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Stability charts for uniform slopes in soils with nonlinear failure envelopes

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ABSTRACT

Based on the results of an extensive parametric study, charts were developed for assessment of the stability of uniform slopes in soils with nonlinear shear strength failure envelopes. The study was conducted using envelopes formed to represent the realistic shapes of soil nonlinear drained strength envelopes and the associated different degrees of nonlinearity. The introduction of a simple methodology to describe the nonlinear envelopes and a stability parameter, the value of which depends on the degree of this nonlinearity has made it possible to produce such charts. The presented charts are easy to use and do not require an iterative procedure when determining the safety factors. They can be used for the analysis of dry slopes, slopes subjected to pore-water pressures represented by piezometric surfaces or pore-water pressure ratios, and slopes exposed to seismic forces. Numerical examples are given to illustrate the different applications of the presented charts, as well as the importance of considering nonlinearity of the soil strength envelope in the analysis of uniform slopes.

1. Introduction

Stability charts provide a means for rapid or preliminary analysis of slope stability. They are still routinely presented in the literature (e.g., Baker, 2003a; Eid et al., 2006; Michalowski, 2010; Steward et al., 2011) and used in practice in spite of the availability of many sophisticated slope stability software. The preciseness of slope stability charts is usually as good as the accuracy with which soil shear strength can be measured. Factors of safety against sliding (F) determined utilizing stability charts or software are sensitive to the type and magnitude of parameters used to describe soil shear strength or failure envelope.

It has long been recognized that failure envelopes of many soils are significantly nonlinear especially at low normal stress range (Terzaghi and Peck, 1948). Although this range is usually relevant to slope stability analysis since slip surfaces must intersect with the slope surface, few of the available literature (e.g., Bishop et al., 1965; Singh et al., 1973; Chandler, 1984; Day and Axten, 1989; Perry, 1994) include shear strength data derived from drained direct shear, ring shear, or triaxial testing at this stress range. The effect of considering the nonlinearity on slope stability is problem dependent, and increases with decreasing the overlap between the ranges of experimental and relevant effective normal stresses. The calculated value of F may increase or decrease with the degree of such overlap (Baker, 2003b).

The conventional approach in slope stability analysis has been to approximate the actual curved failure envelope to the linear Mohr–Coulomb relationship in terms of cohesion intercept (c') and friction angle ($ø'$) as shown in Fig. 1. Use of these parameters in slope stability analysis could lead to the determination of a considerably deeper critical slip surface and an associated higher factor of safety than those observed and determined using the actual, i.e., nonlinear envelope, as this approximation overestimates shear strength values at low normal stresses (Mesri and Abdel-Ghaffar, 1993; Popescu, 2000; Baker, 2003b; Jiang et al., 2003). However, most of the available stability charts for uniform slopes failing under a drained condition utilize c' and $ø'$ of the linearly approximated strength envelope (e.g., Taylor, 1937, 1948; Bishop and Morhenstern, 1960; Bell, 1966; Spencer, 1967; Janbu, 1968; Singh, 1970; O'Connor and Mitchell, 1977; Cousins, 1978; Barnes, 1991; Baker and Tanaka, 1999; Michalowski, 2002; Baker, 2003a; Michalowski, 2010; Steward et al., 2011).

Through adopting a simple method of describing nonlinear shear strength envelopes, this paper presents charts for determining the uniform slope factors of safety against rotational sliding in static and seismic loading conditions. The presented charts help in understanding the relative sensitivity of such safety factors to the soil strength envelope degree of nonlinearity along with the other soil properties and slope parameters. This was achieved based on results of an extensive parametric study that is described in a subsequent section.

2. Previous investigations

Several methods were suggested to describe soil nonlinear failure envelope to be used in computational tools or graphical representations. These methods were adopted to avoid miss-estimation of shear strength at small or large effective normal stresses that are not covered by the experimental data points and consequently not well represented by c' and

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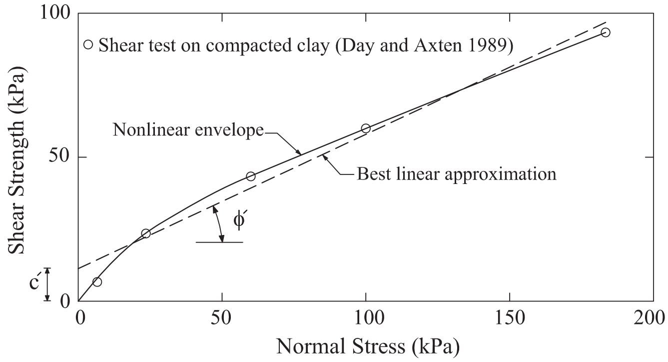

Fig. 1. Typical soil drained strength nonlinear failure envelope and its linear approximation.

ø′ parameters, i.e., Mohr–Coulomb linear envelope, determined using such points. Due to its convexity, the nonlinear envelope provides a conservative estimate of shear strength compared with the Mohr–Coulomb relationship in normal stress ranges where there is no experimental information. Baker (2003b) suggested an iterative process to adjust values of c' and ø′ to better represent the shear strength in normal stress range relevant for a specific uniform slope. The process involves evaluating an initial safety factor and the corresponding maximum normal stress on slip surface utilizing graphical or mathematical tools such as Taylor's stability charts and Janbu's approximation of the normal stress function. Then, an equation should be used for the iteration. A single iteration is usually (but not always) sufficient to have a good estimate of the safety factor.

In slope stability studies presented in Skempton (1985), Mesri and Abdel-Ghaffar (1993) and Eid (2010), the envelope curvature was expressed in terms of the ratio of the secant friction angle at a given stress to that at a standard stress. Strength functions or relations between effective normal stress (σ') and the associated shear strength (τ) were also used to describe the failure envelope nonlinearity. These include bi-linear functions (Lefebvre, 1981), tri-linear functions (De Mello, 1977), and power-law relations (De Mello, 1977; Charles and Watts, 1980; Charles and Soares, 1984; Collins et al., 1988; Maksimovic, 1989; Perry, 1994; Baker, 2004). The most commonly used power-law relation has the general form of $\tau = A(\sigma')^b$, where A and b are constants. The magnitude of τ at any value of σ' is directly proportional to the value of A. In contrast, the degree of envelope curvature is inversely proportional to the value of b which equals to 1.0 in case of linear envelopes passing through the origin. Curve-fitting software should be used to determine values of A and b needed to form the power-law relation that best represents the curved shear strength failure envelope. The power-law relations yield envelopes that have vertical tangents at the origin. In addition, the A and b constants depend on the units used and have no physical meaning.

Utilizing a proposed simple uniform dry rock fill that slopes at an angle with the horizontal (β) of 45° and has values of b between 0 and 1.0, Charles (1982) showed that the depth of the critical slip surface is strongly dependent on the strength envelope degree of curvature, i.e., the value of b, and the factor of safety is inversely proportional to the value of $H^{(1-b)}$, where H is the slope height. Charles and Soares (1984) introduced a stability function Γ for rotational failures in uniform slopes, the magnitude of which should be determined using stability charts and values of β and b, to estimate the factor of safety as $F = \Gamma A/(\gamma H)^{1-b}$. The charts were developed for values of b between 0.5 and 0.9. This narrow range along with the difficulty of determining the values of A and b has limited the use of such charts.

3. Parametric study

A parametric study was conducted on proposed uniform slopes with different inclinations and soil properties to determine the minimum factor of safety against rotational sliding. Slopes with heights of 5, 10, and 15 m were analyzed in this study. Slope angle is taken to be 10, 15, 20, 25, 30, or 35°. Slopes with the commonly used inclinations (i:1) of 2:1, 3:1, and 4:1 were also analyzed (Figure 2). Representing water pressures using different pore-water pressure ratios (r_u) or water-table heights (H_W) was considered. Unit weight of soils (γ) is assumed to be 18 or 21 kN/m^3. Method of analysis and presentation of soil shear strength and pore-water pressures needed for the parametric study were adopted based on the following considerations.

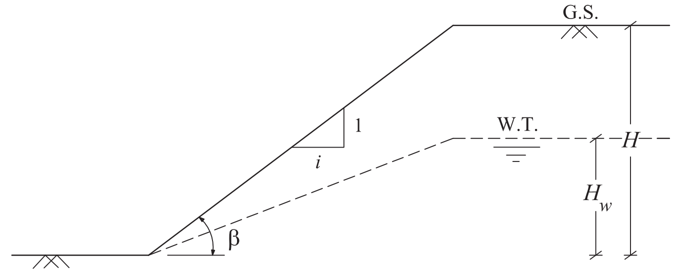

Fig. 2. Slope geometrical parameters used in the parametric study.

3.1. Method of analysis

Spencer's (1967) stability procedure for the method of slices as coded in the slope stability computer program UTEXAS3 (Wright, 1992) was utilized in all of the stability analyses presented in this study. Both force and moment equilibriums are satisfied in Spencer's method. This method is regarded as being accurate, i.e., within 6% of the correct two-dimensional factor of safety (Duncan, 1992). The employed program allows for circular and noncircular slip surface search and the use of both linear and nonlinear failure envelopes. Nonlinear envelope can be modeled using normal and shear stress combinations (points) located along the envelope. The points should be input by the user. The program connects each two successive points by a straight line to create the continuous envelope. Each nonlinear envelope utilized in the analysis was modeled using nineteen points. The points were concentrated at low normal stress range in which the nonlinearity is more pronounced. Due to this high number and distribution of input points, each envelope developed by the program in this research is almost identical to (i.e., perfectly coincides on) the modeled one. This way of modeling nonlinear strength envelopes is unique for the utilized computer program and perfectly suits the nature of the current study.

Following the stability method of slices, this study defines the minimum safety factor as the ratio between the resisting and driving moments around the center of rotation of the critical sliding surface. Because of considering the actual curved failure envelope, the sliding resistance is represented entirely by the friction forces. As a result, the effect of shear strength envelope nonlinearity on the safety factors calculated was included through the dependency of the maximum shear strength on the effective normal stress acting on the base of each slice. The balance between the driving and resisting moments can be simply described as

$$\sum T_d.R = \sum N_e.\frac{\tan\phi'_e}{F}.R \tag{1}$$

where T_d = tangential component of the total weight acting on the slice base, N_e = effective normal stress acting on the slice base, R = radius of rotation, and $ø'_e$ = secant friction angle determined for the nonlinear shear strength envelope at normal stress of N_e. Eq. (1) can be rewritten to clearly define the factor of safety used in this study as

$$F = \frac{\sum N_e.\tan\phi'_e}{\sum T_d}. \tag{2}$$