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Research Article

Application and Analysis of Bolt Support in Mine Driving Roadway

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Mineral resources are one of the main energy sources used in industrial production. While the economy is going up, the mining of coal mines and other mineral resources has also intensified. With the deepening of coal mining, the difficulty of mining has also increased. In order to ensure the safe production of relevant enterprises, it is necessary to vigorously apply the supporting technology of mineral resources excavation to reduce the occurrence of accidents in the mining area. Based on this, this paper, on the basis of collecting the geological conditions of a mine, combined with the stability theory of roadway surrounding rock, the existing bolt (anchor cable) support theory, and the factors affecting the reliability of bolt support, analyzed the bolt (anchor cable) support principle and deduced and calculated the support capacity of a single bolt and a group of bolts in the process of mining excavation through the energy conservation theorem. Through Mohr-Coulomb strength theory and limit line analysis theory, a reasonable mechanical model is established, and it is concluded that the ultimate bearing capacity of the bolt will increase with the increase of the length of the anchorage section no matter what support method is used for roadway surrounding rock support, and the anchorage length and ultimate bearing capacity have a nonlinear positive correlation. However, the ultimate supporting capacity of the suspension bolt cannot meet the actual work demand, while the composite beam and composite arch bolt support meet the conclusion. In addition, according to the conclusion and the suggestion that the design of bolt support mode should start with the study of the mechanism of bolt support on the roadway, the application of bolt support mode in the resource mine heading roadway is comprehensively analyzed.

1. Introduction

Mineral resources can provide various guarantees for national basic industries and industries, and mineral resources occupy an important position in all kinds of resources. According to statistics, more than 90% of the coal resources in China need to be excavated. Incomplete statistics show that the length of the roadway excavated due to coal mining is up to 8000 km every year. Therefore, it is an urgent problem to maintain the roadway unblocked and control the surrounding rock deformation in the coal mine construction and safety production [1]. The accumulation of engineering experience and the improvement of theoretical research have promoted the improvement of support concepts and technical development. With the extensive use of bolts, shed support is gradually replaced by bolt support, and the concept of active support is gradually adopted by many researchers.

It has been more than 100 years since the bolt was first used to reinforce the slope in the open-pit shale mine in North Wales, England in 1872, and the bolt support technology was first used in the underground roadway in the schelnez mine in Germany in 1912. It is the most widely used support method in coal mines and other underground projects [2]. Australia mainly promotes the full-length resin anchored bolt and has formed a systematic design approach for the bolt support system. The application of bolt support technology in China began in the late 1950s. Bolt support entered the mining area in the 1960s and was still in the exploration stage in the early 1970s. Although China has developed bolt technology for more than 50 years, it has only developed rapidly in recent decades [3, 4].

As an indispensable supporting material in the process of underground engineering structure construction, bolt support is also the main development direction of mine construction. Bolt support can better control the stability and safety of the surrounding rock. The support theory provides a theoretical basis for the design of bolt support parameters. The suspension, composite beam (arch) theory, and surrounding rock loose zone theory are the three roadway support theories mainly used at home and abroad. For a long time, the three support theories have guided the design of bolt support parameters in a large number of practical engineering construction, but there are also some application defects. In recent years, many researchers at home and abroad have further improved the roadway bolt support theory and put forward some new support theories [5–8]. For example, Terzaghi and Peck [9] first put forward the "collapse arch" support theory. They believe that an arched fracture zone without bearing capacity will be generated after roadway excavation, and the role of the bolt is to provide the support capacity of supporting the dead weight of the fracture zone. However, a large number of experimental studies show that the rock mass in the arched collapse zone still has a certain bearing capacity. Hematian et al. [10, 11] established a 2-dof model to analyze the influence of stress distribution of roadway surrounding rock and deformation and failure behavior of rock mass and obtained the corresponding roadway support design scheme. Song et al. [12] put forward the "energy support" support theory. They believe that a new support body will be formed when the support structure acts in coordination with the anchored surrounding rock, in which the energy is conserved. However, the theory has too many assumptions and is too theoretical to be verified and popularized. Akyol et al. [13, 14] analyzed how the structural conditions affect the support effect of soft rock roadway, and obtained the corresponding bolt support parameters and layout parameters when the roadway deformation is stable by using the finite element simulation software, so as to make the support effect more effective and improve the roadway support effect. Moosavi [15, 16] studied the interaction mechanism between the surrounding rock and anchor (cable) based on the interaction mechanism of a full-length bonded anchor and the advantages of the DDA algorithm. On the basis of the above research, Malmgren et al. [17] learned from previous experience and believed that the strength and fracture degree of surrounding rock are the main factors affecting the coordinated deformation of shotcrete and supporting rock mass. They analyze the supporting structure formed by the bolt and surrounding rock sprayed with concrete, which lays a foundation for the design of roadway surrounding rock support. Witthaus et al. [18] studied and analyzed the telescopic rod. Its principle is to completely release the plastic deformation energy of the roadway surrounding rock and reduce the bolt support force and the force on the bolt when the surrounding rock is unstable. The theory is put forward after the optimization of roadway support, with remarkable economic effect and high practical value. Li et al. [19–23] analyzed the axial force and shear force of the bolt body from the point of view of mechanical coupling, considering the interaction between the bolt and surrounding rock, and analyzed the mechanical behavior of bolt support, supplementing the theoretical gap in relevant aspects of bolt support theory. On this basis, Osgoui [24] used the bolt density factor to analyze the influence of bolt support on the reinforcement degree of roadway surrounding rock, and derived the analytical solution of stress and displacement of circular roadway surrounding rock under bolt support; Bobet and Einstein [19, 20, 25, 26] established the mechanical coupling model of bolt and roadway surrounding rock, deduced the displacement and stress expressions of roadway surrounding rock under different types of bolt support, and further improved the bolt support theory based on the displacement and stress of roadway surrounding rock.

However, up to now, most scholars' research on the bolt support theory has remained in the archives of the mechanical behavior of bolt support, and there is little research on the mechanical behavior of group bolt support, and the relevant theories, support methods, and applications have not been better developed. Through long-term practice and a large number of experiments, it is shown that with the bolt technology being widely used in underground engineering, the role of the bolt in roadway anchoring is becoming more and more significant. The original deformation state and stress state of surrounding rock can be effectively improved by using group anchor support. For jointed rock mass with poor integrity, group anchors can effectively improve the overall strength of surrounding rock and also increase the stability and integrity of surrounding rock. These existing theories have been confirmed in engineering practice, but there is no complete theoretical basis and explanation. Therefore, based on the above problems, this paper analyzes the mechanical behavior of roadway surrounding rock under the conditions of the single bolt and group bolt, so as to improve the design and construction level of roadway support.

2. Theory and Method of Roadway Bolt Support

2.1. Bolt Supporting Theory of Roadway

2.1.1. Suspension Theory. According to the suspension theory, after the excavation of the roadway, the original in-situ stress in the surrounding rock redistributes, changing from the original three-dimensional stress to two-dimensional corresponding stress, and creating a stress concentration area. In this area, the original joints, fissures, bedding, faults, and other discontinuities in the rock mass may further develop. Affected by this development, some rock loosening, sliding and fracture phenomena will occur. And new discontinuities may be generated, and caving may occur under the action of self-weight. The suspension function of the anchor bolt is to give sufficient restraint to the subregion at this time and anchor these loose and broken rocks in the hard and stable rock stratum inside the surrounding rock (Figure 1).

2.1.2. Composite Beam Theory. According to the composite beam theory, after the roadway is excavated, if the roof has no firm and stable rock stratum in a certain area, the suspension effect of the bolt is very small. Assuming that the roof rock is divided into many layers, there is certain friction

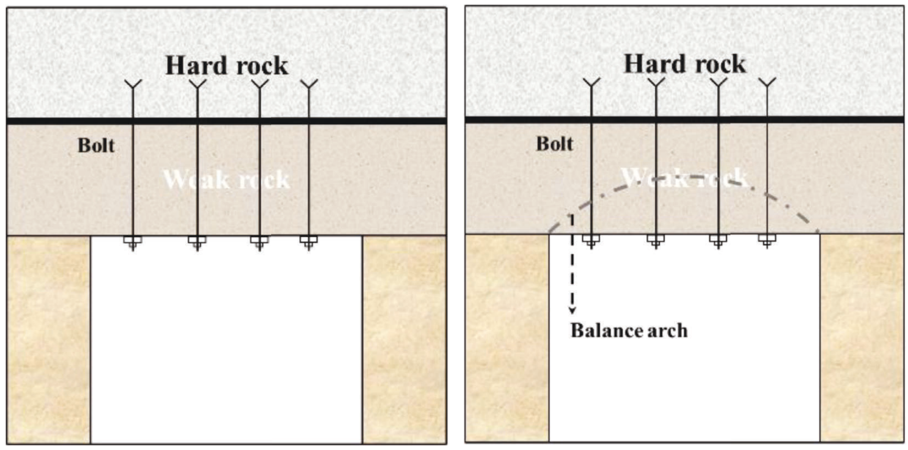


Figure 1: Schematic diagram of suspension theory.

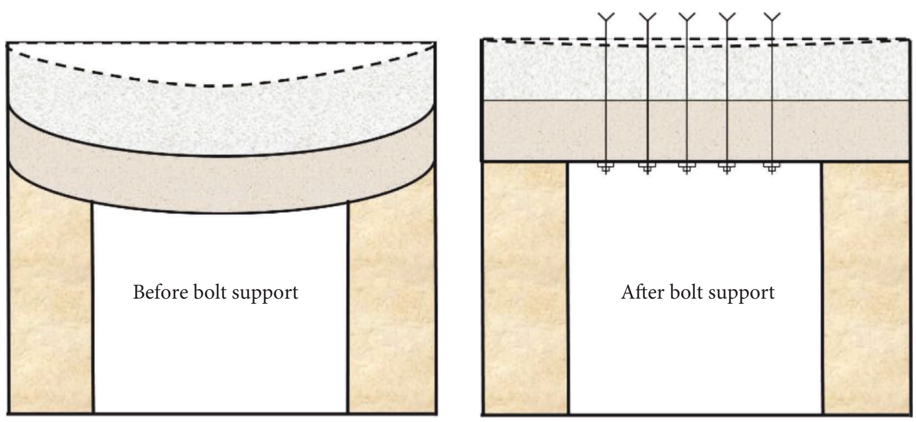


Figure 2: Schematic diagram of composite beam theory.

between layers, and the relative movement between layers is subject to the friction between layers. Bolt in roadway support can reduce the phenomenon of layer separation by increasing the friction between layers. The composite beam theory applies to the roadway whose roof is composed of multi-layer and small-thickness continuous strata. Its principle is to clamp each layer of the roof through the axial force of the bolt to enhance the friction between the layers, and improve the shear strength and bonding degree between the layers of the roof with the help of the bolt's transverse bearing capacity, so that each layer will have overall bending deformation under the action of bending moment, showing the bending deformation characteristics of the composite beam, so as to improve the bending rigidity and strength of the roof. The anchor rod can provide shear force and increase the interlayer friction. It is a combination of several thin layers to form a rock layer composite beam to restrict the rock layer sinking and separation (Figure 2).

2.1.3. Composite Arch Theory. According to the combined arch theory, when the pre-stressed anchor is installed in the fracture zone of the surrounding rock of the arch roadway, conical compressive stress will be formed at both ends of the rod body. If the anchor groups are arranged along the perimeter of the roadway, as long as the anchor spacing is small enough, the compressive stress cones formed by each anchor will be staggered, and a uniform compression zone can be formed in the rock mass, that is, the pressure arch (also known as the combined arch or compression arch). The bearing arch can bear the radial load imposed by the broken rock on its upper part. The rock in the pressure arch is under radial and tangential compression and is in a three-dimensional stress state. A uniformly compressed continuous pressure-bearing zone is formed in the surrounding rock. The strength of the surrounding rock is improved and the support capacity is correspondingly increased. Therefore, the key to bolt support is to obtain a larger bearing arch thickness and higher strength. The greater its thickness, the more conducive to the stability of the surrounding rock and the improvement of support capacity (Figure 3).

2.1.4. Loose Ring Theory. Sahoo and Palei [20, 21] put forward the loose circle support theory (Figure 4). The theory is obtained by carefully studying the deformation state of the roadway surrounding rock. The driving zone of the surrounding rock is the subordinate character of the roadway surrounding the rock. At present, the main method to monitor this range is a multi-point displacement meter or

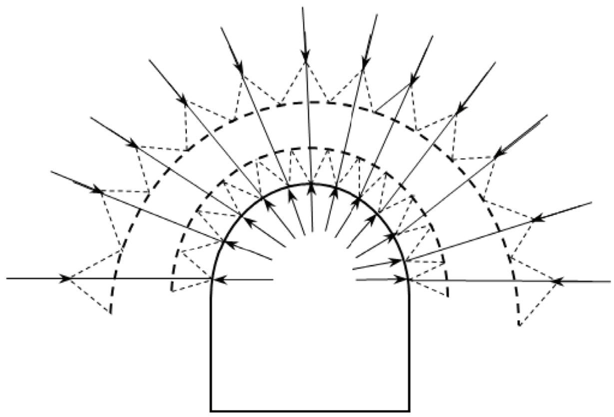


Figure 3: Schematic diagram of composite arch theory.

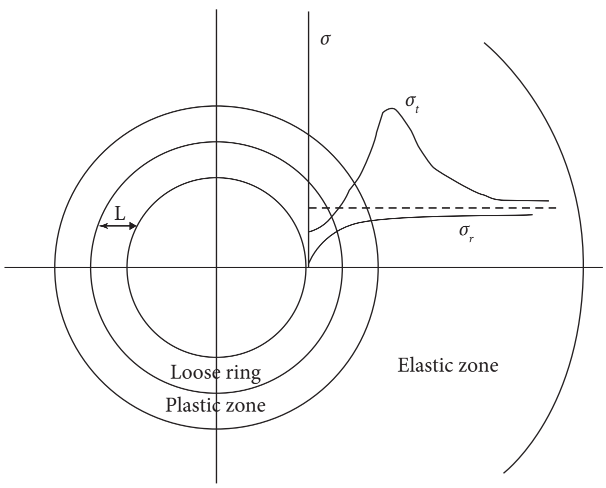


Figure 4: Schematic diagram of loose ring theory.

acoustic monitor. According to the loose circle theory, the main purpose of roadway support is to produce loose and rock fracture and expansion deformation force in the process of excavation. The anchoring force mainly comes from the generation process of the loose ring. The thickness of the loose ring is divided into three categories: small, medium, and large.

2.2. Roadway Bolt Support Mode. With the increasing number of mining projects of mineral resources, the technical processes and construction mean used by them are becoming more and more diversified. On the basis of ensuring and improving the safety of tunneling roadway support, the introduction and application of convenient construction technology should be accelerated, and the cost should be reduced to the greatest extent. Applying different forms of bolt support to the field operation links, on the one hand, can improve the efficiency of support construction in the tunneling operation stage; on the other hand, it also depends on fitting the field construction environment and ensuring the quality of coal mine roadway tunneling operation. At present, there are various bolt support methods used in the process of roadway excavation. From the perspective of support theory, the bolt support methods for the above theory include the following.

2.2.1. Suspended Bolt Support. As one of the earliest support methods used in roadway excavation suspended bolt support has been widely used in most coal mining operations. However, by observing and analyzing its practical application in field support, it can be found that its application time is generally short, and its utilization rate is not high, so it is difficult to achieve a more ideal support effect. In addition, to organize and carry out the construction of a coal mine driving roadway, it usually needs to face more complex surrounding rock lithology, which also brings more difficulties and obstacles to the on-site bolt support. If the stability of the surrounding rock is low during the construction of a coal mine driving roadway, the application of suspended bolt support is likely to cause a collapse of surrounding rock and serious damage to the whole surrounding rock structure, which not only increases many risks for on-site operation but also fails to ensure the personal safety of on-site construction personnel.

2.2.2. Composite Beam Bolt Support. It can be found from the actual situation of most coal mine tunneling roadway construction that, during roadway construction, not only the rock strata in the whole link are complex and changeable, but also their lithological characteristics are quite different, and most of them are multi-layered rock strata. In the face of this construction condition, the composite beam bolt support method can be selected, which mainly depends on the different functions reflected by the different lithology of the rock stratum, and further strengthens the anchoring of multi-layer surrounding rock to improve the bearing capacity of surrounding rock.

2.2.3. Combined Arch Bolt Support. In the process of organizing and carrying out the construction of a coal mine driving roadway, if most of the rock strata are broken, it is appropriate to adopt the combined arch bolt support. Compared with the support form of a combined beam bolt, it can play a better role in stabilizing the whole rock stratum structure and give full play to its advantages. In recent years, the application of this form of support is also common in coal mine tunneling. In the anchor support construction stage of large section roadways and arch roadways, the application of combined arch bolt support can achieve a more significant stability effect, which provides a reliable guarantee for the safety of roadway tunneling construction and greatly improves the reliability of surrounding rock support.

3. Analysis of the Upper Limit of Bearing Capacity of Bolt Support in Mine Driving Roadway

In the process of tunneling in different mines, the choice of roadway bolt support depends on the ultimate bearing capacity of the roadway surrounding rock and the upper bearing limit of bolt support. How to judge the potential failure form and failure range of surrounding rock when the surrounding rock reaches the critical state of failure becomes the basis for judging the stability of surrounding rock in the process of tunneling. Nowadays, most of the roadways surrounding rock stability problems are simulated by some finite element software. Although finite element software has been widely used in engineering practice, the displacement vector diagram, plastic zone range, and stress nephogram simulated by the software is not accurate enough. Therefore, this paper deduces the external force power and internal energy dissipation power of the allowable velocity field when the surrounding rock is damaged by using the limit upper bound analysis method, so as to achieve the accurate support of the roadway in the process of mine excavation.

3.1. Determination of Ultimate Bearing Capacity of Single Anchor. Based on the plastic limit equilibrium theory and assuming that the damaged rock mass is cone-shaped, the calculation formula of the ultimate bearing capacity of a single anchor can be derived. According to this calculation method, the calculation formula of the ultimate bearing capacity of group bolts is further derived. The calculation method has a clear idea, and the assumption is more in line with the actual project, which is conducive to the application of geotechnical engineering design. The following assumptions are made for this method:

(1) The rock mass is an ideal rigid medium and meets the conditions of the Mohr-Coulomb failure criterion.

(2) The broken rock mass takes the anchor rod as the axis and the rock mass shear plane as the bus, and the included angle between the two is a $45^{\circ} - \varphi/2$ angle cone.

(3) Within the shear failure range, the failure block is a three-dimensional axisymmetric block.

3.1.1. Calculation of Ultimate Bearing Capacity of Single Roof Bolt. According to the plastic limit theory of rock, when a small slip occurs in the rock mass, assume that the strain rate of the sliding rock block is V, the strength of the sliding surface follows the Mohr-Coulomb strength theory, the gravity of the rock mass is γ, the bonding force is C, the internal friction angle is φ, the included angle between the bolt and the vertical plane is α, and F is the bearing capacity of a single bolt, then the work done by the external force (bolt tension and gravity) is

$$W_{\text{External Force}} = (F + W\cos\alpha)V\cos\left(45^{\circ} - \frac{3}{2\varphi}\right), \tag{1}$$

where $W = 1/3\pi\gamma L_p^3\tan(45^{\circ} - \varphi/2)$, L_p is the length of the free section of the anchor rod, m, and L_m is the length of the anchor bolt anchoring section, m.

$$W_{\text{Internal Force}} = c\pi L_m^2\frac{\tan(45^{\circ} - \varphi/2)}{\cos(45^{\circ} - \varphi/2)}V\cos\phi. \tag{2}$$

According to the comprehensive formulas (1) and (2), the ultimate bearing capacity of a single bolt is

$$\begin{aligned} F &= c\pi L_m^2\frac{\cos\alpha\tan(45^{\circ} - \varphi/2)}{\cos(45^{\circ} - \varphi/2)\cos(45^{\circ} - 3\varphi/2)} \\ &\quad - \frac{1}{3\pi\gamma}L_p^3\tan^2\left(45^{\circ} - \frac{\varphi}{2}\right)\cos\alpha. \end{aligned} \tag{3}$$

3.1.2. Calculation of Ultimate Bearing Capacity of Single Anchor at the Side. It can be seen from the stress on the top bolt that the external force of the side bolt is only the bolt tension:

$$W_{\text{External Force}} = F\cdot V\cos\left(45^{\circ} - \frac{3}{2\varphi}\right). \tag{4}$$

Internal power dissipation work is

$$W_{\text{Internal Force}} = c\pi L_m^2\frac{\tan(45^{\circ} - \varphi/2)}{\cos(45^{\circ} - \varphi/2)}V\cos\varphi. \tag{5}$$

From: $W_{\text{External Force}} = W_{\text{Internal Force}}$:

$$F\cdot V\cos\left(45^{\circ} - \frac{3\varphi}{2}\right) = c\pi L_m^2\frac{\tan(45^{\circ} - \varphi/2)}{\cos(45^{\circ} - \varphi/2)}V\cos\varphi. \tag{6}$$

Then: the bearing capacity of the single anchor of the upper is

$$F = c\pi L_m^2\frac{\tan(45^{\circ} - \varphi/2)}{\cos(45^{\circ} - \varphi/2)\cos(45^{\circ} - 3\varphi/2)}\cos\varphi. \tag{7}$$

3.2. Determination of Ultimate Bearing Capacity of Group Anchors. According to the failure form of a single bolt, the maximum influence range of a single bolt is the diameter $R = 2L\tan(45^{\circ} - \varphi/2)$ of the cone. When the axial spacing of anchor rods in a group of anchor rods is greater than the maximum influence range of a single anchor, the stress zones of the anchor rods do not affect each other, and the ultimate total bearing capacity of the group anchor is not affected, which is equal to the sum of the ultimate bearing capacity of each single anchor rod, that is, F Group anchor $= nF$ (n is the number of group anchor rods).

3.2.1. Calculation of Ultimate Bearing Capacity of Roof Group Anchors. The formula for calculating the ultimate bearing capacity of group anchors can be derived by using the single anchor ultimate bearing capacity calculation theory. Set the size of the group anchor along the vertical and roadway direction as SX, and the size parallels to the roadway direction as SY. Then the external work done by the pulling force and the gravity of the damaged block is

$$W'_{\text{External Force}} = \left(F_{\text{Group anchor}} + W' \cos\alpha\right)V \cos\left(45^\circ - \frac{3}{2\varphi}\right),$$

$$W' = \frac{1}{3\gamma}L_p S_X S_Y + \left(S_X + 2L_p \tan\left(45^\circ - \frac{\varphi}{2}\right)\right)\left(S_Y + 2L_p \tan\left(45^\circ - \frac{\varphi}{2}\right)\right) + \sqrt{S_X S_Y \cdot \left(S_X + 2L_p \tan\left(45^\circ - \frac{\varphi}{2}\right)\right)\left(S_Y + 2L_p \tan\left(45^\circ - \frac{\varphi}{2}\right)\right)}. \tag{8}$$

Due to the large spacing of anchor bolts, the internal loss work of the anchor section during a shear failure is

$$W'_{\text{InternalForce}} = c \cos\alpha\left(\frac{2L_m\left(S_X + S_Y + 2L_m \tan\left(45^\circ - \varphi/2\right)\right)}{\cos\left(45^\circ - \varphi/2\right)} + S_X + S_Y\right). \tag{9}$$

From: $W'_{\text{External Force}} = W'_{\text{Internal Force}}$

$$\left(F_{\text{Group anchor}} + W' \cos\alpha\right)V \cos\left(45^\circ - \frac{3}{2\varphi}\right) = c \cos\alpha\left(\frac{2L_m\left(S_X + S_Y + 2L_m \tan\left(45^\circ - \varphi/2\right)\right)}{\cos\left(45^\circ - \varphi/2\right)} + S_X + S_Y\right). \tag{10}$$

The group bolts at the top of the roadway are arranged in a square grid. When the distance between the horizontal and vertical anchor bolts is less than $2L \tan(45^\circ - \varphi/2)$, the ultimate bearing capacity of group anchors is

$$F_{\text{Group sanchor}} = \frac{c \cos\alpha\left(2L_m\left(S_X + S_Y + 2L_m \tan\left(45^\circ - \varphi/2\right)\right)/\cos\left(45^\circ - \varphi/2\right) + S_X + S_Y\right)}{\cos\left(45^\circ - 3\varphi/2\right)} - W' \cos\alpha. \tag{11}$$

3.2.2. Calculation of Ultimate Bearing Capacity of Group Anchors at the Upper Part. According to the stress of the top group anchor, the external force of the side group anchor is only the anchor tension:

$$W_{\text{External Force}} = F_{\text{Group anchor}} \cdot V \cos\left(45^\circ - \frac{3}{2\varphi}\right). \tag{12}$$

The internal loss work on the shear plane is

$$W'_{\text{Internal Force}} = c \cos\alpha\left(\frac{2L_m\left(S_X + S_Y + 2L_m \tan\left(45^\circ - \varphi/2\right)\right)}{\cos\left(45^\circ - \varphi/2\right)} + S_X S_Y\right). \tag{13}$$

From: $W_{\text{External Force}} = W_{\text{Internal Force}}$:

$$F_{\text{Group anchor}} V \cos\left(45^\circ - \frac{3}{2\varphi}\right) = c \cdot V \cos\alpha\left(\frac{2L_m\left(S_X + S_Y + 2L_m \tan\left(45^\circ - \varphi/2\right)\right)}{\cos\left(45^\circ - \varphi/2\right)} + S_X S_Y\right). \tag{14}$$

The bolts of the roadway side group are arranged in a square lattice. When the distance between the horizontal and vertical anchor bolts is less than $2L \tan(45^\circ - \varphi/2)$, the bearing capacity of the side group anchor is

$$F_{\text{Group anchor}} = \frac{c \cos\alpha\left(2L_m\left(S_X + S_Y + 2L_m \tan\left(45^\circ - \varphi/2\right)\right)/\cos\left(45^\circ - \varphi/2\right) + S_X S_Y\right)}{\cos\left(45^\circ - 3\varphi/2\right)}. \tag{15}$$

4. Application Analysis of Bolt Support in Mine Driving Roadway

4.1. Project Overview. The mining area is located in Western China. The coal seams in the heading roadway are controlled by a northeastward dipping syncline. The axial direction is SW-NE, the northwest wing inclines to east-ne, with an inclination of 0° 11′–0° 52′, and the southeast wing inclines to the northwest, with an inclination of 0° 77′–1° 26′, with an amplitude of 5.4 m–10.9 m. The elevation difference between the South and North coal seams in this area is expanded from 1.5 m at the west end to 11.7 m at the east end. The coal

FIGURE 5: Schematic diagram of loose ring theory.

seam structure is simple, and there may be a roof sandstone scour body locally, with a simple geological structure. The upper part of the coal seam contains a layer of gangue with a thickness of 0.1–0.7 m, which gradually thickens from west to East. The thickness of the coal seam is 3.6–4.9 m, the average thickness is 4.5 m, and the burial depth is about 87.2–185.0 m, of which the bedrock is 46.4–80.0 m thick and the soil layer is 22.3–80.0 m thick. The coal seam has a simple structure and stable occurrence Figure 5.

4.2. Coal Seam Condition

4.2.1. Coal Quality Index. The coal quality indexes can be obtained through indoor experiments on coal seams, as shown in Table 1.

4.2.2. Properties of Coal Seam Roof and Floor. According to the control of the upper part of the area, the strike of the coal strata is nearly north-south, dipping to the East, with an average dip angle of 40°, and the area is monoclinal. The coal seam structure is very complex. The coal seam contains 2–8 layers of lenticular stones, which occur irregularly and frequently. Its lithology is mainly grayish-black sandy shale or grayish-white medium-grained sandstone, with a small amount of carbon shale, argillaceous shale, and aluminous shale. See Table 2 for roadway roof and floor information.

TABLE 1: Coal quality index.

Serial number	Entry name	Index	Company
1	Ad(Ash content)	6.98	%
2	Mad(Water content)	6.54	%
3	Std(Sulfur content)	0.24	%
4	Qnet, d(Low calorific value on dry basis)	28.00	MJ/kg
5	Qnet, dof(Analytical basis high calorific value)	27.54	MJ/kg

4.3. Field Monitoring and Data Analysis. Before the bolt support design and support mode selection, we need to evaluate the existing support mode, so as to provide a theoretical basis for the subsequent support design calculation and support mode selection. The field-measured surrounding rock deformation and bolt stress are the most

Table 2: Coal quality index.

Name	Rock stratum	Thickness (m)	Features
Old roof	Medium-grained quartzitic sandstone	20.0–40.0	Light gray, poor sorting, and weak water content
Direct roof	Sandy shale	2.0–3.0	Gray, with a large number of layered joints
False bottom	Argillaceous shale	0.5–1.0	Grayish black, mainly siltstone
Old background	Coarse-grained sandstone	10.0–50.0	Gray, with massive bedding, easy to break

direct and reliable evaluation basis. Therefore, it is necessary to monitor the surrounding rock convergence, roof separation, and bolt axial force, analyze the data, analyze and evaluate the support effect, and judge whether the roadway is safe and stable under the corresponding support parameters. In order to analyze and evaluate the support effect of bolts on the roadway surrounding rock, two monitoring faces (section 2 is common to support, and section 1 is enhanced bolt support) are arranged at the front and back of 1000 m of auxiliary transportation roadway of S1 working face. During the excavation process, the surrounding rock separation, convergence, and bolt stress are monitored on site, and then the monitoring data are analyzed to determine the impact of excavation on roadway stability and judge whether the roadway support scheme is reasonable and the effect of the bolt in roadway surrounding rock support.

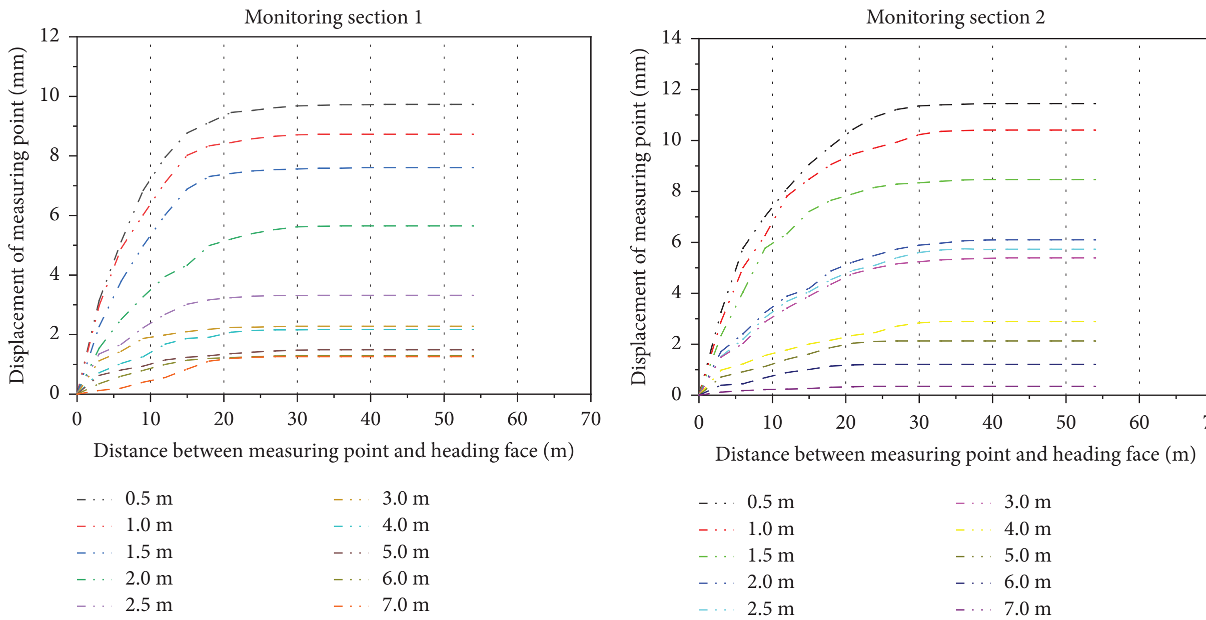
4.3.1. Separation Layer Monitoring. The monitoring points of roadway roof separation are generally arranged at the central axis of the roof. The deepest measuring points of the roof separation layer are arranged at 10 points according to the length of the anchor cable. The buried depths of the roof base points are 0.5 m, 1.0 m, 1.5 m, 2.0 m, 2.5 m, 3.0 m, 4.0 m, 5.0 m, 6.0 m, and 7.0 m respectively. The monitoring points for the separation layer of the upper part are arranged at the middle horizontal position of the two upper sides. The monitoring points for the separation layer of the two upper parts are usually arranged at 5 points depending on the length of the anchor rod. The depth of the top measuring points is 0.5 m, 1.0 m, 1.5 m, 2.0 m, and 2.5 m respectively.

Figures 6(a) and 6(b) are on-site monitoring charts of roof delamination at two different monitoring sections on working face S1. It can be seen from the figures that when the heading face is more than 30.0 m away from the monitoring section, the roof delamination remains unchanged with the advance of the heading face. Rock layer separation occurs at 1.5 m~2.0 m and 2.5 m~3.0 m of section 1, with separation values of 1.96 mm and 1.04 mm respectively, and the maximum separation is 3.32 mm; section 2 has delamination at 1.5 m~2.0 m and 3.0 m~4.0 m, with delamination values of 2.37 mm and 2.5 m respectively. It can be inferred that the thickness of the top anchor structure is about 1.5 m~4.0 m, and the anchor structure in this range has a bearing effect. Therefore, when designing the anchor rod, the length of the anchor rod can be designed as 4.0 m according to the data of this study. In addition, it can be seen from the section separation results that the separation displacement of section 1 supported by reinforced bolts is significantly smaller than that of section 2, which shows that the bolt has a significant control effect on the separation of roadway surrounding rock.

4.3.2. Tunnel Convergence Deformation Monitoring. The convergence deformation of the roadway is monitored by the triangular point distribution method as shown in Figure 7. Two sections are arranged in total, and 9 monitoring points are arranged for each section. Figures 8(a) and 8(b) are on-site monitoring diagrams of roadway convergence deformation in the roof layer of two different monitoring sections on working face S1. It can be seen from the figures that the closer the heading face is to the monitoring section, the greater the deformation rate. As the working face goes on, the roof also begins to sink, and the two sides of the roadway also begin to converge. As the working face goes on, the roadway deformation rate also gradually decreases. When the heading face is about 30.0 m away from the monitored section, the deformation of the roadway remains unchanged and the roadway is stable. The final convergence of the three measuring points on the two sides of Section 1 is 10.34 mm, 4.72 mm, and 4.92 mm, respectively. The final convergence of the three measuring points on the two sides of Section 2 is 14.55 mm, 6.44 mm, and 5.98 mm, respectively. It can be seen from the surrounding rock convergence deformation that the convergence deformation between the two sections is significantly different. The convergence deformation of the surrounding rock of the roadway in ordinary section 2 is significantly larger than that in section 1 and is as large as 4.21 mm, 1.72 mm, and 1.06 mm, respectively. This shows that the anchor rod has a significant control effect on the convergence deformation of the surrounding rock of the roadway.

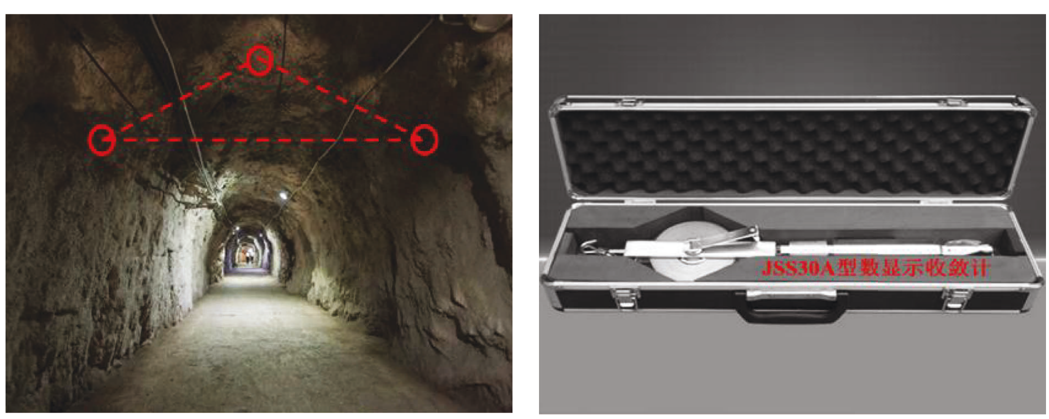
4.3.3. Bolt Axial Force Monitoring. The anchoring force of the bolt needs to be monitored by a bolt dynamometer, and the deformation of the surrounding rock will cause the bolt to play a greater role. The prestress of the anchor rod and the deformation of the surrounding rock make the axial tension and shear of the anchor rod. This force will change the resistance or frequency of the anchor rod dynamometer in a proportional relationship, and then the axial force of the anchor rod can be converted through the formula. There are many monitoring instruments for anchor rod axial force, and the monitoring instruments we use are shown in Figure 9. During on-site monitoring, monitoring tables are set in two sections, respectively at M2 in the middle of the auxiliary wall and M1 in the middle axis of the roof.

As shown in Figure 10, the axial force of the anchor rod at the monitoring section S1 changes more slowly with the



(a) (b)

Figure 6: Field monitoring data of roof separation at different monitoring sections of the S1 working face. (a) Monitoring section 1. (b) Monitoring section 2.



(a) (b)

Figure 7: Field monitoring of S1 roadway convergence deformation. (a) Site monitoring points. (b) Field monitoring instrument.

advance of the heading face, and the stress on the surface of the anchor rod gradually stabilizes. The maximum axial force of the bolt is less than the initial design value, and the bolt body is not yielding, which indicates that the surrounding rock is in a stable state. The bolt dynamometer shows that the axial force of the side bolt is less than that of the roof bolt. The monitoring results of the two sections are very similar, and the shear force is less than the yield value of the bolt. Therefore, the normal operation of the bolt can be guaranteed. However, when the force of the anchor rod is small, it means that its support effect is not fully exerted, the support design is not reasonable and the economy is poor, and there is room for further optimization. The stress of the top anchor and side anchor of section 1 is 37.41 kN and 17.59 kN respectively. The stress of the top anchor and side anchor of section 2 is 42.62 kN and 26.42 kN respectively. It can be found from the axial force of the anchor rod of sections 1 and 2 that the axial force of the anchor rod of section 2 is significantly higher than that of section 1, and is 5.21 kN and 8.83 kN higher, 13.93% and 50.20% higher, respectively. It can be seen that the axial force of the local anchor rod is too large, and more than half of that of the anchor rod 1. The reason is that the bearing capacity of the surrounding rock of the roadway is fully developed under the effect of strengthening the anchor rod support of section 1, which shows that with a certain number of anchors, With the increase in the number of bolts, the better the self-stabilization effect of surrounding rock.

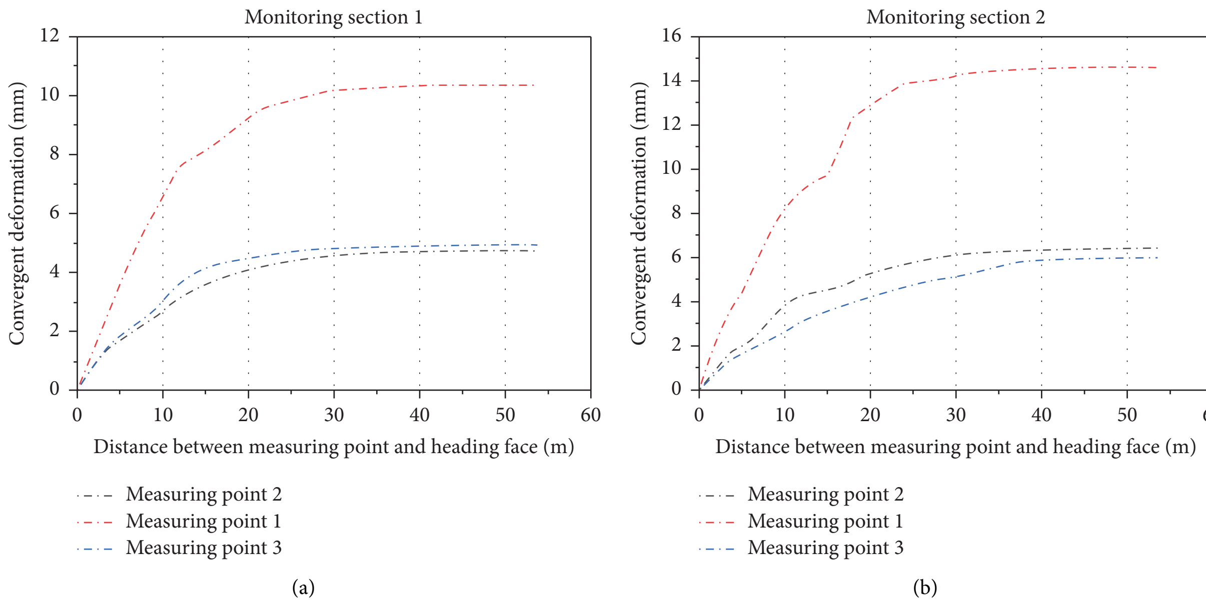


Figure 8: Field monitoring data of roof convergence at different monitoring sections of the S1 working face. (a) Monitoring section 1. (b) Monitoring section 2.

Figure 9: Anchor rod dynamometer.

4.4. Calculation of Ultimate Bearing Capacity of Bolt under Different Support Modes. When the suspended bolt support is used for roadway surrounding rock support, due to the suspension bolt support mode and its characteristics, the support effect can be approximately equivalent to that of single bolt support. Therefore, when calculating the ultimate bearing capacity of the bolt, the bearing capacity of a single bolt can be directly used for calculation. Composite beam bolt support and composite arch bolt support can be similar to group anchor support. However, a composite beam cannot be fully utilized by bolt and surrounding rock when anchoring, so it is only regarded as a side group anchor in the calculation, while a composite arch can be regarded as a top group anchor. After calculation, the relationship between the support result of a single bolt and the length of the bolt under each support condition is shown in Figure 11, and the change in the ultimate bearing capacity of the group of bolts is shown in Figure 12 (where a represents the tensile force borne by the suspension bolt group, B represents the tensile force borne by the composite beam bolt group, and a represents the tensile force borne by the composite arch bolt group). From its change curve, it can be seen that under any support form, with the continuous increase of the length of the anchorage section, the ultimate bearing capacity of a single bolt also increases, and the anchorage length has a nonlinear positive correlation with the ultimate bearing capacity. However, in the suspended bolt support, when the anchorage length of a single bolt is increased from 20 cm to 40 cm, the ultimate bearing capacity F of a single bolt is increased from 27.71 kN to 39.87 kN, which is less than the measured bearing capacity of the actual roadway bolt support. In the composite beam bolt support, when the anchorage length of a single bolt of bolt increases from 20 cm to 40 cm, the ultimate bearing capacity F of a single bolt increases from 32.97 kN to 46.51 kN, which is greater than the measured bearing capacity of the actual roadway bolt support. In the combined arch bolt support, when the anchorage length of a single bolt of bolt is increased from 20 cm to 40 cm, the ultimate bearing capacity F of a single bolt is increased from 30.12 kN to 51.08 kN, which is much greater than the measured bearing capacity of the actual roadway bolt support and has certain safety reserves.

To sum up, in the roadway surrounding the rock support of this project, no matter what support method is used for roadway surrounding rock support, the ultimate bearing capacity of the bolt will increase with the continuous increase of the length of the anchoring section, and the anchoring length has a nonlinear positive correlation with the ultimate bearing capacity. However, the ultimate bearing capacity of suspended bolt support

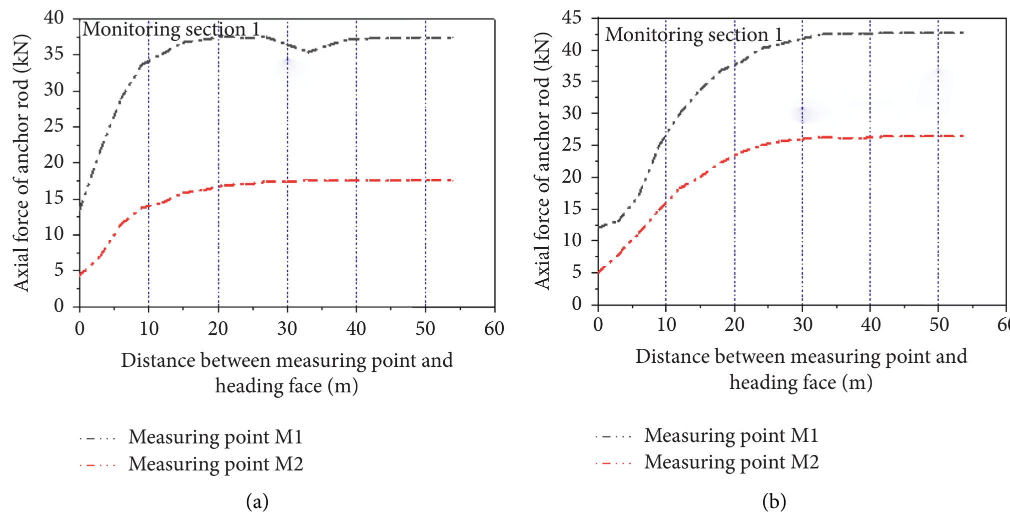


FIGURE 10: Monitoring data of axial force of bolts at different monitoring sections of the S1 working face. (a) Monitoring section 1. (b) Monitoring section 2.

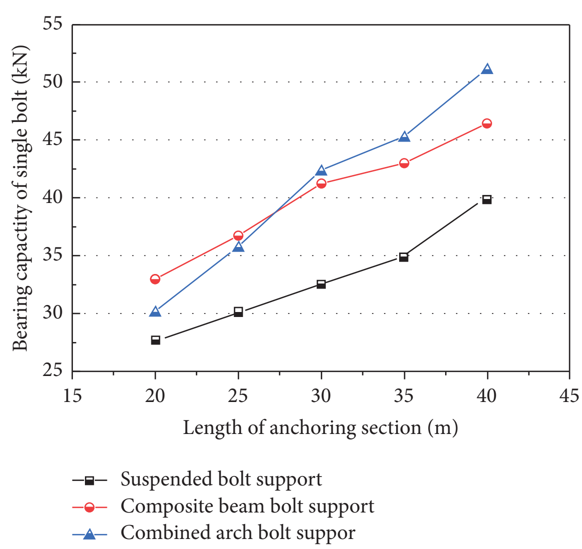


FIGURE 11: Variation curve of ultimate bearing capacity of single anchor rod with the length of anchorage section.

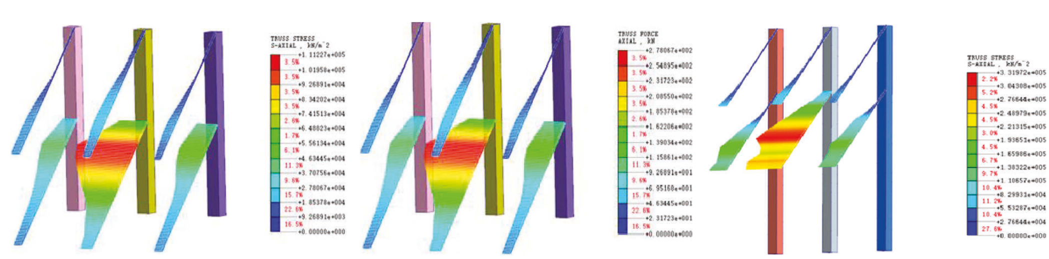


FIGURE 12: Variation curve of ultimate bearing capacity of group anchors with the length of anchorage section.

cannot meet the actual work needs, while the composite beam and composite arch bolt support can meet the requirements. Therefore, in the design, in order to reduce the support cost of the roadway, the design of the bolt support mode should start with the research on the support mechanism of the bolt on the roadway, analyze the joint action of the support body and surrounding rock, determine the geological conditions of the surrounding rock, calculate the stress of the bolt support, and select the support mode and length of the bolt, so as to seek the best support period and method and reduce the support cost of the roadway surrounding rock.

5. Conclusion

Based on a coal mine roadway support project, combined with the roadway surrounding rock stability theory, the existing bolt (an anchor cable) support theory, and the factors affecting the reliability of bolt support, this paper analyzes the bolt (an anchor cable) support principle and deduces and calculates the support bearing capacity of the single bolt and group bolt in the process of mine excavation through the energy conservation theorem. The conclusions are as follows:

(1) Based on Mohr-Coulomb strength theory and limit line analysis theory, a reasonable mechanical model is established to analyze the deformation law and failure mechanism of roadway surrounding rock, and the ultimate bearing capacity of group bolts can be calculated; The influence of surrounding rock mass parameters on the ultimate bearing capacity of roadway roof bolts is analyzed, which provides a basis for the long-term stability evaluation of roadway surrounding rock.

(2) Based on the field monitoring and theoretical analysis, the convergence deformation of roadway surrounding rock, roof separation, and the change of bolt axial force on different sections of the S1 working face are studied. It is concluded that the bolt has a significant reinforcement effect on the roadway surrounding rock. When the anchoring length of a single bolt of bolt increases from 20 cm to 40 cm, the ultimate bearing capacity F of a single bolt increases from 30.12 kN to 51.08 kN, which is far greater than the measured bearing capacity of the actual roadway bolt support, and has certain safety reserves.

(3) According to the field monitoring data, combined with theoretical analysis and formula calculation, the support conditions of different bolt support modes are analyzed, and the support ultimate bearing capacity values of three different bolt support modes of suspension, composite beam, and composite arch are calculated. The results show that the effect of the composite arch in the roadway surrounding rock support is better than the other two

Data Availability

The experimental 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 known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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