Optimization and Field Application of Key Parameters for Gob-Side Entry Retaining by Roof Cutting Pressure Relief at Longfeng Coal Mine

Youwen TIAN1), Yuanxu ZHU2), Li WANG1), Linxiao WANG1), Jie DAI1)
1) Longfeng Coal Mine, Guizhou Lindong Coal Industry Development Co., Ltd., Bijie, Guizhou 551899, China
2) Mining College, Guizhou University, Guiyang, Guizhou 550025, China
* Corresponding author: email: 455562112@qq.com (Y. Zhu)

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ABSTRACT

To mitigate resource waste caused by coal pillar-protected entries, tight mining-excavation replacement schedules and severe stress concentration in coal pillar zones, this study takes the No.120902 auxiliary air entry of Longfeng Coal Mine as the engineering prototype and adopts the gob-side entry retaining technology by roof cutting pressure relief on the goaf-side roof of the entry. To address the large surrounding rock deformation of entries induced by unreasonable roof cutting parameters, theoretical calculations are first performed to obtain the theoretical ranges of roof cutting height and cutting angle, and the internal support scheme for the No.120902 entry is formulated accordingly. Subsequently, FLAC3D numerical modelling is adopted to characterize roof displacement of the retained entry and vertical stress distribution within the solid coal rib under various roof cutting parameter schemes, and the optimal roof cutting parameters are ultimately determined. Field industrial trials are carried out to verify the reliability of the proposed parameter optimization strategy.The numerical results show that under vertical roof cutting conditions, roof subsidence can be reduced by 29.6% when the cutting height increases from 7 m to 9 m, while only an additional 13% reduction in roof subsidence is achieved as the cutting height rises from 9 m to 11 m. The roof cutting angle imposes a marginal effect on vertical stress of the solid coal rib, and the minimum roof subsidence of 30 mm is captured at a cutting angle of 15°. Therefore, the combined scheme with a cutting height of 9 m and a cutting angle of 15° is identified as the optimum configuration to sustain the stability of entry surrounding rock. Field observations reveal two symmetric upward-extending through fractures developed at a borehole depth of 8.67 m, and the strike of fracture propagation is consistent with the advancing direction of the working face, which confirms the satisfactory forming quality of on-site pre-split roof cutting. Measurements recorded by roof separation monitors indicate that rock deformation at two monitoring stations is fully stabilized at 190 m and 220 m behind the working face, respectively, with the steady separation magnitude of deep rock strata controlled below 33 mm. The effective containment of entry surrounding rock deformation substantiates the validity of the optimized roof cutting parameters.

KEYWORDS: *roof cutting pressure relief; gob-side entry retaining; parameter optimization; surrounding rock control*

1 INTRODUCTION

As China's core fundamental energy source, coal plays an irreplaceable role in the national energy supply system. Traditional fully-mechanized mining layouts generally adopt entry protection by sectional coal pillars and delayed gob-side entry driving. The long-term retention of sectional isolating coal pillars leads to permanent massive loss of coal resources, resulting in a low overall recovery rate of working faces and prominent drawbacks in mining economic benefits. Furthermore, sectional coal pillars induce severe stress concentration, which aggravates intense mine pressure disasters such as large entry deformation, rib spalling and roof collapse, seriously restricting the safe and high-efficiency mining of working faces **Błąd! Nie można odnaleźć źródła odwołania.Błąd! Nie można odnaleźć źródła odwołania.**.To ease the tight connection of fully-mechanized working faces, reduce the excavation quantity of coal entries, realize continuous mining and improve coal resource recovery, this study takes the No.120902 working face of Longfeng Coal Mine as the engineering background and introduces the technology of gob-side entry retaining by roof cutting pressure relief. Through directional pre-split blasting, this technology controls roof caving and releases mine pressure to achieve pillar-free entry retaining. It fundamentally mitigates stress concentration induced by coal pillars, reduces the risk of gas outburst caused by repeated entry excavation, and improves mining efficiency and safety guarantee **Błąd! Nie można odnaleźć źródła odwołania.Błąd! Nie można odnaleźć źródła odwołania.**. He et al. **Błąd! Nie można odnaleźć źródła odwołania.** established a mechanical analysis model of "surrounding rock structure – roadside support body" based on different roof occurrence characteristics, and proposed three fracture positions of the main roof during gob-side entry retaining, namely the solid coal rib, above the entry and the gob side. The calculation methods of roadside support resistance were derived for each case respectively. Shi et al. **Błąd! Nie można odnaleźć źródła odwołania.** constructed a roof-cutting gob-side entry retaining model of the 1301N working face using PFC2D numerical software, and adopted the control variable method to analyze the response characteristics of roof stress, displacement and fabric tensor of retained entries under various roof cutting heights and angles. Yuan et al. **Błąd! Nie można odnaleźć źródła odwołania.** adopted numerical simulation to investigate the variation law of the axial force coefficient of anchor cables in retained entries, as well as the vertical stress distribution characteristics of sectional coal pillars and adjacent entries. They concluded that a cutting height of 11 m and a cutting angle larger than 0° can cut off stress transmission between roof strata. Zhao et al. **Błąd! Nie można odnaleźć źródła odwołania.** combined theoretical analysis and numerical simulation to reveal the directional fracture law of rock under bidirectional energy-gathered blasting and the crack propagation law of rock under double-hole energy-gathered blasting with different hole spacings. Gong et al. **Błąd! Nie można odnaleźć źródła odwołania.** established an analytical model for roof deformation and roadside support stability of backfill gob-side entry retaining in deep fully-mechanized mining with large mining height, and derived the prediction formula for roof subsidence.

In summary, extensive research has been carried out on the technology of gob-side entry retaining by roof cutting pressure relief, yet few studies focus on thin coal seam mining in Southwest China. To further explore the control effect of this technology on entry surrounding rock stability under the geological conditions of the target mining area, the No.120902 auxiliary air entry is selected as the research object in this paper. The overlying strata movement laws and stress-deformation response characteristics of surrounding rock under different roof cutting parameter schemes are compared to optimize key parameters including roof cutting height and cutting angle. Meanwhile, an integrated construction technology consisting of directional pre-split blasting, advance reinforcement support, in-entry strengthened support and gob-side gangue retaining sealing is synchronously designed, which can provide theoretical references for pillar-free mining of similar coal seams **Błąd! Nie można odnaleźć źródła odwołania.Błąd! Nie można odnaleźć źródła odwołania.**.

2 WORKING FACE GEOLOGICAL OVERVIEW

The No.120902 auxiliary air entry breaks through the left rib of the No.120502 floor drainage entry III at the mileage position K0+829.5 m, with an elevation of +1045 m at the opening point. The entry is arranged within the No.9 coal seam, which has a thickness ranging from 2.3 m to 3.1 m with an average thickness of 2.7 m and stable overall occurrence, and the average dip angle of the coal seam is 2°. The No.120902 auxiliary air entry adopts a rectangular cross-section design with a width of 5 m and a height of 3 m. It is laid out along the strike of the coal seam, with a total excavation length of 935 m. The planar layout of the gateway construction is shown in Figure 1.The No.9 coal seam lies in the middle of the Longtan Formation, 10 m below the No.5 coal seam and 31 m above the No.13 coal seam. The immediate roof of the coal seam is siltstone with a thickness of 1.5 m, and the main roof is limestone with a thickness of 5.9 m. The immediate floor is siltstone with a thickness of 0.9 m, and the main floor is siltstone with a thickness of 8.8 m. The comprehensive borehole columnar section of the No.120902 working face is presented in Figure 2.

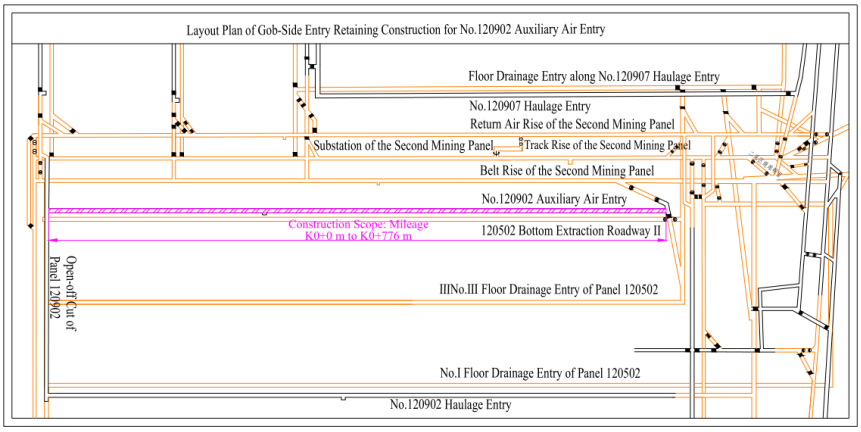


Fig. 1 Layout Plan of Gob-Side Entry Retaining Construction for No.120902 Auxiliary Air Entry

Thickness(m) Min-Max Average	Accumulated (m)	Columnar	number	Lithology Description
0-11.06 / 5.65	189.35			The roof strata mainly consist of carbonaceous mudstone and black mudstone, locally interbedded with mudstone or thin coal seams. The upper section is dominated by gray to dark gray sandstone and sandy mudstone, where calcareous nodules and plant fossil fragments are widely developed. A thin coal seam approximately 0.3 m thick is interlayered in the middle stratum, featuring stable occurrence but obvious thickness variation. The lower section is medium-bedded sandstone characterized by horizontal bedding and lenticular bedding structures.
0.10-3.93 / 1.18	190.53		4	The coal is black massive and powdery semi-dull to semi-bright coal with banded structure and simple macerals, containing 0–3 mudstone partings (mostly 0–2 layers).
1.70-12.37 / 6.91	197.44			The upper dark gray mudstone and siltstone bear calcareous nodules and plant root fossils with local thin coal seams. The middle mudstone interbeds 1–2 locally mineable thin coal seams. The lower sandstone and black mudstone contain nodules and plant fossils.
0.80-4.28 / 2.32	199.76		5	Semi-dull to semi-bright banded coal interlayered with mudstone partings.
4.39-14.46 / 10.16	209.92			Gray to dark gray siltstone and silty mudstone are developed with horizontal and wavy bedding and plant fossil fragments. The upper thin coal seam has poor continuity and is non-mineable. The middle-lower coal seam is 0.56 m thick with minor mudstone partings, locally thickening to 2.00 m; this seam features unstable occurrence and abrupt thickness variation. The basal black mudstone bears siderite nodules and plant fossils.
2.51-4.17 / 3.18	213.1		9	This coal seam features high-quality coal and stable stratigraphic occurrence; it locally splits into branches interbedded with mudstone partings, serving as the primary mineable seam of this mine.
0.25-6.05 / 3.30	216.4			Dark gray sandstone with horizontal bedding, pyrite nodules and variable lithology.

Fig. 2 Comprehensive Borehole Column of Panel 120902

3 SUPPORT SCHEME AND THEORETICAL ANALYSIS OF GOB-SIDE ENTRY RETAINING BY ROOF CUTTING PRESSURE RELIEF

Without roof cutting, the working face roof forms a long cantilever beam spanning the gob, and the load of overlying strata continuously transfers to the entry and solid coal rib, triggering severe stress concentration. Continuous cutting cracks are generated on the goaf-side roof via directional pre-split blasting to cut off the long cantilever and transform the roof into a short cantilever structure. The self-weight of overlying strata is released toward the gob along the cutting cracks and borne by caved gangue, which significantly reduces the abutment pressure on the solid coal rib and realizes stable pillar-free entry retaining. The main construction procedures of gob-side entry retaining by roof cutting pressure relief include advance support, borehole pre-split blasting, in-entry reinforced support, gangue retaining support and gob sealing technology.

3.1 Mechanical Calculation of the Mechanical Model for Gob-Side Entry Retaining by Roof Cutting Pressure Relief

Two mechanical models of gob-side entry retaining, namely the model with roof fracture above the entry and the model with roof cutting pressure relief, are illustrated in Figure 3. Directional pre-split blasting is implemented on the roof along the working face side to cut the roof. After working face mining, the roof strata collapse along the roof cutting line. The bulking effect of caved gangue can fully fill the entire gob. Compared with the conventional gob-side entry retaining method, the contact time of the main roof with gangue is significantly advanced after roof cutting, which reduces the area of the arched triangular block structure at both ends of the working face. This structure directly determines the stability of the retained entry, and all relevant analyses are carried out based on the static equilibrium principle.Before the fracture of the main roof, the static load F_1 acting on the roadside support body is expressed as:

$$F_1 = q_1 L_1 + L_1 h_1 \rho_1 g + L_2 h_2 \rho_2 g \tag{1}$$

Where:

h_1 — Thickness of the main roof, m;

h_2 — Tthickness of the immediate roof, m;

ρ_1 — Density of the immediate roof, kg/m³;

ρ_2 — Density of the main roof, kg/m³.

The dynamic load coefficient K_{d1} considering mining disturbance is introduced, and the required support resistance F of the roadside support body for conventional gob-side entry retaining is derived as follows:

$$F = K_{d1} F_1 = K_{d1} \left(q_1 L_1 + L_1 h_1 \rho_1 g + L_2 h_2 \rho_2 g \right) \tag{2}$$

After implementing roof cutting pressure relief on the entry roof, the loads acting on the roadside support body consist of the abutment force F_2 and the static load exerted by the immediate roof, which can be expressed as:

$$F_1 = F_2 + L_{hangdao} h_2 \rho_2 g \tag{3}$$

$$F_2 + F_3 = q_1 L_1 \cos\theta + L_1 h_1 \rho_1 g \tag{4}$$

Where:

$L_{hangdao}$ — Width of entry cross-section, m;

F_2 — Force exerted by Block *B* on the immediate roof;

F_3 — Abutment force applied by caved gangue to Block *B*.

The coal seam thickness is denoted by m, and θ is the rotation angle of the main roof. The geometric relationship is expressed as follows:

$$\tan\theta = \left(m + h_2 - \frac{h_2}{k-1} \right) \Big/ L_1 \tag{5}$$

Since the abutment force exerted by caved gangue on Block *B* is difficult to quantify, it is assumed that:

$$F_2 = k\left(q_1 L_1 \cos\theta + L_1 h_1 \rho_1 g \right) \tag{6}$$

Where:

k — Coefficient less than 1.

Taking the dynamic load coefficient K_{d2} generated during mining disturbance into consideration, the required support resistance of the roadside support body for gob-side entry retaining by roof cutting pressure relief **Błąd! Nie można odnaleźć źródła odwołania.Błąd! Nie można odnaleźć źródła odwołania.** is expressed as follows:

$$F = K_{d1}\left[k\left(q_1 L_1 + L_1 h_1 \rho_1 g + L_2 h_2 \rho_2 g \right) + L_{hangdao} h_2 \rho_2 g \right] \tag{7}$$

The support resistance of the roadside support body is presented in Equations (2) and (7). By comparing the two types of gob-side entry retaining methods, it can be found that the load borne by the roadside support body is significantly reduced after roof cutting via directional pre-split blasting.

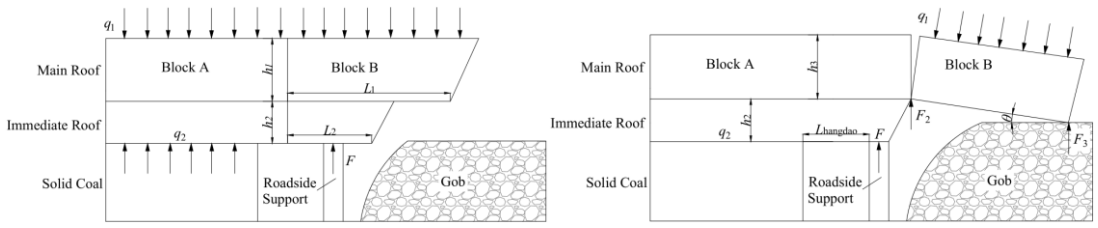


Fig. 3 Mechanical Models of Gob-Side Entry Retaining: Fracturing above the Entry (Left) and Roof Cutting Pressure Relief (Right)

3.2 Support Scheme for the No.120902 Auxiliary Air Entry

(1) Advance Reinforced Support of the Working Face

The original support system adopted for the No.120902 auxiliary air entry is the combined support of rock bolts, anchor cables, steel mesh and steel ladder. The spacing and row spacing of rock bolts are 800 mm × 800 mm, while those of anchor cables are 2400 mm × 1600 mm. On this basis, an enhanced support system consisting of anchor cables, constant-resistance devices and W-shaped steel belts is supplemented. The planar layout of the reinforced support for the No.120902 auxiliary air entry is shown in Figure 4. For roof support, three rows of Φ21.6 mm × 9300 mm anchor cables are drilled along the entry strike, which are interlocked with constant-resistance devices and 2700 mm-long W-shaped steel belts. The first row is arranged 600 mm away from the mining rib; the second and third rows are set 1500 mm and 2400 mm away from the previous row, respectively. The anchor cables in the first row incline 10° toward the vertical roof direction, those in the second row are arranged vertically, and the third row deflects 15°. Two rows of short anchor cables with specifications of Φ21.6 mm × 5000 mm are installed along the strike of the solid coal rib, matched with 5200 mm-long W-shaped steel belts. The first row of anchor cables is constructed 1600 mm above the floor at an inclination angle of 0°, and the second row is laid 600 mm above the floor with an inclination angle of −15°. The spacing and row spacing of the short anchor cables are 1600 mm × 1000 mm.

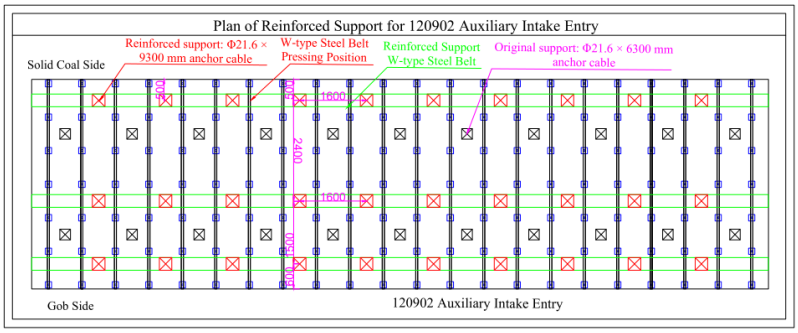


Fig. 4 Plan of Reinforced Support for 120902 Auxiliary Intake Entry

(2) Reinforced Support for Gob-Side Entry Retaining

Single hydraulic props and cross articulated beams are adopted to reinforce the retained entry. The spacing of single hydraulic props is 1000 mm, and the initial setting force is no less than 12 MPa. The articulated beams are arranged in three rows, with distances of 1000 mm, 2200 mm and 3600 mm from the mining rib, respectively. When the entry deformation is slight, a single row of support is sufficient. For sections with fractured surrounding rock, fault crossing or severe deformation, the number of rows shall be increased to 2–3. After the working face advances more than 200 m, if the roof outside the 200 m range behind the working face remains stable after mining, the single hydraulic props in this section can be removed and reused in the advance support zone.

(3) Gangue Retaining and Gob Sealing

To prevent caved gangue from the gob roof from rushing into the entry, a composite structure consisting of cement mortar shotcrete layer, U-shaped steel, steel mesh, sealing cloth and another layer of steel mesh is constructed on the gob side to realize integrated gangue retaining and gob sealing. According to the construction height of the No.120902 auxiliary air entry and the construction requirements of roof cutting support, U-shaped steel is

applied to fabricate the gangue retaining beams with an interval of 500 mm. The cross-section layout of roof cutting support, gangue retaining and gob sealing construction for the No.120902 auxiliary air entry is presented in Figure 5.

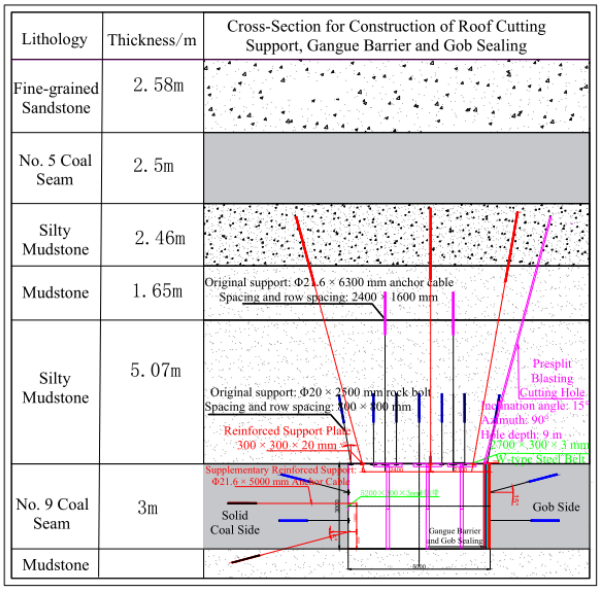


Fig. 5 Cross-Section of Roof Cutting Support, Gangue Barrier and Sealing Construction in the 120902 Auxiliary Intake Entry

3.3 Theoretical Analysis of Roof Cutting Parameters

(1) Roof Cutting Height

The roof cutting height directly determines the bulking filling volume of caved gangue in the gob and exerts a prominent influence on the load borne by the short cantilever beam of the roof after roof cutting pressure relief. Roof cutting pressure relief shortens the cantilever length of the coal seam roof and cuts off the roof strata to realize sufficient roof caving for gob filling. If the roof cutting height is insufficient, mine pressure cannot be effectively transferred to the deep gob, resulting in aggravated deformation of entry surrounding rock. On the contrary, an excessively large roof cutting height may trigger excessive roof collapse, raising construction difficulty and entry deformation. Therefore, the selection of an appropriate roof cutting height is particularly critical. A reasonable cutting height can not only improve the bulking filling performance of gangue to support overlying strata, but also effectively control roof subsidence and mitigate stress concentration on the entry rib. Based on the rock bulking theory **Błąd! Nie można odnaleźć źródła odwołania.**, the height of directional pre-split cutting crack H_f is expressed as:

$$H_f = \frac{H_m - \Delta H_1 - \Delta H_2}{K - 1} \tag{8}$$

where H_m is the mining height of the coal seam, and the average thickness of the working face is 3m; ΔH_1 is the roof subsidence, m; ΔH_2 is the floor heave, m; K is the bulking coefficient of rock strata, ranging from 1.3 to 1.5, and the design value is taken as 1.4.

Ignoring roof subsidence and floor heave and only considering the influence of mining height, the calculated cutting crack depth H_f is 7.5 m by substituting the above parameters

into the formula. Combined with the comprehensive borehole columnar section, the geological conditions of roof strata, crack formation rate, length of energy-gathered tubes and stemming length of blastholes are comprehensively considered. Accordingly, the borehole depth for directional pre-split cutting is preliminarily designed as 9 m, with stemming length of 3 m.

(2) Roof Cutting Angle

The roof cutting angle directly governs the mechanical state of the cantilever beam. When the cutting angle is too small, the fracture surface is nearly vertical. During the rotation of the main roof, roof blocks slide downward along the cutting crack and generate intense horizontal thrust on the roadside support body, resulting in entry convergence and rib spalling. In contrast, an excessively large cutting angle advances the caving of upper roof strata, and the early accumulation of caved gangue blocks the gob space. The lower immediate roof cannot cave in a timely manner, forming a secondary long cantilever beam and failing to release mine pressure.

The force analysis diagram of rock blocks on both sides of the roof cutting crack is shown in Figure 6, where θ denotes the dip angle of directional pre-split cutting crack. Block *B* bears horizontal compressive force *T* and vertical load *R*, while the roadside structural body provides vertical reaction resistance *M*. The roof cutting angle can adjust the force transfer pattern between rock blocks. A reasonable cutting angle facilitates the sliding instability of Block *B* on the gob side along the cutting crack **Błąd! Nie można odnaleźć źródła odwołania.Błąd! Nie można odnaleźć źródła odwołania.**.

The dip angle of directional pre-split cutting crack is derived based on the geometric equation of caved gangue bulking characteristics **Błąd! Nie można odnaleźć źródła odwołania.**:

$$\theta = 90^{\circ} - \arctan\left(\frac{L_Z - L_H}{L_M}\right) \tag{9}$$

where L_Z is the filling width of caved gangue, m; L_H is the retained entry width, m; L_M is the roof cutting height, m. Combined with field geological conditions, the calculated range of θ is 12°–17°, and the roof cutting angle of 15° is preliminarily selected for the test.

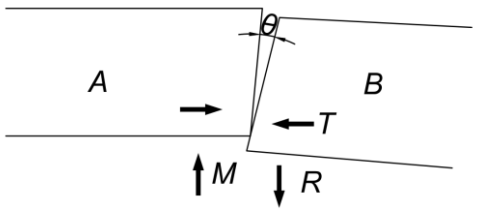


Fig. 6 Stress of Rock Blocks on Both Sides of Cutting Seam

4 NUMERICAL SIMULATION ANALYSIS OF GOB-SIDE ENTRY RETAINING BY ROOF CUTTING PRESSURE RELIEF

4.1 Simulation Scheme

Based on the geological conditions of the No.9 fully-mechanized working face, a three-dimensional FLAC3D numerical calculation model is established with dimensions of width × height × thickness = 200 m × 150 m × 50 m. Displacement constraints are applied to the bottom boundary, front, rear, left and right lateral boundaries of the model. The total buried

depth corresponding to the upper surface of the model is 401 m, and a compensation stress of 10 MPa is applied on the top surface derived from the self-weight formula of overlying strata **Błąd! Nie można odnaleźć źródła odwołania.**. The retained entry has a rectangular cross-section with a width of 5.0 m and a height of 3.0 m, and the mining length of the working face is 150 m. The excavation of the working face is realized by the step-by-step excavation method, namely the model reaches mechanical equilibrium after each 10 m excavation. The numerical calculation model is shown in Figure 7.

The Mohr–Coulomb constitutive model is adopted for model calculation, and the mechanical parameters of each rock stratum are listed in Table 1. The null model is utilized to generate cutting cracks for directional pre-split blasting. The cutting heights are set as 7 m, 9 m and 11 m, and the cutting angles are 0°, 10°, 15° and 20°, respectively. The gob-side entry retaining technology by roof cutting pressure relief is implemented in the No.120902 auxiliary air entry, which serves as the transportation entry for the adjacent No.120909 working face. Monitoring points are arranged above the entry roof and on the solid coal rib of the No.120902 working face to observe the distribution characteristics of surrounding rock stress and displacement field.To optimize the key roof cutting parameters, a stepwise single-variable numerical simulation scheme is adopted in this study. In the first stage, the cutting angle is fixed at 0°, and three working conditions with cutting heights of 7 m, 9 m and 11 m are simulated to screen the optimal cutting height. In the second stage, the optimized cutting height is retained unchanged, and comparative simulations with cutting angles of 0°, 10°, 15° and 20° are carried out to comprehensively reveal the evolution law of surrounding rock pressure relief under the synergistic effect of roof cutting height and cutting angle. Roof subsidence of the retained entry and lateral abutment pressure on the solid coal rib are two critical factors governing the stability of gob-side retained entries. A total of 50 monitoring points are arranged on the entry roof within the range of 50 m behind the working face, and 100 monitoring points are laid out along the coal seam dip 5 m ahead of the working face to monitor the lateral abutment pressure of the solid coal rib. The final roof cutting scheme is optimized by comparing the surrounding rock stability under various key roof cutting parameter schemes.

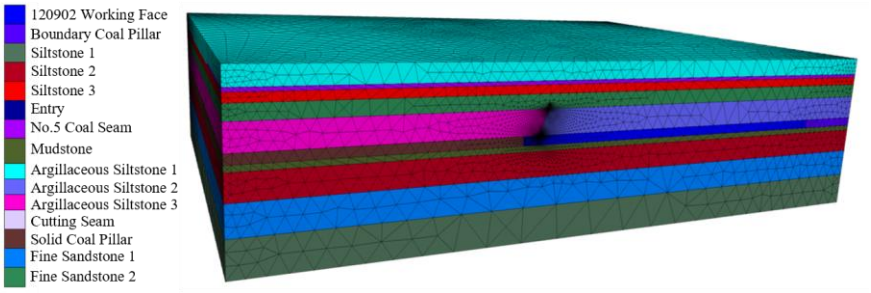


Fig. 7 Numerical Calculation Model

Tab. 1 Mechanical Parameters of Each Rock Stratum

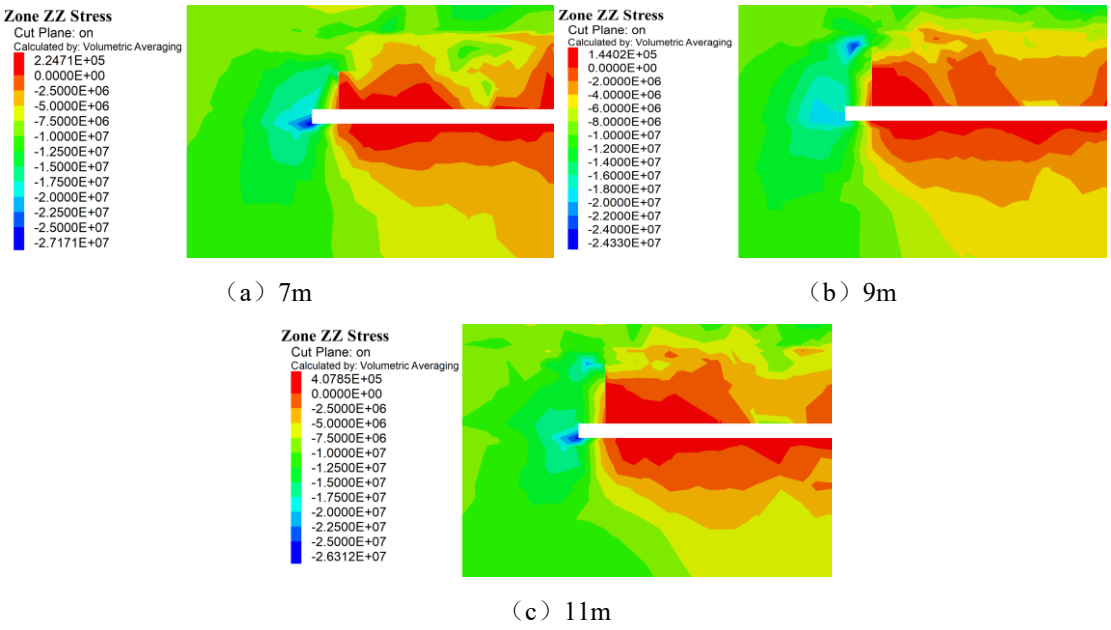
Lithology	Density /(kg·m^{-3})	Bulk Modulus/GPa	Shear Modulus/GPa	Internal Friction Angle (°)	Cohesion/MPa	Tensile Strength/MPa
Coal Seam	1480	1.9	0.85	30	1.1	1
Fine Sandstone	2580	8.8	4.9	35	3.9	1.6
Siltstone	2500	5.9	3.2	31	2.5	0.98
Argillaceous Siltstone	2510	5.8	3.1	31	2.6	1
Mudstone	2420	3.6	1.9	26	1.8	0.55

4.2 Analysis of Influence Laws of Different Roof Cutting Heights

Figure 8 presents the vertical stress nephograms at 10 m behind the working face under various roof cutting heights. With the roof cutting angle fixed at 0°, numerical simulations and analyses are carried out for three cutting height schemes of 7 m, 9 m and 11 m. The

simulation results indicate that vertical stress gradually concentrates from the gob side to the solid coal rib of the entry roof after roof cutting. The maximum vertical stress of the left solid coal rib reaches 16.9 MPa at a cutting height of 7 m, decreases to 14.6 m at 9 m, and further reduces to 14 MPa when the cutting height rises to 11 m. It can be concluded that the stress on the solid coal rib of the entry gradually declines with the increase of roof cutting height, while the stress variation is negligible as the cutting height increases from 9 m to 11 m.

At the cutting height of 7 m, the insufficient cutting depth fails to form fully-through pre-split fractures cutting off the upper bearing key strata, and the cantilever structure of the main roof cannot be completely broken. The load from overlying strata continuously transfers to the solid coal rib, forming a peak stress of 27.17 MPa and inducing severe disturbance to the entry surrounding rock. When the cutting height is increased to 9 m, the cutting cracks penetrate the key roof strata, and the peak abutment stress drops to 24.33 MPa. Further increasing the cutting height to 11 m leads to a rebound of peak stress to 26.31 MPa. This phenomenon reveals that a larger cutting height expands the fractured zone along the cutting line and intensifies mining disturbance on the solid coal rib of the entry.



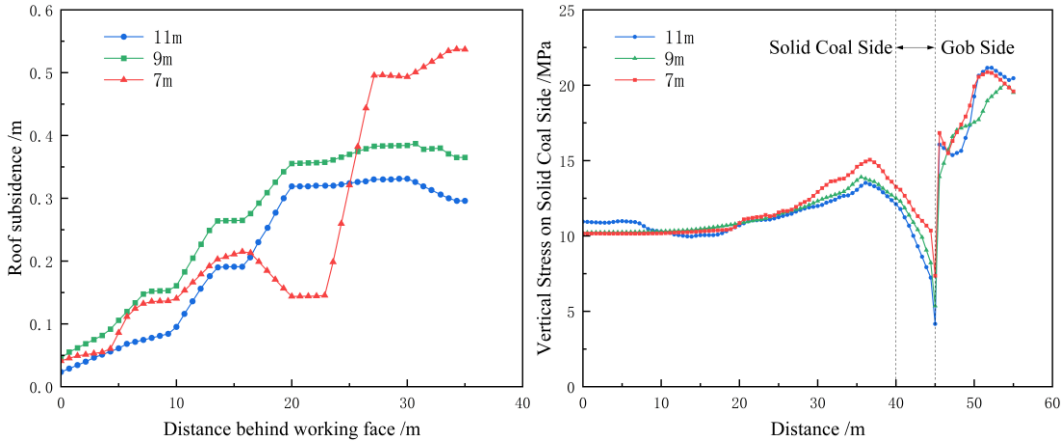
（a）7m　　（b）9m

（c）11m

Fig. 8 Vertical Stress Contours under Different Roof Cutting Heights

Figure 9 presents the variation curves of entry roof displacement and vertical stress on the solid coal rib under different roof cutting heights. Overall, as the distance behind the working face increases, the roof subsidence continuously rises and then gradually stabilizes, whereas remarkable differences exist among various cutting height schemes. As shown in Figure 9(a), the stabilized roof subsidence decreases with the increase of cutting height, yet the reduction amplitude of roof subsidence becomes insignificant when the cutting height rises from 9 m to 11 m. The maximum roof subsidence reaches 0.54 m at 35 m behind the working face under the cutting height of 7 m, while the maximum subsidence is 0.33 m for 11 m cutting height and merely 0.38 m for 9 m cutting height, representing a reduction of approximately 29.6% compared with the 7 m scheme. At this cutting height, the cutting cracks exactly penetrate the load-bearing key roof strata, which can maximally restrain continuous roof subsidence.In Figure 9(b), the horizontal axis ranges of 0–40 m, 40–45 m and 45–60 m correspond to the solid coal zone, interior of the entry and gob side, respectively. It can be observed that the surrounding rock stress first rises and then declines as the monitoring point moves away from the solid coal rib. The peak vertical abutment stress

occurs at the position 5 m away from the solid coal rib, and the peak value gradually decreases with the increase of roof cutting height. The peak abutment stresses corresponding to cutting heights of 7 m, 9 m and 11 m are 15.1 MPa, 14.2 MPa and 13.8 MPa, respectively. The variation of vertical abutment stress is much slighter when the cutting height increases from 9 m to 11 m than that from 7 m to 9 m. In summary, the numerical simulation results demonstrate that the optimal control performance can be achieved when the roof cutting height is set to 9 m; thus, a cutting height of 9 m is determined for field construction.



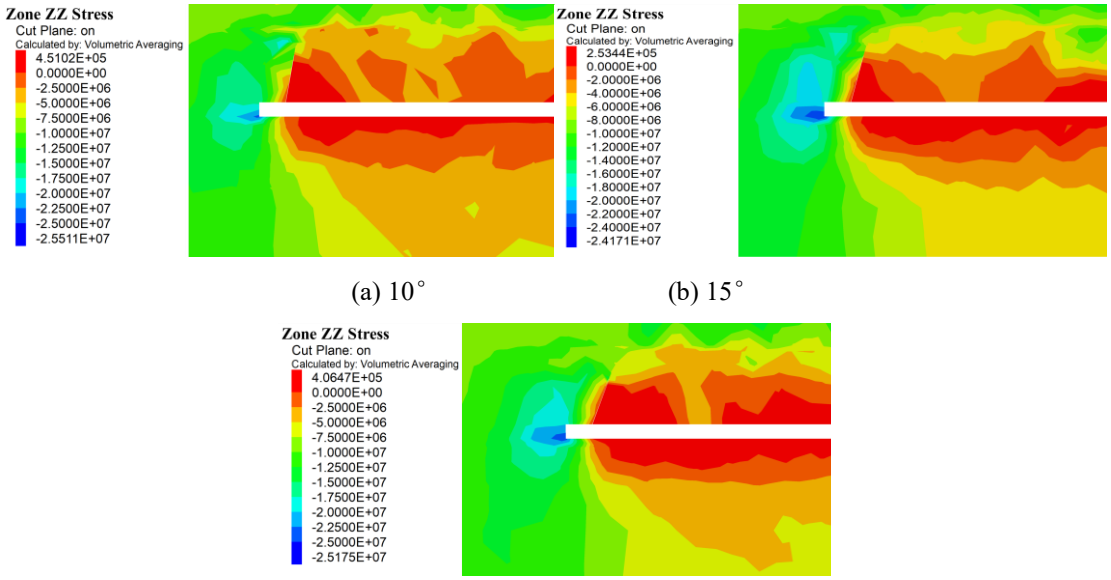
(a) Roof Subsidence (b) Vertical Stress on Solid Coal Side

Fig. 9 Roof Subsidence of Entry and Vertical Stress on Solid Coal Side under Different Roof Cutting Angles

4.3 Analysis of Influence Laws of Different Roof Cutting Angles

Vertical stress nephograms obtained 10 m behind the working face under various roof cutting angles are illustrated in Figure 10. Increasing the roof cutting angle facilitates the collapse of roof strata into the gob and improves the filling performance of caved gangue. Nevertheless, an excessively large cutting angle elongates the cantilever beam, which aggravates stress concentration above the entry roof and on the solid coal rib. Multiple influencing factors should be comprehensively considered to determine the rational roof cutting angle and achieve the optimal mine pressure relief effect.

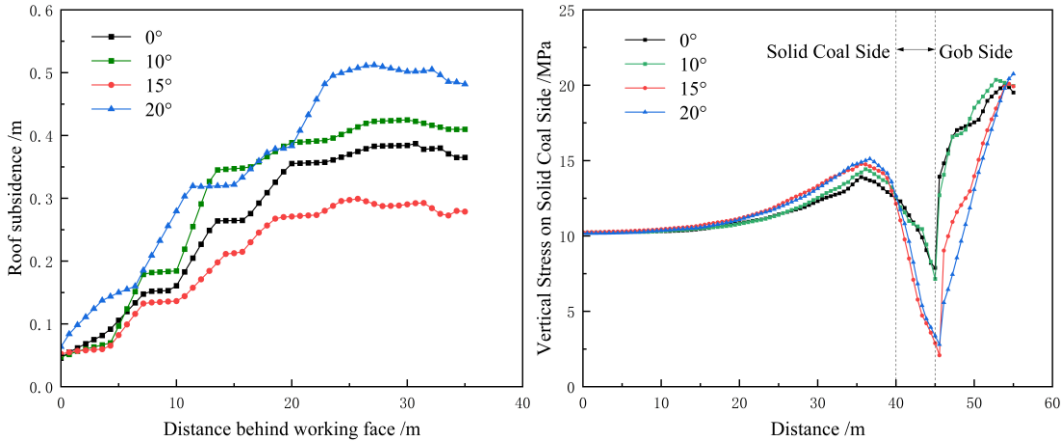
Figure 11 shows the variation curves of entry roof subsidence and vertical abutment stress on the solid coal rib under different roof cutting angles. As presented in Figure 11(a), the overall entry roof subsidence rises with the increase of roof cutting angle. However, when the cutting angle is set to 15°, the stabilized roof subsidence is approximately 0.3 m, lower than the value of 0.38 m at 0°, which demonstrates that the 15° cutting angle achieves the optimum control effect of entry roof subsidence. As shown in Figure 11(b), the peak vertical abutment pressure on the solid coal rib gradually increases with the rise of cutting angle. The peak abutment stresses corresponding to cutting angles of 0°, 10°, 15° and 20° are 13.6 MPa, 14 MPa, 14.6 MPa and 15.3 MPa, respectively. The peak value rises mildly with limited variation amplitude. Combined with the roof subsidence performance at the cutting angle of 15°, this scheme synchronously realizes a relatively low peak stress on the solid coal rib and the minimum roof subsidence of the entry. Therefore, the optimal roof cutting angle is determined as 15°.



(a) 10° (b) 15°

(c) 20°

Fig. 10 Vertical Stress Contours under Different Roof Cutting Heights



(a) Roof Subsidence (b) Vertical Stress on Solid Coal Side

Fig. 11 Roof Subsidence of Entry and Vertical Stress on Solid Coal Side under Different Roof Cutting Angles

5 FIELD TEST

5.1 Effect of Directional Pre-Split Blasting

To evaluate the field performance of roof cutting pressure relief implemented in the No.120902 auxiliary air entry, two random blastholes are selected after blasting, and inspection boreholes are drilled at the midpoint between them for borehole camera observation. The roof cutting effect after blasting is presented in Figure 12. As shown in the figure, affected by entry excavation, the dominant blasting zone is located 7–9 m from the hole opening. Two symmetrically distributed propagating fractures are detected at the depth of 8.67 m inside the borehole, and these fractures extend upward toward the entry roof. Field observations reveal that the propagation direction of fractures coincides with the advance direction of the working face. This indicates that the energy-gathered tube blasting generates tensile stress concentration along the preset direction to induce rock mass fracture, which forms continuous pre-split cutting cracks and achieves favorable pre-splitting performance.

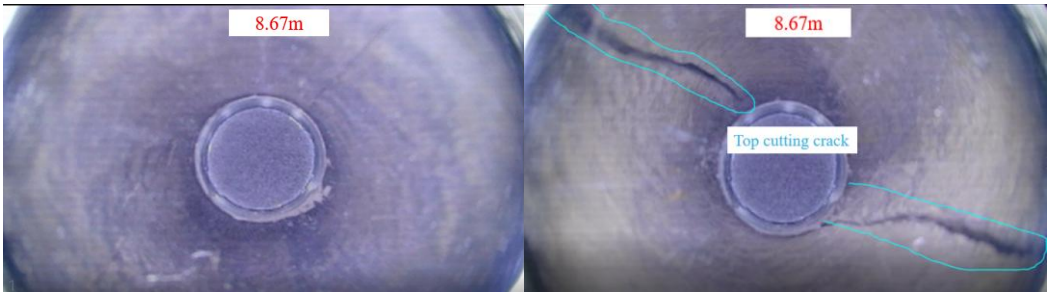


Fig. 12 Borehole Camera Images Before and After Blasting

5.2 Roof Separation Monitoring

Roof separation monitoring was carried out at two measuring point groups L3 and L5 within the retained entry, which are 30 m and 50 m away from the starting position of the retained entry, respectively. The variation laws of layered displacements of deep and shallow base points with the distance behind the working face are illustrated in Figure 13. The whole evolution process can be divided into four stages: separation initiation, rapid separation, slow separation and deformation stabilization.

(1) Separation Initiation Stage (3 m ahead of the working face to 50 m behind the working face)

This stage corresponds to the rapid separation zone. Roof separation occurs at approximately 3 m ahead of the working face, and tiny layered fractures generate inside the roof rock mass. The separation develops sharply within the range of 0–50 m behind the working face, and the growth rate of the deep base point is far higher than that of the shallow base point. The overall evolution trend coincides with the subsidence law of the entry roof surface. The displacement of the entry roof develops rapidly within 30 m behind the working face and then gradually stabilizes. In this stage, the mining-induced abutment pressure is released intensively, and the rock blocks on both sides of the pre-split cutting crack slide and rotate, forming the stage with the most severe layered deformation of roof strata.

(2) Slow Separation Development Stage (50 m to 200 m behind the working face)

The roof separation at measuring points L3 and L5 gradually stabilizes at 220 m and 190 m behind the working face, respectively. The growth rates of displacements at deep and shallow base points decrease significantly in this stage, which indicates that the layered deformation of the shallow immediate roof is basically restrained after compaction by early caved gangue. The curve of the deep base point rises slightly in a stepped pattern, revealing that the deep main roof still undergoes slow bending subsidence, and interlayer fractures keep expanding slightly. The overall separation displacement curve rises gently, and the mining-induced stress decays progressively.

(3) Deformation Stabilization Stage (beyond 200 m behind the working face)

When the distance behind the working face exceeds the critical value, the displacement curves of deep and shallow base points turn horizontal, which demonstrates that the caved gangue in the gob has been fully compacted and a stable equilibrium structure of overlying strata is formed.

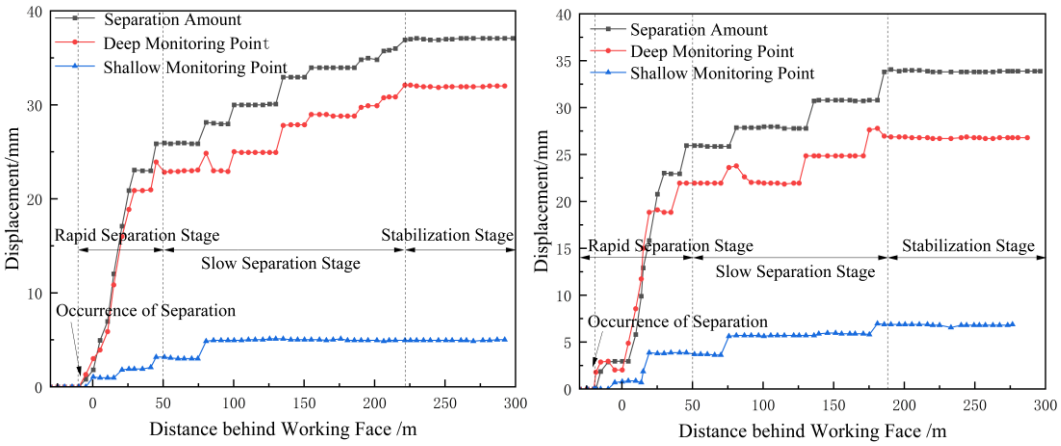


Fig. 13 Variation Curves of Roof Separation at Monitoring Station L3 (Left) and L5 (Right)

5.3 Retention Performance of the Retained Entry

The roadway forming effect of gob-side entry retaining by roof cutting pressure relief implemented in the No.120902 auxiliary air entry is shown in Figure 14. The retained entry within 200 m behind the working face maintains favorable maintenance performance. A total length of 776 m of entry is successfully retained in this field test, which reduces conventional entry excavation by 1076 m and directly cuts the entry excavation cost by 9.43 million RMB.In terms of technical and economic benefits, the unit excavation cost of conventional excavated entry reaches 15,000 RMB per meter, while the cost of the roof cutting retaining scheme is reduced to 8,000 RMB per meter, achieving a cost reduction rate of 46.7%. This scheme not only improves economic benefits, but also greatly elevates coal resource recovery ratio.

(a) Barrier Support (b) Temporary Support

Fig. 14 Entry Retaining Effect of 120902 Working Face

6 CONCLUSIONS

(1) Comparative theoretical calculations are carried out on the mechanical models of gob-side entry retaining with and without roof cutting pressure relief. The results reveal that the required support resistance of the roadside support body is remarkably reduced after roof cutting. Based on the coal and rock strata geological conditions of the 120902 working face, the rational roof cutting height is calculated as 9 m, and the rotation angle of the main roof ranges from 12° to 17°. These parameters provide a reference for the subsequent numerical simulation design.

(2) FLAC3D numerical simulations are conducted to investigate the lateral abutment pressure of the solid coal rib and roof subsidence of the retained entry under various roof cutting heights and angles. Generally, the roof displacement rises with the increase of the distance behind the working face and tends to stabilize at approximately 30 m. The roof subsidence gradually declines as the roof cutting height increases. The maximum roof subsidence is 0.38 m at the cutting height of 9 m, with a reduction amplitude of about 29.6%. As the monitoring point moves away from the solid coal rib, the surrounding rock stress first rises and then falls, and the peak stress occurs at the position 5 m away from the rib. The peak vertical abutment pressure decreases continuously with the increase of cutting height, and the maximum stress reduction is obtained at 9 m. When the cutting height exceeds 9 m, the variations of peak lateral abutment pressure and entry roof displacement are negligible compared with the scheme of 9 m cutting height.The overall entry roof displacement rises with the increase of roof cutting angle, while the minimum roof subsidence of 0.3 m is achieved at the cutting angle of 15°. The roof cutting angle imposes a slight influence on the peak stress of the solid coal rib. Accordingly, the optimal roof cutting parameters are preliminarily determined as the cutting height of 9 m and cutting angle of 15°.

(3) Field test results show that two symmetric propagating fractures are observed at the depth of 8.67 m inside the blasthole via borehole camera inspection, and the propagation direction of fractures is consistent with the advance direction of the working face. The overall evolution law of roof separation in the separation initiation stage coincides with the subsidence characteristic of the entry roof surface. The roof displacement develops rapidly within 30 m behind the working face, which demonstrates that the retaining performance of the gob-side entry is satisfactory.

7 AUTHOR CONTRIBUTIONS

Youwen Tian: Methodology, Writing – original draft. **Yuanxu Zhu**: Conceptualization, Supervision, Writing – review & editing, Project administration, Funding. **Li Wang:** Methodology, Writing – original draft. **Linxiao Wang:** Methodology, Writing – original draft. **Jie Dai:** Methodology, Writing – original draft.

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9 DATA AVAILABILITY

The raw data supporting the conclusions of this study are available from the corresponding author upon reasonable request.

10 COMPETING INTERESTS

The authors declare no conflict of interest.

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