



Mechanical Model and Control Technology of Roadside Gangues in Gob-Side Entry Retaining by Roof Cutting

Zhen Zhu · Manchao He · Xuchun Wang · Hongping Yuan

Received: 3 May 2019 / Accepted: 23 September 2019 / Published online: 28 September 2019
© Springer Nature Switzerland AG 2019

Abstract Gob-side entry retaining by roof cutting (GERRC) is a new technique regarding a non-pillar mining method based on the “cutting cantilever beam theory” proposed in recent years. In this technology, the composition, formation mechanism, load transfer mode and stability mechanism of roadways are quite different from those of traditional coal mining methods. Based on the technical principle of the GERRC, the formation mechanism of the sidewall composed by collapsed gangues is clarified. Also, on basis of the observation of engineering site, the movement characteristics of the gangues in goaf are analyzed, and the movement processes are mainly divided into two stages, i.e. the rapid collapse stage and the slow compaction stage. Then, the interaction between the gangues and retaining structures in different

movement stages is revealed. Meanwhile, a mechanical model of the roadside gangues was established, and the mechanical characteristics of the retaining structures were analyzed. Besides, a control concept, considering both dynamic and static pressure in the lateral direction and making it extensible to release pressure in the axial direction, was put forward to support the gangues in goaf based on the interaction characteristics of the gangues and the retaining structures. At last, three different retaining structures for the gangues were proposed in view of different mining heights, and the roadside gangues control system was established, which has been proved to be of good practicality in the engineering site. The research results can provide technical guidances for the control of roadside gangues in the GERRC and accelerate the process of popularization and application of the GERRC, which is of positive significance.

Z. Zhu (✉) · M. He
State Key Laboratory for GeoMechanics and Deep
Underground Engineering, China University of Mining
and Technology, Beijing 100083, China
e-mail: zhuzhen88@foxmail.com

M. He
e-mail: hemanchao@263.net

X. Wang
School of Civil Engineering, Qingdao University of
Technology, Qingdao 266033, China
e-mail: xcwang2008@foxmail.com

H. Yuan
Shaanxi Ruineng Coal Co., Ltd, Yanan 727307, China
e-mail: yuanhongping66@163.com

Keywords Roof cutting and pressure relief · Gob-side entry retaining · Non-pillar mining technology · Roadside gangues · Mechanical model · Control technology

1 Introduction

Coal is one of the most precious non-renewable energy resources, which has made tremendous contributions

to human scientific and technological development and economic construction. Long wall mining method with comprehensive mechanization is widely used in underground coal mining because of its advantages of excellent adaptability, good safety and high production efficiency (Brady and Brown 1992). For the traditional longwall mining method, it is necessary to excavate mining entries including headentry and tailentry in advance at both ends of the working face, and to retain at least one section coal pillar between adjacent coal panels to protect the entry that serves the next panel. The layout of the coal panels and entries of this mining method can be shown in Fig. 1a. Compared with the room-pillar mining method and the strip mining method, this comprehensive mechanized longwall mining method obviously has many advantages. However, with the gradual understanding of the concept of scientific mining, its shortcomings are also particularly obvious. The most unacceptable defect is the serious waste of resources because of the indispensable section coal pillars left between adjacent coal panels, while it is our responsibility and obligation to try our best to save the earth's resources. Besides, many mining roadways or mining entries need to be excavated in advance, which leads to a large amount of excavation works and high excavation costs.

In the 1950s, a non-pillar mining technology, the gob-side entry retaining by filling (GERF, as shown in Fig. 1b), was introduced into China, which is of great significance in reducing the roadway excavation and increasing the coal recovery rate. In recent years, many scholars have carried out lots of researches on

this mining method, and have achieved fruitful research results, which promoted the development of the gob-side entry retaining technology (Zhang et al. 2015, 2018; Wang et al. 2014, 2015; Li et al. 2018). While this technology is realized by the high strength artificial filling bodies beside the gob-side entry, it can achieve good application results in eliminating section coal pillars. However, the complicated filling system, high labour intensity and low efficiency of the filling body have gravely restricted the popularization and application of these techniques (Luan et al. 2018).

In order to solve the above problems, a new non-pillar mining technology, the gob-side entry retaining by roof cutting (GERRC, as shown in Fig. 1c) based on the “cutting cantilever beam theory” was proposed by professor Manchao He in 2009. (He et al. 2015, 2017, 2018). Through presplitting the roof in front of the working face and using the mine pressure to motivate the collapse of the roof in goaf, the sidewall of the entry is automatically formed after the roof collapses in the goaf. At the same time, making full use of the dilatancy characteristics of the rock mass makes the coal gangue quickly form a cushion support for the overlying rocks. As the presplitting weakens the mechanical constraints of the roof between the roadway and the goaf, the stress environment of the surrounding rocks is improved (Sun et al. 2014). In recent years, lots of researches on the key parameters of the roof cutting, the caving effect of gangues in goaf, the deformation laws and stability control of roadway surrounding rocks, and the spontaneous combustion characteristics in goaf were

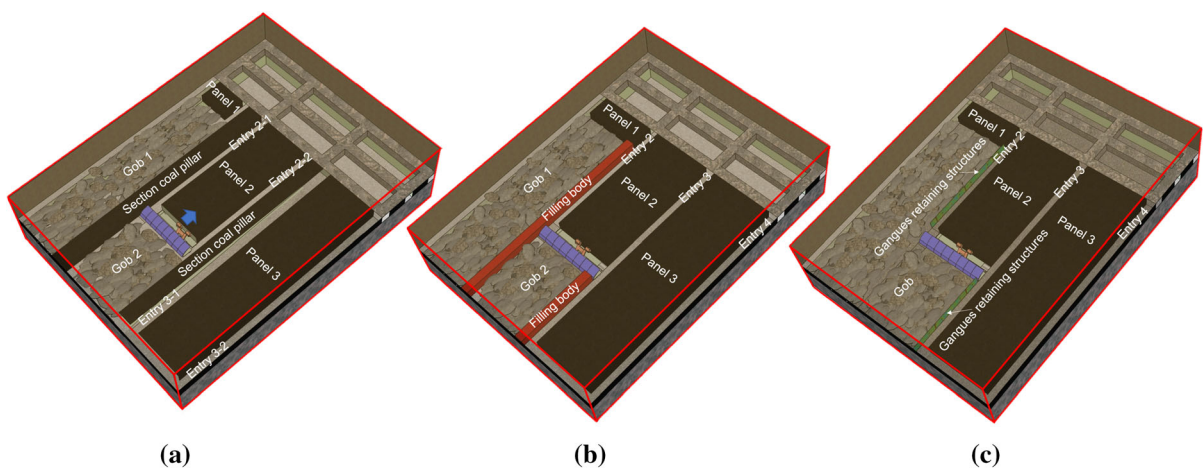


Fig. 1 Schematic diagrams of the three mining technologies. **a** Traditional longwall mining method, **b** gob-side entry retaining by filling and **c** gob-side entry retaining by roof cutting

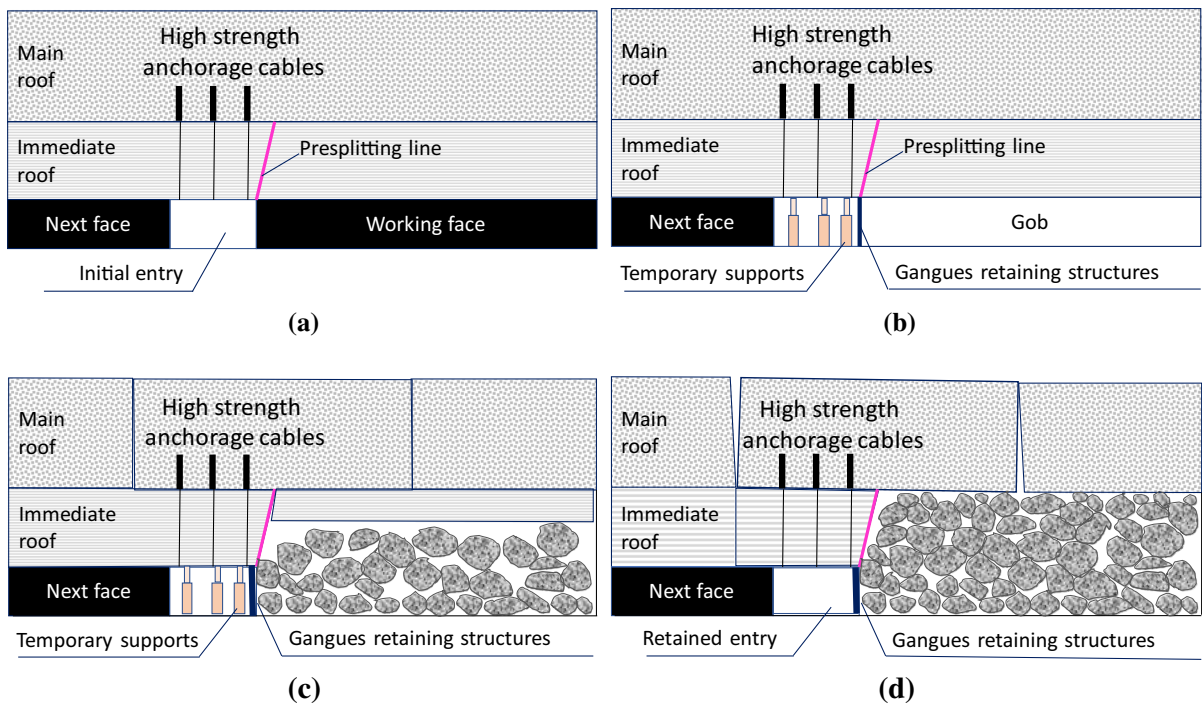


Fig. 2 Formation of the gangue sidewall. **a** Supporting and blasting the roof, **b** supporting the roof and preventing the gangues, **c** roof collapse and **d** forming the gob-side entry

carried out, which are of great significance for the promotion and application of this non-pillar mining technology (Guo et al. 2016, 2017; Gao et al. 2017, 2018; He et al. 2019; Chen et al. 2019).

The sidewall that composed the gob-side mining entry in the GERRC is significantly different from that of other mining methods. However, through the analysis of all the current literatures about the GERRC, it can be found that few articles have made special researches on the roadside gangues and its control technology, which is a very important defect for the popularization and application of the GERRC. Hence, in this paper, the mechanical model of the roadside gangues is specially analyzed, and a control system with several retaining structures are put forward for the stability control of roadside gangues.

2 Formation and Movement Characteristics

2.1 Formation of the Gangue Sidewall

The generation process of the gangue sidewall can be shown in Fig. 2. Firstly, the roof of the entry should be

supported by the high strength anchorage cables and then blasted through the directional presplitting technology in designed location. What needs special attention is that the two tasks should be completed sequentially before the coal is mined. Secondly, when the coal is mined by the shearer, the temporary supports for the roof and the gangues retaining structures in the gob should be set in time. The gangues supported by the retaining structures will form the gangue sidewall for the new entry. The mechanical constraints of the roof between the entry and the gob will be weakened to a great extent because of the directional presplitting. As a result, the rock strata in the gob will collapse in time and fill the mined-out area when the mining face is pushed over. Within a certain distance behind the mining face, the gangues are pressed to dense and form supports for overlying strata. At this moment, the surrounding rocks tend to be stable, and finally a new roadway is formed.

2.2 Movement Characteristics of the Gangues

As the physical connection between the roadway and the gob is cut off by the roof pre-splitting, the restraint

of the rock strata will be significantly weakened. When the hydraulic support is pulled forward, the roof of the gob will lose its support and collapse quickly into the goaf. According to the existing research results and the on-site observation of the gangues caving process, the movement process of the gangues in the goaf can be divided into two stages, namely, the rapid collapse stage and the slow compaction stage (Gao et al. 2017; Zhu et al. 2019). The movement characteristics of the gangues in different stages are described as follows.

2.2.1 Rapid Collapse Stage

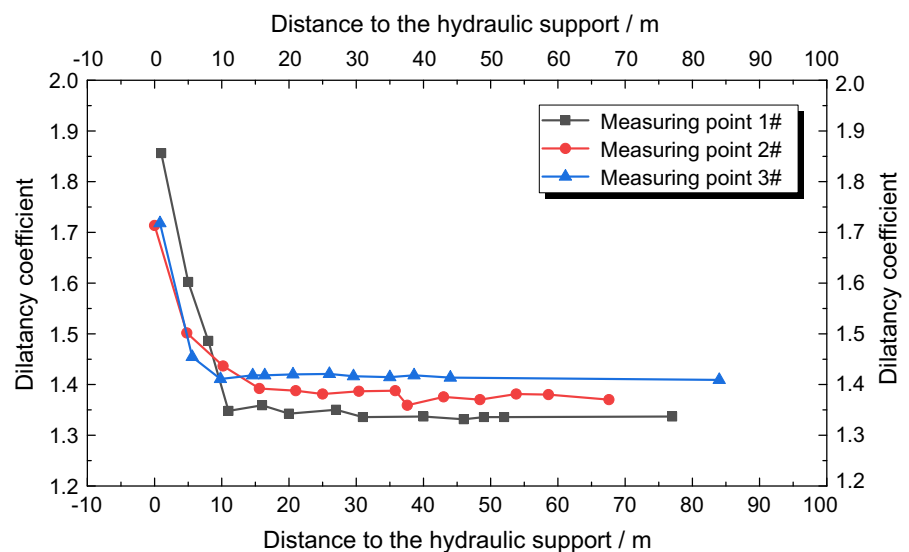
When the hydraulic support is pulled forward, the roof in the goaf breaks and collapses rapidly. At this stage, the movement of roof strata is very intense, and often accompanied by violent sounds that caused by rock fracture and gangues collision. The roof collapse process produces impact a small dynamic load on the gangues retaining structures, but when the mining height is very large, the impact effect will be obvious. When the roof collapses completely, the goaf will be filled with gangues. At this time, the first movement stage is completed, and then it will enter the second movement stage, and the gangues will be gradually compacted.

2.2.2 Slow Compaction Stage

With the collapse process of roof strata, the main roof above the roadway will produce rotary subsidence deformation inclined to the goaf. After entering the second movement stage, the key block B of the main roof will touch the gangues in the goaf, and the loads above the roadway will gradually transfer from the coal seam and the vertical support structures to the goaf. At this time, the gangues are being compacted, which can be confirmed by the change of the dilatancy coefficient of the gangues. Figure 3 shows the dilatancy coefficient curve of gangues near the roadway measured in panel 117 of Ruineng coal mine.

From Fig. 3, it can be seen that the dilatancy coefficient is very large at the early stage of gangue collapse, and the maximum value is almost 1.8. With the action of overlying strata loads, the gangues are gradually compacted and finally stabilized at about 1.35, which shows the characteristics of slow compaction. According to a large number of studies, the residual dilatancy coefficient of the roof in goaf is generally about 1.1 after it collapses and is compacted. This indicates that the vertical stress in the goaf near the roadway is not very large. That is to say, near the roadway, there is a stress reduction area, which provides a good stress environment for the maintenance of the roadway along the goaf.

Fig. 3 Dilatancy coefficient of the gangue near the retained entry in Ruineng coal mine



3 Failure Mode of Gangues Retaining Structures

Unlike those coal roadways or rock roadways that composed of intact coal or rock mass, the medium that constitutes the roadways along the goaf in the GERRC is loose debris, and its physical and mechanical properties have its unique properties. Correspondingly, the supporting structures of the roadways also show different failure modes. Field practice shows that there are mainly two instability modes of the gangues retaining structures, which are described as follows.

3.1 Bending Instability

If the retaining structures do not have or only have weak longitudinal deformation capacity, it will be prone to bending instability under the opposite extrusion of roof and floor, or under the lateral extrusion of gangues, as shown in Fig. 4.

The reasons for this instability maybe:

- The lateral extrusion force caused by the gangues in goaf is too large, while the flexural capacity of the retaining structures is very limited, which results in flexural instability under the large lateral loads;
- The axial load caused by the opposite movement of the roof and the floor is too large, while the axial resistance of the preventing structures is very small, which leads to buckling instability under the axial load. In fact, the deformation of the gangues retaining structures caused by the opposite

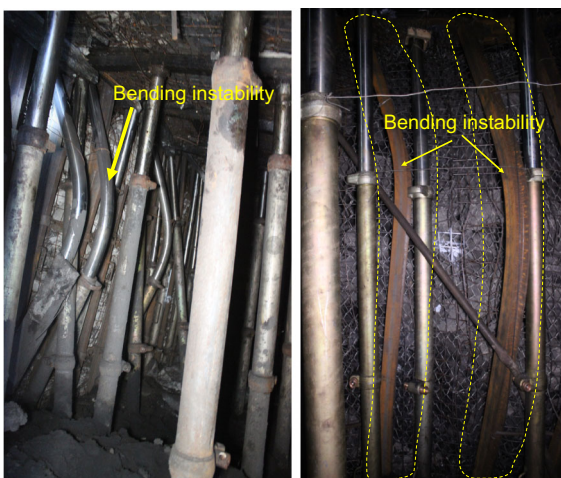


Fig. 4 Bending instability of the gangues retaining structures

movement of the roof and the floor can be considered as a given deformation. If the retaining structures can not produce corresponding axial deformation due to excessive axial stiffness, huge energy will accumulate inside the retaining structures, which will eventually lead to the failure of the supporting structures.

3.2 Slipping Instability

If the lateral restraint forces at both ends of the retaining structures are too small, it is easy to collapse or slip under the lateral extrusion force of gangues, as shown in Fig. 5. The main reason for this instability is that the friction forces between the retaining structures and the roof/floor of the roadway is too small to resist the transverse loads transmitted by the gangues in the goaf, which ultimately leads to the extrusion of the structures.

4 Mechanical Model

It is of great theoretical significance to study the mechanical characteristics of the gangues and the retaining structures for the rational selection of supporting forms and strength. Obviously, the denser the gangues are pressed, the greater the vertical stress will be. Correspondingly, the lateral extrusion force exerted by the gangues on the retaining structures will also be greater. Therefore, the gangues will need greater support resistance to maintain their balance.

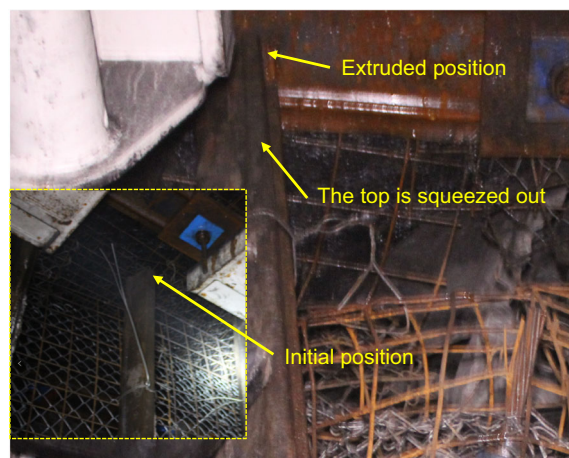


Fig. 5 Slipping instability of the gangues retaining structure

The upper and the lower surfaces of the collapsed gangues are respectively constrained by the compression of the overlying strata and the floor of the coal seam, while the left interface is constrained by the “cutting short cantilever beam” and the resistance of the gangues retaining structures. Assuming that a horizontal line is drawn from the roof surface, the gangues in the goaf can be divided into the upper part and the lower part. As the upper part has constraints around it, the lower part can be taken as the research object, and the upper part and the overlying strata can be applied as loads (they are q_0 and q respectively) on the lower part, as shown in Fig. 6.

Combining with the retaining wall theory, the gangues in the goaf can be regarded as ideal granules without cohesion. It is assumed that the stacked gangues have a potential sliding surface. When the supporting force applied on the surface of the gangue sidewall decreases gradually, the wedge-shaped body above the sliding surface will have a sliding trend. When the wedge-shaped body is in its ultimate equilibrium state, the force exerted by the supporting structure on the surface of the gangue sidewall is the minimum supporting resistance required by the gangues. Based on the structural model of the gangues shown in Fig. 6, the mechanical model of the wedge-shaped body and the retaining structures can be established as shown in Fig. 7. In order to simplify the derivation process, the overlying strata load q is assumed to be uniformly distributed. In fact, this hypothesis is not very different from the actual situation, so it can be considered reasonable.

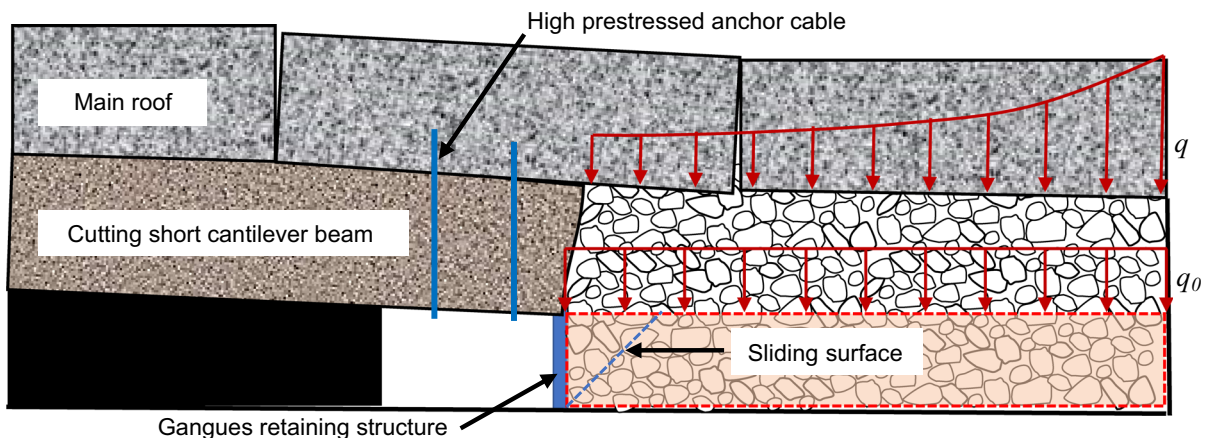


Fig. 6 Structural model of the gangues in the gob

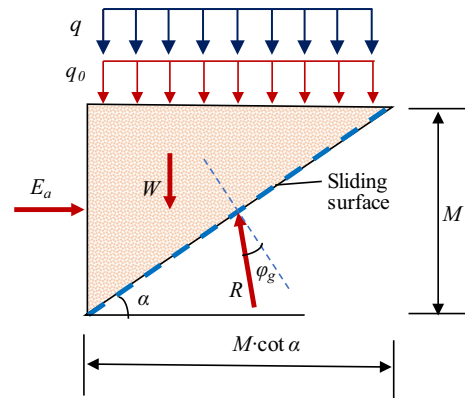


Fig. 7 Mechanical model

Where q_0 is the gravity load transferred from the upper part gangues to the lower part gangues (kN/m); q is the load transmitted from the overlying strata (kN/m); W is the gravity load of the wedge-shaped body (kN/m); E_a is the minimum support resistance needed to maintain the stability of the wedge-shaped body (kN); α is the angle between the imaginary sliding surface and the horizontal surface ($^\circ$); M represents the height of the roadway (m); R is the supporting force of the wedge-shaped body by the lower gangues (kN); and ϕ_g stands for the internal friction angle of gangues ($^\circ$).

In view of the above mechanical model, the following basic assumptions should be made:

1. As the angle between the cutting line and the plumb line is usually only 0° to 10° in the engineering practice, it is ignored;

2. Supposing that the retaining structures is rigid;
3. Supposing the retaining structure contacts with the gangue smoothly, that is, the friction between the gangue and the retaining structure in the vertical direction is neglected;
4. Assuming that the gangues in the goaf are ideal granulars without cohesion;
5. Assuming that the potential sliding surface is a plane and vias the bottom of the preventing structure;
6. Regarding the wedge-shaped body above the sliding surface as a rigid body;
7. Assuming that the load applied on the wedge-shaped body from the overlying strata is approximately linear.

Obviously, the gravity load W of the wedge-shaped body can be expressed by Formula (1):

$$W = \frac{1}{2} \gamma_g M^2 \cot \alpha \tag{1}$$

where γ_g represents the volume-weight of the gangues (kN/m^3).

The load q_0 transferred from the upper part gangues to the surface of the wedge can be regarded as a uniform load, which can be expressed in Formula (2).

$$q_0 = \gamma_g h_d \tag{2}$$

where h_d is the stacking height of the upper part gangues (m).

According to the limit equilibrium principle, Formulas (3) and (4) can be easily obtained:

$$E_a = R \sin(\alpha - \varphi_g) \tag{3}$$

$$W + q_0 M \cot \alpha + q M \cot \alpha = R \cos(\alpha - \varphi_g) \tag{4}$$

By combining the four formulas above, the E_a can be expressed as:

$$E_a = M \left(\frac{1}{2} \gamma_g M + q_0 + q \right) \cot \alpha \tan(\alpha - \varphi_g) \tag{5}$$

As the sliding surface is assumed arbitrarily and the inclination angle is unknown, the load of the retaining structures is a function of the inclination angle, that is $E_a = E_a(\alpha)$. When the inclination angle α changes, different E_a can be obtained, in which the maximum value of $E_a(\alpha)$ is the minimum support resistance required. In theory, the extreme value of $E_a(\alpha)$ and the

corresponding angle α can be obtained by differential analysis of $E_a(\alpha)$, which can be shown in Formula (6)

$$\frac{dE_a}{d\alpha} = M \left(\frac{1}{2} \gamma_g M + q_0 + q \right) \left[\frac{\cot \alpha}{\cos^2(\alpha - \varphi_g)} - \frac{\tan(\alpha - \varphi_g)}{\sin^2 \alpha} \right] \tag{6}$$

Let $\frac{dE_a}{d\alpha} = 0$, then Formula (6) can be obtained:

$$\sin 2\alpha = \sin(2\alpha - 2\varphi_g) \tag{7}$$

Obviously, $\varphi_g \neq 0$. Therefore, according to the properties of trigonometric functions, α can be obtained as Formula (8):

$$\alpha = 45 + \frac{\varphi_g}{2} \tag{8}$$

Further, the value of E_a can be obtained:

$$E_a = M \left(\frac{1}{2} \gamma_g M + \gamma_g h_d + q \right) \tan^2 \left(45 - \frac{\varphi_g}{2} \right) \tag{9}$$

When the gangues are in the first movement stage, the load applied on the wedge-shaped body by the overlying strata is 0, so the lateral pressure of the gangues can be expressed by Formula (10).

$$E_a = \gamma_g M \left(\frac{1}{2} M + h_d \right) \tan^2 \left(45 - \frac{\varphi_g}{2} \right) \tag{10}$$

According to some research results, the load q near the roadway is a little small, and some researchers have given several empirical values. By substituting the relevant engineering parameters into the above formula, the required supporting parameters can be obtained.

5 Supporting Technology

5.1 Interaction Between Gangues and Retaining Structures

From the above analysis of the movement characteristics of the gangues in the goaf, it can be seen that the lateral extrusion force of the gangues on retaining structures presents obvious space–time characteristics, which are mainly manifested in:

1. In the initial stage of gangue collapse, the movement of gangues has a certain dynamic impact on the retaining structures. The impact

force is generally positively correlated with the mining height. That is, the greater the mining height, the greater the potential energy before gangue collapse, and the greater the kinetic energy generated during the collapse, so the impact on the supporting structure is stronger.

2. At a certain distance behind the hydraulic support in the working face, the movement of the gangues enter into the slow compaction stage, and the gangues produce a similar static squeezing effect on the retaining structures.
3. Far away from the hydraulic support, when the gangues are compacted, the surrounding rock structure reaches equilibrium again. At this time, the lateral extrusion force of the gangue on the retaining structures is static extrusion force.

In the rapid collapse stage of gangue movement, the impact time of gangue on retaining structures is very short, so it is difficult to accurately measure the impact force. However, due to the pre-cracking of the roof, the gangues soon collapsed, so the scope of the movement stage is very small. When the mining height is less than 4 m, the range is generally less than 10 m. When the mining height is small, the impact load is also small. When the mining height is high, it can be protected by adding special anti-scour structure. After entering the slow compaction stage, the force can be accurately measured by arranging dynamometers between the gangues and the retaining structures.

5.2 Stability Control of Roadside Gangues

Based on the movement characteristics of the gangues in goaf and the interaction between the gangues and the retaining structures, the supporting structures of the gangues should not only have different lateral support performance in different movement stages, but also be able to adapt to the given deformation caused by the roof rotation and subsidence.

In view of the above characteristics, a control ideal, considering both dynamic and static pressure in the lateral direction and making it extensible to release pressure in the axial direction, was put forward to prevent the gangues in the gob. Then, three types of gangues retaining structures are proposed for different mining heights, they are “Scalable U-section steel + single pillar + metal mesh” structure (UPM

retaining structure), “Scalable U-section steel + single pillar + strike plate + metal mesh” structure (UPPM retaining structure) and “Scalable U-section steel + miniature hydraulic support + strike plate + metal mesh” (USPM retaining structure). These different retaining structures are shown in Fig. 8.

5.2.1 UPM Retaining Structure

If the mining height is small (e.g. less than 2 m), the impact load of the gangues on the retaining structures is very small at the initial stage of the collapse of the gangue, and the supporting strength requirement can be met only by using UPM retaining structure. The adjacent U-section steel are articulated by metal tie rods. On the one hand, it can transfer the lateral load to the single pillar, on the other hand, it enhances the overall stability of U-section steel, as shown in Fig. 9.

5.2.2 UPPM Retaining Structure

When the mining height is slightly larger (e.g. 2–3 m), the impact load of the supporting structure can not be ignored in the process of the gangue collapse. At this time, an additional steel plate which can resist the impact is needed to resist the dynamic load, as shown in Fig. 10. Compared with the UPM retaining structure, the UPPM retaining structure added a strike plate towed to the tail of the hydraulic support. The impact load generated by the collapse of the gangues will first act on the strike plate, and then be dispersed by the strike plate to the nearby single pillars. The local impact of gangues on retaining structures is reduced, so it can play a good anti-impact role.

5.2.3 USPM Retaining Structure

For large mining height working face (e.g. greater than 3 m), the impact load of the gangues on retaining structures will be very large during the collapse process, and the lateral extrusion force will still be very large after entering the slow compaction stage. Therefore, additional miniature hydraulic supports with high supporting capacity must be added, as shown in Fig. 11.

Compared with the UPPM retaining structure, in the USPM retaining structure, the single pillars are replaced by miniature hydraulic supports, which not

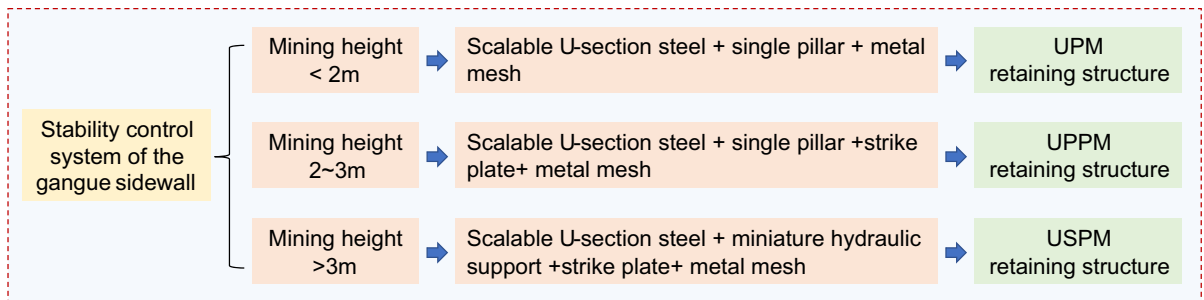


Fig. 8 Stability control system for roadside gangues

Fig. 9 UPM retaining structure for roadside gangues

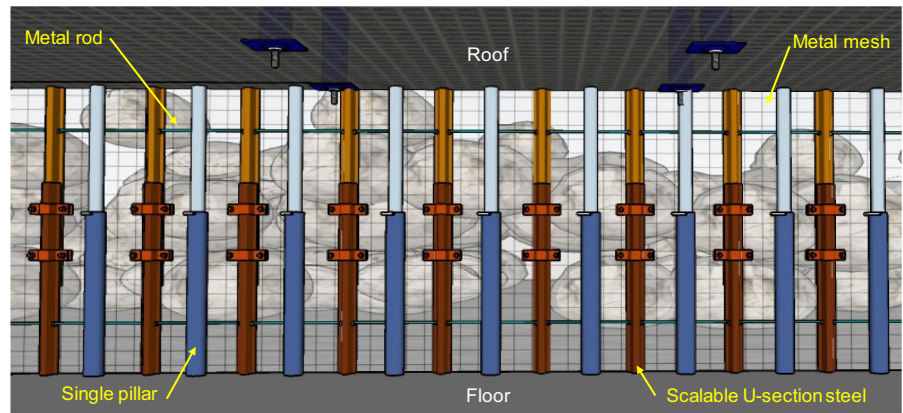
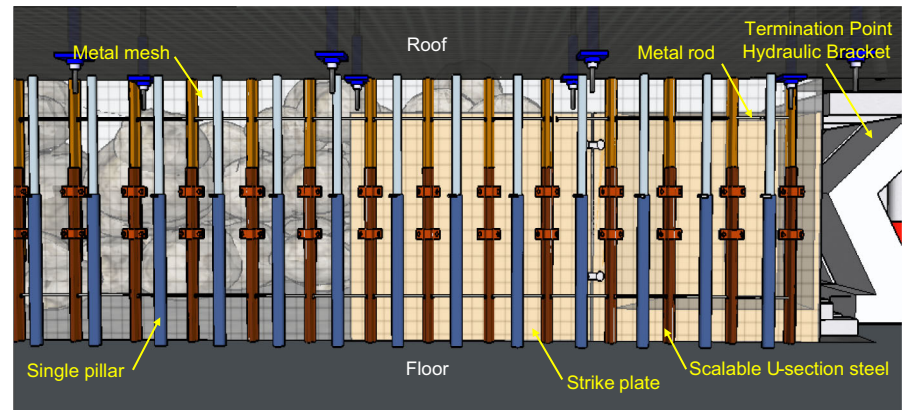


Fig. 10 UPPM retaining structure for roadside gangues



only provide a strong vertical support force, but also have a large lateral support capacity.

5.3 Field Application Cases

5.3.1 Test in Thin Coal Seam Working Face

The support test for thin coal seam was carried out in Ruineng coal mine in 2017. The length of the test

section is 500 m, the thickness of the coal seam is 0.8–1.5 m, the mining height is controlled at 1.5–2.0 m, and the coal seam is approximately horizontally distributed. The roadside gangues are supported by the UPM retaining structure for roadside gangues, where: the U-section steel is 25U with a spacing of 500 mm; the single pillars are interlaced and evenly distributed among the adjacent U-section steel; and the metal mesh is reinforcing steel mesh

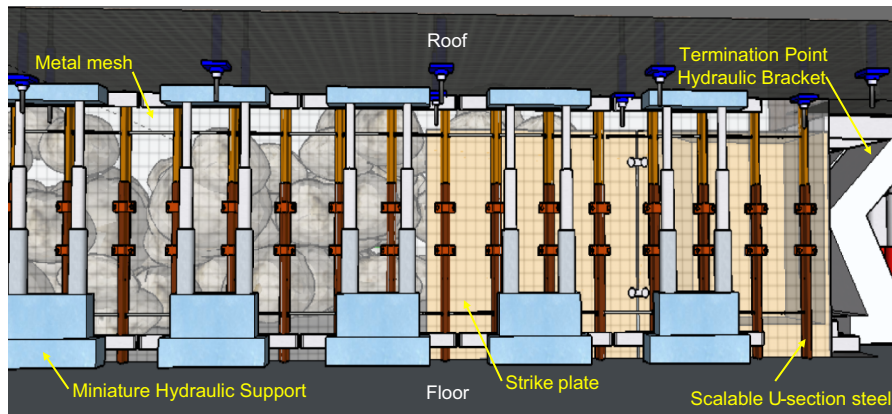


Fig. 11 USPM retaining structure for roadside gangues

with diameter of 6 mm and orifice size of 100 mm × 100 mm. The test results show that in the supporting process, the U-section steel does not produce serious bending or deformation, and the roadside gangues do not appear obvious side heave. The application effect is shown in Fig. 12.

5.3.2 Test in Thick Coal Seam Working Face

The support test for thick coal seam was carried out in Ningtiaota coal mine in 2016. The mining height of the test face is about 4.1 m, and the coal seam is

approximately horizontally distributed. The roadside gangues are supported by the USPM retaining structure, where: the spacing of the U-section steel and the miniature hydraulic supports is 600 mm and 2400 mm respectively; the length of the strike plate is about 6 m, which is hung behind the termination point hydraulic bracket and moved synchronously with the bracket. The test results show that the retaining structures have no obvious deformation or damage after using the support structures, and the overall effect is shown in Fig. 13.



Fig. 12 USPM retaining structure for thin coal seam in Ruineng coal mine

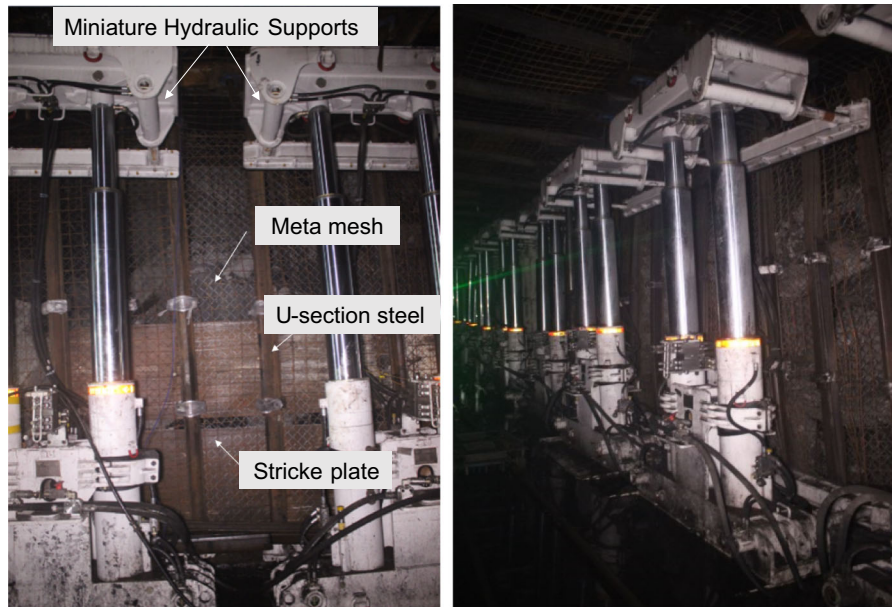


Fig. 13 USPM retaining structure for thick coal seam in Ningtiaota coal mine

6 Conclusions

1. By establishing the mechanical model of the gangues in the goaf, the expression of support resistance of the gangues retaining structures is derived.
2. The analysis results show that the supporting structures for the roadside gangues must have the ability of longitudinal deformation to adapt to the given deformation caused by the roof and the floor moving closer to each other and avoid the collapse of the retaining structures.
3. The analysis also shows that the movement process of the gangues in the goaf can be divided into two main stages, i.e. the rapid collapse stage and the slow compaction stage. In different movement stages, the interaction between the gangues and the retaining structures is different. Near the hydraulic supports, the gangues produce dynamic impact load on the retaining structures, while far behind the hydraulic support, the gangues produce static or nearly static extrusion effect on the retaining structures.
4. The internal relationship between the action force of the gangue-structure system and the mining height is revealed. The research shows that the greater the mining height, the greater the extrusion

force. Finally, according to the different mining heights, an effective roadside gangues control system is designed and developed, and the field application results confirm the reliability and scientificity of the control system.

Acknowledgements The authors wish to acknowledge the funding support from Fund Project: the National Key Research Development Program (China) (Grant No. 2016YFC0600900).

References

- Brady BHG, Brown ET (1992) Rock mechanics for underground mining. Chapman and Hall, London
- Chen XJ, Li LY, Guo ZB, Chang TH (2019) Evolution characteristics of spontaneous combustion in three zones of the goaf when using the cutting roof and release pressure technique. *Energy Sci Eng* 7(3):710–720
- Gao YB, Yang J, He MC, Wang YJ, Gao Q (2017) Mechanism and control techniques for gangue rib deformations in gob-side entry retaining formed by roof fracturing in thick coal seams. *Chin J Rock Mech Eng* 36(10):2492–2502
- Gao YB, He MC, Yang J, Ma XG (2018) Experimental study of caving and distribution of gangues influenced by roof fracturing in pillarless mining with gob-side entry retaining. *J China Univ Min Technol* 47(1):21–31, 47
- Guo ZB, Wang J, Cao TP, Chen L, Wang J (2016) Research on key parameters of gob-side entry retaining automatically formed by roof cutting and pressure release in thin coal seam mining. *J China Univ Min Technol* 45(5):879–885

- Guo PF, He MC, Wang J, Zhou HT (2017) Test study on multi tray bolt in gob-side entry retaining formed by roof cut and pressure releasing. *Geotech Geol Eng* 35(5):2497–2506
- He MC, Zhu GL, Guo ZB (2015) Longwall mining “cutting cantilever beam theory” and 110 mining method in China: the third mining science innovation. *J Rock Mech Geotech Eng* 7:483–492
- He MC, Chen SY, Guo ZB, Yang J, Gao YB (2017) Control of surrounding rock structure for gob-side entry retaining by cutting roof to release pressure and its engineering application. *J China Univ Min Technol* 46(5):959–969
- He MC, Gao YB, Yang J, Guo ZB, Wang EY, Wang YJ (2018) An energy-gathered roof cutting technique in no-pillar mining and its impact on stress variation in surrounding rocks. *Chin J Rock Mechan Eng* 39(1):254–264
- He MC, Ma XG, Yu B (2019) Analysis of strata behavior process characteristics of gob-side entry retaining with roof cutting and pressure releasing based on composite roof structure. *Shock Vib*. <https://doi.org/10.1155/2019/2380342>
- Li JZ, Zhang M, Li Y, Hu H (2018) Surrounding rock control mechanism in the gob-side retaining entry in thin coal seams. *J South Afr Inst Min Metall* 118:471–480
- Luan HJ, Jiang YJ, Lin HL, Li GF (2018) Development of a new gob-side entry-retaining approach and its application. *Sustainability* 10(2):470
- Sun XM, Liu X, Liang GF, Wang D, Jiang YL (2014) Key parameters of gob-side entry retaining formed by roof cut and pressure releasing in thin coal seams. *Chin J Rock Mechan Eng* 33(7):1449–1456
- Wang HB, Chao A, Zhang SD (2014) Application on gob-side entry retaining technology with coal gangue bag packing in medium-thick coal seams. *Appl Mech Mater* 446–447:1364–1368
- Wang M, Bai JB, Li WF, Wang XY, Cao SG (2015) Failure mechanism and control of deep gob-side entry. *Arab J Geosci* 8(11):9117–9131
- Zhang ZZ, Bai JB, Chen Y, Yan S (2015) An innovative approach for gob-side entry retaining in highly gassy fully-mechanized longwall top-coal caving. *Int J Rock Mech Min Sci* 80:1–11
- Zhang ZZ, Wang WJ, Li SQ, Yu XY (2018) Analysis on rockbolt support interaction with roof dilatancy above roadside backfill area in gob-side entry retaining. *Geotech Geol Eng* 36(4):2577–2591
- Zhu Z, He MC, Wang Q, Gao YB, Wang YJ (2019) An innovative non-pillar mining method for gateroad formation automatically and its application in Ningxiaota coal mine. *J China Univ Min Technol* 48(1):46–53

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.