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Study on Failure Characteristics and Ultimate Pullout Resistance of Soft Rock Bolt

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ABSTRACT: Soft soil is a kind of special soil with large water content, high compressibility, low strength and poor water permeability. It has a wide distribution range and is easy to cause building settlement and foundation instability in civil engineering. Therefore, according to the shape parameter equation of the fracture surface of the prestressed anchor, the nonlinear Mohr-Coulomb strength criterion and the upper bound theorem under the effect of pore water pressure, a formula for calculating the ultimate uplift bearing capacity of the anchor is derived, which can fully consider the characteristics of soft soil. The theoretical calculation results and example analysis show that the theory and its solution method are effective and reliable.

KEYWORDS: bolt fracture surface ; strength criterion ; upper bound theorem ; ultimate pullout resistance.

I. INTRODUCTION

Soft soil usually refers to saturated clay soil with large natural void ratio, high compressibility and low shear strength. Due to its special physical and mechanical properties, soft soil is considered to be a bad foundation material in construction engineering. In 2015, a large area of ground subsidence occurred in Guangming New District of Shenzhen, which was caused by the instability of soft soil foundation. In this incident, about more than 20 buildings were affected, resulting in huge economic losses. Therefore, when carrying out construction activities in soft soil areas, it is necessary to have an in-depth understanding of its characteristics and take appropriate engineering measures to ensure the stability and safety of the building.

Prestressed anchor bolt can give full play to the self-bearing potential of rock mass. By adjusting and enhancing the inherent strength and self-stability of rock and soil, it can reduce the weight of supporting structure and save engineering construction materials, so as to ensure the safety and stability of construction process. It has significant economic and social benefits and can effectively solve the problem of building instability and damage in soft soil area.

Although the supporting effect of the bolt is closely related to its ultimate pull-out force [1-2], most researchers usually pay more attention to how the frictional resistance of the bolt is distributed along the anchorage length and the attenuation of prestress when studying the bolt [3-5]. Although many scholars have conducted in-depth research on the ultimate pull-out resistance of bolts, these studies are often based on the Hoek-Brown strength criterion as the criterion for rock and soil failure, and the theoretical formula is derived accordingly. For example, Serrano A and Olalla C et al. [6] assumed that the failure of rock and soil mass follows Hoek-Brown strength criterion, and proposed the theoretical expression of the ultimate pullout force of the bolt according to the limit equilibrium principle, but the solution is difficult to apply to practice ; some scholars have considered the fracture surface factors of pullout anchorage systems such as anchor bolts, but the theory provided does not match the actual fracture surface of anchor bolts well. He Siming et al [7-10] adopted a more comprehensive analysis method, and took into account the various failure surfaces that may occur when the anchor reaches the ultimate bearing capacity, but these analyses are limited to the failure mode of the rock and soil mass following the Hoek-Brown strength criterion. For soft soil, its mechanical properties are more in line with the nonlinear Mohr-Coulomb strength criterion. In addition, soft soil is rich in groundwater, and its stress strength is greatly affected by pore water pressure. Therefore, it is necessary to calculate water and soil separately. Therefore, based on the previous work, according to the shape parameter equation of the fracture surface of the prestressed anchor, the nonlinear Mohr-Coulomb strength criterion and the upper bound theorem under the effect of pore water pressure, the theoretical solution of the ultimate pullout force when the anchor is damaged in soft soil area is given. This is a useful exploration both in theory and in engineering applications.

II. RELATED WORK

(1) Analysis of fracture surface characteristics

It is known that the shape of the fracture surface of the bolt is closely related to the strength of the anchorage body and the rock and soil mass. When the strength of the anchorage body is much smaller than that of the rock and soil mass, a cylindrical fracture surface will appear in Fig.1 (a). When the strength of the anchorage body is greater than or equal to the strength of the rock and soil mass, a curved fracture surface will appear in Fig.1 (b) [7].

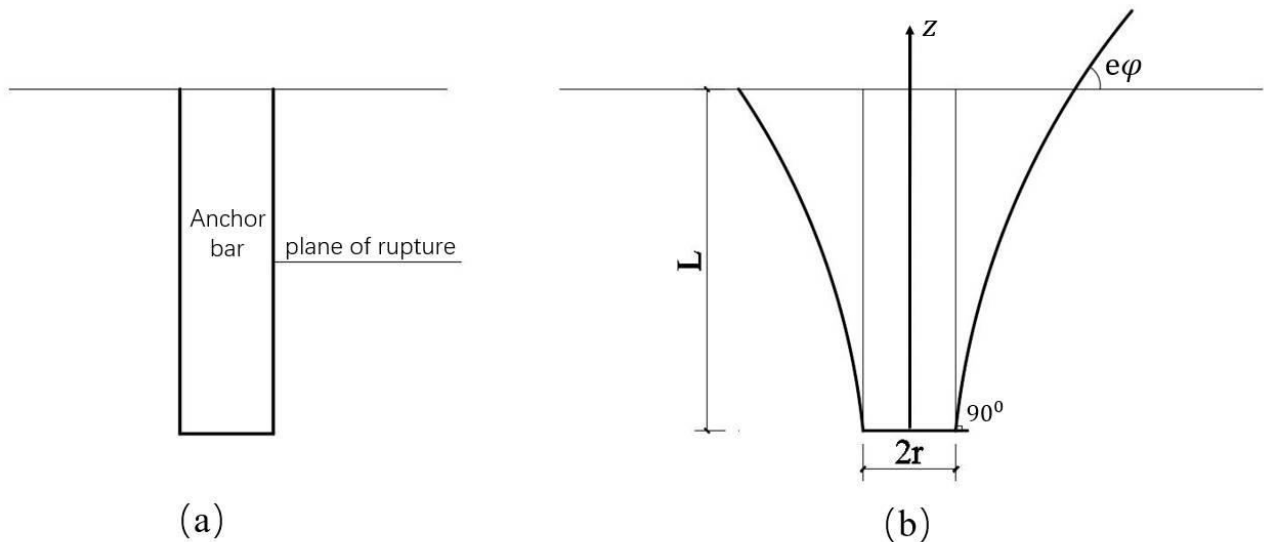


Fig.1 Typical fracture surface diagram of bolt

According to Reference [11], the parameter equation of the following fracture surface can be established :

$$x = r + \frac{L}{n \cdot \tan(e\phi)} \left(\frac{z}{L}\right)^n \tag{1}$$

where “r” is the radius of anchorage body ; “L” is the length of anchorage section ; “φ”is the internal friction angle of rock and soil ; “e”, “n” are undetermined parameters.

It is not difficult to see that when z = L, the failure range at the top of the anchoring section of the bolt can be obtained as follows :

$$x = r + \frac{L}{n \cdot \tan(e\phi)}, \quad n \neq 0 \tag{2}$$

According to the formula (2), when $n \rightarrow \infty$, it corresponds to the rupture surface (a) in figure 1 ; in other cases, it corresponds to the fracture surface (b) of figure 1. The parameter equation given by the formula (1) is consistent with the actual situation when the bolt is destroyed.

(2) Nonlinear Mohr-Coulomb strength criterion

A large number of scholars at home and abroad have shown that the nonlinear Mohr-Coulomb failure criterion is more suitable for weak surrounding rock [12-13]. In the stress space, its expression is as follows :

$$\tau = c_0 \left(1 + \frac{\sigma_n}{\sigma_t}\right)^{\frac{1}{m}} \tag{3}$$

The expression (3) is drawn into a curve as shown in Figure 2. In figure 2 and formula (3), “c₀” is the intercept between the curve and the longitudinal axis, and “c₀”, “σ_n” and “σ_t” are the geotechnical material parameters determined by the triaxial consolidated undrained shear test.

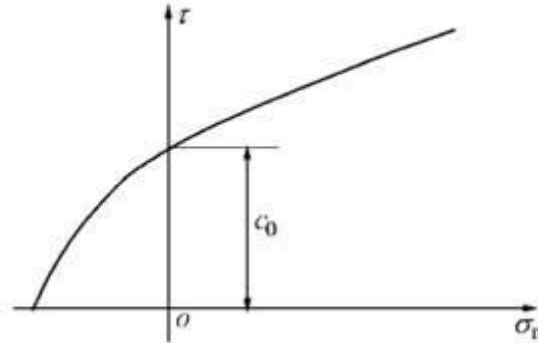


Fig.2 Nonlinear criterion envelope diagram

(3) Upper bound theorem under pore water pressure effect

Bishop [14] proposed a formula for calculating pore water pressure, which is widely used in geotechnical engineering. The specific expression is as follows :

$$u = r_u \gamma z \tag{4}$$

In the formula : “ u ” is the pore water pressure ; “ r_u ” is the pore water pressure coefficient determined by triaxial test ; “ γ ” is the weight of rock and soil ; “ z ” is the vertical distance between the rock and soil water level line and the surface.

III. METHODOLOGY

It is assumed that the action environment of the bolt is a static semi-infinite homogeneous rock and soil mass with groundwater layer. In order to ensure the universality of the calculation results, figure 1 (b) is used as the fracture surface analysis, and the calculation model shown in figure 3 is established. The nonlinear Mohr-Coulomb strength criterion, the upper bound theorem of pore water pressure and the limit equilibrium principle are used to study the equilibrium of the force on the fracture surface, and the ultimate pullout force of the bolt is finally determined. On this basis, the groundwater level is set at the interface between the free end of the bolt and the anchorage end, and the load on the free section of the bolt is “ $q_0 = \gamma h$ ”, where “ γ ” is the weighted weight of the rock and soil mass in the free section, and “ h ” is the length of the free section of the bolt. A micro-element in Figure 3 is taken for limit equilibrium analysis. The tangential stress acting on the fracture surface of the micro-element is “ τ^* ”, the normal stress is “ σ^* ”, and the length of the fracture surface is set to ΔL .

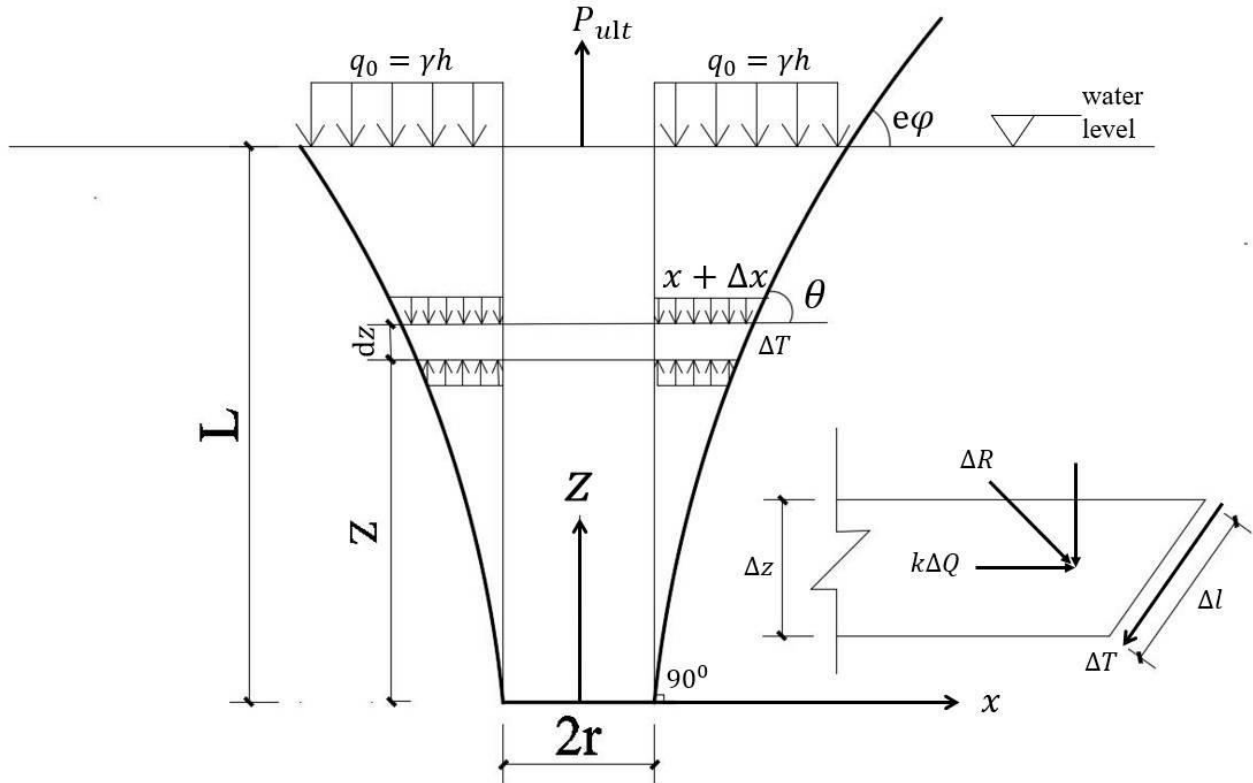


Fig.3 Calculation model of ultimate pull-out force of bolt

The calculation formula of normal stress “ τ^* ” is as follows :

$$\sigma^* = [\gamma h + \gamma'(L - z) - u](\cos \theta + k_0 \sin \theta) \quad (5)$$

In the formula, “ k_0 ” is the lateral pressure coefficient, $k_0 = \mu / (1 - \mu)$, “ μ ” is the Poisson's ratio of the rock and soil in the anchorage section ; “ γ' ” is the average gravity of the rock and soil in the anchorage section ; “ θ ” is the angle between the tangential direction and the horizontal direction of the fracture surface of the micro-unit.

From the vertical force balance condition of the micro-element body:

$$\Delta P' = \pi q \Delta x (2x + \Delta x) + \pi \Delta q (x + \Delta x)^2 + \pi (x + \Delta x / 2)^2 \gamma' \Delta z + 2\pi (x + \Delta x / 2) (\tau^* \sin \theta + \sigma^* \cos \theta) \Delta z \quad (6)$$

By omitting the higher-order terms of the differential and taking limits on both sides of the equation, we obtain:

$$dP' = 2\pi q dx + \pi (\gamma' - \frac{r_u \gamma h}{L-z}) x^2 dz + 2\pi (\tau^* \sin \theta + \sigma^* \cos \theta) x dz \quad (7)$$

In the formula, $\tau^* = c_0 (1 + \sigma_n / \sigma_t)^{1/m}$, $q = \gamma h + (\gamma' - \frac{r_u \gamma h}{L-z})(L - z)$, $\cot \theta = dx / dz$.

According to the nonlinear Mohr-Coulomb strength criterion, the above equilibrium equation can be transformed into the following equation :

$$\frac{dP'}{dz} = \left\{ 2\pi \left[\gamma h + \left(\gamma' - \frac{r_u \gamma h}{L-z} \right) (L - z) \right] \cot \theta + \pi \left(\gamma' - \frac{r_u \gamma h}{L-z} \right) x^2 + 2\pi x \left\{ c_0 \left(1 + \frac{\sigma_n}{\sigma_t} \right)^{\frac{1}{m}} \cot \theta + \right. \right. \\ \left. \left. [(1 - r_u) \gamma h + \gamma' (L - z)] (\cos \theta + k_0 \sin \theta) \right\} \right\} \quad (8)$$

According to the formula (8), the following effective vertical stress of rock and soil can be obtained by integral :

$$P' = \int_0^L \left\{ 2\pi \left[\gamma h + \left(\gamma' - \frac{r_u \gamma h}{L-z} \right) (L-z) \right] \frac{dx}{dz} + \pi \left(\gamma' - \frac{r_u \gamma h}{L-z} \right) x^2 + 2\pi x \left\{ c_0 \left(1 + \frac{\sigma_n}{\sigma_t} \right)^{\frac{1}{m}} \frac{dx}{dz} + [(1 - r_u) \gamma h + \gamma' (L-z)] (\cos \theta + k_0 \sin \theta) \right\} \right\} dz \quad (9)$$

In the formula, there is the following relationship between $\cos \theta$, $\sin \theta$, and $\frac{dz}{dx}$:

$$\cos \theta = \sqrt{\frac{1}{1 + \tan^2 \theta}}$$

$$\sin \theta = \sqrt{\frac{\tan^2 \theta}{1 + \tan^2 \theta}}$$

$$\tan \theta = \frac{dz}{dx} = \tan(e\varphi) (L/z)^n$$

Finally, the formula for calculating the pullout resistance of the anchor rod can be obtained by the separate calculation of water and soil.

$$P = P' + u \quad (10)$$

Substituting the above equation into formula (10), a parameter equation for calculating the uplift bearing capacity of anchor rod about “e” and “n” can be obtained.

In order to calculate the ultimate pull-out capacity of the bolt, the following extreme value principle is proposed : among all possible fracture surfaces, the real fracture surface will minimize the pull-out force corresponding to the bolt. Its mathematical formula is as follows :

$$\left. \begin{aligned} \frac{dP}{de} &= 0 \\ \frac{dP}{dn} &= 0 \end{aligned} \right\} \quad (11)$$

According to Eq. (10), the parameters “e” and “n” can be determined, and the corresponding fracture surface equation and the corresponding ultimate pull-out bearing capacity of the bolt can be obtained.

IV. VERIFICATION

The length of the anchoring section of the anchor bolt is 8.5 m, the length of the free section is 5 m, the diameter of the borehole is 110 mm, the rock and soil of the free section is clay, the weighted weight is $= 17.4 \text{ kN/m}^3$, and the rock mass of the anchoring section is argillaceous slate. Through the triaxial test, the main parameters are as follows : $\gamma' = 22.7 \text{ kN/m}^3$, $\varphi = 9.60^\circ$, $c_o = 55 \text{ kPa}$, $\sigma_n = 2.5 \text{ MPa}$, $\sigma_t = 50 \text{ MPa}$, $m = 2.55$, $r_u = 0.44$, $\mu = 0.30$.

According to the above model and corresponding parameters, the calculation is carried out. The parameters to be determined are “ $e = 0.23$, $n = 1.56$ ”. The corresponding ultimate pullout force of the bolt is 1377.8 kN.

V. CONCLUSION

(1) In this paper, the nonlinear Mohr-Coulomb strength criterion is used to analyze the effective normal stress of rock and soil. According to the shape parameter equation of the fracture surface of the prestressed anchor and the upper bound theorem under the pore water pressure effect, a formula for calculating the ultimate uplift bearing capacity of the anchor is derived, which can fully consider the characteristics of soft soil.

(2) Through the example test, it is found that the theoretical calculation is basically consistent with the measured results, which shows the reliability of the theory in this paper. At the same time, it also shows the rationality of using the nonlinear Mohr-Coulomb strength criterion and the upper bound theorem under the pore water pressure effect to analyze the ultimate pullout force of the bolt.

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