A new method for the stability analysis of geosynthetic-reinforced slopes

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Abstract: This paper is concerned with the stability analysis of reinforced slopes. A new approach based on the limit equilibrium principle is proposed to evaluate the stability of the reinforced slopes. The effect of reinforcement is modeled as an equivalent restoring force acting the bottom of the slice and added into the general limit equilibrium (GLE) method. The equations of force and moment equilibrium of the slice are derived and corresponding iterative solution methods are provided. The new method can satisfy both the force and the moment equilibrium and be applicable to the critical failure surface of arbitrary form. Furthermore, the results predicted by the proposed method are compared with the calculation examples of other researchers and the centrifuge model test results to validate its correctness and effectiveness.

Keywords: Reinforced slope; Stability analysis; Limit equilibrium; General limit equilibrium method; Centrifuge model test

Introduction

In recent years, geosynthetic-reinforced soil structures, such as slopes, embankments and retaining walls are widely used in China and elsewhere due to the increasing infrastructural development demands, as is shown in Figure 1. Construction of slopes at steeper angles can be realized by the use of geosynthetics, thereby decreasing land requirements for slope construction. The stability analysis of reinforced slopes can be conducted using the limit equilibrium method. Leshchinsky and Reinschmidt (1985), Leshchinsky and Boedeker (1989) presented an analytical approach for the stability analysis of reinforced slopes based on limit equilibrium theory. In the analysis, the failure surfaces are either logarithmic or bilinear and two extreme inclinations of reinforcement force are investigated: tangential to the slice base and horizontal. Rowe and Soderman (1985) extended the simplified Bishop slip circle method by incorporating the reinforcement effect and estimated the stability of geotextile-reinforced
embankments. Sabhahit et al. (1994) conducted the stability analysis of a reinforced embankment constructed on a non-homogeneous clay deposit of finite depth by modifying Janbu’s generalized procedure of slices. Shahgholi et al. (2001) presented horizontal slice method for the stability analysis of reinforced slope. Some researchers performed stability analysis of slopes using finite element method (FEM). Griffiths and Lane (1999), Dawson et al. (1999) conducted stability analysis of slopes by means of shear strength reduction technique in finite element method (FEM). Mehdipour et al. (2013) calculated the factor of safety and the location of failure surface of geocell reinforced slope using the strength reduction method by employing the finite difference program FLAC 2D. Although FEM can be applied to a lot of complex conditions, the accuracy of the results depends greatly on the appropriate constitutive model adopted in the analysis. In addition, in many practical situations, its sophistication cannot be warranted due to the insufficiency of time and fund. Therefore, among the many approaches, limit equilibrium method is still very popular and generally preferred for the stability analysis of reinforced slopes because of its simplicity, accuracy and familiarity for engineers. The limit equilibrium techniques for unreinforced slopes have been modified and extended to incorporate the effect of reinforcement by a lot of researchers. However, some approaches have the limitations of the shapes of failure surfaces. For example, the method of Jewell (1991) can only be suitable for bilinear failure surfaces. Leshchinsky and Boedeker (1989) assumed logarithmic spiral failure mechanism in the analysis. Besides, the circular failure surfaces were adopted by Hird (1986), Wright and Duncan (1991), Mandal and Labhane (1992), Mandal and Joshi (1996), Palmeira et al. (1998). In addition, some methods can only satisfy moment equilibrium such as those extended from the simplified Bishop slip circle analysis (Rowe and Soderman 1985), while others can only satisfy force equilibrium such as those extended from the Janbu’s method (Greenwood 1990; Sabhahit et al. 1994).

In this paper, a new rigorous approach satisfying both force and moment equilibrium is proposed to evaluate the stability of geosynthetic-reinforced slope by the extension of general limit equilibrium (GLE) method (Fredlund and Krahn 1977; Fredlund et al. 1981; Chugh 1986; Zhang 2005). The proposed method can be applied to both circular and arbitrary polygonal shape. The effectiveness of the method is confirmed by the comparison with other researchers and the centrifuge model test results.

1 Formulation of the Method

1.1 Determination of the reinforcing force

According to the pullout test results of Mitchell and Christopher (1990), the pullout resistance of the geosynthetic material can be estimated by the following equation:

$$t = 2 \cdot k \cdot \tan \phi \cdot \sigma_v \cdot l_e$$  \hspace{1cm} (1)

where $t$=the pullout resistance per unit width of geosynthetic sheet; $k$= a parameter related to the coefficient of friction at the interface between the soil and the geosynthetic material (within the range of 0.6~1.0); $\phi$ = the internal friction angle of the soil; $\sigma_v$ = average normal stress along the embedment length; $l_e$ = the embedment length beyond the failure surface.

In order to be conservative in the design in engineering practices, a factor of safety is introduced to present the mobilized pullout resistance of the geosynthetic material by the following equation:

$$t_m = 2 \cdot k \cdot \tan \phi \cdot \sigma_v \cdot l_e$$  \hspace{1cm} (2)

where $t_m$ = mobilized pullout resistance of the