Hindawi
Advances in Materials Science and Engineering
Volume 2019, Article ID 8736103, 13 pages
https://doi.org/10.1155/2019/8736103

Research Article

Automatic Roadway Backfilling of Caving Gangue for Cutting Roofs by Combined Support on Gob-Side Entry Retaining with No-Pillars: A Case Study

Shengrong Xie, Xiaoyu Wu, Dongdong Chen, Yaohui Sun, Junchao Zeng, Qing Zhang, Chunwei Ji, Qiong Cheng, En Wang, and Yuxin Ren

School of Energy and Mining Engineering, China University of Mining & Technology, Beijing 100083, China

Correspondence should be addressed to Dongdong Chen; chendongbcg@163.com

Received 24 September 2019; Accepted 22 November 2019; Published 27 December 2019

Academic Editor: Dimitrios E. Manolakos

Automatic roadways on gob-side entry retaining with no-pillars are used for longwall mining technology. The mining technology with no-pillars can recover coal pillar resources and reduce the amount and cost of roadway excavations. Automatic roadway technology for cutting roofs by combined support on gob-side entry retaining with no-pillars is adopted for the condition of thick immediate roof and medium-thick coal seam mining, cutting off the immediate roof and the main roof on the gob by combined support. The fractured roof forms gangue blocks to fill the gob and loads the overlying strata. The gangue control system is placed on the roadside, which controls the caving gangue to form a gangue rib. In this paper, the viewpoints and key technologies (the roof-cutting technology, the reinforcement and support technology, the gangue rib control technology, and the auxiliary support technology) of automatic roadway technology for cutting roofs by combined support on the gob-side entry retaining with no-pillars are introduced. Furthermore, the formation and control process are explained. The numerical simulation is used to simulate and analyze the roof hanging and the roof cutting structures. In addition, a field engineering test is performed. The field test shows that automatic roadway technology for cutting roofs by combined support on gob-side entry retaining with no-pillars is feasible. This process uses construction techniques and technologies to meet on-site production needs. The combined support has high resistance strength and is shrinkable. In engineering applications, the combined support has a low damage rate. The deformation of the automatic roadway with gob-side entry retaining is small, and the control effect is significant.

1. Introduction

Longwall mining is one of the most widely used coal mining methods in coal mining [1, 2]. Coal mining projects can be divided into no-pillar mining and coal pillar mining. Coal pillar mining means protecting the roadway by coal pillars, thereby reducing the deformation and damage to the roadway caused by rock pressure. The most common method for no-pillar mining is the technology of gob-side entry retaining. The layout of a roadway uses backfilling materials (such as high water materials, concrete materials, and gangue) on the side of the gob to construct a backfilling body. This technology is used to maintain the original roadways along the gob-side after upper working face mining and is used as the tailentry and headentry for the next working face, which reduces the amount of roadway excavation work and the excavation cost. Many researchers have conducted extensive research on the rock pressure and its operating laws with no-pillar mining and coal pillar mining. On the basis of studying the theory of rock pressure, Qian proposed the "voussoir beam" theory, which entails retaining a large coal pillar to support the roof and balance the roof pressure [3]. Song proposed the "transmission rock beam" theory. After the coal seam is produced, the interior and exterior stress fields will be formed on the side of the gob. The interior stress field is in the low stress area under the protection of the roof's broken arch structure. In this way, the roadway is projected in the interior stress field, and the narrow coal pillar is retained to ensure the stability of the roadway and increase the recovery of coal pillar resources [4]. He proposed a directional blasting cutting technology that helps the roof fall in the gob. This is used to eliminate the influence of the roadway by cutting the roof in advance, the purpose of unloading roof pressure is achieved, and the low pressure range is increased. In this way, the local stress concentration disappears [5, 6]. Han et al. studied the mechanism of pressure relief and the structural stability of the transverse cantilever structure of the stope roof. Under the intermittent fault and superimposed disturbance of the overburden, the roadside support load of the gob was obtained [7]. Some researchers have studied the width, strength, and stability control of the roadside backfilling body on the roadside [8–12]. Tan et al. established a mechanical model of "soft-strong" support along the gob on the gob-side entry retaining and obtained the support characteristics of the roadside backfilling body, which provided a basis for rational filling and shrinkage design [13]. Some researchers have studied the support resistance and the structural load of roof fracture. Williams extended the mining cantilever beam model to the study of gob-side entry retaining and obtained the calculation formula for the support resistance for calculating the immediate roof cutoff by the roadside support [14]. Li and Hua [15] proposed that the "fracture arch" and the "stress arch" in the overlying strata constitute a "large structure" and bear most of the overburden load. The "small structure" of the surrounding rock was formed from the roadside support body, bolt combination support, and anchorage composed of the surrounding rock of the roadway, which bears the load transmitted from the "hinged rock beam" of the roof of the "large structure" secondary breaking zone. Zhang et al. [16] proposed a roof structure model of the wedge-shaped area on the gob-side, studied the upward pressure transfer bearing mechanism of the layer-by-layer roof in the gob, and analyzed the support resistance of the backfilling body.

In coal pillar mining technology, the roadway is projected between the retaining coal pillar and the adjacent working face. Under the influence of strong mining, the retaining coal pillar is the main bearing body of the stope pressure. If the coal pillar stress is concentrated (Figure 1), the roadside of the coal pillars becomes severely broken. Under the support of grouting and anchor cables, it is still difficult to control, and the maintenance cost is high. With the no-pillar mining technology, the roadway is projected between the gob and the adjacent working face. The coal body of the adjacent working face is the main carrier of the stope pressure and resides in the high stress area. However, the gob-side entry retaining is projected in the low stress zone, as shown in Figure 2, but a large number of practices at present have proven that under the influence of strong mining, rock pressure appears severe. The support strength of the coal pillars and backfilling body is usually insufficient to maintain the stability of the surrounding rock of the roadway. The large deformation of the rock surrounding the roadway is shown in Figure 3. Large deformation coal mining accidents in the rock surrounding the roadway frequently occur, and roadway accidents account for more than 70% of working face accidents. In this regard, many researchers recommend using blasting, hydraulic pressure, and combined support to cut off the roof with pressure relief on gob-side entry retaining [17–19]. Liu et al. [20] studied on the pressure relief effect of hard roof blasting and cutting, and the roof-cutting position and angle obviously affected the stability of the rock surrounding the gob-side entry. He et al. [21] explored the characteristics of rock pressure distribution with roof cutting and pressure releasing under different composite roof structures. Wang [22] proposed a liquid directional roof-cutting technology. The effects of the four main cutting parameters (type of abrasive, pump station pressure, speed of cutting head, and nozzle diameter) on cutting capacity were examined. The practice of directional cutting on the roof using liquid directional roof-cutting technology is feasible. Furthermore, the use of a dedicated directional unit to fix the cutting direction ensures that the seam direction is basically a straight line. Some researchers have studied the pressure of the large pillar and small pillar and nonpillar mining [23–25]. Sun [26] proposed that the peak stress was the smallest under nonpillar mining, and compared with the mining of the large pillar and small pillar, nonpillar mining decreased by 12–21% and 3–10%, respectively.

Meanwhile, many scholars have suggested that the volume expansion characteristics of rock mass destruction should be used to automatically fill the gob [27–29]. Roadway stability can be enhanced by the self-bearing property of the gangue in the gob and the synergistic supporting effect of the rock surrounding the roadway [30–33]. Therefore, based on the above suggestions, the method combining roof cutting with pressure relief and reducing roadway support pressure by the volume expansion characteristics of the caving rock mass can effectively ensure the safe and efficient production of coal mines.

2. Technical Principles for Roof Cutting

The principle of the automatic roadway technology for cutting roofs by combined support on gob-side entry retaining is to project the combined support on the roadside. When the stope periodically encounters pressure, the immediate roof and the main roof are cut off on the gob, thereby reducing the mechanical transmission of the overlying strata. In this way, the goal of roof cutting with pressure relief is achieved. In addition, the rock mass caves and their volume expansion can fill the gob. The gangue is controlled by the gangue control system in the gob to form the gangue rib. As shown in Figure 4, the gangue rib supports the roof to reduce the support pressure of the roadway.

In the past, roadside support structures were made of rafts, piers, gangue, and a backfilling body (high water material and paste material). These roadside support bodies have poor initial support and cannot contact the roof to provide active support in the early stage. Thus, support resistance is insufficient in the later stage. The main roof is fractured in the solid coal due to the influence of the high supporting pressure of the solid coal, causing severe damage to the surrounding rock of the roadway, resulting in failure

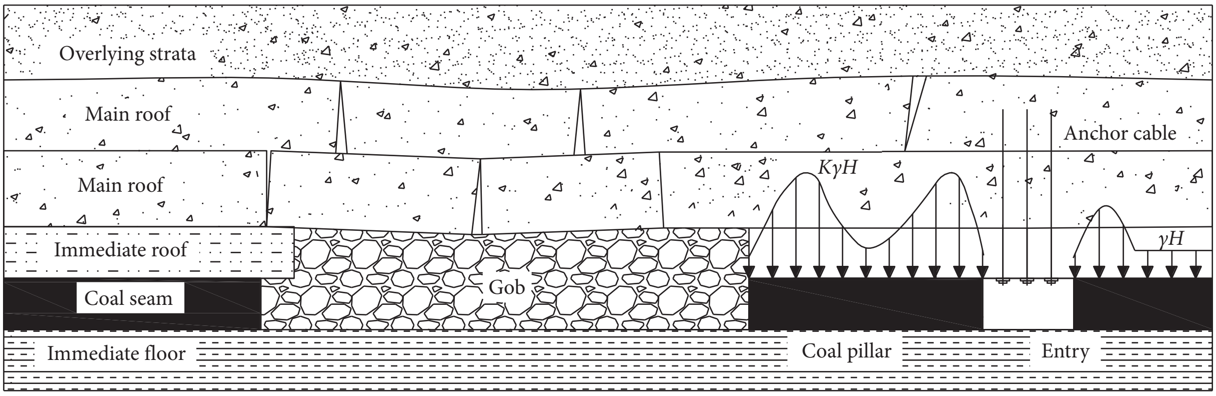


FIGURE 1: Mining with coal pillars.

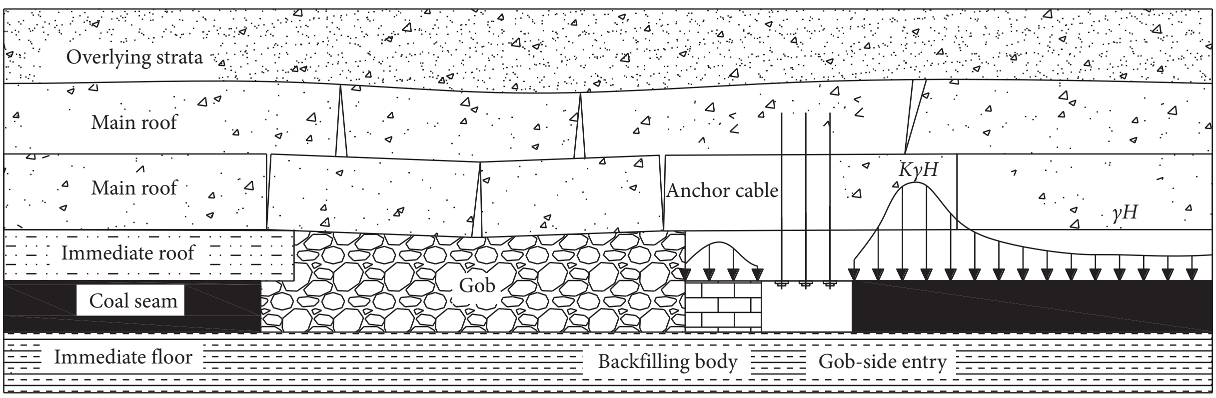
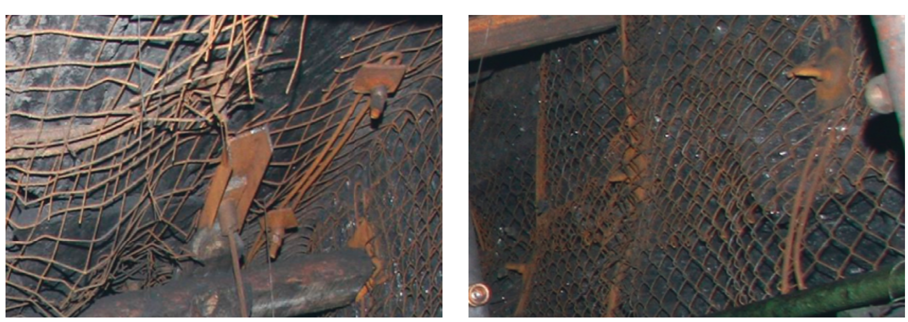


FIGURE 2: Gob-side entry retaining with no-pillars.



(a)

(b)

FIGURE 3: Large deformation of the surrounding rock.

of the gob-side entry retaining. A large number of studies in China have shown that roadside support resistance is large enough to cut off the immediate roof and the main roof on the gob. In this way, it is proposed to use combined support as the roadside support. This support is composed of π-shaped steel, a crossing articulated roof beam, and a single prop support for gob-side entry retaining. The combined support has higher compressive strength and deformation resistance, which provide higher support resistance to realize roof cutting with pressure relief and effectively control the surrounding rock.

The road-in support and the roadside support have limited restraining effects on the main roof rotation and settlement movement, and it is impossible to control the part of the roof cantilever beam protruding from the gob. Under the influence of strong mining, the roof cantilever beam is easy to rotate and subsides intensely, which causes roof subsidence, roof collapse, floor expansion, and other rock pressure manifestations. Therefore, the automatic roadway technology for cutting the roof by combined support on gob-side entry retaining can cut off the immediate roof and the main roof on the gob, thereby reducing the mechanical

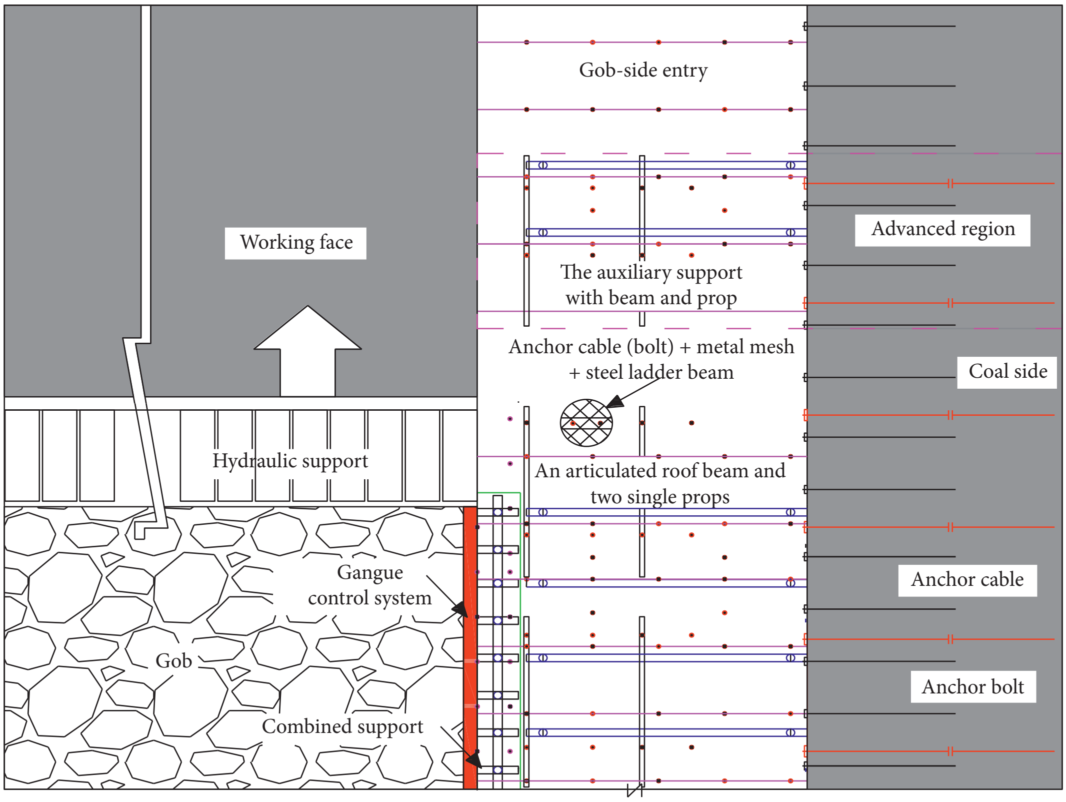


Figure 4: The automatic roadway technology for cutting roofs by combined support with gob-side entry retaining.

transmission of the overlying strata and forming a stable structure with a short cantilever beam. In addition, the volume of the caving rock mass expands and fills the gob. Then, the caving rock mass forms a gangue rib to support the roof cantilever beam on the roadside. According to the principles of physical mechanics, the force and the moment are inversely proportional. The gangue rib provides a small supporting force to the roof cantilever beam, which can inhibit the rotation and settlement movement of the roof cantilever beam, maintain the stability of the surrounding rock of the roadway, and protect the combined support on the roadside from being crushed.

The stress distribution of the automatic roadway technology for cutting roofs by combined support on gob-side entry retaining is shown in Figure 5. The stress distribution on both sides of the roadway on the gob-side entry retaining is as follows: (a) in the advanced section, the stress distribution of the coal on both sides of the roadway presents a single stress peak, and the stress peak reaches 2-3 times that of the original rock stress; (b) in the direction of the propulsion of the working face, the stress distribution is a high stress area on the coal; the stress peak reaches 3–5 times that of the original rock stress value, and the gob forms a low stress area, which is generally lower than the original rock stress; (c) in the lag section, a high stress area is formed along the coal of the gob-side entry retaining; the stress peak reaches 2–4 times of the original rock stress value, the low stress area is formed on the gob, and the stress peak is lower than the original rock stress.

3. Key Techniques

The process of forming and controlling involved in the production of automatic roadway technology for cutting roofs by combined support on gob-side entry retaining with no-pillars mainly includes key elements like the roof-cutting technology with combined support, the reinforcement and support technology in the advanced region, the gangue rib control technology in the gob, and the auxiliary support technology with beam and prop in the roadway.

3.1. Reinforcement and Support Technology. The action mechanism of the advancing support pressure indicates that the surrounding rock of the roadway in the advanced section is affected by strong mining and the surrounding rock of the roadway continues to have large deformation. Even if the strength of the bolt and cable support is relatively high, the deformation of the surrounding rock is still going to occur. In order to maintain the stability of the surrounding rock of the roadway, the supporting measures should be strengthened on the basis of the original bolt-cable support. The most effective method is to add an anchor cable in the roadway, increase the intrinsic strength of the surrounding rock, adapt to the large deformation of the surrounding rock caused by mining, and ensure the service life and overall stability of the roadway.

In the engineering field, the roof and coal side of the roadway are supplemented with anchor cables within 70 m

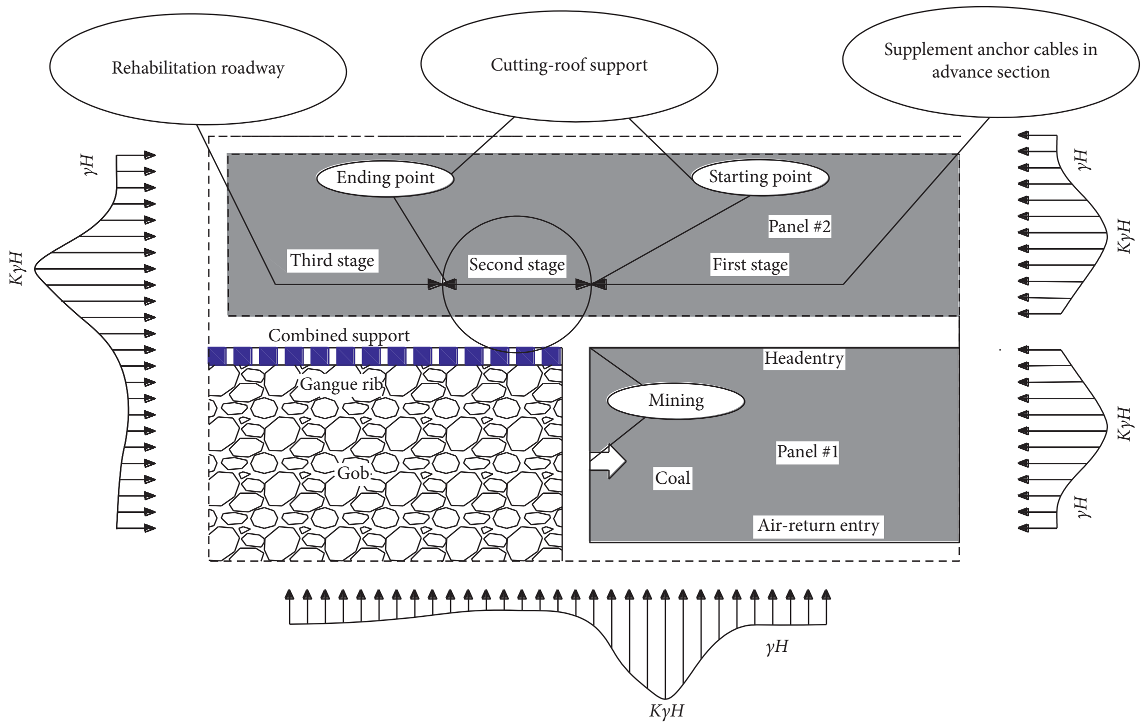


Figure 5: The stress distribution of automatic roadway technology for cutting roofs by combined support on gob-side entry retaining.

from the advance support section of the working face. The concrete measures add two rows of anchor cables to the roof and a row of anchor cables to the coal rib. One row of anchor cables on the roof in the center of the roadway is 0.1 m near the working face side, and the other row of anchor cables is 0.4 m near the working face side. A row of anchor cables on the coal rib is 0.2 m from the coal center, and the cable angle is inclined upward 15°, as shown in Figure 6.

3.2. Auxiliary Support Technology. The auxiliary support technology with beam and prop in the roadway projects the single props on the two sides of the roadway, respectively. Adding an articulated roof beam to the single props forms a "one beam and two props" integral supporting structure. This structure has the characteristics of strong pressure resistance and high stability, as shown in Figure 7. A large number of practices in China have proven that auxiliary support provides initial support force in the initial stage of gob-side entry retaining, which can produce an early restraining effect on the roof separation of the immediate roof and main roof, further preventing the separation layer and causing the bolt and anchor support to fail. In the early stage of gob-side entry retaining, the roof pressure is primarily increased. In the late stage of gob-side entry retaining, the constant pressure is used as the main position. The single props are used to quickly increase the resistance, shrinkage, and initial support characteristics, which can meet the roadside support requirements of the gob-side entry retaining and maintain coordinated movement with the immediate roof and the main roof.

3.3. Gangue Rib Control Technology. A gangue control system is projected at the gob-side of the roadway and consists of double-layer metal meshes, a wooden backboard, and combined support and bolts, which can effectively control the lateral pressure of the gangue to the roadside supporting body, and makes the caved gangue accumulate to form a gangue rib, as shown in Figure 8. In the engineering field, a long double-layer metal mesh is used. One end is laid on the inside of the gob, and the other end is fixed on the roof over the combined support with bolts. In this way, the flexibility and ductility of a double-layer metal mesh are used to block the gangue. At the same time, a wooden backboard is added between the metal mesh and the combined support to form a mesh net support structure with a skeleton. When the caved gangue is pressed on the metal net, the metal mesh itself can resist the pressure and the bending resistance, and the back plate support can provide restraint force. The restraining effect on the gangue rib can be enhanced, and the overall stability control of the caved gangue can be realized. Wearing iron shoes with welding teeth at the bottom of the combined support can increase the friction coefficient to the floor, thus ensuring that the excessive lateral pressure of the gangue is not so large that it topples the combined support on the roadside.

3.4. Roof Cutting Technology. In the process of implementing automatic roadway technology for cutting roofs on gob-side entry retaining, the combined support needs higher support resistance to cut off the immediate roof and the main roof on the gob of the roadway. In the meantime, the caved gangue impacts on the combined support to cause large lateral pressure, so requiring high bending resistance can maintain

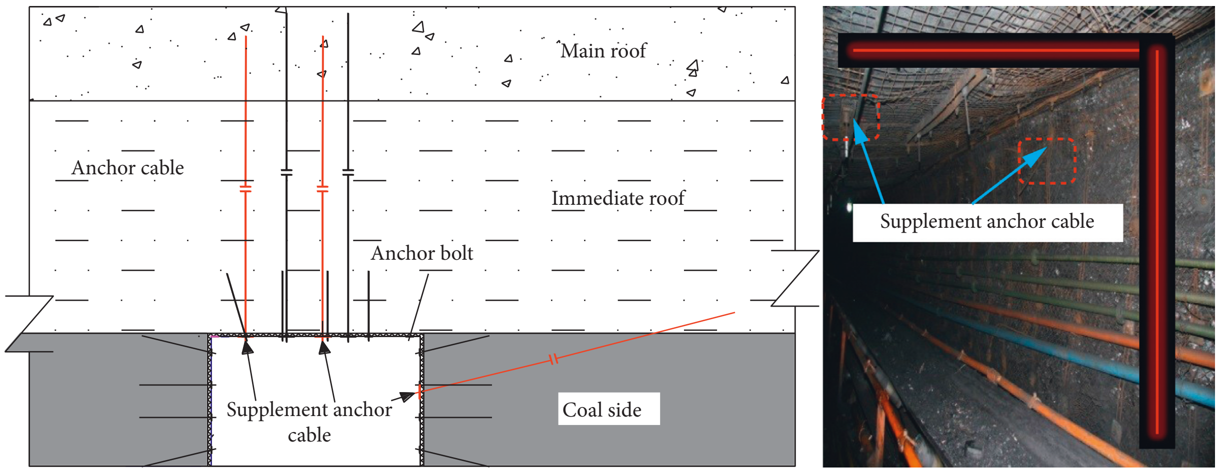


Figure 6: The reinforcement and support technology with the roof and the coal rib in the advanced region.

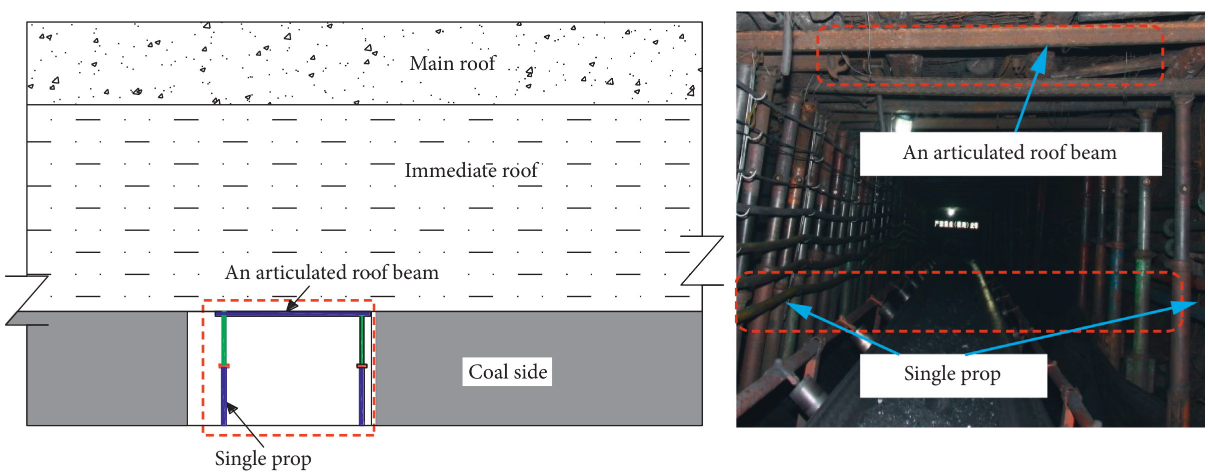


Figure 7: The auxiliary support technology with beam and prop in the roadway.

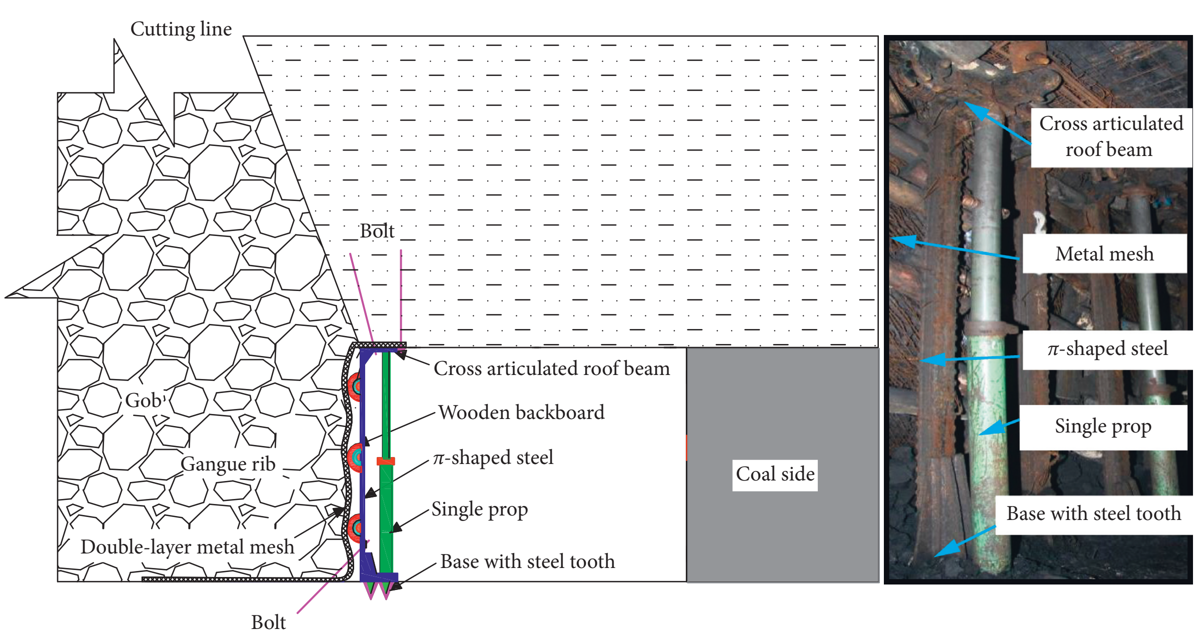


Figure 8: The gangue rib control technology in the gob.

stability. The commonly used single prop has low bending resistance and low support resistance. When the roof pressure is in a large area, the single prop is easily crushed and damaged. Only the single prop is used as the combined support. Furthermore, the single prop has low bending resistance, and its supporting resistance is not high. When the roof caving presses on a large area, the single prop is easily crushed and damaged. In order to solve this problem, a combined support is adopted by the combination of a π-shaped steel, a cross articulated roof beam, a steel tooth base, and a single prop, so the support strength and bending resistance are increased. The support characteristic curves of the single prop and the combined support are shown in Figure 9. As the roof sinks, the support resistance increases rapidly to the rated working resistance. Then, the roof continues to sink, and the support resistance remains unchanged. The mechanical parameters of the single prop are such that the initial support force (vertical pressure) is 16 MPa, the rated working resistance (vertical pressure) is 28 MPa (Figure 9(a)), and the maximum bending resistance (lateral pressure) is 32 kPa (Figure 9(b)). The mechanical parameters of the combined support are such that the initial support force (vertical pressure) is 18 MPa, the rated working resistance (vertical pressure) is 34 MPa, and the bending resistance (lateral pressure) is 68 kPa. The results indicate that the support strength and bending resistance (lateral pressure) of the combined support are higher than those of the single prop. In the engineering field test, the combined support is used for roadside support on the gob-side entry retaining. Under the roof pressure and the lateral impact of the gangue, the damage rate of the combined support is less than 5%.

4. Numerical Simulation and Engineering Field Test

4.1. Numerical Simulation of Roof Hanging and Roof Cutting. FLAC3D is used to simulate the two states of roof hanging and roof cutting with the 1528 headentry on gob-side entry retaining. The geological conditions of the 1528 working face are the average thickness of the coal seam is 2.35 m (2# coal), the immediate roof is 5 m thick (muddy siltstone), the main roof is 2.1 m thick (fine sandstone), and the immediate floor is 4.5 m thick (politic siltstone). According to the actual borescopes, the length of roof hanging is 8 m. After cutting the roof, the roof break angle is 60°, the length of roof cutting is 4 m, and the height of roof cutting is 7 m. (1) The stress distribution, plastic zone distribution, and deformation and failure characteristics of the surrounding rock of the roof hanging roadway are shown in Figures 10(a) and 10(c). The rotation and sinking of the roof hanging cause large deformation of the surrounding rock of the roadway. Near the roof of the gob, the sinking deformation is larger. The main supporting stress is concentrated on the solid coal, and the stress concentration load is 30.5 MPa. The roof and the floor are in a stress reduction zone, which indicates that the surrounding rock deformation and damage are serious, and the surrounding rock loses its bearing capacity. The depth of the plastic side of the solid coal is 2.5 m, and the depth of the plastic zone of the floor is 3 m. The plastic zone of the roof extends to the deep rock, indicating that the overburden is highly disturbed. (2) Plastic zone distribution and deformation and failure characteristics of stress distribution in surrounding rock of roadway with roof cutting are shown in Figures 10(b) and 10(d). The concentrated load of the coal side of roadway is 27.8 MPa, and the load of the self-forming lane of the gangue rib (rib) is 2.7 MPa. The depth of the plastic side of the solid coal side of roadway is 2 m, the depth of the plastic zone of the floor is 2 m, and the plastic depth of the roof is 5 m.

Through numerical simulation, the stress distribution, plastic zone distribution, and roadway deformation of the surrounding rock are analyzed and compared. The roof cutting can greatly reduce the stress concentration of the solid coal side of roadway, the load is from 30.5 MPa to 27.8 MPa, and the difference is 2.7 MPa. The gob-side of roadway forms a caving gangue rib, and the load of the self-forming gangue rib is 2–4 MPa. After the roof cutting, the plastic zone distribution range is greatly reduced, especially the depth of the plastic zone of the roof, extending from the deep to the deep rock formation, and the depth of the plastic zone of the roof is 5 m. After cutting the roof, the deformation of the surrounding rock of the roadway section is reduced, and the section area of the roadway is maintained.

4.2. Engineering Survey and Supporting Technology. The roadway is the 1528 working face headentry of the Gequan mine, which is located in Xingtai, Hebei, China. The elevation of the coal seam in the working face is between −190 m and −60 m. The corresponding ground elevation of the working surface is between +110 m and +138 m. The section of the roadway is designed to be $4.0\,\text{m} \times 2.8\,\text{m}$ (width × height), and the amount of roadway construction is 500 m. For the 1528 working face mining 2# coal, the average thickness of the coal seam is 2.35 m, the average inclination angle is 8°, the immediate roof is 5 m thick (muddy siltstone), the main roof is 2.1 m thick (fine sandstone), and the immediate floor is 4.5 m thick (politic siltstone).

The roof bolt ($\Phi 22 \times 2200$ mm) was made of a left-handed and nonlongitudinal threaded steel anchor bolt. The spacing between the bolts was $800\,\text{mm} \times 900\,\text{mm}$. The pallet used was a $120\,\text{mm} \times 120\,\text{mm} \times 8\,\text{mm}$ steel plate. The roof cable ($\Phi 17.8 \times 7000$ mm) was a high-strength and prestressed anchor cable, with an elongation of 5%. The spacing between the cables was $1200\,\text{mm} \times 1500\,\text{mm}$. To the roof of the roadway was added two rows of anchor cables ($\Phi 17.8 \times 6000$ mm); the row spacing was $1400\,\text{mm} \times 1500\,\text{mm}$. The roof anchor cable was connected by a $\Phi 16 \times 4000$ mm ladder-shaped steel strip. The distance between the steel strip and the anchor cable was 3–5 m, and the row spacing was 1.2–1.5 m. The road-in support was supported by one articulated roof beam and two single props with a DW28—250/100 single prop. The row spacing was 1 m.

The anchor bolt on the solid coal rib was made of A3 round steel of $\Phi 16 \times 1800$ mm, the row spacing between the

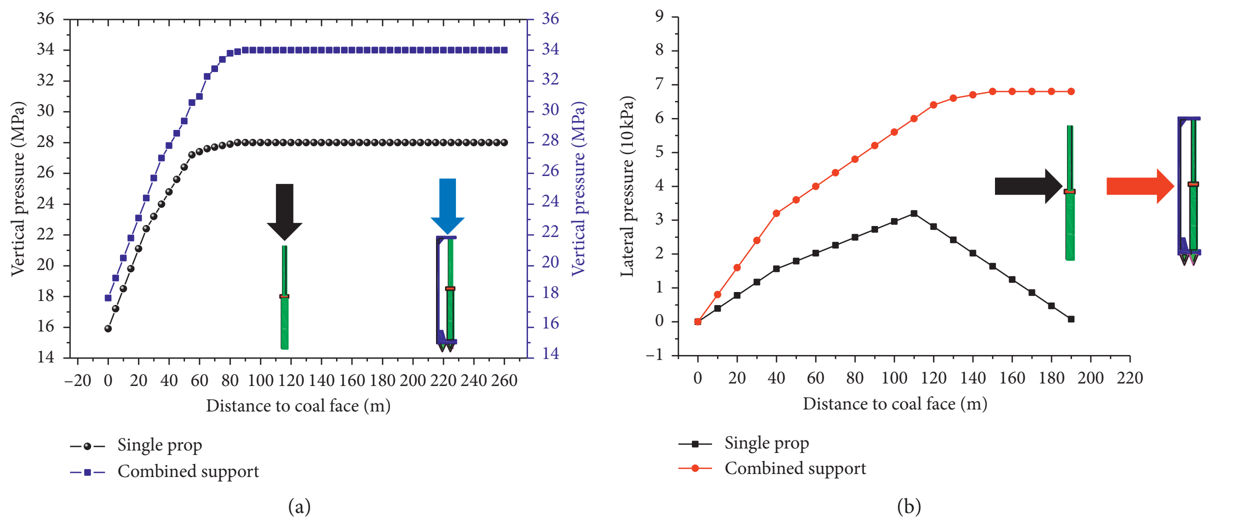


Figure 9: The support characteristic curves of the single prop and the combined support: (a) vertical pressure; (b) lateral pressure.

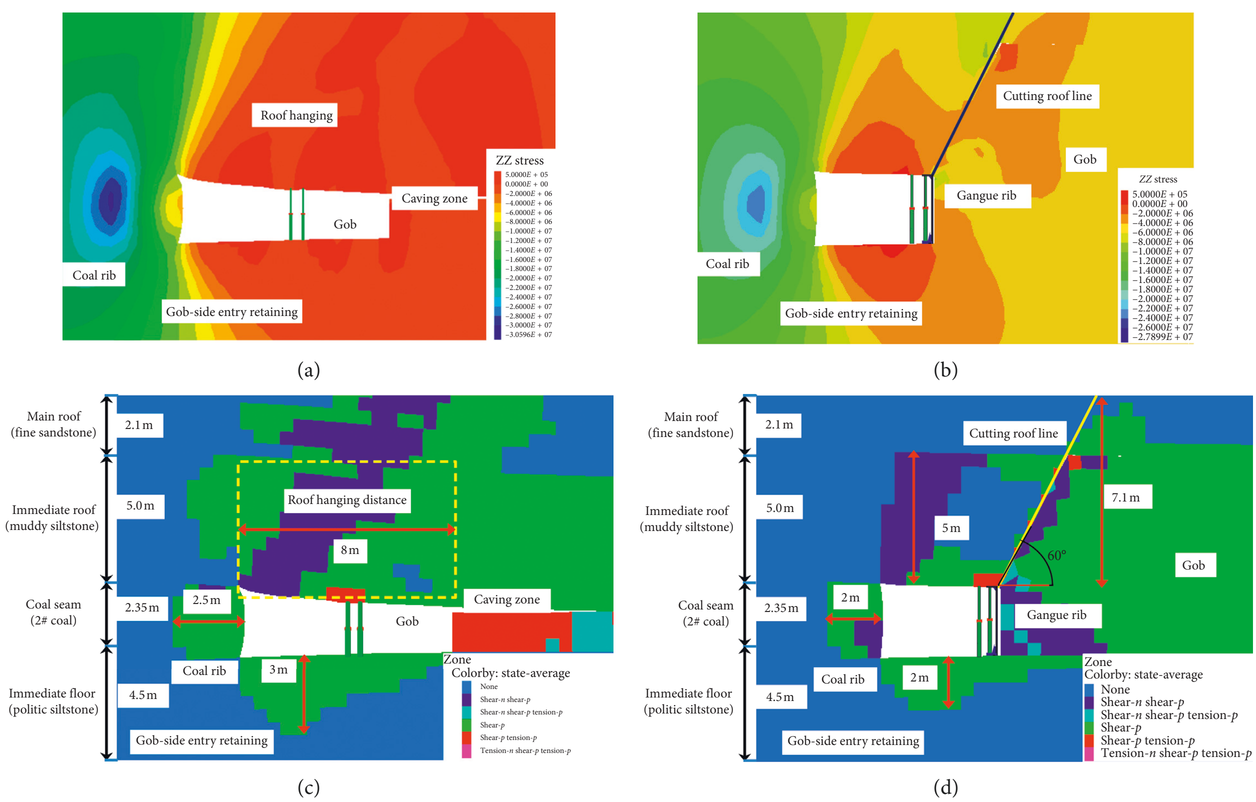


Figure 10: Numerical simulation: (a) vertical stress of roof hanging; (b) vertical stress of roof cutting; (c) plastic zone of roof hanging; (d) plastic zone of roof cutting.

anchor bolts was 700 mm × 700 mm, the steel ladder beams were connected with the anchor bolts, and the tray size was 140 mm × 140 mm × 6 mm. The anchor cable on the solid coal rib was a high-strength and high-elongation prestressed anchor cable (Φ17.8 × 7000 mm) with an elongation of 5% and row spacing of 1500 mm. The anchor cables were connected by steel ladder beams along the strike direction.

The roadside support on the gob-side entry retaining adopts combined cutting-roof support with a row spacing of 0.5 m, which was composed of a single prop, a π-shaped steel, a steel tooth base, and a cross articulated roof beam. The type of the single prop is a DW28-250/100 single prop. The type of the π-shaped steel is a 7# π-shaped steel, and the material of the π-shaped steel is 27SiMn. The backside of the combined cutting-roof support was placed within three

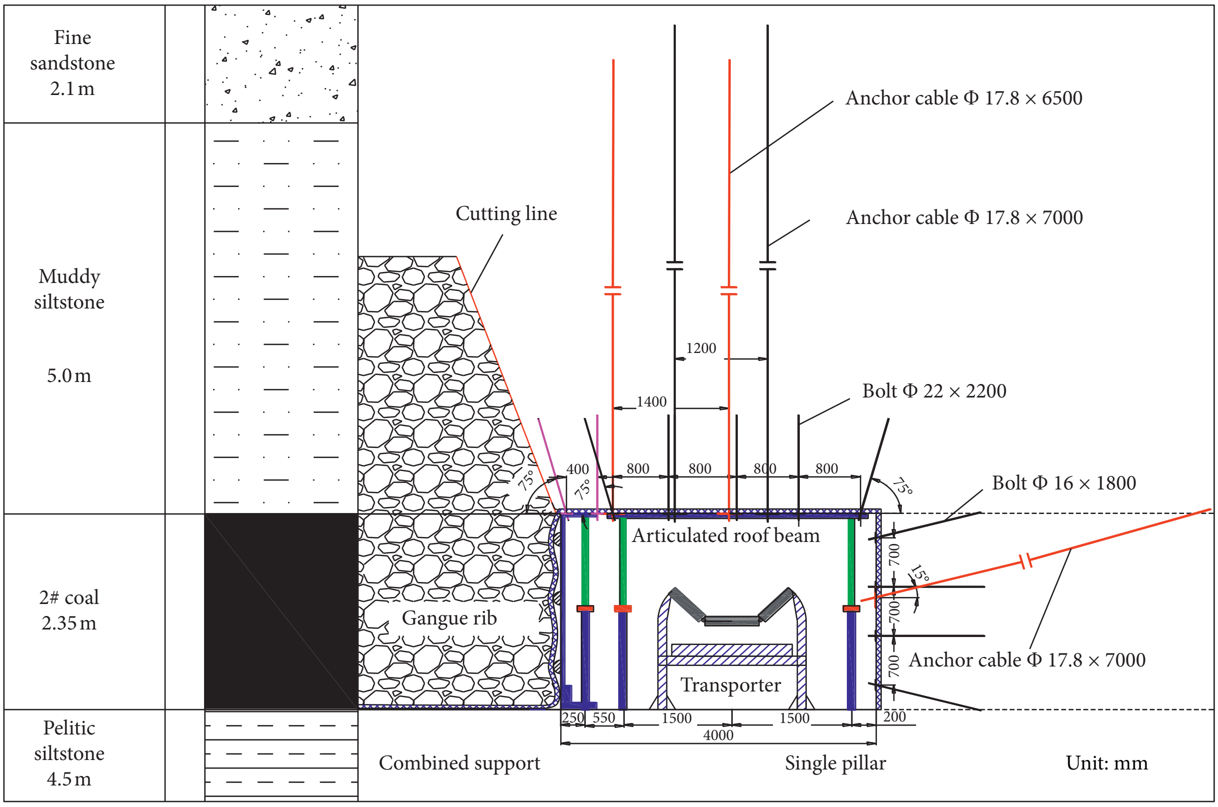


Figure 11: The support design of the gob-side entry retaining.

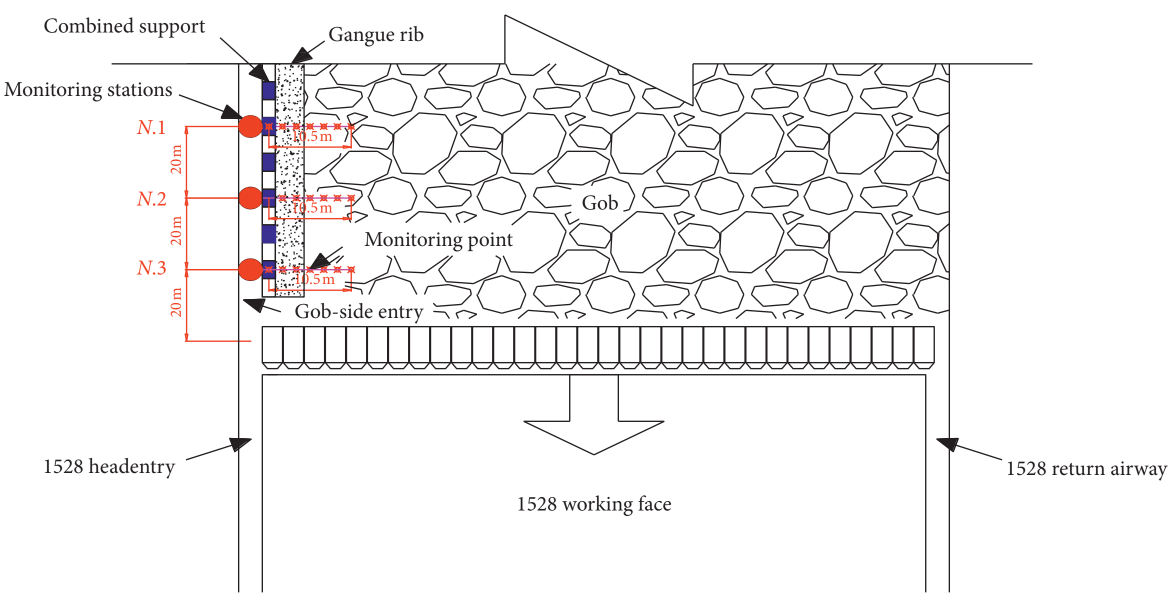


Figure 12: Monitoring stations.

semicircular pieces of wood used to enhance the protective performance of the roadside. The semiround wood specifications are Φ180 × 1400 mm. In addition, the double-layer flexible metal meshes were projected on the gob behind the combined cutoff brackets. The metal mesh specifications were 1 m × 10 m, and the metal meshes were ligated to each other. The metal mesh was tied together to form a whole metal mesh, one end was fixed on the roof with bolt, with the other end buried 1.8 m in the gob. The semicircular wood and the combined support were used as the skeleton for the metal meshes to enhance their ability to protect the surface and effectively prevent gangue from penetrating into the roadway. The support design of the gob-side entry retaining is shown in Figure 11.

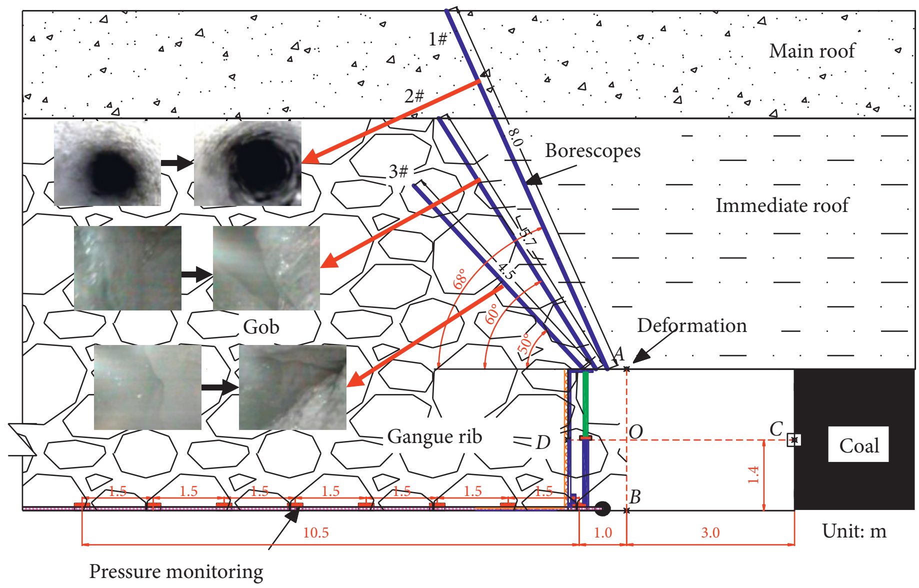


Figure 13: Monitoring layout.

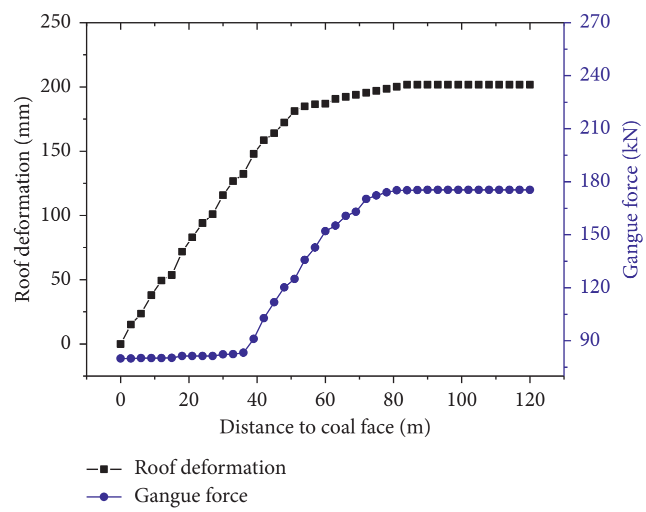


Figure 14: Monitoring results.

4.3. Engineering Field Monitoring. In order to evaluate the support effect of the roof-cutting combined support and the feasibility of the automatic roadway technology for cutting roofs by combined support on gob-side entry retaining with no-pillars, the displacement of the roof to the floor and the displacement of coal rib to the gangue rib were measured by crossing points. The displacement sensors were installed at each monitoring point to record displacement monitoring data. The breakage of the side roof in the gob was observed, and the breakage location of the roof was recorded by borescopes. The pressure of the gangue rib in the gob was measured by pressure sensors. There are three survey stations along the 1528 transport roadway. The survey station N.1 is located at the beginning of the gob-side entry retaining. After that, the survey stations N.2 and N.3 were projected sequentially, and the interval of stations N.1, N.2, and N.3 was 20 m, as shown in Figure 12. In order to monitor the vertical stress of the gangue in the gob on the gob-side entry retaining, pressure sensors were projected within a 0–10.5 m interval of 1.5 m to record pressure monitoring data, as shown in Figure 13.

4.4. Analysis of Roadside Support Resistance and Roof Movement. The field observation data show that the actual detection results of the borescopes determine that the breakage angle range of the thickness of the immediate roof is 51°–68°. It is observed that the gangue filled the gob and is in contact with the inclined surface formed after the roof break (Figure 13).

The measured initial bearing pressure of the gangue rib is 81 kN, and the final bearing pressure of the gangue rib is 178 kN. The actual weight of the caved gangue is about 125 kN, so the gangue has supporting force after upper

Figure 15: Image of the automatic roadway technology for cutting roofs by combined support on gob-side entry retaining.

compaction. The difference of the supporting force between the final bearing pressure of the gangue rib and the actual weight of the caved gangue is 53 kN. In the initial stage (0–35 m), the bearing pressure of gangue is small; in the compaction stage (35–80 m), the bearing pressure of gangue increases rapidly; and in the stable stage (80–120 m), the bearing pressure of gangue tends to be stable gradually. The cumulative displacement of the roof is 212 mm, as shown in Figure 14. The surrounding rock control on the gob-side entry retaining is effective, as shown in Figure 15.

5. Conclusions

In this paper, we introduced the supporting principles and key technologies of automatic roadway technology for cutting roofs by combined support on gob-side entry retaining with no-pillars in longwall mining. Engineering field tests were carried out. The results show that these technologies can be applied effectively. The main research conclusions are as follows.

The main principle of the mining technology behind automatic roadway technology for cutting roofs by combined support on gob-side entry retaining with no-pillars has two aspects. On the one hand, the immediate roof and the main roof are cut off at the side of the gob by the combined support, so the length of the cantilever beam of the roof is reduced, and the mechanical transmission of the overburden is reduced. On the other hand, the volume expansion of caved gangue after breaking is used to fill the gob and form the gangue rib of the roadway. Through the contact and compaction process between the overlying strata and the gangue, the movement of the overlying strata is slowed down, the support pressure of roadway is reduced, the deformation and destruction of the surrounding rock are reduced, and the stability of the rock surrounding the roadway is improved.

The key techniques behind automatic roadway technology for cutting roofs by combined support on gob-side entry retaining with no-pillars mainly include the roof-cutting technology with combined support, the reinforcement and support technology with the roof and the coal rib in the advanced region, the gangue rib control technology in the gob, and the auxiliary support technology with beam and prop in the roadway. In the advanced support area, the roof and coal rib of the roadway are supplemented with anchor cables, which can enhance the inherent strength of the surrounding rock and reduce the continuous deformation of the surrounding rock caused by mining. The auxiliary support of two single props with one articulated roof beam is situated in the roadway. This support can inhibit the early separation of the roof. Projecting combined support on the roadside can provide higher support resistance and stronger lateral pressure resistance, which can not only cut off the immediate roof and the main roof on the gob, thereby reducing the mechanical transmission of the overlying strata, but also prevent damage to the combined roof-cutting support caused by the lateral impact of the gangue. In addition, after the caved rock mass is broken, its volume expands and fills the gob. The gangue control system controls the caved rock mass to form a gangue rib, which can support the roof by the bearing of the gangue rib.

A field engineering test of the surrounding rock based on the automatic roadway technology for cutting roofs by combined support on gob-side entry retaining shows that due to roof-cutting technology with combined support, the reinforcement and support technology with the roof and coal rib in the advanced region, the gangue rib control technology in the gob, and the auxiliary support technology with beam and prop in the roadway, the deformation rate and deformation scale of the rock surrounding the roadway are significantly reduced. In addition, the aforementioned control measures are effective. Thus, this study proves the rationality and feasibility of the automatic roadway technology for cutting roofs by combined support on gob-side entry retaining.

Data Availability

All data contained in this study are available upon request from the corresponding author.

Conflicts of Interest

The authors declare no conflicts of interest.

Acknowledgments

The authors would like to thank the continuous support from Gequan Coal Mine and Mine Manager Xiaoming Wang during the on-site sampling and monitoring. This research was funded by the China Postdoctoral Science Foundation (Grant no. 2019M650895), the National Natural Science Foundation of China (Grant no. 51504259), the Fundamental Research Funds for the Central Universities (Grant no. 2010QZ06), and the Yue Qi Young Scholar Project, China University of Mining & Technology, Beijing (Grant no. 800015Z1104).

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] M. G. Qian, "Structure model of overlying strata in longwall faces and its application," *Journal of China University of Mining & Technology*, vol. 16, no. 16, pp. 2–6, 1982.

[4] Z. Q. Song, "Basic motion rules of overlying strata in longwall faces," *Journal of Shandong Mining Institute*, vol. 25, pp. 12–25, 1979.

[5] 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.

[6] M. He, X. Zhang, and S. Zhao, "Directional destress with tension blasting in coal mines," *Procedia Engineering*, vol. 191, pp. 89–97, 2017.

[7] C.-l. Han, N. Zhang, B.-y. Li, G.-y. Si, and X.-g. 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.

[8] R. Wu, Q. He, J. Oh, Z. Li, and C. Zhang, "A new gob-side entry layout method for two-entry longwall systems," *Energies*, vol. 11, no. 8, p. 2084, 2018.

[9] G. C. Zhang and Y. L. Tan, "Numerical estimation of suitable gob-side filling wall width in a highly gassy longwall mining panel," *International Journal of Geomechanics*, vol. 18, no. 8, Article ID 04018091, 2018.

[10] S. Yan and T. X. Liu, "Key parameters of gob-side entry retained in A gassy and thin coal seam with hard roof," *Processes*, vol. 6, 15 pages, 2018.

[11] J. Z. Li, M. Zhang, Y. Li, and H. Hu, "Surrounding rock control mechanism in the gob-side retaining entry in thin coal seams, and its application," *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 118, no. 5, pp. 2225–6253, 2018.

[12] P. S. Zhang, Z. H. Kan, W. Yan, B. Shen, Y. P. Zhao, and S. X. Wu, "Experimental study on the stability of surrounding soft rocks of gob-side entry retained in fully mechanized caving," *Journal of the Southern African Institute of Mining and Metallurgy*, vol. 118, no. 5, pp. 2225–6253, 2018.

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

[14] D. C. Williams, "Packing technology," *Mining Technology*, vol. 3, pp. 73–76, 1988.

[15] Y. F. Li and X. Z. Hua, "Mechanical analysis on the stability of surrounding rock structure of gob-side entry retaining," *Journal of China Coal Society*, vol. 42, no. 9, pp. 2262–2269, 2017.

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

[17] B. B. Chen and C. Y. Liu, "Analysis and application on controlling thick hard roof caving with deep-hole position presplitting blasting," *Advances in Civil Engineering*, Article ID 9763137, 15 pages, 2018.

[18] X. G. Ma, M. C. He, Y. J. Wang, Y. Zhang, J. B. Zhang, and Y. X. Liu, "Study and application of roof cutting pressure releasing technology in retracement channel roof of Halagou 12201 working face," *Mathematical Problems in Engineering*, vol. 2018, Article ID 6568983, 15 pages, 2018.

[19] T. Zhao, C. Liu, A. K., B. Zhang, and S. Zhang, "Fractural structure of thick hard roof stratum using long beam theory and numerical modeling," *Environmental Earth Sciences*, vol. 76, no. 21, 2017.

[20] H. Liu, J. Dai, J. Jiang, P. Wang, and J. Yang, "Analysis of overburden structure and pressure-relief effect of hard roof blasting and cutting," *Advances in Civil Engineering*, vol. 2019, Article ID 1354652, 14 pages, 2019.

[21] M. C. He, X. G. Ma, and B. Yu, "Analysis of strata behavior process characteristics of gob-side entry retaining with roof cutting and pressure releasing based on composite roof structure," *Shock and Vibration*, vol. 2019, Article ID 2380342, 12 pages, 2019.

[22] X. Sun, Y. Liu, and J. Wang, "Study on three-dimensional stress field of gob-side entry retaining by roof cutting without pillar under near-group coal seam mining," *Processes*, vol. 7, no. 9, p. 552, 2019.

[23] E. Zhen, Y. Gao, Y. Wang, and S. Wang, "Comparative study on two types of nonpillar mining techniques by roof cutting and by filling artificial materials," *Advances in Civil Engineering*, vol. 2019, Article ID 5267240, 15 pages, 2019.

[24] X. Chen, L. Li, Z. Guo, and T. Chang, "Evolution characteristics of spontaneous combustion in three zones of the goaf when using the cutting roof and release pressure technique," *Energy Science & Engineering*, vol. 7, no. 3, pp. 710–720, 2019.

[25] P. Zhou, Y. Wang, G. Zhu, and Y. Gao, "Comparative analysis of the mine pressure at non-pillar longwall mining by roof cutting and traditional longwall mining," *Journal of Geophysics and Engineering*, vol. 16, no. 2, pp. 423–438, 2019.

[26] Y. Wang, J. Yang, M. He et al., "Test of a liquid directional roof-cutting technology for pressure-relief entry retaining mining," *Journal of Geophysics and Engineering*, vol. 16, no. 3, pp. 620–638, 2019.

[27] W. Janach, "The role of bulking in brittle failure of rocks under rapid compression," *International Journal of Rock Mechanics and Mining Sciences & Geomechanics Abstracts*, vol. 13, no. 6, pp. 177–186, 1976.

[28] R. Doostmohammadi, M. Moosavi, and B. N. Araabi, "A model for determining the cyclic swell-shrink behavior of argillaceous rock," *Applied Clay Science*, vol. 42, no. 2, pp. 81–89, 2008.

[29] X. X. Miao, X. B. Mao, and G. W. Hu, "Research on broken expand and press solid characteristics of rocks and coals," *Journal of Experimental Mechanics*, vol. 12, no. 3, pp. 395–399, 1997.

[30] J. F. Zha, G. L. Guo, Y. X. Liu, and B. Wu, "The nonlinear features of waste deformation and its impaction on strata movement," *Journal of the China Coal Society*, vol. 34, no. 8, pp. 1071–1075, 2009.
[31] Z. Q. Song, Z. D. Cui, H. C. Xia, J. Q. Tang, and Z. J. Wen, "The fundamental theoretial and engineering research on the green safe no coal pillar mining model by mainly using coal gangue backfill," *Journal of the China Coal Society*, vol. 35, no. 5, pp. 705–710, 2010.
[32] C.-l. Han, N. Zhang, R. Gao, and H.-Q. Yang, "Superposed disturbance mechanism of sequential overlying strata collapse for gob-side entry retaining and corresponding control strategies," *Journal of Central South University*, vol. 25, no. 9, pp. 2258–2271, 2018.
[33] P. Gong, Z. Ma, X. Ni, and R. R. Zhang, "An experimental investigation on the mechanical properties of gangue concrete as a roadside support body material for backfilling gob-side entry retaining," *Advances in Materials Science and Engineering*, vol. 2018, pp. 1–11, 2018.