IN THE FIELD

An innovative approach for gob-side entry retaining in deep coal mines: A case study

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Abstract
Due to the complex geostress and mining conditions in the coal seam with depth of 800 m, stability of surrounding rock for gob-side entry retaining is very difficult to achieve. In this paper, we firstly propose an innovative bolt-grouting controlled roof-cutting for gob-side entry retaining (BCR-GER) approach for deep coal mines. Secondly, a mechanical model of “surrounding rock-supporting body” for BCR-GER is constructed, which consists of coal wall, roadside props, and gangues in gob (the whole supporting body). Thirdly, the key parameters (ie, cutting height, cutting angle, grouting cable length, and row of roadside props) are designed. Finally, field practice was applied at the No. 31120 haulage roadway of the Suncun coal mine in China, and in situ investigations were conducted for verification. Field measurement results show that maximum convergences of roof-to-floor and side-to-side were 264 mm and 113 mm, respectively. What is more, the maximum support resistance of roadside props was reduced by approximately 58%. The deformation and failure of surrounding rock were effectively controlled, and the pressure on roadside props was greatly reduced. This research fully considers the bearing properties of gangues in gob, eliminates the secondary disasters caused by borehole blasting, and provides guidance and reference for deep surrounding rock control of the same or similar gob-side entry.

KEYWORDS
BCR-GER approach, deep-mining condition, mechanical model, parameters optimization

INTRODUCTION
Gob-side entry retaining technology is used to maintain the original roadway for the next working face mining by building pastes or high-water backfills with 1-3 m wide along the gob as roadside support.1-5 This technology has good economic and social benefits, because it omits the protective coal pillar...
in the roadway, fundamentally eliminates the stress concentration in coal pillars and improves the recovery rate of coal resources. Furthermore, it effectively alleviates tense situations between mining and excavation. Currently, gob-side entry retaining has become a major reform for surrounding rock control technology, and one of the most important development directions of coal mining.6-9

Many theoretical studies and field practices on gob-side entry retaining technology have been completed, and four major advancements should be considered. First, roof-and-floor movement evolution and transfer bearing mechanism of gob-side entry have been revealed. Roof movement is divided into three stages: early stage, transition stage, and later stage; and two basic forms: roof rotation and subsidence.10-14 On this basis, Zhang et al.15-18 proposed the concept of a wedge-shaped bearing area and further clarified the transmission and bearing mechanism of the gob-side roof. Additionally, floor deformation and failure processes of gob-side entry retaining were studied during roadway driving, primary mining, and secondary mining periods. These researches revealed that the floor-strata strain turns from tensile to compression with mining depths increasing.19-23 Second, quick-setting high-water materials with constant resistance features24-28 and paste materials with high strength and low costs29-33 were developed to construct roadside backfill. Compared with traditional wooden stacks, intensive individual props, gangue bags, and concrete blocks, these new materials have greater resistance, faster increasing-resistance, higher filling efficiency, and better sealing effects.34-36 Third, the loading structure of the roadside backfill has been optimized, greatly improving its stress environment. Tan et al.37-40 proposed a soft-strong combined roadside support structure under the condition of long-lateral hanging roof, transferring the weight of roof strata to the gangues in gob by moderately yielding of roadside support. This not only significantly reduces the pressure on the hanging roof but can also induce dynamic impact disasters.

This paper firstly proposes an innovative approach of bolt-grouting controlled roof-cutting for gob-side entry retaining (BCR-GER) in deep coal mines. Secondly, the mechanical model of the “surrounding rock-supporting body” for the BCR-GER approach is constructed and the mechanical analysis of the co-bearing structure of the “coal wall-roadside props-gangues” is conducted. Thirdly, the key parameters (ie, cutting height, cutting angle, grouting cable length, and row of roadside props) are designed. Finally, field practice is carried out at the No. 31120 haulage roadway of the Suncun coal mine.

2 | AN INNOVATIVE APPROACH OF BCR-GER

2.1 | Approach principle and stages

Compared with shallow mining, the stress environment of the deep surrounding rock changes greatly, including high-ground pressures and large dynamic load disturbances, causing large-scale deformation and serious damage to roadside supports. Roof-cutting can use load-bearing characteristics of gangues in gob to effectively reduce the stress on roadside supports and improve the stability of the surrounding rock. Considering that there are many problems in roof-cutting via borehole blasting, an innovative approach of BCR-GER is proposed in this paper. Here, boreholes with diameter of 60 mm are added along the gob side beyond the influence of front abutment pressure to form the presplitting surface, so that the hanging roof can be cut down smoothly. According to the theory of rock dilatancy, the volume of the hanging roof will become larger after collapsing and can be directly used as a load-bearing structure to support the upper roof. This not only significantly reduces the pressure on the hanging roof subsidence, limits the sinking movement space and controls the surrounding rock deformation, it also fully utilizes the bearing characteristics of gangues in gob to bear the weight of overlying strata as much as possible. Specifically, the BCR-GER approach includes the following four stages:
Stage one: roof presplitting. Large-diameter roof-cutting boreholes are constructed with certain spacing, heights, and angles beyond the influence of front abutment pressures, making the surrounding rock near the boreholes fully crack and expand. This forms a roof-cutting presplitting surface to create appropriate conditions for roof-cutting.

Stage two: high-strength grouting. High-strength grouting cables are installed along the inside of the cutting line within the influence of front abutment pressures during the mining period. Simultaneously, the grouting cables are constructed in the roadway to reinforce the surrounding rocks. Then, delay grouting is conducted for 1-2 days. On one hand, the cables firmly suspend the immediate roof on the main roof, which makes the roofs move synchronously while avoiding impact caused by separation layers. On other hand, the damaged surrounding rocks can be actively repaired via grouting, which can improve the roof strength and integrity and can maintain the stability of surrounding rock. Most importantly, the fissure development in surrounding rock of newly excavated roadways is insufficient. If grouting is constructed immediately after excavation, and then the original surrounding rock fissures will continue to expand and develop, and even generate new fissures under the front abutment pressure, which cannot achieve the desired grouting effect. The delayed grouting is carried out after the surrounding rock fissures are fully developed. It can further fracture the surrounding rocks under the front abutment pressure, which is conducive to the diffusion of grouting slurry, and greatly improving the reinforcement effect.

Stage three: roadside roof-cutting. Roadside props are set as active supports when constructing high-strength grouting cables. First, roadside props provide support resistance to prevent the roof from rapidly sinking. Second, owing to roof-cutting and the construction of grouting cables, the roof strata attain an unequal strength beam structure. Thus, the strength of the roadway roof becomes high and the strength of the hanging roof becomes low. Under these circumstances, setting up roadside props can cause inconsistent deformations between the roadway and hanging roofs, which is beneficial to roof-cutting. Third, the roadside props can produce a lateral restraint to the gangues, which can effectively improve its bearing capacity.

Stage four: supplementary supporting. Other supporting measures are adopted according to the conditions of roof-cutting and surrounding rock deformations or failures after the working face is mined. For example, metal mesh is hung along the gob-side to retain gangues, and bolt-grouting is applied to reinforce the gangue wall when its deformation is large. Then, the gangue wall is sprayed with concrete to prevent air leakage while gradually withdrawing the roadside props. The technological process of the BCR-GER approach is shown in Figure 1. The profiles of the BCR-GER approach are shown in Figure 2.

2.2 | Key techniques

The technological process of the BCR-GER approach mainly includes the following key techniques: advanced borehole presplitting, high-strength grouting cable support, and roadside props support.

2.2.1 | Advanced borehole presplitting technique

Advanced borehole presplitting technique drills boreholes with diameter of 60 mm upward along the gob-side beyond
the influence of front abutment pressure to generate the initial fracture around the boreholes, as shown in Figure 3. With the working face advancing, the influence range of the front abutment pressure also moves forward, and the initial crack expands farther under the high abutment pressure and periodic weighting. Finally, several surrounding rock fissures interpenetrate to form the presplitting surface, effectively blocking the transmission of roof-rock pressure, significantly eliminating stress concentrations, and creating conditions for subsequent roof-cutting.

2.2.2 | High-strength grouting cable supporting technique

During roof-cutting in deep mines, the deformation of surrounding rock experiences many stages, including deformation caused by working face advancing, deformation caused by strata restabilization, and deformation caused by the next working face mining. Because traditional cable supports cannot effectively improve roof integrity, cable falling, and deformations occur frequently, as shown in Figure 4A, which does not meet normal production requirements. As shown in Figure 4B, a high-strength grouting cable comprises a hollow grouting cable and high-strength grouting slurry. The grouting slurry is injected into the roof-rock strata through a grouting hole at the bottom of the cable. The high-strength grouting cable can not only suspend the immediate roof strata on the main roof, it can also improve the integrity of the rock strata via grouting. During the mining period, the grouting cables are constructed obliquely upward along the cutting line within the influence range of the front abutment pressure and the grouting construction is delayed for a period. Therefore, the roof-rock strata along the gob can be regarded as a rock beam structure with unequal strength. This means the rock strata has high strength in the roadway roof and low strength in the gob-side roof. This is beneficial for the hanging roof to collapse along the presplitting surface to the gob. Moreover, delayed grouting can effectively facilitate the diffusion of grout and enhance the reinforcement effect.

2.2.3 | Roadside props support technique

A row of roadside individual props are arranged inside the cutting line during the construction of grouting cables. On one hand, they provide greater support resistance, which can serve to actively support the restriction of subsidence movement and can provide adequate time for slurry condensation. On other hand, roadside props are at the fixed end of the hanging roof, which can produce large stress concentrations on the cutting line. Thus, the primary cracks in roof strata and the cracks formed by mining will extend and develop until a presplitting surface is formed, which can ultimately enable the hanging roof to be cut down. Additionally, a metal mesh

FIGURE 2 The profiles of the BCR-GER approach. A, A-A directional profile. B, B-B directional profile

FIGURE 3 Large-diameter advanced presplit borehole
3 | MECHANICAL ANALYSIS AND KEY PARAMETERS DESIGN

3.1 | Mechanical model establishment

High-ground pressures and huge mining dynamic stresses are superimposed with the advancing working face in deep gob-side entry retaining, causing serious deformation and failure of the surrounding rock. Additionally, the main roof fractures on the coal wall and subside along the caving line.10-14 Under these conditions, it becomes very difficult for the traditional roadway support to resist the huge pressures caused by the surrounding rock deformation and hanging roof subsidence, which is harmful to roadside supports. The BCR-GER approach can effectively improve the stress environment of the surrounding rock by cutting the hanging roof and exerting the bearing properties of collapsed gangues. A simplified structural mechanical model of the “surrounding rock-supporting body” is established for the BCR-GER approach, as shown in Figure 6.

The roadway roof can be approximately regarded as an unequal strength beam structure comprising a coal wall at one end and a hanging roof with grouting anchor cables at the other. As shown in Figure 6, the mining height is \( h \); the immediate roof thickness is \( h_Z \); the main roof thickness is \( h_E \); the distance from the caving line to the coal wall is \( L_0 \); the width of the roadway is \( L_R \); the length of the hanging roof is \( L_S \); the in-site stress \( q \), of overlying strata is uniformly applied on the main roof; and the length of the rock beam B is \( L_E \).

The supporting resistance of the coal wall can be expressed by \( F_{M} \), and the supporting effect of gangues can be expressed by a triangular distributed load, ranging 0–\( q_2 \). The right edge of rock beam B contacts the gangues in gob first, and the bearing length of gangues without roof-cutting is \( L_{G1} \). As the hanging roof continues to subside, the contact point gradually moves to the left and \( L_{G1} \) increases accordingly.

3.2 | Mechanical analysis

3.2.1 | Main roof rotation angle

As shown in Figure 6, in the process of continuous subsidence of rock beam B, the ultimate subsidence, \( \Delta h \), is determined per the theory of elasticity.16,24

\[
\Delta h = h - h_Z (K_A - 1)
\]  

(1)

\( K_A \) is bulking factor of the rock, which is related to the nature of the collapsed gangue. It generally ranges 1.15–1.35. According to the movement feature of overlying...
strata, the rotation angle of rock beam B is determined as follows:

$$\theta = \arcsin \frac{\Delta h}{L_E}$$  \hspace{1cm} (2)

### 3.2.2 Cutting force

To effectively cut the roof along the gob-side, cutting force $P_c$ must satisfy the following mechanical condition:

$$P_c = \max \{ P_A, P_B \}$$ \hspace{1cm} (3)

$P_A$ is the force generated by the collapsed roof, kN, and $P_B$ is the support resistance provided by the roadside props when the hanging roof collapsed, kN. As shown in Figure 6, force $P_A$, generated by the collapsed roof, can be determined as:

$$P_A = h_z \gamma E L_S$$ \hspace{1cm} (4)

$\gamma_E$ is the volumetric weight of immediate roof strata, kN/m$^3$. As we can see in the figure, the weight of rock beam B, $F_E$, and the weight of immediate roof $F_Z$ can be determined, respectively.

$$F_E = h_E \gamma_E L_E$$ \hspace{1cm} (5)

$$F_Z = \frac{h_z \gamma_E (L_0 + L_R)}{\cos \theta}$$ \hspace{1cm} (6)

$\gamma_E$ is the volumetric weight of rock beam B, kN/m$^3$. Based on Salamon’s equation,\textsuperscript{61} the support resistance of gangue $q_2$ can be determined:

$$q_2 = \frac{E_0 \varepsilon}{1 - \frac{\varepsilon K_A}{K_A - 1}}$$ \hspace{1cm} (7)

$E_0$ is initial tangential modulus, $\varepsilon$ is the volumetric strain under the in-site stress $q$. Assuming the distribution of gangue support resistance is linear, $F_G$ can be determined as follows \textsuperscript{61-64}:

$$F_G = \frac{1}{2} q_2 L_{G1}$$ \hspace{1cm} (8)

According to rock dilatancy\textsuperscript{46-49} we assume that the collapsed gangues fill the gob. So the length of gangue in gob after roof-cutting is $L_{G2}$.

$$L_{G2} = L_E \cos \theta - L_0 - L_R$$ \hspace{1cm} (9)

Assuming the roof pressure is uniformly applied to the roadside support, and the support resistance in the roadway is not considered, then the mechanical equilibrium equation is established as follows:

$$\sum F = F_A + F_G - F_Z - F_E - qL_E = 0$$

$$\sum M = \frac{1}{2} F_G (L_0 + L_R) + F_E \sin \theta - \frac{1}{2} F_Z (L_0 + L_R) - \frac{1}{2} F_E \cos \theta - \frac{1}{2} qL_E \sin \theta = 0$$ \hspace{1cm} (10)

According to Equation (9):

$$P_B = \frac{\frac{1}{2} L_E \cos \theta (qL_E + F_E) + \frac{1}{2} F_Z (L_0 + L_R) - F_G (L_E \cos \theta - \frac{1}{2} L_0) - \frac{1}{2} L_0 (qL_E + F_E + F_Z)}{\frac{1}{2} L_0 + L_R}$$ \hspace{1cm} (11)

Therefore, support resistance $P_B$ can be obtained by substituting Equations (5), (6), and (7) into Equation (10). Then, the required cutting force $P_c$ can be obtained by comparing the magnitude of force $P_A$ and support resistance $P_B$.

### 3.3 Key parameter design

#### 3.3.1 Cutting height

Theoretically, the cutting height should be greater than or equal to the height of the immediate roof to ensure...
the gangue generated by roof-cutting can fill the gob. Additionally, cutting height is determined by the dilatancy of the roof rock and the ultimate subsidence of the main roof. Therefore, cutting height \( h_C \) should satisfy the following relationship:

\[
h_C \cdot K_A + L_E \sin \theta - (h_C - h_Z) = h_Z + h
\]  

From this, cutting height \( h_C \) can be determined:

\[
h_C = \frac{h - L_E \sin \theta}{K_A - 1}
\]

### 3.3.2 Cutting angle

According to many field engineering practices, the different cutting angles make a great difference to the roof-cutting effect, and they greatly influence movement features and stress distributions of overlying strata. Taking the immediate roof as the study object, the mechanical model is shown in Figure 7.

As shown in Figure 7A, the bending deformation of the immediate roof occurs under the self-weight load, \( F_Z \), and the main roof load, \( q_E \). The extrusive friction resistance, \( \tau \), is generated near the cutting line. Therefore, the conditions for roof-cutting should be:

\[
q_E L_S + F_Z > \tau
\]

As shown in Figure 7B, when the roof-cutting has a certain angle, the extrusive friction resistance, \( \tau^* \), near the cutting line, is:

\[
\tau^* = \tau \cdot \cos^2 \alpha
\]

The extrusive friction resistance here is far less than that of the vertical roof-cutting. Therefore, the borehole should be perpendicular to the roadway axis and inclined to the working face at a certain angle so that the roof can be cut down smoothly. According to many field construction experiences, the effect of roof-cutting is much better when the inclined angle, \( \alpha \), is 65°-85°.

### 3.3.3 Grouting cable length

To ensure that grouting cables are suspended into the stable rock strata, grouting cable length, \( L_M \), should be larger than the cutting height to a certain range. Based on theoretical analysis and field engineering practices, the grouting cable length, \( L_M \), is determined as follows:

\[
L_M = \max \left( L, h_c / \sin \alpha + 1.0 - 2.0 \right)
\]

where \( h_c / \sin \alpha \) is the length of roof-cutting borehole, m, and \( L \) is the grouting cable length during roadway development, m.

### 3.3.4 Roadside props row

According to the above analysis, the cutting force, \( P_C \), can be obtained and the row, \( b \), of roadside props can be determined:

\[
b = \frac{P_C}{R}
\]

\( R \) is the rated working resistance of roadside props, kN/m.

### 4 ENGINEERING APPLICATION

#### 4.1 Project overview

Suncun coal mine is in Tai’an, Shandong Province, China, as shown in Figure 8. The mine field is 9.1 km long, 3 km wide, and covers an area of 21.2 km². The southern boundary of the minefield is a coal seam outcrop. The northern boundary is a coal seam with 1050 m contour. The western boundary is the original position of fault F8. The eastern boundary is the boundary of the northern Jurassic scouring boundary between faults F6 and F10. The coal mine contains 19 coal seams, where No. 2, No. 4, and No. 11 are main seams. The geological coal reserves are 96.634.900 t and the recoverable reserves are 49.958.400 t, among which the recoverable reserves below −800 level account for 64%. Additionally, the mine service life is 29.7 years, which has a very good development prospect.

The 31120 working face of Suncun coal mine is located at level −800 m, group 11, 3rd mining area. This working face has 595 m strike length and the 172.2 m inclination length on average. Its elevation is −750.93-840.93 m.
and the buried depth is 930.93-1032.93 m. Besides, the thickness of the coal seam is 2.3-3.7 m, with an average of 3.0 m. The immediate roof is siltstone with a thickness of 4.7-5.9 m at an average of 5.3 m. The top of the immediate roof is the main roof, comprising fine sandstone with an average thickness of 4.8 m and medium sandstone with an average thickness of 6.1 m. The upper part of the main roof is the overlying strata, comprising limestone with an average thickness of 2.8 m, sandy mudstone with an average thickness of 4.4 m, and mudstone with an average thickness of 24.0 m. Moreover, the immediate floor is siltstone with a thickness of 3.3-5.1 m at an average of 4.2 m. The main floor is mudstone with a thickness of 15.3-17.5 m at an average of 16.4 m. The stratigraphic sequence of the No. 11 coal seam and its roof-and-floor rock strata are shown in Figure 9.

The No. 31120 haulage roadway is a gob-side entry, and the roadway section is rectangular with net width of 4.0 m × net height, 3.0 m. Before optimization, the roadway support adopted the joint support of cables and metal nets. The roof was supported by Φ20 × 4000 mm cables, and three rows were arranged with spacing of 1500 × 1000 mm, paired with net. The coal wall used Φ20 × 4000 mm cables. Three rows of cables were arranged at a spacing of 1000 × 800 mm. Along the gob-side, the 1500-mm-wide paste backfill was set as the support structure and the roadway support section, as shown in Figure 10. Owing to the complex environmental factors (e.g., three highs and one disturbance) in deep mines, the roof of No. 31120 haulage roadway subsided greatly, and the surrounding rock was extremely damaged, causing many serious accidents, such as rib spalling and roof falls, as shown in Figure 11.
4.2 Parameter optimization

Based on the above theoretical analysis and derivation results, the support scheme of No. 31120 haulage roadway was optimized. The main supporting materials included individual props, hollow grouting anchor cables, grouting slurry. Based on field monitoring results, parameters of the BCR‐GER approach were selected, as listed in Table 1. Substituting the above parameters into Equations (1) and (2), the ultimate subsidence of rock beam B was \( \Delta h = 1.8 \) m, and the hanging main roof rotation angle was \( \theta = 6.5^\circ \). The above parameters can be brought into Equation (12) to determine the cutting height, \( m_C = 6.0 \) m. According to the theoretical analysis and practical experience of the project, the cutting angle, \( \alpha = 70^\circ \), was determined and the high‐strength grouting cable length was \( L_M = 7.8 \) m during the mining period. Thus, \( F_E = 2150.4 \) kN, \( F_Z = 813.5 \) kN and \( F_G = 8767.6 \) kN. Substituting these parameters into Equations (4) and (10), \( P_A = 424 \) kN and \( P_B = 5506.4 \) kN. Then, the cutting force, \( P_C = 5506.4 \) kN, can be obtained via Equation (3), and the row of the roadside props, \( b = 0.8 \) m, can be obtained via Equation (16).

The postoptimization support scheme is as follows: a roof‐cutting borehole 6 m long; 0.6 m spacing; and 70° horizontal elevation angle to presplit the roof. Then, there are three rows of \( \Phi 22 \times 7000 \) mm high‐strength grouting cables spaced 600 × 800 mm, set up in the gob‐side entry to support the roof. To enhance the cutting ability, a row of \( \Phi 22 \times 7800 \) mm high‐strength grouting cables spaced 600 × 800 mm is added near the cutting line. The coal wall is equipped with \( \Phi 22 \times 7000 \) mm grouting cables, and three rows spaced 1000 × 800 mm are arranged for support. Additionally, in order to guarantee that the grouting slurry has sufficient compressive strength, we use the modified slurry whose water‐cement ratio is 1:1.5, and the additive content is 8%. The compressive strength can reach up to 72MPa through pull‐out test. Moreover, the grouting construction is delayed by the cable construction for 1‐2 days. For the roadside support, hydraulic props are selected, and
one row is arranged as roadside support at 800mm distance. The optimized section of No. 31120 haulage roadway is shown in Figure 12.

4.3 | Effect analysis

4.3.1 | Surrounding rock displacement monitoring

To test the supporting effect of the BCR-GER approach in the No. 31120 haulage roadway, three laser range finders (1#, 2# and 3#) were, respectively, arranged at 50 m, 100 m, and 150 m from the working face to monitor the displacement of the surrounding rock surface.

The relationship between the displacement of the surrounding rock surface and the distance from the working face is shown in Figure 13. It can be seen from the figure that the side-to-side displacement is obviously smaller than that of the roof-to-floor. On the advanced working face, the displacement of the surrounding rock is almost 0 within 100-32 m, indicating that the roadway is not affected by mining yet. Although the deformation of surrounding rock increases sharply within about 32 m, it infers that this range is the influence range of front abutment pressure.

Monitoring of surrounding rock displacement continues after mining the working face. In the lagged working face, the displacement of surrounding rock increases rapidly within a range of 2-23 m and the deformation speed slows down at a range of 23-45 m. Then, the deformation tends to stabilize after about 45 m. This infers that the displacement of surrounding rock is large, owing to the main roof subsidence within the range of 2-23 m. The gangues in gob play a supporting role on the roof and slow the deformation speed within the range of 23-45 m. Then, the main roof movement tends to be stable and the surrounding rock is nearly undeformed after 45 m behind the working face. When the surrounding rock movement is stabilized, the maximum displacements of roof-to-floor and side-to-side are 264 mm and 113 mm, respectively. The integrity of surrounding rock improves remarkably, which meets the normal utilization.

4.3.2 | Roadside props support resistance monitoring

The supporting resistance monitoring of roadside props is carried out under the influence of front abutment pressure in the No. 31120 haulage roadway. The measuring points are increased forward as the working face advances. Some of the props are selected to monitor support resistance with piezometers, which can inflect their working state during the gob-side entry retaining. The measuring point arrangement is shown in Figure 14.

According to the regulations and requirements of mining pressure monitor, a continuous and systematic observation should be carried out. The relationship between support resistance of the roadside props and the distance from the working face is shown in Figure 15. When the measuring points are 60 m ahead of the working face, the support resistance begins to rise. The support resistance increases rapidly within the range of 60-32 m, indicating that the peak value of the front abutment pressure is about 32 m ahead of the working face. As the working face continues to advance, the support resistance decreases. When the measuring points lag the working face at about 8 m, the support resistance is minimized, because the hanging roof collapses along the cutting line and the gangues in gob play a supporting role with the roof. As the main roof continues to subside, the support resistance increases slightly as the gangues are gradually compacted. It tends to be stable about 45 m behind the working face. The maximum support resistance is 33 MPa during the influence of front abutment pressure, whereas the maximum support resistance is 14 MPa during the lagged working face. Thus, the maximum support resistance of roadside props is reduced about 58%. These results show that the BCR-GER approach can clearly reduce the pressure on the roadside props.

TABLE 1 Parameter selection

| Parameter | \( h/m \) | \( L_{q}/m \) | \( L_{w}/m \) | \( L_{S}/m \) | \( L_{G}/m \) | \( h_{q}/m \) | \( h_{w}/m \) | \( h_{S}/m \) | \( h_{G}/m \) | \( \gamma_{q}/ \) \( m^{3} \) | \( \gamma_{w}/ \) \( m^{3} \) | \( q/ \) MPa | \( q_{2}/ \) MPa | \( R/ \) kN/m | \( K_{A} \) |
|-----------|-------|--------|--------|--------|--------|-------|--------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| Values    | 3.0   | 2.1    | 4.0    | 16.0   | 3.2    | 9.8   | 10.9   | 5.3    | 28.0   | 25.0   | 2.55   | 1.8    | 6800.0 | 1.2    |

FIGURE 12 Section of roadway support after optimization
According to the above monitoring results, the BCR-GER approach greatly improves the bearing capacity of surrounding rock and effectively cuts off the hanging roof. The pressure on the roadside props is obviously reduced, and the surrounding rock displacement is very small, meeting production requirements.

5 | DISCUSSION

In this paper, the BCR-GER approach for deep coal mines was proposed, the “surrounding rock-supporting body” mechanical model was established to determine the key parameters (ie, cutting height, cutting angle, grouting cable length, and row of roadside props), and field practice is carried out at the No. 31120 haulage roadway of the Suncun coal mine for verification.

Currently, many domestic and foreign scholars have built structural mechanics models for surrounding rock support of gob-side entry retaining. For example, the superposed laminate model revealed the basic characteristics and laws of roof movement in gob-side entry retaining. The flexible-hard gob-side retaining mechanical model provided both compression and supporting forces required for a gob-side backfill by considering hard-roof weighting. In this paper, a mechanical model of the “surrounding rock-roadside support” is established, and emphasis is placed on the bulking characteristic of gangues in gob, and fully exerts the bearing capacity of gangues. It not only reduces the stress of roadside support significantly, but also eliminates the phenomenon of stress concentration, realizing the effective control of surrounding rock displacement. Then, the design method of key parameters is given, and the field application at No. 31120 haulage roadway of the Suncun coal mine is completed: an excellent supporting achievement.

It should be noted that the effect of the BCR-GER approach may not be ideal for hard-roof conditions. The large-diameter advanced borehole presplitting technique cannot fully presplit the hard roof along the gob-side. It will lead to inadequate roof-cutting, which may cause large deformations of surrounding rock or even rock burst. Thus, it is necessary to explore more powerful roof-cutting techniques. Additionally, the influence of primary cracks in the roof is not considered in the key parameters of the BCR-GER approach, which directly affects roof-cutting. In future work, the key techniques of the BCR-GER approach will be further studied to make it more widely applicable.
6 | CONCLUSION

Aimed to control the stability of surrounding rock of gob-side entry retaining in deep coal seams, in this paper, an innovative approach of BCR-GER for deep coal mines is proposed, three key techniques of the approach are introduced, the mechanical model of “surrounding rock-supporting body” is developed for key parameters determination, and field practice verify the effect of the BCR-GER approach. Compared with current published works, this work has at least two original aspects:

1. an innovative BCR-GER approach for the complex geostress environment of deep coal seams was proposed. It contained four stages: roof presplitting, high-strength grouting, roadside roof-cutting, and supplementary supporting.
2. the co-bearing mechanism of coal wall, roadside props, and gangues in gob was revealed by developing a mechanical model of “surrounding rock-supporting body.” And the key parameters, cutting height, cutting angle, grouting cable length, and roadside props row, of the new approach were quantitatively designed for site support optimization.

Field practice and monitoring results showed that the maximum convergences of roof-to-floor and side-to-side were 264 mm and 113 mm, respectively. Additionally, the maximum support resistance of the roadside props prior to roof-cutting was 33 MPa, whereas the maximum support resistance after roof-cutting was 14 MPa, which was reduced about 58%. These results indicated that the failure and deformation of surrounding rock was effectively controlled, and the pressure on the roadside props was greatly reduced. It also proved that the BCR-GER approach can completely meet the requirement for the deep-mining conditions. Moreover, the bearing capacity of gangues was fully exerted. The weight of the overlaying strata was transferred to the gangues in gob when the hanging roof was collapsed.
This study provides guidance and reference for surrounding rock control of the same or similar gob-side entry.

Although quantitative parameters of the new approach were designed, and good field application results have been achieved, it should be noted that some influential factors, such as primary cracks, water conductivity, are not considered in the designing process. In future work, these factors will be taken into consideration, which could make the BCRGER approach more widely applicable.

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CONFLICTS OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

Deyuan Fan and Xuesheng Liu equally contributed to this work; Deyuan Fan and Xuesheng Liu conceived and designed this paper; Yunliang Tan, Jianguo Ning amended this paper; Xuesheng Liu wrote “Introduction” of this paper; Deyuan Fan wrote the other parts of this paper; Shilin Song and Lei Yan helped to reviewed this paper.

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