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Parametric study of a loess slope based on unified strength theory

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ABSTRACT

The unified strength theory takes into consideration the effects of intermediate principal stress, and a series of yield surfaces can be determined using various values of parameter *b* which reflects the effects of the intermediate principal stress. The lower bound (obtained using $b = 0.0$) is the widely used Mohr–Coulomb failure law, and the upper bound (obtained using $b = 1.0$) is generalized as the twin-shear strength theory. In this study, a combination of a physical model experiment and numerical simulations using unified strength theory is used to analyze the influence of *b* on the failure and stability of a loess slope. An analysis shows that the size of the computed failure zone decreases noticeably with an increase in *b*. In contrast, the factor of safety (FOS) of the slope increases linearly with an increase in *b*, and an increase of 23–25% in the FOS can be obtained using $b = 1.0$ as compared to that for $b = 0.0$. A comparison of the physical model experiment and simulation shows that the range of $b = 0.25$–0.50 is valid for determining the failure characteristics and stability of the experimental loess slope.

1. Introduction

Slope stability is a crucial consideration in the field of slope engineering, as slope failure is often catastrophic and can involve the loss of lives and property. In the assessment of slope stability, the most basic theories are factor of safety (FOS) computation methods and the theory of material strength.

The methods for calculating the FOS of slopes can be grouped into at least four categories: (i) traditional limit equilibrium approaches (Bishop and A.M.I.C.E, 1955; Chen and Morgenstern, 1983; Lam and Fredlund, 1993; Morgenstern, 1965; Sarma, 1973; Stolle and Guo, 2008; Sun et al., 2016; Zhang, 1988; Zhou and Cheng, 2013; Zhu et al., 2003); (ii) upper bound approaches (Chen et al., 2001; Farzaneh and Askari, 2003; Gao et al., 2013; Yang et al., 1999; Yu et al., 1998); (iii) numerical simulation approaches (Griffiths and Fenton, 2007; Huang and Jia, 2009; Liu et al., 2017; Tu et al., 2016; Wei et al., 2009; Yu et al., 2014); and (iv) other approaches that include the uncertainty analysis method using fuzzy mathematics, reliability analysis method, grey system theory, and neural networks theory (Ching et al., 2009; Cho, 2013; Chowdhury and Xu, 1995; Dou et al., 2014; Hong and Roh, 2008; Li et al., 2014; Li et al., 2015b; Li et al., 2017; Oka and Wu, 1990; Park et al., 2012; Wang et al., 2005a). From among these methods, the first category remains the most widely used approach in engineering owing to its simplicity and practicability.

The literature (Yu, 1998, 2011) shows that the slope FOS values calculated using these methods are relatively similar. For example, the results calculated using the methods of Morgenstern and Chen and those calculated using fuzzy mathematics are almost the same, even though each method considers the equilibrium of forces and the shape of the sliding surfaces differently. This comparison also shows that regardless of the complementarity assertions or assumptions made, as long as the methods satisfy the overall equilibrium conditions, the deviation in the FOS calculated using various methods is < 5%.

In addition to the computational methods, the theory of material strength is also one of the most basic theories for assessing slope stability. At present, the Mohr–Coulomb failure law is the most widely used strength theory in practical engineering. The Mohr–Coulomb failure law is generalized as a single-shear strength theory, which cannot be used to explain several soil mechanics problems cannot be explained well. For example, the angle of internal friction obtained from a plane strain test is always greater than that from a conventional triaxial test, and the failure envelope of soil obtained from complex stress tests is generally difficult to reconcile with the Mohr-Coulomb failure law. These phenomena are known to be the result of the effects of the intermediate principle stress (σ_2) on the soil strength. While the Mohr–Coulomb failure law remains the most widely used strength theory in practical engineering, it does not take into account the effects of σ_2 or those of the intermediate principal shear stresses τ_{12} or τ_{23} ($\tau_{12} = (\sigma_1 - \sigma_2)/2$, $\tau_{23} = (\sigma_2 - \sigma_3)/2$, and $\sigma_1 > \sigma_2 > \sigma_3$, where σ_1, σ_2, and σ_3 are the three principal stresses). The slope FOS values

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calculated using the Mohr–Coulomb failure law are generally lower than the actual values. Therefore, a greater cost will be incurred in the slope engineering construction, which will result in a great deal of waste.

The unified strength theory, which takes into account the effects of the intermediate principal stress, is based on the assumption that the yielding of materials begins when the sum of the two larger principal shear stresses and the corresponding normal stress function reaches a magnitude *C*. The mathematical model of the unified strength theory can be expressed as follows (Yu, 1998; Yu et al., 1992):

$$F = \tau_{13} + b\tau_{12} + \beta(\sigma_{13} + b\sigma_{12}) = C \text{ when } \tau_{12} + \beta\sigma_{12} \geq \tau_{23} + \beta\sigma_{23} \tag{1a}$$

$$F = \tau_{13} + b\tau_{23} + \beta(\sigma_{13} + b\sigma_{23}) = C \text{ when } \tau_{12} + \beta\sigma_{12} \leq \tau_{23} + \beta\sigma_{23} \tag{1b}$$

In Eqs. (1a, 1b), σ_{13}, σ_{12}, and σ_{23} are the principal normal stresses, where $\sigma_{13} = (\sigma_1 + \sigma_3)/2$, $\sigma_{12} = (\sigma_1 + \sigma_2)/2$, and $\sigma_{23} = (\sigma_2 + \sigma_3)/2$; τ_{13}, τ_{12}, and τ_{23} are the three principal shear stresses, where $\tau_{13} = (\sigma_1 - \sigma_3)/2$, $\tau_{12} = (\sigma_1 - \sigma_2)/2$, and $\tau_{23} = (\sigma_2 - \sigma_3)/2$; β is the coefficient that represents the effects of the principal normal stress on the yield of materials; *C* is a strength parameter; and *b* is a yield criterion parameter that represents the effect of the intermediate principal shear stress on the yield of materials. The determination of the value of parameter *b* is important for the application of this theory. Till date, the parameter *b* could be investigated via various approaches such as the hollow cylinder compression–torsion test, true triaxial test, or the method of revised calculation.

With the unified strength theory, a series of yield surfaces can be determined using various values of parameter *b*. The lower bound can be obtained using $b = 0.0$, which is the widely used Mohr–Coulomb failure law. The upper bound, obtained using $b = 1.0$, is generalized as the twin-shear strength theory. Limit loci of the unified strength theory, which cover all regions of the convex limit loci in the stress space, are shown in Fig. 1. The strength behavior of a wide range of materials such as concrete, rock, sand, and clay can be modeled using unified strength theory provided that the value of *b* is appropriately chosen (Guo and Wang, 1991; Nakai and Matsuoka, 1983; Yu, 2011). Researchers have conducted true triaxial tests to determine parameter *b* in the unified

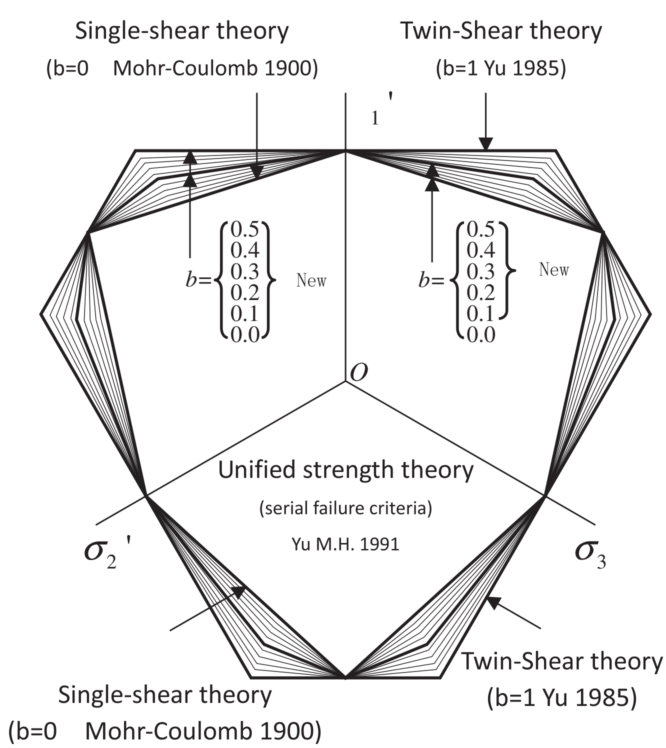

Fig. 1. Yield surfaces of the unified strength theory in the stress space.

strength theory, and the value $b = 0.5$ is reasonably recommended for compacted loess (Fang, 1986), undisturbed loess, as well as remolded loess (Xing et al., 1992). Recently, the unified strength theory has received considerable attention and has been widely used in fields such as civil engineering, geological engineering, and geotechnical engineering (Fan et al., 2013; Li et al., 2015a; Liao et al., 2008; Ma et al., 1999; Ma et al., 2012; Wang et al., 2005b; Yu, 1998, 2011; Yu et al., 2002; Zhang et al., 2012).

The main purpose of this paper is to study the influence of parameter *b* on loess slope behaviors under complex conditions and to propose appropriate *b* values for various applications. A physical model experiment combined with numerical simulations and the method of revised calculation was therefore performed in order to realize the above-mentioned objective. A physical model experiment was first conducted to determine the distributions of stress, deformation, and crack characteristics of a loess slope under loading. Next, the code for the unified strength theory was programmed using Visual Studio C + + and saved as a Dynamic Link Library (DLL) file that could be called by the FLAC3D program. Numerical simulations of a geo-technical model identical to the physical model experiment were conducted to evaluate the states of the stress, deformation, failure zones, and slope FOS. Finally, the influence of the unified strength theory on a loess slope is determined by analyzing computer simulations using various values of *b*. Appropriate values of *b* are determined for the experimental loess slope by comparing the results of the physical model experiment and the numerical simulations.

2. Behavior of a physical model of a loess slope under loading

2.1. Physical model experiment design

A loaded 1-g physical model slope, which is a widely used method owing to its economy and practicability, is adopted in this work to evaluate the failure of a loess slope and to study the influence of the strength theory on the loess slope under loading. According to statistics and literature, the width and thickness of the failure zone in a slope with a given height are generally limited. The use of improper dimension ratios for the physical model will result in a great deal of waste. Consequently, in order to obtain representative relative dimension ratios for the physical model slope and to reduce testing costs, numerous classical loess landslides have been studied as prototypes. The characteristics of these loess landslides were derived from corresponding journals and are presented in Table 1, where *W, L, H,* and *S* represent the width, length, and height of the slope, and the length of the slope crest, respectively. The values of *L/H* and *S/H* of the physical model were determined on the basis of the median values, and the model was designed to have a value of $W/H > 3.0$ because the three-dimensional spatial effects on the slope failure can be ignored when $W/H > 3.0$ (Yan and Zhu, 2011). The dimensions of the physical model are represented in Eq. (2).

$$\begin{cases} W_m > 3H_m \\ L_m > 2.5H_m \\ S_m = 0.6H_m \end{cases} \tag{2}$$

where the subscript *m* denotes "model."

Our physical model was designed as a single-stage slope with a horizontal crest and foot. Based on Eq. (2) and the experimental budget, the value of H_m was set as 0.85 m; the value of S_m, which is equal to the length of the side of the load-bearing plate, was set as 0.5 m; and the slope angle, height, and length of the slope foot were set as 60°, 0.5 m and 1.01 m, respectively. Considering the boundary conditions of the potential sliding range and taking the headspace above the slope crest into account, the dimensions of the final design of the physical model box were 3.0 m × 2.5 m × 1.8 m. The box was welded using steel U beams and steel plates, with an attached trestle and track set for