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Technical Note

A simplified approach to determine the unique direction of sliding in 3D slopes

Yukuai Wan [a,b], Yufeng Gao [a,b,*], Fei Zhang [a,c]

[a] Key Laboratory of Ministry of Education for Geomechanics and Embankment Engineering, Hohai University, No. 1, Xikang Road, Nanjing 210098, China
[b] Jiangsu Research Center for Geotechnical Engineering Technology, Hohai University, Nanjing 210098, China
[c] Key Laboratory of Failure Mechanism and Safety Control Techniques of Earth-rock Dam of the Ministry of Water Resources, 223 Guangzhou Road, Nanjing 210029, China

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ABSTRACT

Based on the Spencer's method, this paper presents a simplified approach to assess the stability of three-dimensional (3D) asymmetrical slopes. The approach allows for satisfaction of the force equilibrium in all three directions and the moment equilibrium about two co-ordinate axes. A unique direction of sliding is involved here to calculate the factor of safety. The direction of sliding (DOS) is always parallel to the plane of symmetry for symmetrical slopes. However, the DOS in asymmetrical slopes could deviate from the symmetrical plane and affect the stability assessments. Through two simple asymmetrical examples, the calculated results demonstrate that the deviation of the sliding from the symmetry could destabilize the slopes and cause failures. Neglecting the DOS in 3D asymmetrical slopes will overestimate their stability. Application of the presented approach into complex asymmetrical problems is straightforward.

1. Introduction

Stability analysis of slopes involves idealized two-dimensional (2D), plane-strain conditions; however, in most cases, the geometry of the slopes has three-dimensional (3D) characteristics, such as corners, conical heaps and dams in narrow valley. Field observed failure surfaces for slopes possess spatial variability. The 2D idealization ignores the 3D effect and may lead to a conservative result. Many attempts have thus been made to extrapolate the application of traditional methods for slope stability analysis from the 2D to the 3D case. These 3D analyses mostly include limit equilibrium (LE) method, limit analysis (LA) method and finite element (FE) method. The traditional two-dimensional LE methods are widely used in practice to evaluate the slope stability. In the past few decades, many LE methods were developed to estimate the 3D effects on the safety of slopes, such as Baligh and Azzouz (1975); Hovland (1977); Hungr et al. (1989); Hungr (1987, 1994) and Lam and Fredlund (1993, 1994). However, these proposed approaches are limited to symmetrical slopes. Most natural slopes are under the asymmetrical conditions induced by the complex geometry, variable soil stratigraphy, external loading, seismic forces, or other factors. Current 3D analyses based on LE have not been satisfied and three drawbacks (Cheng and Yip 2007) can be attributed to LE as: direction of sliding (DOS) neglected in the LE formulations, difficult determination of the critical nonspherical 3D failure surface and instability of the numerical calculations under transverse horizontal forces. So far, all the issues are difficult to be solved in one LE approach. The paper will focus on the DOS in LE analysis of 3D slope stability.

In a symmetrical slope, the DOS is always parallel to the plane of symmetry in geometry. When asymmetrical conditions prevail in a slope, the DOS needs to be determined in the 3D analysis as it could impact to the assessment of slope stability. The potential failure mass of 3D slope is discretized into many vertical columns in LE analysis, as shown in Fig. 1. Hungr et al. (1989) applied Bishop's method and Janbu's method into 3D asymmetrical slopes. However, these methods do not take the DOS into account. Huang and Tsai (2000) developed a 3D Bishop's simplified method based on two-directional moment equilibrium to calculate the safety factor of 3D slope. The different DOS for each soil column is taken into account and given as a part of the solution. Huang et al. (2002) then extended the method to involve the arbitrary-shaped failure surface using two-directional force and moment equilibrium. The extended method can be regarded as a Janbu's method. This method may yield a failure to converge under the transverse loads (e.g., earthquakes). Chen and Yip (2007) attributed the problem to the assumption of the different DOS in each soil column and then adopted a unique DOS of the soil columns to develop the 3D analysis based on Bishop's simplified, Janbu's simplified and Morgenstern-Price's methods. However, the unique DOS is determined for a given factor of safety. Based on simplified Bishop's and Janbu's

* Corresponding author at: Key Laboratory of Ministry of Education for Geomechanics and Embankment Engineering, Hohai University, No. 1, Xikang Road, Nanjing 210098, China.
E-mail addresses: wanyukuai@163.com (Y. Wan), yfgao66@163.com (Y. Gao), feizhang@hhu.edu.cn (F. Zhang).

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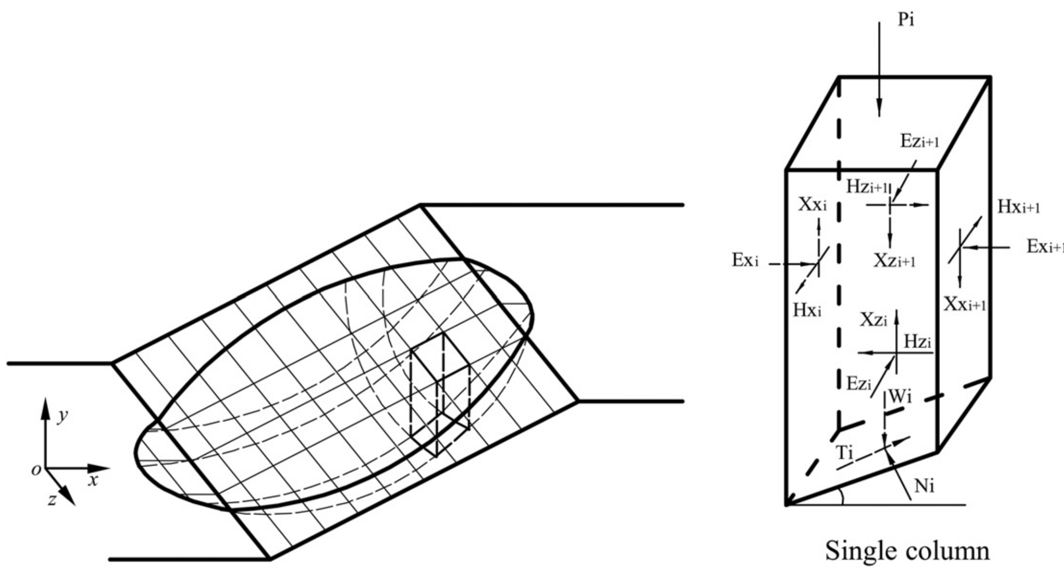

Fig. 1. Discretization of a failure mass.

methods, Kalatehjari et al. (2014) minimized the safety factor of the asymmetrical slope and obtained the corresponding unique DOS. Although these proposed methods can be used to predict the safety of complex asymmetrical slopes, the vertical shear force components of the inter-column force are neglected in their methods based on simplified Bishop or Janbu. Assuming the parallel inter-column forces on row-interfaces, Chen et al. (2003) extended Spencer's method from 2D into 3D conditions and then developed a simplified approach to assess stability of 3D slopes. Two examples of practical applications demonstrate the good use of such approach to solving asymmetrical problems. However, this method made a simple assumption on the distribution of the direction of the shear force (or DOS) on the base of each soil column. Such an assumption may have influences on the stability assessment of asymmetrical slopes. The purpose of this study is to predict the unique direction of 3D sliding using the simplified Spencer's method (Chen et al. 2003). To minimize the factor of safety, its associated unique DOS can be determined in asymmetrical problems. Meaningful comparisons are made to demonstrate the performance between the presented approach and other methodologies.

2. Formulation of 3D Spencer's method

Performing LE analysis of 3D slope stability, the potential failure mass of a slope is discretized into a number of columns with vertical interface. The internal and external forces acting on the various faces of each column are illustrated in Fig. 1. To establish the force and moment equilibrium, the following assumptions are made.

(1) Mohr-Coulomb failure criterion is adopted.
(2) The conventional definition for factor of safety F reduces the available shear strength parameters c' and ϕ' by the following equations to bring the slope to a limiting state.

$$c'_d = \frac{c'}{F} \tag{1}$$

$$\tan\phi'_d = \frac{\tan\phi'}{F} \tag{2}$$

where c' and ϕ' = the effective cohesion and friction angle of the soil, respectively; c_d' and ϕ_d' = soil strength parameters necessary to maintain the structure in limit equilibrium, respectively.

(3) The horizontal shear forces, Hx_i and Hz_i, are not included in the formulation. Such an assumption was also adopted in other methods by researchers (e.g., Hungr 1987; Huuang and Tsai, 2000; Cheng and Yip 2007). It is assumed that the relationships between the intercolumn vertical shear forces, Xx_i and Xz_i, and normal forces, Ex_i and Ez_i, in the x- and z-directions are given as

$$Xx_i = Ex_i\lambda_x \tag{3}$$

$$Xz_i = Ez_i\lambda_z \tag{4}$$

where λ_x and λ_z = intercolumn shear force factors in the x- and z-directions, respectively. The weight of soil column, W_i, and the vertical external force acting on the top of the column, P_i, are assumed to act at the center of each column for simplicity. The normal and shear forces, N_i and T_i, on the base of each soil column can be treated as vectors, $\mathbf{N_i}$ and $\mathbf{T_i}$, as

$$\mathrm{N_i} = N_i(n_{xi}, n_{yi}, n_{zi}) \tag{5}$$

$$\mathrm{T_i} = T_i(m_{xi}, m_{yi}, m_{zi}) \tag{6}$$

where (n_x, n_y, n_z) and (m_x, m_y, m_z) are unit vectors for $\mathbf{N_i}$ and $\mathbf{T_i}$, respectively.

(4) Soil columns are assumed to move in the same direction, i.e. the DOS is unique on the x-z plane for all columns. The unique DOS, a, is equal to the angle between positive z-axis and the projection of the shear force $\mathbf{T_i}$ on the base of each soil column in x-z plane (measured counterclockwise from the positive z-axis).

The unit vector, (m_x, m_y, m_z), for $\mathbf{T_i}$ can be determined by the following equations:

$$\begin{cases} m_x^2 + m_y^2 + m_z^2 = 1 \\ m_x * n_x + m_y * n_y + m_z * n_z = 0 \\ m_x = \tan a * m_z \end{cases} \tag{7}$$