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Research Article

Efficient Excavation and Support Cooperation Technology for Surrounding Rock of Deep Buried Long-Distance and Large Section Gob-Side Roadway: A Case Study

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The gob-side roadway technology is widely used in coal mining in China, as it can improves the recovery rate of coal resources and alleviate the shortage of mining replacement. However, it is still difficult to control the stability of surrounding rock in gob-side roadway under deeper mining depth and more complex stress environment. With the auxiliary transportation roadway 30207 (ATR 30207) of the Muduchaideng Coal Mine as engineering background, this paper introduces the engineering case of gob-side roadway characterized by deep buried, long-distance, and large section. Through comprehensive methods, we studied and put forward the efficient excavation-support cooperation technology for surrounding rock of gob-side roadway. The research shows that the head-on cutting of gob-side roadway causes the stress to transfer and gradually adjust in the heading face to form a steady-state advanced abutment stress field. The coupling effect of the advanced abutment stress and the lateral abutment stress of goaf are the main reasons for repeated hole collapse of anchor cable drilling in solid coal rib, development and expansion of the roof separation fracture, and the low excavation speed. Supposed that upon the heading face support is completed, the next excavation-support cycle is quickly started during the early stage of stress adjustment, and the time effect can be fully utilized to alleviate the disturbance intensity of the advanced abutment stress in the heading face, as well as reduce the damage of rock mass. This paper puts forward the time-effect collaborative control countermeasures of the roof and rib in gob-side roadway of "hole collapse anchor cable of solid coal rib lag construction and waits for pressure relief and rapid excavation-support cycle in the heading face." Engineering practice shows that the mine pressure behavior of roadway roof and solid coal rib is effectively controlled, and the roadway forming speed is greatly improved, which can provide reference for the efficient excavation-support design of gob-side roadway under the conditions of deep buried, long-distance, and large section in similar deep mines.

1. Introduction

With the gradual mining of shallow coal resources, deep mining has become an inevitable trend of coal mining [1–3]. However, the stability control of gob-side roadway is the major technical problem in deep mining under conditions of high ground stress and increasingly complex mining environment [4–6]. Under the coupling effect of the lateral abutment stress in goaf and high ground stress, the surrounding rock of the gob-side roadway is seriously damaged with reduced bearing capacity, which requires more effective supporting control technology. During the excavation of the roadway, large deformation and failure of the support structure occur frequently, restricting the safe and efficient mining of coal resources [7, 8].

A large number of scholars have carried out detailed research on the stability control of deep gob-side roadway. Bai et al. studied the deformation and failure law of gob-side roadway mining under the action of abutment stress in advanced and lateral working face, established the dynamic mechanical model of roadway roof structure, and proposed the roof failure criterion, which regards the roof center as an important area for control [9]. Aiming at the problem of surrounding rock deformation control of gob-side roadway driving with retained top coal, Ma et al. proposed the support method of strengthening roof support to control the stability of top coal and strengthening coal rib support to achieve collaborative control, which effectively controlled the stability of surrounding rock of such roadways [10]. Han et al. studied the partition control technology of gob-side roadway driving with small coal pillar in the special isolated working face and found the following: for the heading area, the control method of anchoring first and then pressure relief was adopted; for the mining-influenced zone, the control method of synchronous coordination of pressure relief and anchorage is adopted; and for the mining-stability zone, the control method of only anchorage without pressure relief is adopted [11]. Wang et al. studied the key factors affecting the stability of surrounding rock in gob-side roadway driving in fully mechanized caving face and pointed out that the height of basic roof and its fracture location significantly affected the stability of surrounding rock in gob-side roadway [12]. In order to solve the weakening problem of lateral constraint caused by support failure on the gob-side of narrow coal pillar, Zhang H. et al. proposed a stability control method of narrow coal pillar based on grouting filling/reinforcement of caving coal and rock mass at the upper section, which effectively controlled the overall stability of narrow coal pillar [13]. Shi et al. systematically studied the movement law, failure mechanism, and fracture evolution characteristics of overlying strata of gob-side roadway driving in thick coal seam and proposed the deformation control technology of roadway surrounding rock by optimizing support parameters and roof cutting pressure relief [14]. Tai et al. studied and proposed the roof-cutting technology with a chainsaw arm and its equipment to solve the disturbance control problem of the triangular cantilever beam on the gob-side roadway in the lateral hard roof of the goaf, which achieved successful practice in the engineering site [15]. Liu et al. established the load transfer model of the internal stress field in the surrounding rock of the gob-side roadway driving along the fully mechanized caving face in the inclined thick coal seam and deduced the expression of the "internal stress field" in the inclined coal seam mining. Moreover, they put forward the asymmetric control technology with the roof of the roadway which regards the upper and middle coal pillars as the core, which achieved effective control effect on the deformation of the surrounding rock [16]. Xue et al. established a mathematical model of coal pillar along goaf from the perspective of energy accumulation and dissipation and analyzed the energy equilibrium relationship of the mechanical system. The rock burst mechanism of coal pillars in gob-side entry was obtained based on a fold catastrophe mathematical model [17]. In order to reveal the asymmetric large deformation mechanism of surrounding rock in deep gob-side roadway, Li et al. studied the influence of principal stress on the expansion of butterfly plastic zone in gob-side roadway and pointed out that under the combined action of high ground stress and disturbed stress, the surrounding rock of the deep front edge of the gob in the central area of the main stress could form a large range for the butterfly leaf plastic area [18].

The above research expounds the deformation mechanism and control technology of surrounding rock of gob-side roadway in different aspects, which provides an important reference for further study on the stability control of surrounding rock of gob-side roadway under deep stress conditions. However, there is still a lack of research in the existing literature on how to achieve efficient coordination of excavation and support by using time effect arising from disturbance stress adjustment in gob-side roadway. During the excavation of gob-side roadway, the surrounding rock is more prone to damage, resulting in strong mine pressure under the coupling effect of disturbance stress caused by excavation and lateral abutment stress of goaf. Therefore, it is of great significance to study the time effect evolution characteristics of disturbance stress caused by excavation and make full use of the time effect of disturbance stress adjustment to effectively control the stability of surrounding rock, as well as improve the excavation-support efficiency. Taking the ATR 30207 of Muduchaideng Coal Mine as the engineering background, this paper introduces the engineering case of deep buried, long-distance, and large section of gob-side roadway and found the characteristics of stress disturbance caused by head-on cyclic cutting of gob-side roadway through comprehensive research methods. The countermeasures of time-effect collaborative control countermeasures of the roof and rib in gob-side roadway are put forward. The industrial tests show that the stability of roadway surrounding rock is effectively controlled; meanwhile, the efficient excavation-support cooperation of roadway is also achieved.

2. Engineering Geological Conditions

2.1. Overview of Roadway Location and Basic Conditions. Muduchaideng Coal Mine is located in Hujierte Mining Area, Ordos City, Inner Mongolia Province, China. The average buried depth of working face 30208 is 640 m, the average coal seam thickness is 5.8 m, the working face width is 300 m, and the mining length is 5888 m. At present, the mining of working face 30208 has been completed. The working face 30207 is adjacent to the east side of working face 30208 with the average buried depth of 643 m. The maximum vertical stress is 16 MPa, and the maximum horizontal principal stress is 19.2 MPa. The average thickness of coal seam is 5.7 m, the width of working face is 326 m,

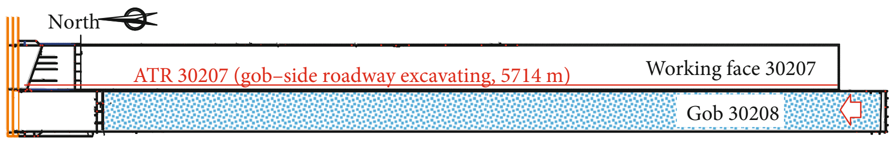


Figure 1: Roadway location and mining relationship.

and the mining length is 5714 m. Four months after finishing the mining of working face 30208 (when the overburden movement in the gob is stable), the working face 30207 is excavating gob-side roadway driving with small coal-pillar, that is, excavating ATR 30207 by setting a 6 m coal-pillar along gob 30208 (Figure 1). The total length of ATR 30207 is 5714 m, with roadway section is rectangular, the width is 5.8 m, the height is 4.1 m, and the sectional area is 23.78 m^2. In summary, this roadway belongs to the long-term stability control problem of long-distance and large section of gob-side roadway driving with small coal pillar under deep buried, high stress, and strong disturbance in the west.

2.2. Lithology of Roadway Roof and Floor. According to the occurrence of rock stratum in working faces 30208 and 30207, the direct roof of 3-1 coal mining is mudstone, siltstone, or fine sandstone, with multiple hard roofs above the direct roof. The horizon of the roof aquifer is 6~7 m, which is easy to flow through the rock fissures, resulting in the weakening of the strength of the surrounding rock in the roadway when encountering water. Specific rock stratum occurrence and mechanical parameters are shown in Table 1.

2.3. Roadway Support Scheme and Existing Problems

2.3.1. Support Scheme

(1) Roof supporting: as shown in Figure 2, the roof adopts the combination support of "anchor bolt +anchor cable," and foundation supporting adopts five $\Phi 22 \times 2600$ mm left-handed spiral steel anchor pressure W type steel belt support. Each row adopts seven bolts with different spacing, and the row spacing is 900 mm. All anchor bolts are installed perpendicular to the roof. Each anchor bolt is anchored with one CK2335 mm and one K2360 mm resin cartridge, and the pretightening force of bolt is 60 kN

What is more, the reinforcement supporting of roof adopts $\Phi 22 \times 6300$ mm anchor cables. Each row adopts three cables with alternative arrangement, the spacing of 1850 mm and the row spacing is 1800 mm. All anchor cables are installed perpendicular to the roof. Each anchor cable is anchored with one CK2360 mm and two K2360 mm resin cartridge, and the pretightening force of cable is 200 kN.

(2) Coal rib supporting: the support parameters of the two coal ribs are consistent, and the foundation supporting adopts $\Phi 22 \times 2600$ mm left-handed spiral steel anchor steel belt support. Each row adopts five bolts with spacing of 850 mm, and the row spacing is 900 mm. All anchor bolts are installed perpendicular to the coal rib. Each anchor bolt is anchored with one CK2335 mm and one K2360 mm resin cartridge, and the pretightening force of bolt is 60 kN

What is more, the reinforcement supporting of coal rib adopts $\Phi 21.8 \times 4300$ mm anchor cables. Each row adopts three cables with the spacing of 1150 mm and the row spacing is 1800 mm. All anchor cables are installed perpendicular to the coal rib. Each anchor cable is anchored with one CK2360 mm and two K2360 mm resin cartridge, and the pretightening force of cable is 200 kN.

2.3.2. Maintenance Effect and Problem Analysis

(1) Construction and Maintenance Effect

(a) The anchor cable drilling of solid coal rib repeatedly collapsed. During the construction and installation of coal rib anchor cables (two anchor cables in the middle and lower parts of three anchor cables in each row of coal rib), the cable drilling holes collapsed repeatedly, making it difficult to send the anchor agent to the hole bottom, which inhibited the efficient construction of anchor cables

(b) Development of roof separation fractures. There are separated layer fractures outside the anchorage zone of roof bolt (3~7.6 m), with fracture shapes are mainly ring fractures and vertical fractures

(c) The excavation speed is slow. The roadway excavation speed is 14 m/day, with a monthly advance of 420 m, which is far from the expected 600 m/month

(2) Reason Analysis

(a) High stress environment leads to repeated hole collapse of anchor cable drilling in solid coal rib. Generally, the gob-side roadway driving with small coal-pillar is located in the lateral low stress area of goaf, while the coal body inside the entity coal rib of gob-side roadway is located in the high stress environment (lateral abutment stress). Therefore, before the excavation of ATR 30208, the coal body inside the roadway entity coal rib locates in the lateral abutment stress environment of gob 30208, which bears high stress. When the roadway is excavated, the hole collapse of anchor cable is easy to occur under the action of high stress

Table 1: Rock stratum occurrence and mechanical parameters.

Number	Lithology	Thickness (m)	Density (kg·m-3)	Bulk modulus (GPa)	Shear modulus (GPa)	Internal friction angle (°)	Cohesion (MPa)	Tensile strength (MPa)
7	Medium sandstone	49.4	2700	11.3	6.7	38.0	6.2	2.7
6	Siltstone	12.6	2460	10.8	8.1	38.0	2.8	1.8
5	Medium sandstone	16.4	2700	11.3	6.7	38.0	6.2	2.7
4	Coal	1.2	1820	1.9	1.6	24.2	1.9	1.9
3	Siltstone	14.9	2460	10.8	8.1	38.0	2.8	1.8
2	Medium sandstone	8.9	2700	11.3	6.7	38.0	6.2	2.7
1	Siltstone	3.8	2460	10.8	8.1	38.0	2.8	1.8
0	3-1 coal	5.8	1820	1.9	1.6	24.2	1.9	1.9
-1	Siltstone	4.9	2460	10.8	8.1	38.0	2.8	1.8
-2	Medium sandstone	2.1	2700	11.3	6.7	38.0	6.2	2.7
-3	Siltstone	6.0	2460	10.8	8.1	38.0	2.8	1.8

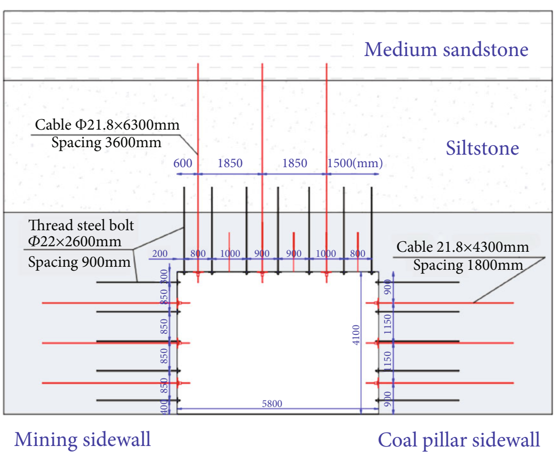


Figure 2: Supporting scheme of ATR 30207.

At the same time, with the head-on cyclic cutting of the working face, the stress is transferred to the unmined area in front of the heading face to form the advanced abutment stress. Therefore, the rock mass in front of the heading face is damaged under the coupling effect of the lateral abutment stress of goaf and the advanced abutment stress caused by excavation. When the working face is excavated here, the loose and broken coal body is likely to result in the collapse of the anchor cable drilling during construction.

(b) The advanced abutment stress in front of the heading face is fully adjusted, which leads to the damage and failure of rock mass. When waiting for the repeated anchor cable construction for hole collapse, the advanced abutment stress caused by excavation adjusted completely since the delay of next cycle of cutting, bringing great damage to the coal rock mass. As a result, the development depth of roof separation fracture is quite large

(c) Lower efficiency of coal rib support leads to slower roadway formation. The next excavation-support cycle can be started only after both the roof support and cable support are completed. However, the repeated hole collapse of the coal rib anchor leads to the low installation efficiency of the anchor cable, as well as longer cycle operation time of the single row excavation-support, resulting in the low speed of roadway formation

3. Stress Disturbance Characteristics of Head-on Cyclic Cutting in Gob-Side Roadway

As the excavation of working face, the surrounding rock behind the heading face will be pressure relieved and the stress will be reduced in the roadway roof and two ribs. Therefore, the research on the distribution law of advanced abutment stress in front of the working face and the pressure relief stress characteristics of surrounding rock behind the heading face during roadway excavation helps to find out the opportunity of roadway surrounding support, which not only avoids the phenomenon of repeated hole collapse but also improve the roadway excavation-support efficiency.

3.1. Model Establishment. In order to study the distribution law of advanced abutment stress in front of the heading face and the pressure relief characteristics of surrounding rock behind the heading face during the excavation of ATR 30207, a finite element FLAC3D numerical model is established based on the engineering background of ATR 30207. The dimensions of the model are 188 m in X direction, 60 m in Y direction, and 126 m in Z direction (Figure 3). The mining coal seam (3-1 coal seam) is 5.8 m in thickness and 640 m in depth. The coal seam is 107.2 m away from the upper boundary of the model, and the vertical stress is calculated as 2.5 MPa/100 m. Therefore, the vertical load applied on the upper boundary is 13 Mpa, and the lateral pressure coefficient is 1.2. The left boundary, right boundary, and lower boundary of the model are fixed to eliminate displacement. The occurrence of rock strata in the model is consistent with the actual situation, and the specific occurrence of rock strata and rock mass mechanical parameters

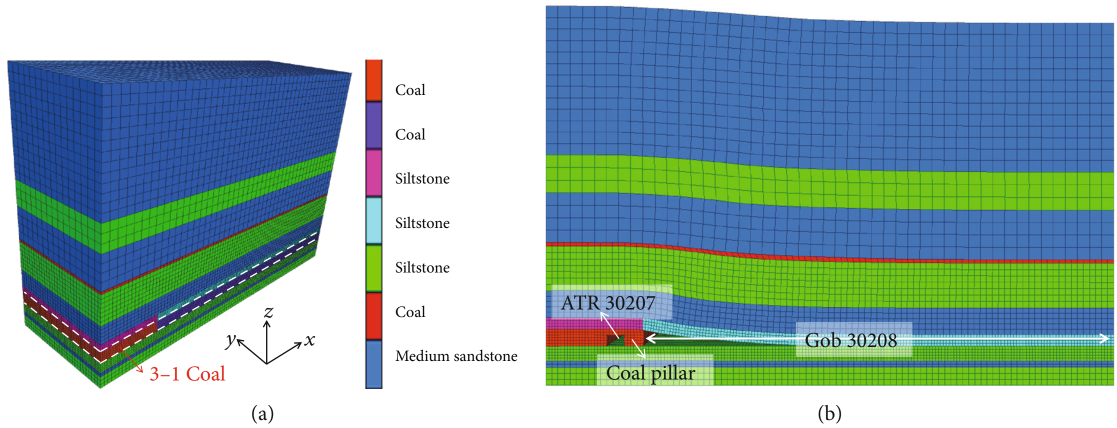


Figure 3: Numerical model establishment: (a) three dimensional view of the model and (b) model plan.

are shown in Table 1 [19]. The model adopts Mohr Coulomb yield criterion.

3.2. Simulation Methods and Results

3.2.1. Simulation Methods. The numerical calculation process is as follows: (1) Calculate the original rock stress to the initial equilibrium; (2) Excavate working face 30208 until the roof rock stratum in the goaf collapses, and calculate it to balance; and (3) Excavate the ATR 30207 step by step by setting a 6 m wide coal-pillar. Each step is excavated for 1 m until the calculation is balanced, followed with the next cycle of excavation (simulating the roadway head-on cyclic excavation at the project site). A total of 30 operations (30 m excavation) are carried out.

3.2.2. Monitoring Methods and Results

(1) *Roof*: when the ATR 30207 is excavated for 15 m, in order to monitor the variation characteristics of the vertical stress of the roadway roof, a 30 m measuring line is arranged at the depth of 2 m of the roadway roof along the axial direction of the roadway (Figure 4). The monitoring results are shown in Figure 5(a). Moreover, Figure 5(b) shows the variation curve of vertical stress of the rock stratum at the depth of 2 m of the roof; meanwhile, $y = 15.5$ m during the roadway excavation of 30 m

It can be seen from Figure 5(a) that when the roadway is excavated to 15 m, the stress in front of the heading face is transferred to form the advanced abutment stress, and the peak stress reaches 56.4 MPa at 22 m of the roadway mileage (7 m ahead). From the front analysis, it can be concluded that this peak stress is due to the coupling effect of the lateral abutment stress in gob 30208 and the advanced abutment stress in ATR 30207 excavation. It can be seen from Figure 5(b) that when the roadway is excavated to 9 m, the peak vertical stress of the roof reaches 54.7 MPa at 15.5 m of the roadway mileage (6.5 m ahead). After that, the vertical stress decreases with the excavation of the roadway until the roadway excavation reaches 21 m (5.5 m behind), and the stress value after stabilization is 3.4 MPa.

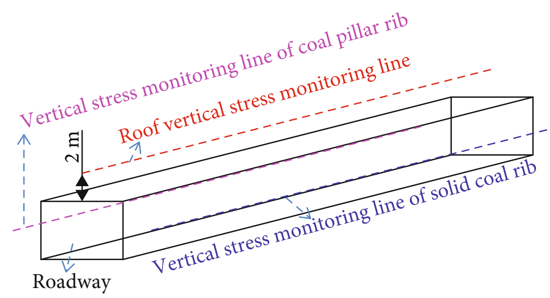
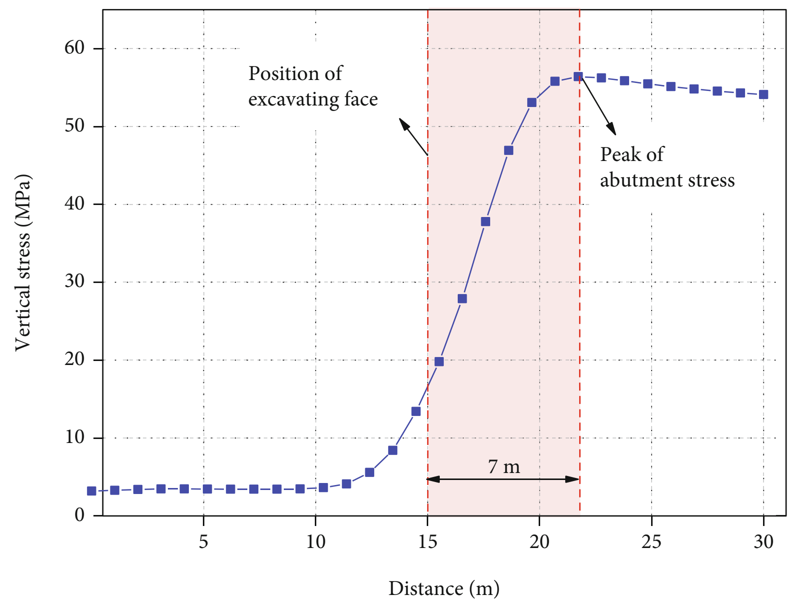


Figure 4: Layout of vertical stress monitoring line of roadway surrounding rock.

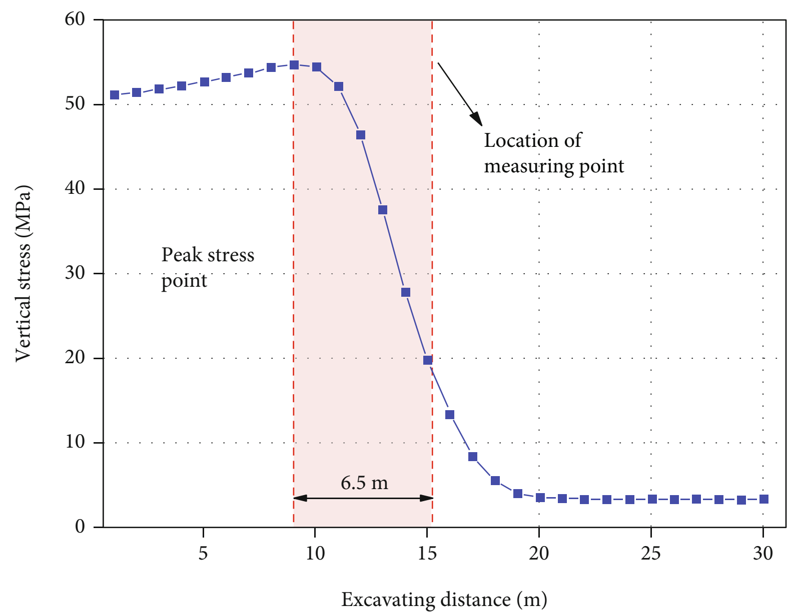
(2) *Solid coal rib:* when the ATR 30207 is excavated to 15 m, in order to monitor the stress variation characteristics of roadway solid coal rib, a 30 m measuring line is arranged at the depth of 2 m along the axial direction of roadway solid coal rib. The monitoring results are shown in Figure 6(a). Figure 6(b) shows the variation curve of the vertical stress of the coal body at the depth of 2 m of the solid coal rib; meanwhile, $y = 15.5$ m during the roadway excavation of 30 m

It can be seen from Figure 6(a) that when the roadway is excavated to 15 m, the stress of solid coal rib in front of the heading face is transferred to form the advanced abutment stress, and the peak stress reaches 61.3 MPa at 16.5 m of the roadway mileage (1.5 m ahead). It can be seen from Figure 6(b) that when the roadway is excavated to 14 m, the peak vertical stress of the solid coal rib reaches 61.1 MPa at 15.5 m of the roadway mileage (1.5 m ahead). After that, the vertical stress decreases with the excavation of the roadway until the roadway excavation reaches 25 m (9.5 m behind), and the stress value after stabilization is 25 MPa.

(3) *Coal pillar rib:* when the ATR 30207 is excavated to 15 m, in order to monitor the stress variation characteristics of coal pillar rib, a 30 m measuring line is



(a)



(b)

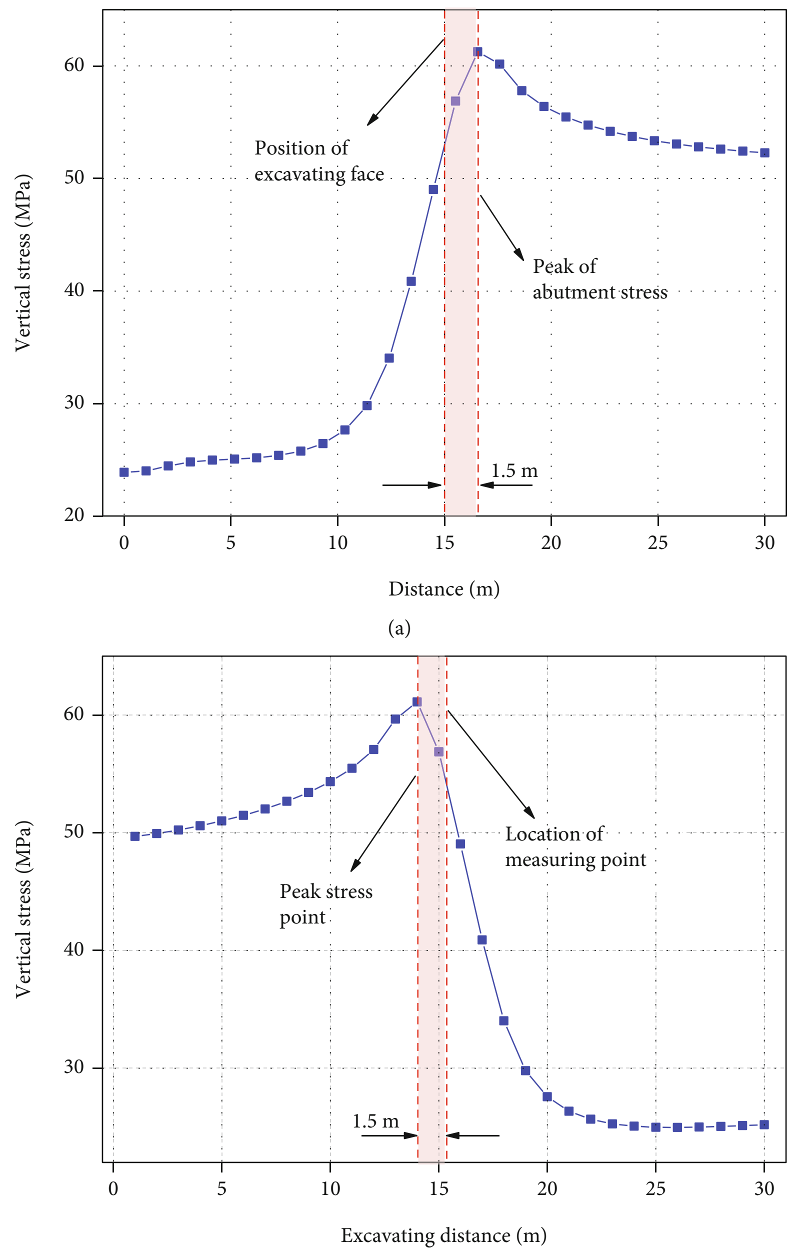
Figure 5: Characteristics of the roof stress disturbance during cyclic excavation of gob-side roadway: (a) the vertical stress distribution law of the roof along the axial direction of the roadway when the roadway is excavated to 15 m and (b) the vertical stress evolution law of the roof at 15.5 m of roadway mileage during 30 m of roadway excavation.

arranged at the depth of 2 m along the axial direction of roadway coal pillar rib. The monitoring results are shown in Figure 7(a). Figure 7(b) shows the variation curve of the vertical stress of the coal body at the depth of 2 m of the coal pillar rib; meanwhile, $y =$ 15.5 m during the roadway excavation of 30 m

It can be seen from Figure 7(a) that when the roadway is excavated to 15 m, the stress of coal pillar rib in front of the head is transferred to form the advanced abutment stress, and the peak stress reaches 33.7 MPa at 16.5 m of the roadway mileage (1.5 m ahead). It can be seen from Figure 7(b) that when the roadway is excavated to 14 m, the peak vertical stress of the coal pillar rib reaches 33.5 MPa at 15.5 m of the roadway mileage (1.5 m ahead). After that, the vertical stress decreases with the excavation of the roadway until the roadway excavation reaches 22 m (6.5 m behind), and the stress value after stabilization is 15.3 MPa.

3.3. *Analysis*

(1) With the excavation of the ATR 30207, the stress in front of the heading face is transferred to form the advanced abutment stress, among which the



(a)

(b)

Figure 6: Characteristics of solid coal rib stress disturbance during cyclic excavation of gob-side roadway: (a) the vertical stress distribution law of the solid coal rib along the axial direction of the roadway when the roadway is excavated to 15 m and (b) the vertical stress evolution law of solid coal rib at 15.5 m of roadway mileage during 30 m of roadway excavation.

peak stress of the roof is located 6.5~7 m ahead (Figures 5 and 8(a)), with the peak value of 54.7~56.4 MPa. The peak stress of solid coal rib is located 1.5 m ahead (Figures 6 and 8(b)), with the peak value of 61.1~61.3 MPa. The peak stress of coal pillar rib is also located 1.5 m ahead (Figures 7 and 8(b)), and the peak stress is 33.5~33.7 MPa. To sum up, the disturbance range of advance abutment stress caused by excavation on the roof, solid coal rib, and coal pillar rib is 6.5~7 m, 1.5 m, and 1.5 m, respectively

(2) σ_1 is the stress of coal and rock mass in the area not disturbed by excavation, which is superimposed by the original stress of rock mass and the lateral abutment stress of gob 30208. σ_2 is the peak stress of coal and rock mass in the area disturbed by the advanced abutment stress of excavation, which is formed by the coupling of the original stress of coal and rock mass, the lateral abutment stress of gob 30208, and the advanced abutment stress in front of the heading face during excavation. It can be concluded that from Figure 5 to Figure 7, the σ_2 of both solid coal

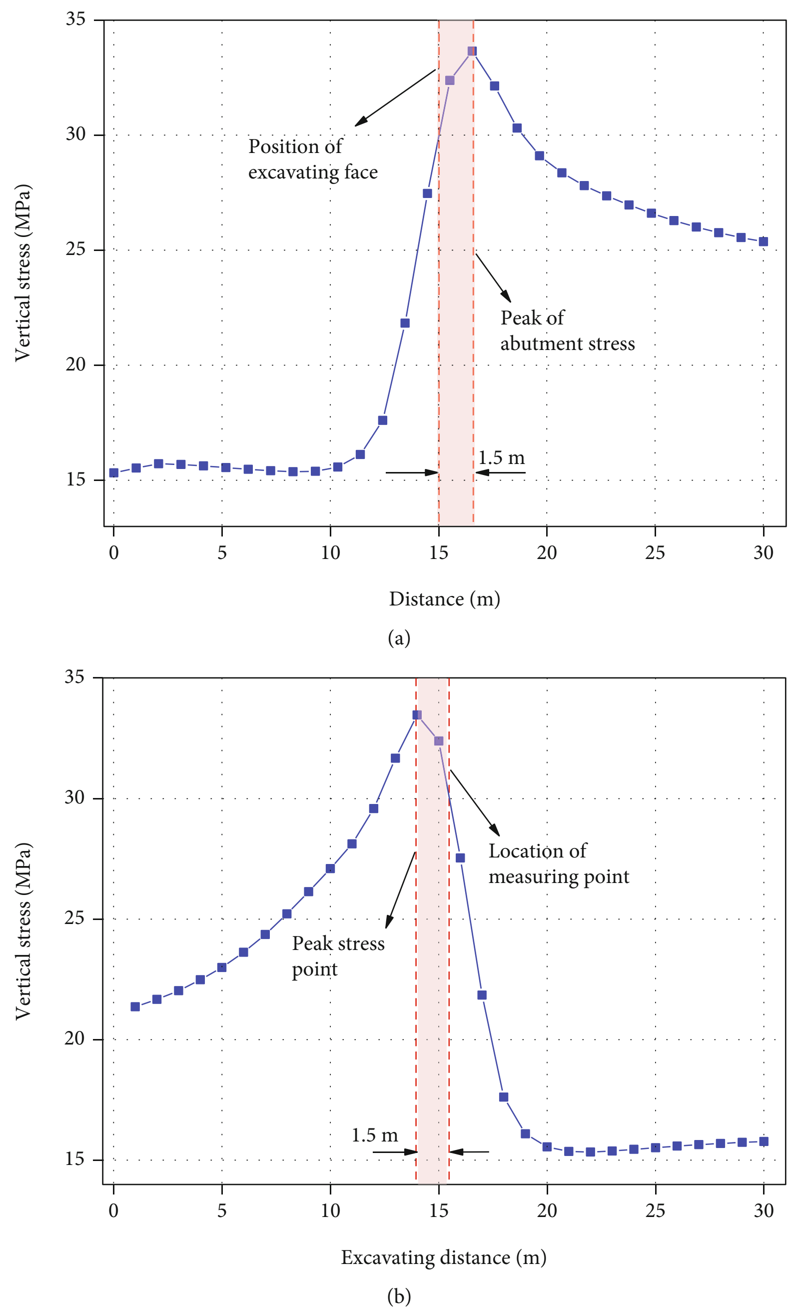


FIGURE 7: Characteristics of coal pillar rib stress disturbance during cyclic excavation of gob-side roadway: (a) the vertical stress distribution law of the coal pillar rib along the axial direction of the roadway when the roadway is excavated to 15 m and (b) the vertical stress evolution law of coal pillar rib at 15.5 m of roadway mileage during 30 m of roadway excavation.

rib and coal pillar rib are 8 MPa higher than that of σ_1, and the σ_2 of the roof is 2 MPa higher than that of σ_1. That is, the increase of abutment stress of solid coal rib and coal pillar rib caused by excavation is higher than that of the roof

(3) With the advance of the heading face, the surrounding rock stress of the roadway behind the heading face shows a trend of reducing first and then stabilizing, which is mainly due to the stress disturbance caused by the excavation. From the previous analysis, it can be concluded that the disturbance range of the excavation pressure relief on the roof is 5.5 m behind the heading face. The Figure 9 is the evolution characteristics of the vertical stress cloud chart of the roof at the roadway mileage $y = 15$ m (monitoring point position). As the working face excavates, the distance between the monitoring point and the head is larger, so is the range of the low value stress area of the roadway roof at the monitoring point. When the monitoring point position lags 5~6 m behind the heading face, the height range

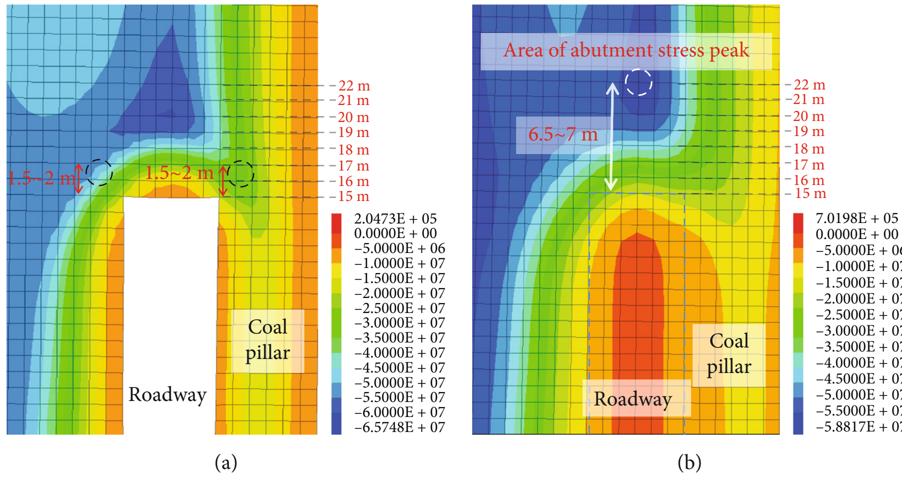


Figure 8: The vertical stress distribution law of coal and rock mass in the unmined area in front of excavation working face: (a) roof rock area and (b) two ribs of the roadway coal area.

of the low value stress area of the roof tends to stabilize within 3.1~3.2 m, that is, the disturbance range of the excavation pressure relief on the roof is 5~6 m, which verifies the previous analysis (5.5 m). Similarly, the disturbance ranges of excavation pressure relief on solid coal rib and coal pillar rib are 9.5 m and 6.5 m, respectively

4. Time-Effect Collaborative Control Countermeasures of Roof and Rib in Gob-Side Roadway

4.1. Analysis on Evolution Characteristics of Advanced Abutment Stress in front of Roadway Head. The head-on cyclic cutting of coal and rock mass of gob-side roadway causes the stress to transfer and form the advanced abutment stress, which is not completed instantaneously but gradually adjusted under the coupling effect of coal and rock mass bearing damage. As shown in Figure 10, after finishing cutting the coal and rock mass in the working face, the stress gradually evolves from curve a to curve c during the stress adjustment stage of the coal and rock mass in front of the heading face. After the shallow coal and rock mass are damaged, the advanced abutment stress continues to transfer to the deep; meanwhile, the damage range of coal and rock mass is further expanded until the advanced abutment stress is fully adjusted to form a steady-state stress field [20].

Numerical simulation results show that the disturbance range of the advanced abutment stress caused by excavation to the roof, solid coal rib, and coal pillar rib is 7 m, 1.5 m, and 1.5 m, respectively, after the formation of the steady-state stress field. Taking the roof as an example, the action range of advanced abutment stress in front of the heading face is 7 m after cutting, and the abutment stress in this range is not instantaneously adjusted but gradually adjusted from the heading face to the rock layer in front of the heading face to form a steady-state stress field σ_2. Supposed that the heading surrounding rock support is timely completed and followed with the next cycle of excavation-support in the early stage of the adjustment, the time effect can be fully utilized to alleviate the action time of the advanced abutment stress and inhibit the full adjustment, which can not only reduce the damage range of roof strata but also effectively reduce the peak abutment stress σ_2.

4.2. Time-Effect Collaborative Control Countermeasures of Roof and Rib in Gob-Side Roadway. As mentioned above, during the excavation of the ATR 30207, the repeated hole collapse during the construction of anchor cable drilling in the roadway solid coal rib results in the slow excavation speed. As soon as the cutting is completed, the roof and anchor cable support in coal pillar rib shall be carried out firstly, followed with the anchor bolt support in solid coal rib and anchor cable support without repeated hole collapse, remaining the unfinished anchor cable (repeated hole collapse of anchor cable drilling) for subsequent construction. Subsequently, start the next excavation cycle quickly, and finish the support above in time until the stress of the solid coal rib is fully pressure relieved and adjusted with the advance of excavation. At last, carry out the lag support and anchorage of the anchor cable remained unconstructed in the coal rib. This kind of time-effective excavation and support circulation operation has the following advantages:

(1) Avoiding the repeated hole collapses in anchor cable drilling of solid coal rib and enhancing the excavation support efficiency. When repeated hole collapse occurs, the support of other parts of roadway surrounding rock shall be completed first. With the advance of the heading face, the support anchorage can be carried out after the stress of the solid coal rib is fully pressure relieved and adjusted. As a result, the problem of repeated hole collapse in anchor cable drilling of solid coal rib can be effectively improved

(2) Slowing down the action time of advanced abutment stress in front of the heading face and reducing the damage degree of coal and rock mass. The rapid start

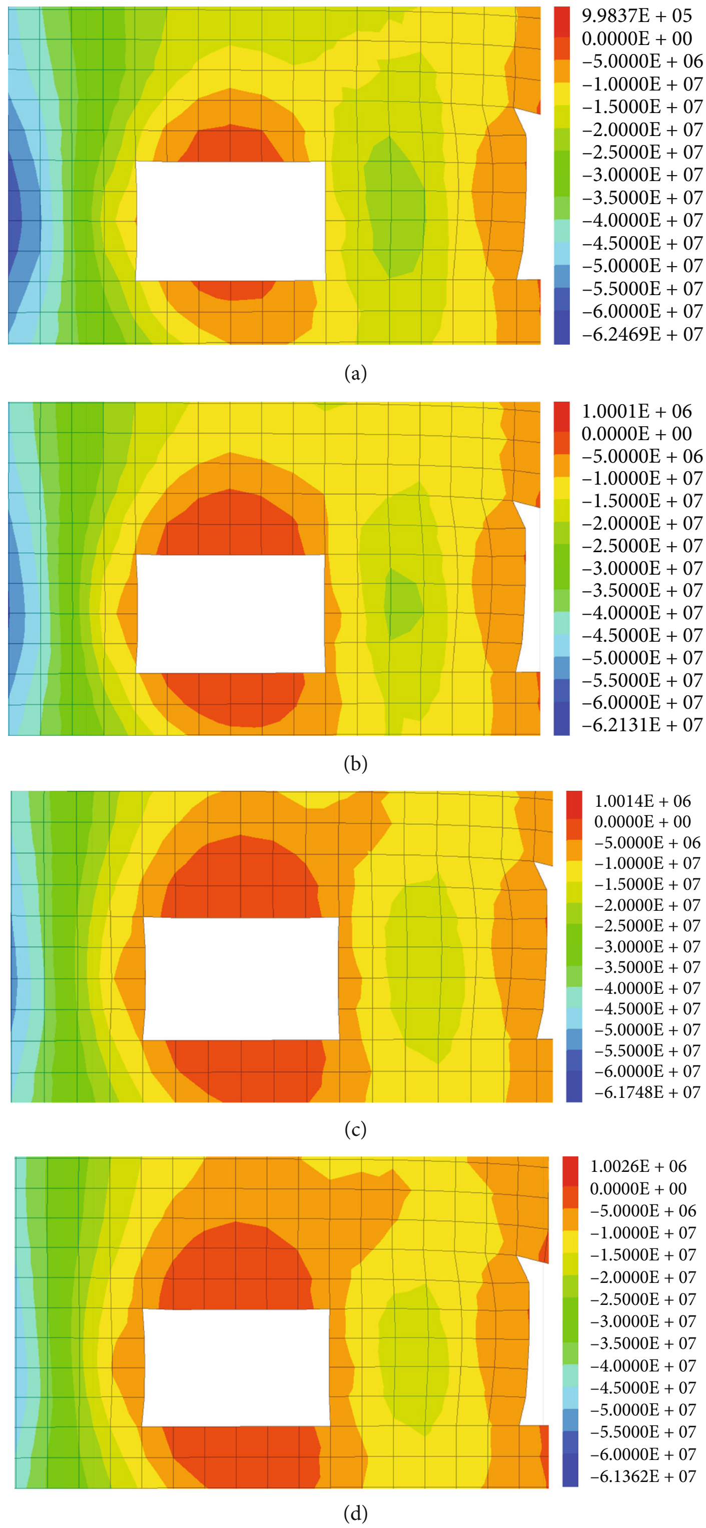
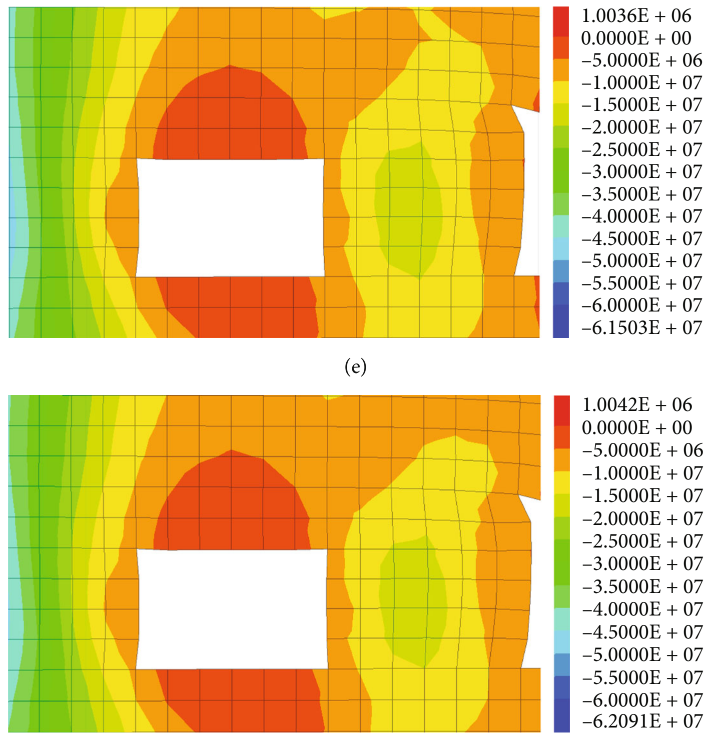


FIGURE 9: Continued.



(e)

(f)

Figure 9: The evolution law of vertical stress of surrounding rock at roadway mileage $y = 15$ m: (a) 1 m behind the heading face: (b) 2 m behind the heading face; (c) 3 m behind the heading face; (d) 4 m behind the heading face; (e) 5 m behind the heading face; (f) 6 m behind the heading face.

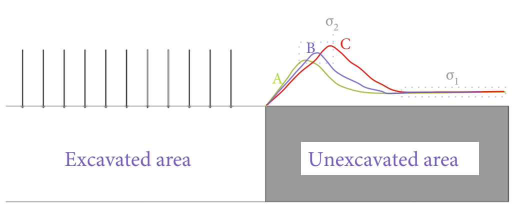


Figure 10: Evolution law of advanced abutment stress in front of heading face caused by roadway excavation.

of the next excavation-support cycle is conducive to make full use of the velocity effect of pressure relief disturbance [21], effectively alleviate the action time of abutment stress, and reduce the damage degree of coal and rock mass in front of the heading face

(3) Improving the efficiency of excavation-support cycle construction and accelerating the speed of roadway formation. Through the lag installation and construction of anchor cable whose drilling hole collapse repeatedly, as well as the fast completion of next excavation-support cycle, the single row cycle operation time can be effectively improved, which accelerates the speed of roadway formation

5. Industrial Test

5.1. Optimization and Adjustment of Excavation-Support Technology of Gob-Side Roadway. According to the numerical simulation results and theoretical analysis above, for the problems of repeated borehole collapse and slow excavation speed in the process of ATR 30207 excavation, the optimization and adjustment of excavation-support technology are as follows: When the cyclic cutting of the working face is completed, the support of the roof, coal pillar rib, and solid coal rib shall be completed in time, followed with the next excavation cycle, so as to improve the stress environment of the coal and rock mass in front of the heading face and speed up the excavation-support efficiency. For the anchor cable prone to hole collapse in the solid coal rib, the construction and installation shall be delayed by 15 m behind the working face, so as to carry out the support and anchorage after the full pressure relief and adjustment of the stress in the solid coal rib.

5.2. Effect Analysis

5.2.1. Control Effect of Surrounding Rock

(1) *Solid coal rib:* after adopting the new excavation-support technology, the problem of repeated hole collapse is basically solved when the anchor cable drilling of solid coal rib is constructed by 15 m delay of the heading face. At the same time, the control effect of solid coal rib deformation is good (Figure 11(a)).

(2) *Roof:* the roof surface rock is relatively flat, with good deformation control effect (Figure 11(b)).

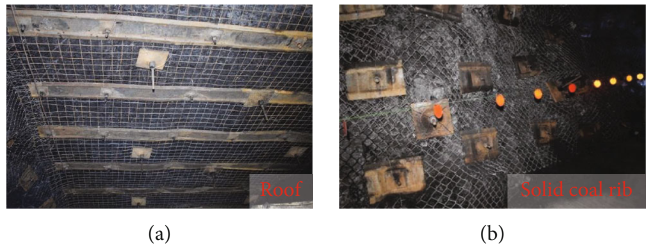


Figure 11: Photos of the roadway roof during excavation: (a) roadway solid coal rib and (b) roadway roof.

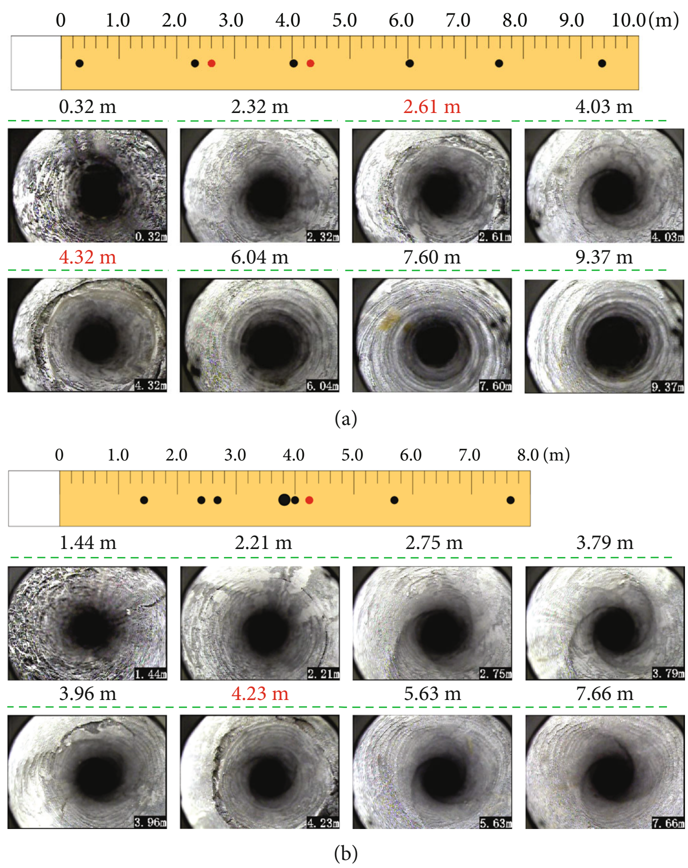


Figure 12: Monitoring results of separation fractures in roof stratum: (a) monitoring results of stations numbered a# and (b) monitoring results of stations numbered b#.

In order to monitor the development of strata separation fractures inside the roof, two monitoring stations for roof separation fractures are arranged, numbered as a# and b#, respectively. The monitoring results are as follows: The drilling peep reaction and roof rock integrity of station a# is shown in Figure 12(a), with peep depth of 10 m. There are only micro fractures found in 2.61 m and 4.32 m, with good rock integrity in other areas. For the station b# with peep depth of 8 m, there are only circumferential fractures found at 4.23 m, and the rock strata in other areas are relatively integral (Figure 12(b)). It is worth noting that there are still some small and circumferential cracks outside the roof bolt anchorage area. The cause is determined as that during the lateral mining disturbance of 30208 working face, the degree and scope of coal and rock mass damage in the roadway area are relatively large. After the roadway is excavated, the surrounding rock stress is adjusted and distributed again, resulting in roof rock mass damage and some separation fractures

In conclusion, the rapid excavation-support cycle in the roadway heading face can effectively reduce the damage degree of coal and rock mass in front of the heading face, avoid the phenomenon of broken deformation of coal body in solid coal rib under high stress, and effectively control the displacement of roof surface and the development of internal strata separation fractures.

5.2.2. Excavation Speed. After adopting the new excavation-support technology, the roadway excavation speed is increased from the original 14 m/day to 20 m/day, and the monthly footage reaches 600 m/month, with an increase of 42.9%. The roadway formation speed has been greatly improved, which creates a prerequisite for the rapid advance of mining in the working face.

6. Conclusion

Based on the typical engineering case of deep buried, long-distance, and large section gob-side roadway, the main factors that affect the surrounding rock control effect and excavation-support speed are revealed, and the disturbance characteristics of cyclic cutting stress at the heading face of gob-side roadway are analyzed. The targeted time-effect collaborative control countermeasures of roof and rib in gob-side roadway are put forward and verified by industrial tests which shows great control of surrounding rock stability and realizes efficient excavation-support collaboration. From these studies, the following conclusions are drawn:

(1) The maintenance effect and existing problems of surrounding rock in deep buried, long-distance, and large section gob-side roadway are analyzed. It is considered that the lateral abutment stress of goaf is the prerequisite for inducing repeated hole collapse of anchor cable drilling in the coal rib. The longer cycle time of single row operation is the result of repeated hole collapse of anchor cable in the coal rib. As the advanced abutment stress caused by excavation sufficiently adjusts, the damage and failure of coal and rock mass leads to the development of roof separation fractures, which further exacerbate the hole collapse. Moreover, the longer cycle time of single row operation leads to the slow speed of roadway formation, which fails to meet the requirements of rapid advancement of the working face

(2) The FLAC3D numerical simulation method is used to study the stress disturbance characteristics of the head-on cyclic cutting in gob-side roadway. The disturbance ranges of the advanced abutment stress in front of the heading face caused by excavation on the roof, solid coal rib, and coal pillar rib are 7 m, 1.5 m, and 1.5 m, respectively. Among them, the stress disturbance intensity on the two ribs of the roadway is higher than that on the roof. The ranges of pressure relief disturbance stress caused by heading face on the roof, solid coal rib, and coal pillar rib are 5.3 m, 9.3 m, and 6.3 m, respectively

(3) The time-effect collaborative control countermeasures of the roof and rib in gob-side roadway are put forward. During the initial adjustment stage of cutting stress in heading face, supposed that upon the surrounding rock support is completed, the next cycle of excavation-support is quickly started, and the time effect can be fully utilized to alleviate the action time of the advanced abutment stress and inhibit the full adjustment, which can reduce the damage range coal and rock mass. For the anchor cable prone to hole collapse in the solid coal rib, the construction and installation shall be delayed by 15 m behind the heading face after the full pressure relief and adjustment of the stress

(4) Industrial test results show that the deformation of roadway roof and solid coal rib is well controlled, and the problem of repeated hole collapse of anchor cable drilling is basically solved. Besides, the development and expansion of separated fractures in the roof stratum are also significantly improved. The driving speed is increased from 420 m/month to 600 m/month, with an increase of 42.9%, which not only improves roadway formation speed but also creates a prerequisite for the rapid advance of mining in the working face

Abbreviations

ATR 30207: Auxiliary transportation roadway 30207.

Data Availability

Data is contained within the article.

Conflicts of Interest

The authors declare no conflict of interest.

Authors' Contributions

Data curation was done by C.H. Formal analysis was done by H.Y., C.H., and N.Z.. Funding acquisition was done C.H. Investigation was done C.H. and H.Y.. C.H., N.Z., X.L., Y.L., W.L., and W.Y administer the project. Writing—original draft was done C.H. and H.Y.. Writing—review and editing were done by H.Y., C.H., K.S., and Y.G. All authors have read and agreed to the published version of the manuscript.

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