Research Article

Simulation Study on Mechanical Characteristics of Rock Bolt in Rock Mass with Bedding Separation Based on the Nonlinear Bond Slip Relationship

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The mechanical equation on the mechanical characteristics of rock bolt in rock mass with bedding separation is established, based on the bond slip relationship of anchoring interface by the load transfer method. The validity of the numerical simulation is verified by the analytical solution of mechanical equation, when the bond slip relationship is linear. Further, the nonlinear bond slip relationship of anchoring interface is input into Flac3D by FISH. The mechanical characteristics of rock bolt are studied with the single and multiple bedding separation by numerical simulation. The results show that the axial force and the interfacial shear stress distribution curves on both sides are symmetrically distributed with the single bedding separation in rock mass, when the bedding separation is located in the center of the anchoring segment. When the bedding separation positions are not located in the center of the anchoring segment, the bedding separation value at different positions versus the axial force curves shows a single peak distribution. The axial force of rock bolt is mainly controlled by the side with the shorter anchoring length. Compared with the single bedding separation in rock mass, the additional stress of rock bolt occurred by the multiple bedding separation will superimpose each other. This paper leads to a better understanding for the load transfer mechanism for grouted rock bolt systems in rock mass with bedding separation and provides a reference for scientific support design and evaluation method.

1. Introduction

In the past few decades, rock bolt and cable bolt support technologies have become the main means to strengthen surrounding rock strength in the fields of construction, water conservancy, underground space, and so on, with the advantages of low cost, high reliability, and high carrying capacity [1–4]. After the roadway is excavated, the surrounding rock deforms towards the roadway, and the uneven deformation of the rock mass activates the rock bolts. At the same time, the rock bolts inhibit the further deformation of the rock mass and reach the final equilibrium state [5–9]. To study the load transfer mechanism between the rock bolts and surrounding rock, it is necessary to study the bond slip relationship of anchoring interface [10–13]. Many scholars have conducted theoretical study and numbers of indoor pullout tests and have proposed many models to describe the bond slip relationship of anchoring interface. Benmokrane et al. [14] proposed a trilinear bond slip model to describe the relationship between the interfacial shear stress and the relative displacement between the rock bolt and rock mass. Ma et al. [15, 16] proposed a nonlinear bond slip model for a fully grouted rock bolt which is verified by experiment. Previous studies on the influencing factors of anchorage in homogeneous rock have obtained many beneficial results, but the stress distribution characteristics of rock bolt in rock mass with bedding separation need further study.

Hyett et al. [10] assumed a linear shear behavior at the anchoring interface and analyzed the effects of bond stiffness, joint position, joint aperture, and multiple joints on
the mechanism characteristics of rock bolts. Cai et al. [17] pointed out that rock bolt would be tension due to the opening of the rock joints and used a linear drop model to analyze the stress distribution characteristics of the bolt under the action of the opening of the jointed rock mass. Li [18] believed that rock bolt would bear additional tensile force when the rock joints were opened and studied the stress distribution characteristics of rock bolt under the static tension through laboratory experiments. Moosavi and Grayeli [19] inputted the cable bolt element into the DDA algorithm based on the spring model. Nie et al. [20] assumed that the interfacial shear stress had a linear relationship with respect to the relative displacement of the bolt and the surrounding rock, and parameter study was carried out to analyze the effectiveness of rock bolt under various end conditions, joint locating, and bonding stiffness by the DDA software. The above research has a certain theoretical reference for understanding the stress distribution characteristics of the rock bolt in rock mass with bedding separation. However, the interfacial shear stress is usually assumed to have a linear relationship with respect to the relative slipping distance, which means that the anchoring interface is always in the elastic stage, and the softening and decoupling characteristics of the anchoring interface are not considered.

Therefore, this paper establishes the mechanical equation of the stress distribution characteristics of rock bolt in rock mass with bedding separation, based on the nonlinear bond slip relationship of the anchoring interface. The nonlinear bond slip relationship is inputted in Flac3D by FISH. The influence of the bedding separation position and bedding separation value on the stress distribution characteristics of rock bolt with single and multiple bedding separation is analyzed.

2. Analysis Model of Rock Bolt in Rock Mass with Bedding Separation

As we all know, sedimentary rock strata are often encountered in tunnel, slope, underground space, and other projects. After the roadway excavation, the roof rock strata are bent and subsidence. Due to the different bending stiffness of each rock stratum, the bending disturbance is not coordinated, and the separation phenomenon is easy to occur on the bedding interface as show in Figure 1(a). The position of the bedding separation can be within the anchoring segment or without the anchoring segment. This paper focuses on the stress distribution characteristics of rock bolts in rock mass with bedding separation, only considering the separation within the anchoring segment.

The anchoring interface failure mostly occurs at the bolt-grout interface in many pullout tests [21–25]. The stress distribution in an elementary length $dx$ is taken for analysis, as shown in Figure 1(b). The coordinate system is established at the anchor end, and $x$-axis is along the rock bolt. There is a bedding separation at the position of $x = x_s$, and the bedding separation value is $\delta$. The deformation of the rock mass is negligible with respect to the bedding separation value. The bedding separation value is the sum of the interfacial shear displacement on both sides. Assuming that the axial force of rock bolt before bedding separation is zero, the axial force of rock bolt on both sides at the bedding separation position is equal and the direction is opposite. According to the mechanical equilibrium relationship, it can be obtained:

$$ (\sigma(x) + d\sigma(x) - \sigma(x)) \cdot A = \tau(x) \cdot U \cdot dx, $$

(1)

$$ \frac{du(x)}{dx} = \frac{\sigma(x)}{E}, $$

(2)

where $\sigma(x)$ is the axial tensile stress of rock bolt, $\tau(x)$ is the interfacial shear stress, $E$ is the elastic modulus of rock bolt, $A$ is the cross-section area of the bolt, and $U$ is the circumference of the bolt cross section.

Substituting Equation (2) into Equation (1) gives

$$ \frac{d^2 u(x)}{dx^2} = \frac{U \cdot \tau(x)}{E \cdot A}. $$

(3)

According to load transfer method, the relative slip of anchoring interface $s(x)$ at any position is equal to the axial displacement $u(x)$ of the rock bolt. That is,
Assuming that the interfacial shear stress is a function of the relative slip, the following formula is satisfied:

\[ \tau(x) = f(s(x)). \]  

(5)

By adding Equation (4) and Equation (5) into Equation (3) gives

\[ \frac{d^2 u(x)}{dx^2} = \frac{U}{EA} f(u(x)). \]  

(6)

### 3. The Rock Bolt Element in Flac3D

Flac3D is commonly used in mining and civil engineering for simulating soil, rock, and structural behavior. Pile structural element interacts with the surrounding rock mass via shear and normal coupling spring-slider system as seen in Figure 2 [26]. Springs represent the bond stiffness and slider represents the maximum bond force. This paper is aimed at studying the shear behavior of the bond interface and does not take into account the normal behavior. The mechanical properties of the pile structural element shear coupling spring are shown in Figure 3 [26].

\[ \frac{F_s}{L} = k_s \times |u_s|, \]  

(7)

where \( F_s \) is shear stress in shear coupling spring, \( k_s \) is the coupling spring shear stiffness (in the Flac3D: \( cs_{sk} \)), and \( u_s \) is the relative displacement between structural elements and surrounding rock mass.

\[ \frac{F_s^{max}}{L} = c_s + \sigma_m \times \tan(\phi_s) \times \text{perimeter}, \]  

(8)

where \( c_s \) is cohesive strength of the shear coupling spring (in the Flac3D: \( cs_{scoh} \)), \( \sigma_m \) is mean effective confining stress normal to the pile element, \( \phi_s \) is friction angle (in the Flac3D: \( cs_{sfric} \)), and perimeter is exposed perimeter of the pile element.

If the friction angle of the shear coupling spring is not considered, that is, \( cs_{sfric} = 0 \), the maximum shear stress per unit length of the structural unit is only related to \( cs_{scoh} \). Among them, \( cs_{scoh} \) represents the bond strength of the shear spring per unit length, which can be expressed by the following formula:

\[ cs_{scoh} = \pi \cdot d \cdot r, \]  

(9)

where \( d \) is the rock bolt diameter (m) and \( r \) is the shear stress along with the rock bolt (Pa).
If $c_{s \text{ _coh}}$ is set a large value, the bond slip relationship of anchoring interface is linear elastic. If $c_{s \text{ _cst}}$ is used to represent the relationship between shear coupling spring bond strength and relative displacement, the mathematical relationship of the bond slip relationship can be transferred into the relationship between the shear displacement and $c_{s \text{ _coh}}$ by Equation (9). Then, the bond slip relationship is putting into the numerical simulation model by user-defined $c_{s \text{ _cst}}$ for expressing the nonlinear characteristics of the anchoring interface [27].

4. Numerical Simulation Method Verification

4.1. Theoretical Calculation. It is assumed that the shear stress and relative displacement of the anchoring interface have a linear relationship. The theoretical calculation results are compared with the numerical calculation to verify the feasibility of the numerical method. The shear stress of anchoring interface can be expressed by the following formula:

$$\tau(x) = f(u(x)) = ku(x), \quad (10)$$

where $k$ is the stiffness coefficient of anchoring interface. Substituting Equation (10) into Equation (6) gives

$$\frac{d^2 u(x)}{dx^2} = \frac{4k u(x)}{Ed}. \quad (11)$$

Let $\beta = \sqrt{4k/Ed}$, and solve the differential equation:

$$u(x) = C_1 e^{\beta x} + C_2 e^{-\beta x}. \quad (12)$$

Substituting Equation (12) into Equation (2) gives

$$P(x) = \frac{\pi d^2 E}{4} \cdot \left( C_1 e^{\beta x} - C_2 e^{-\beta x} \right). \quad (13)$$

Assuming that the axial force of rock bolt before bedding separation is zero, and the additional load caused by bedding separation is $P$, then Equation (13) needs to meet the following boundary conditions: when $0 \leq x \leq x_0$, the boundary condition is satisfied $P(x)|_{x=0} = 0$ and $P(x)|_{x=x_0} = P$; when $x_0 \leq x \leq L$, the boundary condition is met $P(x)|_{x=L} = 0$ and $P(x)|_{x=x_0} = P$. The coefficients $C_1$ and $C_2$ are obtained, respectively, to obtain the axial force and the shear stress on both sides of the bedding separation.

$$u_1(x) = \frac{4P}{\pi Ed^2 \beta \sinh (\beta x_0)} \cosh (\beta x), \quad u_2(x) = \frac{4P}{\pi Ed^2 \beta \sinh (\beta x_0)} \cosh (\beta (L-x)), \quad (14)$$

$$P_1(x) = \frac{P \sin h(\beta x)}{\sin h(\beta x_0)}, \quad P_2(x) = \frac{P \sin h(\beta (L-x))}{\sin h(\beta (L-x_0))}, \quad (15)$$

$$\tau_1(x) = \frac{\beta P \cos h(\beta x)}{\pi d \sin h(\beta x_0)}, \quad \tau_2(x) = \frac{\beta P \cos h(\beta (L-x))}{\pi d \sin h(\beta (L-x_0))}. \quad (16)$$

The separation value $\delta$ is equal to the sum of the interfacial shear displacement on both sides, which can be expressed as follows:

$$\delta = u_1(x_0) + u_2(x_0) = \frac{4P}{\pi Ed^2 \beta} \left( \cosh (\beta x_0) + \cosh (\beta (L-x_0)) \right). \quad (17)$$

Let $H = \cosh (\beta x_0) + \cosh (\beta (L-x_0))$, and rewriting Equation (20), we have

$$P = \frac{\pi Ed^2 \beta \delta}{4H}. \quad (18)$$

Substituting Equation (18) into Equations (14)–(16), the equations for the axial force distribution and interfacial shear stress distribution on both sides can be obtained.

$$P_1(x) = \frac{\pi Ed^2 \beta \delta}{4H} \frac{\sin h(\beta x)}{\sinh (\beta x_0)} \quad P_2(x) = \frac{\pi Ed^2 \beta \delta}{4H} \frac{\sin h(\beta (L-x))}{\sinh (\beta (L-x_0))}. \quad (19)$$

$$\tau_1(x) = \frac{\beta \delta P}{4H} \frac{\cosh (\beta x)}{\sinh (\beta x_0)} \quad \tau_2(x) = \frac{\beta \delta P}{4H} \frac{\cosh (\beta (L-x))}{\sinh (\beta (L-x_0))}. \quad (20)$$

It can be seen from Equations (19) and (20) that when the interfacial shear stress is linearly related to the interfacial shear displacement, the axial force and the interfacial shear stress are linearly related to the bedding separation value $\delta$. The greater the bedding separation value is, the greater the axial load of rock bolt is.

4.2. Numerical Simulation Model. In order to verify the feasibility of numerical simulation method, the numerical model is shown in Figure 4(a). Block A and block B are both cubes with a side length of 0.5 m. Block A and block B are modeled separately, and then, block B is moved to the adjacent but not shared node with block A. Then, the center of two blocks is the bedding separation. The surrounding rock mass is modelled using an isotropic elastic model, and the rock bolt is assumed to be elastic and does not consider the yielding or breaking. The anchoring length is 1.0 m, and the stiffness coefficient of anchoring interface $k$ is 10 GPa. Young’s modulus of rock bolt is 210 GPa. The diameter of rock bolt is 22 mm. Since the deformation of the surrounding rock mass is neglected, the block A is fixed, and block B is applied $x$-velocity to simulate bedding separation. In order to maintain the static load, the velocity speed is $1 \times 10^{-7}$ m per step. The bedding separation value $\delta$ can be determined according to the loading steps. Bedding separation is simulated by applying velocity to block B; thus, the gravity of both block A and block B is not considered. The numerical simulation model and boundary conditions are shown in Figure 3(b). $C_{s \text{ _sk}}$ represents shear coupling spring stiffness per unit length and can be expressed by the following formula:

$$c_{s \text{ _sk}} = k \cdot \pi d. \quad (21)$$
4.3. Simulation Result Verification. Figure 5 is the axial force and interfacial shear stress curves between the numerical simulation results and theoretical calculation results when δ is 1, 3, and 5 mm. It can be seen from Figure 4 that when the bedding separation is located at the center of the anchoring section, the axial force and the interfacial shear stress curves are symmetrically distributed, and the maximum axial force and the maximum interfacial shear stress are both located at the bedding separation position. The curves gradually attenuate as the position move away from the bedding separation. As the bedding separation value increases, the peak values of axial force and shear stress continue to increase. The numerical simulation results are in agreement with the theoretical calculation results, which show that numerical simulation method is feasible to study the mechanical characteristics of rock bolt in rock mass with bedding separation.

5. Study on Stress Distribution
Characteristics of Rock Bolt with Bedding Separation Based on Nonlinear Bond Slip Relationship of Anchoring Interface

5.1. Nonlinear Bond Slip Relationship. Ma et al. [15, 16] proposed a nonlinear bond slip model for a fully grouted rock bolt. The nonlinear bond slip relationship is shown in Equation (22).
\[ \tau(x) = \frac{EA}{U} \frac{\alpha}{\beta^2} \left( e^{-\delta(x)/\alpha} - e^{-2\delta(x)/\alpha} \right). \]  

where \( E \) is Young’s modulus of rock bolt, \( A \) is the cross-sectional area of rock bolt, \( U \) is the circumference of rock bolt cross section, and \( \alpha, \beta \) is the undetermined coefficient.

Substituting Equation (5) and Equation (22) into Equation (6) gives

\[ \frac{d^2 u(x)}{dx^2} = \frac{4}{Ed} f(u(x)) = \frac{\alpha}{\beta^2} \left( e^{-u(x)/\alpha} - e^{-2u(x)/\alpha} \right). \]  

Equation (23) is a second-order nonlinear differential equation and has no analytical solution. It can be solved by numerical simulation.

Rong et al. [28] applied a tensile load to a 1 m long and 32 mm diameter rock bolt encapsulated in concrete. Young’s modulus of rock bolt is 210 GPa. The bond slip relationship is obtained to describe the behavior of Rong et al.’s test by Ma et al. [15, 16], where \( \alpha = 0.2563 \text{ mm} \) and \( \beta = 140.7 \text{ mm} \); the bond slip relationship is show in Figure 5. A set of key points in Figure 6 are selected from the bond slip curve for the pile structural element of the Flac3D model, and the shear stress is transferred into cs_scoh by Equation (9). This model is rewritten and implemented as a subroutine by FISH language in Flac3D Version 5.0. Then, the nonlinear bond slip relationship is putting into the numerical simulation model by user-defined cs_cstable for expressing the nonlinear characteristics of the anchoring interface [27, 29].

5.2. Analysis of the Stress Distribution Characteristics of Rock Bolt in Rock Mass with Single Bedding Separation

5.2.1. Numerical Simulation Model. The numerical simulation modeling method is the same as that in Section 4.2.

Figure 6: Comparison of bond slip curves at different nodes (nodes 12 and 13) with the input bond slip relationship.

The distance \( x_0 \) from the anchoring end to the bedding separation is 0.5, 0.6, 0.7, 0.8, and 0.9 m, respectively. Schematic diagram of the simulation scheme with single bedding separation and the numerical model when \( x_0 = 0.8 \text{ m} \) is show in Figure 7. The nonlinear bond slip relationship of anchoring interface is shown in Figure 6. The parameters taken from pile structural elements are shown in Table 1.

The coupling stress shear and coupling displacement for nodes 12 and 13 were monitored and used to compare with the input bond slip relationship as show in Figure 6. It can be seen that the different nodes along the rock bolt have the same bond slip relationship and have a good agreement with the input bond slip relationship.

5.2.2. Influence of Bedding Separation Values. Figure 8 shows that the interfacial shear stress and axial force distribution curves with single bedding separation. It can be seen from Figure 7 that when the bedding separation position is at the center of the anchor segment (\( x_0 = 0.5 \text{ m} \)), the axial force and interfacial shear stress curves on both sides are symmetrically distributed and the interfacial shear stress curves are obviously nonlinear. At the initial stage of bedding separation (e.g., \( \delta = 0.1 \text{ mm} \)), the interfacial shear stress on both sides is less than the interfacial shear strength of 5.44 MPa (as shown at \( m \) point in Figure 5), indicating that the anchoring interface on both sides is in the elastic state. The maximum axial force and maximum interfacial shear stress are at the position of bedding separation and gradually attenuate away from the bedding separation. As the bedding separation values increase (\( \delta = 0.385 \text{ mm} \)), the interfacial shear stress on both sides reaches the interfacial shear strength and began to enter the softening stage. Afterwards, with the increase of the bedding separation amount (\( \delta = 0.7 \text{ mm} \)), the shear stress curve gradually evolved into a single peak curve, and the peak value gradually shifted.
away from the bedding separation direction. When $\delta = 0.908$ mm, the axial force reaches the maximum pulling out load (240 kN). At this time, the shear stress curve of the anchor interface and the area enclosed by the $x$-axis are the largest. After that, with the further increase of bedding separation (e.g., $\delta = 1.000$ mm), the interfacial shear stress and axial force on both sides gradually decreased, and finally, the pullout failure occurred.

**5.2.3. Influence of the Bedding Separation Position.** When the bedding separation position is not in the center of the anchoring segment, the distribution curves of the axial force and interfacial shear stress have a significant difference due to the different anchoring segment lengths on both sides of bedding separation. When $x_0$ is 0.8 m, the distribution curves of the axial force of rock bolt and the interfacial shear stress are shown in Figure 9. It can be seen from Figure 9 that the axial force and interfacial shear stress curves on both sides are asymmetrically distributed. When the bedding separation value is small (e.g., $\delta = 0.100$ mm), the interfacial shear stress on both sides of the bedding separation does not reach its interface shear strength, and the anchoring
interface is in elastic state. The maximum axial force and shear stress are located in the bedding separation position and gradually attenuate away from the bedding separation. When $\delta$ is 0.304 mm, the interfacial shear stress on the right side reaches interfacial shear strength and enters the softening stage, and the peak value begins to transfer to the deep part. The anchoring interface on the left side is still in the elastic state. With the increase of the bedding separation value (e.g., $\delta = 0.356$ mm), since the anchorage length on the right side is short, the curve is approximately horizontally distributed. At this time, the axial force reaches the maximum value (116 kN). The anchoring interface on the left is still in the elastic stage. When $\delta$ is 0.5 mm, the anchoring interface on the right side has been in the softening stage, the shear stress decreases, and the interfacial shear stress and axial force on the left side also decrease until the rock bolt is pulled out. The anchor length on the left is large, and the anchoring interface is still in the elastic stage. The softening and decoupling of the anchoring interface on the right leads to the reduction in the axial force of rock bolt.

Figure 9: (a) Axial force and (b) interfacial shear stress distribution curves when $x_0$ is 0.8 m.

Figure 10: Comparison curves of axial force versus the bedding separation value at different bedding separation positions.

Figure 11: Numerical model diagram with double bedding separation.

maximum value (116 kN). The anchoring interface on the left is still in the elastic stage. When $\delta$ is 0.5 mm, the anchoring interface on the right side has been in the softening stage, the shear stress decreases, and the interfacial shear stress and axial force on the left side also decrease until the rock bolt is pulled out. The anchor length on the left is large, and the anchoring interface is still in the elastic stage. The softening and decoupling of the anchoring interface on the right leads to the reduction in the axial force of rock bolt.

Figure 10 is the comparison curves of axial force versus the bedding separation value at different bedding separation positions. It can be seen from Figure 10 that the axial force versus the bedding separation value curves at different bedding separation positions are all single-peak distributed. In prepeak stage, the axial of rock bolt increases nonlinearly to peak as the bedding separation value increases. In the postpeak stage, as the bedding separation value increases, the axial force of rock bolt gradually attenuates. The greater axial force of rock bolt, the higher the stored elastic energy. The elastic energy is released in the postpeak stage. Therefore, the greater the axial force of rock bolt, the greater
attenuation gradient the curves. It can be seen from the peak point curve that the bedding separation position is closer to the center of the anchoring segment, the greater the axial force of rock bolt. Therefore, when the bedding separation position is not in the center of the anchoring segment, the axial force of rock bolt is mainly controlled by the side with the shorter anchoring length.

5.3. Stress Distribution Characteristics of Rock Bolt in Rock Mass with Multiple Bedding Separation. Assuming that there are two bedding separation in the rock mass, the numerical simulation modeling method is the same as that in Section 4.2, and the numerical simulation model is shown in Figure 11. After the roadway excavation, the deformation of the surrounding rock gradually decreases in the radial direction. In order to better express the characteristics of on-site bedding separation, the bedding separation \( \delta_1 \) and \( \delta_2 \) are 0.05, 0.1 mm, 0.3, 0.5 mm, and 0.5, 0.8 mm, respectively. Multiple bedding separation simulation is realized by means of single bedding separation open in turn. The specific method is as follows: the block A is fixed, the block B and block C as a whole apply \( x \)-velocity to simulate 1# bedding separation, and the speed is \( 1 \times 10^{-7} \) m per step. After reaching a certain bedding separation value, the block B is fixed, and the block C applies \( x \)-velocity to simulate 2# bedding separation to reach a certain bedding separation.

Figure 12 is the interfacial shear stress and axial force distribution curves versus different bedding separation values with double bedding separation. It can be obtained from Figure 11 that when \( \delta_1 = 0.05 \) mm and \( \delta_2 = 0.1 \) mm, the maximum interfacial shear stress is at the bedding separation position. The interfacial shear stress on both sides does not reach interfacial shear strength, and the anchoring interface is in the elastic stage. The maximum axial force of rock bolt is at the bedding separation position. When \( \delta_1 = 0.3 \) mm and \( \delta_2 = 0.5 \) mm, the maximum interfacial shear stress on the left side of 1# bedding separation is 4.88 MPa, and that on the right side is 3.99 MPa. The interfacial shear stress on both sides of 2# bedding separation began to decrease, indicating that the anchoring interface has entered the softening stage, the peak value gradually moves away from the bedding separation, and the interfacial shear stress curve gradually shows a single peak distribution. In block B, the axial force of rock bolt is superimposed on each other in a saddle shape by the influence of double bedding separation, and the interfacial shear stress has a zero point. When \( \delta_1 = 0.5 \) mm and \( \delta_2 = 1.0 \) mm, the interfacial shear stress in block C is a certain value, and the axial force of rock bolt is linearly attenuated, which indicate that the anchoring interface have all been debonding. The anchoring interface on both sides of 1# bedding separation has partially entered the softening stage. Due to the debonding effect of anchoring interface in block C, the axial force of rock bolt at 2# bedding separation position is reduced, and the interfacial shear stress in block B is redistributed. Therefore, compared with the single bedding separation in rock mass, the additional force of rock bolt generated by the multibedding separation will superimpose each other.

6. Conclusion
The mechanical characteristics of the stress distribution characteristics of rock bolt in rock mass with single and multiple bedding separation are studied by numerical simulation. Based on the analysis of results, the conclusions are as follows:
(1) When the bedding separation is located in the center of anchoring segment with single bedding separation, the axial force and shear stress curves on both sides of bedding separation are symmetrically distributed. As the bedding separation value increases, the axial force and shear stress are gradually transferred away from the bedding separation. When the interfacial shear stress reaches the shear strength and begins to enter the softening stage, the interfacial shear stress exhibits nonlinear characteristics.

(2) When the single bedding separation is not located in the center of anchoring segment, the axial force and shear stress curves on both sides of bedding separation are asymmetrically distributed. The axial force versus the bedding separation value curves at the different position are all single-peak distribution. The closer the bedding separation is to the center of anchoring segment, the greater the axial force of rock bolt. The peak axial force of rock bolt is mainly controlled by the side with the shorter anchoring length.

(3) Compared with the single bedding separation, the additional stresses of rock bolt generated with the multiple bedding separation will superimpose each other, and the load transfer is affected by the stress superposition.

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.

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