

Research Article

Study on the Lagging Support Mechanism of Anchor Cable in Coal Roadway Based on FLAC^{3D} Modified Model

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Aiming at the broken failure of anchor cable in the mining roadway roof during the mining process, the lagging support scheme of anchor cable is proposed. Based on the results of indoor anchor cable pull-out test, the Cable element in FLAC^{3D} is modified to realize the extension breaking of anchor cable in the calculation process. Furthermore, the minimum principal stress and volume strain rate mutation point are used as the failure criteria of the anchor cable. Through the comparative analysis of five anchor cable lagging support schemes of 6208 transport tunnel in Wangzhuang Mine Coal, the results demonstrate that the lagging support reduces the initial support resistance of the supporting structure. With the increase of lagging time, the ability of anchor cable to adapt to deformation increases gradually. When the lagging time reaches the gentle area of roadway deformation, its ability to adapt to deformation remains stable. Finally, it was determined that the support should start at 10–15 m of the anchor cable lagging head of the 6208 transport tunnel. Industrial tests show that the lagging support scheme ensures that the anchor cable can withstand a certain deformation, and the support body has no broken failure, which effectively controls the large mining-induced deformation of surrounding rock.

1. Introduction

With the continuous development of coal mining technology, roadway support technology has developed from passive support to active support. A large number of engineering practices have proved that the combined support technology of bolt and cable can effectively improve the stability of surrounding rock [1–4]. With the increase of coal mining depth, the deep complicated geomechanical environment makes the rock mass exhibit obvious nonlinear large deformation mechanical properties [5, 6]. With the increase of the load acting on the supporting structure, coupled with the superposition of dynamic loads such as mining, mine earthquake, and rock burst, the stress and deformation of the supporting body can easily exceed its limit value. The broken failure becomes more and more prominent, which seriously affects the stability of roadway surrounding rock [7–12].

According to many field observation results of roadway support, most of the bolts are anchored in the shallow surrounding rock within 2 m of the roadway, and their elongation rate is large. Generally, they will not break due to tensile deformation. Most anchor cables are anchored in the deep surrounding rock within 5–8 m of the roadway. Because the relative displacement between the deep and shallow surrounding rocks is relatively large, but the elongation of the anchor cable is small, the anchor cable is more prone to broken failure [13, 14].

In order to adapt to the deformation characteristics of deep surrounding rock, the coupling support relationship between anchor cable and roadway surrounding rock should be satisfied, which usually shows the coupling of strength, stiffness, and force [15]. (1) Strength coupling: the surrounding rock of the roadway has a large deformation energy, so it is difficult to prevent the deformation of the surrounding rock by bolt and anchor cable alone. Therefore,

bolt and anchor cable should be used to support the surrounding rock without damaging the bearing strength of the surrounding rock. (2) Stiffness coupling: in view of deformation, the surrounding rock of the roadway is mainly broken due to the incongruous deformation. The coupling between the stiffness of the supporting body and the surrounding rock is the basis to ensure that the surrounding rock will not be destroyed. However, the deformation limit of bolt and anchor cable supporting structure should be considered to ensure its stiffness, so that it will not break and fail. (3) Force coupling: the force of bolt and anchor cable in roadway support is interrelated, and the coupling effect of force will directly affect the stability of surrounding rock.

In fact, the supporting time is very important in the strength, stiffness, and force coupling mechanism of bolt and anchor cable support structure. The supporting time choice will affect the bearing state of the whole supporting system, which determines the overall supporting effect. For many years, many scholars have found that reasonable supporting time is particularly important to control the deformation of surrounding rock in the study of bolt and anchor cable coupling support [16–18]. Based on the modified nonlinear rheological Nishihara model, Yu et al. [19] obtained the best secondary supporting time in Jinchuan mining area through reverse analysis and proposed the bolt and anchor cable combined support technology. Meng et al. [20] analyzed the coupling deformation mechanism of supporting structure and surrounding rock, revealed the relationship between plastic zone expansion and stress release rate, and finally determined the optimal supporting time. According to the deformation monitoring data of roadway in Xingdong Mine, Liu and Li [21] obtained the optimal supporting time of each supporting element in the combined support scheme. Yu et al. [22] and Wu et al. [23] established a piecewise linear strain softening model to analyze the influence of different anchoring methods and different secondary support time on the stability of roadway in soft rock and finally put forward a reasonable design principle of support scheme. Previous studies have not well analyzed and verified the reasonable time of anchor cable lagging support from the perspective of the coupling force of the supporting body and its supporting effect. In order to adapt to the large deformation of surrounding rock without breaking and to enhance the complementarity of supporting between bolt and anchor cable, the scheme of installing anchor cables at a certain distance in lagging tunneling head is put forward in this paper.

Up to now, numerical simulation has made great contributions to the study on deformation and support of surrounding rock. The anchor cable structural element in FLAC^{3D} has obvious advantages in simulating the working state of bolt and anchor cable [24, 25]. However, because the axial force of the Cable element will maintain the ultimate load even after reaching its tensile strength, the bolt in the model will not fail when it is stretched [26]. Currently, few scholars consider the tensile failure of bolt and anchor cable in simulation calculation, so it is not accurate to use it to further study the supporting law of anchor cable.

Therefore, based on the pull-out test of solid anchor cable, FISH language is used to modify the anchor cable

structural element in FLAC^{3D} to achieve the simulation of the anchor cable breaking effect under extension deformation. Meanwhile, based on the modified anchor cable structure element, the law of the force action of the anchor cable lagging support on the supporting structure is studied, the influence law of surrounding rock support effect is revealed, and reasonable anchor cable lagging support scheme is determined.

2. FLAC^{3D} Anchor Cable Element Modification Based on Pull-Out Test

The Cable element built into FLAC^{3D} can simulate the stress and deformation of the anchor cable with small deformation, which cannot be used to reveal the extended failure process of the anchor cable in large deformation. Based on the deformation behavior characteristics of the measured anchor cable in the tensile process, Fish language is used to modify the Cable element, so that the simulation results are closer to the reality.

2.1. Pull-Out Test of Mechanical Properties for Anchor Cable. MZ-II anchor cable installation and LW-1000 horizontal tensile testing machine are used in test. The structure characteristics and working principle of horizontal tensile testing machine are shown in Figure 1. The machine is mainly composed of host, control cabinet, measurement and control system, servo oil source, and other parts.

In the test, a mine-used steel strand anchor cable with a diameter of 17.8 mm was selected as the research object, which was anchored inside the seamless steel pipe with an inner diameter of 26 mm and an anchoring length of 800 mm. A mine-used steel strand anchor bolt with a diameter of 20 mm was selected as the research object, which was anchored inside the seamless steel pipe with an inner diameter of 30 mm and an anchoring length of 600 mm. The relevant parameters of the test anchor cable are shown in Table 1, the test results are shown in Table 2, and the load-displacement curve of the anchor cable is shown in Figure 2.

The test results show that the tensile strength of this type of anchor cable is 1591 MPa, the maximum tensile force that it can bear is about 400 kN, and its elongation is only 3.5%–4%. The maximum force that the bolt can withstand is about 180 kN, and the elongation is about 16%–18%. Based on the mechanical parameters and deformation law of this kind of anchor cable, the cable structural element in FLAC^{3D} will be modified.

2.2. Fish Language Optimization of Cable Element. Based on the mechanical behavior characteristics of anchor cable, the state of Cable element is divided into three categories: (1) elastic stage: it fails to reach the maximum load that it can bear, and the deformation and stress are both less than the maximum. The structural element will continue to deform in elastic stage and then enter the plastic stage. (2) Plastic stage: in this stage, the force of Cable element is equal to the maximum load it can bear, but the deformation does not reach the critical value, and it will continue to deform in this

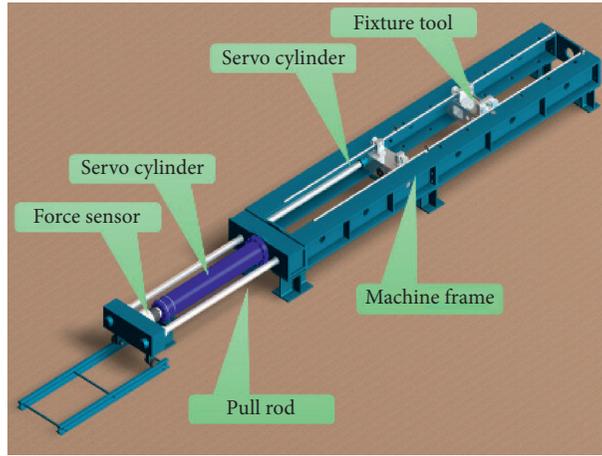


FIGURE 1: Structure of horizontal tensile testing machine.

TABLE 1: Mechanical properties test scheme of cable bolt.

	Length (m)	Diameter (mm)	Anchor length (mm)	Diameter of anchor hole (mm)
Bolt	2.2	20	600	30
Cable	2.5	17.8	800	28

TABLE 2: Experimental results of cable bolt pull-out test.

Variable/unit	Bolt/value	Cable/value
Tensile strength (Rm)/MPa	561	1591
Maximum force (Fm)/kN	176.2	395.62
Upper yield strength (ReH)/MPa	409	1532
Upper yield force (FeH)/kN	128.46	381.21
Lower yield strength (ReL)/MPa	402	1524
Lower yield force (FeL)/kN	128.43	379.13

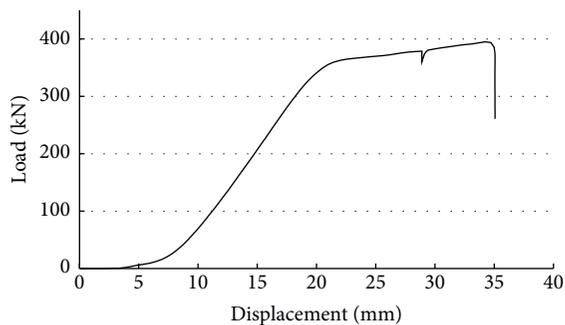


FIGURE 2: Load–displacement curve of cable bolt pull-out test.

stress state. (3) Failure stage: the deformation of the structural element exceeds the maximum deformation it can withstand, and it will break and fail. The optimized force model of Cable element is shown in Figure 3.

When the anchor cable enters the yielding state and its axial deformation reaches the specified breaking criterion, the anchor cable will enter the breaking state. After breaking, the axial force of the anchor cable drops to zero, and the axial restraint on the deformation of the surrounding rock is lost.

In FLAC^{3D}, except for the anchorage section, the interaction between Cable element and surrounding rock is realized through the connection between nodes at its ends and solid elements, which can be used to simulate the role of tray and nut in the actual support. This kind of node can be removed from modified Cable element through programming, and the specific process is shown in Figure 4.

2.3. Simulation Test of Modified Structural Element. In order to test the effectiveness of the modified scheme, the tensile simulation experiment of anchor bolt was carried out in FLAC^{3D}. The experimental object is the left-hand screw bolt with a diameter of 20 mm, the theoretical breaking load is 180 kN, and the breaking elongation is 16%. The established tensile test model of the bolt is displayed in Figure 5. The total length of the bolt model is 2 m, and the fixed section and the anchor section are both 0.5 m. The bolt is divided into 20 elements, with 0.1 m in length. The element number (CID) is 1 to 20 from right to left, and the monitoring element is element 10.

The experiment tests include the original model test and two modified model tests. During the test, a speed of $1e-5$ was applied to the left side of the model for calculation. The displacement and force of element 10 are continuously monitored, and experiment results are shown in Figure 6.

The modified model realizes the tensile failure when the Cable element reaches the maximum elongation in the calculation process. With the increase of displacement, the load presents a trend of fluctuating decrease, which is obviously different from the change rule of the vertical line of the load in the pull-out test results. The reason is that the numerical experiment monitors the force change of the small element in the cable structural element, and there is a certain lag and

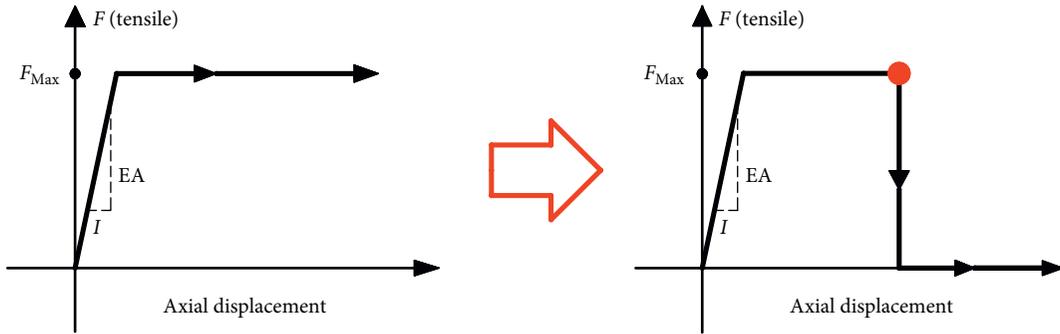


FIGURE 3: Anticipated result of cable unit modification.

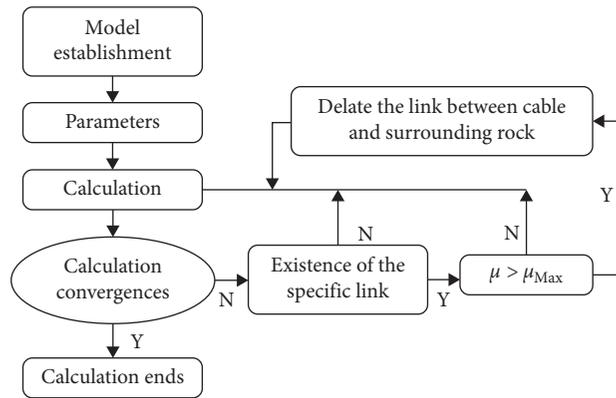


FIGURE 4: Flowchart of revised plan for the anchor cable unit.

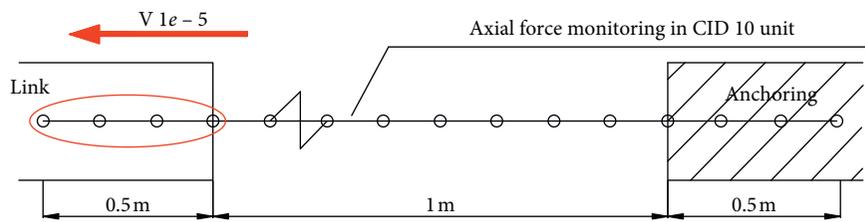


FIGURE 5: Simulation experiment of Cable element modification model.

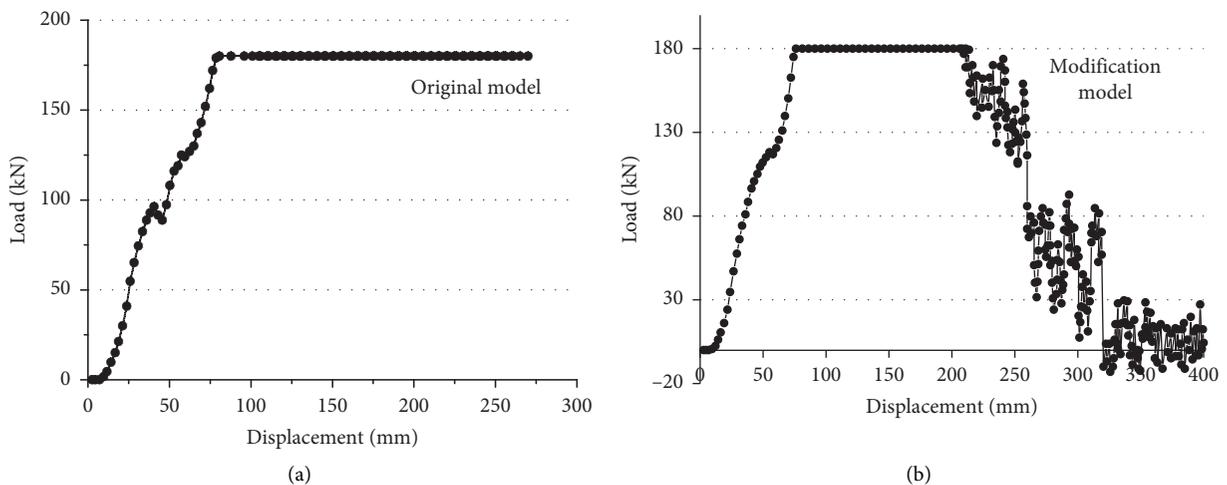


FIGURE 6: Comparison of the load-displacement curves between the original model and the modified model. (a) Original model. (b) Modified model.

fluctuation in the monitoring of the force change. The modification method is to equate the failure behavior of anchor cable by removing the connection point (link point) between the end of cable structural element and solid element. The released structural element no longer interacts with the solid element (surrounding rock), so this fluctuating load drop will not affect the simulation results. Meanwhile, this equivalent simulation method can realize the continuous action of the structural elements in the anchorage section, which is in good agreement with the actual situation. Therefore, it is considered that this modification scheme is feasible and can simulate the action law of anchor cable deformation failure on the surrounding rock of the roadway more truly.

3. Mechanical Effect of Anchor Cable Lagging Supporting Time under Mining Dynamic Pressure

3.1. Establishment of Numerical Calculation Model and Parameters Determination. The supporting time of anchor cable lagging support needs to consider many factors, such as roadway surrounding rock properties, joint structure, and support parameters. In this study, taking roadway driving along goaf at 6208 working face of Wangzhuang Coal Mine for example. Because the upper section 6207 transportation along the roadway uses the same support parameters, the relative movement of the roof and floor of the roadway is relatively large, and the roof squeeze transfer machine appears. Circumstances, along with a certain amount of anchor cable breakage, seriously affected safe and efficient production. The modified numerical analysis model is used to study the time of anchor cable lagging support. In Wangzhuang Coal Mine, one side of 6208 transport tunnel is a solid coal bank, and the other side is adjacent to the mined area of 6207 working face. The width of coal pillars for roadway protection is 7.6 m. The plan sketch of the mining engineering is shown in Figure 7. The length, width, and height of the numerical model are 200 m, 130 m, and 66 m, respectively. The bottom boundary of the model is fixed in the vertical direction, while the two sides and front-rear boundaries are fixed in the horizontal direction. Using the numerical model parameter modification method of Zhang et al. [27, 28] and based on the laboratory results, the physical and mechanical parameters of each rock layer in the model are finally determined, as shown in Table 3. The mechanical parameters of the anchor cable are selected from the experimental parameters; that is, the elastic modulus of the anchor is 200 GPa, the diameter is 20 mm, the length is 2.2 m, the breaking load is 180 kN, and the anchoring length is 0.6 m. The diameter of the anchor cable is 17.8 mm, the length is 6.0 m, the breaking load is 400 kN, and the anchoring length is 1.2 m. The roof is arranged with 6 anchor rods with a distance of 800 mm, and the roof is arranged with 2 anchor cables with a distance of 1.8 m.

3.2. Simulation and Monitoring Programs. In order to determine the reasonable time of anchor cable support, based on the property that the deformation amount and

deformation rate of surrounding rock are significantly different with the increase of the distance from the tunneling face, taking the distance from the tunneling face as the index, five kinds of anchor cable lagging support schemes were determined, as shown in Table 4. This scheme can be used to simulate the supporting effect of surrounding rock in different deformation periods, that is, the severe deformation period, gentle period close to surrounding rock deformation, and gentle period completely entering into the surrounding rock deformation. The bolt/mesh/anchor combined support in the model is shown in Figure 8. The mechanical behavior of the anchor cable under advanced support stress in the mining face and its influence on the stability of the roadway in five schemes are simulated, respectively.

Without support conditions, the leading support pressure distribution of the working face and the deformation law of the roadway roof are shown in Figure 9. The leading support pressure of the working face first increases and then decreases. The peak value is 14 MPa, and the peak point is 18 m away from the working face. The peak value area is about 12–22 m from the working face, and the severe influence area is about 0–35 m. In order to study the influence of the deformation behavior of surrounding rock on the supporting structure when the anchor cable lagged support, 3 measuring points at a depth of 2 m in the roof were set up before and after the peak zone of the leading support pressure. The measuring points are used to monitor the failure time of anchor cable and the change rule of supporting effect. The 3 measuring points are 15 m, 20 mm, and 25 m away from the working surface in sequence.

3.3. Determination Condition of Anchor Cable Failure. In order to accurately reflect the failure time of the anchor cable and the change of the support effect before and after the failure, the minimum principal stress (σ_{\min}) and the volume strain rate (VSR) of the surrounding rock within 2 m of the shallow part of the roadway when the anchor cable fails are proposed as the determination indicators for the failure. In order to prove the validity of the determination indicators, model tests were carried out. The numerical model is shown in Figure 10. High in situ stress is applied to the model to make the surrounding rock of the roadway deform greatly until the anchor cable extends and fails. The minimum principal stress and the volumetric strain rate of the surrounding rock within 2 m of the roadway roof were monitored continuously during the calculation process.

The numerical simulation results are shown in Figure 11. The figure reveals that the minimum principal stress and volume strain rate within 2 m of the roadway roof monitored before and after the failure of the anchor cable have obvious abrupt changes, which are in one-to-one correspondence with the time of the failure of the anchor cable. When the modified model is not adopted (Figure 11(a)), the anchor cable does not fail in the process of roadway deformation and has always played a supporting role for the surrounding rock. When the modified model is not adopted (Figure 11(b)), the anchor cable does not fail in the process of roadway deformation and has always played a supporting

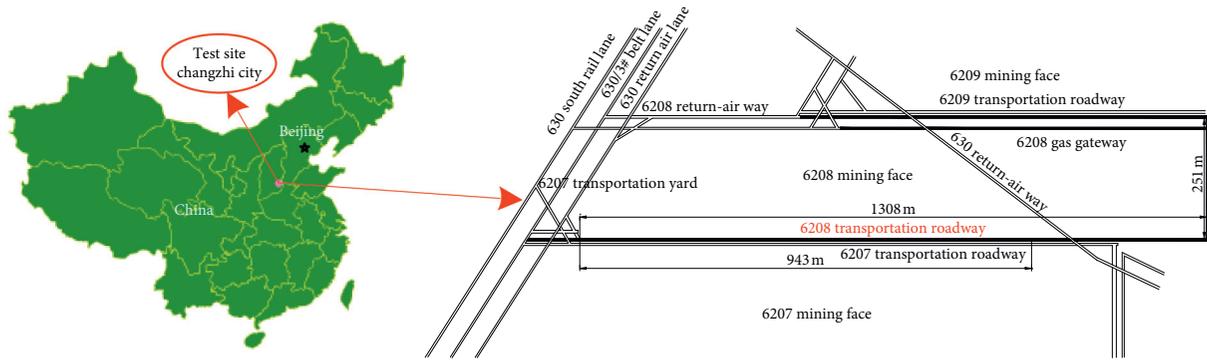


FIGURE 7: Schematic diagram of 6208 roadway engineering plane in Wangzhuang coal mine.

TABLE 3: Mechanical parameters used in the model.

Stratum	Thickness (m)	Density ($\text{kg}\cdot\text{m}^{-3}$)	Elastic modulus (GPa)	Poisson's ratio	Cohesion (MPa)	Interior friction angle ($^{\circ}$)
Fine sandstone	28	2550	10.5	0.29	7.5	39
Mudstone	6	2400	7.0	0.33	4.5	35
Coal	6	1400	5.3	0.30	2.5	30
Mudstone	6	2400	7.0	0.33	4.5	35
Medium grained sandstone	20	2500	9.0	0.30	6.5	37

TABLE 4: Comparison scheme of cable delayed supporting.

Scheme	Scheme I	Scheme II	Scheme III	Scheme IV	Scheme V
Lag distance (m)	Timely support	5	10	15	20
Deformation period	Severe deformation	Severe deformation	Tending to be slowly	Beginning to be slowly	Slow deformation period

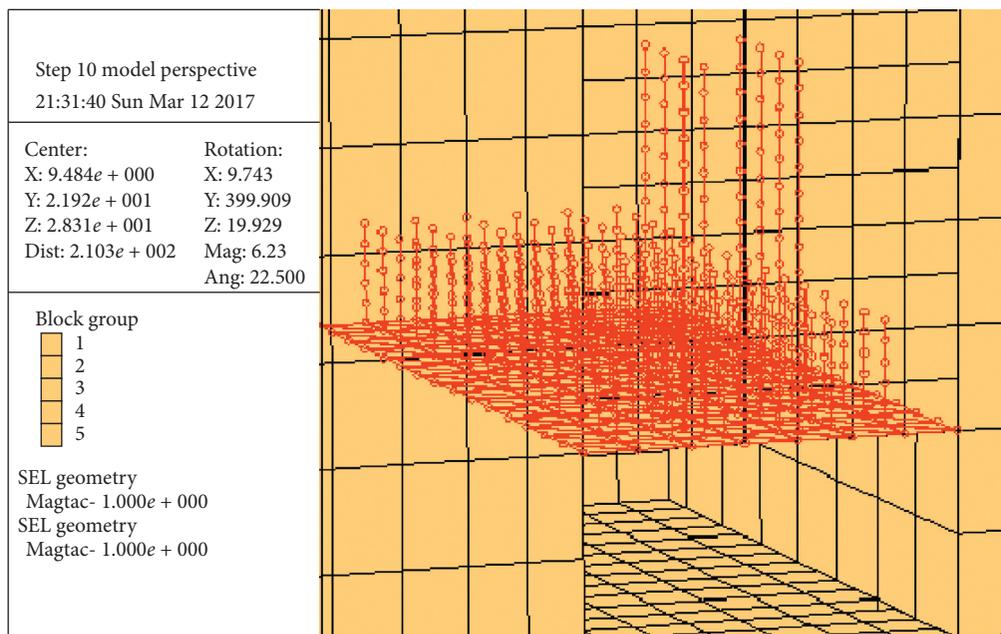


FIGURE 8: Schematic diagram of bolt-mesh-anchor cable supporting in the model.

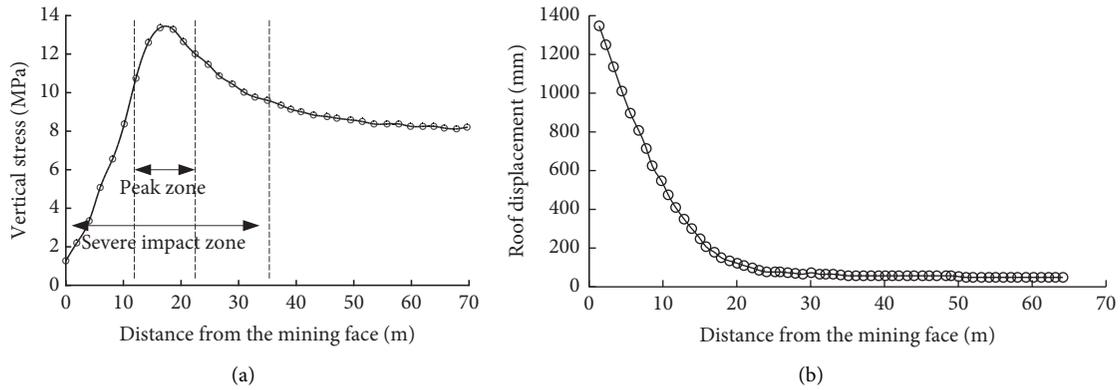


FIGURE 9: The behavior of advanced strata pressure in mining period. (a) Advancing support pressure distribution. (b) Roadway deformation.

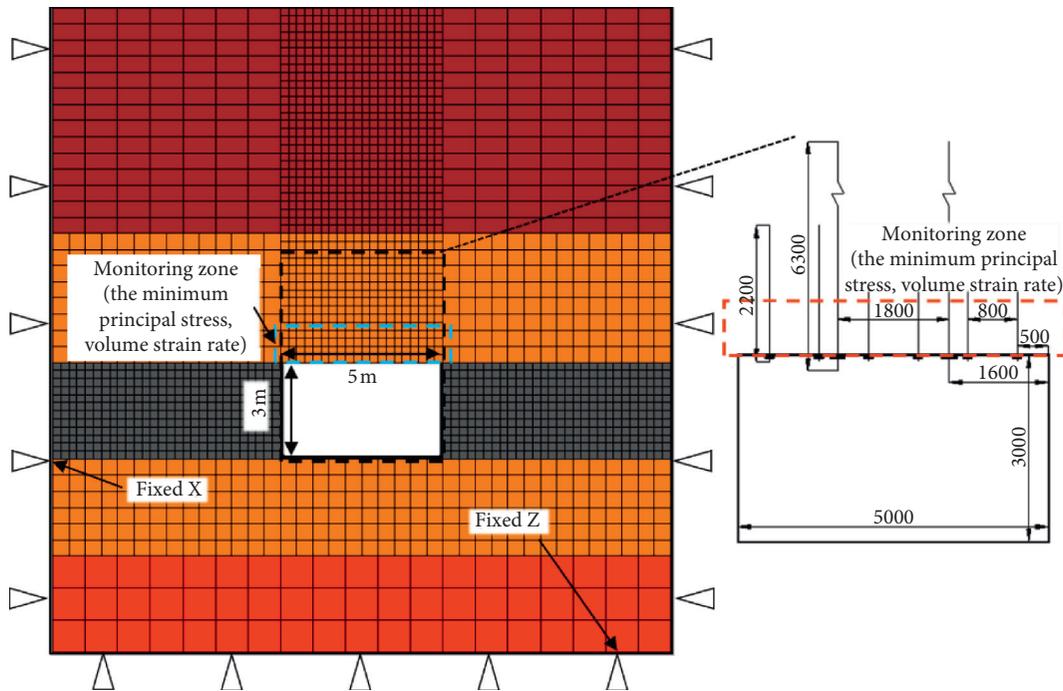


FIGURE 10: Test model of judgment index.

role for the surrounding rock. In the later stage when the deformation of surrounding rock is stable, the minimum principal stress within the monitoring range changes around 1.55 MPa, while the volume strain rate keeps around 0, and both tend to be stable without large fluctuations. However, after adopting the cable modified model (Figure 11(b)), the deformation of roadway surrounding rock drives the extension of structural elements, and the anchor cable fails. The failure of anchor cable can also be verified by intuitively displaying the force of Cable element in the FLAC^{3D} model. With the failure of the anchor cable, the minimum principal stress of surrounding rock in the monitoring area will suddenly decrease and the volumetric strain rate will suddenly increase. The sudden failure of the anchor cable causes the supporting resistance provided by the supporting structure to suddenly disappear, and the internal stress state

of the surrounding rock changes, causing a sudden change in volume strain rate of the surrounding rock. This one-to-one characterization relationship is verified, and the feasibility of the two failure determination indicators, the minimum principal stress and volume strain rate, is determined.

3.4. Variation Law of Failure Criterion of Anchor Cable in Front of Mining Working Face. During the stopping of working face, the variation rules of anchor cable failure determination indexes under the five lagging support schemes are shown in Figure 12. It is found that the failure time of several anchor cable lagging schemes is obviously different due to the different supporting time and coupling stress state in the early stage. With the increase of the lagging distance of anchor cable support, the ability of the anchor

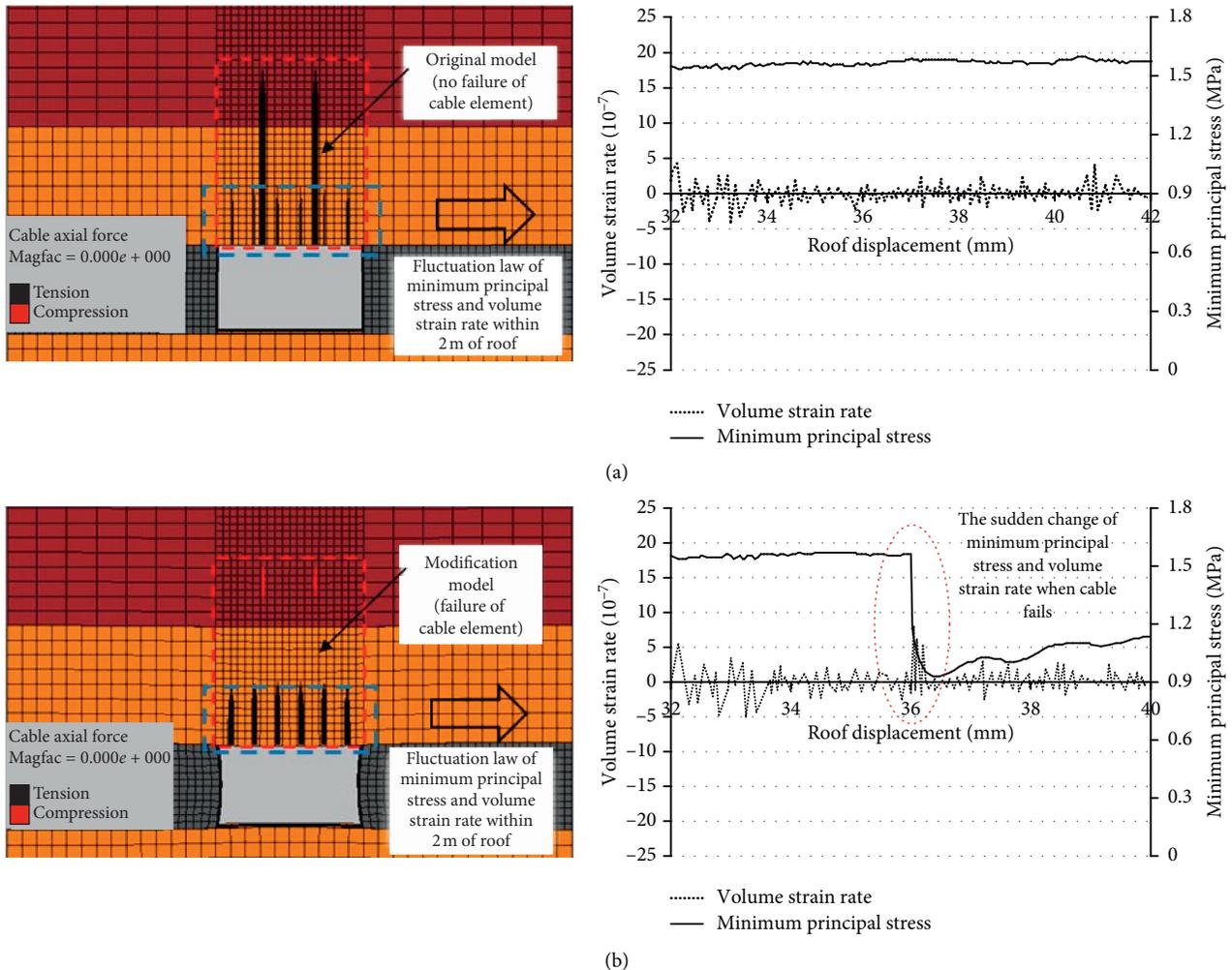


FIGURE 11: Variation of index. (a) Variation of assessment index before anchor Cable element is failure. (b) Variation of assessment index after anchor Cable element is failure.

cable to adapt to deformation gradually increases. In schemes 3, 4, and 5, the adaptability of anchor cable to deformation is significantly improved compared with schemes 1 and 2. When the lagging time of the anchor cable is a gentle area of roadway deformation (schemes 4 and 5), the ability increment of the anchor cable to adapt to deformation has been reduced.

The lagging support of the anchor cable significantly improves the deformation bearing capacity, but the different supporting time leads to the different coupling stress conditions of the supporting body. The initial resistance of the supporting structure is significantly different, which is reflected in the mechanical phenomenon in the figure that the minimum principal stress increases with deformation. For scheme 3, there is no anchor cable failure at the position of the 20 m measuring point, but it also shows that the maximum working resistance cannot be reached in time during the initial deformation process of the roof under the advanced supporting pressure. Due to the certain hysteresis of the anchor cable, the initial axial force of the anchor cable decreases, and the reduction of the minimum principal

stress in the surrounding rock at the initial stage of the surrounding rock deformation caused by this is not strong. Therefore, scheme 3 is considered to be feasible. It can be seen from schemes 4 and 5 that when the anchor cable lagging support is completely located in the gentle period of roadway deformation, the initial minimum principal stress in the surrounding rock is significantly reduced. The supporting body needs a long process of surrounding rock deformation to reach its maximum support resistance, so the supporting effect of the supporting structure cannot be fully exerted in the early stage, which is not conducive to the deformation control.

Therefore, considering the improvement of the deformation bearing capacity of the anchor cable by different schemes and the supporting capacity of the anchor cable in the early stage of roadway deformation, the lagging support time of the anchor cable is the best when it is close to the stable period of the surrounding rock deformation of the roadway. It is determined that the lagging support time of anchor cable in 6208 transport tunnel in Wangzhuang Coal Mine is within 10–15 m behind the head.

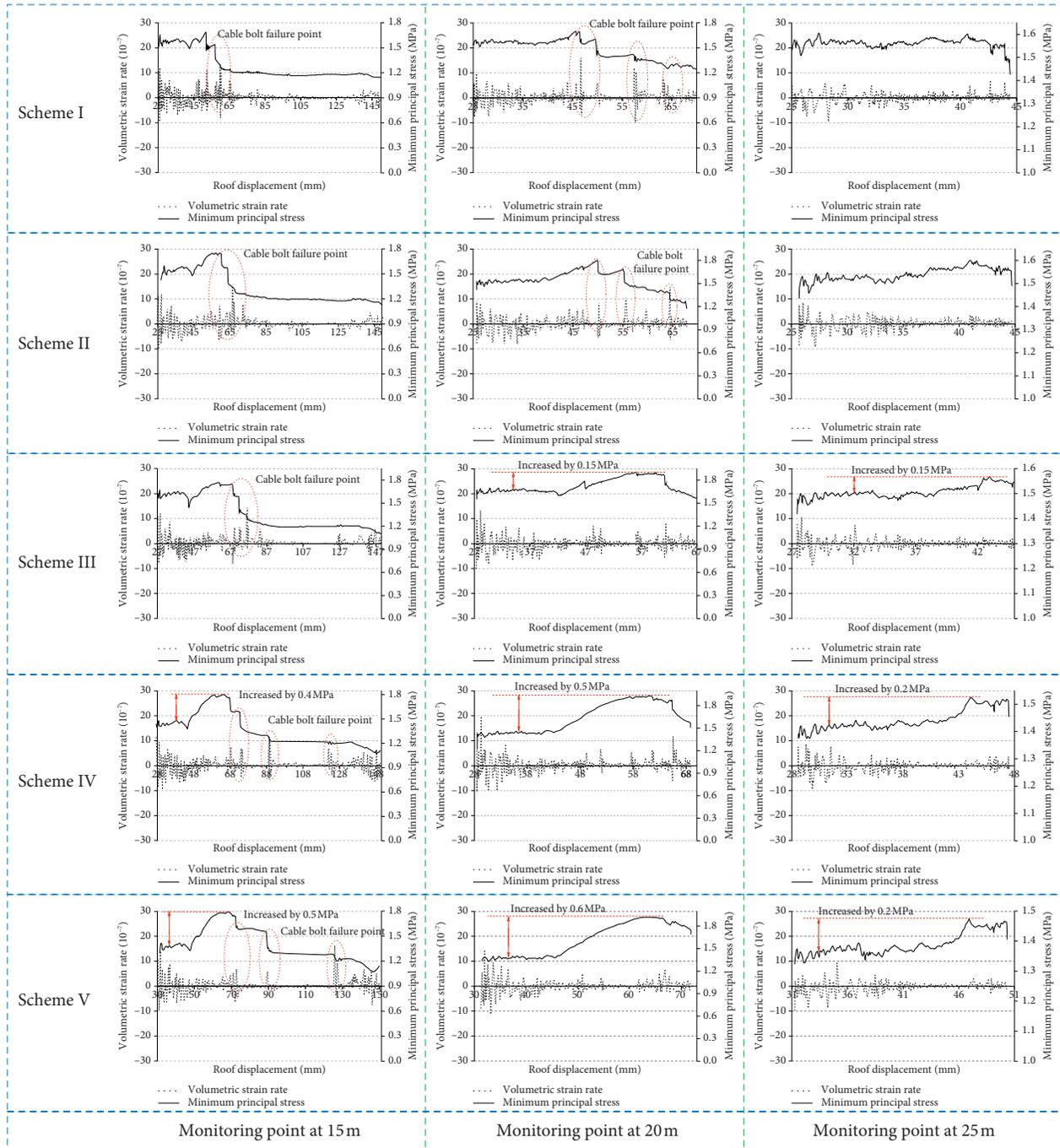


FIGURE 12: Change of the failure judgment index for the cables during the advancing of the working face.

4. Industrial Tests

In order to verify the effectiveness of the optimization support scheme of 6208 tunnel in Wangzhuang Coal Mine, three groups of surface displacement and anchor cable stress measurement stations are set up. The monitoring scheme is shown in Figure 13. In the process of tunneling and mining, the bolt dynamometer is used to monitor the strain of the load-measuring bolt and the load-measuring cable, and then

the stress state is calculated according to the mechanical parameters of the bolt and the cable. The monitoring results of the 1# comprehensive measuring station are shown in Figure 14.

After raising the prestress of the bolt and adopting lagging support for the anchor cable, roof anchor bolt and cable show good coupling and cooperative stress relationship (Figure 14). In the later stage of tunneling, the coupling force range is basically reached. Meanwhile, the reasonable

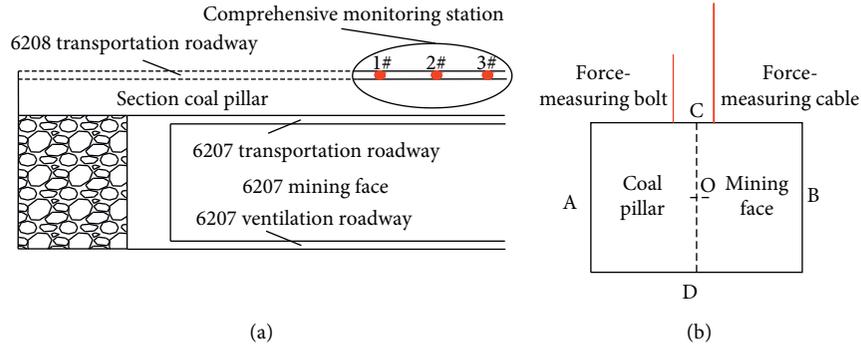


FIGURE 13: Integrated station layout.

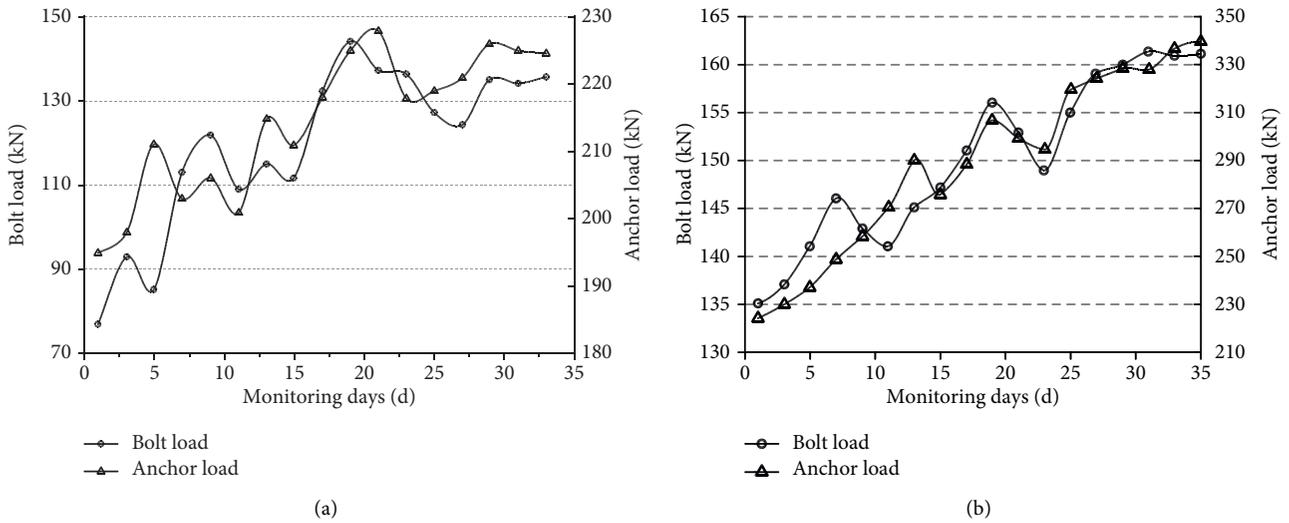


FIGURE 14: Force change of bolt and cable. (a) The period of drilling. (b) The period of mining.

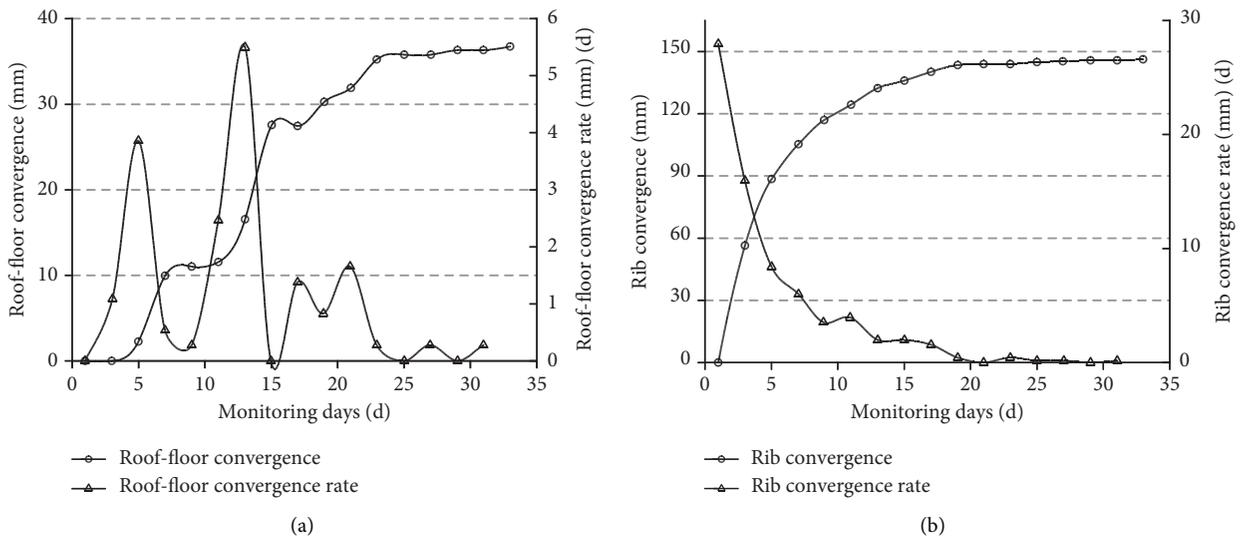


FIGURE 15: Continued.

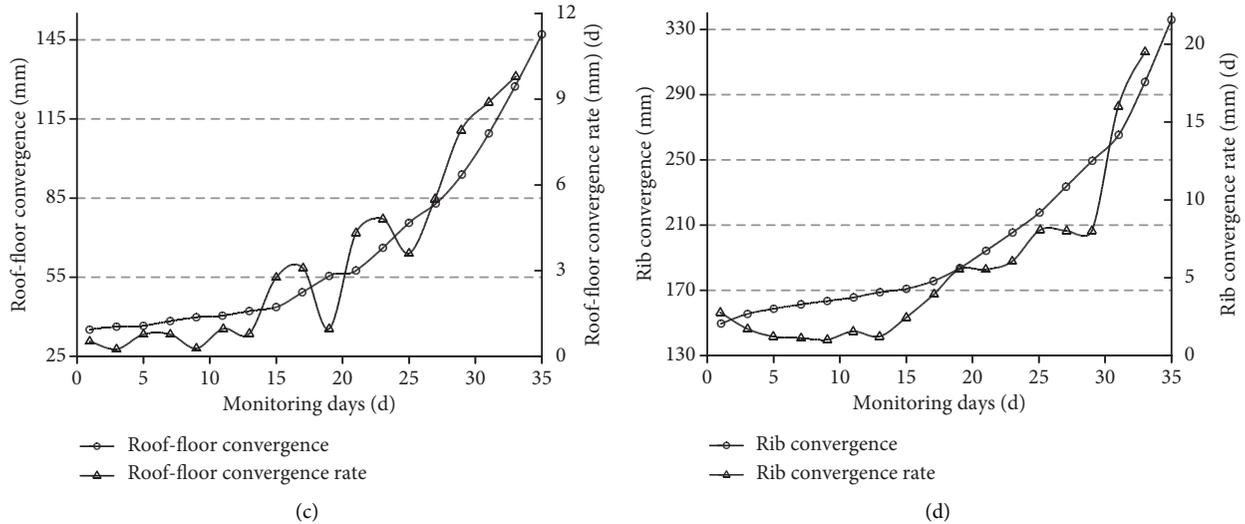


FIGURE 15: Evolution of the surface displacement around the roadway. (a) Displacement of roof and floor during excavation. (b) Displacement of two sides during excavation. (c) Displacement of roof and floor during extraction. (d) Displacement of two sides during extraction.

lagging support also ensures that the anchor cable can withstand a certain deformation during mining without broken failure, which ensures the safe use of the roadway.

The surface displacement of surrounding rock is shown in Figure 15. After adopting the optimized support scheme, the deformation of the surrounding rock of the roadway has been well controlled. In the mining and stopping stages, the final relative approaching quantities of roof and floor are 37 mm and 147 mm, respectively, and the corresponding relative approaching quantities of roadway sides are 149 mm and 330 mm, respectively, in the two stages. In view of the overall control effect of surrounding rock, the roadway surrounding rock is in a relatively stable state, and its deformation is effectively controlled.

5. Conclusion

In mining engineering, the failure of anchor cable of the mining roadway roof induces by mining is very serious; therefore, solving the failure of anchor cable is very important to maintain the stability of roadway. As a result, a solution for anchor cable lagging support is proposed in this study. Moreover, based on the modified Cable element in FLAC^{3D}, the real breaking effect of anchor cable in the calculation process is realized. Through the simulation analysis of five anchor cable lagging support schemes of 6208 transport tunnel in Wangzhuang Mine Coal, industrial tests are carried out, and the feasibility of the scheme is verified successfully. The main conclusions are as follows:

- (1) Based on the results of indoor anchor cable pull-out test, the deformation behavior of anchor cable is obtained. Then, the deformation property of Cable element in FLAC^{3D} is modified so that the extension breaking effect of anchor cable can be realized in the calculation process.

- (2) The minimum principal stress and volumetric strain mutation point are used as the mechanical criterion for the failure of anchor cable. It is proved that with the increase of anchor cable support lagging time, the ability of anchor cable to adapt to deformation increases gradually, the increase rate decreases gradually, and the initial support resistance decreases gradually.
- (3) According to the modified numerical model, it is determined that the lagging time of the anchor cable along the 6208 transport tunnel in Wangzhuang Coal Mine is within 10–15 m of lagging head. The industrial test verifies the feasibility of the scheme and ensures the safe use of the roadway.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

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