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Study on Stress Distribution Law of Anchorage Body

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ABSTRACT

In order to reveal the stress distribution law of the anchorage body during the drawing process, through the analysis and research on the anchoring mechanism of the anchor rod, it is found that the bonding mechanism of the interface between the anchor rod and the anchoring material is mainly determined by three factors : bonding force, mechanical interlocking and friction force. The bonding mechanism of the anchorage material-surrounding rock interface is mainly determined by two factors : bonding force and friction force. Then, the mechanical model of anchorage body is established, and the distribution equations of axial force and interfacial shear stress of anchorage body are obtained by theoretical analysis. The axial force and shear stress curves are obtained by substituting the relevant parameters. It is found that the axial force and interfacial shear stress curves are exponentially decreasing. The axial force of the bolt is approximately equal to the load applied on the bolt, and at the end of the anchorage, the axial force approaches zero.

KEYWORDS

Anchorage Body; Theoretical Analysis; Anchor Axial Force; Interfacial Shear Stress.

1. INTRODUCTION

China's coal mines are mainly underground mining, and roadways play a vital role in underground mining, creating conditions for mine transportation, ventilation, pedestrians, and pipeline laying. Therefore, it is of great significance to maintain the stability of roadway for mine safety construction and production[1]. The supporting effect of bolt anchoring on surrounding rock belongs to active support, which improves the stability of surrounding rock and plays an important role in ensuring underground safety production. As one of the most economical and effective methods to maintain the stability of roadway surrounding rock and solve the problem of supporting engineering, roadway bolt anchoring support technology has gradually occupied the main position in roadway support after continuous progress and development[2-5].

In the past ten years, scholars at home and abroad have done a lot of research on the load distribution, load transfer mechanism and reinforcement mechanism of anchorage body, and have achieved certain academic results. However, many relevant design specifications assume that the shear stress on the anchorage interface is uniformly distributed[6], Hu Bin and Cui Qianli[7, 8]studied the influence of the shape parameters of the threaded steel anchor, the ' three-diameter matching ' relationship, the strength of the constraint material on the anchoring force and the axial force of the anchor rod and its surface shear stress along the axial distribution of the anchor rod by using the scheme of steel pipe and concrete to carry out the pull-out test; In order to analyze the nonlinear process of the anchorage section of the tensile bolt, Huang[9, 10]established a double exponential curve bond-slip model and solved the transfer mechanism of the pull-out load; Based on the trilinear bond-slip model, Yang[11]established a mathematical model of the tensile process of soil anchor and carried out numerical calculation with Matlab; Benmokrane[12]introduced the trilinear linear function model to describe the shear stress-displacement curve relationship of the bolt anchorage interface in 1995; Based on the existing shear-slip mechanical model of FRP bars, a continuous curve model considering the nonlinear characteristics of the anchorage interface and the influence of the residual shear strength of the anchor is proposed[13]; Through the field pull-out test, Fu[14]believed that coal strength, anchorage length, bolt pre-tightening force and row spacing had a great influence on the diffusion effect of bolt pre-tightening force, which in turn affected the bolt support effect. The above research is different from each other in the theoretical analysis of the stress of the anchorage body. Therefore, this paper will also analyze the stress distribution law of the anchorage body from the theoretical analysis, which is of great significance to the design and failure mechanism of the bolt support.

2. ANALYSIS OF ACTION MECHANISM AND FAILURE MODE OF BOLT ANCHORING

2.1. Basic principle of bolt support

The supporting process of the bolt is to punch the bolt into the rock layer around the roadway, so that the bolt can directly reinforce it. The bolt can lock the broken or fractured rock mass around the roadway, and transform the broken and loose rock and soil structure around the roadway into mosaic structure, block structure and overall structure, so that the strength of the surrounding rock around the roadway can be improved. The joint action of the bolt and the surrounding rock is used to achieve the supporting effect on the surrounding rock of the roadway.

The bolt support theory is mainly divided into : suspension theory, composite beam theory, composite arch theory, maximum horizontal stress theory, etc.

The core idea of the suspension theory is to suspend the gravity of the supported structure in the surrounding more stable and solid rock mass through the bolt anchorage system. Its significance is to reduce the downward deflection deformation of the lower rock layer of the composite roof after excavation due to the vertical pressure. Reducing or even preventing the deflection deformation of the initial roof can effectively improve the strength of the roof. However, due to the limitation of the length of the anchor rod, the thickness of the rock layer suspended by the anchor rod directly affects the suspension effect. In addition, the lithology of each rock layer of the composite roof, the density of the anchor rod and the strength of the anchor rod itself will also affect the effect of the suspension support. The details are shown in Figure 1.

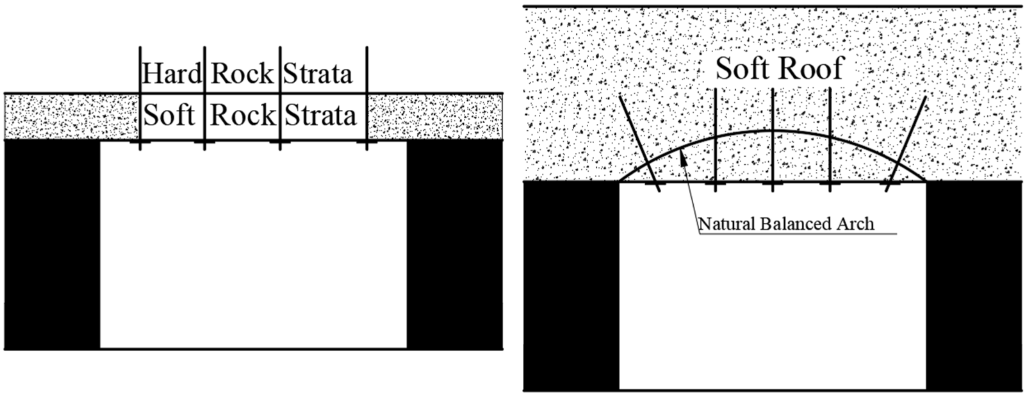


Figure 1. Suspension theory diagram

The composite beam theory holds that by applying prestress to the bolt, the lower part of the composite roof will be closely combined with the loose rock layer through the anchoring effect of the bolt, so as to improve the integrity of the lower loose rock layer and greatly improve its stiffness and strength. After the loose rock stratum under the composite roof is combined with the anchor bolt, the two roadway sides are used as the fulcrum to bear the vertical load of the upper rock stratum of the roof in the form of beams. In the design of bolt support, this theory can control the separation of roof strata and the cohesive force between strata as much as possible, so as to improve the integrity of roof. However, if longitudinal cracks appear in the roof strata, the theory will have certain limitations. The details are shown in Figure 2.

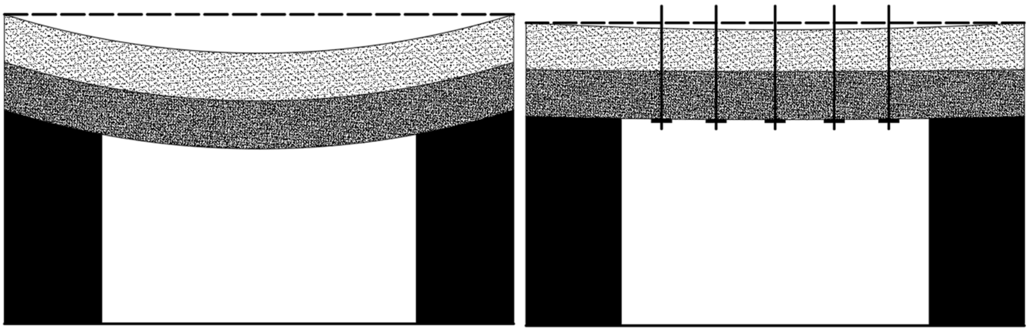


Figure 2. Theoretical diagram of composite beam

The combined arch theory holds that if the bolt is properly arranged in the arched roadway, the conical pressure zone at the end will overlap, which will promote the emergence of a certain thickness of rock pressure arch in the roof strata of the arched roadway. The greater the thickness of the arch, the stronger the stability of the surrounding rock, and the stronger the bearing capacity of the roadway roof. However, the combined arch theory is only suitable for the roof support design of arched roadways. For rectangular roadways, the roof will not form a pressure arch, so its application is limited. The details are shown in Figure 3.

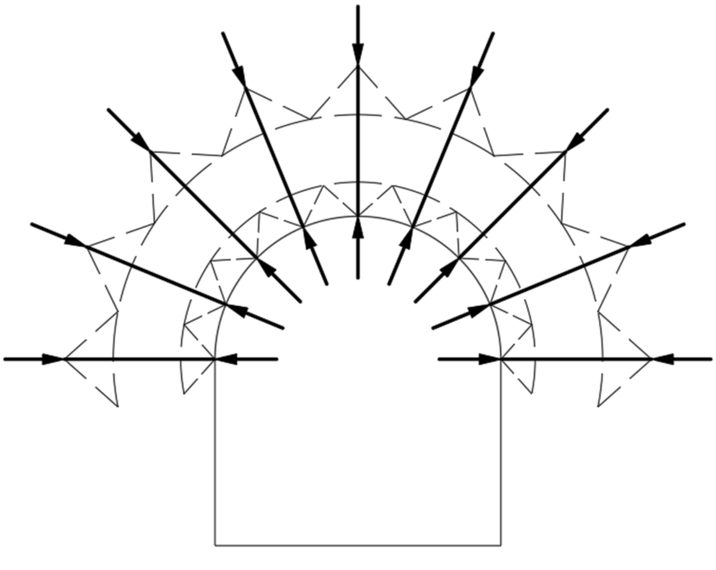


Figure 3. Theoretical diagram of composite arch

The maximum horizontal stress theory holds that the horizontal tectonic force of roadway surrounding rock has a great influence on the stability of roadway surrounding rock. If the vertical direction of the roadway is parallel to the maximum horizontal tectonic stress of the surrounding rock, the stability of the surrounding rock of the roadway is the best ; if the angle between the vertical direction of the roadway and the maximum horizontal tectonic stress of the surrounding rock is less than 90 °, the surrounding rock of the roadway will produce stress concentration damage. If the angle between the vertical direction of the roadway and the horizontal tectonic stress of the surrounding rock is 90 °, the stability of the surrounding rock of the roadway is the worst. Therefore, the relationship between the vertical direction of the roadway and the direction of the maximum ground stress should be considered when designing the roadway support, and the vertical distribution of the vertical direction of the roadway and the maximum ground stress should be avoided as much as possible. The details are shown in Figure 4.

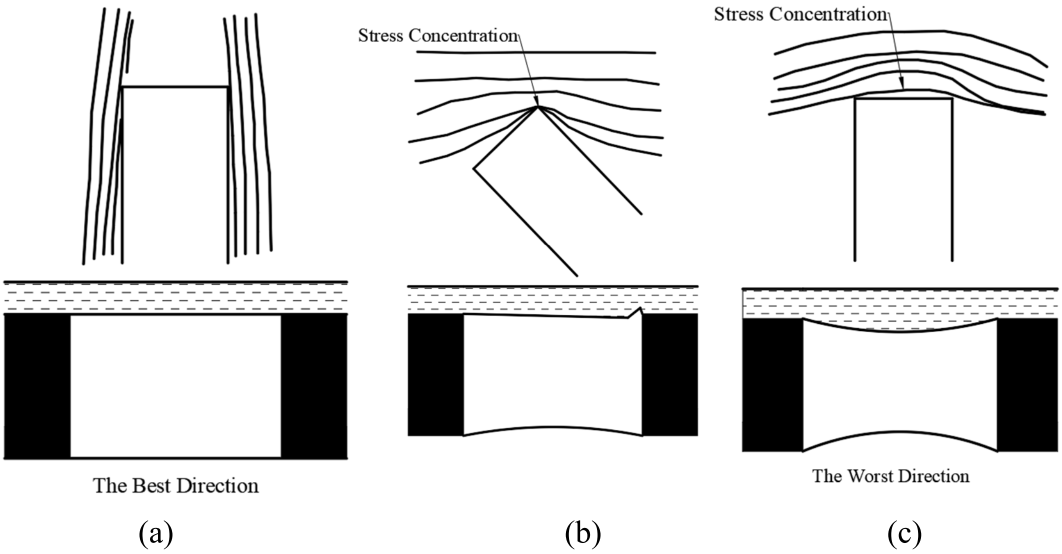


Figure 4. The maximum horizontal stress theory diagram

2.2. Study on anchoring mechanism of bolt

The bolt body and the surrounding rock are closely combined by the anchoring material to form a common system. The maximum pull-out force that the bolt can withstand in the project is called the anchoring force. The main factors affecting the anchoring force are the bolt, the anchoring material and the roadway surrounding rock. The magnitude of anchoring force is not only related to the bond strength between anchoring material-borehole rock layer and anchor-anchoring material, the strength of surrounding rock and the extrusion degree between hole walls, but also closely related to the surrounding strata structure, the magnitude and direction of in-situ stress, the water content of rock layer and other factors. The schematic diagram of force transmission is shown in Figure 5.

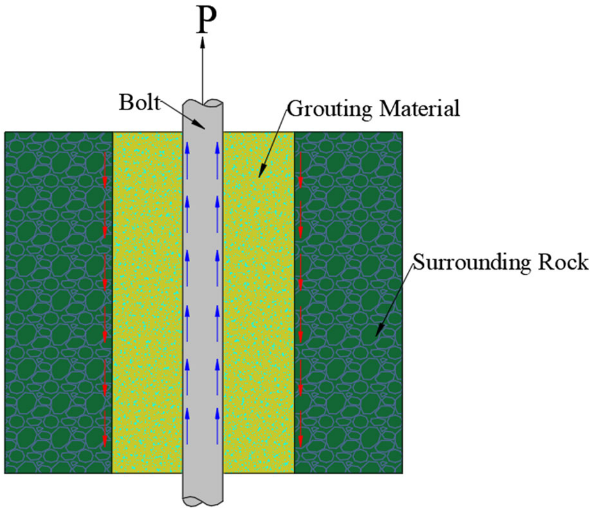


Figure 5. Mechanical transfer model of each interface of anchorage system

From the above analysis, it can be seen that the main factors determining the pull-out force of the anchor rod under the pull-out load are : the bonding force between various materials in the anchoring system, the strength of the anchor rod material and the strength of the rock layer around the borehole.

2.3. Failure Type Analysis of Anchor Bolt

In view of the type and mechanism of anchorage failure, scholars at home and abroad have carried out a large number of laboratory tests and field tests. Through the analysis of the existing research results, the main failure types of bolt anchorage can be divided into the following categories :

(1) Fracture of anchor rod body

When the rock mass of the anchored surrounding rock is hard, and the bond strength between the bolt and the anchoring material, the anchoring material and the rock mass is also large enough, the anchorage failure form will be determined by the tensile strength of the bolt. When the pull-out load is greater than the tensile strength of the bolt, the bolt body will be pulled off, and the fracture site generally occurs at the end of the anchorage and outside the place, because the position will produce stress concentration, in addition, in the poor part of the anti-corrosion treatment will also break.

(2) Bond failure occurs between the bolt and the anchoring material.

When the bolt is anchored in a relatively hard rock stratum, the maximum pull-out resistance of the anchorage system will depend on the bond strength between the bolt and the anchorage material. When the pull-out load exceeds the bond strength between the bolt and the anchorage material, the bond slip failure will occur between the bolt and the anchorage material, resulting in anchorage failure. The general bond failure starts from the beginning of the anchorage, and gradually develops to the deep part of the anchorage, which has the characteristics of progressive failure.

(3) Bond failure occurs between the anchoring material and the surrounding rock of the borehole.

When the bolt is anchored in the soft rock layer, the maximum pull-out resistance of the anchoring system will depend on the bond strength between the anchoring material and the surrounding rock of the borehole. Because the bonding force between the anchoring material and the rock mass is much smaller than that between the bolt and the anchoring material, the bonding failure occurs first at the interface between the anchoring material and the rock mass under the load, and the anchoring failure occurs as the entire anchoring body is pulled out.

(4) Destruction of anchoring materials

For the tensile bolt, when the pull-out load on the bolt is transferred to the anchoring material, the anchoring material will be subjected to the combined action of tensile stress and shear stress, and the tensile and shear strength of the anchoring material is determined. With the increase of the pull-out load, when the tensile stress and shear stress exceed its ultimate strength, the anchoring material will produce shear tensile failure.

(5) Failure of rock mass around anchorage system

When the surrounding rock around the anchorage system is weak or broken rock, and the anchorage length is small, with the increase of pull-out load, shear failure may occur in the rock mass around the anchorage body, resulting in the whole anchorage body being pulled out in a cone shape, resulting in the failure of the whole anchorage system.

(6) Anchorage failure

Due to the influence of many factors, such as the invasion and corrosion of water, the structural damage of the bolt and the surrounding rock, the uneven installation and mixing of the anchoring agent and the separation of the rock layer, etc., resulting in the anchoring cavity between the bolt and the anchoring material or the anchoring material and the borehole rock mass.

3. THEORETICAL ANALYSIS OF FORCE DISTRIBUTION TRANSFER LAW OF ANCHORAGE BODY

In the process of stress analysis, the anchor rod and anchoring agent are regarded as a whole, which is called the anchoring body. The length is L, the radius of the borehole is R, the elastic modulus of the anchoring body is E, and the radius of the anchor rod is r. Under the action of the drawing force P, the anchoring body produces tensile deformation and finally the anchoring failure occurs. As shown in Figure 6, a micro-element of the anchorage body is taken along the axial direction of the bolt for force analysis.

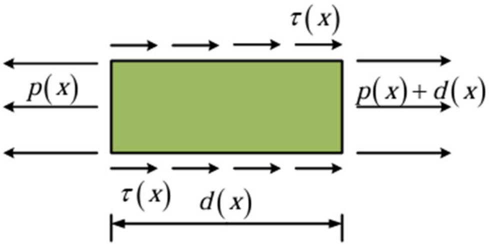


Figure 6. Anchorage solid micro-element force analysis diagram

In the figure : $P(x)$ is the axial force of the bolt along the direction of the rod at the coordinate x ; $\tau(x)$ is the shear stress of the anchorage interface at the coordinate x.

According to the force balance, it can be obtained :

$$\mathrm{d}P(x)+2\pi R\tau(x)\mathrm{d}x=0 \tag{1}$$

Assuming that the anchorage body is in the elastic range, the axial displacement is. $u(x)$ According to Hooke 's law, the axial force of the bolt can be expressed as :

$$P(x) = E\pi R^2 \varepsilon(x) \tag{2}$$

Which:

$$\varepsilon\left(x\right) = \frac{\mathrm{d}u(x)}{\mathrm{d}x} \tag{3}$$

$$\mathrm{E} = \frac{\mathrm{E}_1\left(\mathrm{R}^2\text{-}\mathrm{r}^2\right) + \mathrm{E}_2\mathrm{r}^2}{\mathrm{R}^2} \tag{4}$$

In the formula : $\varepsilon\left(x\right)$ represents the strain generated by the bolt along the direction of the rod body ; E_1 and E_2 are the elastic modulus of anchoring agent and anchor rod respectively.
The simultaneous formula (2) and formula (3) can be obtained :

$$P(x) = E\pi R^2 \frac{\mathrm{d}u(x)}{\mathrm{d}x} \tag{5}$$

Combining Formula (1) and Formula (5), we can get :

$$\frac{\mathrm{d}^2u(x)}{\mathrm{d}x^2} - \frac{2}{ER}\tau(x) = 0 \tag{6}$$

$$\tau(x) = K_1 u(x) \tag{7}$$

Substitute the formula (7) into the formula (6) to obtain :

$$\frac{\mathrm{d}^2u(x)}{\mathrm{d}x^2} - \frac{2K_1}{ER}u(x) = 0 \tag{8}$$

Let $a = \sqrt{\frac{2K_1}{ER}}$, then Formula (8) can be simplified as follows :

$$\frac{\mathrm{d}^2u(x)}{\mathrm{d}x^2} - a^2u(x) = 0 \tag{9}$$

Solving available

$$u\left(x\right) = C_1e^{ax} + C_2e^{-ax} \tag{10}$$

Substitute the formula (10) into the formula (5) and the formula (7) respectively to obtain :

$$P(x) = aE\pi R^2\left(C_1e^{ax} - C_2e^{-ax}\right) \tag{11}$$

$$\tau(x) = K_1\left(C_1e^{ax} + C_2e^{-ax}\right) \tag{12}$$

According to the bolt stress model, there are two boundary conditions :

$$P(x)\big|_{x=0} = P \tag{13}$$

$$P(x)\big|_{x=L} = 0 \tag{14}$$

According to the boundary conditions, the parameters C_1 and C_2 can be determined :

$$C_1 = \frac{P}{aE\pi R^2\left(1-e^{2aL}\right)} \tag{15}$$

$$C_2 = \frac{Pe^{2aL}}{aE\pi R^2\left(1-e^{2aL}\right)} \tag{16}$$

When the anchorage interface is in an elastic-plastic critical state, the shear stress at z=0 just reaches the ultimate bond strength of the interface, so it can be obtained :

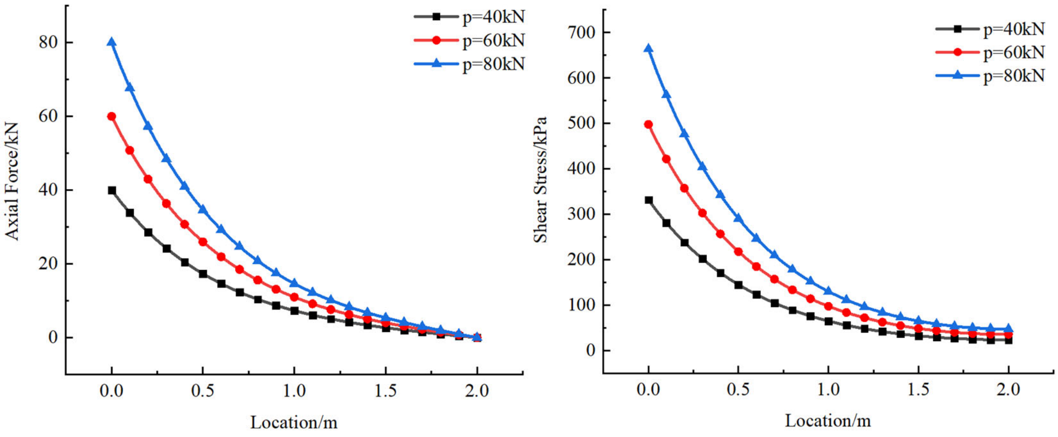
$$\tau(0) = K_1(C_1 + C_2) = \tau_1 \tag{17}$$

The ultimate pull-out force of the anchor bolt in the elastic state can be obtained by the upper-type simultaneous (15) and (16) :

$$P_{\max} = \frac{\tau_1 aE\pi R^2(1-e^{2aL})}{K_1(1+e^{2aL})} \tag{18}$$

When the axial force of the bolt is greater than its tensile strength, the ultimate pullout force of the bolt is equal to the tensile strength of the bolt. In summary, the ultimate pull-out force of the bolt in the elastic stage is equal to the minimum value of the two.

Suppose that the length of the anchoring section of the anchor rod is L=2m, the diameter of the borehole is R=32mm, and the diameter of the anchor rod is r=20mm. An anchoring defect section divides the anchoring section of the anchor rod into three parts and the defect is located in the center. If the defect anchoring section b_1=0.2m, then L_1=L_2=0.9m, take the elastic modulus of the anchor rod E2=200GPa, the elastic modulus of the anchoring material E_1=20GPa, K_1=4MPa·mm^{-1}, and the maximum bonding strength of the interface between the anchoring body and the borehole rock wall τ_1=4MPa. By substituting the above parameters into the relevant formulas, the stress distribution curve of the bolt in the anchorage section of the anchorage body can be obtained, as shown in the following figure.



(a) axial force distribution (b) shear stress distribution

Figure 7. Stress distribution curve of anchored bolt under different loads

It can be seen from Figure.7 that the axial force curve of the anchorage body is exponentially decreasing. At the initial position of the loading end, the axial force of the bolt is approximately equal to the load applied on the bolt, and at the end of the anchorage, the axial force approaches zero. The interface shear stress curve and the axial force curve are similar to the exponential decreasing distribution, but the shear stress at the end of the anchorage is not or close to zero.

4. CONCLUSION

(1) The mechanism of bolt anchoring in bolt support system is analyzed and studied, and the failure modes of anchoring are classified and analyzed. It is found that the bonding mechanism of bolt-anchorage material interface is mainly determined by three factors : bonding force, mechanical linkage and friction force. The bonding mechanism of the anchorage material-surrounding rock interface is mainly determined by two factors : bonding force and friction force.

(2) Through the analysis of the established mechanical model of the anchorage body, the analytical equations of the axial force and interface shear stress distribution of the anchorage body bolt are obtained. The axial force and shear stress curves are obtained by substituting the relevant parameters. It is found that the axial force and interface shear stress curves are exponentially decreasing. The axial force of the bolt is approximately equal to the load applied on the bolt, and at the end of the anchorage, the axial force approaches zero.

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