastic zone is as follows: when the working face passes through the roof roadway, the front coal wall on the initial advancing working face is affected by the advanced stress. The development depth in the plastic zone is 6.2 m, and the development depth in the plastic zone on the sidewall of the abandoned roadway near the working face is 2.4 m. Plastic deformation occurs on the roof and the sidewall. The development of solid coal between the working face and the track roadway is distributed as “plastic zone-elastic zone-plastic zone.” When the working face continues to advance, the development of the coal pillar plastic zone between the working face and the abandoned roadway is gradually connected.

In the actual mining process, the roof thickness changes with the strike of strata, and the thickness distribution of the immediate roof on the working face is uneven. Therefore, the weak part of the immediate roof requires additional reinforcement.

**3.3. Analysis of the Position of the Weak Roof in the Working Face.** The safe rock pillar thickness refers to the minimum rock pillar thickness when the roof can bear the concentrated stress caused by coal mining and the support does not collapse as it moves downwards. The section where the thickness of the abandoned roadway and the roof rock pillar on the working face is less than or equal to the safe rock pillar thickness is the short-distance cross-mining section, and the mining of this section needs to be strengthened.

The thickness of the safe rock pillar ( $T$ ) is composed of the maximum depth of plastic failure on the panel roof ( $T_1$ ), the thickness of the effective bearing rock stratum ( $T_2$ ), and the maximum height of roof failure in the underlying roadway ( $T_3$ ), that is,  $T = T_1 + T_2 + T_3$ .

- (1) Calculation of the maximum depth of roof failure on the working face ( $T_1$ )

$$T_1 = \frac{L \sin \varphi}{2 \cos \left( \left( \frac{\pi}{4} \right) + \left( \frac{\varphi}{2} \right) \right)} \times \exp \left[ \cos \left( \frac{\pi}{4} + \frac{\varphi}{2} \right) \tan \varphi \right]. \quad (9)$$

In the formula,  $L$  is the distance from the peak bearing pressure to the coal wall (taken as 5 m) and  $\psi$  is the internal friction angle of roof rock ( $34^\circ$  for sandy mudstone).

- (2) Calculation of bearing stratum thickness ( $T_2$ )

The thickness of the bearing rock stratum shall be greater than the minimum thickness when shear or tensile failure occurs, i.e.,  $T_2 > \text{Max} \{T_{2S}, T_{2T}\}$ .  $T_{2S}$  is the minimum thickness of the bearing stratum in the case of shear failure, and  $T_{2T}$  is the minimum thickness of the bearing stratum in the case of tensile failure.

$$T_{2S} = \frac{3q(L_1 + L_2)}{8R_S}, \quad (10)$$

$$T_{2T} = \sqrt{\frac{3q(L_1 - L_2)^2}{16EI R_T}}.$$

In the formula,  $q_1$  is the uniform load of bearing pressure on the working face (taken as 0.67 MPa),  $R_S$  is the shear strength of the roof rock beam (10.35 MPa),  $L_1$  is the length of the hydraulic support (4.7 m),  $L_2$  is the roadway width (4.0 m),  $EI$  is the product of elastic modulus and inertia distance of the roof rock (4 MPa,  $m^4$ ), and  $R_T$  is the tensile strength of the roof rock beam (5.6 MPa).

- (3) Calculation of the height of roadway roof failure ( $T_3$ )

Within the normal range, the height of roadway roof failure should not exceed the caving arch height of the roadway roof. The value is related to the roadway width and the firmness coefficient of roof rock.

$$T_3 = \frac{L_2}{2f} \leq T_M. \quad (11)$$

In the formula,  $T_M$  is the carving arch height of the roadway roof (m),  $f$  is the firmness coefficient (taken as 3.3), and  $L_2$  is the roadway width (4.0 m).

Through calculation, the thickness of the safety rock column is  $T = 3.61$  m (taken as 4 m). It is understood that the short-distance cross-mining position is the section where the thickness of the slate pillar of the roadway and the coal seam roof is not greater than 4 m. In the roof roadway, reinforcement measures can be taken for the roadway section within 4 m above the coal seam. The area to be reinforced in the no. 23 pillar working face is shown in Figure 11. In the abandoned roadways of the internal roof on the working face, there are 12 roof tunnels in which roof reinforcement is required.

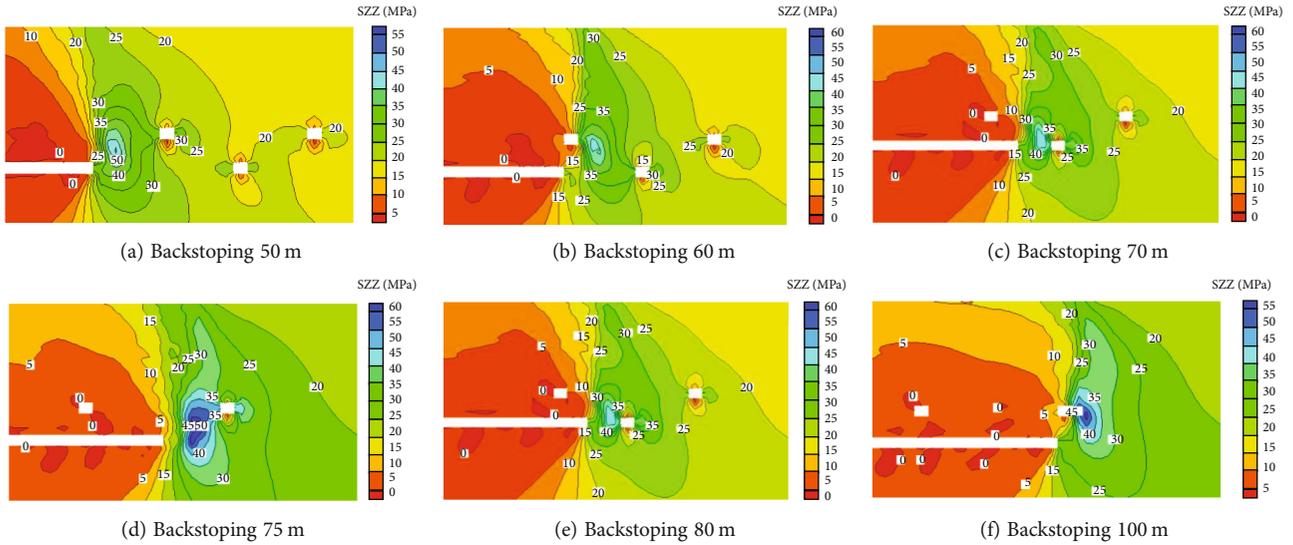


FIGURE 9: Stress distribution at different positions when the working face passes through the abandoned roadways.

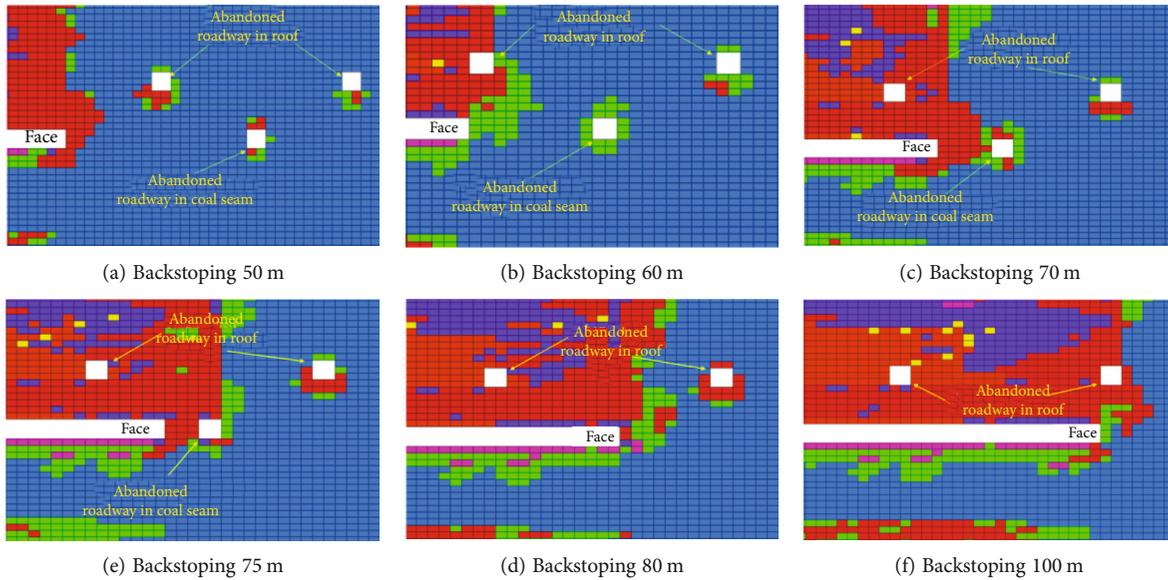


FIGURE 10: Development of plastic zones at different positions when the working face passes through the abandoned roadways.

#### 4. Reinforcement Support Scheme and Effect for the Working Face Crossing the Abandoned Roadway

**4.1. Reinforcement Support Measures for the Working Face Crossing the Abandoned Roadway.** As the roadway is located in the coal seam, with long support length and time, the design is to carry out pseudoinclined mining in the working face and to add anchor cable to the coal seam abandoned roadway to reinforce the support. In the no. 23 mining area, the inclined coal outlet of roadway 2311 and the combined coal outlet of roadway 2311, roadway 2314, and roadway 2312 are coal roadways. The reinforcement scheme is to construct two rows of anchor cables along the lines on the left and right from the roadway centerline, with an anchor cable spacing of 1.6 m. The specification of the anchor cable

is  $\Phi 21.6 \times 9200$  mm, equipped with a  $300 \times 300$  mm anchor cable tray. The reinforcement support by means of the anchor cable is adopted to improve the roadway support strength and achieve the support resistance of crossing the empty roadway. The layout of the anchor cable for the reinforcement roof in the headentry is shown in Figure 12.

**4.2. Reinforcement Measures for the Weak Roof in the Working Face Crossing the Abandoned Roadway.** In the previous reinforcement measures for the abandoned roadway roof, both the wood pile supporting and filling technologies can strengthen the roof support capacity. Also, when used as a false roof, they allow the hydraulic support to hold the wood pile or filling body above when the roof collapses, so that there is no empty roof above the support. The supporting effect is relatively excellent [22–25].

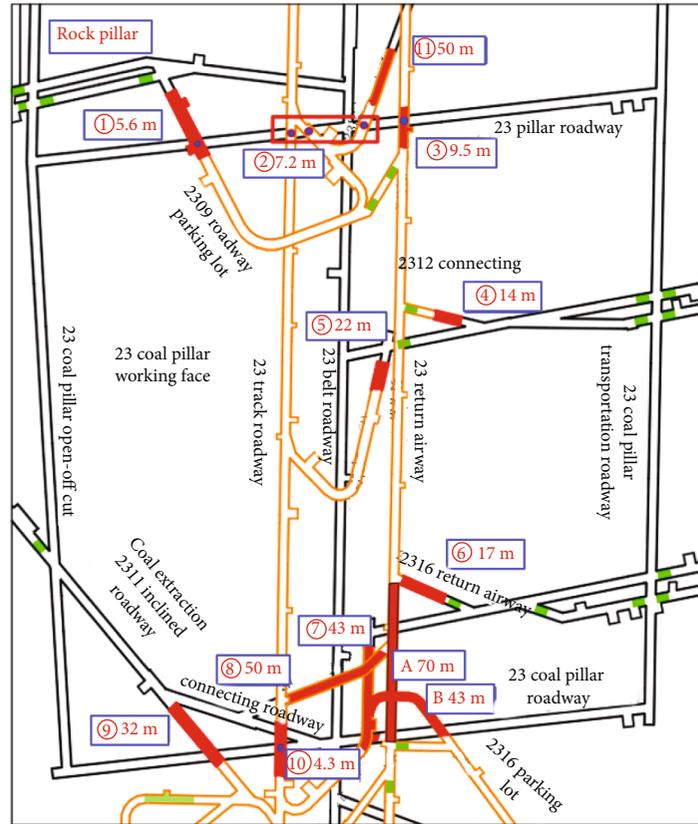


FIGURE 11: Positions requiring to be reinforced when the working face passes through the roof abandoned roadway.

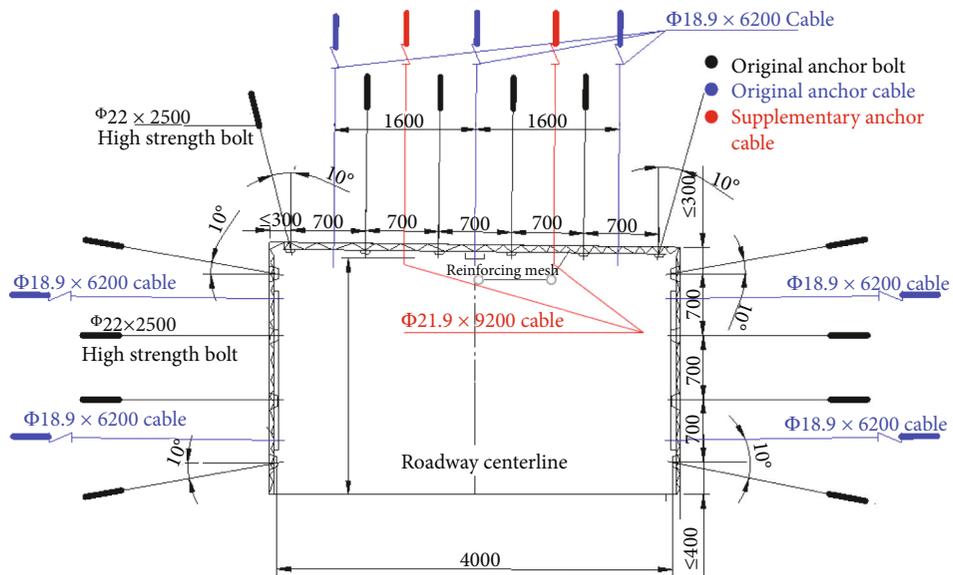


FIGURE 12: Layout of anchor cables for the reinforcement roof in the headentry.

The no. 23 working face contains many abandoned roadways, each of which needs a small support area. If the filling technology is adopted, the construction process is complex and the cost is high. The wooden pile supporting process is simple, and the mining period of the working face is short; thus, it can meet the supporting requirements and

can be a reasonable choice for the no. 23 coal pillar crossing the working face. The design scheme for strengthening the weak roof with wooden pile support is as follows:

- (1) At no. 2, no. 3, and no. 10 reinforcement points, the rock columns exceed 4 m, and there is no risk of roof



FIGURE 13: Field support effect on the working face.

fall in passing through the roadway normally; thus, no reinforcement measures are required. At the no. 1 point, the rock pillar is 5.6 m, and the roadway in this section needs to be reserved along the goaf. Therefore, the spatial intersection in the roadway at the no. 1 point needs to be reinforced, to ensure the roadway supporting effect during roadway retention. The roadway reinforcement length is 5 m, and the reinforcement method is to set up wooden stacks connecting the top to the bottom, which are bound firmly to prevent collapse

- (2) No. 4 to no. 9 reinforcement points are all the junctions of the coal roadway and the rock roadway, with the highest risk of roof fall during backstopping; thus, key reinforcement is required. The reinforcement length is 14 m at the no. 4 point, 22 m at the no. 5 point, 17 m at the no. 6 point, 43 m at the no. 7 point, 50 m at the no. 8 point, and 32 m at the no. 9 point. The reinforcement method is to arrange a layer of wood beams at an interval of 1 m along the disposal and roadway side on the bottom plate, arrange a layer of reinforcement mesh on the wood beam 2 m before the junction of coal and rock, and then set wood cribs on the wood beam to connect the top and bind them together to form a whole
- (3) The reinforced sections A and B are both rock roadways near the coal seam, where the rock pillar is less than 4 m and the minimum rock pillar is 1.8 m. They are locations with high risks of roof fall during backstopping and need to be reinforced. The reinforcement length is 70 m for section A and 43 m for section B

**4.3. Support Effect of the Working Face Crossing the Abandoned Roadway.** After the support scheme is implemented, when the working face passes through the coal seam abandoned roadway, all the coal pillars between the coal seam abandoned roadway and the working face have undergone plastic failure. With the continuous reduction of the coal pillar width and under the mining impact, the plastic zone of the surrounding rock in the abandoned roadway extends to the deeper part, the shear failure state develops

to tensile failure, and the coal pillar loses its bearing capacity. After the working face is strengthened by wood pile classified and anchor cable reinforcement, the stress concentration is reduced, the stress of surrounding rock declines, and the impact of the abandoned roadway on the working face mining is reduced. The effect after abandoned roadway support is shown in Figure 13.

After the reinforcement measures are taken, the roadway support effect is good. Therefore, the reinforcement measures are feasible.

In the mining process, the hydraulic support resistance on the working face was monitored. The monitored objects were the three abandoned roadways in the middle part of the working face, namely, the track roadway, the transit roadway, and the return airway. The headentry was taken as the 0 position on the working face, the support resistance was tested and collected within 100 m before and after the transit roadway, and the characteristics of the working resistance of hydraulic support were at different positions when the working face was pushed to the abandoned roadways. The average support resistances were drawn into a curve, as shown in Figure 14. The impact on the support resistance on the working face in passing through the abandoned roadways is analyzed.

As shown in Figure 14:

- (1) In the advancement of the working face, the influence range of the abandoned roadway is 50 m. Beyond 50 m, the support resistance remains 29.4 MPa, basically not affected by the abandoned roadway. Within 50 m and nearing the abandoned roadway, the influence degree gradually increases. When the working face is pushed to the roof abandoned roadway, the working resistance reaches the peak
- (2) When the working face advances to the track roadway, the headentry, and the return airway, the working resistances reach the peak values 39.3, 40.6, and 39.6 MPa, respectively. After the working face passes through the track roadway, the support resistance, under the overlapped impact of the track roadway and the transit roadway simultaneously, first decreases and then increases. But the resistance peak is still within the pressure range of the support safety

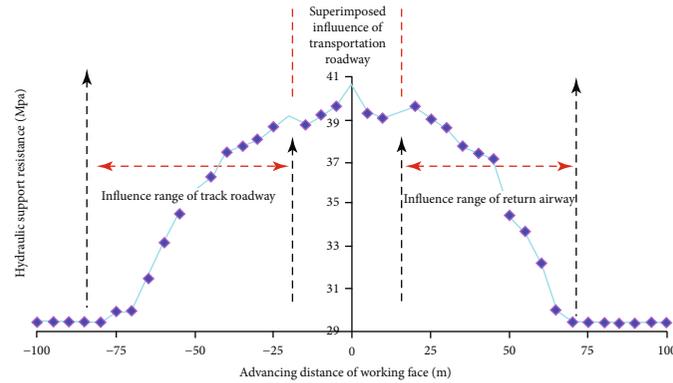


FIGURE 14: Support resistances when the working face is pushed to different positions in the abandoned roadway.

valve, and the hydraulic support can continue to work normally

The monitoring of hydraulic support resistance shows that the methods of wood pile reinforcement and anchor cable reinforcement on the working face are effective. The hydraulic support can operate normally, which ensures safe mining on the no. 23 coal pillar working face.

## 5. Discussions

The working face crossing the abandoned roadway under complex stress conditions in deep mining is a complicated engineering issue. Before the support design scheme was made, a large number of field researches and knowledge were made, a mechanical model was established for the characteristics of the main roof fracture, and its characteristics of fracture were analyzed. A numerical simulation analysis was carried out on the characteristics of the surrounding rock stress and the plastic area changes when the working face passed through the abandoned roadway group. A support scheme is designed for the working face crossing several abandoned roadways as per different roadway positions in the working face, and the characteristics of working resistance change as the working face hydraulic support advances are monitored throughout the process, to verify the feasibility of the support scheme. The support scheme designed in this paper is the final result of a series of work above.

The working face is buried deep, the immediate roof is thick, and the rock pressure is not obvious. Even in the same mine, the surrounding rock structure changes greatly and has different characteristics. The support scheme required still needs to be reevaluated and designed. The mechanical model established herein is not perfect in details. The establishment of the model is considered from the view of the main roof but the influence when the immediate roof contains two layers of rocks with an accumulative thickness of 5.92 m. The monitoring result of the support resistance on the hydraulic support shows that the fluctuations are as we expected. If the surrounding rock control theory is optimized, the simulation effect of the mechanical model can be closer to the engineering practices, and the error can even be limited within a range, so that the utilization rate of mine

resources will be improved. Therefore, more relevant practices and researches are required in the future.

## 6. Conclusions

- (1) The mechanical model of the coal pillar working face crossing the abandoned roadway is constructed. The process of fracture when the working face crosses the abandoned roadway is analyzed, which mainly shows that key block *B* crosses the abandoned roadway and the solid coal, forming the “cross-roadway long key block.” It is calculated that the minimum support resistance required for the abandoned roadway is 6700 kN
- (2) The stress distribution when the working face passes through the abandoned roadway is simulated and analyzed. The results show that when the working face passes through the roadway, the stress gradually increases, stress concentration appears, the plastic zone gradually extends to the deeper part, and the plastic zones of surrounding rocks of the abandoned roadway are connected, which affect the normal mining of the no. 23 coal pillar working face
- (3) The support scheme of the working face crossing the abandoned roadway is proposed. According to the roof abandoned roadway, the thickness of the safe rock column is calculated to be 4 m, and wood pile filling is applied to strengthen reinforcement. The coal seam abandoned roadway is used for pseudoinclined mining and anchor cable reinforcement support on the working face. The field observation shows good supporting effect
- (4) The monitoring scheme of working resistance on the hydraulic support in the working face is put forward. When the working face advances to the headentry, under the overlapped impact of the headentry abandoned roadway group, the support resistance reaches the peak value of 40.6 MPa, which is still within the normal range of the safety valve. The wood pile classified reinforcement and anchor cable reinforcement scheme can ensure that the working face passes through the abandoned roadways safely

## Data Availability

The data used to support the findings of this study are included within the article.

## Conflicts of Interest

The authors declare no conflicts of interest.

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## References

- [1] M. G. Qian and P. W. Shi, "Mine pressure and strata control," China University of Mining and Technology Press, 2003.
- [2] M. G. Qian, X. X. Miao, and F. He, "Analysis of key block in the structure of voussoir beam in longwall mining," *Journal of China Coal Society*, vol. 19, no. 6, pp. 557–563, 1994.
- [3] J. L. Xu and J. F. Ju, "Structural morphology of key stratum and its influence on strata behaviors in fully-mechanized face with super-large mining height," *Chinese Journal of Rock Mechanics and Engineering*, vol. 30, no. 8, pp. 1547–1556, 2011.
- [4] J. B. Bai and C. J. Hou, "Research on principle of roof stability of abandoned workings and supporting technology," *Journal of China Coal Society*, vol. 30, no. 1, pp. 8–11, 2005.
- [5] G. M. Feng, K. J. Jia, and B. B. Shang, "Application and prospect of ultra-high water filling materials in mining engineering," *Coal Science and Technology*, vol. 43, no. 1, pp. 5–9, 2015.
- [6] H. F. Zhou and Q. X. Huang, "Study on the law of roof breakage and mine pressure passing large cross-section gob group in the fully-mechanized face with high mining height," *Coal Science and Technology*, vol. 48, no. 2, pp. 70–79, 2020.
- [7] H. F. Zhou, "Roof cutting mechanism and control technology of high cutting coal mining face passing through large cross section abandoned gateway," *Coal Science and Technology*, vol. 42, no. 2, pp. 120–123, 2014.
- [8] B. Q. Liu, Z. J. Li, S. C. Dai, X. H. Yuan, and X. D. Xing, "The failure mechanism and control technology of the surrounding rock of the coal pillar crossing abandoned roadway," *Coal Science and Technology*, vol. 48, no. 2, pp. 1–11, 2020.
- [9] Q. Y. Xu, Z. X. Ning, R. S. Zhu, and K. S. Zeng, "Study on instability mechanism and top control of overfilled roof in fully mechanized caving face," *Journal of Mining & Safety Engineering*, vol. 36, no. 3, pp. 505–512, 2019.
- [10] C. Y. Yin, G. M. Feng, P. Gao, and Y. Zhao, "Research on instability mechanism of surrounding rock in stage of working face passing abandoned roadway," *Journal of Mining & Safety Engineering*, vol. 35, no. 3, pp. 457–464, 2018.
- [11] D. Zorkov, A. Renev, K. Filimonov, and R. Zainulin, "The roof support load analysis for pre-driven recovery room parameters design," *E3S Web of Conferences*, vol. 174, no. 10, 2020.
- [12] C. S. Tadolini, S. P. Mills, and R. D. Burkhard, "Tekcrete Fast®: fiber-reinforced, rapid-setting sprayed concrete for rib and surface control," *International Journal of Mining Science and Technology*, vol. 28, no. 1, pp. 29–34, 2018.
- [13] G. S. Esterhuizen, D. F. Gearhart, and I. B. Tulu, "Analysis of monitored ground support and rock mass response in a long-wall tailgate entry," *International Journal of Mining Science and Technology*, vol. 28, no. 1, pp. 43–51, 2018.
- [14] W. Yu and K. Li, "Deformation mechanism and control technology of surrounding rock in the deep-buried large-span chamber," *Geofluids*, vol. 2020, Article ID 8881319, 22 pages, 2020.
- [15] C. Liu, P. L. Gong, K. Wang, X. Q. Zhang, and Y. D. Liu, "Roof stability for repeated mining workface passing through abandoned parallel gateway," *Journal of China Coal Society*, vol. 40, no. 2, pp. 314–322, 2015.
- [16] C. Liu, J. W. Zhang, Z. Q. Yang et al., "Mechanism of advance fracture of main roof and its control technology when workface crossing abandoned roadway," *Rock and Soil Mechanics*, vol. 39, no. 44, pp. 1411–1421, 2018.
- [17] C. Liu, Z. Q. Yang, P. L. Gong et al., "Mechanism and control technology of supports crushing induced by main roof breaking ahead of workface crossing abandoned roadway," *Journal of China Coal Society*, vol. 40, no. 2, pp. 314–322, 2015.
- [18] X. N. He, Y. Chen, and Y. Z. Qin, "Application and study on technology of fully-mechanized top coal caving mining face passing through mine abandoned roadway," *Coal Science and Technology*, vol. 45, no. 6, pp. 124–130, 2017.
- [19] H. P. Kang, H. Lv, X. Zhang, F. Gao, Z. Wu, and Z. Wang, "Evaluation of the ground response of a pre-driven longwall recovery room supported by concrete cribs," *Rock Mechanics and Rock Engineering*, vol. 49, no. 3, pp. 1025–1040, 2016.
- [20] W. Fangtian, Z. Cun, W. Shuaifeng, Z. Xiaogang, and G. Shenghua, "Whole section anchor-grouting reinforcement technology and its application in underground roadways with loose and fractured surrounding rock," *Tunnelling and Underground Space Technology*, vol. 51, no. 1, pp. 133–143, 2016.
- [21] W. Yu, K. Li, Z. Liu, B. An, P. Wang, and H. Wu, "Mechanical characteristics and deformation control of surrounding rock in weakly cemented siltstone," *Environmental Earth Sciences*, vol. 80, no. 9, pp. 33–48, 2021.
- [22] B. Zhao, F. T. Wang, N. N. Liang, and W. L. Wang, "Reasonable segment pillar width and its control technology for fully mechanized top-coal caving face with high stress," *Journal of Mining & Safety Engineering*, vol. 35, no. 1, pp. 19–26, 2018.
- [23] B. Zhao, N. N. Liang, F. T. Wang, and Z. X. Liu, "Surrounding rock broken zone evolution law of high-intensity mining affected roadway in shallow coal seam," *Coal Science and Technology*, vol. 46, no. 5, 2018.
- [24] Z. Z. Zhang, J. B. Bai, Z. T. Han, X. Y. Wang, Y. Xu, and M. Wang, "Roof mechanics analysis and backfill technology for abandoned roadway," *Journal of Mining & Safety Engineering*, vol. 30, no. 2, pp. 194–198, 2013.
- [25] H. Yu, Z. Y. Niu, L. G. Kong, C. C. Hao, and P. Cao, "Mechanism and technology study of collaborative support with long and short bolts in large-deformation roadways," *International Journal of Mining Science and Technology*, vol. 25, no. 4, pp. 587–593, 2015.