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Research Article

Study on the Constant Resistance Coupling Support Technology for Rock Column at the Intersection Point of Deep Soft Rock Large Section Roadway: A Case Study in China

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In order to solve the problem on the serious deformation and failure of the rock column at the intersection of large cross sections in Shiyakou coal mine, based on field engineering geomechanics analysis, theoretical analysis, and three-dimensional numerical simulation, combined with the mutual coupling between the constant resistance coupling support cable and surrounding rock, a dual-control constant-resistance coupling control technology with high prestressed constant resistance coupling support cable as the core solution is proposed. The field engineering practice and field monitoring data show that the dual-control constant resistance coupling support control technology has a good control effect on the deformation of the rock column at the large cross section intersection of the deep soft rock roadway and can be effectively used in the engineering practice.

1. Introduction

The mining depth of coal mines in China is increasing at a rate of 8–12 m per year. The number of medium and deep mines has increased markedly [1, 2]. With the increase of mining depth, the stress of the surrounding rock of the roadway increases. The nonlinear large deformation phenomenon of soft rock is more obvious [3–5]. The intersection point is passed by two or more roadways. Under the effects of high stress concentration and large span, the rock column at the intersection point bulges out horizontally and the roof subsides heavily, affecting the normal functions of roadway pedestrians, ventilation, and transportation [6–8]. At the same time, a long service life and higher reliability requirement of support of the intersection point are required. Therefore, how to effectively control the stability of the rock column at the intersection point of deep soft rock large section roadway is key part to study [9–16].

Based on a large number of investigations on the geological characteristics and deformation of the rock column at the intersection of large cross sections in Shiyakou Coal Mine, Yunnan Province, this paper studied the deformation and failure mechanism of the rock column at the intersection point of the soft rock roadway, puts forward the constant resistance coupling support strategy with the constant resistance and large deformation anchor cable as the core solution, meets the needs of the project, and successfully applies it at the crossing point of 1770 track roadway and 1770 track stone gate. It provides a detailed reference for similar projects.

2. General Situation of the Project

2.1. Roadway Layout and Surrounding Rock Lithology. Shiyakou Coal Mine is located in Zhaotong City, Yunnan Province. It is developed by an inclined shaft. The depth of the mine is about 770 m. The mining area is located in the west wing of the Shangxiong block syncline. In the course of excavation, silty mudstone, argillaceous siltstone, and coal seams with different properties are passed successively. In the cross section of 1770 track and 1770 track stone gate, the strata are silty mudstone and argillaceous siltstone. The roadway layout is shown in Figure 1(a). The surrounding rock is soft and fragile, and the joints are well developed. It is a typical structural type of cataclastic rock mass. The lithologic distribution of roadway is shown in Figure 1(b). The shape of the roadway is straight wall and semi-circular arch, and the gross section size is as follows: ① track roadway: 5200 mm (width) × 4100 mm (height); ② track stone gate: 5200 mm (width) × 4100 mm (height).

2.2. Clay Minerals Analysis and Sem Scanning. The following conclusions can be drawn from the analysis of component (Table 1) and scanning by SEM of rock samples in situ (Figure 2):

(1) Clay minerals are the main mineral constituents in the rock at the intersection of the 1770 track roadway and the track stone gate section in Shiyakou Coal Mine, with an average content of 80%.

(2) The highest content of clay minerals in each stratum is the Illinois/Smectite mixed mineral, which accounts for more than half of the total clay mineral composition.

(3) From the SEM scanning, it can be seen that the rock samples are composed of flaky illite, dolomite, and lots of pores and gaps. The clay minerals are mostly arranged in disordered mixed layers, showing sheet, block, and strip distribution. There are many corrosion holes on the surface, including many microfissures, which are filled with muddy and illite minerals.

More clay mineral content in surrounding rock resulting in obvious expansive deformation when meet the water.

3. Analysis of Deformation and Failure Mechanisms

3.1. Deformation and Failure Characteristics. During the excavation of the intersection roadway, due to the influence of the overlapping pressure relief zone of the roof of the intersection roadway and the support pressure zone of the two sides, the rock column at the intersection point will become the most concentrated part of the stress in the intersection area. In addition, the depth of the coal mine in Shiyakou is deep and the ground stress is large, so the rock columns have a variety of deformation, and destruction. The deformation and destruction are mainly column bulging, type I crack, type *X* crack, and roof subsidence, as shown in Figure 3.

3.2. Mechanism of Deformation Mechanics. The rock at the roadway excavation horizon is argillaceous rock mainly composed of mudstone, and the surrounding rock is easily softened when it encounters water. According to relevant engineering experience, the deformation can be divided into type I (physical and chemical expansion) I_{AB} mechanism, that is, water absorption + colloid expansion [17]. The horizontal burial depth of the roadway is about 770 m. I burial depth is large, and the self-weight stress is high, which can be classified as the II_B mechanism in the type II (stress expansion type), that is the gravity mechanism. The deformation of the rock has obvious characteristics of two groups of deformation, which can be classified as the II_C mechanism, that is the tectonic stress mechanism; and after the excavation of the roadway, the surrounding rock stress changes greatly, especially the stress concentration phenomenon at the intersection point the intersection, so it is classified as the II_D type mechanism, that is the engineering deviatoric stress mechanism; the fault was found during the tunnel excavation, it was preliminarily determined that the tunnel trend and the exposed fault formed an angle of 55°, and the bedding trend was the same as that of the exposed fault. The direction of the roadway also forms an included angle of about 57°, revealing that the surrounding rock joints in the section are randomly arranged, so it is classified as the III_{AB} III_{CB} III_E mechanism in type III (structural deformation type).

In summary, the deformation mechanics mechanism of the intersection of 1770 track roadway and track stone gate can be summarized as I_{AB} II_{BCD} III_{AB} III_{CB} III_E composite deformation mechanics mechanism.

3.3. Transformation of Deformation Mechanics Mechanism. Based on the composite deformation mechanics mechanism of 1770 track roadway and track stone gate intersection section, the following countermeasures can be provided [18, 19]:

(1) I_{AB}: Reserve deformation amount can be used to release deformation energy, and shotcrete can be used to seal surrounding rock for mechanism transformation.

(2) $III_{AB}III_{CB}III_E$: Adopt three-dimensional optimization of bolt and coupling control technology of bolt/cable with large transverse resistance.

(3) II_C: Adopt three-stage prevention and control technology for base heave.

(4) II_D: A dual-control constant-resistance coupling control technology has been adopted for key points.

Through (1)-(4), we can transform I_{AB} II_{BCD} III_{AB} III_{CB} III_E into a single deformation mechanics mechanism II_B

4. Dual-Control Constant Resistance Large Deformation Coupling Support Technology

4.1. Numerical Simulation and Analysis. Based on the analysis of deformation and failure characteristics of the large cross section intersection of the deep soft rock roadway and the engineering geological conditions of Shiyakou coal mine, a numerical model is established by a numerical simulation method to reproduce the failure process and

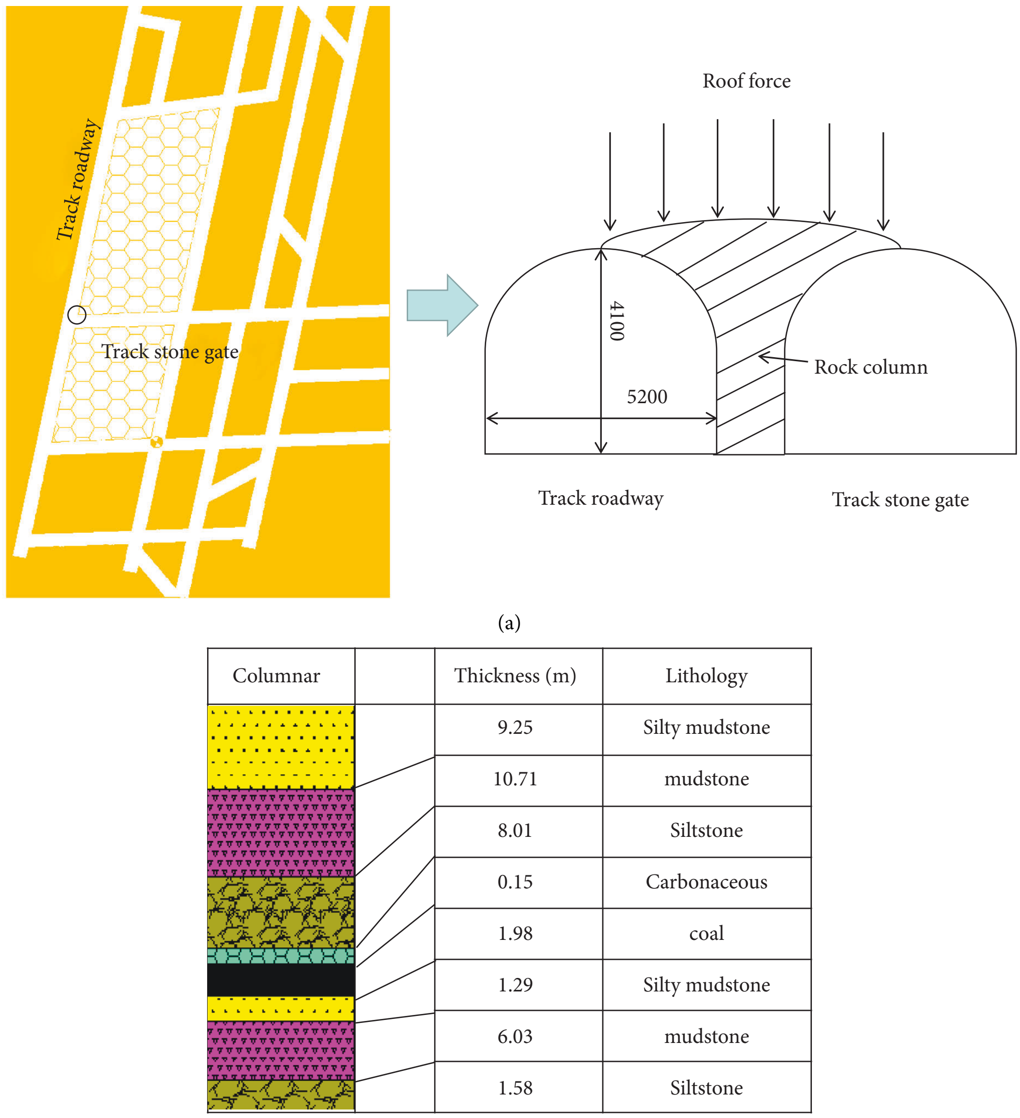


Figure 1: Layout of the mining roadway and lithology of the roof and floor. (a) Schematic diagram of intersection of mining roadway, (b) Lithology of roof and floor.

Table 1: Mineral composition content of clay.

Rock sample number	Relative content of clay minerals/%						Mixed layer ratio S/%	
	Smectite	Illinois/Smectite	Illinois	Kaolinite	Chlorite	Chlorite/Smectite	Illinois/Smectite	Chlorite/Smectite
Rock sample 1	—	66	11	15	8	—	20	—
Rock sample 2	—	56	7		14	—	20	—

further verify the rationality of dual-control constant resistance coupling support technology.

4.1.1. Establishment of Numerical Calculation Model. The object of this numerical simulation is the actual engineering rock mass of $40\,m \times 40\,m \times 40\,m$. Both roadways are straight-wall semi-circular arch the angle between roadways is 77, and the depth of roadways is 770 m. The model consists of 19800 elements and 22551 nodes. The mesh is constrained by horizontal supports around the mesh and fixed twisted supports at the bottom. The model adopts the Mohr-Coulomb model. The numerical simulation model is shown in Figure 4. The calculation model is shown in Figure 5. The rock mechanics parameters are shown in Table 2.

In the process of this simulation experiment; three models of original support, high prestressed constant resistance coupling support, and dual-control constant resistance anchor support are established respectively in the process of roadway excavation. Then, the displacement field, stress field,

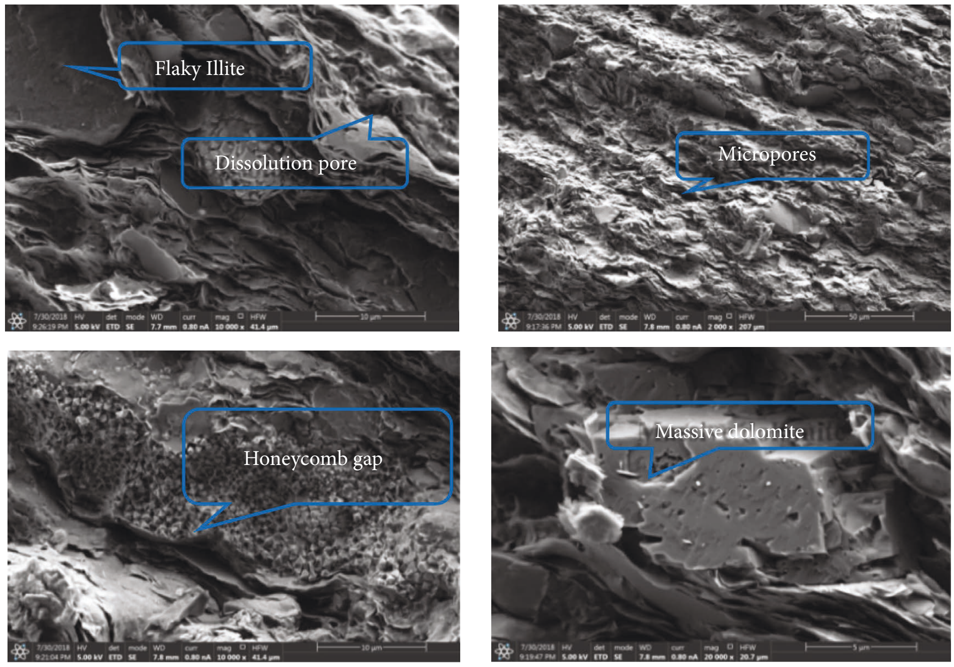


Figure 2: SEM of rock samples.

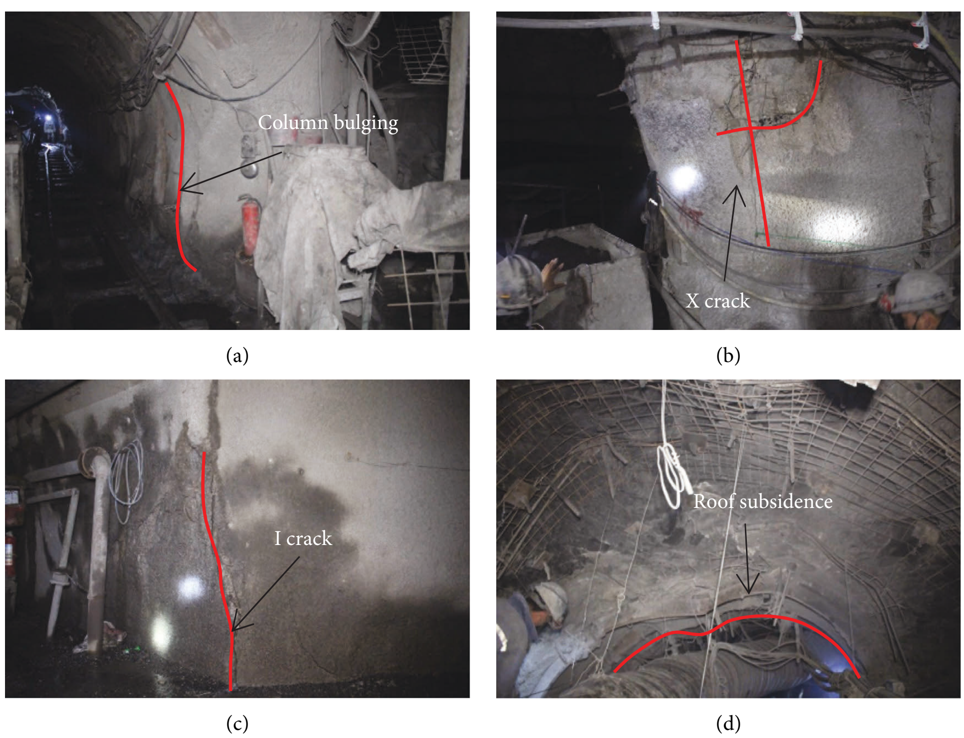


Figure 3: Deformation and failure characteristics. (a) Middle rock column bulging; (b) Type X crack; (c) Type I crack; (d) roof subsidence.

and displacement monitoring of surface measuring points at the intersection of three models are compared one by one. Finally, the simulation experiment results are analyzed to verify the advantages and rationality of the dual-control constant resistance coupling support technology. The original support system is shown in Figure 5(c). The high prestressed constant resistance coupling support system is shown in Figure 5(d). The high prestressed constant resistance coupling support with dual-control constant-resistance coupling control is shown in Figures 5(d) and 5(e).

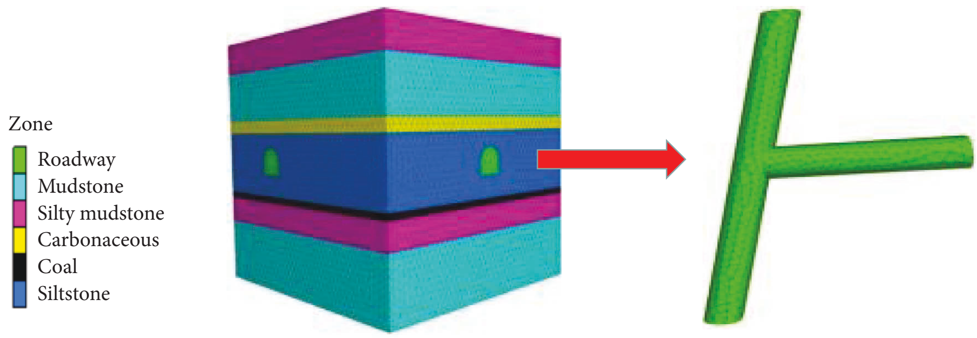
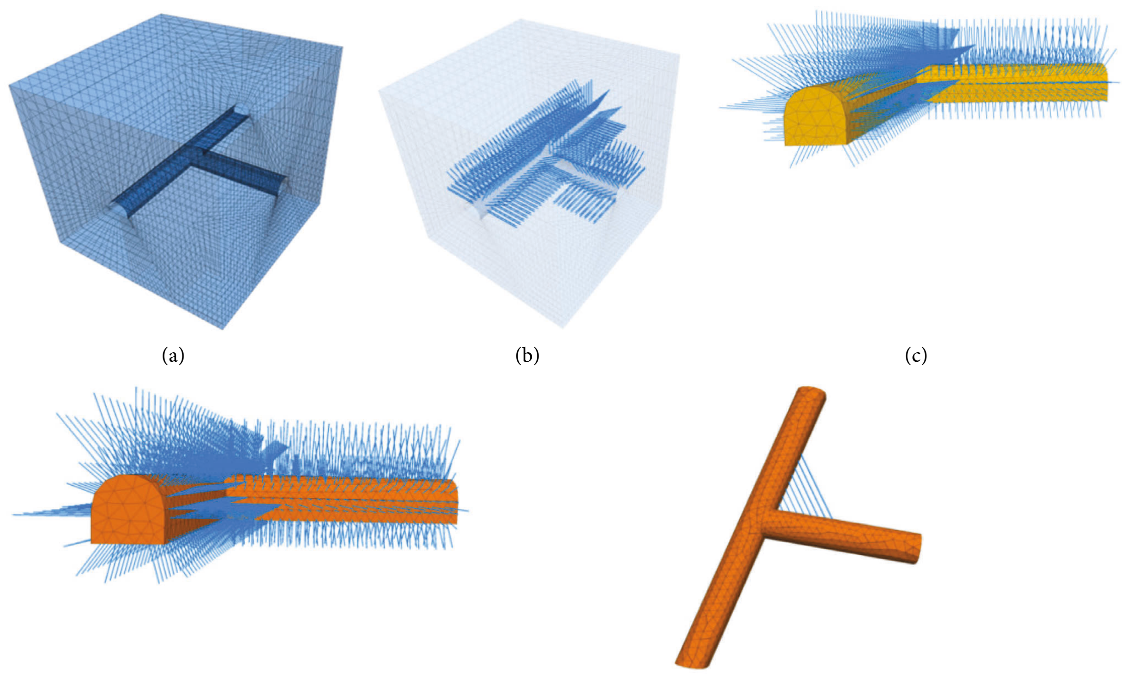


Figure 4: Numerical simulation model.



(a) (b) (c) (d) (e)

Figure 5: Numerical calculation model: (a); (b) schematic diagram of computational model; (c) the original bolt/cable unit; (d) the constant resistance coupling support bolt/cable unit; and (e) dual-control constant-resistance coupling control.

Table 2: Rock mechanics parameters.

Lithology	Bulk density (kg·m^{-3})	Compressive strength (MPa)	Tensile strength (MPa)	Bulk modulus (GPa)	Shear modulus (GPa)	Internal friction angle (°)
Mudstone	2688	4.3	2.1	4.53	2.32	35
Silty mudstone	2550	5.5	2.3	5.20	2.74	32
Carbonaceous	2600	4.8	2.2	4.78	2.53	34
Coal	1470	2.6	1.3	2.50	1.12	27
Siltstone	2583	5.8	2.8	5.53	2.92	35

4.1.2. Analysis of Numerical Simulation

(i) Contrast of Displacement Field. It can be seen from Figures 6-7, when ordinary support is adopted, the maximum value of roof subsidence at the intersection point reaches 627 mm, and the lateral bulging of the intermediate rock column occurs under the action of self-weight stress and lateral extrusion force, and the maximum value of the bulging amount reaches 234 mm. When high prestressed constant resistance coupling support is used, the deformation of surrounding rock is obviously controlled. The maximum roof subsidence is reduced to 211 mm, and the bulge at the intersection of the middle rock column becomes 115 mm. Under the dual-control constant-resistance

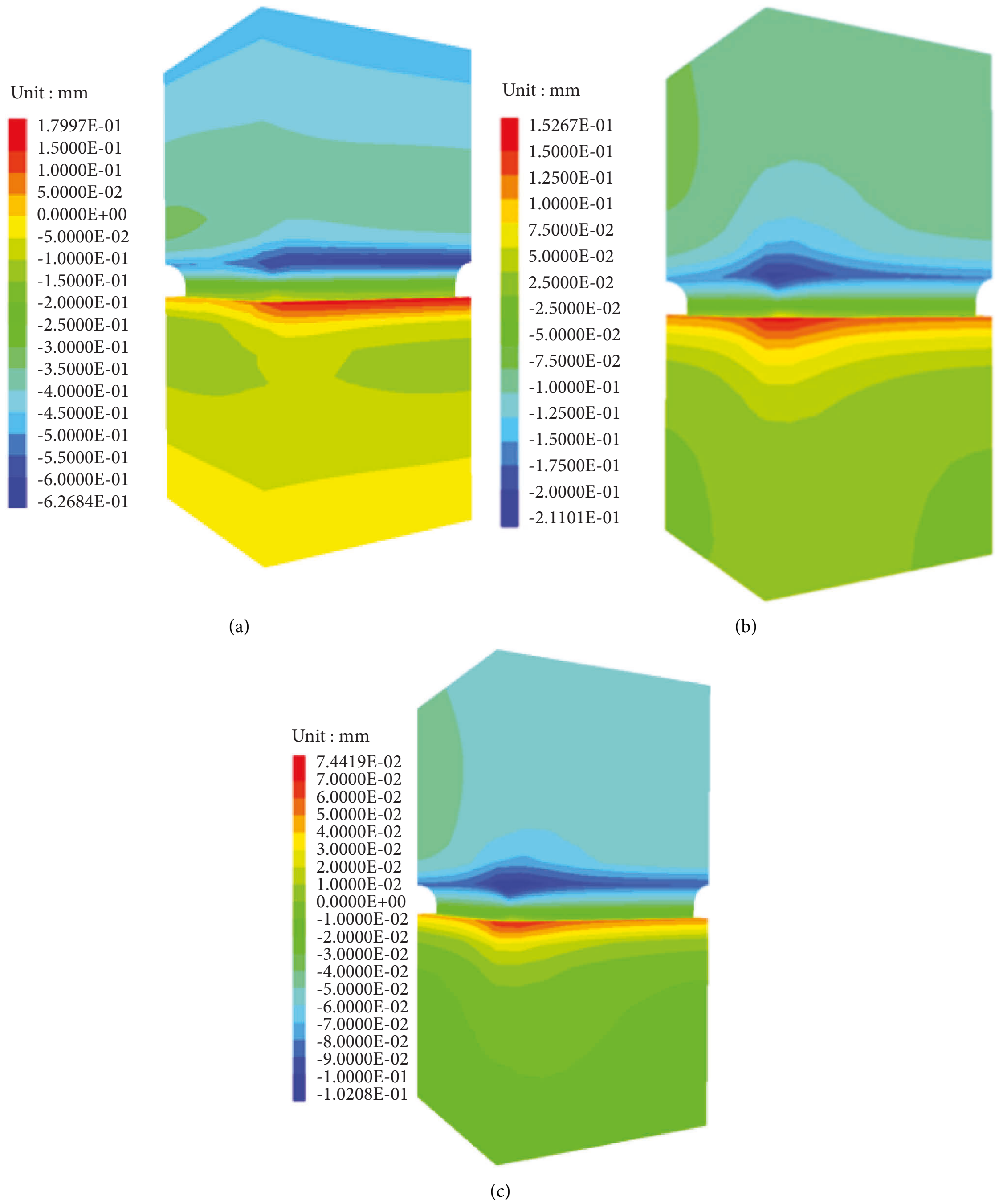


Figure 6: Vertical displacement field, (a) original support system, (b) high prestressed constant resistance coupling support system, (c) dual-control constant-resistance coupling control system.

coupling control system, the roof subsidence at the intersection point is only 102 mm, and the outburst of the middle rock column is also reduced to 42 mm. The deformation of surrounding rock has been greatly improved, which fully reflects the advantages and feasibility of the dual-control constant resistance anchor support.

(ii) Stress Field Comparison. It can be seen from Figure 8 that when ordinary support is adopted, the stress concentration phenomenon occurs at the crossing point, with the concentration coefficient reaching 2.5, which has a great impact on the stability of the crossing point; when a high prestressed constant resistance coupling support system is adopted, the stress concentration coefficient drops to 1.6, but the stress concentration is still large at the middle rock column; when a dual-control constant-resistance coupling control system is adopted at the connecting post, the stress concentration coefficient is 1.35, and not concentrated in the middle of the rock column, which greatly increases the stability of the surrounding rock at the intersection.

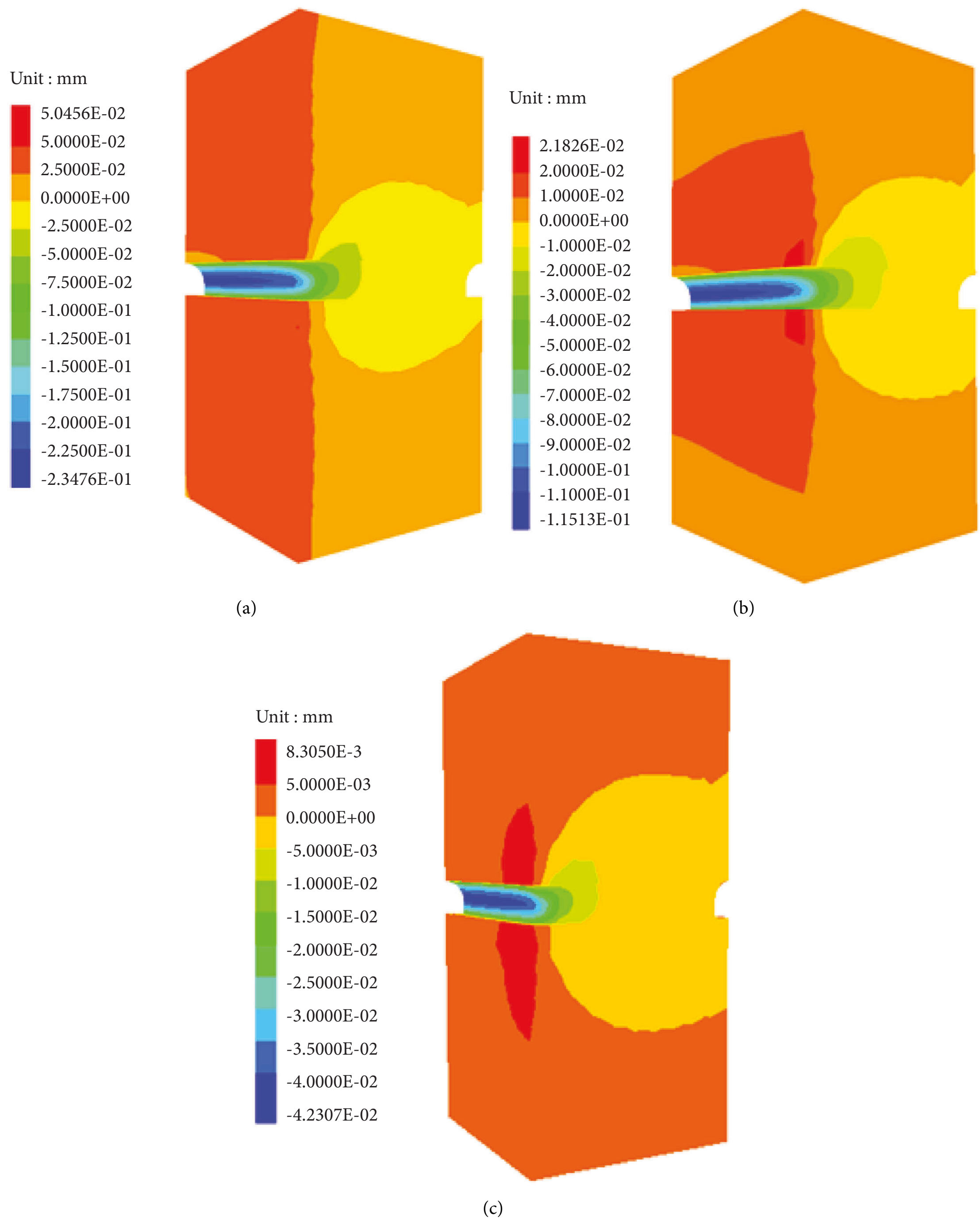


Figure 7: Horizontal displacement field, (a) original support system, (b) high prestressed constant resistance coupling support system, (c) dual-control constant-resistance coupling control system.

(iii) Monitoring and Analysis of Roadway Displacement. In order to monitor the surface displacement of the surrounding rock at the intersection in the process of calculation, measurement points are arranged at both sides of the roof of the intersection and 5 m from the rock column in the middle of the intersection. The vertical displacement of the roof and the convergence displacement of the two sides are monitored respectively. The layout of measuring points is shown in Figure 9, and the monitoring curve is shown in Figure 10.

According to the monitoring curve, the original support system not only has large deformation but also cannot be effectively controlled in the deformation process. When high-prestressed constant resistance coupling support system is adopted, the surrounding rock will deform to a certain extent at the initial intersection. When the calculation reaches 80000 steps, the deformation of the surrounding rock tends to be stable. On this basis, the deformation of surrounding rock is greatly reduced by the dual-control constant-resistance coupling control system, which verifies

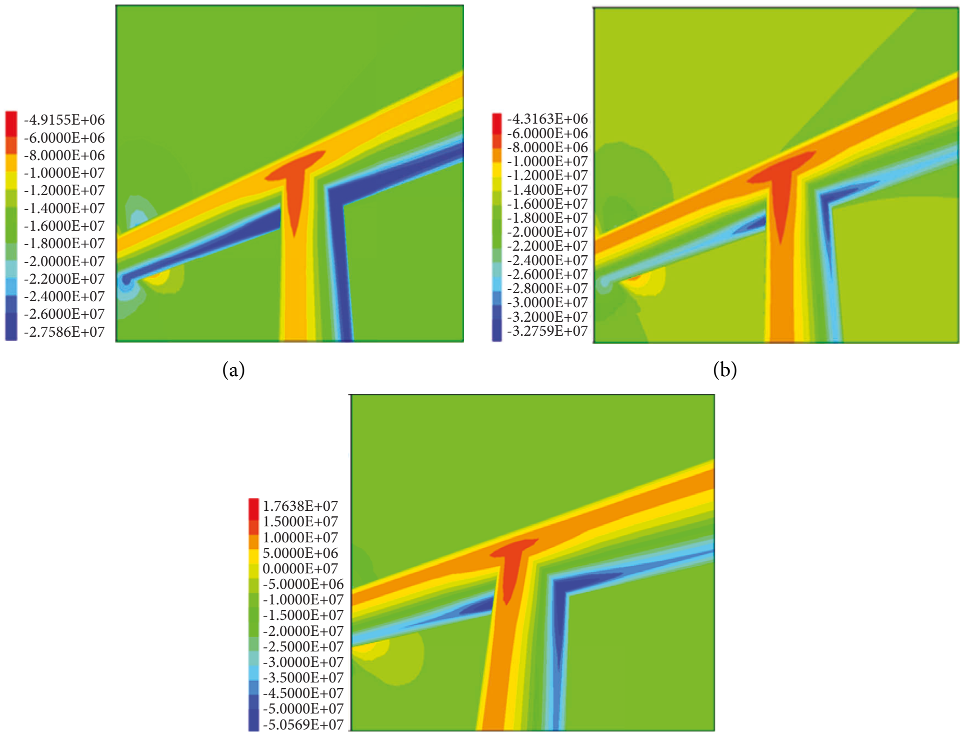


Figure 8: Stress field contrast diagram, (a) original support system, (b) high prestressed constant resistance coupling support system, and (c) dual-control constant-resistance coupling control system.

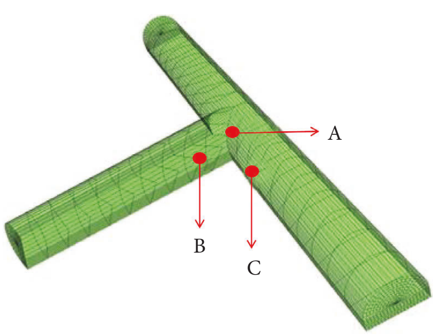


Figure 9: Layout of measuring points.

the rationality of the dual-control constant resistance coupling support technology.

4.2. Support Parameter Design. In conclusion, at the intersection of the test section, the dual-control constant resistance coupling support strategy with the core of high prestressed constant resistance coupling support is adopted, and the detailed design scheme is shown in Figure 11:

4.3. Introduction of Constant Resistance Large Deformation Anchor Cable. The constant resistance large deformation anchor cable is composed of constant resistance, anchor body, tray, and nut. The constant resistance is the core component of the constant resistance and large deformation anchor cable, as shown in Figure 12. Compared with the traditional prestressed anchor cable, the new anchor cable has the characteristics of high prestress, high constant resistance, and large deformation.

The constant resistance and large deformation anchor cable can produce a deformation of about 400 mm under the condition of static tension. The average constant working resistance is about 320–370 Kn, and the effective working stroke under constant resistance is about 310 mm, as shown in Figure 13. Constant resistance part can realize the function of large deformation under a high constant resistance state.

Its constitutive relation can be expressed by the ideal elastic-plastic two element model. The constitutive relation is as follows:

$$p = \begin{cases} \text{kx}, & (0 \le x \le x_0, p < p_{\max}), \\ p_{\max} - p_{\min} = k\Delta x, & (p > x_0), \end{cases} \quad (1)$$

where p is the static tensile load, k is the stiffness of the anchor cable with constant resistance and large deformation, and x is the tensile length.

5. Application Analysis

5.1. Surface Displacement Monitoring at Intersection Points. The key parts of the intersection point between the 1770 track roadway and the 1770 track stone gate in the coal mine adopt dual-control constant resistance large deformation anchor cable coupling support technology. The deformation of the roadway is effectively controlled, and the shape of the

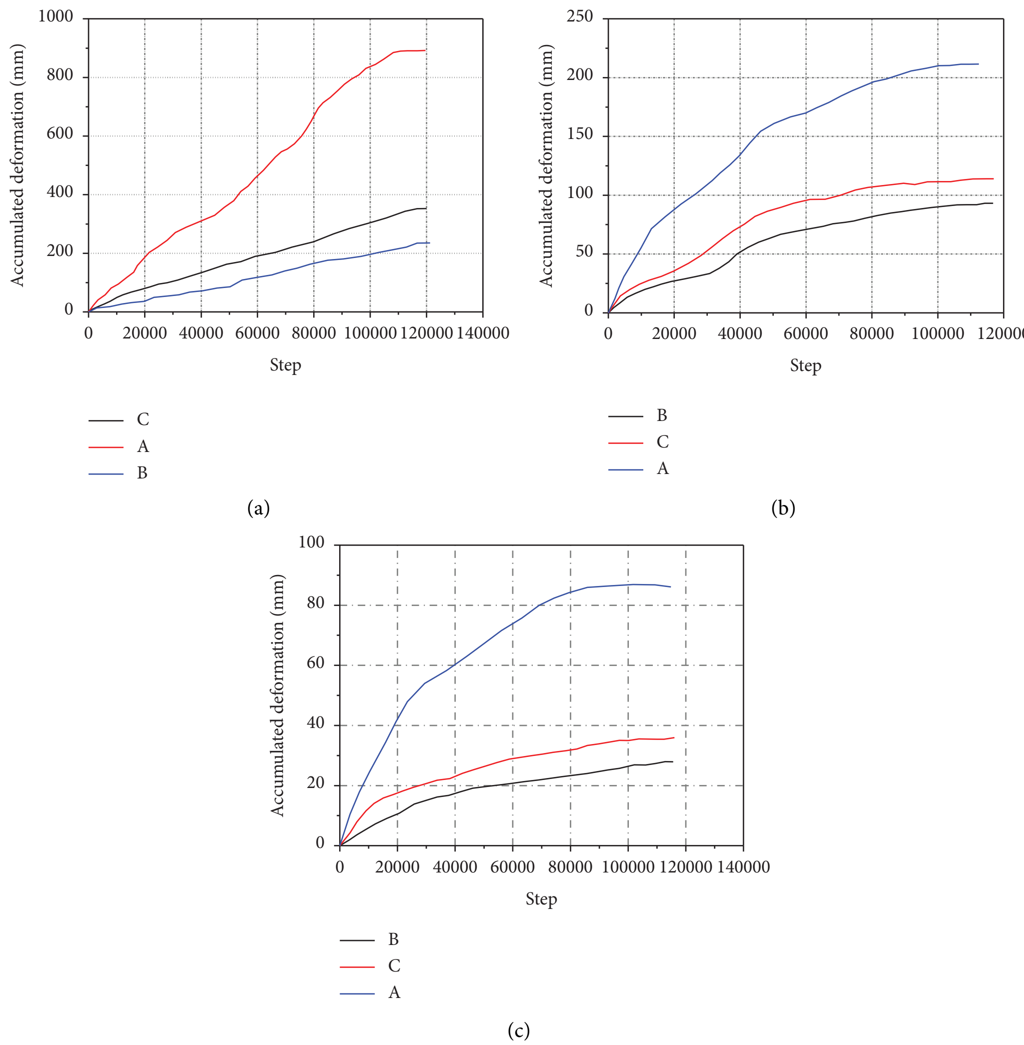


Figure 10: Contrast of monitoring curves, (a) original support system, (b) high prestressed constant resistance coupling support system, and (c) dual-control constant-resistance coupling control system.

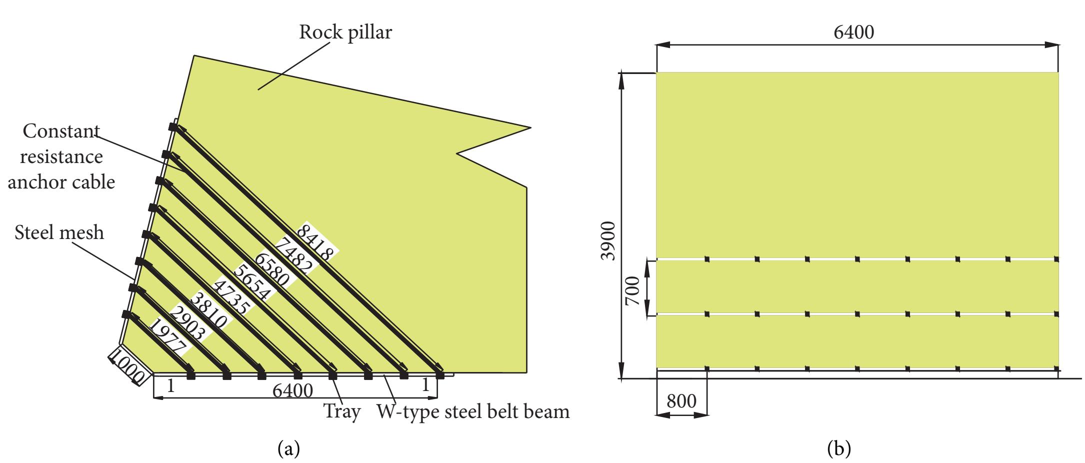


Figure 11: Layout of dual-control constant-resistance coupling control system, (a) Layout plan of dual-control anchor cable, (b) 1–1 section map.

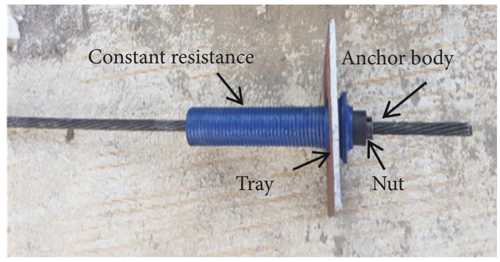


Figure 12: The constant resistance large deformation anchor cable.

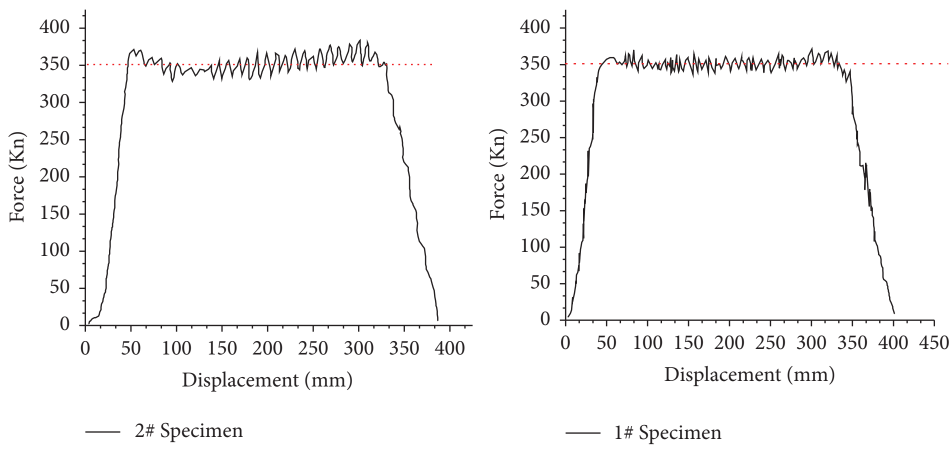


Figure 13: Static test system of NPR bolt.

roadway is good. In order to test the rationality and validity of the new support method and understand the deformation law of surrounding rock under the action of excavation and blasting, a group of measuring stations were set up on both sides of the rock column at the intersection point 1 m away from the top part of the rock column, respectively, to monitor the deformation of the roof and the two sides of the intersection of the surrounding rock at the intersection point. The monitoring layout of the surface displacement of the surrounding rock at the intersection point is shown in Figure 14. After 50 days of monitoring, the displacement-time curves of two groups of measuring points are obtained as shown in Figure 15.

By analyzing the displacement-time curve (Figure 15), the deformation process of the surrounding rock at the intersection can be divided into three stages as follows:

(1) Accelerated deformation stage: the surrounding rock deformation is large from the first day to the fifteenth day after excavation, and the deformation rate is fast, and the rock mass is in an unstable state.

(2) Slow deformation stage: the deformation of surrounding rock decreases gradually from the 16th day to the 30th day after excavation. The deformation rate slows down, and the head tends to be stable.

(3) Stage of deformation stabilization: After 31 days of excavation, the deformation of the surrounding rock is basically stable, and the rock columns at the intersection point are basically no longer deformed.

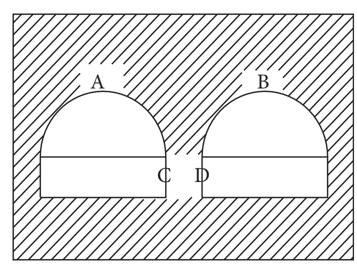


Figure 14: Layout of measuring points.

From the monitoring data, it can be seen that the new support method can effectively control the large nonlinear deformation of the large cross-section intersection point of deep soft rock roadway, greatly reduce the phenomenon of surrounding rock shrinkage at large cross-sections, and the deformation tends to be stable after 50 days, effectively guaranteeing the normal use of the roadway.

5.2. Cable Shrinkage Monitoring. By analyzing the deformation of anchor cable with constant resistance and large deformation during the supporting process, it can analyze its working state and provide the basis for adjusting and modifying the supporting parameters of large deformation anchor cable in the future. Three groups of stations in the first, fourth, and eighth rows of dual-control cables are set to monitor the contraction of the cables. The monitoring is shown in Figure 16.

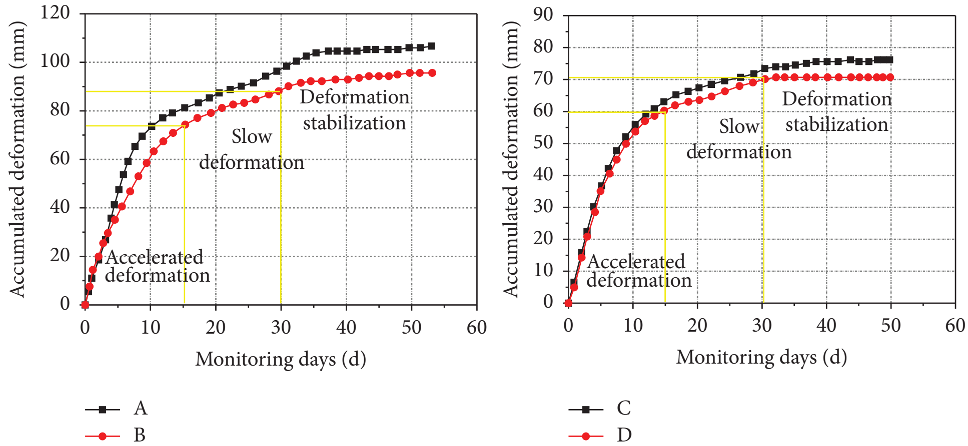
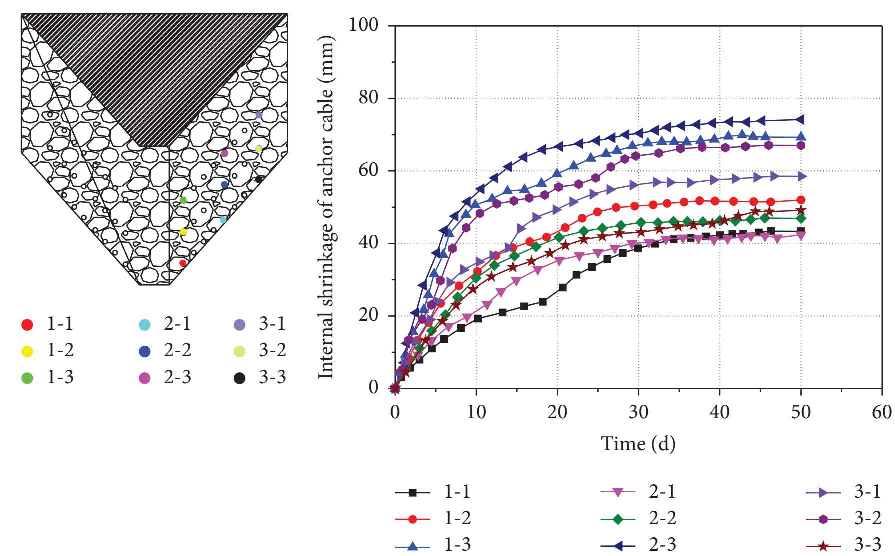


Figure 15: Displacement-time curve.



(a) (b)

Figure 16: Monitoring of anchor cable support effect, (a) Layout of measuring points, (b) Monitoring curve of shrinkage in anchor cable.

From the monitoring curve, it can be seen that the change in shrinkage of constant resistance large deformation anchor cable is consistent with that of surrounding rock, which shows that the anchor cable has played a very good role in constant resistance deformation and verifies the validity of constant group large deformation anchor cable.

6. Conclusion

In this paper, in order to solve the problem on the serious deformation and failure of the rock column at the intersection of large cross section in Shiyakou coal mine, a dual-control constant-resistance coupling control technology with high prestressed constant resistance coupling support cable as the core solution is proposed. Through the engineering application of the support solution and the corresponding data monitoring analysis, the reliability of the solution is proved. The following main conclusions are drawn:

(1) The deformation and destruction are mainly column bulging, type I crack, type *X* crack, and roof subsidence. The deformation mechanics mechanism of the intersection of 1770 track roadway and track stone gate can be summarized as I_{AB} II_{BCD} III_{AB} III_{CB} III_{E} composite deformation mechanics mechanism. A reasonable and effective transformation technology is adopted to transform it into a single deformation mechanics mechanism II_{B}.

(2) The strategy of using the high prestressed constant resistance coupling support with dual-control constant-resistance coupling control to control rock column at intersection point of deep roadway is proposed. The reliability of the support strategy is verified by numerical simulation test compared to other strategies.

(3) The support countermeasure technology is applied to practical engineering, and the shrinkage of anchor

cables and the deformation of surrounding rock are monitored. The reliability of high prestressed constant resistance coupling support with dual-control constant-resistance coupling technology to control the deformation of rock column at the intersection point of deep soft rock large section roadway is verified through engineering practice.

Data Availability

All data generated or analyzed during this study are included in this article.

Conflicts of Interest

The authors declare that there are no conflicts of interest.

Acknowledgments

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