

Research Article

Research on Control Mechanism of Surrounding Rock of Deep Gob-Side Entry Retaining

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To address the large deformation of the surrounding rock of deep gob-side entry retaining under high stress, lithological characteristics of the surrounding rock and failure model of support body and their evolutionary processes are analyzed through field investigation and theoretical analysis. Failure mechanisms of surrounding rock and the technology to control it are studied systematically. The results show that the causes of the large deformation of the surrounding rock are weak thick mudstones with softening property and water absorption behavior, as well as its fragmentation, dilatancy, and long-term creep during strong disturbance and highly centralized stress states. The cross-section shape of the roadway after deformation and failure of the surrounding rock is obviously asymmetric in both the horizontal and vertical directions. Since the original system supporting the surrounding rock is unable to completely bear the load, each part of the supporting system is destroyed one after the other. The failure sequences of the surrounding rock are as follows: (1) roadway roof fracture in the filling area, (2) filling body fracture under eccentric load, (3) rapid subsidence of the roadway roof, and (4) external crack drum and rib spalling at the solid coal side. Due to this failure sequence, the entire surrounding rock becomes unstable. A partitioned coupling support and a quaternary control technology to support the surrounding rock are proposed, in which the roof of the filling area plays a key role. The technology can improve the overall stability of gob-side entry retaining, prevent support structure instability caused by local failure of the surrounding rock, and ensure the safety and smoothness of roadways.

1. Introduction

The deformation of surrounding rock of gob-side entry roadways in deep and shallow coal mines is very different. The coal-rock mass is in an environment of high ground stress, high geothermal temperature, and high water pressure and experiences multiple strong effects from mining activity [1, 2]. In the deep gob-side entry retaining in the Huainan Mining Group, the strata often behave violently, resulting in severe damage to the surrounding rock. This damage includes the incline and sinking of the broken roof due to insufficient load-bearing capacity of the load-bearing structure, structure fracturing of the filling body, external crack drum and rib spal-

ling of the solid coal side, and serious floor heave. At present, a method of grading gob-side entry retaining is widely adopted by the Huainan Mining Group. However, the surrounding rock is difficult to control, resulting in serious large-scale deformation, which is very unfavorable for the safe construction, ventilation, and reuse of gob-side entry retaining. Therefore, a systematic investigation of the failure mechanism and control method of the surrounding rock in deep gob-side entry retaining is of practical significance for gob-side entry retaining technology in deep mines.

Many studies have been conducted on the failure mechanism, control theory, and technology of surrounding rock in coal mines. Kang et al. [3] proposed design principles

and suggestions for supporting surrounding rock by analyzing the deformation and failure characteristics of gob-side entry retaining of a working face with multiple roadways; Xie et al. [4] presented a new method of roadside support using a concrete-filled steel tubular scaffold by investigating the settlement and failure of surrounding rock structures of gob-side entry retaining with large mining height; Han et al. [5] presented a concept of roadside composite bearing and revealed the stability mechanism of roadside structures. Tan et al. [6] investigated the mechanical relationship between the overlying strata of a gob-side entry retaining and the filling body and proposed a support technology comprising a soft and hard composite layer filling body; Chen et al. [7] clarified the mechanism of roadside support by analyzing the response characteristics between the roadside support and the distribution of the stress field and displacement field in surrounding rock. From a national perspective, the mine has a larger burial depth resulting in strong mine pressure, large deformation, expansion, and poor stability of the deep gob-side entry retaining, which makes it difficult to reuse. It is still necessary to further study the stability of the surrounding rock and supporting technology under conditions of high pressure and large deformation [8–11].

Using gob-side entry retaining of the 12512 working face as the research object, this article systematically analyzes the characteristics of the surrounding rock, the failure characteristics of the supporting structure, and the deformation and failure process of gob-side entry retaining under deep soft rock conditions. This study illustrates the failure mechanism of the surrounding rock and proposes a quaternity control technology and roof partition coupling support to support the surrounding rock, with the filling area's roof playing a key role. This technology is also verified through field engineering to determine whether it provides a good supporting effect.

2. Engineering Condition Analysis

2.1. Geological Conditions. Located in the south of the anticline transition, the eastern area of the coal mine, on the whole, is a south-dipping monoclinic structure with a relatively simple geological structure. The dip angle of the coal seam in the 12512 working face is 3° , the coal seam floor elevation is -821.4– -853.2 m, and the depth is more than 900 m. According to the geological conditions of the mining area, an in situ stress test of the rock in the 12512 working face floor was carried out; the results show that the direction of the maximum horizontal principal stress of the coal seam is approximately east-west and that its magnitude is about 29.1–30.8 MPa; the magnitude of the vertical stress is 23.54 MPa. Figure 1 shows the section of the roadway roof and floor rock layers.

The mineral compositions of the mudstone samples in roadway roof and floor as tested by X-ray diffraction are as follows: 65.3% kaolinite, 14.2% quartz, 10.9% montmorillonite, 5.1% illite, and 4.5% of other minerals. According to the classification criteria of expansive soft rock proposed by academician He Manchao [12], it is determined to be a moderately expansive soft rock; the strength of which is reduced after soaking in water.

Histogram	Lithology	Thickness (m)
	Sandy mudstone	$\frac{1.0\sim 5.3}{3.2}$
	Fine sandstone	$\frac{0.8\sim 9.6}{2.6}$
	Carbon mudstone	$\frac{1.7\sim 10.0}{3.5}$
	Sandy mudstone	$\frac{0.9\sim 6.7}{3.1}$
	11-2 coal	$\frac{0.5\sim 6.9}{2.5}$
	Sandy mudstone	$\frac{1.4\sim 4.2}{4.5}$
	Carbon mudstone	$\frac{0.6\sim 7.2}{3.5}$

FIGURE 1: Strata distributions of roadway roof and floor.

2.2. General Engineering Situation. Figure 2 shows the 12512 working face; the section net width \times net height = 4.8 m \times 2.8 m. For mining, gob-side entry retaining is adopted by the half in situ mode with an opening gap width in the working face end, a filling body width \times height = 2.5 m \times 2.5 m, and a shift distance of 0.6 m toward the roadway with a width of 4.2 m.

- (1) The support parameters of the section track drift: there are 6 anchor bolts of Φ 20 mm \times L2 200 mm in each row of the roadway roof with a yow line space of 850 mm \times 850 mm. A row of anchor cables with Φ 20 mm \times L7 300 mm are vertically arranged between the two rows of anchor bolts in accordance with the “3-3” mode and a yow line space of 1200 mm \times 850 mm. The support parameters of the coal sides: there are 4 anchor bolts in each row with a yow line space of 850 mm \times 850 mm and a metal mesh. Finally, the top slope is sprayed to seal the surrounding rock
- (2) The support parameters of the opening gap in the roadway roof at the working face end: there are 4 anchor bolts in each row with a yow line space of 850 mm \times 850 mm. A Φ 20 mm \times L7 300 mm single anchor cable is vertically arranged between the two rows of anchor bolts, adopting 4 rows of canopy auxiliary support

Utilizing the above supporting parameters, at the first mining stage of the 12512 working face, serious deformation and failure of the surrounding rock occurred in gob-side entry retaining accompanied by the crushing of the shallow surrounding rock and an obvious decrease in the mechanical properties of the surrounding rock.

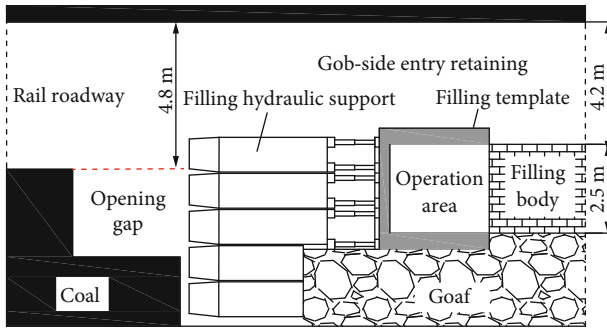


FIGURE 2: Spatial layout of the working face end.

3. Failure Law of the Deep Gob-Side Entry Retaining in High-Stress Soft Rock

3.1. Failure Form of the Surrounding Rock. To fully understand the internal destruction of the surrounding rock, a borehole peeping instrument was used to detect and analyze the damage within the rock. There are 5 boreholes in each section of gob-side entry retaining. Based on the development of borehole fractures, the fractured area and fissure area of the surrounding rock were drawn as shown in Figure 3. As can be seen in the figure, the fracture development degree of the surrounding rock in gob-side entry retaining ranges from large to small as follows: the filling area roof (6.9 m) > the roadway roof (4.0 m) > the roof of the solid coal side (3.8 m) > the upper part of the solid coal side (2.8 m) > the lower part of the solid coal side (2.1 m). Thus, the damage degree of the filling area roof and the upper part of the solid coal side is obviously larger than that of the solid coal side, respectively. Moreover, the overall deformation and failure of the surrounding rock are obviously asymmetric relative to the vertical and horizontal directions of the roadway cross-section.

3.2. Failure Process Analysis of the Surrounding Rock. The activity of the surrounding rock and its deformation characteristics in gob-side entry retaining can be divided into 3 stages, which in chronological order are initial activity, transition period activity, and later stage activity [13–17]. Considering the strong mining impact at the front section of the section track drift, the deformation and failure process of the surrounding rock can be roughly divided into 4 stages. Figure 4 shows the mining period of the leading working face, the early stage of a gob-side entry retaining, the active period of the overlying rock (the deformation and subsidence period of the overlying rock), and the creep period of the surrounding rock; among these, the creep period of the surrounding rock is lengthy and restricted by space resulting in the monitored data only being available in the range within 200 m behind the working face. The deformation and failure of the surrounding rock are as follows:

(1) The mining-affected period of the leading working face (0–100 m ahead of the working face): at 80 m ahead of the working face, the deformation velocity of the surrounding rock increases, especially at the

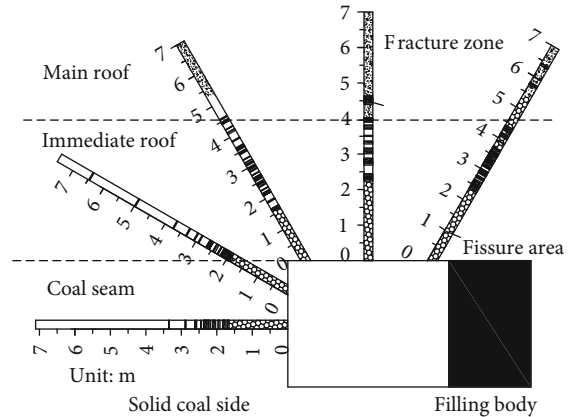


FIGURE 3: Fracture development status of the surrounding rock.

coal side and floor, which show the fastest deformation rate. Together with the effect of the high abutment pressure in the working face and the repeated “jacking and pressing” disturbance of the end hydraulic support in the working face, the mudstone of the filling area’s roof shows shallow fragmentation and deep separation

- (2) The initial stage of gob-side entry retaining (0–50 m behind the working face): with the advancing of the working face, the soft immediate roof at the edge of the goaf loses support and then falls, resulting in a gradual increase in the roof pressure and the stress concentration degree. Due to the influence of the main roof and the vertical stress of the upper strata on the thick soft immediate roof, the stratum at the edge of the goaf first undergoes tensile and shear failure, as well as loose expansion, and then flows in the direction of the goaf. The deformation and failure of the surrounding rock in this stage are mainly manifested as follows: ① The filling area’s roof is in a weak support state and does not form a complete bearing structure with the roadway roof, leading to the rapid subsidence of the roof and a direct pressing on the filling template (see Figure 5(a)). ② The load of the filling area’s roof on the filling body is large and uneven, and together with the low strength of the early filling body and the poor roof connection, it gives rise to the asymmetric fracturing of the weak area on both sides and a decreased width of the main bearing area
- (3) The active period of the overlying strata of gob-side entry retaining (-50–110 m behind the working face): due to the severe activity and higher stress concentration degree of the surrounding rock, the roof, floor, and solid coal side all move at 10–25 mm/d accompanied by a fast deformation speed. The main roof of the stope edge is broken at one side of the solid coal and inclined to the goaf edge, which forces

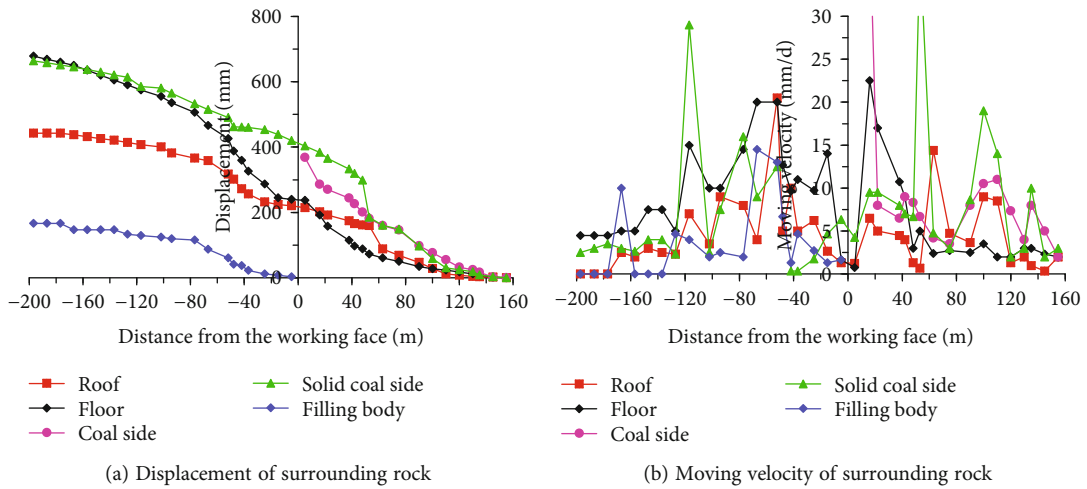


FIGURE 4: Displacement curves of surrounding rock of deep gob-side entry retaining.

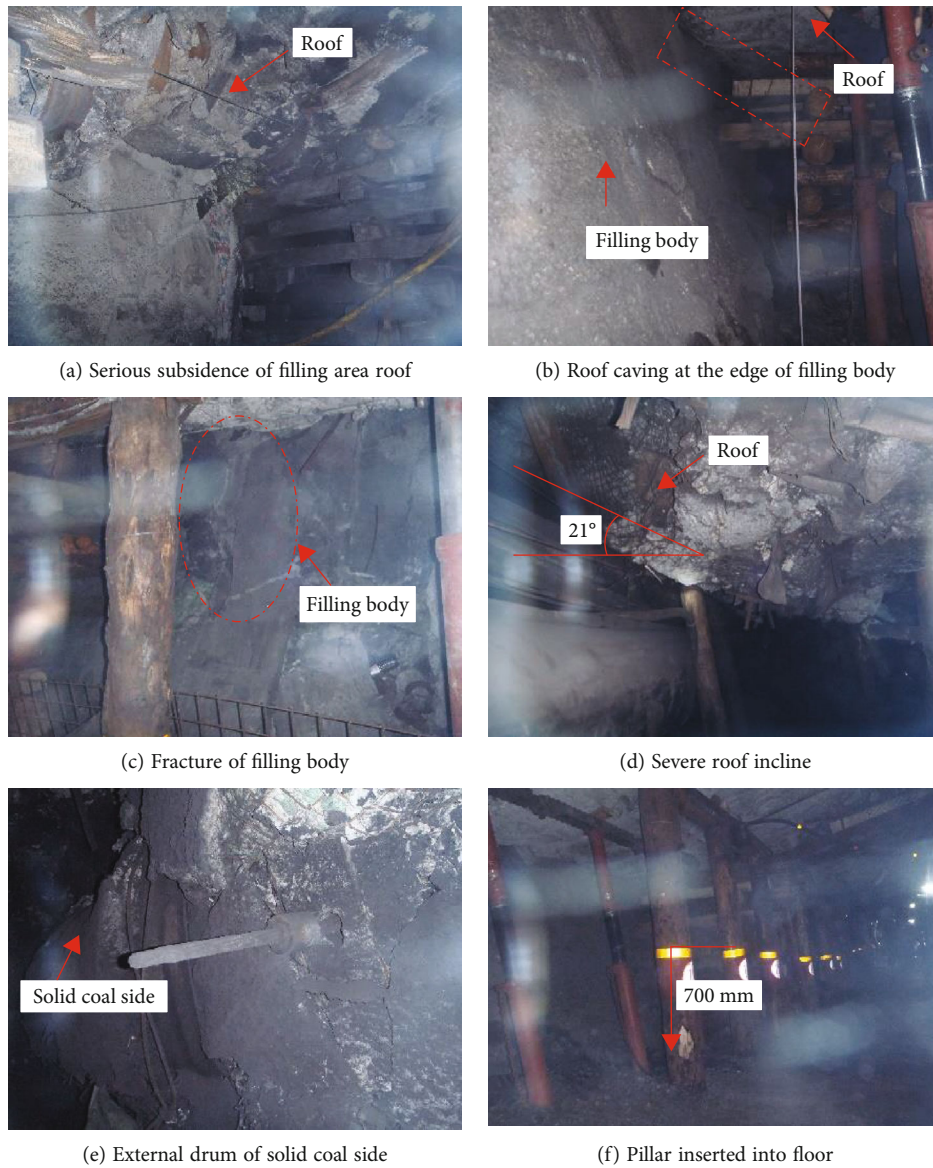


FIGURE 5: Failure status of deep gob-side entry retaining.

the filling body and roof to bear the high abutment pressure that is further transferred to and concentrated at the deeper part of the solid coal seam; this causes a marked expansion of the fracture zone, the fissure zone, and the plastic zone in the surrounding rock. The deformation and failure of the surrounding rock in this stage are mainly manifested by the following: ① The filling area's roof is strongly disturbed and extremely broken, causing roof caving along the filling body (see Figure 5(b)). ② The filling body is inclined and rotated; the crack extending to the filling body makes it unable to reach its designed carrying capacity and destroys its stability ahead of time (see Figure 5(c)). ③ The filling body and its roof are continuously destroyed in the filling area. The load on the anchor bolt (cable) vertically arranged on the roof increases linearly with the inclined subsidence of the roof, the shearing dislocation, and the separation layer, causing more tensile failure of the anchor bolt (cable); the roadway roof shows an unstable state of multizone separation (see Figure 5(d)). ④ In the upper part of the solid coal side, there is an outer drum and even severe spalling (see Figure 5(e)) as well as an overall shift. ⑤ A large amount of water accumulated in gob-side entry retaining leads to the softening expansion of the thick mudstone soaked in water. In addition, the filling body with the heavy load is embedded in the floor, causing serious floor heave (see Figure 5(f))

- (4) The creep period of the surrounding rock (over 200 m behind the working face): the activity of the overlying strata slows down. The stress of the surrounding rock is relatively balanced, but the creep rate is still high, especially in the floor (4.5 mm/d), followed by the solid coal (3.5 mm/d). Before the completion of the working face and the roadway repair, after 11 months or more, the displacement of the roof-floor and the coal sides and the roadway section shrinkage rate can be up to 1211 mm, 743 mm, and 54%, respectively; this does not meet the production requirements of the next working face due to a huge amount of roadway repair works needing to be completed

The deformation and failure of support structures in gob-side entry retaining are uneven, which causes the overall instability of the structure due to the significant deformation and a part failure [18, 19]. Based on the results of field investigations and simulation tests on the deformation and failure of the surrounding rock in gob-side entry retaining (Figure 6), the following conclusions are drawn: the support structure of the surrounding rock is first destroyed at the edge of the goaf and then toward the solid coal side. The evolution process of the deformation and failure of the surrounding rock is roadway excavation → stress state change in the surrounding rock → plastic collapse expansion in the surrounding rock → shallow fissure increase in the surrounding rock → slow creep period of the surrounding rock → restress of overlying strata in the stope edge caused by mining → fracture development in

the filling area's roof → filling body instability under eccentric load or roof cutting at the edge of the filling body → crack increase in the roadway roof in the course of turning and sinking → transfer of high support stress from the roof to the solid coal side → fracture propagation in the solid coal seam → sharp increase in the vertical and horizontal displacements in the solid coal seam leading to rib spalling and outer drum → acceleration unbalance of the roof strata; all this finally causes gob-side entry retaining to become completely unstable.

The above analysis shows that the support system of gob-side entry retaining does not form a complete whole integer and the original supporting system cannot fully mobilize the bearing capacity of the deep surrounding rock, resulting in damage to the support structure one after the other. This is generally manifested in the following 4 aspects: ① The roof support structure exhibits poor integrity and weak bearing capacity. Especially in the filling area, the roof is seriously damaged and unstable, which is the key component to strengthen the support. ② The anchoring depth of the solid coal side is not enough, causing the overall displacement. ③ The filling body has low strength and uneven force. ④ The bare soft thick mudstone floor without the support structure is affected by water.

4. Support Technology of Deep Gob-Side Entry Retaining in High-Stress Soft Rock

Based on the movement characteristics of the surrounding rock in the deep gob-side entry retaining in high-stress soft rock, and considering the initial point and key point of the chain reaction of the deformation and failure of the support structure, a quaternary control technology and roof partition coupling support to support the surrounding rock is proposed, with the filling area's roof playing a key role. This quaternary control technology consists of the roof P_1 with anchor bolt and mesh injection coupling support, solid coal support P_2 with anchor bolt (cable) support, P_3 with high bearing capacity, and roadway auxiliary support P_4 . Among them, the roadway roof P_1 is divided into 3 areas, namely, the filling area roof I zone, the roadway roof II zone, and solid coal side roof III zone. Among these, the filling area roof I zone is the key surrounding rock supporting structure in both the horizontal and vertical directions of gob-side entry retaining. The support structure model of gob-side entry retaining and the quaternary control technology for the surrounding rock are shown in Figure 7.

4.1. Coupling Support in the Roof 3 Zone. The key to successful gob-side entry retaining is to maintain roof integrity. To achieve the best supporting effect requires making all-round plans for the roof 3 partition coupling support. The coupling supporting steps in the roof 3 zone are as follows. The first step is to arrange the cable stayed anchor in the section track drift roof near both the coal sides. The anchor cable end goes deep into the crack-free area of the shoulder corner of the roadway roof, including the deep strata of the I and III zones, which strengthens the support of the roadway shoulder corner to prevent the roof from falling at the edges of the corners of the coal during gob-side entry retaining. The

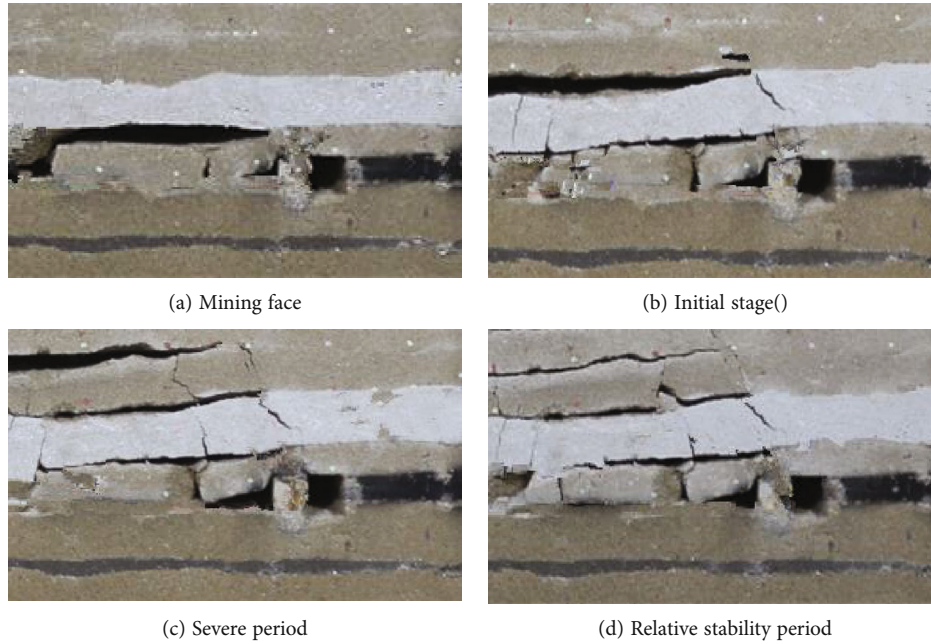


FIGURE 6: Fracture development process of deep gob-side entry retaining.

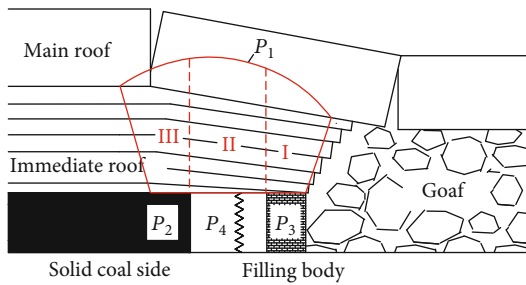


FIGURE 7: The support structure model of gob-side entry retaining.

second step is to provide support at a certain distance ahead of the working face. A hollow grouting anchor rope^[120-21] is arranged in the II zone of the roadway roof to achieve grouting and integration of the bolting and grouting, which will reconsolidate the deep and shallow cracks and the broken strata in the roadway roof, improve the mechanical properties of the coal-rock mass and its bearing capacity, provide a reliable basis for the anchor (cable), improve the stress condition of surrounding rock, and ensure anchor bolt (cable) anchorage reliability. The third step is to utilize the “three high” (high strength, high stiffness, and high pretension) anchor bolts and the large diameter anchor cables to strengthen the working face end to prevent the collapse of the filling area’s roof and provide a good condition for the smooth implementation of the roadside filling. The roof 3 partition coupling support will eventually fix the roof together to prevent its discontinuous deformation, including roof layer separation, dislocation, crack opening, and new crack generation; this will also ensure roof leveling.

4.2. Reinforcement of the Solid Coal Side. Strong support can not only improve the vertical bearing capacity of the roof but also restrain floor heave [22–24]. The formation of the serious outer drum is attributed to the insufficiently effective anchor length of the anchor bolt, which leads to the entire displacement of the bolt-grouting body. From the section track drift to gob-side entry retaining, a fracture zone, plastic zone, and elastic zone have formed on the solid coal side from the outside to the inside. To maintain stability, the anchorage range should be greater than the sum of width of the broken zone and the plastic zone, which is the limit equilibrium area width x_0 that is calculated by the following equation [25]:

$$x_0 = \frac{MA}{2 \tan \varphi_0} \ln \left(\frac{k\gamma H + (c_0/\tan \varphi_0)}{(c_0/\tan \varphi_0) + (p_x/A)} \right), \quad (1)$$

where M is the mining height with a value of 2.50 m, A is the lateral pressure coefficient with a value of 0.42, H is the mining depth with a value of 820 m, φ_0 is the coal-rock interface internal friction angle with a value of 30° , c_0 is the cohesion of the coal-rock interface with a value of 0.34 MPa, k is the maximum stress concentration factor with a value of 2.7, γ is the overburden average value with a value of 22 kN/m^3 , and p_x is the support strength of the solid coal side with a value of 0.21 MPa. These values are based on engineering experience and the designed quantity and pretightening force of the bolt (cable) per unit area of the coal side.

According to the formula, the limit equilibrium area width of the solid coal side is 3.54 m. Because of the soft coal body, the anchor bolt is designed to enter more than 2.30 m into the elastic zone, and the anchor cable length for the solid coal body is finally determined to be 7.30 m.

4.3. Optimization of Bearing Capacity of Filling Body. The vertical bearing capacity and deformation capacity of the filling body should match the support mode and strength of the roof-floor; this makes the filling body match the roof-floor movement and fully provide its packing effect. Improving the bearing capacity of the filling body is mainly achieved in the following 3 ways:

- (1) Select filling materials that in the early stage have rapid solidification and high strength: paste material, which is mainly composed of silicate, fly ash, sand, water, and additives, is used in gob-side entry retaining because of its advantages of being extensive, low cost, high strength, and so on

To verify the bearing performance of the filling body, the strength of the paste filling material was tested. 4 groups of specimens were directly sampled and manufactured in the roadside filling field. There are 3 specimens with a length of 150 mm, a width of 150 mm, and a height of 150 mm in each group. The change in the uniaxial compressive strength of the specimens with time as measured in the laboratory is shown in Table 1. The values in the table indicate that the strength of the filling material can meet the relevant regulations.

- (2) The reasonable reinforcement of reinforced skeleton in the filling body: for a large volume of a filling body, the uniaxial compressive strength of filling body is much lower than the uniaxial compressive strength. Moreover, during the interaction with the overlying strata, the filling body is unevenly subjected to both the vertical and horizontal forces. To increase the compressive strength and shear strength of the filling body and prevent the filling body from slipping to the goaf, a reinforcing steel skeleton should be preset in the filling body
- (3) The optimization of construction technology: when filling work is carried out beside a section track drift, the filling body should be fully connected to the roof so that the load can be uniformly borne; the contact floor area of the filling body should be increased to prevent the filling body from getting embedded in the thick mudstone of the roadway floor; the filling body should also be connected to the roof-floor to form a composite bearing structure of "roof-filling body-floor" to avoid the slippage or rotation of the filling body

4.4. Auxiliary Strengthening Support. During the violent activity of overlying strata, the roof pressure is high and the support structure is still unable to maintain the stability of the roadway. Therefore, it is necessary to make use of auxiliary strengthening support to brace the roof, assist the filling body to bear the load, and restrain the floor deformation. The auxiliary support in a roadway is mainly composed of a single hydraulic prop+ π type steel beam+high strength and large postbase, which can ensure an initial large support force at the beginning of mining. Because of the deformation of the roof-floor, the load on the single hydraulic prop

TABLE 1: Strength tests of filling material.

Days (d)	Compressive strength value (MPa)
1	4~7
3	10~15
7	15~20
28	29~33

increases; the hydraulic prop can restrain roof separation and floor heave in time by yield and additional resistance limiting its deformation to finally achieve the double control of the roof and floor.

5. Support Scheme Optimization and Control Effect Analysis

5.1. Optimization of the Supporting Scheme. Considering the field conditions, a quaternary control technology for deep gob-side entry retaining is optimized reasonably. The optimized support scheme is shown in Figure 8.

- (1) The coupling support on the roof 3 zone: a group of large diameter anchor cables with $\Phi 20 \text{ mm} \times L7 300 \text{ mm}$ and 16[#] channel beam with a length of 3000 mm and a hole distance of 850 mm are arranged on both sides of the section track drift roof. At 110 m ahead of the working face, a hollow grouting anchor cable with $\Phi 20 \text{ mm} \times L7 300 \text{ mm}$ and high-strength tray are added to each row of the anchor beam end on the roof via the step-by-step arrangement method, and spray grouting operations are performed to reinforce the roof
- (2) The reinforcement of the solid coal side: three $\Phi 20 \text{ mm} \times L7 300 \text{ mm}$ anchor cables equipped with 20[#] channel steel are arranged along the roadway; these three cables are 400 mm, 1200 mm, and 2000 mm away from the roof
- (3) The reinforcement of the opening gap roof at the working face end: there are four $\Phi 20 \text{ mm} \times L2 200 \text{ mm}$ "three high" bolts equipped with M5 steel belts in each row; the pretightening force is 60~80 kN, and the yow line space is 850 mm \times 850 mm; then, an anchor cable with $\Phi 20 \text{ mm} \times L7 300 \text{ mm}$ and high-strength tray are arranged between the two rows of bolts. The pretightening force is 80~100 kN, and the array pitch is 850 mm; two rows of anchor cables with 16[#] channel are arranged along the tunnel direction layout, and the hole distance is 1200 mm
- (4) The bearing performance optimization of the filling body: when the special paste filling material is selected, the water-cement ratio should be strictly controlled to ensure that the material strength is up to standard. Three-dimensional reinforcing steel bars are preset in the formwork before roadside filling, and the reinforcing ribs are replaced by $\Phi 20 \text{ mm} \times L2 200 \text{ mm}$ bolts, with $\Phi 6 \text{ mm}$ grid bars

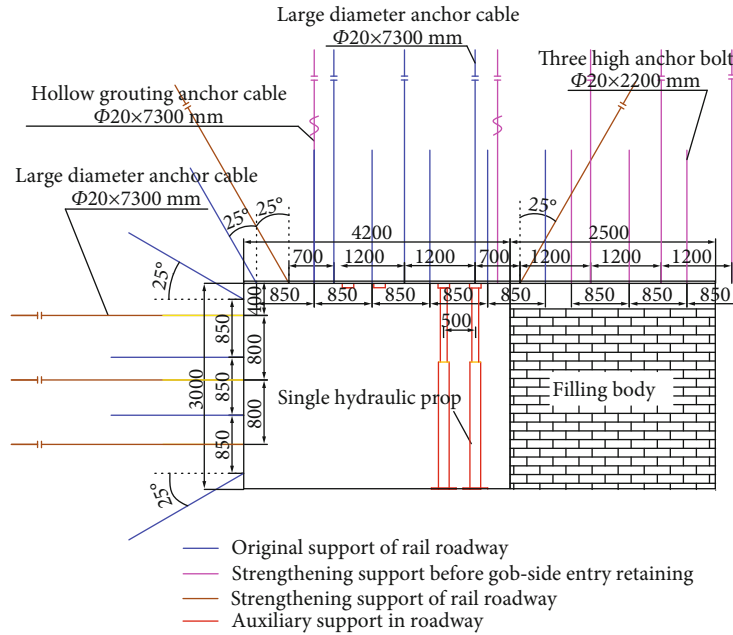


FIGURE 8: Support scheme of deep gob-side entry retaining.

which mutually butt to form a three-dimensional framework; here, the upper anchor bolts and lower anchor bolts of the vertical 3D stiffener are fixed inside the roof and floor, respectively. In addition, a 4000 mm long I-beam is placed under the filling body with a spacing of 800 mm, which increases the contact area and prevents the filling body from cutting into the thick mudstone of the floor

- (5) The auxiliary strengthening support in the roadway: the auxiliary reinforcement in the roadway is arranged close to the filling body layout by setting one single hydraulic prop with an $11^{\#}\pi$ type steel beam and $300\text{ mm} \times 300\text{ mm} \times 10\text{ mm}$ postbase with high strength and large postbase along the roadway. There are 2 single hydraulic props in each section and two sides near the filling body and the roadway center; this is an asymmetric support state with an initial bearing capacity not less than 100 kN

5.2. Control Effect of the Surrounding Rock. After adopting this scheme, five sets of displacement measuring stations were installed in the surrounding rock of gob-side entry retaining of the 12512 working face, and these were used to monitor the deformation of the surrounding rock at different distances behind the working face. The displacement curve of the surrounding rock along gob-side entry retaining was shown in Figure 9.

After gob-side entry retaining in the range of 250 m behind the working face experienced strong dynamic pressure, the displacement of the filling body, the solid coal, and the roof was 40 mm, 294 mm, and 152 mm, respectively. The floor heave was 351 mm. The filling body and roof were basically stable, and the displacement of solid coal and floor

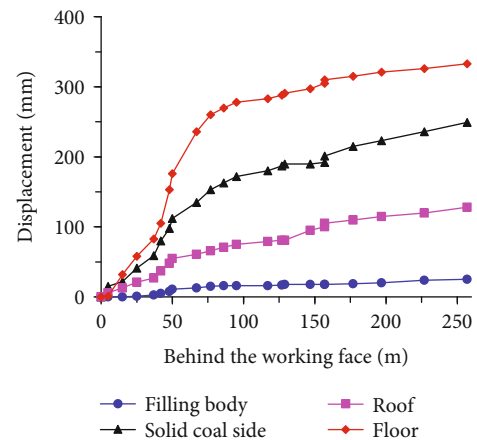


FIGURE 9: Periodical deformation curves of gob-side entry retaining.

increases slowly. The roadway cross-section can meet the requirements of gob-side entry retaining at different stages.

For the record, in this paper, a new support method is proposed for gob-side entry retaining in soft rock with high stress. The deformation of the surrounding rock is effectively controlled to a certain extent, which is beneficial for the safe reuse of the next working face. However, more simple, economic, and effective methods are needed to continually improve the supporting technology and reduce the cost.

6. Conclusion

- (1) The large deformation of the deep gob-side entry retaining in soft rock with high stress is mainly attributed to the low uniaxial compressive strength,

softening and swelling of thick mudstone under the influence of water, cataclastic dilatancy, and long-term creep under strong mining activity and high-stress states; through verifying the failure characteristics of shallow and deep surrounding rock, the overall deformation and failure are obviously asymmetrical relative to the vertical and horizontal directions of the cross-section of the roadway

- (2) By analyzing the deformation and failure characteristics of the deep gob-side entry retaining in soft rock with high stress and the failure mechanism of the surrounding rock, it is found that the original supporting system of gob-side entry retaining is not sufficient, leading to the supporting system getting destroyed one by one. The surrounding rock first starts from the filling area's roof, resulting in an eccentric loading fracturing of the filling body. Then, the roadway roof begins to incline and sink steeply due to the external drum and rib spalling at the solid coal side and severe floor heave, which eventually leads to the instability of the surrounding rock
- (3) The gob-side entry retaining roof is divided into three zones for coupling support. A quaternary control technology for controlling surrounding rock is proposed with the filling area's roof as the key factor. This technology mainly includes the roof with anchor bolt mesh grouting coupling support, solid coal with anchor bolt (cable) support, roadside filling body with high bearing performance, and auxiliary strengthening support in the roadway during the mining stress adjustment period. The technology has been applied to gob-side entry retaining of the 12512 working face and has achieved good results and satisfied the ventilation demand of gob-side entry retaining at different stages

Data Availability

All data used to support the findings of this study are included within the article. There is not any restriction on data access.

Conflicts of Interest

The authors declare no conflicts of interests.

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