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Research Article

Stability Control and Quick Retaining Technology of Gob-Side Entry: A Case Study

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In Chinese coal mines, gob-side entry retaining, an efficient technique for coal mining, has been widely used. However, severe roadway deformation and slow retaining speed have gravely restricted the popularization and its application. Hence, in order to solve the existing problems, the deformation mechanism of gob-side entry was studied. Then, a new approach for gob-side entry retaining technique (GERT) was proposed to increase the speed of gob-side entry retaining. Finally, the application effect of the new GERT method was tested and analysed. The results show that the rotation and subsidence of roof key block B lead to severe deformation of roadway. And the proposed gob-side entry stability control technology can affectively resist the severe roadway deformation. Compared with the conventional support method for gob-side entry retaining, GERT has completed the complex wall construction work in advance, thereby simplifying the process of gob-side entry retaining and increasing the speed of gob-side entry retaining. When retaining the entry in panel 183U04 with the new support method, the entry retaining speed significantly improved from 0.25 m/h to 1.0 m/h compared with the traditional method, and then the problem of gob-side entry severe deformation was solved.

1. Introduction

In most Chinese coal mines, the longwall mining method has prominent advantages and has been widely used [1, 2]. However, one of the most important problems of longwall mining is roadway excavation and maintenance. Gob-side entry retaining, which is the entry of current panel retained and reused for next panel mining, is of great significance to improve mining efficiency [3], and the gob-side entry retaining technique (GERT) has been widely applied in longwall mining. A few decades ago, gob-side entry retaining has been used in the UK, Germany, Poland, Russia, and other countries, and it is mainly used in China, currently [4]. It can improve the recovery rate of coal, reduce roadway drivage ratios, extend the service life, and reduce gas accumulation in the upper corner as well as prevent mining disasters caused by the remaining coal pillars [5–9]. However, field engineering demonstrated that it still encounters many difficult problems, such as severe roadway deformation and the slow speed of gob-side entry retaining [10–14]. The severe deformation of roadway does not meet the production requirements, often requiring much cost and time to repair for reusing; moreover, the slow speed of gob-side entry retaining is not consistent with the rapid mining and inevitably restricts the efficient production. The above problems have seriously hindered the popularization and application of GERT. Hence, considerable studies with regard to solving these problems were conducted. For instance, Han et al. [15] established a mechanical model of lateral cantilever fractured structure according to the clarification for the stress environment of gob-side entry retaining, and the equation of roof given deformation and

the balance judgment for fracture block were obtained. He et al. [16] proposed an innovative approach for nonpillar mining, whose basic principle is using the spontaneous caved gangues to maintain the entry. Gong et al. [17] introduced a GERT method with fully mechanized gangue backfilling mining, and a similar material simulation experiment was conducted to simulate the gob-backfilled GER process by using the similar model test system. Luan et al. [18] developed a new gob-side entry retaining approach including lightweight and high-strength foam concrete and a mortise-and-tenon structure hollow-block wall. Yang et al. [4] discussed six geological factors to evaluate the adaptation of gob-side entry retaining and proposed the adaptation grades of gob-side entry retaining technique under site-specific geological conditions and their support methods. Li et al. [19] investigated crack evolution characteristics in a gob-side filling wall for various locations of the critical rock block fracture. In this paper, the severe deformation characteristics and mechanisms of gob-side entry were studied by numerical simulation first, and the method of roadway deformation control was proposed according to the engineering geological conditions of the Jining No. 3 coal mine. Then, a new approach for GERT was proposed to increase the speed of gob-side entry retaining. Finally, the new GERT was tested in a GER panel in a Chinese coal mine, and the application effect was analysed.

2. Engineering Background and Numerical Simulation Model

2.1. Engineering Geological Conditions. Panel 184U04 is the first face and locates in the middle of 18th district. Its west side is panel 183U05, and the east side is panel 183U03. Its design stopping line is 120 m away from the 3U coal seam belt roadway, and the open-off cut is 337 m away from the mine boundary. Figure 1 depicts the layout of the panel 183U03.

The mining coal seam of panel 183U04 is marked as 3U coal. The mining depth is average 758 m. The thickness of the coal seam is about 2.50 m. The main roof is siltstone and fine sandstone interbed, and the average thickness is 7.23 m. The immediate roof is siltstone, and the average thickness is 10.16 m. The main floor is silt-fine stone, and the average thickness is 5.92 m. The main immediate floor is mudstone, and the average thickness is 1.37 m.

2.2. Establishment of the Numerical Simulation Model

2.2.1. Establishment of the Physical Model. According to the occurrence characteristics of the coal measure strata and considering the convenience of calculation, a simplified three-dimensional model was established. The model size is 230 m wide, 320 m long, and 80 m height. The mining coal seam thickness is 2.0 m. The full-seam mining caving method was used. The thickness of roof strata is 43 m, and the floor is 35 m. Considering the symmetry of strata movement, half of the working face width of 100 m was subject to the excavation operation.

2.2.2. Establishment of Numerical Model. The numerical model is simulated with six block grids (brick) as the basic unit in the model. The grid density is suitably increased in the focusing remaining area to improve the computing efficiency. The established three-dimensional model is shown in Figure 2. It has a total of 460000 units and 460000 nodes. The boundary conditions of the model are as follows: upper boundary is stress boundary, and a stress of 18.0 MPa is applied which is equivalent to the weight of overlying strata with a thickness of 720 m; the horizontal displacements of the four vertical planes are fixed and set to zero in the normal direction, and the vertical displacement at the base of the model is fixed and set to zero; the horizontal-to-vertical stress ratio is set to 1.0.

2.2.3. Constitutive Model and Mechanical Parameters. The constitutive model is used to describe the stress-strain behaviour of the rock materials. The model can express the mechanical properties of rock materials under an external force. The Mohr–Coulomb model was selected to describe the stress-strain behaviour of rock materials in the numerical model. The double-yield model available in FLAC3D was applied to model the strain stiffing behaviour of the gob materials, in which support capacity increases as its volume is gradually compressed, which is induced by roof strata subsidence. According to the field geological survey, the rock mechanics test results and, considering the rock size effect, the rock mechanics parameters adopted in the simulation calculation are determined, as shown in Table 1.

2.2.4. Simulation Scheme. The numerical model for the calculating process was as follows: the original rock stress loading → auxiliary roadway excavation of panel 183U04 → panel 183U04 mining → panel 183U04 auxiliary roadway side support establishment → the calculation result output.

The advancing distance in the model is set as 150 m. The in situ gob-side entry retaining, with the size of 5.3 m wide and 3.0 m height, is implemented during the panel 183U04 auxiliary crossheading. The size of the roadway side support is 1.5 m wide and 3.0 m high. The maximum length of the retained roadway is 145 m.

3. Gob-Side Entry Surrounding Rock Characteristics

Figure 2 depicts the position of the selected section of 240 m behind the working face because of the deformation and stress distribution of the roadway that is stable at this position. The shear stress characteristics of surrounding rocks are shown in Figure 3(a). It can be seen that the concentrated shear stress occurs in roof strata of the gob side, and its value rises from 7.5 MPa to 14.2 MPa. Moreover, the rock mass in this area exhibits longitudinal fracture development and provides the conditions for the fracture failure and rotation subsidence of the lateral roof according to the mechanical characteristics of the rock mass. Therefore, the probability of the lateral roof fracture boundary is higher. The rock characteristics of elastic and plastic zones are shown in

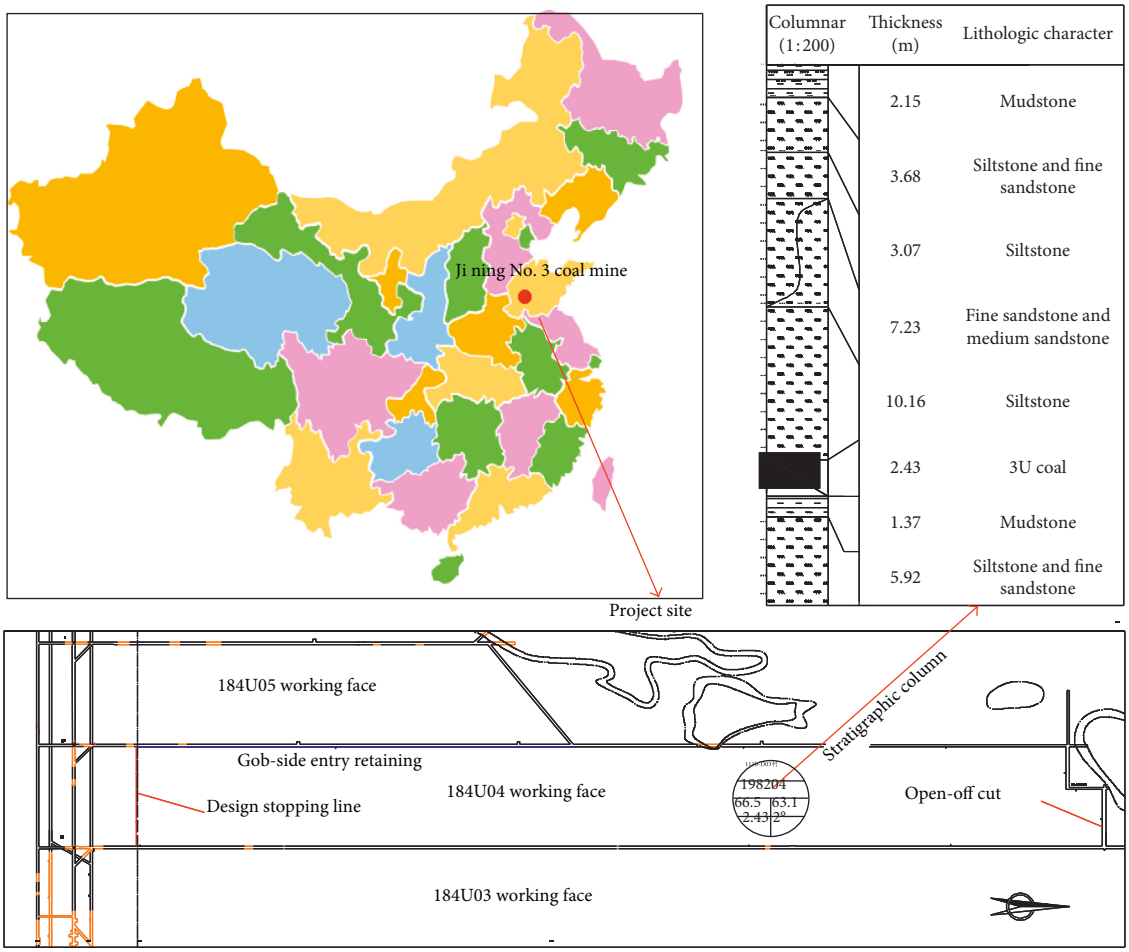


Figure 1: The engineering geological conditions.

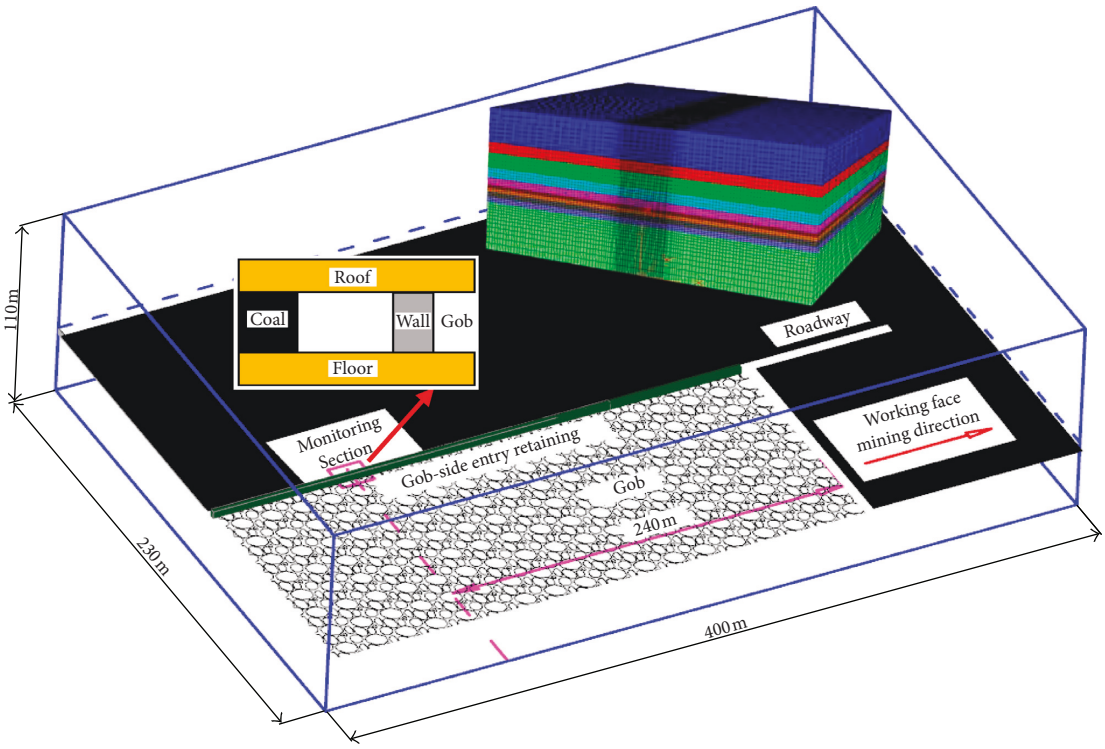
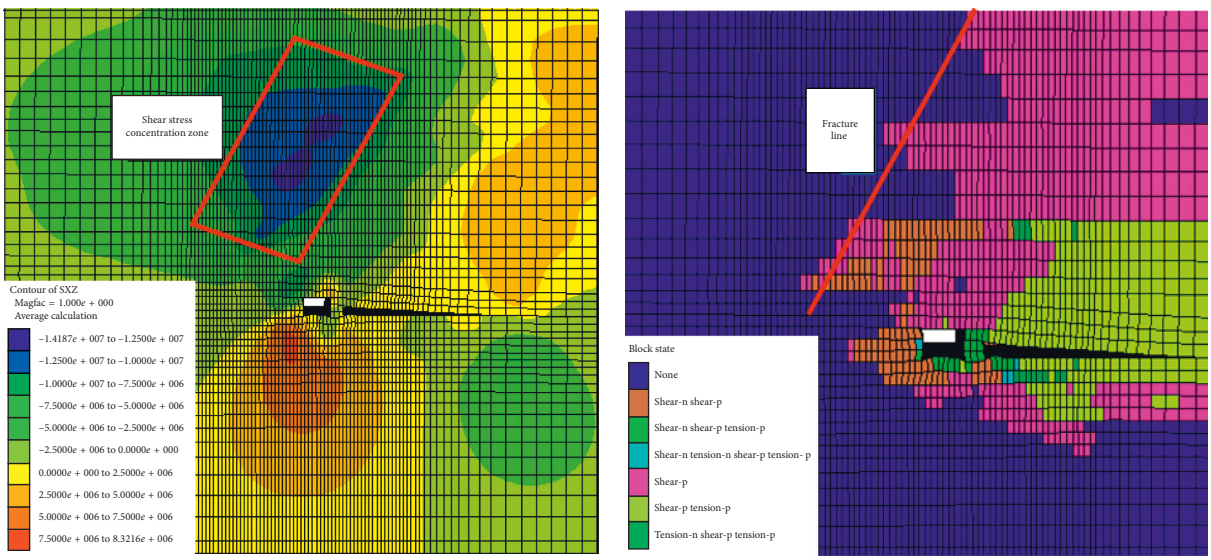


Figure 2: Gob-side entry retaining physical model and numerical calculation model.

Table 1: The rock mechanics parameters of the numerical simulation model.

Lithology	Layer thickness (m)	Density ($kg \cdot m^{-3}$)	Volume modulus (GPa)	Shear modulus (GPa)	Cohesion (MPa)	Tensile strength (MPa)	Internal friction angle (°)
Fine sandstone	15.0	2700	11.6	9.0	12.6	6.2	35
Medium sandstone	15.0	2510	4.8	2.5	8.7	3.8	24
Fine sandstone	3.0	2700	5.8	3.0	13.9	8.2	29
Siltstone	10.0	2700	2.7	1.4	4.2	2.9	32
No. 3 upper coal	2.0	1340	2.4	1.0	4.2	1.4	20
Mudstone	1.5	2300	1.6	1.0	4.5	1.8	23
Siltstone and fine sandstone	6.0	2700	3.9	1.2	10.6	4.0	27
Siltstone	27.5	2510	2.8	1.3	12.8	5.3	28
Artificial wall	3.0	2500	16.7	12.5	10.0	4.2	55



(a) (b)

Figure 3: Gob-side entry retaining surrounding rock characteristics: (a) distribution characteristic of shear stress; (b) distribution characteristics of the elastic and plastic zones.

Figure 3(b). We can see that the coal and rock mass in the left side is almost in the elastic state, and a wide range of plastic zones exist in the right side. During the strenuous movement period, the rock in the plastic area undergoes shear failure. After the stable collapse of the roof, the stress was released. The elastic deformation was restored, but the rock mass strength was significantly weakened. The characteristics of gob-side entry retaining surrounding rock show that a lateral roof fracture occurs between the two sides. After the lateral roof of each layer is fractured, the fissures can be connected into a line called the roof fracture line.

Figure 4 shows the surrounding rock characteristics of vertical stress. It can be seen that a weakened zone close to the ellipse in the surrounding rock within 3.0 m of the roadway roof and floor occurs. In this zone, the stress concentration is low, and the peak stress is less than 5.0 MPa. The roof load transfers to the coal side and the roadside wall. In the shallow area of coal roadway within 2 metres, the stress value in coal seam drops because of the decrease in the bearing capacity of coal seam caused by its plastic failure. The vertical stress increases gradually in the deep part of the coal side. The vertical stress at 5.0 m in the coal seam reaches the maximum value of 36.2 MPa with the stress concentration factor of 1.9. The maximum peak stress value in the roadside wall is 25.0 MPa. A certain degree of stress concentration also appears in top and bottom of the wall within 2 metres of the upper and lower walls. The stress value is 15.0 MPa. There is a small range of stress concentration of the roof strata caused by the support and constraint function of the wall. However, this phenomenon does not appear in the strata above the main roof. This result shows that the roadside wall only has the constraint function to the subsidence of the main roof strata and cannot change the movement of the roof. Thus, the wall may fracture under the action of roof movement.

4. Gob-Side Entry Severe Deformation Mechanism and Stability Control Technology

4.1. Gob-Side Entry Severe Deformation Mechanism. Gob-side entry encounters severe roadway deformation problems, such as wall fracturing, roof breakage, and floor

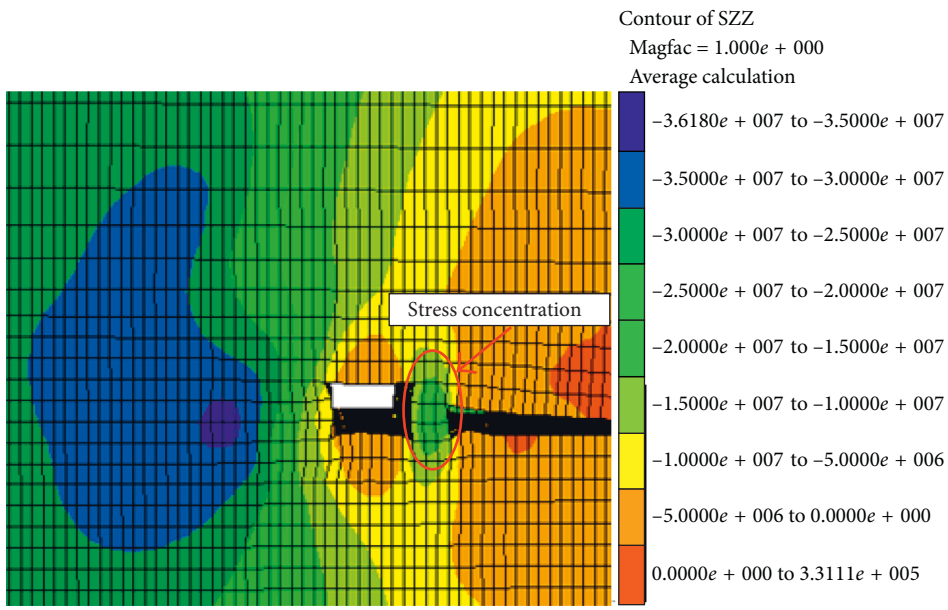


Figure 4: The vertical stress distribution characteristic of the roadway surrounding rock.

heave, which often cause destruction of the roadway, especially in the deep mine, as shown in Figure 5. The characteristics of gob-side entry surrounding rock are crucial for the research of gob-side entry severe deformation and stability control mechanisms. The numerical simulation results in Section 3 is consistent with the well-accepted surrounding rock structure model of the gob-side entry retaining, as shown in Figure 6. Along the slope of the work face, the main roof above the retaining roadway or the coal side is fractured to key block A, key block B, and the key block C as the working face advances. The key block B rotates and subsides along the fracture line; however, it can form articulated structures through the occlusion between key block A and key block C, namely, the "big structure" of the gob-side entry retaining surrounding rock. The roadway immediate roof, the solid coal, the roadway side support, and the floor together formed the "small structure" of the gob-side entry retaining surrounding rock. It can be seen that the "small structure" can deform and break during the movement of the main roof and thus it affects the normal use of the roadway [20–22]. The roof key block B will produce greater rotation and subsidence, resulting in stress concentration on the wall (Figure 4). This stress will lead to severe roadway deformation, such as wall fracturing, roof breakage, and floor heave, causing destruction of the "small structure", as shown in Figure 6.

4.2. Gob-Side Entry Stability Control Technology

4.2.1. Pressure-Releasing Support Wall. In order to retain the gob-side entry successfully, the small structure formed by the gob-side entry retaining surrounding rock must be stable. Unfortunately, the subsidence deformation of large structures against small structures is irresistible due to mining disturbance. The deformation and movement of rock strata within a large structure, including the rotation subsidence of the main roof key block, inevitably affected the stability of the small structure. Hence, small structures should not only have certain support resistance but also have the certain yieldable capacity to release the stress concentration. Hence, although a certain rotation subsidence of the main roof key block in the big structure happens, it could remain stable. If a reasonable support technology and the roadside support technology can maintain the stability of small structures, then the gob-side entry retaining process can be accomplished [23–25]. Therefore, a pressure-releasing support wall is proposed, as shown in Figures 7 and 8. The lower part of the wall is made of concrete block, and the upper part is made of concrete mortar. When the main roof rotates and subsides, the concrete mortar has good yieldable capacity to release the stress concentration and avoid destroying the "small structure".

4.2.2. Strengthen Structure of Wall Bearing Performance. In the process of gob-side entry roof fracture, collapse, and rotation subsidence, the support wall not only bears the static load but also bears the dynamic load of the roof load. However, as a brittle material, concrete has poor antiseismic performance, and brittle failure may occur under the dynamic load. The bearing capacity of concrete will reduce after the fracture develops. In addition, the key block B above the wall is in an inclined state, and the contact between the wall and the roof is inadequate. This will cause the uneven load distribution on the wall and increase the possibility of wall shearing or splitting failure. It is known from the rock mechanics that the triaxial compressive strength of the rock mass is greater than the biaxial compressive strength. Changing the force state of the wall from biaxial compression to triaxial compression

(a) (b)

Figure 5: Pictures of failure characteristics: (a) roof breakage and wall fracturing; (b) floor heave.

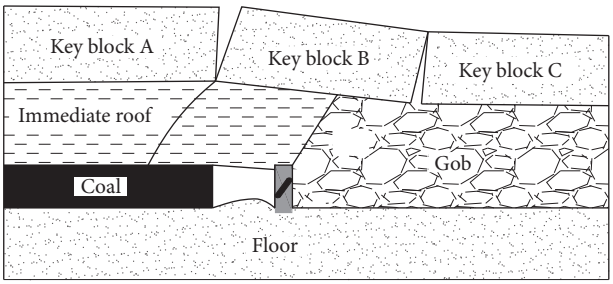


Figure 6: Diagram of the surrounding rock structure of gob-side entry retaining.

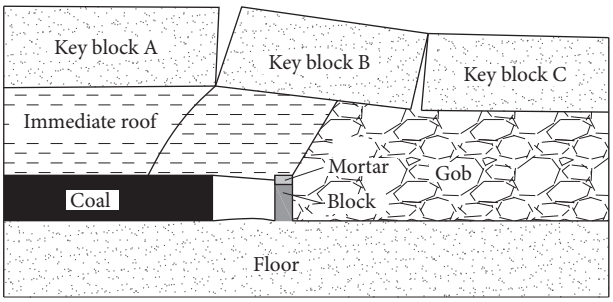


Figure 7: Diagram of the surrounding rock structure of gob-side entry retaining when a pressure-releasing support wall is used.

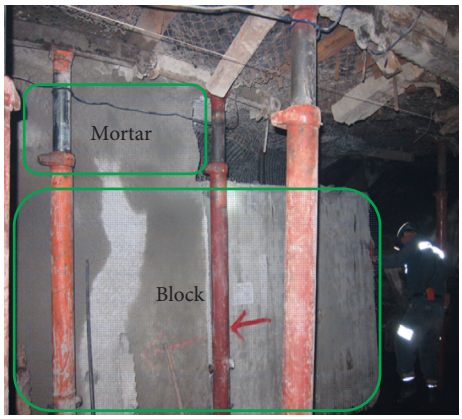


Figure 8: Picture of pressure-releasing support wall.

will improve the wall bearing and antideformation ability. Therefore, the strengthen structure is designed to improve the wall bearing performance, as shown in Figure 9. The strengthen structure is composed of old steel pipes, rock bolts, or angle irons, and they are welded together.

4.2.3. Roadway Supplement Support. In the conventional approach for gob-side entry retaining, the artificial wall is mainly placed in the gob, and no reinforcement is taken on the roof of wall. However, there is stress concentration on the roof of the wall, as described in Section 3, and the rock mass of the roof has been weakened. Therefore, the roof easily fails, and this will result in the failure of gob-side entry retaining. To solve the problem, a wider gob-side entry is adopted and supplement support is taken on the roof of the wall to improve its strength, as shown in Figure 10. The width of the gob-side entry in the application field is 5.5 m. The roof of roadway was supported by rock bolts with 22 mm in diameter and 2500 mm in length and anchor cables with 22 mm in diameter and 6200 mm in length; the coal sides were supported by bolts, which are 20 mm in diameter and 2200 mm in length. Note that two rock bolts and an anchor cable are installed on the roof of the wall. Hence, the roof of the roadway can be kept intact to avoid failure.

5. Gob-Side Entry Quick Retaining Technology

The retaining speed is one of the key factors of the gob-side entry retaining technique. As the process of gob-side entry retaining must be tightly integrated with the face mining, only when the speed of the gob-side entry retaining matches the advancing speed of the working face, the advantages of the technique can be fully realized. An artificial wall usually is required on the gob side of the entry to allow the roadway to still be used normally after deformation. In the conventional approach for gob-side entry retaining, the construction of the artificial wall is mainly conducted by means of stacking sacked gangue (Figure 11(a)), building concrete blocks (Figure 11(b)), pouring concrete or high-water material into the mould (Figure 11(c)), and so on. However, such construction processes of the artificial wall are mostly conducted in the roadway

(a) (b)

Figure 9: Pictures of strengthen structure for block bearing performance.

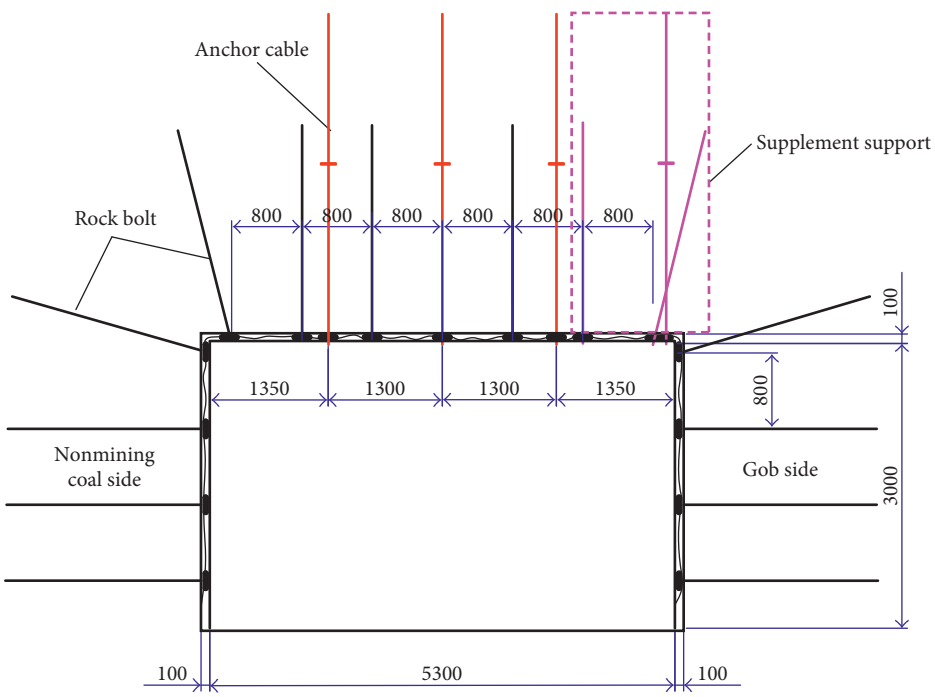


Figure 10: Support parameters of the gob-side entry retaining (unit: mm).

behind the working face (Figure 12(a)), and they can be conducted only when the working face is mined. This process usually requires a long time because of its complex construction procedure and low level of mechanization or because the strength of the wall increases slowly and some other reasons. Therefore, it is difficult for the gob-side entry retaining method to adapt to the rapid advancing of the fully mechanized face, and this will inevitably restrict the efficient production of the mine.

To solve this problem, the gob-side entry quick retaining approach by preconstruction of a large-size concrete block wall is proposed (Figure 12(b)); the principle of this approach is briefly described as follows: first, the block is installed, and then the block position is adjusted, and finally it is connected with the roof of the roadway. In other words, a movable wall can be preconstructed with large-size concrete blocks near the nonmining side of the large section of roadway in front of the working face. As the working faces advance and every time the block reaches the rear of the working face, it is pushed into the gob side of the roadway by single hydraulic prop. Finally, a certain thickness concrete mortar is sprayed onto the block to connect the wall with the roof of the roadway. It can be seen that it simplifies the

Figure 11: Different types of artificial wall for gob-side entry retaining: (a) stacking sacked gangue; (b) building concrete blocks; (c) pouring concrete or high-water material into the mould. In each panel, the picture on the left represents the construction of the artificial wall, and the picture on the right represents the completed wall.

process of gob-side entry retaining and thus increases the speed of gob-side entry retaining because the approach has completed the complex wall construction work in advance. Hence, the adverse effect of gob-side entry retaining on mining speed is avoided. Note that this technique can be successfully implemented with the assistance from two conditions. First, the roadway section is relatively large, and then the underground transportation equipment is a trackless rubber-tire vehicle that allows the large-size concrete blocks to be transported into the roadway. The technique cannot be used in a mine where tramcars are used.

6. Case Study

A field application was conducted to verify the effect of the new approach on gob-side entry quick retaining. The position of field application is located at panel 183U04 of Jining No. 3 coal mine located in Yankuang Group, Shandong Province, China.

6.1. Production of Large-Size Concrete Blocks. In the process of production of large-size concrete blocks, the construction quality is particularly important. Not only should the mix ratio of concrete be strictly controlled, but it should also be fully vibrated and carefully maintained. To ensure the quality of concrete blocks, commercial concrete is used. Meanwhile, to improve the efficiency, ten block mould boxes are made so that the flow operation process of filling, vibration, and maintenance can be formed. Detailed production details are shown in Figure 13. Compared with pouring concrete in underground, the prefabricated block is easy to guarantee the quality of the project.

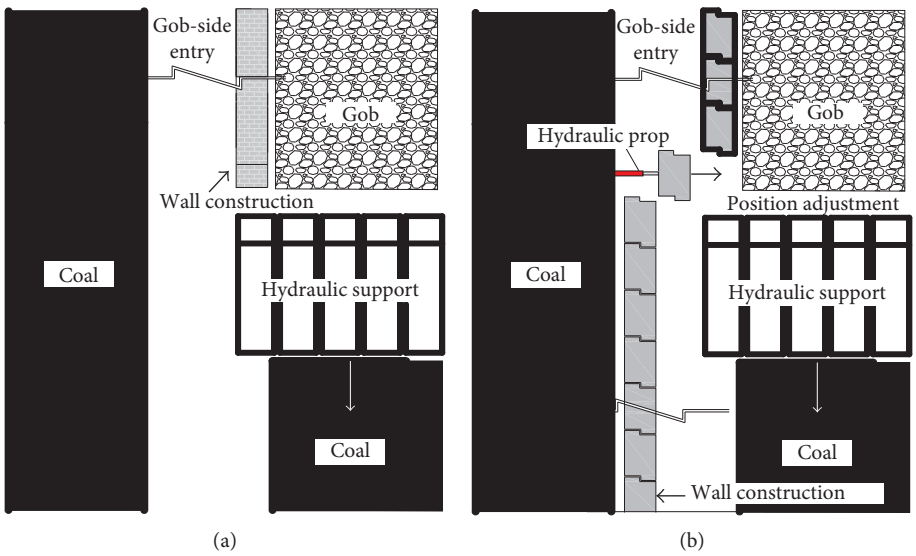


Figure 12: Approach for gob-side entry retaining: (a) conventional approach; (b) new approach.

Figure 13: Pictures of production of large-size concrete blocks: (a) pouring commercial concrete material into the mould; (b) vibratory mixing of concrete; (c) formed concrete block; (d) curing of concrete block.

6.2. Construction Procedure. The construction procedure of the new approach is shown in Figure 14. First (Stage I), the large concrete blocks are transported by a trackless rubber-tire vehicle to the entry front of the working face and are placed in order near the nonmining side of the large section entry (Figure 15(a)). The distance between the block and the calibration line of the entry is 1285 mm. Next (Stage II), a single hydraulic prop and a hinged girder are used to increase the supporting strength 30 metres in front of the face. To release the support space for a single hydraulic prop and a hinged girder, the blocks move towards the working face by a short single hydraulic prop (Figure 15(b)). At this moment, the distance between the block and the calibration line of the entry changes to 685 mm. Third (Stage III), as the working faces advance, every time the block reached the rear of the working face, a single hydraulic prop and an I-steel

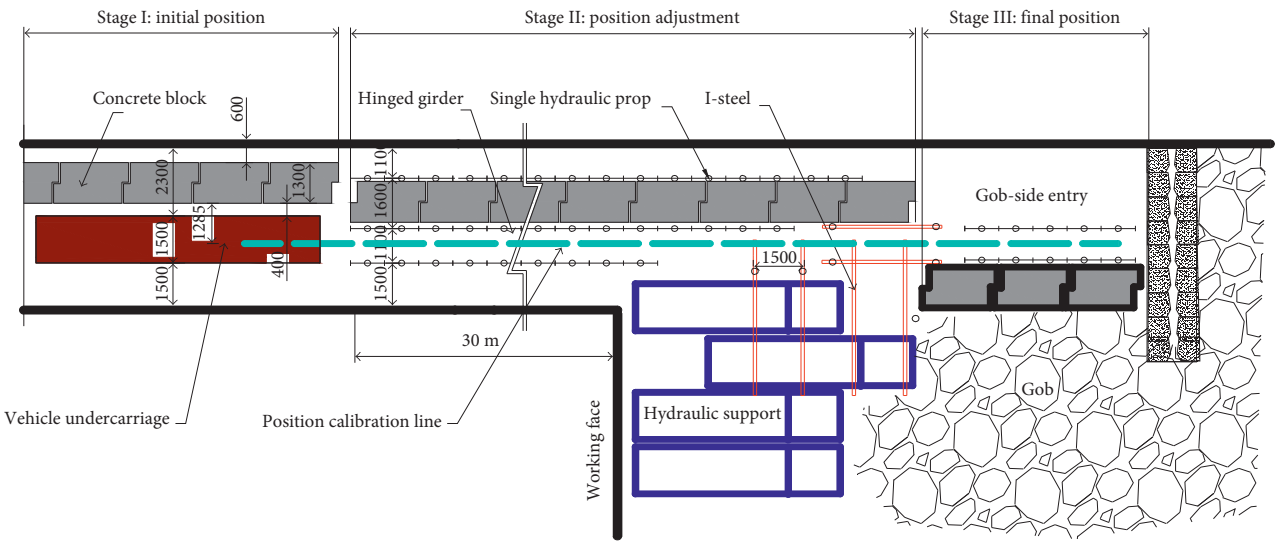


Figure 14: Construction procedure of the artificial wall for gob-side entry retaining.

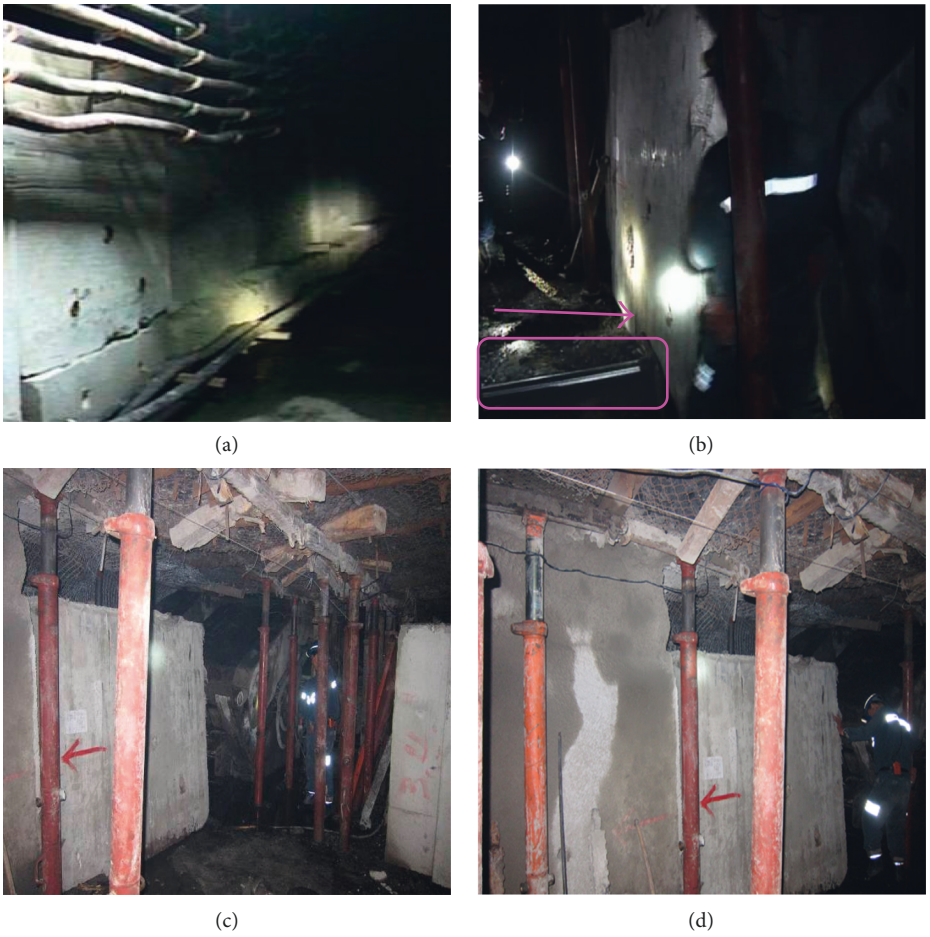


Figure 15: Pictures of the gob-side entry retaining artificial wall construction: (a) initial placement of a block; (b) position adjustment by the hydraulic prop; (c) final position of the block; (d) connection with the roof of the entry.

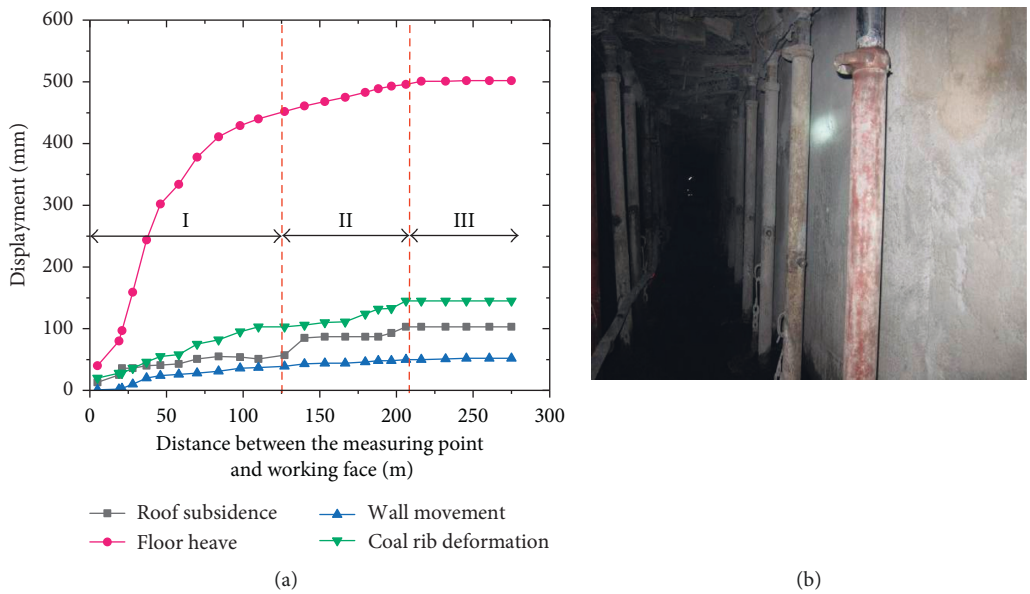


Figure 16: Gob-side entry retaining effect: (a) surrounding rock deformation of the gob-side entry; (b) pictures of the gob-side entry retaining.

were used to increase the support the entry roof, and then the block was pushed into the gob side of the entry by a single long hydraulic prop (Figure 15(c)). Finally, when the block is adjusted to the final position, concrete mortar is sprayed onto the wall and between the blocks to close the gob and connect the block with the roof of the entry (Figure 15(d)).

6.3. Application Effect

6.3.1. Gob-Side Entry Retaining Efficiency. When retaining the entry in panel 183U04, only the processes of the adjustment of the wall position and shotcrete procedures are conducted. Each 2-metre long section of gob-side entry retaining can be completed within 2 hours by the new approach for gob-side entry quick retaining. In contrast, much more time is required by the conventional approach for gob-side entry retaining because of its complex construction procedure, low level of mechanization, or some other reasons. Taking the conventional approach of building concrete blocks (Figure 11(b)) as an example, 300 concrete blocks are required for each section of 2-metre long gob-side entry retaining, and the blocks are very heavy (60 kg); as a result, the speed of building concrete blocks is very slow. In addition, concrete mortar is required to connect the blocks into one unit; this process is also time-consuming. Thus, 8 hours is required to finish the 2-metre long gob-side entry retaining using a traditional method. Therefore, compared with traditional methods, the speed of gob-side entry retaining was greatly improved, from an average of 0.25 m/h to 1.0 m/h, and the gob-side entry quick retaining was completed. The new approach solved the problem that gob-side entry retaining is difficult to adapt to the rapid advancing of the fully mechanized working face.

6.3.2. Gob-Side Entry Retaining Effect. At panel 183U04, the gob-side entry with a length of 720 metres was successfully retained. The gob-side entry retaining effect is shown in Figure 16. It can be seen that the roadway deformation includes three stages. In Stage I (0–125 m), the deformation of the roadway rapidly increased with the advance of the working face. In Stage II (125–210 m), the deformation gradually increased and the velocity of deformation was obviously reduced. In Stage III (210–280 m), the deformation tended to be stable. The final deformation of roof subsidence, floor heave, and wall movement and coal rib deformation are 103 mm, 502 mm, 52 mm, and 145 mm, respectively. Taken together, the deformation of the roadway was not large, and it can meet the production requirements after cleaning the floor. The problem of gob-side entry severe deformation was solved. Moreover, the adjacent panel 183U05 is successfully mined using the retained gob-side entry.

7. Conclusions

(1) There is a shear stress concentration area in the roof of the gob side. The rock mass in the shear stress concentration area is longitudinal fracture development and provides the conditions for the fracture failure and rotation subsidence of the lateral remaining rock. The coal and rock mass in the left side is almost in the elastic state, and there is a wide range of plastic zones in the coal and rock mass in the right side. The gob-side entry retaining surrounding rock characteristics suggest that there is a roof fracture line between these two sides. A stress concentration also appears in top and bottom of the wall within 2 metres of the upper and lower walls. The roadside wall only has constraint function to the

subsidence of the main roof strata and cannot change the movement of the roof. Thus, the wall may fracture under the action of roof movement.

(2) The roof key block B of the gob-side roadway has greater rotation and subsidence, resulting in stress concentration on the wall. This block will lead to severe roadway deformation. Under the influence of mining, the subsidence deformation of large structures against small structures is irresistible. Hence, small structures should not only have certain support resistance but also have certain yieldable capacity to release the stress concentration. Hence, a pressure-releasing support wall is proposed: the lower part of the proposed wall is made of concrete block, and the upper part is made of concrete mortar. With main roof rotation and subsidence, the concrete mortar has good yieldable capacity to release the stress concentration and avoid destroying the "small structure".

(3) Retaining speed is one of the key factors of the gob-side entry retaining technique: only when the speed of the gob-side entry retaining matches the advancing speed of the working face, the full advantages of the technique can be utilized. In the conventional approaches for gob-side entry retaining, the construction of the artificial wall is mostly performed in the roadway behind the working face; this process usually takes a long time. Therefore, it is difficult for the gob-side entry retaining method to adapt to the rapid advancing of the fully mechanized face. Because the new approach involves completion of the complex wall construction work in advance, it simplifies the process of gob-side entry retaining after mining and thus increases the speed of gob-side entry retaining.

(4) When retaining the entry in panel 183U04, compared with the traditional method, the speed significantly improves from an average of 0.25 m/h to 1 m/h; and the gob-side entry quick retaining is completed. The new technique solves the problem of the gob-side entry retaining being difficult to adapt to the rapid advancing of fully mechanized working face. The gob-side entry with the length of 720 metres is successfully retained, and the problem of gob-side entry severe deformation was solved.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflicts of interest.

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References

[1] A. Vakili and B. K. Hebblewhite, "A new cavability assessment criterion for longwall top coal caving," *International Journal of Rock Mechanics and Mining Sciences*, vol. 47, no. 8, pp. 1317–1329, 2010.

[2] M. Shabanimashcool and C. C. Li, "Numerical modelling of longwall mining and stability analysis of the gates in a coal mine," *International Journal of Rock Mechanics and Mining Sciences*, vol. 51, pp. 24–34, 2012.

[3] Z. Z. Zhang, J. B. Bai, and Y. Chen, "An innovative approach for gob-side entry retaining in highly gassy fully-mechanized longwall top-coal caving," *International Journal of Rock Mechanics and Mining Sciences*, vol. 80, pp. 1–11, 2015.

[4] H. Yang, S. Cao, S. Wang, Y. Fan, S. Wang, and X. Chen, "Adaptation assessment of gob-side entry retaining based on geological factors," *Engineering Geology*, vol. 209, pp. 143–151, 2016.

[5] Y. Q. Zhang, J. X. Tang, and D. Q. Xiao, "Spontaneous caving and gob-side entry retention of thin seam with large inclined angle," *International Journal of Mining Science and Technology*, vol. 24, no. 4, pp. 441–445, 2014.

[6] Z. Y. Zhang, S. Hideki, D. Y. Qian, and S. Takashi, "Application of the retained gob-side gateroad in a deep underground coalmine," *International Journal of Mining, Reclamation and Environment*, vol. 30, no. 5, pp. 371–389, 2016.

[7] Y. Chen, J. B. Bai, and X. Y. Wang, "Support technology research and application inside roadway of gob-side entry retention," *Journal of Coal Science and Engineering*, vol. 36, pp. 903–910, 2012.

[8] P. Wang, L. Jiang, J. Jiang, P. Zheng, and W. Li, "Strata behaviors and rock burst–inducing mechanism under the coupling effect of a hard, thick stratum and a normal fault," *International Journal of Geomechanics*, vol. 18, no. 2, article 04017135, 2018.

[9] X. Wang, Z. J. Wen, Y. J. Jiang, and H. Huang, "Experimental study on mechanical and acoustic emission characteristics of rock-like material under non-uniformly distributed loads," *Rock Mechanics and Rock Engineering*, vol. 51, no. 3, pp. 729–745, 2018.

[10] D. S. Zhang, X. B. Mao, and W. D. Ma, "Testing study on deformation features of surrounding rocks of gob-side entry retention in fully-mechanized coal face with top-coal caving," *Chinese Journal of Rock Mechanics and Engineering*, vol. 23, pp. 331–334, 2002.

[11] H. P. Kang, D. L. Niu, and Z. Zheng, "Deformation characteristics of surrounding rock and supporting technology of gob-side entry retention in deep coal mine," *Chinese Journal of Rock Mechanics and Engineering*, vol. 29, pp. 1977–1987, 2010.

[12] N. Zhang, L. Yuan, and C. L. Han, "Stability and deformation of surrounding rock in pillarless gob-side entry retention," *Safety Science*, vol. 50, no. 4, pp. 593–599, 2012.

[13] B. J. Zhou, J. H. Xu, M. S. Zhao, and Q. Zeng, "Stability study on naturally filling body in gob-side entry retention,"

International Journal of Mining Science and Technology, vol. 22, pp. 423–427, 2012.

[14] X. Q. Wang, N. Zhang, J. G. Kan, and N. C. Zhang, "Cracking mechanism and control strategy of concrete roadside wall with large scale," *Journal of China University of Mining and Technology*, vol. 46, pp. 237–243, 2017.

[15] C. Han, N. Zhang, B. Li, G. Si, and X. Zheng, "Pressure relief and structure stability mechanism of hard roof for gob-side entry retaining," *Journal of Central South University*, vol. 22, no. 11, pp. 4445–4455, 2015.

[16] M. He, Y. Gao, J. Yang, and W. Gong, "An innovative approach for gob-side entry retaining in thick coal seam longwall mining," *Energies*, vol. 10, no. 11, p. 1785, 2017.

[17] P. Gong, Z. Ma, R. R. Zhang, X. Ni, F. Liu, and Z. Huang, "surrounding rock deformation mechanism and control technology for gob-side entry retaining with fully mechanized gangue backfilling mining: a case study," *Shock and Vibration*, vol. 2017, Article ID 6085941, 15 pages, 2017.

[18] H. Luan, Y. Jiang, H. Lin, and G. Li, "Development of a new gob-side entry-retaining approach and its application," *Sustainability*, vol. 10, no. 2, p. 470, 2018.

[19] X. Li, M. Ju, Q. Yao, J. Zhou, and Z. Chong, "Numerical investigation of the effect of the location of critical rock block fracture on crack evolution in a gob-side filling wall," *Rock Mechanics and Rock Engineering*, vol. 49, no. 3, pp. 1041–1058, 2016.

[20] Z. B. Guo, J. Wang, T. P. Cao, L. Chen, and J. Wang, "Research on key parameters of gob-side entry retaining automatically formed and pressure release in thin coal seam mining," *Journal of China University of Mining and Technology*, vol. 45, pp. 879–885, 2016.

[21] Y. L. Tan, F. H. Yu, and J. G. Ning, "Design and construction of entry retention wall along a gob side under hard roof stratum," *International Journal of Rock Mechanics and Mining Sciences*, vol. 77, pp. 115–121, 2015.

[22] M. C. He, G. L. Zhu, and Z. B. Guo, "Longwall mining "cutting cantilever beam theory" and 110 mining method in China-The third mining science innovation," *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 7, pp. 483–492, 2015.

[23] Y. L. Tan, F. H. Yu, and J. G. Ning, "Adaptability theory of roadside support in gob-side entry retention and its supporting design," *Journal of China Coal Society*, vol. 42, pp. 376–382, 2016.

[24] J. G. Ning, P. F. Ma, and X. S. Liu, "Supporting mechanism of "yielding-supporting" beside roadway maintained along the gob under hard rocks," *Journal of Mining and Safety Engineering*, vol. 30, pp. 369–374, 2013.

[25] J. G. Ning, J. Wang, and X. S. Liu, "Soft-strong supporting mechanism of gob-side entry retention in deep coal seams threatened by rock burst," *International Journal of Mining Science and Technology*, vol. 24, pp. 805–810, 2014.