

Research Article

Stability Mechanism and Control Factors on Equipment Removal Area under “Goaf-Roof-Coal” Structure

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One of the main difficulties in longwall mining (LM) is the movement of mining equipment from one panel to the next panel during mining process. The shields of the LM face may be damaged by the collapse of the roof in shallow coal seam under the “Goaf-Roof-Coal” (GRC) structure, especially when moving the shields from the current panel to the next panel. In order to solve this problem, the stability mechanism and its control factors during the LM equipment removal were investigated by using comprehensive methods including theoretical analysis, numerical simulation, and field validation based on the working conditions of Panel 31102 in Liangshuijing Coal Mine. The numerical simulations demonstrate that four different failure zones, shear failure zone, tension failure zone, partly elastic zone, and plastic failure zone, appear around the area due to the position of rock and the arrangements of the supports. The shear failure zone, which is controlled by shield working resistance and roof supporting strength, is the main cause of the failure in the removal area. To minimize the shear failure zone, several measures such as optimizing the end position for LM face, decreasing the width of removal area, and increasing the amount of cable support were taken to ensure the stability of surrounding rock in removal area, which have successfully controlled the damage of roof and equipment in Panel 31102. The field observation confirms that the proposed stability mechanism and control measures are effective under GRC structure.

1. Introduction

It is necessary to move the equipment (i.e., shields, armoured face conveyor, shearer, etc.) from the current working face to the next one at the end of excavation in LM face [1]. If this process is not designed and implemented properly, it will significantly affect the productivity of the LM face and even cause damage of mining equipment and serious safety problems [2]. The removal area is prepared by cutting the coal without advancing the shields [3]. This space is difficult to remain stable due to high stress and deformed rock strata. In shallow coal seam with thin bedrock, the overburden can form the structure of “short masonry beam” or “step rock beam,” and fractures within single-key stratum will lead to an unstable state of working face [4]. As shown in Figure 1, if

the structure fails, the whole roof will collapse at coal wall, which breaks the GRC structure and results in the shields crushing accident [5].

At present, studies on the removal area mainly focus on the suitable position and supporting method. Some scholars put forward a concept of yield mining, which controls the face advancing speed to control roof movement [6–8]. The slower the advancing speed is, the smaller the periodic roof weighting interval is. The reasonable advancing speed is used so that the roof can be in steady state instead of periodic roof weighting when the working face advances to the stopping line. Therefore, the removal area can be set at a relatively stable position. Alternative supporting methods include the combination of rock bolt and mesh to support the area and its stability [9–12]. As

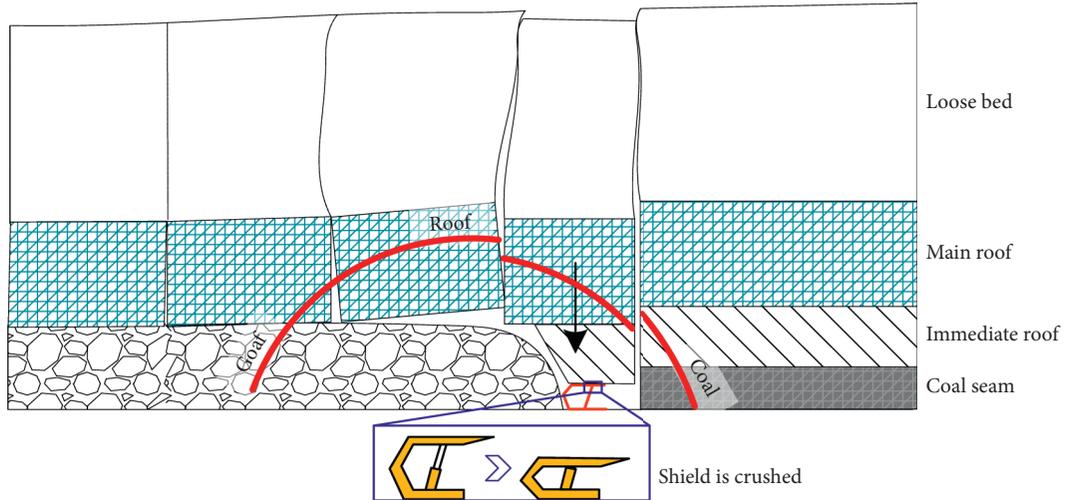


FIGURE 1: Complete failure of equipment removal area.

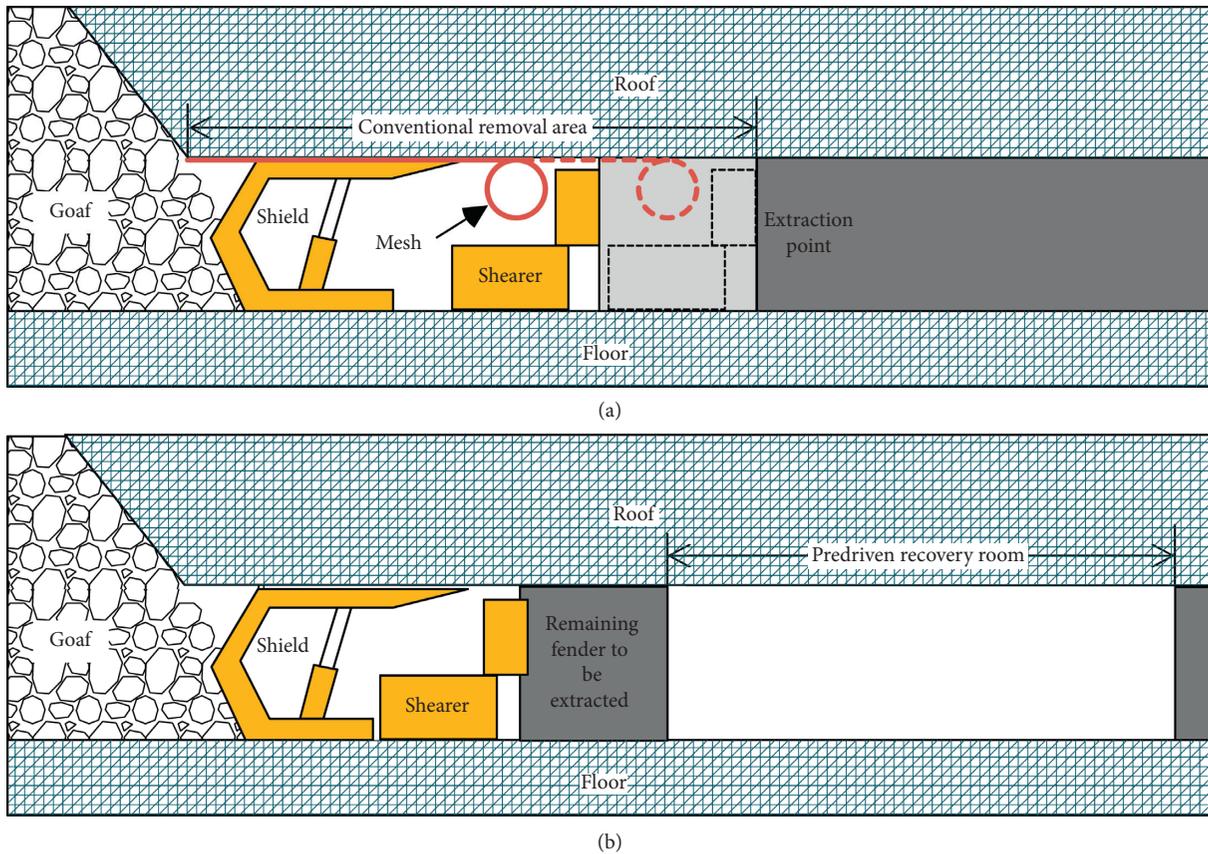


FIGURE 2: Equipment removal method. (a) Conventional removal area. (b) Pre-driven recovery room.

shown in Figure 2, there are two types of removal methods: conventional removal area and pre-driven recovery room. These studies focus on pre-driven recovery room in LM faces with shallow coal seam. For instance, Gu et al. [13] proposed the method of load transfer by coal pillar and determined the optimum pillar width. However, the conventional equipment removal area is still the primary option for many coal mines.

The conventional removal area is potentially unstable due to the goaf in its one side. The roof above the goaf breaks into waste rock. On the one hand, these waste rocks contribute to the instability of the removal area; on the other hand, these waste rocks are compacted gradually and, as a result, can provide support to the roof structures. The waste rocks in goaf form a GRC structure around the removal area where different elements, including shields, rock bolts, or

cables, play different roles in maintaining the stability of removal area. Therefore, the purpose of this study is to investigate the structure stability through theoretical analysis and study the failure mode and support mode by numerical simulation.

2. Stability of GRC Structure above Removal Area

2.1. Engineering Background. Liangshuijing Coal Mine is in Shaanxi Province, northwest of China, which is a typical shallow buried coal seam with thin laminated roof strata. Panel 31102 is at a depth of 110.0 m below the surface with a 3.3 m thick coal seam. The laminated roof strata (immediate roof and main roof) are 17.8 m thick and are covered by weathered rock and sand layer. The geological conditions of roof and floor are shown in Table 1. The roof is siltstone and medium grained sandstone, with compressive strength of 27.4–37.2 MPa, natural water content of 1.48–2.12%, and softening coefficient of 0.22–0.66. The floor is carbonaceous mudstone, with compressive strength of 37.4–45.3 MPa, natural water content of 0.45–1.4%, and softening coefficient of 0.32–0.48.

The ZY8000/17.5/35 shields are employed in the working face and the technical parameters are shown in Table 2. The pressure monitor equipment in this panel shows that the average distance of periodic weighting is 7.1 m, with the minimum of 4.5 m and the maximum of 10.1 m, and the structure of main roof is short masonry beam. As is shown in Figure 3, the fractured rock blocks are hinged together and the rock blocks in short masonry beam have smaller aspect ratio than that of general masonry beam. Short masonry beams are prone to sliding instability rather than rotational deformation instability [2].

2.2. Structure Characteristics above Removal Area. When the removal area is formed at the end of mining, the roof may appear in three forms: the main roof is broken behind the stopping line, above removal area, or in front of the coal wall, among which the first structure (main roof broken behind the stopping line) is stable [14, 15]. According to the principle of yield mining [8], combined with the monitor of working face pressure, measures such as pressure relief are taken to initiate the break of the main roof behind the stopping mining line. However, in the final stage of removal area, only two scenarios could happen to the structure, a complete failure or a relative success, as shown in Figures 1 and 4. If the GRC structure fails, the whole roof will collapse at coal wall, which breaks the GRC structure and results in the shield being crushed by the roof bedrock. If the structure holds, the GRC structure will be stable and bear the overburden to maintain the integrity of removal area.

As shown in Figure 4, the roof structure is analyzed as two parts. The key rocks behind removal area are treated as one part and the roof above the roadway is treated as the other. Through the analysis of “short masonry beam,” the following formulas are obtained [16]:

$$T = \frac{4i \sin \theta + 2 \cos \theta}{2i + \sin \theta (\cos \theta - 2)} P_1 l_0 \partial, \quad (1)$$

$$Q_A = \frac{4i - 3 \sin \theta}{4i + 2 \sin \theta (\cos \theta - 2)} P_1 l_0,$$

where T is the horizontal thrust between rock blocks, Q is the shear force between blocks, P_1 is loading of rock block, i is aspect ratio, θ is rotation angle of rock block, and l_0 is the distance of periodic weighing.

For the roof above the removal area, the balance formula of force and moment is given:

$$\begin{aligned} \sum F_y &= 0, \\ \sum M &= 0. \end{aligned} \quad (2)$$

The bending moment and shear force of roof are obtained:

$$M = \frac{1}{2} P_3 l^2 + Tl + \frac{1}{2} Q_C (h_1 - a) - F_s l_1, \quad (3)$$

$$F = P_3 l + T - F_s,$$

where l is the length of the rock above the removal area, a is the height of interface, F_s is the force of shield, and l_1 is the distance from the center of the support to the end of the rock beam.

The maximum normal stress and maximum shear stress of the beam with width of unit width are as follows:

$$\begin{aligned} \sigma_{\max} &= \frac{6M}{h_1^2} = \frac{3}{h_1^2} (P_3 l^2 + 2Tl + Q_C (h_1 - a) - 2F_s (l - l_1)), \\ \tau_{\max} &= \frac{3F}{2h_1} = \frac{3}{2h_1} (P_3 l + T - F_s). \end{aligned} \quad (4)$$

In Panel 31102, P_3 is 2.3 MPa, which represents the load above the rock, h_1 is 13.2 m, l_0 is 7.1 m, i is 1.8, a is 6.4 m, l_1 is 4.8 m, Q_C or Q_A is 17.051 MN, and F_s is 14.997 MN. After the supports were recycled, there is no support for the removal area, and the supporting force of the roof F_s is 0. At this time, the internal stress at roof is as follows:

$$\sigma_{\max} = 42183.2l^2 + 240946.6l + 1996436.17 \text{ (Pa)}, \quad (5)$$

$$\tau_{\max} = 278409.1l + 1704214.84 \text{ (Pa)}. \quad (6)$$

The maximum internal stress is related to the length of the rock; in other words, the stability of this structure has a connection with the width of removal area. As shown in Figure 5, according to formulas (5) and (6), the maximum normal stress or shear stress increases with the increase of rock length. The wider area leads to a more instable structure; therefore, the span of removal area should be reduced as much as possible to ensure the stability of GRC structure.

The ultimate tensile strength and shearing strength of the main roof are 7.0 MPa and 33.0 MPa, respectively. The

TABLE 1: Condition of roof and floor.

Roof and floor	Rock unit	Min-Max (average)/m	Lithological characteristics
Main roof	Medium grained sandstone	12.0–14.35 (13.15)	Grey, light white, muddy cementation, wavy and massive bedding.
Immediate roof	Siltstone	2.68–6.50 (4.65)	Grey, deep grey, argillaceous cementation, horizontal bedding.
False roof	Mudstone	0.0–0.1 (0.05)	Grey, easy to muddy when encountering water.
Floor	Carbonaceous mudstone	0.00–3.06 (1.02)	Grey, muddy cementation, easy to soften when encountering water.

TABLE 2: Shield technical parameters.

Item	Technical parameters
Model number	ZY8000/17.5/35
Support height	1.75~3.50 m
Width	1750 mm
Centre-to-centre spacing	1750 mm
Rated working resistance	8000 kN
Rated initial support force	6413 kN

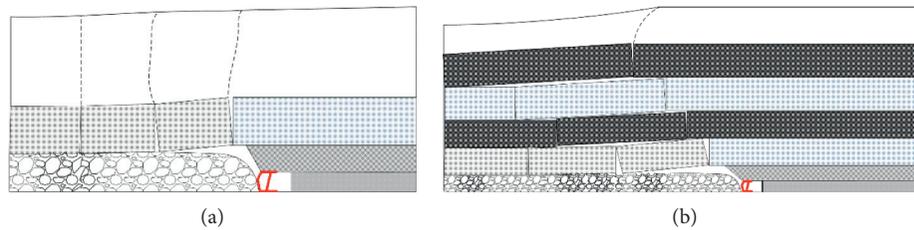


FIGURE 3: Schematic diagram of masonry beam structure. (a) Short masonry beam. (b) General masonry beam.

maximum length of rock block above the removal area is calculated as 8.4 m with formulas (5) and (6), which means that the maximum span of the area is 8.4 m. If the area width is within the allowable range, the GRC structure will be stable and the area could not come into a complete failure.

3. Stability Mechanism of Removal Area under GRC Structure

3.1. Simulation Parameters and Process. Under the GRC structure, the removal area is in a relatively stable state. The failure characteristics of the area at different position are different due to the basic structures and supporting method. FLAC is used to analyze the stability of the area. Firstly, the basic GRC structure will form above the removal area. Then, the removal area is built by cutting the coal face.

The initial model is 120.0 m long and 40.0 m wide, as shown in Figure 6. The boundaries of the model are as follows: the left and right boundaries are restrained by horizontal displacement, and the lower boundary is restrained by vertical displacement; the vertical stress from the gravity of overburden above, 1.75 MPa, is applied on the upper boundary of the model. Then, this model is calculated to obtain the premining rock stress. The model parameters are shown in Table 3.

The goaf is filled with waste rocks, which is composed of the caving immediate roof, as shown in Figure 4. In order to simulate the GRC structure, the immediate roof is deleted manually, and the space is filled with waste rock. The height

of the wasted rock is calculated by the expansion coefficient and thickness of immediate roof.

Stress and deformation in the goaf are difficult to obtain due to the inaccessibility of the waste area. Therefore, Double Yield (DY) model is incorporated in FLAC [17], which can simulate the strain stiffening behavior of the goaf [18]. The DY model parameters used in the modelling are given in Table 4 [19]. The goaf behind removal area is compacted gradually, which forms the GRC structure; see Figure 7. The removal area is generated by cutting the coal without advancing the shield; this process is simulated by deleting the coal in the fourth step, as shown in Figure 8. Support members are used to simulate hydraulic supports, and cable elements are used to simulate rock bolts or cables.

3.2. Support Effect. With the advance of coal shearer, the vertical displacement of roof is shown in Figure 9. Since the goaf behind shield is not compacted completely, the overall trend of roof displacement is continuously increasing from the coal face to goaf. The displacement changes near the rock bolts and cables are smaller than those of the other positions, which indicates that the supporting system works effectively.

The roof above removal area remains stable due to the interaction between rock bolts and surrounding rock. The cable elements in FLAC are used to simulate this situation. Rock bolts in strata are bonded with rocks partly, and the endpoints of bolts are fixed on the rock grid node. The axial force after the roadway formation is shown in Figure 10. The rock bolts behind the removal area have lower axial force due

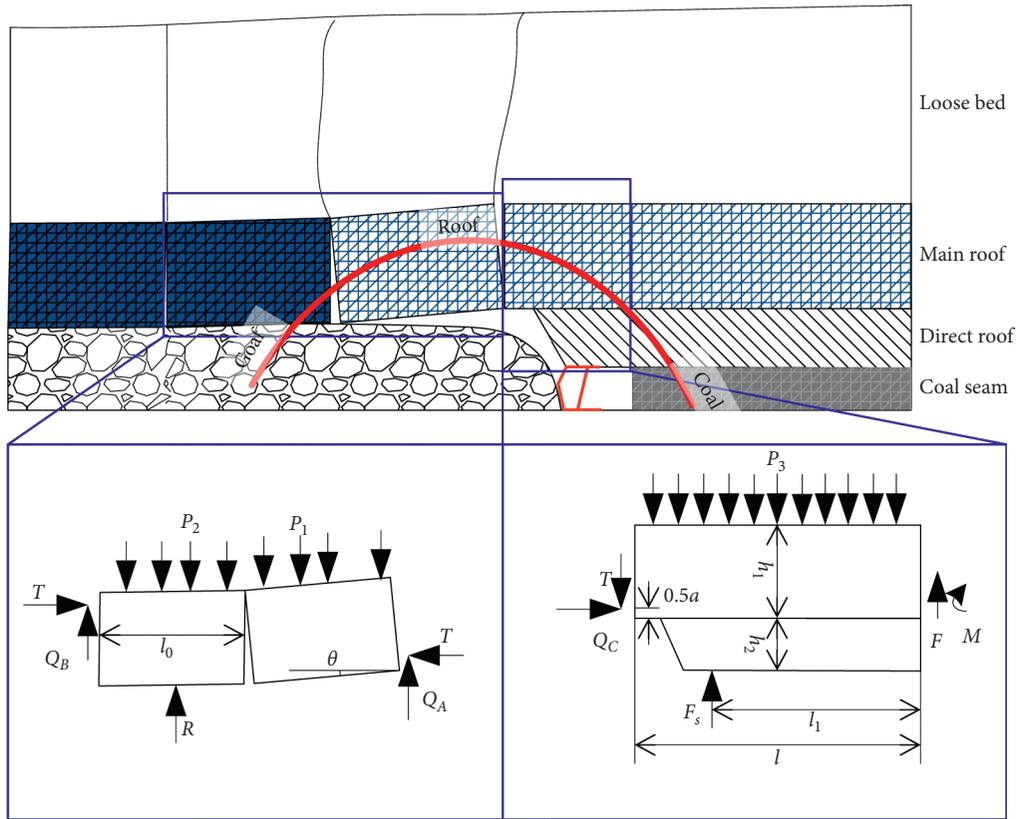


FIGURE 4: Structure characteristics above removal area.

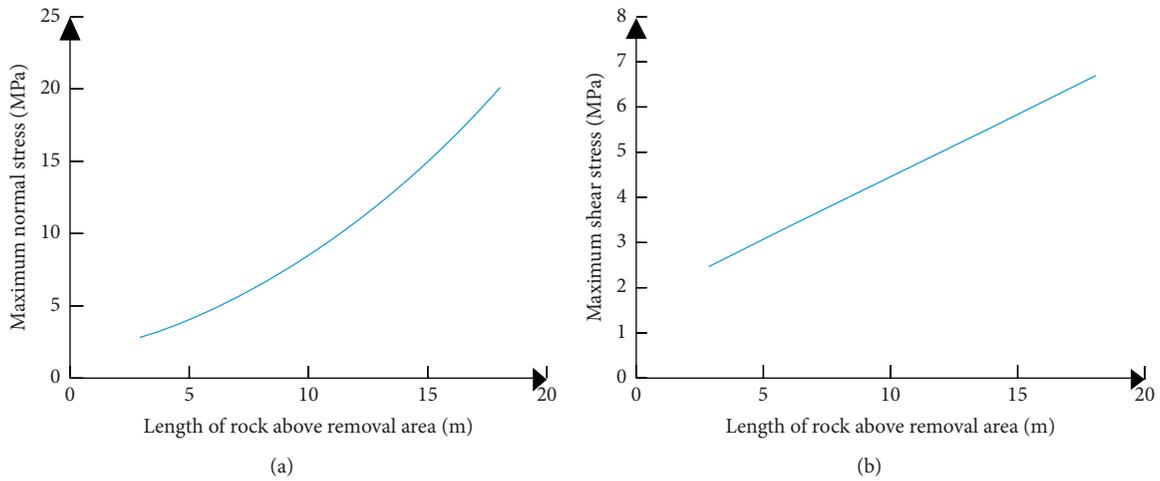


FIGURE 5: Internal stress of rock beam above the removal area. (a) σ_{max} . (b) τ_{max} .

to the supporting function of shields, while the force at the anchor sections is larger due to the interaction between surrounding rock and anchor section. The bolts restrict the deformation of surrounding rock and play a supporting role. With the increase of surrounding rock deformation, the bolt axial force also increases. The greater the bolt axial force is, the greater the effect of bolt on surrounding rock is. The bolt axial force is more than 100.0 kN, which plays an important role in supporting the roof and maintaining the surrounding rock stable.

3.3. Failure Characteristics of Roof and Its Formation Process. With the increasing span of removal area, stress transfer occurs in overburden. The area remains stable because of the combined effect of shields, rock bolts, and cables. Bolts and cables with different lengths act on different areas and play different roles [20]. The failure characteristics of surrounding rock present different states due to different supporting methods. The failure characteristics of different zones are shown in Figure 11. There are four zones of different failure modes: shear failure zone, tension failure

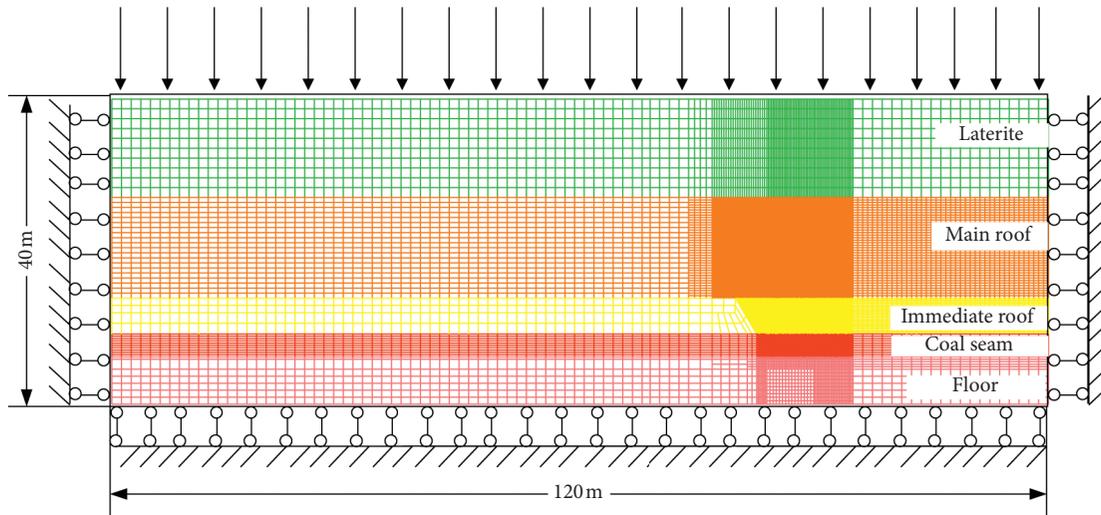


FIGURE 6: Model diagram.

TABLE 3: Parameters of roof, floor, and coal.

Name	Bulk modulus (GPa)	Shear modulus (GPa)	Cohesion (MPa)	Internal friction angle (°)	Bulk density (kN.m ⁻³)
Laterite	1.5	0.6	3.2	12.0	13.0
Main roof	8.3	4.1	8.0	23.0	26.0
Immediate roof	7.3	3.9	6.0	21.0	24.0
Coal seam	2.4	3.2	6.0	26.1	14.0
Floor	8.3	4.1	6.0	21.0	27.0

TABLE 4: Parameters of goaf.

Bulk modulus (MPa)	Shear modulus (MPa)	Cohesion (MPa)	Internal friction angle/°	Bulk density (kN.m ⁻³)
150	13888	0.001	5	19.0

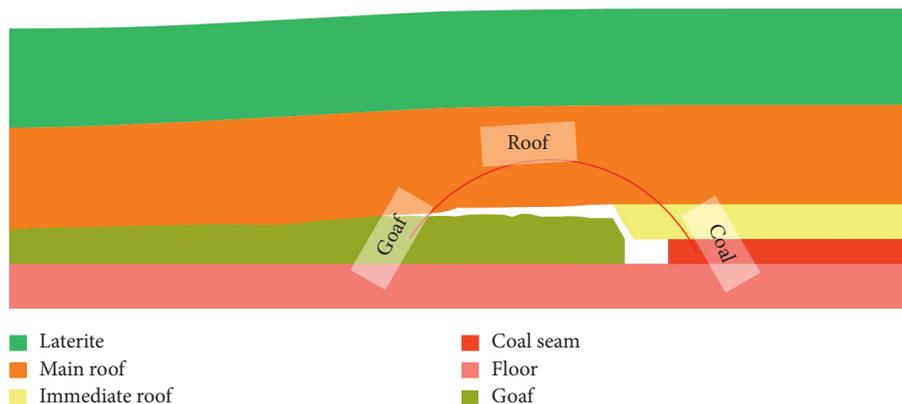


FIGURE 7: The GRC structure in simulation.

zone, partly elastic zone, and plastic failure zone. The shear failure zone, a wedge, is distributed along with rock caving angle. The roof would break in the shear failure zone if there was no supporting form used. Through the shear failure zone, the upper and lower rock masses are connected by the cables. The tension failure zone is distributed at the upper part of immediate roof, which is stretched by the lower part combined by bolts. The rear of bolts and shield provides high

supporting strength, which causes some zones still in elastic state. Plastic failure zones are in the front of the roadway due to the large span. In these zones, the shear failure zone is the main cause for the failure of the removal area. The expansion of this zone should be controlled to prevent the whole roof from being cut down.

During formation of removal area, the distribution of different failure modes is shown in Figure 12(a). At the

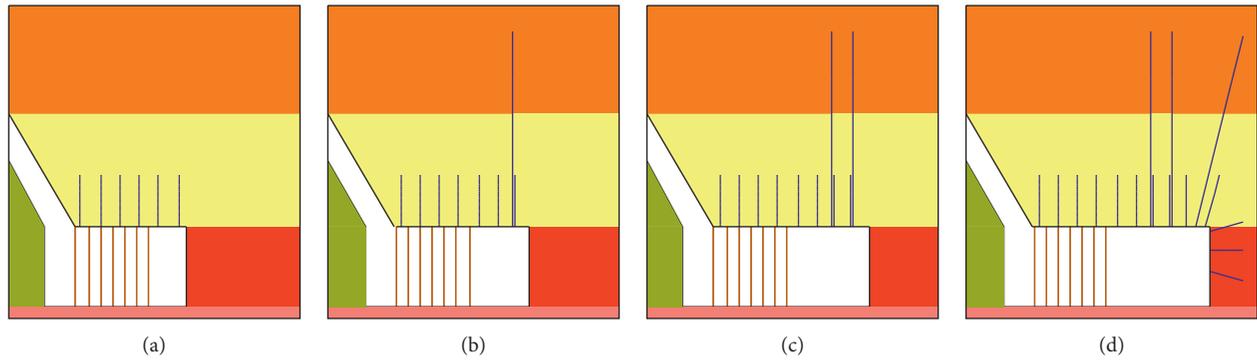


FIGURE 8: Simulation process of removal area. (a) First cutting. (b) Second cutting. (c) Third cutting. (d) Fourth cutting.

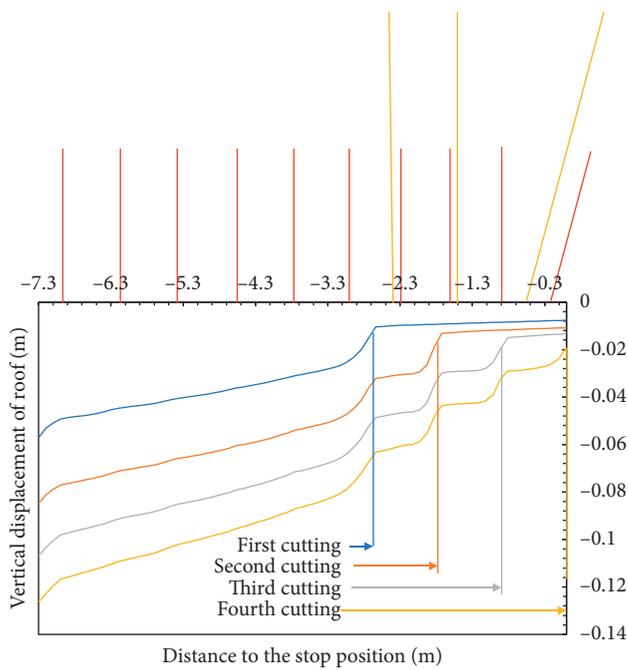


FIGURE 9: Variation of roof displacement during the formation of removal area.

beginning of the construction of the removal area, the shear failure zone shows a scattered distribution. When further mining the coal, the first cable is used to maintain the stability of removal area. The area of shear failure decreases, but this zone centered at the top corner of removal area and it is under the control of the cable. Then the shearer further advances, and the red shear failure zone gathers and expands upward and backward gradually. At the final cutting, the shear failure expands and becomes a wedge at the vertex of the area.

3.4. Analysis of Influencing Factors

3.4.1. Working Resistance of Shield (WRS). The shields remain stationary during the formation of removal area. The WRS is the main parameter of the supports, different WRS

simulations are performed, and the shear failure zones are shown in Figure 13. In order to quantitatively analyze the damage of the roof, the area of shear failure in the roof above removal area is counted.

The shape and area of shear failure of different WRS are similar. When WRS are 6000 kN, 8000 kN, and 10000 kN, respectively, the areas of shear failure above the removal area are 6.24 m², 6.04 m², and 5.64 m², respectively. With the increase of WRS, the area of shear failure decreases. However, the height and range of shear failure are generally the same, which shows that WRS have minor influence on the shear failure around removal area. In other words, the shield cannot affect the stability of the removal area, and the key to the stability of removal area lies in other supporting methods. After the shield is recovered, the removal area can still maintain its integrity.

3.4.2. Roof Supporting Strength (RSS). The shear failure zone occurs in front vertex of the removal area. The cables effectively limit the range and damage state of this zone. The failure state of roof without cable support is shown in Figure 14. When there are no cables in the roof, the shear failure zone develops upward, and the bolts are unable to control the development of the shear failure zone. Since the roof is supported by cables, the area of shear failure decreases significantly, and the range of this zone is limited by cables.

To further analyze the effect of cables, different space and cable length are simulated, as shown in Figures 15 and 16. When the length is not long enough, the area of shear failure increases and the range of this zone expands. When the space increases, the area of shear failure increases and the range of this zone expands similarly. In other words, the space and cable length both play significant roles in the stability of removal area.

The results of the numerical simulation show that the WRS and RSS influence the stability of removal area. Between them, the cable supporting method has more influences on the development of the shear failure zone. The model results predict that the 8.1 m cable with the space of 0.9 m can control the roof effectively and prevent the roof from caving at the coal face.

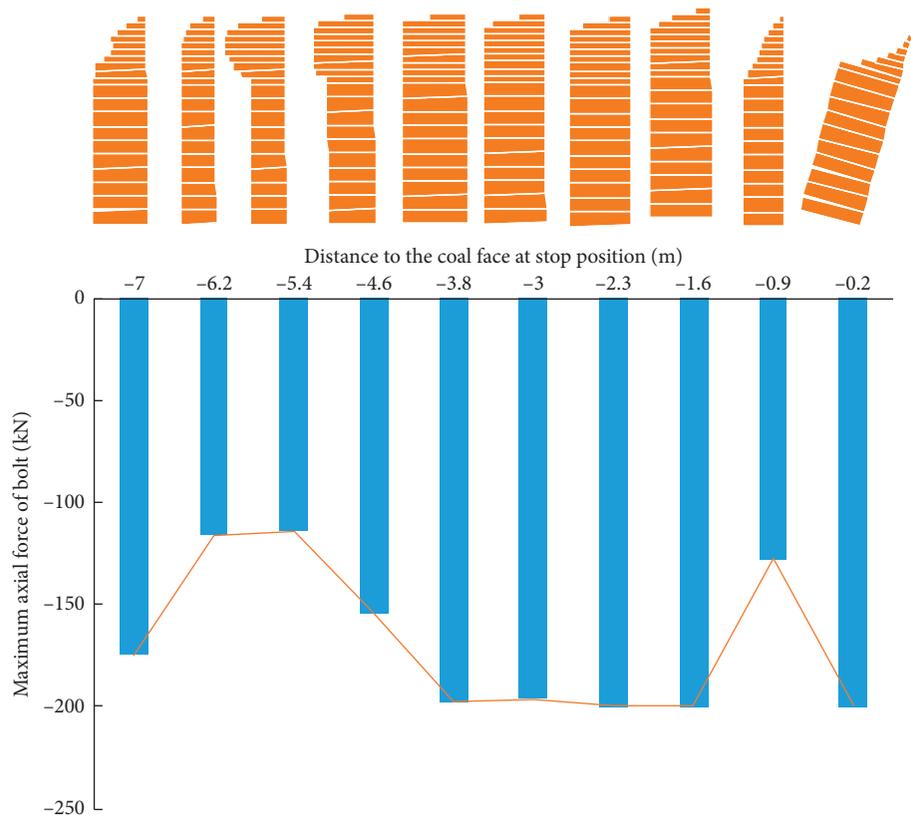


FIGURE 10: Axial force distribution of roof bolt.

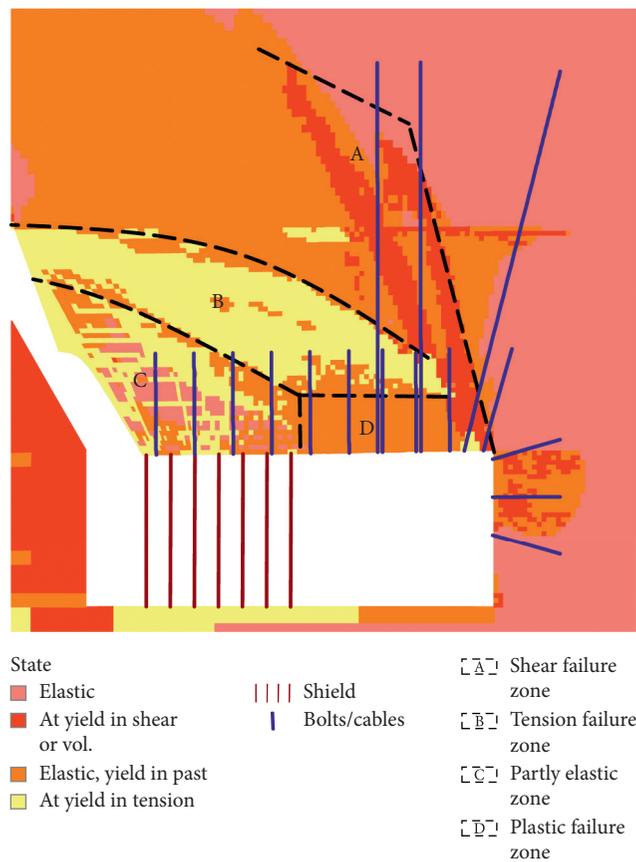


FIGURE 11: Distribution of failure zone around removal area.

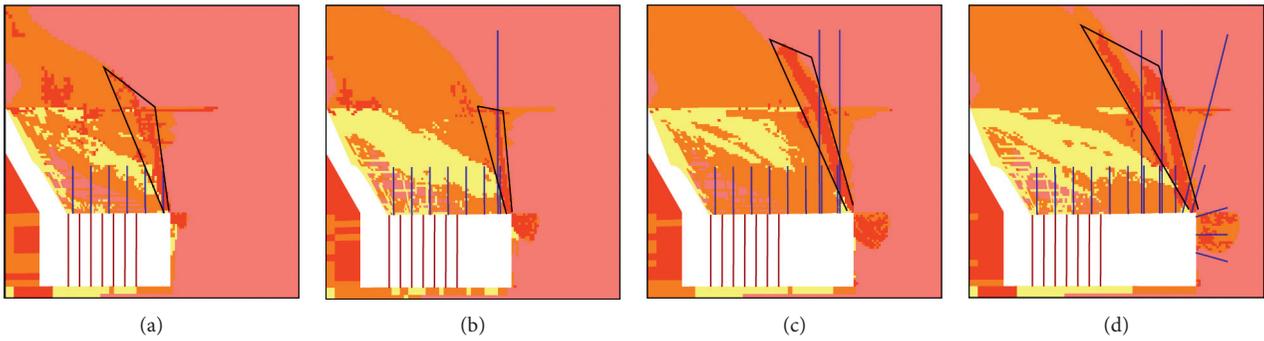


FIGURE 12: Distribution of failure zone during formation process of removal area. (a) First cutting. (b) Second cutting. (c) Third cutting. (d) Final cutting.

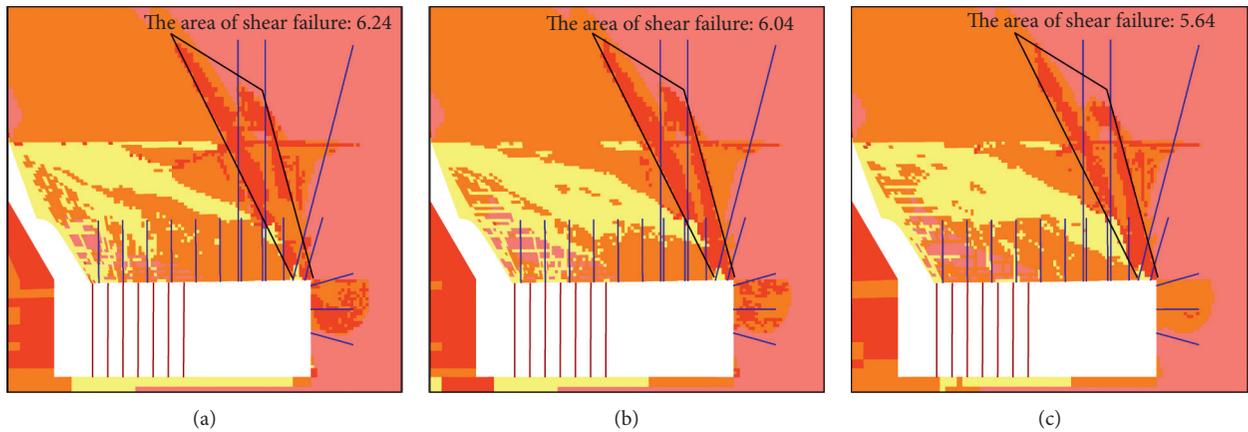


FIGURE 13: WRS influencing the shear failure around removal area. (a) 6000 kN. (b) 8000 kN. (c) 10000 kN.

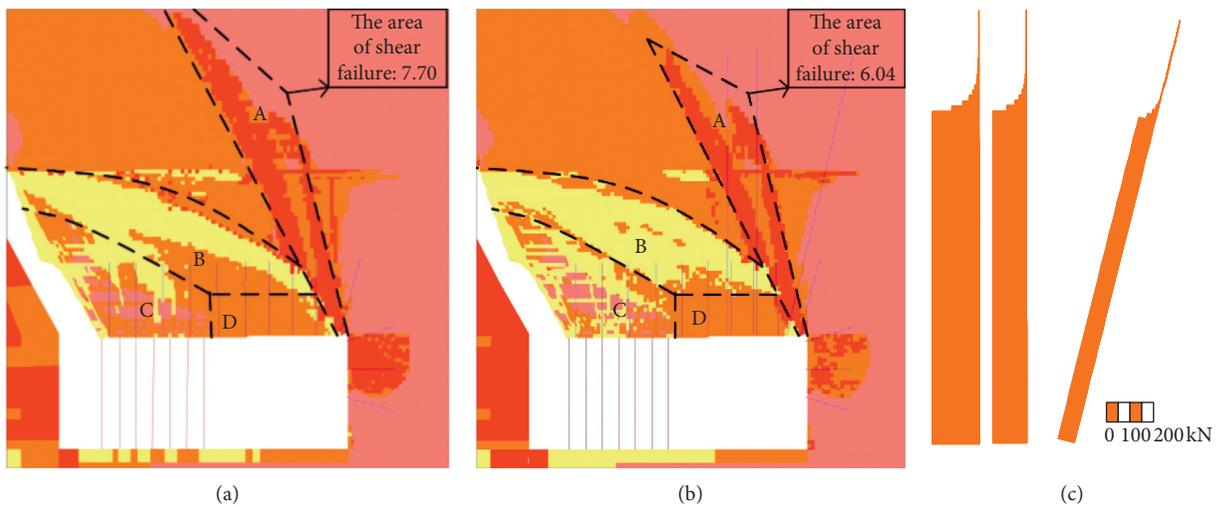


FIGURE 14: The shear failure around removal area with cables or not. (a) Support without cables. (b) Support with cables. (c) Axial force of cables.

4. Field Practice

The shield, rock bolts, and cables are used in Panel 31102. The working resistance of the shield is 8000 kN. The clear

width of removal area is 3.0 m, while the span of the roadway is 7.3 m. The sketch map of removal area is shown in Figure 17. The specific support parameters are as follows: The roof bolt space is 800×700 mm, specification for bolt is

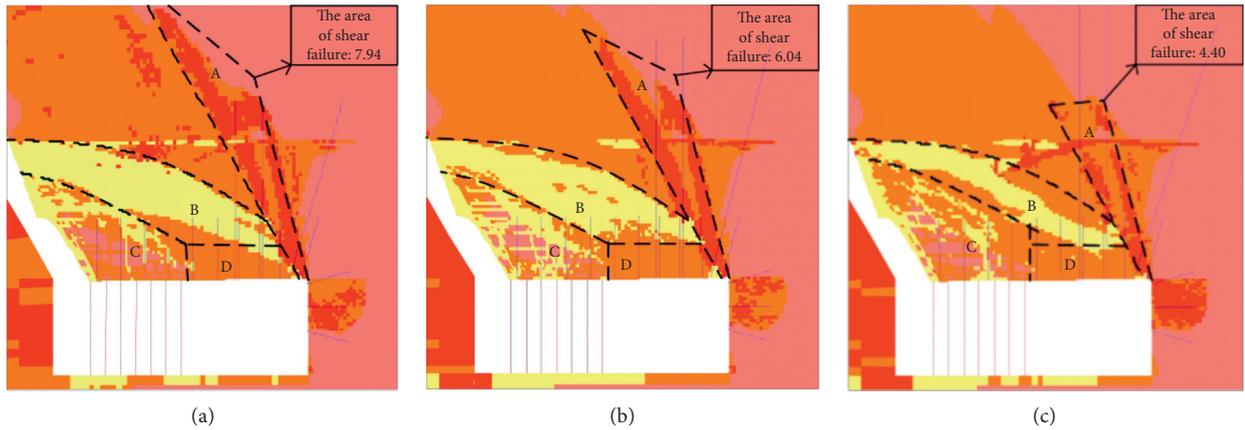


FIGURE 15: Cable length influencing the shear failure around removal area. (a) 6.1 m. (b) 8.1 m. (c) 10.1 m.

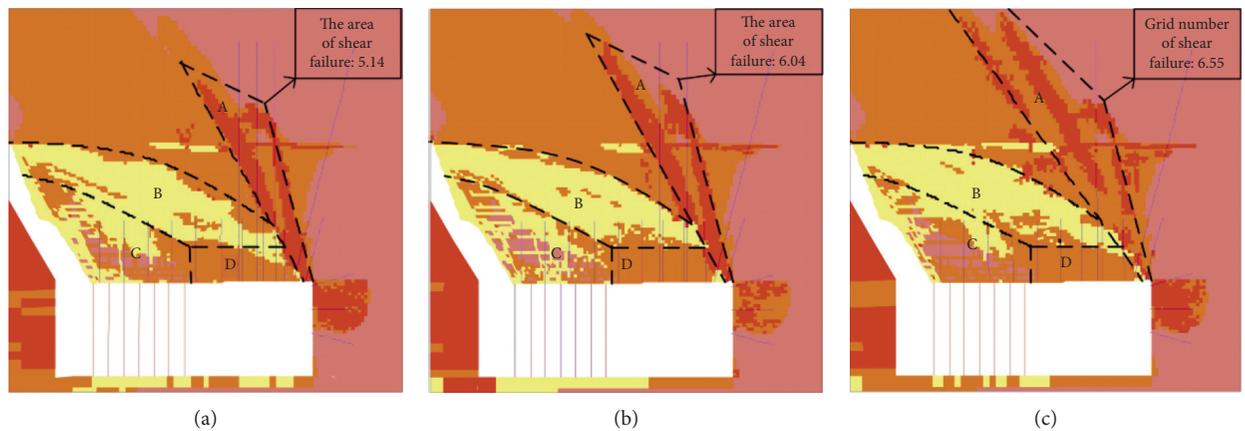


FIGURE 16: Cable space influencing the shear failure around removal area. (a) 0.6 m. (b) 0.9 m. (c) 1.2 m.

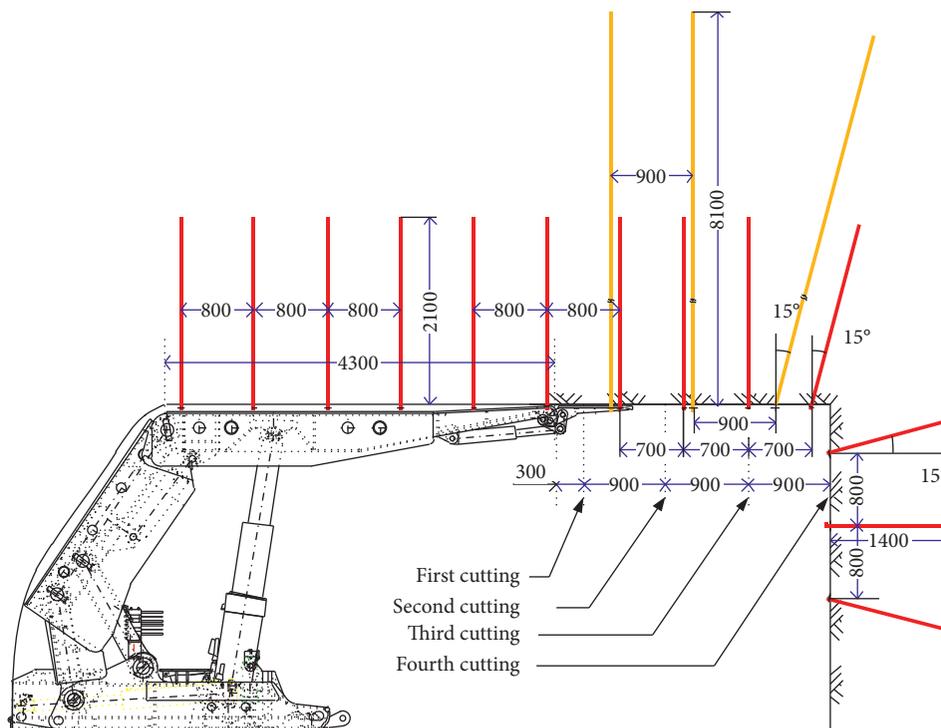


FIGURE 17: Support scheme for removal area.

$\phi 18 \times 2100$ mm, and the yield strength is 705 MPa. The minimum anchorage length is 700 mm. The minimum bolt tightening torque is 200 N M. The exposed bolt should be as less as possible to avoid the damage when moving the shield. The space of cables is $900 \text{ mm} \times 1600 \text{ mm}$. They are arranged in diamond shape. The specification of steel strand cable is $\phi 15.24 \times 8100$ mm and the yield strength is 1770 MPa. The minimum anchorage length is 1200 mm and the minimum tightening torque is 200 N M. At the end of mining, 3 rows of anchor bolts are placed from top to bottom in the coal face. The specification of threaded steel bolts is $\phi 18 \times 1400$ mm, and the yield strength is 705.0 MPa.

At the end period of mining, yield mining measures are taken under the guidance of mine pressure behavior in the premise of continuous advancing and enough hydraulic supporting resistance. The reasonable position is chosen to form a stable roof structure. During the opening of removal area, the pressure of emulsion in shields prop in the middle is 36–44 MPa, which indicates that the goaf has not been compacted completely. This area is supported according to its design, which meets the requirement of support and ensures the safety of equipment recycling. In order to ensure the stability of roof and the normal ventilation during the period of equipment recycling, the wooden cribs are set at an interval of four shields. According to the design, the removal area support was carried out. The implementation of these support schemes and parameters can ensure the support requirements, and the safe removal of LM equipment is therefore guaranteed.

5. Conclusion

- (1) In shallow LM with thin bedrock, a successful GRC structure can provide a stable environment for removal area, and the smaller span is beneficial for the stability. The span of the area should be controlled less than 8.4 m to prevent the failure.
- (2) Under the stable GRC structure, there are four failure zones above the removal area due to different locations and supporting patterns: shear failure zone, tension failure zone, partly elastic zone, and plastic failure zone. The shear failure zone is the main cause of the failure in removal area.
- (3) Both the working resistance of shields and the strength of roof support have effect on the development of shear failure zone. Cable arrangements are the keys to maintain the stability of removal area, which can limit the development of shear failure zone and prevent the roof from breaking at working face.
- (4) Field practice showed that the width of removal area and the cable support design are reasonable in Panel 31102 of Liangshuijing Coal Mine, which ensure the stability of the removal area and can avoid accidents during equipment removing in roadways. This study can provide a reference for LM equipment removal in fully mechanized mining face with similar geological conditions.

Data Availability

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

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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