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Optimal design of anchor cables for slope reinforcement based on stress and displacement fields

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ABSTRACT

How to determine reasonable position and length of anchor cable is a frequently encountered but not well addressed problem in slope reinforcement projects. In this paper, the variable-modulus elastoplastic strength reduction method (SRM) is used to obtain the stress field, displacement field, and factor of safety of slope. Slope reinforcement using anchor cables is modeled by surface loading, i.e. different distributions of surface loading represent various reinforcement schemes. Optimal reinforcement scheme of anchor cables can be determined based on slope stress and displacement fields. By comparing the factor of safety and stress field before and after slope reinforcement, it is found that better reinforcement results can be achieved if strong reinforcement is applied upon the regions with high stress and large displacement. This method can well optimize the arrangement of anchor cables. In addition, several cases are employed to verify the proposed method.

1. Introduction

There are various types of reinforcement schemes for slopes, among which anti-slide piles and anchor cables are commonly used in order to offer resistance forces. It is a frequently encountered but not well solved problem for engineers to determine the reasonable position and length of anchor cable in slope reinforcement projects. The limit equilibrium method (LEM) is one of the commonly used methods; however, it only considers the equilibrium of total force, which means that comparison of different anchor positions of the slope is impossible. The numerical methods, such as finite element strength reduction method (FE SRM) (Zheng, 2012), are able to offer more detailed information, which are, unfortunately, not yet desirable when used.

Numerous researches have been conducted on the optimal reinforcement position of anti-slide piles. Hassiotis et al. (1999) pointed out that arranging anti-slide piles in the middle or top of the slope can increase the entire slope stability. Ausilio et al. (2001) presented that the optimal position of anti-slide piles is the bottom part of the slope. By employing the LEM, Li et al. (2005) proposed that the optimal position of anti-slide piles is the lowest point of the potential sliding surface. Based on the centrifuge tests, Gao et al. (2009) reported that the maximum factor of safety can be reached when piles are inserted in the middle of the slope, and Nian et al. (2012) drew a similar conclusion through a simple three-dimensional (3D) slope calculation. Based on the energy analysis method, Tan et al. (2011) pointed out that the optimal position of piles to reinforce slope should be located at the lower part of the slope. It can be seen that the above conclusions are significantly varied. Thus, a new solution to identify the optimal reinforcement position of anti-slide piles is needed.

In fact, there is a close relationship among stress field, displacement field, and stability of the slope (Huang, 2008). Considering that the stress and strain can be obtained by numerical methods such as finite element method (FEM), many scholars attempted to obtain the optimal reinforcement by analyzing the stress and displacement fields of the slope. Li et al. (2008) presented various methods for active slope reinforcement based on stress control in a critical sliding surface. Using deformation reinforcement theory, Liu et al. (2011) pointed out that the critical reinforcement position can be determined based on the distribution and magnitude of unbalanced forces in terms of strength reduction. Yang et al. (2009, 2012) proposed that the optimal reinforcement position can be determined by the stress and displacement fields of the slope, i.e. the region characterized by higher stress level and larger displacement. The actual anchor

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position is related to the type of sliding: for sliding induced by pushing force, the optimal anchor position is set at the top of the slope; while for sliding induced by traction, the optimal position is determined at the middle to bottom parts.

Therefore, it is more reasonable to identify the failure mechanism and determine the corresponding anchor position by investigating the stress and displacement fields of slope. Likewise, the optimal arrangement of anchor cables can be determined based on the stress and displacement fields of the slope. As a result, the variable-modulus elastoplastic strength reduction method (SRM) is adopted to calculate the stress field, displacement field, and factor of safety of slope. This method is proposed based on the variable-modulus elastoplastic model (Yang et al., 2009) that is more appropriate for soil.

Moreover, how to simulate the anchor cable is another critical issue. The behaviors of anchor cable and soil-anchor interactions have been extensively studied by researchers (e.g. Desai et al., 1986; Briaud and Lim, 1999). For example, Cai and Ugai (2003) used 3D zero-thickness elastoplastic interface elements to simulate the soil-anchor interactions. In this paper, reinforcement of anchor cable is realized by surface loading (Hryciw, 1991), i.e. different distributions of surface loading represent various reinforcement schemes. Accordingly, the optimal scheme is obtained by comparing the effects of different reinforcement schemes with two slope cases. Finally, the general relationship among the stress field, displacement field, and optimal reinforcement arrangement of anchor cables is obtained by comparing the effects of different reinforcement schemes.

2. Constitutive model and strength reduction method

2.1. Variable-modulus elastoplastic model

In order to obtain more accurate stress and displacement fields, the variable-modulus elastoplastic SRM (Yang et al., 2009) is used in this paper. The constitutive model combines the Duncan-Chang model with the deformation mode of in situ soil (Yang, 2001), which also takes the relationship among deformation modulus, Poisson's ratio, stress level, and strength into account. The deformation parameters related to the model are determined by

$$E_t = \left[1 - R_f \frac{\sigma_1 - \sigma_3}{(\sigma_1 - \sigma_3)_f}\right]^2 E_i \tag{1}$$

$$\mu_t = \mu_i + (\mu_f - \mu_i)\frac{\sigma_1 - \sigma_3}{(\sigma_1 - \sigma_3)_f} \tag{2}$$

where E_t is the deformation modulus; E_i is the initial tangent modulus; R_f is the damage ratio, identical to that of Duncan-Chang model; μ_t is the Poisson's ratio; μ_i is the initial Poisson's ratio; μ_f is the Poisson's ratio at failure, which is basically assumed to be 0.49; σ_1 is the major principal stress; σ_3 is the minor principal stress; $(\sigma_1-\sigma_3)_f$ is the ultimate shear strength of Mohr-Coulomb criterion, and can be written as

$$(\sigma_1 - \sigma_3)_f = \frac{2c\cos\varphi + 2\sigma_3\sin\varphi}{1 - \sin\varphi} \tag{3}$$

As can be seen from Eq. (1), the deformation modulus E_t decreases when the strength of soil decreases or the stress level increases, which coincides with the deformation characteristic of soil. Moreover, the parameters used in this model can be determined through in situ tests (Yang et al., 2014). Therefore, the variable-modulus elastoplastic model is considered to be closer to the actual situation.

The stress level is an important index reflecting the stress state of soil, and it can be defined as the ratio of the deviator stress to the ultimate shear strength, i.e.

$$S = \frac{\sigma_1 - \sigma_3}{(\sigma_1 - \sigma_3)_f} \tag{4}$$

When the stress level (S) approaches 1, the soil element is approaching to failure. Generally speaking, for a region associated with high stress level, the corresponding displacement is large as well; hence, the stress level can be used as an indicator to determine the optimal anchor position. For slope stability problems, the stress level of certain region can be used to estimate whether the region is likely to fail or not.

2.2. Strength reduction method

The SRM (Lian et al., 2001; Zhao et al., 2002; Zheng and Zhao, 2004) is a commonly used method to obtain the factor of safety of slope. This method gradually reduces the strength of soil by a strength reduction factor until the slope fails, the value of strength reduction factor is basically regarded as the factor of safety. The reduction method can be written as

$$c' = \frac{c}{f}, \quad \tan\varphi' = \frac{\tan\varphi}{f} \tag{5}$$

where c and φ represent the cohesion and angle of internal friction, respectively; c' and φ' represent the reduced cohesion and angle of internal friction, respectively; and f is the reduction factor. By using the variable-modulus elastoplastic SRM, the deformation modulus decreases as the strength decreases (Eq. (1)).

2.3. Slope failure criteria

Currently, the slope failure criteria in the SRM are mainly classified into three categories: (a) whether the plastic zone develops from the toe to the top; (b) whether the calculation is convergent; and (c) whether the deformation of the critical point is beyond the limit.

In the case of complex slope model, it is difficult to identify whether the plastic zone develops from the toe to the top of the slope. In addition, the critical point representing the critical displacement of the slope failure is not easy to be identified. Thus, the above-mentioned failure criterion category (b) is adopted as the failure criterion in this paper. The factor of safety is searched by dichotomy, and the search process is described as follows:

1. First, the initial range $[f_1, f_2]$ of factor of safety should be estimated, given that the calculation should be converged when $f=f_1$, and not converged when $f=f_2$.
2. Second, let $f=(f_1+f_2)/2$. If the calculation is convergent, then $f_1=f$; if not convergent, then $f_2=f$. The above steps are repeated until the difference between f_1 and f_2 is less than 0.001.
3. Finally, the factor of safety is $f=(f_1+f_2)/2$.

The 3D finite difference software, FLAC^{3D}, is adopted in this study. The variable-modulus elastoplastic model and the SRM based on dichotomy are realized in FLAC^{3D}, but here it is only used to analyze the plane strain problem.