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Research Article

Control Effect Analysis and Engineering Application of Anchor Cable Beam-Truss Structure on Large-Deformation Roadway in Deep Coal Mine

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In response to the shortcomings of the small support scope of single anchor cable and failure to fully utilize the joint anchoring for surrounding rock, this study summarizes the classification of basic support forms for coal mine roadway surrounding rock and clarifies the main composition and mechanism of anchor cable beam-truss structure. A mechanical model of roadway roof beam under the conditions of no support, single anchor cable support, and anchor cable beam-truss structure support at both ends of the roadway is constructed, and the force and maximum bending moment of roadway roof beam under different support types are compared and analyzed. The study clarifies the bending moment reduction rate of anchor cable beam-truss structure relative to unsupported and single anchor cable support and combines numerical simulation to analyze the response laws of anchor cable beam-truss to prestress distribution and stress shell in roadway surrounding rock. Based on the on-site engineering application of a typical large-deformation mining roadway in a deep coal mine, the important role of anchor cable beam-truss structure in ensuring the safety and stability of surrounding rock in deep high-stress and intense-mining large-deformation roadway is revealed, providing technical references for surrounding rock control of similar conditions in deep roadways.

1. Introduction

As the mining depth of coal mine increases year by year, more and more coal mines have become deep mining mines. The surrounding rock control of large-deformation roadways in deep coal mines has become a key problem restricting the efficient mining of deep coal resources [1, 2]. To this end, scholars have proposed various types of active, passive, and combined supports through a variety of methods [3–5]. Overall, the roadway surrounding-rock control can be divided into five basic support forms, namely, the basic support within the roadway [6, 7] (wood bracket, metal bracket, and stone bracket), strengthening support in roadway [8, 9] (permanent strengthening support and temporary strengthening support such as single hydraulic prop), roadway side support [10, 11] (wood crib, dense pillar, gangue wall, concrete wall, and filling wall), grouting modification [12–14] (ordinary portland cement, Marysan, and new polymer organic and inorganic modified materials), nonsingle support form [15–17] (above two and multiple combined support technologies). The surrounding-rock supporting theory of coal mine roadway mainly includes suspension theory, composite beam theory, composite arch theory, maximum horizontal stress theory, and surrounding rock strength strengthening theory [18]. Bolts and anchor cables are the basic support of coal mine roadway [19, 20]. Among them, bolts mainly include four categories: wood bolt, metal bolt, mortar bolt, and resin bolt, which can be generally divided into mechanical, friction, adhesive, and extendable types [21]. Anchor cables can be divided into expansion shell and steel strand prestressed anchor cable and mortar bonded prestressed anchor cables [22, 23]. Anchor cables also can be divided into single anchor cable, anchor cable bundle, resin anchor cable, cement-grouting anchor cable, resin and cement-grouting combined anchoring anchor cable, end anchoring anchor cable, full-length anchoring anchor cable, prestressed anchor cable, and nonprestressed anchor cable [24, 25]. Sahoo and Palei [26] propose a new type of roadway support technology using risk-based maintenance. Scholars have also developed constant resistance large-deformation anchor cable, negative Poisson's ratio effect anchor cable, high elongation extendable bolt, and anchor cable pressure-relief device [27, 28], clarified the deformation and failure mechanism of underground rock in coal mines [29], and proposed active prefracture method [30]. In terms of grouting technology, the current grouting theory, grouting materials, grouting process, and grouting quality testing technology have been rapidly developed, such as the development of grouting materials from lime, clay, cement to cement—water glass bi-liquid slurry, and the development of various types of chemical slurry suitable for different purposes, resulting in the formation of a wide range of chemical grouting materials for different purposes and with different properties [31]. All of the above work has promoted the development of roadway surrounding-rock support technology and has been successfully applied in many coal mines.

In view of the shortcomings such as the small support scope of single anchor cable and the inability to realize joint anchoring for surrounding rock, this text studies the theoretical mechanics of anchor cable beam-truss structure. The stress and maximum bending moment characteristics of unsupported, single anchor cable, and anchor cable beam-truss support are compared and analyzed, and the resistance of anchor cable beam-truss structure to reducing the maximum bending moment of surrounding rock is clarified. Combined with numerical simulation, the prestressed field and anchoring effect of surrounding rock formed by the structure are studied, and the importance of anchor cable beam-truss structure to ensure the safety and stability of deep large-deformation roadway surrounding rock is revealed.

2. Classification and Principle of Roadway Supports in Coal Mine

Roadway support technologies and means in coal mine are numerous, especially for soft rock and intense-mining large-deformation roadways that exist in various support forms. This section mainly makes a simple classification of basic support forms of coal mine roadway, clarifies the basic composition of anchor cable beam-truss structure, and compares and analyzes the main differences between the structure and ordinary single anchor cable. The working principles of ordinary single anchor cable and anchor cable beam-truss structure are summarized and obtained.

2.1. The Basic Forms of Roadway Support in Coal Mine. According to the position and principle of surrounding rock control of coal mine roadway, the basic support forms of roadway can be divided into five types [32, 33], as shown in Figure 1, namely:

(1) Surface support type of roadway surrounding rock. Binding forces are applied to the roadway surface to control surrounding-rock deformation, including various roadway pillars, hydraulic supports, shotcrete, poured concrete, and masonry arch support

(2) Anchorage type of roadway surrounding rock. The supporting components not only act on the roadway surface but also anchor into the internal surrounding rock, mainly to strengthen the overall surrounding rock, including all kinds of bolt and anchor cable supports

(3) Modification type of roadway surrounding rock. It can improve the strength and integrity of surrounding rock by improving the physical and mechanical properties of roadway surrounding rock, including grouting reinforcement technology of various types of materials

(4) Pressure-relief type of roadway surrounding rock. It can improve the stress state of the roadway surrounding rock, reduce, transfer, or release the high stress of surrounding rock, including pressure-relief mining and various manual pressure-relief technologies

(5) Joint control type. The combined control of roadway surrounding-rock deformation by the above two or more forms

2.2. Support Principle of Ordinary Single Anchor Cable

2.2.1. Vertical Arrangement of Anchor Cables. The vertically arranged anchor cables (Figure 2(a)) can anchor the weak, loose, broken, and easily caving rock strata in shallow roadway to the deep and stable rock strata, so as to enhance the stability of shallow soft surrounding rock. Meanwhile, the high-strength anchorage force can increase the friction force between rock layers, prevent the phenomenon of sliding, horizontal dislocation, or separation, and form a new thick stable rock layer in shallow roadway. These rock layers can form a uniform compression zone (compression arch), significantly improving the stress state, enhancing the strength of surrounding rock, and correspondingly increasing the support capacity. After the comprehensive improvement of anchoring strength of the roadway surrounding rock, the fractured and plastic zone range of surrounding rock and the surface displacement of roadway can be reduced, and the development and expansion of the fractured and plastic zone of surrounding rock can be controlled, which is conducive to maintaining the comprehensive stability of roadway.

2.2.2. Inclined Arrangement of Anchor Cables. When anchor cables in the roof and two ribs of the roadway are inclined, the deep rock mass of two shoulder sockets of the roadway can be used as the anchoring point of anchor cable and the foundation of the supporting structure, thus forming horizontal and vertical compression stress zones in the roof and two ribs of roadway [34], as shown in Figure 2(b). This

Figure 1: Main control types of roadways [32].

arrangement increases the bending capacity of the roadway roof, reduces the tensile stress inside and on the surface of the roof, and makes the action range of anchor cables larger and the effect better.

2.3. Main Composition and Principle of Anchor Cable Beam-Truss Structure. The support system of the anchor cable beam-truss structure is mainly composed of two-way anchor cables, steel ladder beam, and square tray, as shown in Figure 3. The main difference in composition compared to single anchor cables is the addition of a reinforced ladder beam structure, which can form an overall load-bearing structure with inclined anchor cables on both ribs. The supporting principle of anchor cable beam-truss structure is as follows [35]. (1) The combined supporting force exerted by the support system can promote the surrounding rock to be in a state of multidirectional compressive stress, significantly improve the strength and deformation resistance of surrounding rock, and control the stratification and failure of surrounding rock in the central area of roadway roof. (2) The inclined anchor cables arranged on both ribs of the

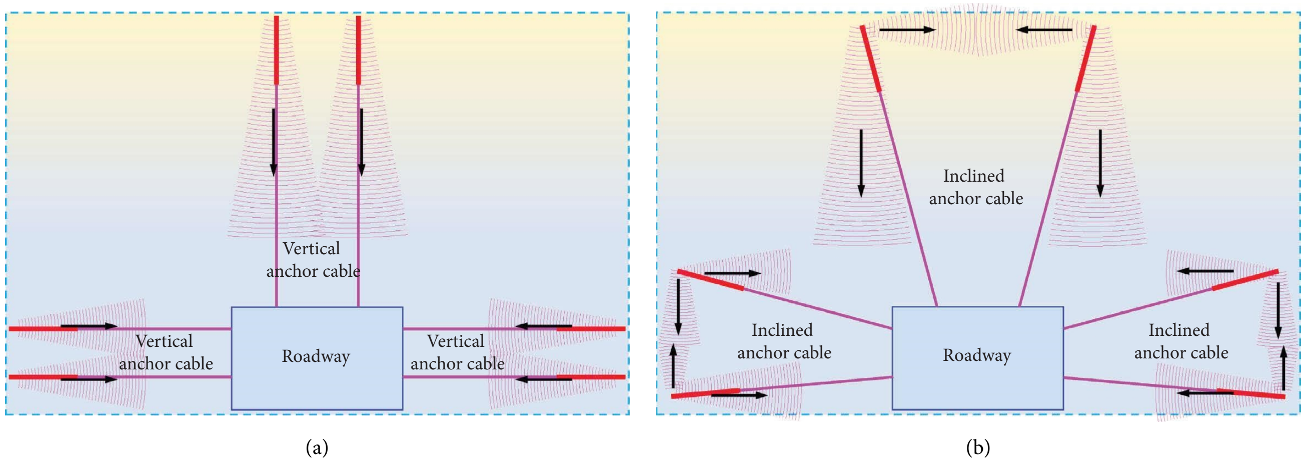


FIGURE 2: Schematic diagram of layout and prestress distribution of single anchor cables: (a) vertical arrangement of anchor cables; (b) inclined arrangement of anchor cables.

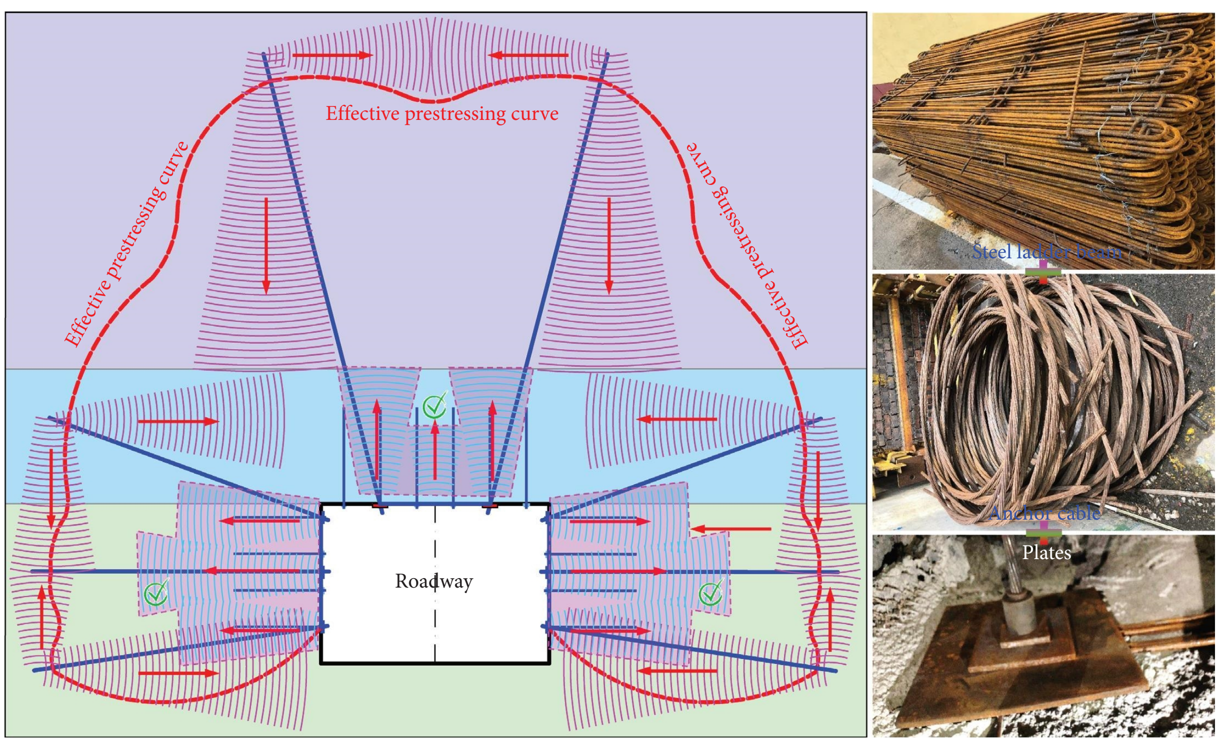


FIGURE 3: Composition and schematic diagram of prestress distribution of anchor cable beam-truss system.

anchor cable beam-truss structure have a large length and strong shear resistance. The long anchor cables on both ribs of the roof can diagonally pass through the maximum shear stress zone at the depth of the roof above the two ribs of the roadway, and it has a large range of action. The inclined long anchor cables can effectively control the shear failure of the roof surrounding rock. (3) The anchoring points of inclined anchor cables on both ribs of the anchor cable beam-truss structure are located on the deep shoulder sockets of the roadway roof and are not easily damaged in the three-dimensional compressive stable rock. Within this range, the rock mass is not easily affected by roof delamination and deformation. The integrated locking structure formed by the anchor cable beam-truss system provides a stable and reliable bearing foundation for exerting the high-strength anchoring force on surrounding rock.

3. Mechanical Analysis of Roadway Stability under Different Supports

The main difference between anchor cable beam-truss support structure and ordinary single anchor cable is that a steel ladder beam is used to connect each two anchor cables. The interconnected anchor cables can significantly improve the stress environment of the surrounding rock and enhance the stability of the roadway surrounding rock. For the roadway with stable roof strata and no obvious bending subsidence, this section establishes the mechanical model of roadway roof rock beam under the support of no support, single anchor cable, and anchor cable beam-truss and illustrates the bending moment changes and stability characteristics of roadway roof rock beam under different supports.

3.1. Mechanical Model of Roadway Roof Beam under Different Supports. According to the force and stress characteristics of anchor cable beam-truss structure on roadway roof, combined with the relatively stable strata of roadway roof, a mechanical model of unequal-strength anchor cable beam-truss structure under the simply supported beam at both ends of the roadway roof is established, as shown in Figure 4. The bending moment changes of roadway roof rock beam under the supporting structure are mainly analyzed. First, the following assumptions need to be made [36, 37]:

(1) Roof: (1) The roadway roof is assumed to be a beam structure model with simple support at both ends. (2) The roof surrounding rock is assumed to be a homogeneous rock mass bearing dead weight. (3) Roof strata are assumed to be continuous material without gaps. (4) The roof has isotropic characteristics along different directions.

(2) Anchor cable beam-truss structure: (1) The supporting rod body of anchor cable is elastic homogeneous material. (2) The influence of anchor cable dead weight on its support force is ignored. (3) The friction caused by the relative movement of the anchor cable rod and surrounding rock is ignored. (4) The force on the reinforced ladder beam connected by two inclined anchor cables is approximately linear. (5) The stresses of anchor cables on both sides of the roadway roof are simplified as binding force F_1 and F_2, respectively. (6) Since the strength of anchor cable support is much greater than that of bolt support, the bolt support force is ignored. (7) The stress of the roof anchor cable under the action of the steel ladder beam is simplified as the uniform load p'. (8) The supporting forces of coal on both ribs of the roadway roof under the action of the anchor cable beam-truss system are calculated as Q_1 and Q_2, respectively. (9) The roof strata of the roadway are approximately considered as horizontal strata, and the stress of the surrounding rock is considered by plane strain problem.

3.2. Analysis of Force and Bending Moment of Roadway Roof Beam under Different Supports. As shown in Figure 4, stress characteristics of rock beam supported by unequal-strength anchor cable beam-truss in roadway roof can be listed as the following equilibrium equation:

$$F_1 + F_2 + p'n + Q_1 + Q_2 - pl = 0, \tag{1}$$

$$F_1 = F_2 = F, \tag{2}$$

$$l = 2m + n. \tag{3}$$

When the bending moment is taken at point O in Figure 4, it exists

$$\frac{pl^2}{2} - F_1 m - F_2 (m+n) - p'n\left(m + \frac{n}{2}\right) - Q_2 l = 0, \tag{4}$$

$$p' = \frac{F_1 + F_2}{20n}, \tag{5}$$

where p is the uniform load of overlying roof strata, then $p = \gamma H$. Q_1 and Q_2 are, respectively, the supporting forces of the coal body on the surrounding rock after anchor cable beam-truss support of the roadway roof. F_1 and F_2 are the actual working resistance of anchor cable support on both sides of the roof and are the measured stress after support stabilization, denoted as F. p' is supporting the strength of the reinforced ladder beam on the roof surrounding rock. l is roadway width. m is the distance between the anchor cable on both sides and roadway wall. n is the effective length of the reinforced ladder beam (anchor cable spacing). H is the thickness of the immediate roof. γ is the bulk density of immediate roof strata. By simultaneous equations (1)–(5), Q_1 and Q_2 can be written as follows:

$$Q_1 = Q_2 = \frac{10pl^2 - 42Fm - 21Fn}{20l}. \tag{6}$$

Shear equations are listed, respectively, according to the stress characteristics of the rock beam in OA, AB, and BC sections in Figure 4. Shear forces of the rock beam in each section can be obtained as follows:

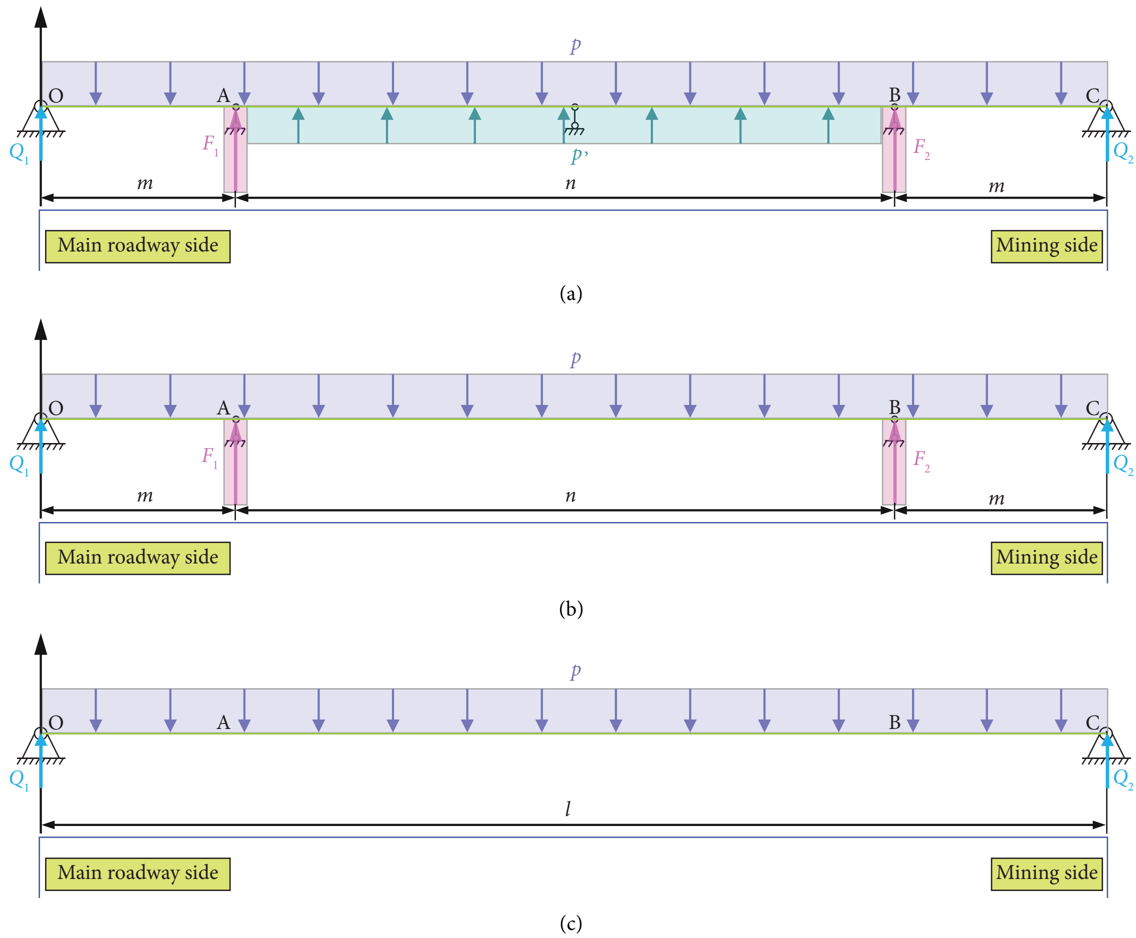


FIGURE 4: Mechanical model of anchor cable beam-truss support with unequal-strength type in roadway roof: (a) no support; (b) single anchor cable support; (c) anchor cable beam-truss support.

$$\begin{cases} F(x)_1 = \dfrac{10pl^2 - 42Fm - 21Fn}{20l} - px, & (0 < x < m), \\ F(x)_2 = \dfrac{10pl^2 - 42Fm - 21Fn}{20l} - px + F + \dfrac{F(x-m)}{2n}, & (m < x < m+n), \\ F(x)_3 = \dfrac{10pl^2 - 42Fm - 21Fn}{20l} - px + \dfrac{5F}{2}, & (m+n < x < 2m+n). \end{cases} \tag{7}$$

The bending moment equation of the rock beam in OA, AB, and BC segments as shown in Figure 4 is listed, respectively, and the bending moment expressions of the rock beam in each roof segment are obtained as follows:

$$\begin{cases} M(x)_1 = \dfrac{10pl^2 - 42Fm - 21Fn}{20l}x - \dfrac{p}{2}x^2, & (0 < x < m), \\ M(x)_2 = \dfrac{10pl^2 - 42Fm - 21Fn}{20l}x - \dfrac{p}{2}x^2 + F(x-m) + \dfrac{F}{4n}(x-m)^2, & (m < x < m+n), \\ M(x)_3 = \dfrac{10pl^2 - 42Fm - 21Fn}{20l}x - \dfrac{p}{2}x^2 + F\left(\dfrac{5x}{2} - \dfrac{5m}{2} - \dfrac{3n}{2}\right), & (m+n < x < 2m+n). \end{cases} \tag{8}$$

According to the expression of shear force and bending moment of roof rock beam supported by unequal-strength anchor cable beam-truss in roadway roof in formulas (7) and (8), it can be seen that shear force and bending moment are closely related to roadway section size and anchor cable beam-truss layout. A typical mining roadway in a coal mine is selected as the study object. According to the geological conditions of roadway surrounding rock and supporting parameters, the parameters of anchor cable beam-truss system are assumed as follows: the specification of inclined long anchor cables on both ribs of roadway roof is $\varphi 21.8 \times 10500$ mm, and the row spacing is 2400×3200 mm. The distance between anchor cables on both ribs and roadway wall is 300 mm, and the actual support force of roof anchor cable after stabilization is 56 kN. The roadway width is 3000 mm, the thickness of immediate roof is 2.32 m, and the bulk density of roof strata is 25 kN/m^3. Then, there are $F = 56$ kN, $m = 300$ mm, $n = 2400$ mm, $l = 3000$ mm, $H = 2.32$ m, $\gamma = 25$ kN/m^3, $p = 58$ kN/m^2, $p' = 2.33$ kN/m^2, and $Q_1 = Q_2 = 28.20$ kN. By substituting the above parameters into equations (7) and (8), the shear force and bending moment of rock beam in different sections of roadway roof can be obtained, as shown in Figure 5(a). The shear force and bending moment of rock beam in roadway roof under conditions without support and single anchor cable support are shown in Figures 5(b) and 5(c).

It can be seen from Figure 5 that the maximum shear forces of roof rock beam under the conditions of no support, single anchor cable support, and anchor cable beam-truss support are, respectively, coal pillar support cross section (87 kN), single anchor cable support cross section (69.9 kN), and anchor cable support cross section of anchor cable beam-truss system (66.8 kN). Among them, the shear force under the concentrated load of anchor cable all shows sudden changes, and the maximum shear force of roadway roof rock beam is minimum when anchor cable beam-truss support is adopted. The maximum bending moment of the roof rock beam is located on the cross section of the roadway center line under different supporting conditions, and the maximum bending moment of the roof rock beam is 65.25 kN·m when the roof is not supported. When a single anchor cable is adopted, the maximum bending moment of roof reaches 48.63 kN·m and the reduction range reaches 25.47%. Therefore, the anchor cable support significantly reduces the bending moment of roof rock beam, which is conducive to the stability of roadway surrounding rock. When anchor cable beam-truss support is adopted, the maximum bending moment of roadway roof rock beam is reduced to 45.93 kN·m, and the reduction rate is as high as 29.61% compared with that without support. Therefore, the maximum normal stress of rock beam and the maximum bending moment of rock beam are effectively reduced when anchor cable beam-truss is adopted, which effectively resists the bending subsidence of roadway roof and significantly improves the bearing capacity and stability of roadway roof surrounding rock. Figure 6 shows the comparison of maximum bending moments of roadway roof rock beam along the direction of roadway center line under different supports.

To sum up, according to the bending moment changes at different positions of roadway roof under the condition of simple support at both ends in Figures 5 and 6, it is concluded that anchor cable beam-truss structure significantly reduces the maximum bending moment of roadway roof. Compared with single anchor cable, the structure has a more significant control effect on surrounding rock. The anchor cable beam-truss structure significantly improves the stress state of surrounding rock and promotes the stability of roadway.

4. Numerical Simulation Analysis of Roadway Stability under Anchor Cable Beam-Truss Support

In order to further analyze the control effect of anchor cable beam-truss support system on roadway stability, the numerical simulation is used to study prestress distribution in surrounding rock under anchor cable beam-truss support and illustrate its important role in ensuring roadway stability.

4.1. Numerical Calculation Model. Based on the engineering geological conditions of test roadway, a three-dimensional numerical model of roadway surrounding rock is established. The geometric size of the model is length × width × height = 80 × 50 × 50 m. The axial direction of roadway is the Y axis of the model, and the axial direction perpendicular to roadway is the X axis and the vertical direction is the Z axis. The top boundary of the model is stress-constrained, with zero velocity in the X direction of the left and right boundaries, zero velocity in the Y direction of the front and rear boundaries, and zero velocity in the X, Y, and Z directions of the bottom boundary of the model. The Mohr–Coulomb model [38] is

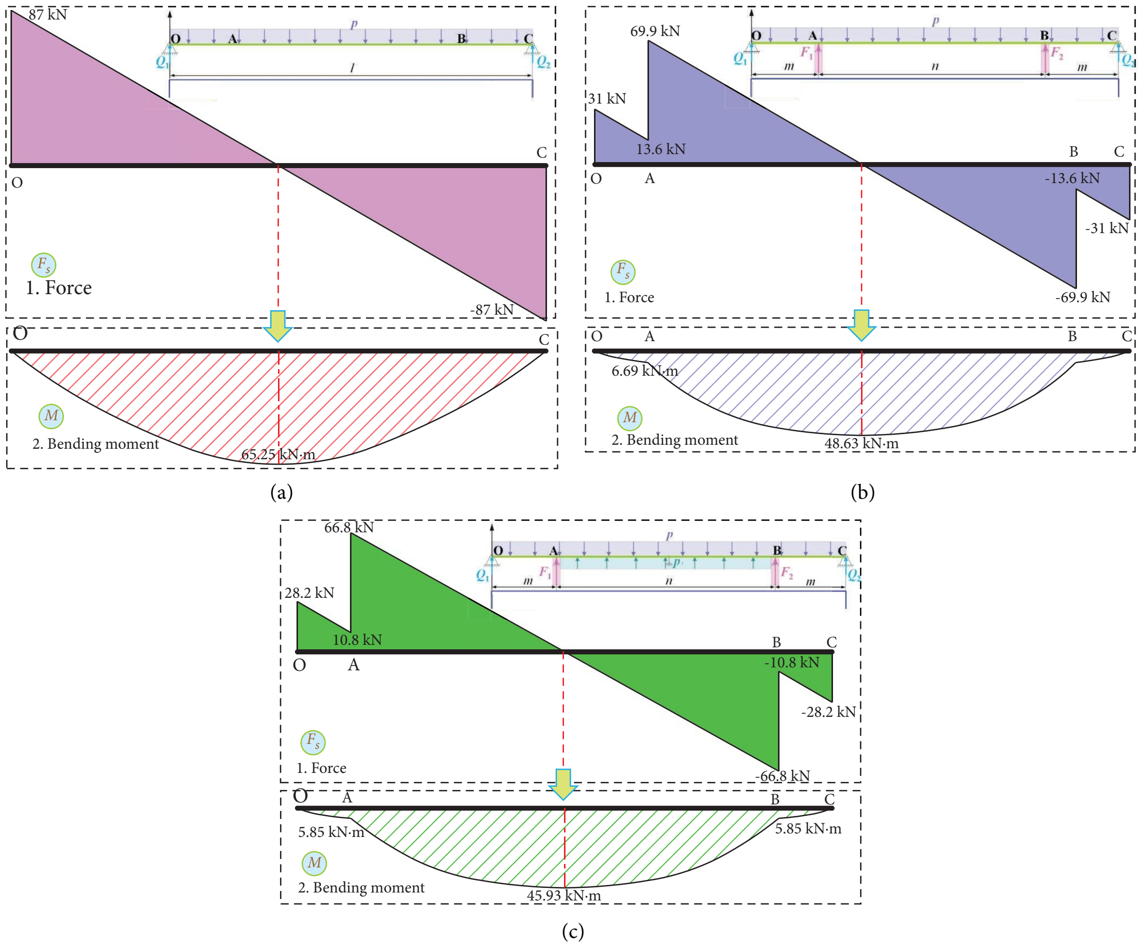


FIGURE 5: Shear force and bending moment comparison under different supports in roadway roof: (a) no support; (b) single anchor cable support; (c) anchor cable beam-truss support.

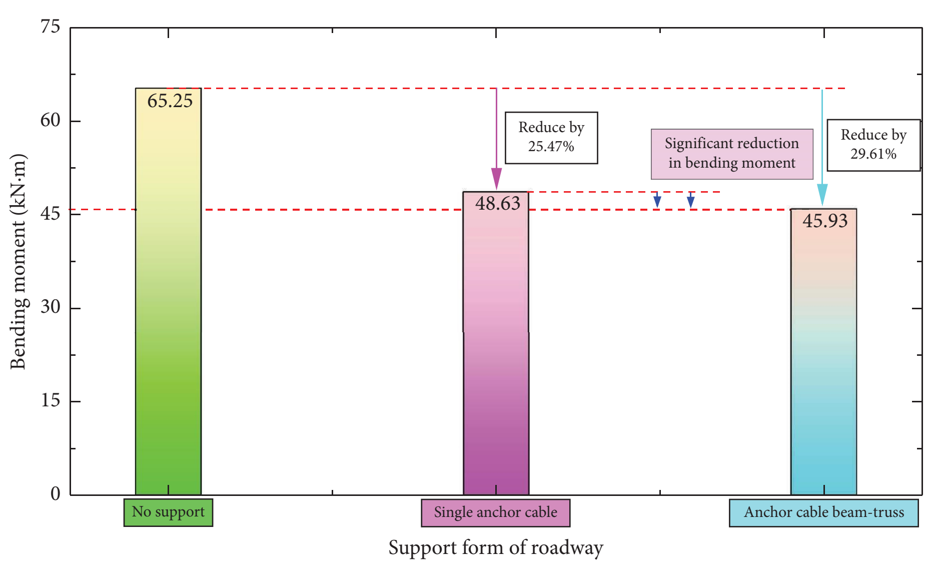


FIGURE 6: Roof bending moment at the center line of the roadway under different roof support forms under the condition of simple support at both ends.

used as the constitutive model for the deformation and failure of roadway surrounding rock. The mechanical parameters of the numerical model are calculated using the Hoek–Brown criterion [39, 40]. The anchor cable is simulated using a cable element. The elastic modulus of anchor cable is 195 GPa, the diameter is 21.8 mm, the length of roof anchor cable is 10.5 m, the length of anchor cable in two ribs is 6.5 m, the tensile load is 600 kN, the pretightening force of anchor cable is 180 kN, and the anchoring length is 1.5 m. The parameters of anchor cable support are shown in Table 1. Two anchor cables are arranged in each row of roadway roof, with a row spacing of 2.4 × 3.2 m. Also, three anchor cables for each row of roadway rib are arranged with a row spacing of 1.2 × 1.6 m.

4.2. The Prestress Distribution Laws of Roadway Surrounding Rock Supported by Anchor Cable Beam-Truss. After adopting the structure of anchor cable beam-truss support, the prestress formed by shallow roadway surrounding rock without considering the crustal stress is shown in Figure 7. Under the support of anchor cable beam-truss, a certain compressive stress is formed and diffused into roadway surrounding rock. The effective compressive stress zones formed by prestressing of adjacent anchor cables overlap with each other, connecting the anchoring action of single anchor cable into a whole, effectively controlling the deformation and damage of surrounding rock between anchor cables, and improving the overall anchoring effect of support system. The wider the effective compressive stress range, the better the support effect.

Due to the use of steel ladder beam connection between each two anchor cables, the effective compressive stress zone formed between anchor cables significantly diffuses along the length direction of steel ladder beam. The effective compressive stress zones of roadway surrounding rock are interconnected, forming a continuously distributed effective compressive stress shell (Figure 8(a)). The prestress diffusion range is large, and it can effectively support surrounding rock between every two anchor cables. The reinforced ladder beam achieves effective diffusion of prestressed anchor cables, significantly improving the support effect on surrounding rock between anchor cables. The overall support effect of roadway surrounding rock under the support of anchor cable beam-truss has been significantly improved.

After applying a certain pretightening force under the support of anchor cable beam-truss, there is a significant concentration of compressive stress near the tail and starting end of anchor cable, and there is a certain compressive stress in the middle of free section of anchor cable (Figure 8(b)). Due to the pretightening force of anchor cable reaching 180 kN, a large compressive stress appears near the tail of anchor cable. Although the compressive stress continues to decrease as it moves away from the tail of anchor cable, an effective compressive stress zone is formed within the length range of free section of anchor cable, which is interconnected and superimposed with each other. The effect of prestressed anchor cables in these areas is relatively obvious. There is an overlap in the effective compressive stress zone between every two anchor cables, which has a significant active support effect on surrounding rock between anchor cables. Therefore, anchor cable beam-truss support can effectively exert the strengthening anchoring effect on roadway surrounding rock.

5. Effect Analysis of Engineering Application

5.1. Geological Overview. The study is conducted based on the engineering background of a mining roadway in a deep coal mine in China. The average thickness of the coal seam is 5.40 m, and the average inclination angle is 5°. The immediate roof of the coal seam is 2.32 m siltstone. The main roof is fine sandstone with a thickness of 11.23 m, and the immediate floor is 1.06 m fine sandstone. The average strike length of the coal face is 1127 m, and the average dip length is 226 m. The average burial depth of the coal seam is 660 m. The mine pressure of the tailgate at the position of 600 m ahead of the open-off cut of the coal face is severe, so a study on control technology of tailgate surrounding rock is conducted using a test section of 600~800 m in front of the open-off cut.

During the mining process of adjacent coal faces, the roadway surrounding rock undergoes significant long-term deformation and damage due to the dynamic pressure disturbance of high mining-height coal face being mined. The roadway in front of the coal face needs to undergo two expansions and repairs to meet the normal mining production. Based on theoretical analysis, the difficulties in controlling the surrounding rock of the mining roadway are as follows: (1) under the influence of intense mining of the coal face, the influence of advanced disturbance is far away and the disturbance extent is severe. The test results in Figure 9(a) indicate that the influence range of advanced mining on the coal face exceeds 130 m. (2) The complex geological conditions such as high stress and loose and fractured coal bodies in deep coal mine have led to severe deformation and failure of roadway, as shown in Figures 9(b) and 9(c).

5.2. Technology and Parameters of Roadway Support. The test tailgate of the coal face is supported by the combination of anchor cable beam, mesh, and truss. Six roof bolts are arranged in each row of roadway roof, and twelve rib bolts are arranged in each row of two ribs. The row spacing of bolts in roof and both ribs is 800 × 800 mm. The roof anchor cable is a double-stranded steel ladder beam anchor cable with a row spacing of 2.0 × 2.4 m, which is arranged in a staggered interlocking manner along the roadway. Two lanes of double-stranded steel reinforcement ladder beams and anchor cables are arranged for each rib, with a row spacing of 1.5 × 2.4 m. Diamond-shaped metal mesh is laid on roadway roof and two ribs, and H-shaped steel strip beams are hung on the roadway. The roadway roof adopts $\varphi 22 \times 2400$ mm fully threaded steel bolt, equipped with S2360 and Z2360 anchoring agents. The anchorage force shall not be less than 15 t, and the torque shall not be less than 300 N·m. Roadway-rib bolt adopts $\varphi 20 \times 2400$ mm

Table 1: Anchor cable support parameters.

Designation	Elastic modulus (GPa)	Tensile load (kN)	Preload (kN)	Diameter (mm)
Anchor cable	195	600	180	21.8

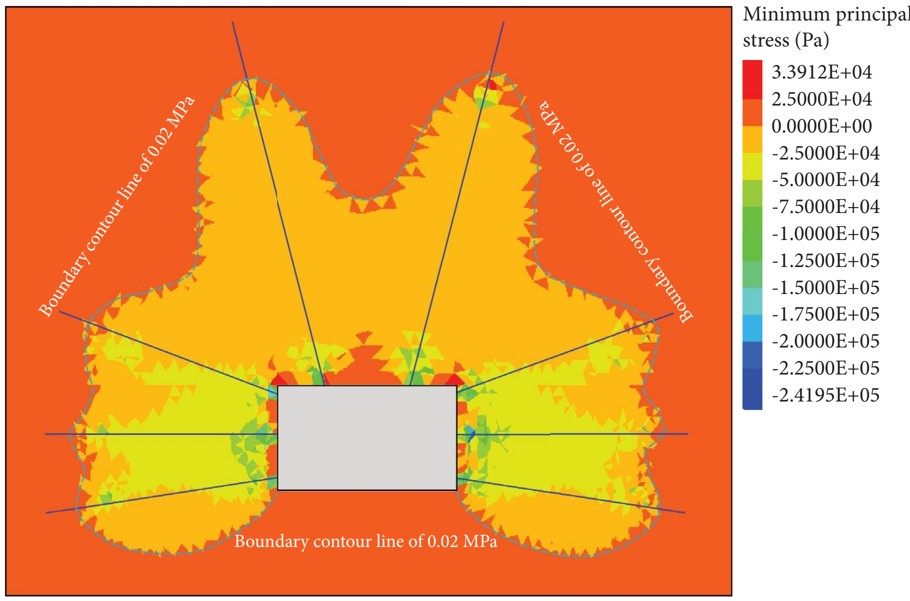
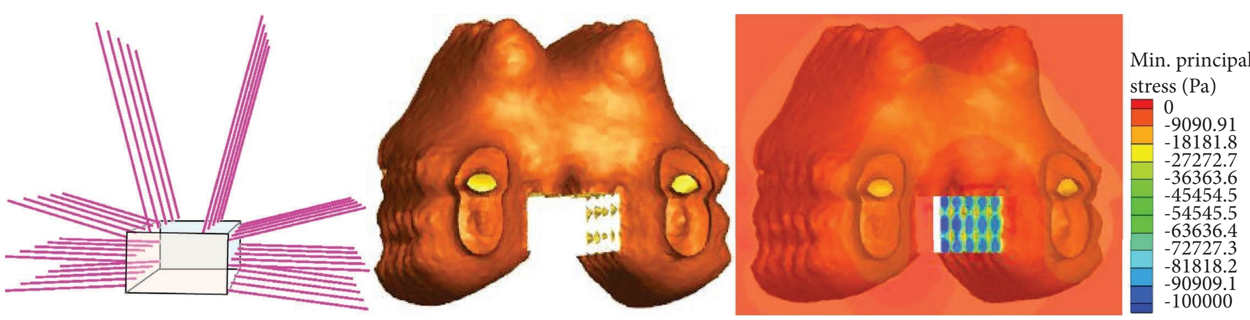
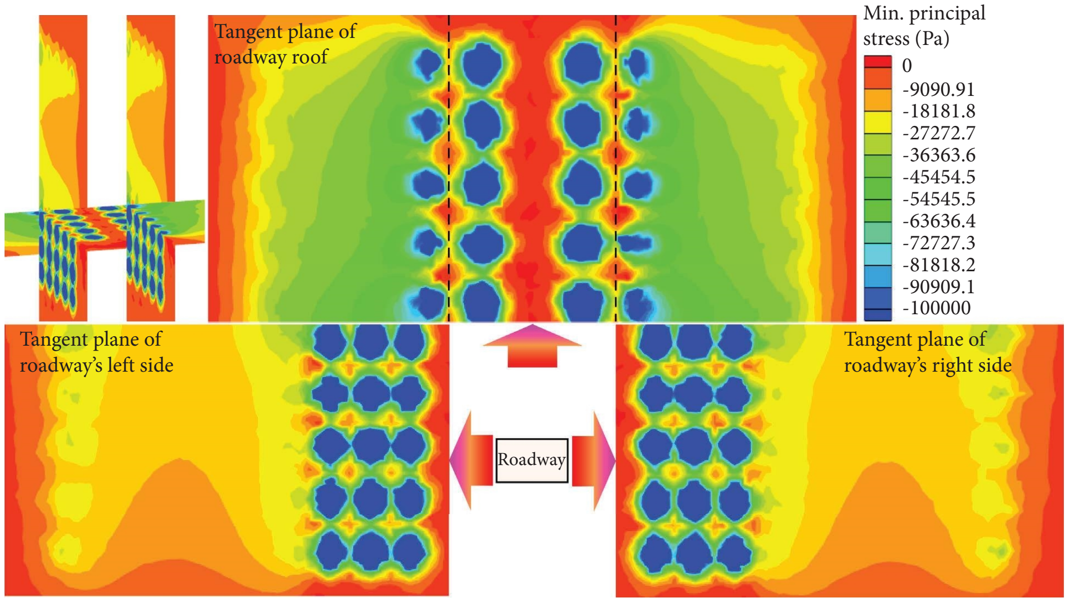


Figure 7: Prestress distribution of roadway surrounding rock under anchor cable beam-truss support.



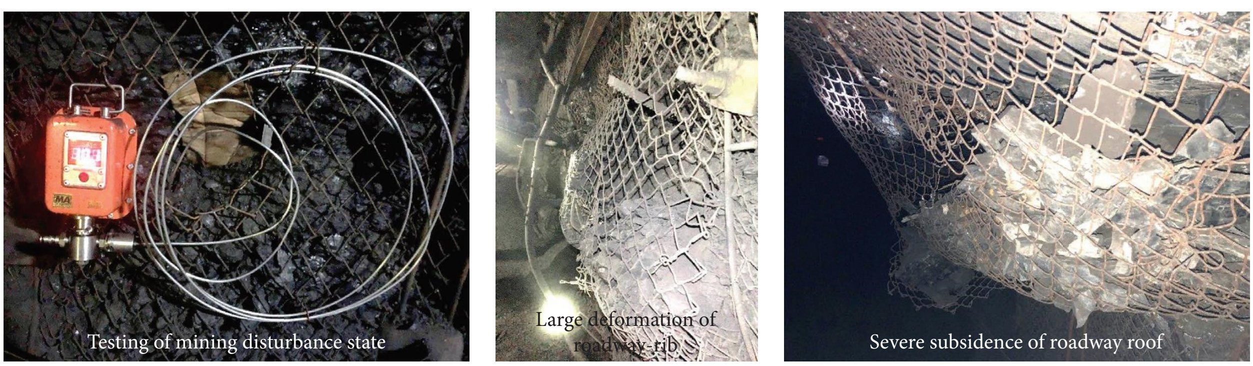
(a)

Figure 8: Continued.



(b)

Figure 8: Multiperspective diagram of prestress distribution in roadway surrounding rock. (a) Three-dimensional view, (b) Section view.



(a) (b) (c)

Figure 9: Characteristics of mine pressure behavior in test roadway: (a) borehole stress testing; (b) roadway-rib deformation; (c) roadway-roof deformation.

HRB335 fully threaded steel bolt, and each hole adopts two Z2360 anchoring agents. The anchorage force is not less than 12 t, and the torque is not less than 250 N·m. The roof anchor cable adopts $\varphi 17.8 \times 8500$ mm steel strand, and the roof anchor cable tilts 15° to the left and right, respectively. Each hole is equipped with one roll of S2360 resin coil and three rolls of Z2360 resin coil for anchoring, and the preloading force is not less than 130 kN. The roadway-rib anchor cable adopts $\varphi 15.24 \times 4500$ mm steel strand. Each hole is equipped with one roll of S2360 resin coil and two rolls of Z2360 resin coil for anchoring, and the preloading force is not less than 100 kN. The steel ladder beam is 12 mm in diameter and 2400 mm in length and is arranged along the roadway. The supporting structure and parameters of the roof and two ribs of roadway are shown in Figure 10.

5.3. Application Effect Analysis

5.3.1. Anchor Cable Stress. After the roof and two ribs of the tailgate are supported by anchor cable beam-truss structure, the anchor cable stress is, respectively, observed in time. The results of the three measuring stations are shown in Figure 11. When not affected by the mining disturbance of the coal face, the anchor cable stress is relatively stable, and the stress is less than 180 kN. When the coal face gradually approaches the measuring station, the anchor cable stress gradually increases, and the closer the distance from the coal face, the greater the growth of anchor cable stress. When the coal face is mined to the measuring station, the maximum stress of the anchor cable can reach 360 kN, and the anchor cable stress is still within the safe and reasonable force range.

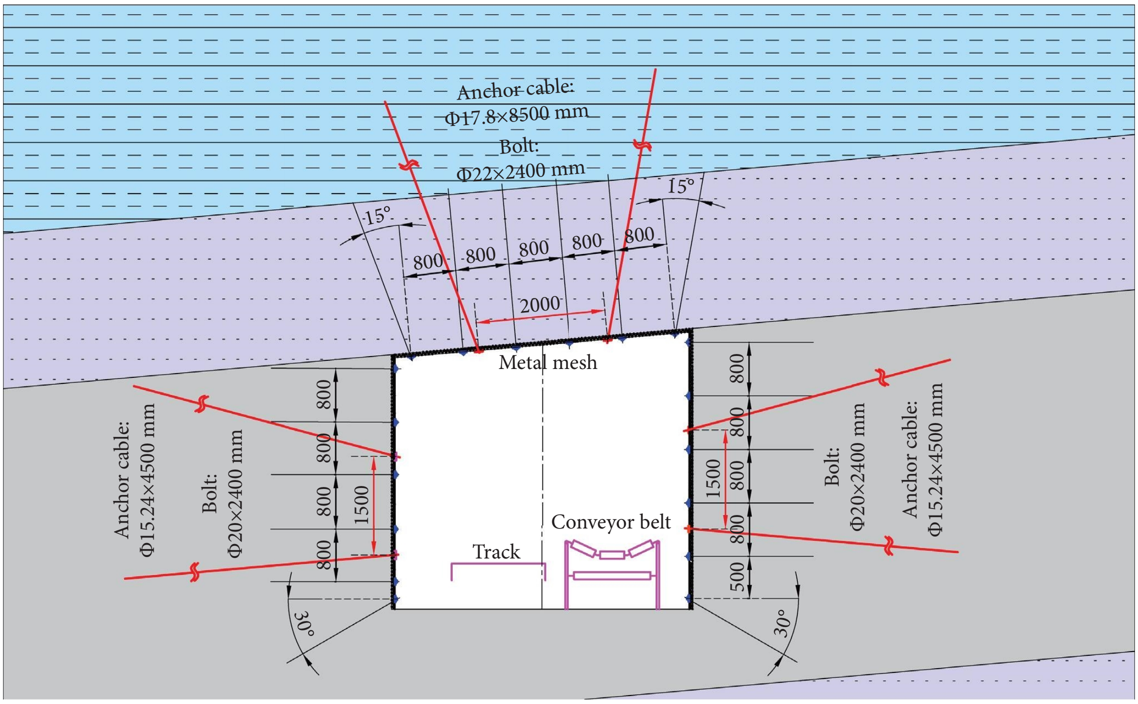


Figure 10: Roadway support parameters (unit: mm).

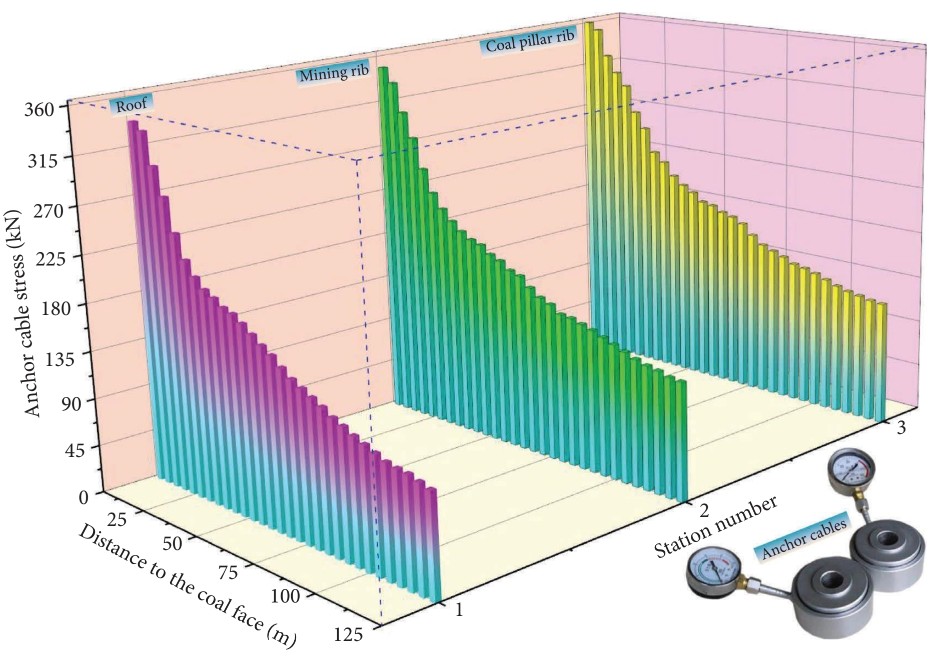


Figure 11: Monitoring results of anchor cable stress in roadway surrounding rock.

5.3.2. Displacement of Surrounding Rock. According to the displacement curves of tailgate surrounding rock during the mining process as shown in Figure 12, the displacement under the mining influence is approximately consistent with anchor cable stress. It presents the typical characteristics of three stages, namely, stable deformation stage beyond 60 m in front of the coal face, slow deformation stage between 32 and 60 m in front of the coal face, and severe deformation stage within 32 m in front of the coal face. In general, the deformation of two ribs of roadway is significantly greater than that of the roof. The maximum deformation of roadway roof at the position of the coal face is about 300 mm, and the maximum deformation of two ribs of the roadway is less than 600 mm. From the overall control effect of the roadway in test coal mine site, the roadway roof and both ribs are smooth and intact after adopting the anchor cable beam-

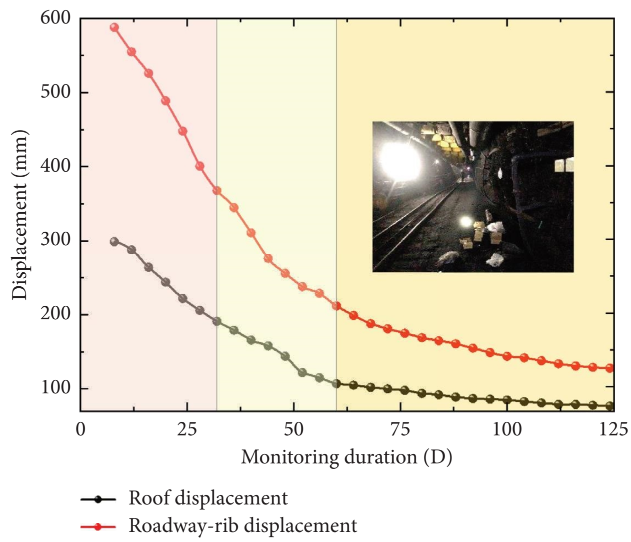


Figure 12: Monitoring results of displacement in roadway surrounding rock.

truss structure support, and there is no obvious large deformation. Therefore, a marvelous surrounding rock control effect has been achieved in tailgate with the support of anchor cable beam-truss structure even under the intense-mining influence of the coal face. It significantly controls the large deformation of roadway surrounding rock and ensures the normal and safe mining of the coal face under the intense-mining influence.

Therefore, the anchor cable beam-truss supporting structure plays an important role in controlling large deformation of surrounding rock in deep high-stress mining roadway, which can ensure the safety, efficiency, and normal mining production of coal mine, and verifies the rationality of theoretical calculation and numerical simulation results in Sections 3 and 4.

6. Conclusions

(1) The basic support forms of roadway are divided into five types, namely, surface support type, anchorage type, modification type, pressure-relief type of roadway surrounding rock, and joint control type. The anchor cable beam-truss structure is mainly composed of anchor cable, steel ladder beam, and square tray. The anchoring point of the structure is located in the stable rock mass under three-directional compression, which can make surrounding rock in the state of multidirectional compressive stress and significantly improve the strength and deformation resistance.

(2) The theoretical calculation results indicate that the maximum bending moment of roof rock beam in the roadway without support reaches 65.25 kN·m The maximum bending moment of the roof reaches 48.63 kN·m by adopting a single anchor cable. The maximum bending moment of the roadway roof is reduced to 45.93 kN·m by using anchor cable beam-truss support system, with a reduction rate of up to 29.61% compared with without support. Therefore, the anchor cable beam-truss structure significantly reduces the maximum bending moment of roadway roof rock beam, plays an important role in controlling the stability of roadway surrounding rock, and improves the stress state of roadway surrounding rock significantly.

(3) The numerical simulation results show that the compressive stress formed after the support of anchor cable beam-truss can be diffused to the anchorage surrounding rock of roadway, and the adjacent anchor cable and steel ladder beam realize the effective prestress diffusion. The effective compressive stress zones formed by combined support overlap each other and combine the action of single anchor cables into a whole, forming a continuous distribution of compressive stress shell, effectively control the deformation and failure of surrounding rock between anchor cables, and improve the overall anchoring effect of support system.

(4) A typical deep-mining roadway with high stress and large deformation is selected as engineering background to carry out the field engineering practice of anchor cable beam-truss supporting structure. The test results show that anchor cable beam-truss structure plays an important role in controlling large deformation of mining roadway and ensures the safety and stability of roadway surrounding rock. It is verified that the control effect of anchor cable beam-truss is more reasonable than that of ordinary single anchor cable, which provides references for surrounding rock control in deep large-deformation roadways.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

EW, SY, and QZ were responsible for conceptualization, methodology, validation, and review and editing. SY and QK were responsible for software, formal analysis, investigation, original draft preparation, and visualization. XZ was responsible for data curation and validation. All authors have read and agreed to the published version of the manuscript.

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