ORIGINAL PAPER

Deformation Mechanism and Control Ttechnology of Surrounding Rock of the Roadway in a Steep Coal seam

Tu Hong-sheng · Liu Song-yong · Huang Chang-wen · Guo Chen-ye · Zhang Xiao-bo · You Zu-feng

Abstract This study combined theoretical analysis, numerical simulation via FLAC3D software, innovative design, and field measurements for establishing the mechanical model of the stressed coal rock and deriving the deformation and failure characteristics of the roadway in a steep coal seam. The No. 49# steep-seam working face of the Xintie Coal Mine, China, was used as a case study with asymmetrical force characteristics of the mining roadway. The roof and the right side of the roadway under study were identified as the main deformation and failure zones in the roadway of the steep working face. Next, a rigid/flexible support method that fully enclosed two sides and the roof was designed and substantiated. It comprised three pre-stressed resin anchor cables combined with anchor rods, iron net, and steel bands for the roadway roof support; besides, three anchor rods were combined with iron net and steel bands for supporting the right side of the roadway. A novel self-mobile forepoling hydraulic support group with side and roof support functions was developed. A grouting reinforcement was applied to the crushed coal rock in the geologic anomaly zone to enhance the overall performance. Finally, the measured displacements of the roof and the floor were found to exceed those of the roadway sides. The whole advancing process of the steep-seam working face was conditionally split into three segments, namely, Segment I with no mining effect (at a distance over 50 m from the working face), Segment II with a mining effect (at 20 ∼ 50 m from the working face), and Segment III with a strong mining effect (20 m in front of the working face). The displacement at the deepest point on the roof was the maximal, followed by that in the range of 0 ∼ 1.5 m, which made it possible to reduce the number of anchors on the left side of the roadway required by the conventional symmetric support mode. The performed field measurements proved that the proposed asymmetric support mode ensured the mining safety requirements of the working face under normal mining operations, being more cost-effective and efficient than the conventional symmetric one.

Keywords Steep coal seam · Roadway support · Grouting filling · Section coal pillar · Strata behavior regularity

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1 Introduction

With gradual exhaustion on of shallow coal resources, coal seams with a pitch of over 45°m, which are referred to as steep coal seams, are increasingly excavated (Qian and Shi 2003). The main challenge in such excavation is that, owing to a large pitch, the fractured roof above the goaf will slide down and fill the lower goaf of the coal seam (Yao 2019; Lv 2019; Lai 2020,). This filling gangue can support the roof in the lower part of the working face to a certain degree, thereby leading to poor stability and difficulty in control of the coal rock stability on the upper part of the working face (Wang 2018, 2019; Zhang 2018; Sun 2019). Besides, it significantly deteriorates the stability of the upper roadway, as shown in Fig. 1.

Since the stability of the mining roadway in the working face is the premise of ensuring mining safety (Yang 2014, 2020; Huang 2018; Wei 2019), it is necessary to investigate the stability control mechanism and method of the upper roadway in the working face.

For the strike longwall mining face, the mining roadway should be horizontally arranged along the strike of the coal seam to satisfy the requirements of mine transport and miners' safety. Considering the great pitch of coal rock bed in a steep working face, the occurrence condition in coal and rock of the mining roadway is inversed in the roadway side and top. At the present stage, the roadway of steeply inclined coal face in Xintie coal mine using symmetrical support as shown in Fig. 2.

The roof was supported by the combination of two pre-stressed resin anchor cable, anchor rod, iron net, and steel bands. The anchor cables were 4.5 m in length and 24 mm in diameter and arranged at a row spacing of 1.5 m and spacing of 2.5 m; the anchor rods, with a length of 1.4 m and a diameter of 20 mm, were arranged at a row spacing of 1.2 m. Three anchor rods, iron net, and steel bands were combined and arranged on the right and left sides of the roadway. The anchor rods on both sides, with a length of 1.6 m and a diameter of 20 mm, were arranged symmetrically at a row spacing of 1.2 m. This symmetrical support mode was not optimal in view of the asymmetric stresses in the roadway, resulting in serious deformation and failure of the roadway and increased support cost.

Scholars from all over the world have conducted a great deal of research on the stability of coal rock under the characteristic occurrence condition. Using a case study of a steep roadway in Anhui, China, Wu et al.(2018) analyzed the force conditions and deformation behavior via numerical simulation and proposed a support method based on using long anchor cables for suppressing large deformation; in addition, short anchor cables and closed U-shaped steel structure were combined for improving the stress state. For a steep coal seam in India under roadway mining, Jawed and Rabindra (2018) examined the formation method of the diamond pillar and the arrangement of the side unloading machines, and designed a kind of support structure for maintaining roadway stability. Wang et al. (2016) investigated the stability criterion for a horizontal slicing face and the roadway support

Fig.1 Filling characteristics of caving roof and stress distribution rule of stope. **a** Caving and filling characteristics; **b** Stress distribution rule of stope

(a) Caving and filling characteristics   **(b)** Stress distribution rule of stope

(a) Symmetrical support design   (b) Actual deformation and failure characteristics
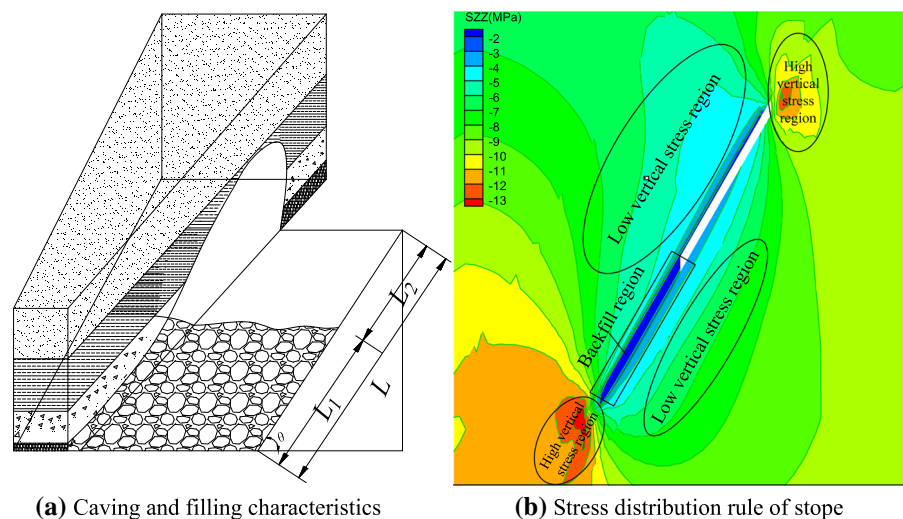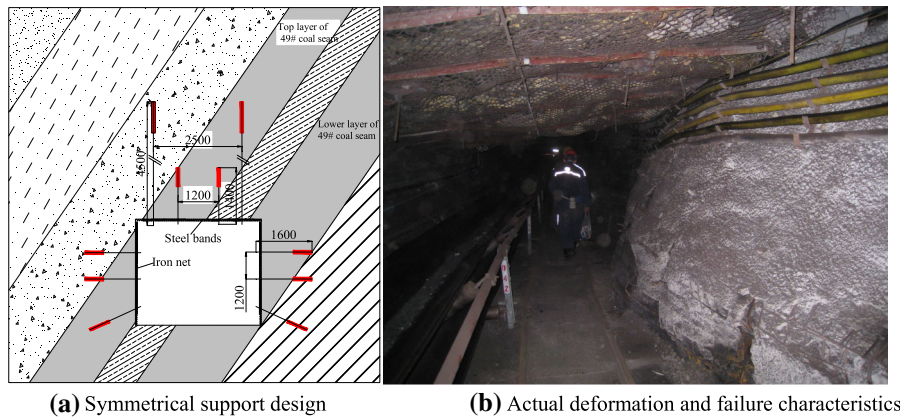
Fig. 2 Symmetrical support design and actual failure characteristics of steep coal seam roadway. **a** Symmetrical support design; **b** Actual deformation and failure characteristics

system in steep coal seam. Yang et al. (2014) employed numerical simulation for exploring the influencing mechanism of the steep mining on the protective pillar and proposed a waste-filling method for the goaf to enhance the pillar stability and ensure the stability of the mining roadway. Based on finite element analysis, Wang et al. (2010) revealed the stress and deformation distribution rules within the mining range of the steep seems and determined the strike protection range of the steep protective layer and roadway arrangement method.

Conclusively, scholars mainly focused on roadway stability mechanism, the working protective pillars size, and the mining influencing range in horizontal slices of steep coal seams and the pillar mining face. However, the stability control mechanism of the mining roadway in steep longwall working face has been poorly investigated. Therefore, this study was aimed to determine the roadway's actual stresses, design the asymmetric support with the optimal parameters, improving the roadway stability and reducing the support cost.

2 Project Profile

The Xintie Coal Mine is under the administration of Qitaihe Branch, Heilongjiang Longmei Mining Group. As shown in Fig. 3, the primary-mining No. 49# steep coal seam, with a ground elevation of + 211 m and a coal seam elevation of −141 ∼ -215 m, can be subdivided into two sub-layers with mean thicknesses of 1.5 and 2.0 m, respectively.

Fig. 3 Composite stratigraphic column

The Protodyakonov hardness is 0.8; the inclination angle ranges from 58° to 62°, with a mean value of 60°; the inclination length and the strike length of the mining face are 84 and 551 m, respectively. Under longwall fully-mechanized mining conditions, an MG2 × 125/580-WD coal cutter is used for coal cutting. A ZQY3600/12/26 hydraulic support ensures the roof management, while an SGZ-730/320 scraper conveyer provides coal transportation. The mining roadway section is a rectangle with a width of 3.6 m and a height of 3.0 m.

3 Deformation Characteristics of the Mining Roadway under Stress

The steep-seam longwall working face and the mining roadway feature inclined and horizontal arrangements, respectively. Due to the special connection mode between the working face and the mining roadway, the coal rock in that section acts on the roadway's right side and roof, as shown in Fig. 4. The instability of the coal pillar in that section aggravates the deformation and failure of the roadway. At that moment, since different coal strata and the joint fissure between the contact surfaces differ by strength values, the strata on the roof and the right side are seriously deformed downward when subjected to forces acting in the parallel plane, accompanied with obvious falling tendency. Therefore, it is generally difficult to achieve stability control of the surrounding rocks. Investigating the deformation mechanism and the related control technologies of the mining roadway in the steep working face is of great practical significance to improving the management of the surrounding rock and achieving safe mining (Donnelly 2006; Ma 2011; He 2019; Wang 2019).

Figure 5 displays the force conditions of the roadway in the steep working face, where Gh denotes the gravity of the surrounding coal strata of the
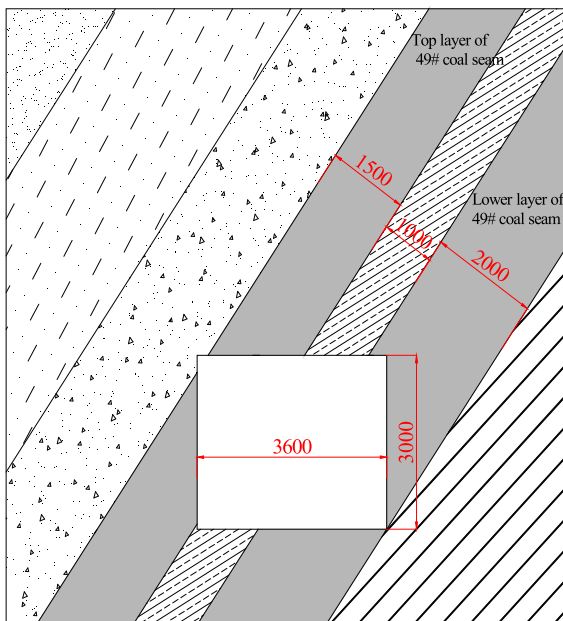

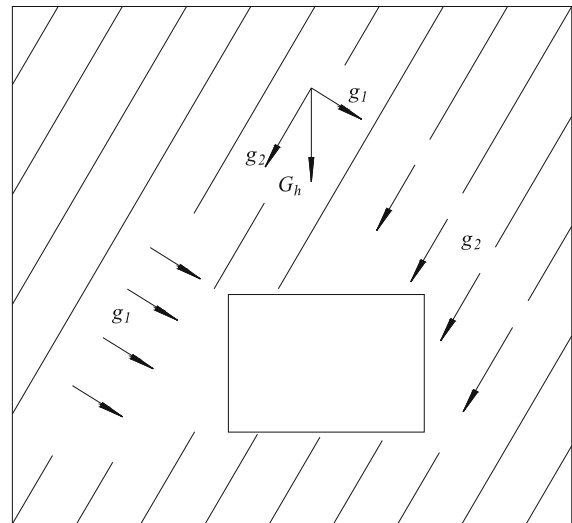**Fig. 4** Surrounding rock occurrence characteristics of roadway

Fig. 5 Mechanical characteristics of roadway in steeply inclined face

roadway, g1 and g2 are the force components acting along the vertical plane and the parallel plane, respectively. While g1 mainly acts on the left side of the roadway along the vertical plane, g2 mainly acts on the roof and the right side of the roadway along the parallel plane. For a steep coal seam, g2 value exceeds that of g1, i.e., the force component force g2 acting along the parallel plane provides the main contribution to failure.

In combination with the force condition on the mining roadway in the steep-seam working face, a level structure with three units was established for describing the two sides and the roof of the roadway, as shown in Fig. 6, where a and b denote the roadway width and height, respectively. The bottom of the model was in a consolidation state. In this study, was assumed that the three sides of the roadway had identical elastic modulus E, cross-sectional area A, and the inertia moments I.

The mechanical structure in Fig. 6 is a three-order statically indeterminate problem, which can be solved by the following matrix displacement method. The stiffness equation can be written as:

$$K\Delta = F_P \tag{1}$$

where K denotes the stiffness matrix, Δ is the node displacement, and F_P is the force applied to the node. As shown in Fig. 6, three units and four nodes were included, and therefore, twelve displacement
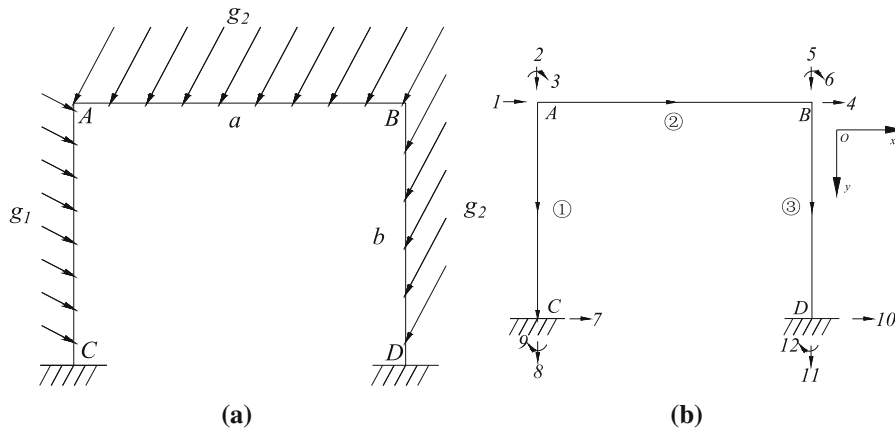
Fig. 6 Force diagram of roadway in steeply inclined face

components could be obtained ($\Delta_1 = u_1$, $\Delta_2 = v_1$, $\Delta_3 = \theta_1$, $\Delta_4 = u_2$, $\Delta_5 = v_2$, $\Delta_6 = \theta_2$, $\Delta_7 = u_3$, $\Delta_8 = v_3$, $\Delta_9 = \theta_3$, $\Delta_{10} = u_4$, $\Delta_{11} = v_4$ and $\Delta_{12} = \theta_4$). Local coordinates were marked by the direction of the arrow in Fig. 6. Accordingly, local coordinate stiffness matrices of three units can be written as:

$$\overline{k}^{\ominus} = \overline{k}^{\ominus} = \overline{k}^{\ominus} = \begin{bmatrix} \frac{EA}{a} & 0 & 0 & -\frac{EA}{a} & 0 & 0 \\ 0 & \frac{12EI}{a^2b} & \frac{6EI}{ab} & 0 & -\frac{12EI}{a^2b} & \frac{6EI}{ab} \\ 0 & \frac{6EI}{ab} & \frac{4EI}{a} & 0 & -\frac{6EI}{ab} & \frac{2EI}{b} \\ -\frac{EA}{b} & 0 & 0 & \frac{EA}{b} & 0 & 0 \\ 0 & -\frac{12EI}{ab^2} & -\frac{6EI}{ab} & 0 & \frac{12EI}{ab^2} & \frac{12EI}{ab^2} \\ 0 & \frac{6EI}{ab} & \frac{2EI}{b} & 0 & -\frac{6EI}{ab} & \frac{4EI}{b} \end{bmatrix}$$

(2)

Next, the stiffness of the global coordinate system was assessed, where the loads in the equivalent nodes and the force applied force to the rod end were calculated. By substituting the actual mechanical parameters of the coal rock in the Xintie Coal Mine into Eq. (2), the bending moment distribution diagram was plotted, as shown in Fig. 7.

The width of the roadway was 3.6 m, the height was 3 m, the elastic modulus was 3.2 GPa, the cross-sectional area was 1 m^2, and the inertia moment was 0.083 m^4, the coal seam angle was 60°, and the buried depth was 352 m. For the bending moment applied within the roadway, its action direction points towards the roadway; for the bending moment applied outside the roadway, the action direction points towards the deep rock outside the roadway.
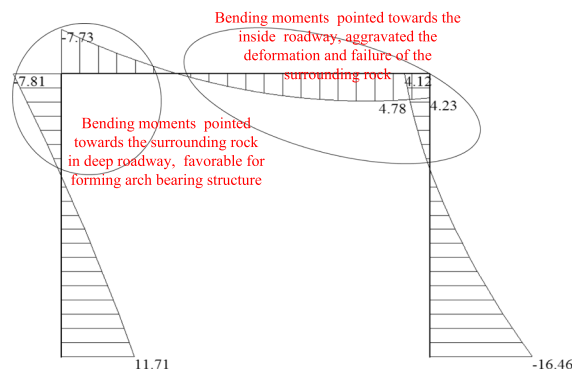

Fig. 7 Bending moment distribution of surrounding of roadway

It can be seen in Fig. 7 that forces acting on the mining roadway in the steep-seam working face have a pronounced asymmetry. The bending moments on the upper right and lower left parts of the roadway point inside the roadway, aggravating the deformation and failure of the surrounding rock. These two parts can be regarded as the main deformation zones under stress. The lower left part of the roadway is generally the coal wall of the working face and requires strengthening management in the recovery process. The bending moments acting on the upper left and the lower right parts of the roadway point towards the surrounding rock in the deep roadway, which is favorable for forming arch-shaped load-bearing structures. Since the surrounding rock is relatively stable, the roadway's right side and roof require are the main zones that require the surrounding rock control in the steep-seam working face, given the difference in coal strength and the joint surface existence.

4 Control of the Surrounding Rock in the Mining Roadway

The deformation and failure of the mining roadway are mainly induced by inconsistent deformations of coal strata around the roadway. This study proposed to enhance the overall performance of the coal rock and the bearing capacity of the surrounding rock by strengthening the coal pillars in the segment, improving the supporting parameters of the surrounding rock, and designing high-strength forepoling hydraulic support groups.

4.1 Asymmetrical Anchor Net Cable Support

Our preliminary analysis revealed that the roof and the upper side of the mining roadway in the steep working face were the main fracture areas and should be regarded as the key areas in surrounding rock control that needed reinforced support. The lower side and the roadway floor were subjected to forces directed towards the deep surrounding rock, with low deformation and failure degree. Therefore, to reduce the support cost and give full play to the support efficiency, this study proposed an asymmetrical support method and the related parameters for the mining roadway in steep working faces. Specifically, the roof was supported by three pre-stressed resin anchor cables, anchor rod, iron net, and steel bands. The iron net was mainly used for supporting the fractured zone in the surrounding rock between the strata on the roof and the right side; the anchor cables were 4.5 m and 6.0 m in length and 24 mm in diameter, and arranged with a row spacing of 1.5 m; the anchor rods, with a length of 1.6 m and a diameter of 20 mm, were arranged with a row spacing of 1.1 m. Three anchor rods, iron net, and steel bands were combined and arranged on the right side of the roadway to form rigid/flexible full-closure support for both sides and the roof. As shown in Fig. 8, the anchor rods on the right side, with a length of 1.8 m and a diameter of 20 mm, were arranged with a row spacing of 1.2 m.

4.2 Full-closure Forepoling Hydraulic Support Group

At a certain distance in front of the working, the surrounding rock experienced mining-induced stresses, where the roadway exhibited great deformation
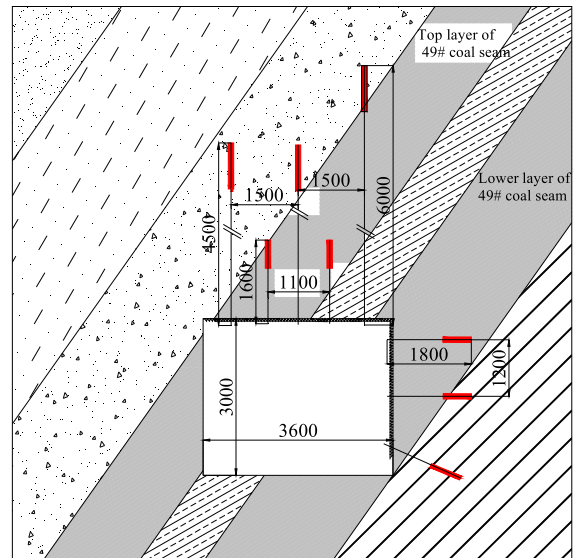

Fig. 8 Asymmetry support design of roadway in steeply inclined mining face

and serious wall caving. In this working face, the fallen coal rock flew into the working face and posed a danger to operators and equipment. Moreover, large fallen rocks may push over the support in the working face. Forepoling support with individual hydraulic supports implies high labor intensity, poor safety, and slow advance of the working face. Moreover, the coal wall on the roadway side cannot be adequately controlled. Therefore, a self-mobile forepoling hydraulic support group was developed in this study.

Forepoling hydraulic support group refers to the connection of two hydraulic supports by moving the jack. Self-motion can be achieved by setting support as the pivot and moving the jack. In addition, to achieve good support of the side coal wall, the side protecting plates of the hydraulic support were designed and rebuilt into the side support plates. Besides, to reduce the effect of the fallen rock on the recovery in the working face, the rear gangue-blocking plates were set at the connection between the upper roadway and the end supports. Accordingly, a full-enclosure operating space was formed after the rear gangue-blocking plates were connected with the upper-end supports in the working face, ensuring mining safety in the steep working face. As shown in Figs. 9 and 10, each forepoling hydraulic support group, with a length of 11.12 m, was arranged in the upper and lower parts of the roadway, respectively.

4.3 Coal Grouting Reinforcement

According to the above analysis, the instability of the coal pillars in the segment is the main cause of serious deformation and failure of the mining roadway in the steep working face. Ensuring the overall stability of the coal pillars in the segment is favorable for controlling the surrounding rock in the roadway. When using the conventional anchor-net-cable support for the working face with special geological structures, the strength points can hardly be found during the piling of anchor rods or cables. Accordingly, the direct support with anchor rods and anchor cables fails to control the surrounding rock. Moreover, it can even increase stresses in the surrounding rock, aggravating the deformation and failure of the roadway. Therefore, the grouting reinforcement method was proposed for the fractured coal rock around the roadway, as shown in Fig. 11.

To evaluate the control performance of grouting reinforcement on the stability of the surrounding rock in the steep working face, we assessed the vertical stresses and displacements, as well as the evolution pattern of the plastic zone before and after the grouting via numerical simulation. Physical and mechanical parameters of the coal seam strata as listed in Table 1.

Figures 12 and 13 illustrate the deformation patterns of the mining roadway in the steep working face under stress before and after grouting reinforcement. Through comparison, the roof, the floor, and the right side of the roadway were the main deformation and plastic failure zones before the grouting reinforcement. After the grouting, the bearing capacity of the crushed coal around the roadway was enhanced, and
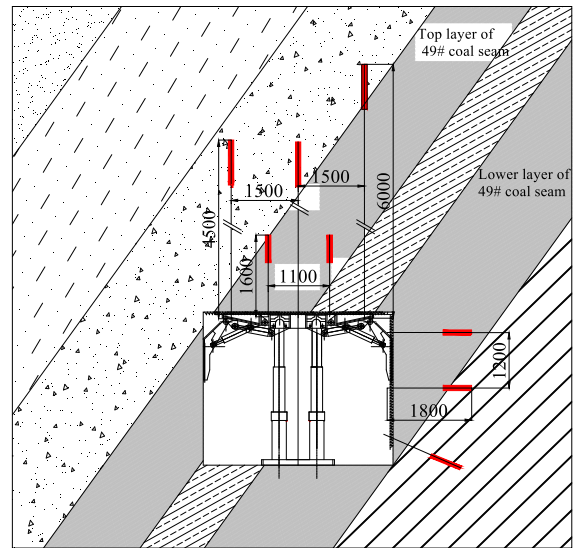

Fig. 10 Roadway reinforcement in advance

the overall bearing arch was formed on the roadway surface. It resisted the action of the overlying strata, thereby reducing the stress on the right side of the roadway and improving the force condition and bearing performance of the surrounding rock.

5 Analysis of the Measured Deformation Data of the Mining Roadway

To gain in-depth knowledge of the deformation characteristics of the surrounding rock in the steep-seam working face, the roadway surface displacement and the displacements at the deep basic points of the surrounding rock during the tunneling process were
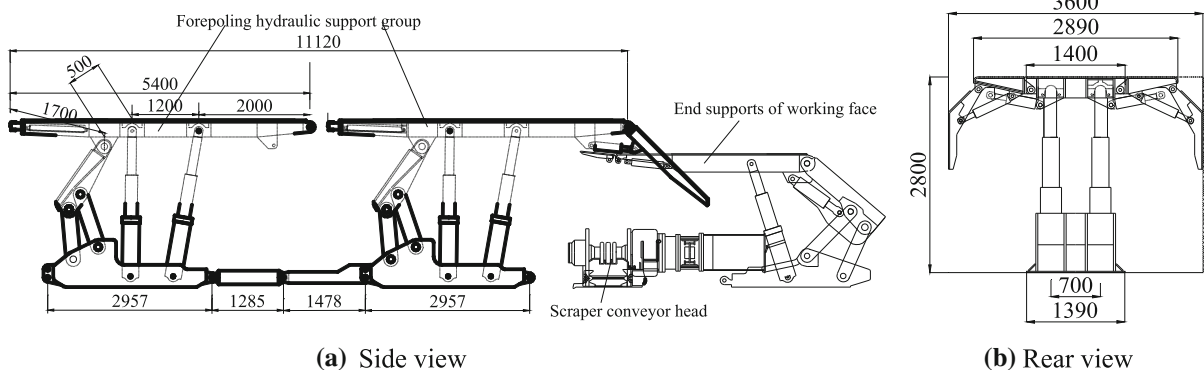

(a) Side view

(b) Rear view

Fig. 9 Hydraulic support group transform figure of advance support. **a** Side view; **b** Rear view
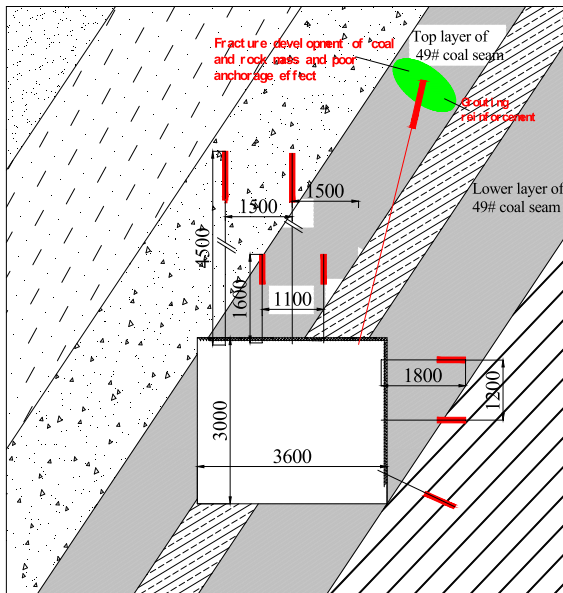
Fig. 11 Schematic diagram of roadway surrounding rock supporting system

measured. Three surface displacement monitoring stations were arranged for monitoring the deformations of the roof, the floor, and two sides of the roadway, which was 70 m away from the open-off cut in the working face. The deep basic point monitoring stations, 70 m away from the open-off cut in the working face, were arranged for monitoring the deformations of the deep surrounding rocks on the roof and the two sides of the roadway (due to the drill difficulty, no measuring points were arranged on the floor of the roadway). Roof separation behavior in the roadway was monitored using the deep base point displacement meter, which could measure the roof separations in four layers located at distances of 1.5, 3, 4.5, and 6 m from the surface of the abandoned

roadway. The layout scheme of roadway deformation monitoring points is shown in Fig. 14.

The crossing observation method was used to get the surface displacement of the roadway. Four wooden stakes were set manually on the roof, floor, left and right sides, and the displacement data were daily measured by personnel. The displacement variations between points A and B were the roof and floor heaves, while those between points C and D were the relative displacement of two sides.

5.1 Analysis of the Measured Data of Surface Displacement

Figure 15 displays the variation of the surface displacement of the roadway during the advancing process of the steep-seam working face. It can be observed that:

(1) Overall, the deformation on the roof and the roadway floor exceeded that on two sides. The maximum convergence between the two sides and the maximum deformation rate were 310 mm and 15 mm/d, respectively. Contrarily, the maximum roof-to-floor convergence was 527 mm, with a maximum deformation rate of 25 mm/d. These data can satisfy the normal operation requirement of the mine.

(2) The whole advancing process of the steep-seam working face can be conditionally split into three segments, namely, Segment I with no mining effect (at a distance over 50 m from the working face), Segment II with a mining effect (at 20 ∼ 50 m from the working face), and Segment III with a strong mining effect (20 m in front of the working face). In the final segment, the deformation of the surrounding rock

Table 1 Physical and mechanical parameters of coal mine stratum

Name	Thickness/m	Elastic modulus /GPa	Poisson ratio	Unit weight / kNm^{-3}	Cohesion / MPa	Friction angle /°	Strength of extension /MPa
Gritstone	5.1	10.2	0.244	27.1	7.9	33	3.1
Fine sandstone	1.3	13.7	0.240	28.3	8.6	38	3.8
Siltstone	1.1	4.9	0.248	26.5	6.1	31	2.6
Top layer of 49# coal seam	1.5	3.2	0.380	14.5	2.7	20	1.1
Siltstone	1.0	4.9	0.248	26.5	6.1	31	2.6
Lower layer of 49# coal seam	2.0	3.2	0.380	14.5	2.7	20	1.1
Fine sandstone	10	6.3	0.246	26.9	7.0	32	2.9

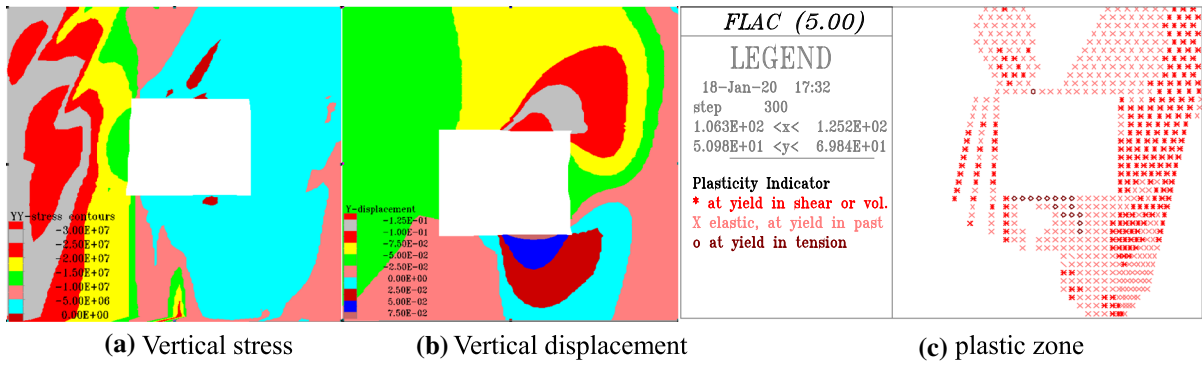**(a)** Vertical stress   **(b)** Vertical displacement   **(c)** plastic zone

Fig. 12 Before grouting the coal body. **a** Vertical stress; **b** Vertical displacement; **c** plastic zone

(a) Vertical stress   **(b)** Vertical displacement   **(c)** plastic zone
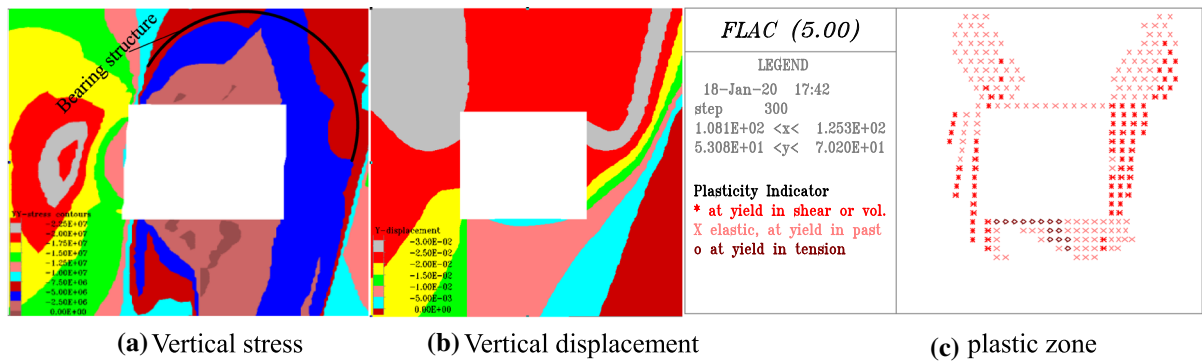
Fig. 13 After grouting the coal body. **a** Vertical stress; **b** Vertical displacement; **c** plastic zone

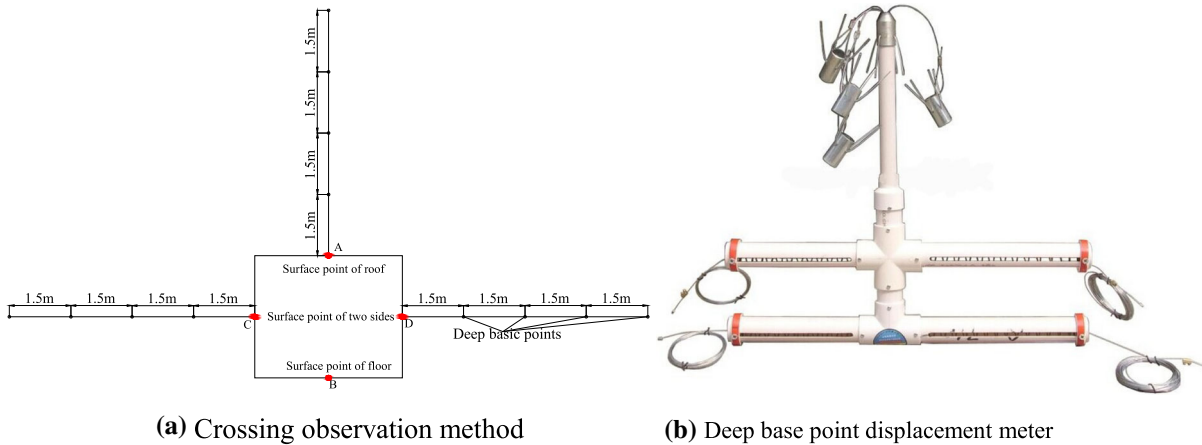**(a)** Crossing observation method   **(b)** Deep base point displacement meter

Fig. 14 The layout scheme of roadway deformation monitoring points. **a** Crossing observation method; **b** Deep base point displacement meter

increased drastically, and the control of the surrounding rock became particularly difficult.

5.2 Analysis of the Measured Displacement Data at Deep Basic Points
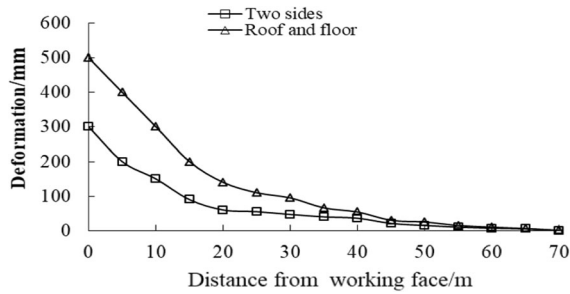
The following observations can be made:

Fig. 15 Roadway surface displacement variation curve in working face with face advancing

(1) Due to the mining activities in the working face, the deep surrounding rock in the roadway exhibited obvious deformation. The displacement at the deep basic point on the roof was the highest, followed by the value on the right side, while the deformation at the deep basic point on the left side was the lowest. Regarding the surrounding rock deformation at the same deep basic point, the deformation increased with the distance from the roadway surface.

(2) The deep surrounding rock in the roadway exhibited nonlinear deformation. According to the observation data, the crushed range of the surrounding rock was approximately $0 \sim 4.5$ m.

Therefore, it can be seen that by designing asymmetric support parameters, one anchor cable was added to the roof for reinforcement of the roadway, three anchor rods were saved on the left side of the roadway, reducing the support costs and improving the efficiency. Combined with the fully closed self-mobile forepoling hydraulic support group, the working face was effectively closed, the forepoling support efficiency was accelerated, and the labor intensity was reduced. Combined with grouting reinforcement in abnormal geological areas, crushed surrounding

rock's bearing capacity was effectively improved. The deformation characteristics of a roadway were verified by the field measurement data of surrounding rock deformation, which proved that the roadway met the mining safety requirements. This method can be applied to steep coal seams with geological conditions similar to the Qitaihe mining area.

6 Conclusions

(1) By taking the No. 49# steep-seam working face in Xintie Coal Mine as an example, the actual occurrence conditions and asymmetrical force characteristics of the mining roadway were taken into overall consideration. Therefore, the roof and two sides of the roadway were simplified as a 3-unit bar structure. Moreover, it was found that the roof and the right side were the main deformation and failure zones in the steep working face.

(2) Using the deformation and failure characteristics of the roadway in the steep working face, a rigid/flexible support method was proposed, which achieved full enclosure of the side and roof. In particular, three pre-stressed resin anchor cables were combined with anchor rods, iron net, and steel bands for roadway roof support, while three anchor rods were combined with iron net and steel bands for supporting the right side of the roadway. Further, a kind of self-mobile forepoling hydraulic support group was developed for roadway roof's and sides' support. Two forepoling hydraulic support groups were arranged in each roadway.

(3) According to the crushed coal rock's crushed condition in the geologic anomaly area, a coal rock grouting reinforcement was proposed for
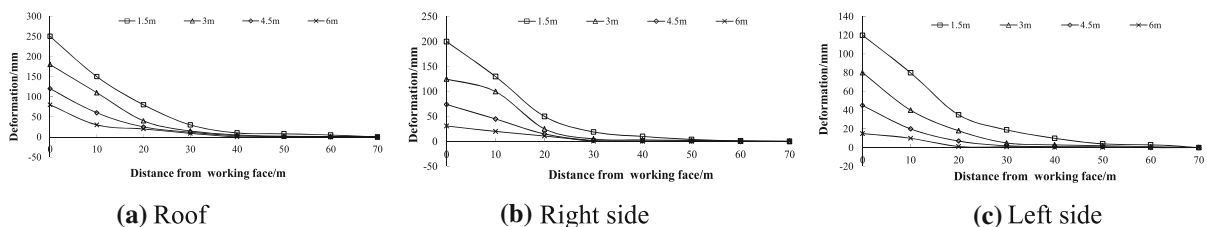

(a) Roof   **(b)** Right side   **(c)** Left side

Fig. 16 Roadway deep surrounding rock displacement variation curve in working face with face advancing. **a** Roof; **b** Right side; **c** Left side

enhancing overall performance. Through comparison, it was found that the bearing capacity of the coal rock was significantly enhanced after grouting.

(4) The displacements of the roadway surface and at the deep basic points in the roadway were measured. The roof and the floor of the roadway underwent greater deformation than two sides. The maximum convergence between the two sides was 310 mm, while the maximum roof-to-floor convergence reached up to 527 mm. The whole advancing process of the steep-seam working face can be conditionally split into three segments, namely, Segment I with no mining effect (at a distance over 50 m from the working face), Segment II with a mining effect (at 20 ∼ 50 m from the working face), and Segment III with a strong mining effect (20 m in front of the working face). The displacement at the deep basic point on the roof was greatest, followed by the value on the right side, while the displacement at the deep basic point on the left side was the lowest. The crushed range of the surrounding rock in the roadway was approximately 0 ∼ 1.5 m.

(5) Upon the implementation of the symmetric support parameters, fully closed self-mobile forepoling hydraulic support group, and grouting reinforcement in the geological anomaly area, the roadway deformation satisfied the requirements of mining safety, which fact was verified by actual measurements. This support method can reduce the support costs and improve support efficiency in steep coal seams with geological conditions similar to those the Qitaihe mining area.

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