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A caving self-stabilization bearing structure of advancing cutting roof for gob-side entry retaining with hard roof stratum

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Abstract. An advancing cutting roof for gob-side entry retaining with no-pillar mining under specific geological conditions is more conducive to the safe and efficient production in a coalmine. This method is being promoted for use in a large number of coalmines because it has many advantages compared to the retaining method with an artificial filling wall as the gateway side filling body. In order to observe the inner structure of the gateway cutting roof and understand its stability mechanism, an equivalent material simulation experiment for a coalmine with complex geological conditions was carried out in this study. The results show that a "self-stabilization bearing structure" equilibrium model was found after the cutting roof caving when the cut line deviation angle was unequal to zero and the cut height was greater than the mining height, and the caving roof rock was hard without damage. The model showed that its stability was mainly controlled by two key blocks. Furthermore, in order to determine the optimal parameters of the cut height and the cut line deviation angle for the cutting roof of the retaining gateway, an in-depth analysis with theoretical mechanics and mine rock mechanics of the model was performed, and the relationship between the roof balance control force and the cut height and cut line deviation angle was solved. It was found that the selection of the values of the cut height and the cut line deviation angle had to conform to a certain principle that it should not only utilize the support force provided by the coal wall and the contact surface of the two key blocks but also prevent the failure of the coal wall and the contact surface.

Keywords: advancing cutting roof; gob-side entry retaining; hard roof; self-stabilization structure; mechanical model

1. Introduction

Coal is among the most important foundational energies, accounting for approximately 30% of total energy consumption around the world (Reaver and Khare 2014; Milici *et al.* 2013). Gob-side entry retaining is one of the most commonly used techniques in the category of long-wall mining belonging to the broader category of no-pillar mining. For the gob-side entry retaining of underground coal seam mining, the headgate of a current mining panel is retained and serviced as the tailgate of a subsequent adjacent panel. Since 1950s, pillarless gateways have been widely used in the underground coal mining industry, mainly in the UK, Germany, Poland, Former Soviet Union, and China. A no-pillar is left in the retained entry, and as a result, the outburst risk during the subsequent panel mining is significantly mitigated. Furthermore, due to its high coal recovery rate and low roadway development rate, this technique has prevailed in some countries, such as China (Han *et al.* 2019, Huang *et al*. 2019, Yang *et al.* 2018, Zhang *et al*. 2019, Yang *et al*. 2019). However, an artificial filling wall is required on the gob side to isolate the gob of previous panel and a specific support scheme is needed so that the cross-section of the retained entry can still satisfy the service requirement after deformation, and the roof with the artificial filling wall can form a stable structure, as shown in Fig. 1 (Tan *et al*. 2015, Tan *et al*. 2019, Yang *et al*. 2016, Zhao *et al*. 2018, Yang *et al*. 2019).

In recent years, many scholars have carried out considerable research on mechanical models and the structural design of gob-side supporting structures, and they have obtained many conclusions. The main gob-side artificial filling walls currently in use include wooden stacks, densely spaced hydraulic props, gangue walls, concrete walls, high-water packing material, and other fill materials (Tan *et al*. 2015, Huang *et al*. 2019, Wu *et al*. 2019, Sun *et al*. 2019). The construction of these above-mentioned structures on the gob-side in a roadway is mainly completed by people. These structures belong to the category of additional artificial supporting structures. Nevertheless, building an artificial filling wall requires a more complicated computation of its bearing capacity and spending more time preparing the support material and doing construction. Sometimes, the material for an artificial filling wall is very expensive.

As technology has advanced, advanced cutting roofs for gob-side entry retaining were invented, which needed no

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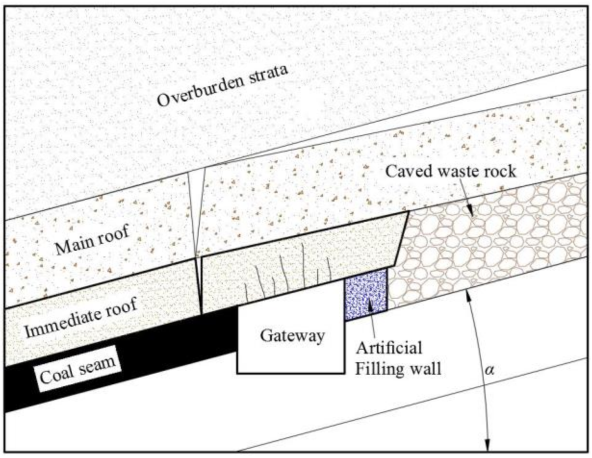

Fig. 1 Schematic of gob-side entry retaining

artificial filling wall (Zhang *et al*. 2019, Zhang *et al*. 2011, He *et al*. 2019, Sun *et al*. 2019). In addition, this technology changed passive "support" to active "cut" and "support" to roof rock mass, making the ground pressure for profit. The technology was first successfully applied to the headgate of a 2422 working face with a hard limestone roof in the Baijiao coalmine in Sichuan province, China (Zhang *et al*. 2011). The technology then had a generalized application in China after the year 2010. The Sunzhuang coalmine headgate of the 12465 II working face was retained using this technology to cut a hard limestone roof . In addition, the Nantun coalmine gateway with a hard limestone roof for the 1610 working face was cut and retained (Sun *et al.* 2014, Zhao *et al.* 2018). Beyond that, the Tangshangou coalmine tailgate of an 8820 working face with a thick-bedded sandstone of roof was effectively cut along the gob, forming a stabilized gateway(Zhang *et al*. 2016). The Bolin coalmine headgate of a 0456(K24) working face was retained through this method, and the surrounding rock deformation decreased significantly compared to the method of constructing an artificial filling wall(Liu *et al*. 2014). A coalmine with a coal seam of 1.6 m and a hard immediate roof of 3.78 m in thickness was chosen to study the engineering application of the cutting roof approach. The roof was still complete and flat, the gangue rib was integrally formed with the help of the gob-side support, and the entry was retained with high quality after mining (Zhang *et al*. 2019). For the Suncun coalmine with a 31120 working face and a 2415 working face, the coal seam had an average thickness of 3.0 m, the immediate roof was siltstone with an average thickness of 5.3 m, and the cutting roof for the retaining gateway achieved good field application results (Fan *et al*. 2019). For the Xiashanmao coalmine, the 8102 and 9101 working faces with a thickness of 12.9 m and an limestone immediate roof with a thickness of 3.78 m were successfully retained by roof cutting without a pillar (Sun *et al*. 2019). The Xinchao coalmine with a 90101 panel had a thick and hard roof retained by roof cutting, successfully ensuring the panel safe production (Zhang *et al.* 2018). The Jining No. 3 coalmine with a 5312 panel based on the geological conditions of hard roof carried out roof blasting and cutting, and verified the pressure-relief effect (Liu *et al*. 2019). It can be seen that the technology of the retaining gateway was usually applied in the gateways with hard or harder roof rock masses, or in coal seams that had a single geological condition (Sun *et al*. 2014, Zhang *et al*. 2016, Wang *et al*. 2016, Ta *et al*. 2019, Liu *et al.* 2018, Ma *et al.* 2018, Hu *et al.* 2019).

Although the technology for retaining gateways is frequently used in the field, the related experimental research in laboratories has not been carried out. This has resulted in many structures with inner roof rock mass being misunderstood. Thus, the aim of this study was to fully comprehend the roof stability mechanism of an advancing cutting roof for gob-side entry retaining, with consideration of equivalent material simulation experiments that have been widely used in the deformation and failure research of the strata and gateways of surrounding rock (Guo *et al.* 2016, Zhou *et al*. 2016, Alencar *et al*. 2019). Experimental methods were used to research a roof structure based on the geological conditions of flat seam and close distance coal seam group in the Baijiao coalmine, China. Therefore, Section 2 of the paper describes the mechanism of a cutting roof for retaining gateways. Section 3 of the paper describes the geological and mining information and the modeling procedures of the equivalent material model available for the case study. The obtained simulation results are covered in Section 4 of the paper. Sections 5 and 6 end the paper with discussion and conclusions.

2. Mechanism of the cutting roof for a retaining gateway

An advancing cutting roof for gob-side entry retaining involves several procedures. First, drilling and blasting is performed for the roof at a certain distance in the original rock stress zone ahead of the working face, and a cutting roof plane is formed whose direction is consistent with the working face advancing direction. A cutting roof line the distance of which to the high side wall was usually 50 mm is shown in Fig. 2 (Zhang *et al*. 2011). As the working face advances, the front abutment pressure and the periodic weighting will cut the roof along the cutting roof plane. The cut roof will form a caving roof wall behind the working face. This will eliminate the influence on the hanging roof

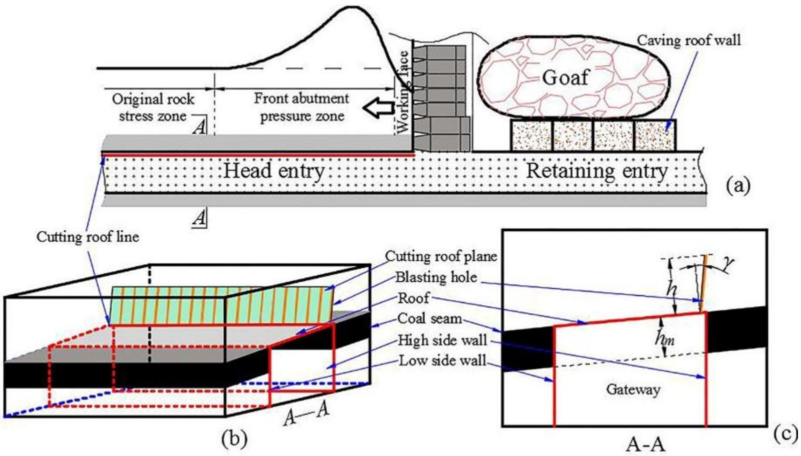

Fig. 2 Model of an advancing cut roof for gob-side entry retaining. (a) Plane graph, (b) parts of the model structure and (c) cross-section diagram

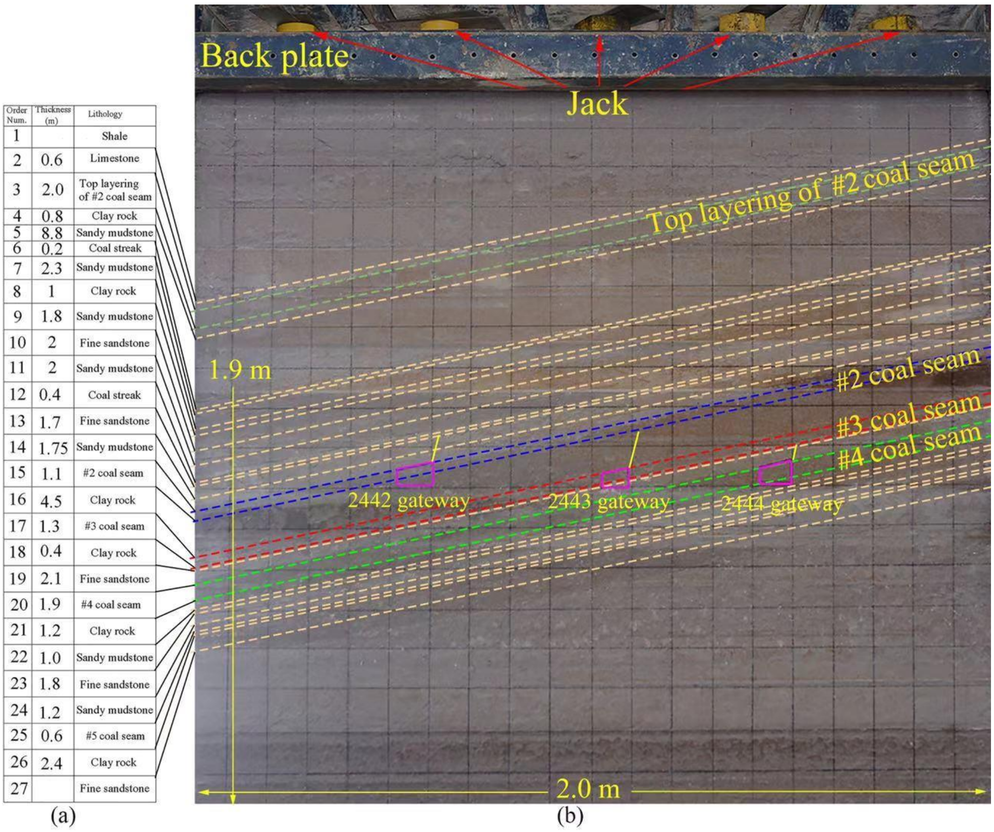

Fig. 3 Schematic of the coal-bearing strata. (a) Formation lithology and (b) equivalent material model

to the gateway surrounding rock, and the retained gateway roof will form a cantilever beam structure.

Simultaneously, the gob caving waste rock will support the overburdened strata, and control the main roof as well as the rotation and weighting deformation. By reducing the abutment pressure at the same time, this will also reduce the dynamic disaster possibilities of rock burst and coal and gas outburst in a coalmine, as well as other disaster possibilities. Furthermore, the support in the retained gateway will preserve the integrity of the roof rock mass and prevent roof separation (Zhang *et al.* 2011, Sun *et al*. 2014, Zhang *et al.* 2016, Yang *et al*. 2017).

Furthermore, in a cutting roof design, the two parameters of cut height (h) and cut line deviation angle (γ) (Fig. 2(c)) play an important role in the roof behavior and the effect of the retained gateway (Sun *et al*. 2014).

3. Equivalent material simulation experiment

In order to gain an in-depth understanding of advancing cutting roof for gob-side entry retaining, including the stabilizing mechanism and caving structure, we carried out a plane stress experiment on an equivalent material model based on the geological conditions of a flat seam and a close distance coal seam group in the Baijiao coalmine,

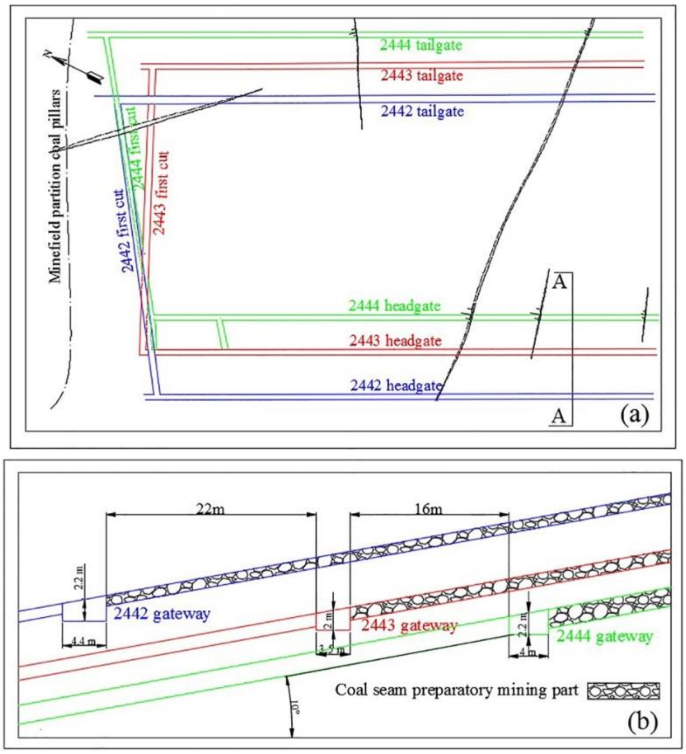

Fig. 4 The gateway layout. (a) Plan view of part of the gateways of the #24 mining district and (b) section view of the study gateways of A–A

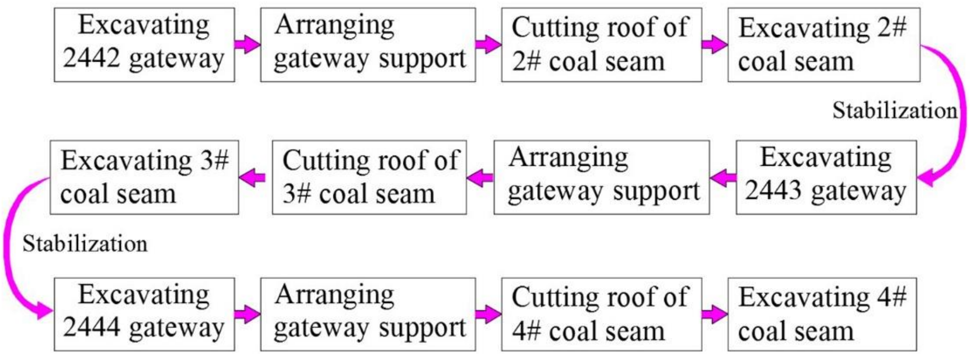

Fig. 5 Excavating sequence

Sichuan Province, China.

3.1 Geological conditions

Permian period strata is the coal-bearing strata of Baijiao coalmine, and the primary working coal seams are #4, #3, #2, and the top layering of the #2 coal seam, as shown in Fig. 3. After a detailed analysis and discussion with engineers, the #24 mining district was chosen as the geological background because the three gateways in that mining district had been retained though the cutting of the roofs. Therefore, we conducted a survey of the geological conditions and found that the average thicknesses of the four coal seams were 1.9 m, 1.3 m, 1.1, m and 2.0 m. The average distances between the adjacent coal seams were 2.5 m, 4.5 m, and 22.75 m from the bottom up, and the average coal seam dip angle was 10°. The coal seams belonging to the flat seam and the close distance coal seam group, as well as the lithology of the coal-bearing strata in the study area, are shown in Fig. 3(a).

Among the four coal seams, #2, #3, and #4 were identified as the coal and gas outburst coal seams. The top layering of the #2 coal seam was treated as the protective coal seam and it was mined in the mining district to produce an unloading pressure effect below the three coal seams. Eventually, the #2, #3, and #4 coal seams were chosen as the experimental coal seam of the equivalent materials simulation. The 2442 headgate, 2443 headgate, and 2444 headgate in each coal seam were the preparatory test gateways for cutting the roof and retaining, as seen in Fig. 3(b). The relationship between the below three coal seams, the gateways, and their sizes in the field is shown in Fig. 4.

3.2 Equivalent material model

When choosing an appropriate geometric similarity ratio

(C_L) before the experiment, the size of the test rig, the size of the excavation gateways, the thicknesses of the coal seam and stratum, and the end effect of the model all had to be considered. Firstly, the equivalent material model test was carried out using a rotating test rig with a size of 2 × 2 × 0.3 m. Secondly, the test involved the mining of three coal seams and the excavation and support of three gateways. Parts of the thicknesses of the coal seams and the stratum were small. The selection of the geometric similarity ratio had to facilitate laying the materials and excavating the gateway and the coal seams. In addition, the test had a large mining area of the model. The geometric similarity ratio had to be chosen to try to reduce the end effect of the model (Luo *et al*. 2013). Considering the above factors, the geometric similarity ratio was determined as $C_L = L_M/L_H = 1/50$, where L_M is the size of the model and L_H is the size of the field. Furthermore, the bulk density similarity ratio was $C_\gamma = 0.667$ (Luo *et al*. 2013) and the strength similarity ratio was $C_\sigma = C_L\ C_\gamma = 0.01334$.

The equivalent material employed fine river sand as an aggregate. Calcium carbonate and gypsum were used as the cementing material, and the size of the laying material was 2 × 1.9 × 0.3 m within the test rig, as shown in Fig. 3(b).

3.3 Load and excavation of the model

The 2442 headgate had a cover depth of 518 m up to the ground level, and the equivalent material model could only provide the overburden thickness of 58 m. Thus, the rest of the gravity of the strata needed load compensatory pressure, and this pressure could be calculated as 0.155 MPa. Finally, five hydraulic jacks were employed for loading, and a steel plate was laid between the jacks and the model's surface to produce uniform pressure. The arrangement of jacks was shown in Fig. 3(b). For safety reasons, the back plate was decorated on both sides of the jacks, which did not have contact with the model material. It mainly prevented the jacks and accessories from falling and injuring people during the loading process after rock failure.

In addition, it must be emphasized that the average spacing of 22.75 m between the upward two coal seams was very large, and the mining of the protective coal seam of the top layering of the #2 coal seam did not badly damage the #2 coal seam and its adjacent stratum. Therefore, the experiment did not excavate the top layering of the #2 coal seam.

In the field, the roof of the 2442 headgate was reinforced by a bolt and cable, and the roofs of the 2443 and 2444 headgates were reinforced by a shed made with I-steel because of the thin roof rock mass. To easily simulate the support and enable convenient operation, when the three gateways were excavated, a wood support was set to support the roof. Then a steel saw was used to cut the roof. The cut line deviation angle was $\gamma = 10°$, the cut height (h) for the 2442 gateway was 69 mm, which was the thickness of the two roof layers, and the cut heights (h) for the 2443 and 2444 gateways were the thicknesses of their roof layers.

The detailed excavating sequence during the test is shown in Fig. 5. This sequence was consistent with the field excavating sequence.

4. Result of the experiment

4.1 The formation process of the roof caving structure

After cutting the roof, the roof above the gob caved in and the gateway of the surrounding rock had a stable state. The overall state of the caving roof and stratum is shown in Fig. 6. The caving process and the cracks in the roof were recorded, as shown in Fig. 7.

The following can be observed from Fig. 7:

(1) The coal side roof of the three gateways experienced no crack stages or longitudinal crack growth stages. After careful observation, it can be found that the cracks in the roofs of the 2443 and 2444 gateway eventually came through the roof, leading to the roof fracturing and sinking on the gob side under overburden pressure.

(2) The cutting roof of the 2442 gateway had two layers and the gob side roof experienced partial caving. The entire caving process (hereinafter referred to as contact) can be seen in Fig. 7(a). Moreover, the cutting roof of the 2443 gateway was single and thicker. The entire roof above the gob caved in, and it had a no contact and a contact process, as seen in Fig. 7(b). Furthermore, the entire cutting roof of the 2444 gateway above gob caved in but had no contact, as seen in Fig. 7 (c). A further analysis of the results showed that the cut heights (h) of the 2442 and 2443 gateways were 3.1 times and 4.3 times the mining height (h_m). The cut height (h) was greater than the mining height (h_m), which led to a stability contact phenomenon for the caving roof. For the 2444 gateway, the cut height (h) was 1.3 times that of mining height (h_m), but the difference was not big. More seriously, the upper layer roof (the immediate floor of the #3 coal seam) was a thin layer of clay rock that experienced serious damage when the #3 coal seam was excavated, leading to the caving roof having no contact.

(3) The no caving roof of the gateway had three support points, including the contact with the caving roof, the support in the gateway, and the coal side. They formed a self-stabilization equilibrium structure and bore the overlying rock mass pressure collectively.

Therefore, according to the analysis of the caving structure of the three gateways, it can be thought that when the roof cut height (h) was greater than the mining height (h_m) and the roof rock caved in without damage, the gateway roof formed a stable contact effect. The roof caving process could be simplified as shown in Fig. 8.

The gob side roof first caved in in the gravity direction when the roof achieved caving pace, but there was no contact. Then the roof on the other side of the caving roof (key block I) also experienced fracturing and caving, as shown in Fig. 8(a). As the excavation advanced and the stress was adjusted, the gateway roof fractured and a vertical fracture line appeared above the shallow coal side and formed key block II. This rotated the point to the gob side along the lower endpoint of the fracture line and had a line contact with key block I, as shown in Fig. 8(b). With the increase of the roof deformation and extrusion pressure, the contact area also increased and formed a further stable surface contact structure: the "load-bearing structure" equilibrium model, as shown in Fig. 8(c). In addition, it can be found from the equivalent material simulation

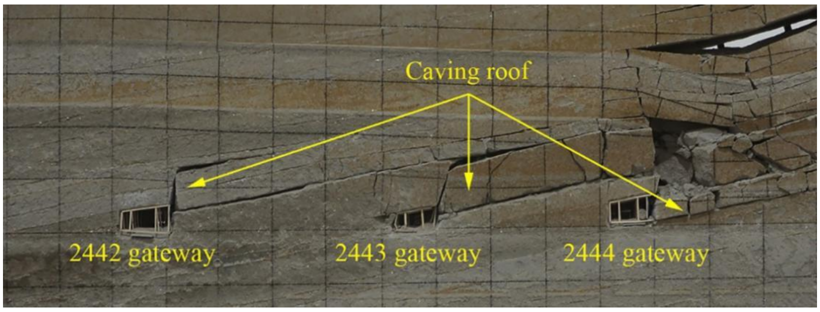

Fig. 6 The overall state after excavation

Fig. 7 Evolution process of the cracks and the caving model of the roof. (a) 2442 gateway, (b) 2443 gateway and (c) 2444 gateway

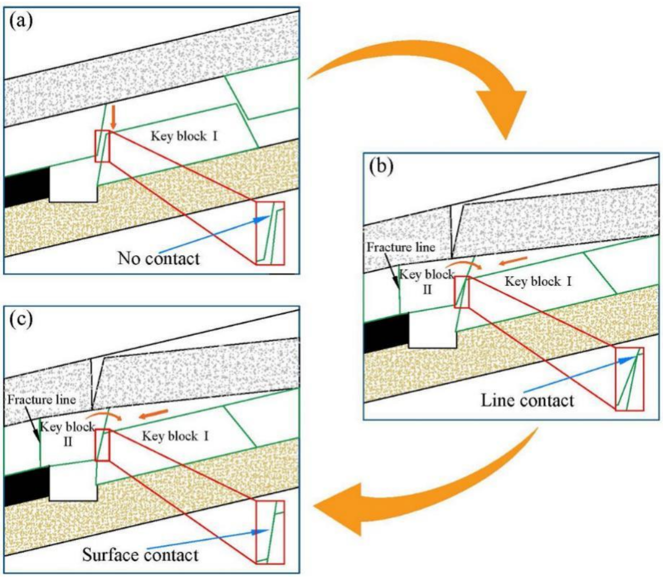

Fig. 8 Caving structure model of the gateway roof that was cut. (a) Key block I fracture and caving, (b) line contact of block I and key block II and (c) surface contact structure of block I and key block II

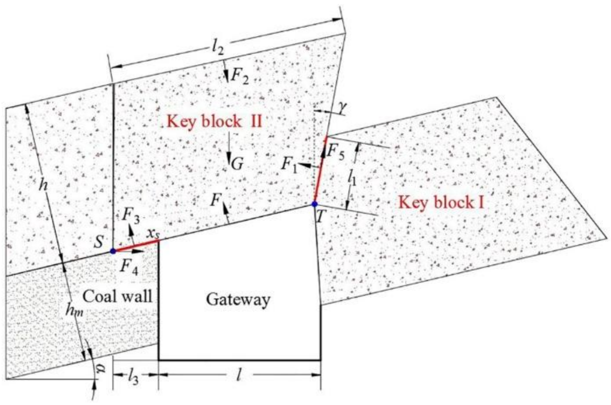

Fig. 9 The force analysis of key block II piece

experiment that the coal and rock mass had serious deformation and failure, but key block II still had contact with the fracture roof above the coal side and produced a mechanical effect.

4.2 The Mechanical structure model of the caving roof

4.2.1 The analysis of the balance control force of the model

The stability of the key block II controlled the equilibrium state of the "self-stabilization bearing structure". In order to carry out the force analysis of key block II, the following assumptions and regulations were used (Qian *et al*. 2012):

(1) It was assumed that key block II was a rigid body that would not deform when forced.

(2) The rotary angle of the key block II point to the gob was very small. Thus, it was assumed that key block II did not rotate after fracturing to simplify the calculation. In addition, the lower endpoint of the fracture line of key block II presented a mechanical effect, and it was assumed that it was subjected to a horizontal force.

(3) It was assumed that there was a surface contact between key block I and key block II, and that a mechanical effect was produced on the contact surface.

(4) It was assumed that the coal wall provided a supporting force to the roof, and that the force was equal everywhere on the acting surface.

According to the above assumptions, the force analysis of key block II was carried out, as shown in Fig. 9.

To gain an in-depth understanding to the above model, the mechanical equilibrium equations: ΣF_h for the horizontal direction, ΣF_v for the vertical direction, the moment ΣM_s for point S and the moment ΣM_t for point T, were established, as shown in Eq. (1):

$$\begin{cases} \sum F_h = 0: \quad F\sin\alpha + F_1\cos\gamma + F_3\sin\alpha - F_2\sin\alpha - F_4 - F_5\sin\gamma = 0 \\ \sum F_v = 0: \quad F\cos\alpha + F_1\sin\gamma + F_3\cos\alpha - F_2\cos\alpha + F_5\cos\gamma - G = 0 \\ \sum M_S = 0: \quad G\sqrt{\frac{l_2}{2}\cdot\frac{x_s+l}{2}}\cos\alpha + F_2(\frac{l_2}{2} + h\tan\alpha) - F_1\left[\frac{l_1}{2} + \frac{(l+l_3)}{\cos\alpha}\sin(\alpha+\gamma)\right] \\ \qquad - F(\frac{l}{2\cos\alpha} + x_s) - F_3\frac{x_s}{2} - F_5\frac{(l+l_3)}{\cos\alpha}\cos(\alpha+\gamma) = 0 \\ \sum M_T = 0: \quad -G(x_s + l - \sqrt{\frac{l_2}{2}\cdot\frac{x_s+l}{2}})\cos\alpha - F_2(x_s + l - \frac{l_2}{2} - h\tan\alpha) - F_1\frac{l_1}{2} \\ \qquad + F\frac{l}{2\cos\alpha} + F_3(\frac{x_s}{2} + \frac{l}{\cos\alpha}) - F_4(l+l_3)\tan\alpha = 0 \end{cases} \tag{1}$$

where F is the roof support force, F_1 is the normal force on the contact surface of the two key blocks, F_5 is the friction on the contact surface of the two key blocks, F_2 is the force from the gateway roof, F_3 is the coal wall support force, F_4 is the horizontal force of the roof acting on key block II, G is the gravity of key block II, l_1 is the contact distance of the two key blocks, α is the coal seam dip angle, x_s is the distance from the roof break point to the coal wall, l_3 is the horizontal distance from the roof break point to the coal wall, and l is the gateway width.

Some variables (in Eq. (1)) are defined as follows

$$l_3 = x_s\cos\alpha \tag{2}$$

$$l_1 = \frac{h - h_m}{\cos(\gamma+\alpha)} \tag{3}$$

$$G = \frac{1}{2}(l_2 + \frac{l+l_3}{\cos\alpha})h\lambda \tag{4}$$

$$F_5 = F_1 w_1 \tag{5}$$

where λ is the bulk density of the gateway roof and w_1 is the friction coefficient of the contact surface of the two key blocks.

Furthermore, the force of F_2 was calculated using Terzaghi's principle(Qian *et al*. 2012), as shown in Eq. (6).

$$F_2 = \frac{\lambda_1 l_2^2}{2A_x\tan\varphi}\cos\alpha \tag{6}$$

where λ_1 is the average bulk density of the loading layer, φ is the average internal friction angle of the loading layer, and A_x is the lateral pressure coefficient.

$$A_x = 1 - \sin\varphi \tag{7}$$

In addition, l_2 is the upper surface length of key block II, as shown in Eq. (8).

$$l_2 = h\tan(\alpha+\gamma) - h\tan\alpha + (l+l_3)/\cos\alpha \tag{8}$$

4.2.2 Solving the mechanical structure model

Through the above analysis, it can be found that the roof

Table 1 Values of the calculation parameters

Parameter	Value	Parameter	Value	Parameter	Value
α	10°	λ	25.9 ×10³ N/m³	x_s	0.9
h	3.9 m	λ_1	18 ×10³ N/m³	w_1	0.5
h_m	1.1 m	γ	10°		
φ	40°	l	4.4		

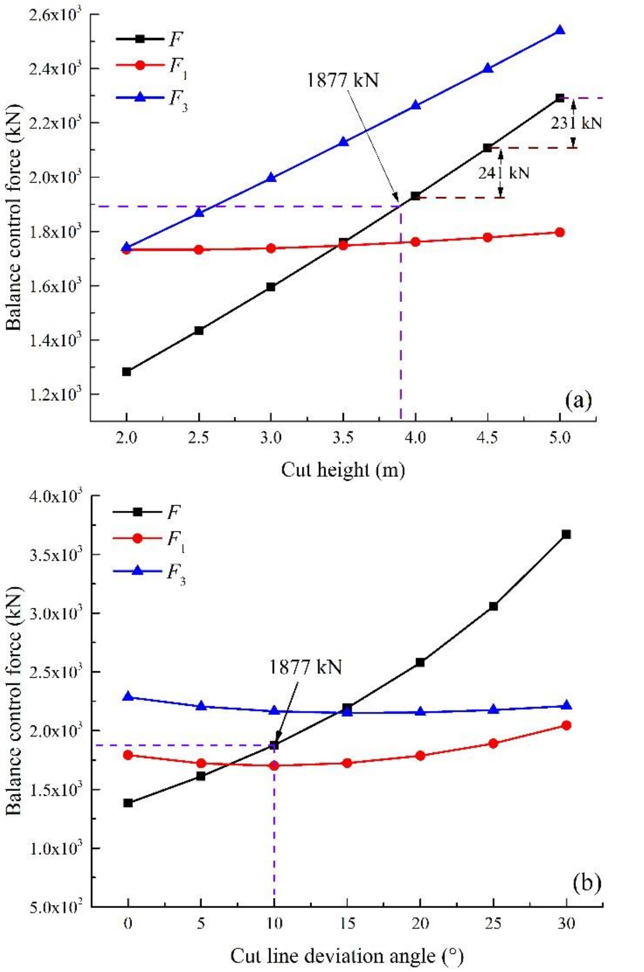

Fig. 10 Calculation results. (a) Balance control force with cut height and (b) Balance control force with cut line deviation angle

support force of F, the normal force on the contact surface of F_1, and the coal wall support force of F_3 played an important role in controlling key block II. Therefore, the relationship between the three balance control forces, the cut height (h), and the cut line deviation angle (γ) was calculated. Firstly, it must be emphasized that the geological conditions and parameters (Listed in Table 1) of the 2442 gateway were chosen as the calculation example, and the following two steps were executed: (1) The cut line deviation angle of γ = 10° was kept constant and the cut height (h) increased from 2 m to 5 m in steps of 0.5 m. The final results are shown in Fig. 10(a). (2) The cut height of h = 3.9 m was kept constant and the cut line deviation angle (γ) increased from 0° to 30° in steps of 5°. The final results are shown in Fig. 10(b).

Fig. 10 shows the following results:

(1) Fig. 10(a) shows that with the increase of the cut height, the roof support force F and the coal wall support force F_3 increased approximately linearly. In contrast, the support force F_1 on the contact surface first decreased and then increased. Moreover, it can be found that the rangeabilities of F and F_3 were significantly higher than that of F_1 was, indicating that the cut height had a greater influence on F and F_3 than that of F_1.

(2) Fig. 10(b) shows that with the increase of the cut line deviation angle, the roof support force F increased approximately linearly. In contrast, the support force F_1 on the contact surface coal wall and the support force F_3 first decreased and then increased. Moreover, it can be found that the rangeability of F was significantly higher than those of F_1 and F_3 were.

Previous studies (Zhang *et al*. 2019, 2011, Song and Konietzky 2019, Song *et al*. 2018) have shown that a low support force is usually selected to control the surrounding rock of a gateway and to further determine the parameters of the cut height and the cut line deviation angle based on the selected support force. As shown in the above analysis, the support forces F, F_3, and F_1 were the most important forces for controlling the gateway roof. Hence, their relationship should be further studied.

It can be seen that when the values of the cut height and the cut line deviation angle were the smallest. Additionally, the support force F was the smallest (Fig. 10), meaning that a worker could provide a low support force F to control the roof. However, the support forces F_3 and F_1 were greater than the support force F at that moment. Moreover, it was realized there was the serious issue of the coal wall and the contact surface of the two key blocks undergoing some deformation, and the coal wall and the key blocks had the hidden dangers of failure and loss of stability when the support forces F_3 and F_1 were larger. In addition, it can also be found that even if the coal wall had no deformation, the roof of key block II was a deformable body whose parts in the coal wall with a width of l_3 and above the roof with a width of l had a different degree of deformation when the values of the support forces of F and F_3 had a big gap. This led to more damage to the roof. Therefore, the smallest values of the cut height and the cut line deviation angle were determined based on the smallest support force F that was unfavorable to the surrounding rock control.

Since the smallest values of the cut height and cut line deviation angle posed a safety hazard, increasing their value was imperative. Further analysis found that with the increase of the value of the cut height, the support force F increased, but the support force F_3 had a substantial increase (Fig. 10(a)), which was more unfavorable to the coal wall stability. In addition, when increasing the cut line deviation angle, the support force F had a sharp increase. The support forces F_1 and F_3 varied weakly but still maintained the high value of a 2 × 10^3 kN magnitude compared to the values in Fig. 10(a), which were also bad for the surrounding rock control. However, according to the values in Fig. 10(b), when cut line deviation angle increased to a certain value, the support forces of F, F_1, and F_3 were close to each other. This could satisfy the coordinate deformation of the different parts of the roof rock mass as far as possible.

Therefore, according to the above analysis, the selection of the values of the cut height and the cut line deviation angle had conform to a certain principle that it should not only utilize the support force provided by the coal wall and the contact surface of the two key blocks, but also prevent the failure of the coal wall and the contact surface. Thus, in choosing the values of the cut height and the cut line deviation angle for advancing the cutting roof for gob-side entry retaining, the following steps had to be adhered to:

(1) In general, to facilitate the construction technology control, the values of the cut height were integral multiples of 0.5 m, and the cut line deviation angles were integral multiple of 5° when the roof was thick.

(2) In practice, the selection of cut height was influenced by the roof layered properties and the spacing between the coal seams. For example, the roof of the 2442 gateway had more layers and the thickness of each layer was thinner, so the cut height had to be larger than the mining height and it was necessary to try to cut several layers together at the same time. In addition, the roofs of the 2443 and 2444 gateway were located below the gob, and they were cut one time. However, the cut line deviation angle was almost controlled by a human. Therefore, the cut height had to be determined first.

(3) The cut line deviation angle was selected according to the above model, and the values of the support forces of F, F_1, and F_3 were made very level to coordinating support for key block II.

(4) After determining the two parameters, the coal wall had to be reinforced to increase its ability to resist deformation in the field.

According to the above principles, the roof cut height of 3.9 m for the 2442 gateway was more appropriate. Moreover, the model in Fig. 10(b) shows that the cut line deviation angles of 10° or 15° could be selected, but the latter was the best.

5. Discussion

An equivalent material simulation experiment was conducted in order to explain other phenomena in the process of the cutting roof for gob-side entry retaining, especially because it was a surprise to discover this "self-stabilization bearing structure" equilibrium model. In addition, the purpose of this study is to expound the discovery process of the model and its mechanical structure. Thus, many parameters of the equivalent material model, such as the mixed ratio of the materials and strength of materials, were not listed in the study. However, they can be found in references (Tang 2004, Li 2006, Yang 2013). However, it can be noted that the value of x_s was 0.8 m, which was calculated according to the geometric similarity ratio of the 1/50 reference of the experimental data in Fig. 7(a). There is no definite answer at present for whether the parameter of x_s was high precision. In addition, the geological condition and excavation impact extent of each gateway were varied, like the above three gateways. Therefore, determining how to acquire the theoretical value of x_s still needs further study.

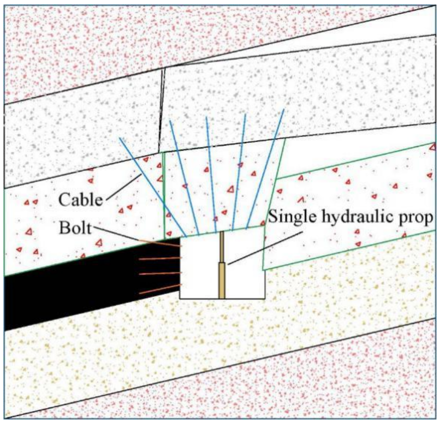

Fig. 11 Support diagram of a gateway with a cable, bolts, and a single hydraulic prop

Moreover, it can be found that the proposed "self-stabilization bearing structure" equilibrium model is equivalent to the hypothesis of a stope "articulated beam" proposed by H. Kuznetsov of the former Soviet Union using an equivalent material model experiment (Qian *et al*. 2012). Furthermore, because the model could take into account the many factors, such as faults and precise physical parameters, present in the actual strata, the analysis results may be considered as some kind of indication for mining engineering practice. However, in reality, this model took full advantage of the strength of the caved in hard roof rock mass to support itself, and could improve the stability of the roof. After the above theoretical analyses, it can be found that if gateway had a better industrial design for advancing cutting roof for gob-side entry retaining, and there were appropriate cables in the roof, bolts in the coal wall, and a single hydraulic prop in gateway, as seen in Fig. 11 (Kang *et al*. 2018, Chen *et al*. 2019, Yang *et al*. 2017, Wang *et al.* 2018, Aksoy *et al*. 2019, Oh *et al.* 2019), the roof stability would be significantly improved, and the coalmine would be more conducive to safe and efficient production with a hard roof stratum.

6. Conclusions

An advancing cutting roof for gob-side entry retaining has many advantages compared with the traditional method of constructing an artificial filling wall, and it will be used in more and more gateways in coalmines. To obtain more in-depth information about this technology, an equivalent material model experiment with a plane stress state was carried out based on the complex geological conditions of a flat seam and a close distance coal seam group for a Baijiao coalmine. Based on the three experimental gateways, it could be found that the cut line deviation angle and the cut height were two important parameters. When the cut line deviation angle was unequal to zero, the cut height was greater than the mining height, and the caving roof rock was hard without damage, a "self-stabilization bearing structure" equilibrium model was ultimately formed, which was conducive to the stability of the gateway roof. The model showed that its stability was mainly controlled by two fractured and caved roof blocks, key blocks I and II. Furthermore, in order to determine the optimal parameters of the cut height and the cut line deviation angle for the cutting roof of a retaining gateway, mechanical analysis of the model was performed assuming that the key blocks were made of rigid material. Additionally, the relationship between the roof balance control force, the cut height, and the cut line deviation angle was solved. After an in-depth analysis of the result calculated by the mechanical model, it was found that the selection of the values of the cut height and the cut line deviation angle had to conform to a certain principle that it should not only utilize the support force provided by the coal wall and the contact surface of the two key blocks but also prevent the failure of the coal wall and the contact surface. Finally, it is predicted that using this structure with a perfect industrial design will be more conducive to safe and efficient production for a coalmine with a hard roof stratum.

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