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Three-dimensional stability analysis of slope in unsaturated soils considering strength nonlinearity under water drawdown

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A B S T R A C T

In slope stability analyses, the soil has been frequently considered dry or saturated, whereas the soil is in fact unsaturated in many cases. Owing to the existence of matric suction, the strength properties of unsaturated soils are greatly different from dry or saturated soil, and thereby leading to diverse stability conditions of the slope. Based on the kinematical approach of limit analysis, in this study, a three-dimensional (3D) stability analysis was conducted for slopes in unsaturated soils. The effects of matric suction distribution patterns, the nonlinearity of the strength under soil-water characteristic curves and the water drawdown were investigated to explore the shear strength and stability of a slope in unsaturated soil. It was found that, when the matric suction is uniformly distributed, the stability factors of the slope increase linearly along with the matric suction. In addition, when the matric suction increases linearly with the depth, the enhancing effect of the matric suction on the slope stability intensifies as the variation magnitude of the matric suction increases, especially for a gentle slope with a narrower width. For nonlinear patterns, different soil-water characteristic curve (SWCC) models will lead to diverse shear strengths and stability conditions of the slope. The water drawdown has significant effects on the functions of the matric suction as well as slope stability.

1. Introduction

A slope stability analysis, which is an important and classical issue in geotechnical engineering, has been mostly performed under two-dimensional (2D) plane strain conditions under the assumption that the soils is dry or saturated. However, soil is in fact generally unsaturated in nature (Hoyos et al., 2015; Oh and Lu, 2015). In addition, a slope stability assessment is typically a three-dimensional (3D) problem, and a number of studies have shown that 2D failure modes will lead to conservative estimations of the slope stability (Michalowski and Drescher, 2009). Owing to the existence of matric suction, the strength behavior and properties of unsaturated soils differ greatly from dry or saturated soil, leading to diverse slope stability conditions. Thus, in many cases, it is inappropriate to ignore the unsaturation of soils and simply treat it as dry or saturated. The pore water pressures and water drawdown are decisive factors on the slope stability, and when the matric suction, in particular is taken into account, the water level drawdown directly influences the slope stability, and more importantly, changes the acting zone and magnitude of the matric suction inside the slope. It is of both theoretical and practical significance to investigate the stability of 3D slopes subjected to a water drawdown in unsaturated soils.

Many methods can be used to investigate the 3D stability of a slope, introducing the rigorous limit equilibrium method (RLE), the discrete element method (DEM), the general particle dynamics numerical method, the discontinuous deformation analysis (DDA) method and the limit analysis method.

With regard to the rigorous limit equilibrium method for a 3D slope stability analysis, which takes the inter-column forces into account, the RLE method was established by Zhou and Cheng (2013) based on the three-axial-direction force equilibrium conditions and three direction moment equilibrium conditions around the three coordinate axes. The relationship between the width of a sliding body and the safety factor as well as the value of the safety factor itself, were determined. The presented method was proved to be valid through a practical application. Zhou and Cheng (2014) investigated the stability of a 3D slope subjected to seismic forces when applying a combination of the RLE and the pseudo-dynamic method. A new limit equilibrium method to analyze the stability and displacement of three-dimensional creeping slopes was proposed by Zhou and Cheng (2015).

For the discrete element method, Assefa et al. (2017) analyzed a deep-seated slope movement in a complex rock formation. The DEM

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approach was adopted to simulate the slope as a complex blocky structure defined by bedding planes, inclined and sub-vertical joints. Different hypotheses regarding the geometry of the slip surface, compatible with field evidences, are discussed. Camones et al. (2013) investigated the step-path failure mechanism in fractured rock masses using the discrete element method (DEM). Crack propagation and coalescence were simulated in biaxial and triaxial laboratory tests, and simple examples of this mechanism were modeled for a better understanding of the failure mechanism. Salmi et al. (2016) analyzed the impacts of underground mining on the stability of a slope using numerical modeling based on a coalmining induced landslide at Nattai North, Australia, as a typical case study. Discontinuous numerical modeling was employed to analyze the mechanisms of the ground movements leading to landslide. The role of geological and geotechnical factors on the slope stability were discussed.

Regarding the general particle dynamics numerical method, Zhou et al. (2015) proposed the general particle dynamics approach (GPD3D) to simulate the failure process (initiation, growth, and coalescence of cracks macro-failures) of a slope.

The discontinuous deformation analysis method (DDA) was presented by Jing (1998) to investigate the deformations of geometrically complex blocks in rock mechanics and engineering geology. The advantages and shortcomings of DDA were illuminated, and the solutions by DDA were compared with the explicit distinct element method and the finite element method.

The limit analysis method, the approach adopted in this study is effective and has been widely used to investigate the stability problems of foundations, tunnels (Li and Yang, 2018; Yang and Zhang, 2018), slopes (Yang and Li, 2018) and other geotechnical structures. Slope analyzed using the limit analysis method can be divided into two parts based on the standard of dimensionality, i.e., (1) a 2D stability analysis and (2) a stability analysis under 3D conditions. In terms of a 2D stability analysis, considering the seismic forces, Qin and Chian (2017) analyzed the stability of a two-stage slope in layered soil, proposed a closed-form solution to the kinematic stability of a slope, and investigated the influences of the soil weight and cohesion, soil nonhomogeneity, and external factors such as seismic forces on the slope stability. Through a numerical analysis approach, Gischig et al. (2015) conducted a rock slope stability analysis to demonstrate the roles of amplification in enhancing the co-seismic slope deformation.

For a slope stability analysis under 3D conditions, Michalowski and Drescher (2009) proposed a 3D rotational failure mechanism of a slope with a spiral conic shape in accordance with the normality rule, and derived the expression of critical height of a 3D slope based on the limit analysis method, and investigated the influences of the 3D geometry characteristics and soil strength on the slope stability. Lim et al. (2016) presented sets of stability charts of a slope in purely cohesive clay using the finite element limit analysis method.

With regard to investigations on unsaturated soil, Fredlund et al. (1978) proposed an extended expression of the Mohr-Coulomb failure criterion to take into account the effects of matric suction on the shear strength of various types of soil. Thereafter, Bao et al. (1998), Fredlund et al. (1996), Khalili and Khabbaz (1998), Vanapalli et al. (1996), and Vilar (2006) also proposed expressions to estimate functions of the matric suction on the shear strength of unsaturated soils. Zhang et al. (2014) performed a stability analysis of 2D slopes in unsaturated soil considering the strength of the nonlinearity aiming at diverse soil types based on the soil-water characteristic curve (SWCC, i.e., permeability function), investigated the effects of soils strength nonlinearity on the slope stability, and proposed relevant recommendations for practical use. Houston et al. (2008) performed a series of unsaturated soil triaxial tests to investigate the strength properties and shear-induced volume change behavior of unsaturated soil, as well as the feasibility of unsaturated soil property estimation functions. Based on the moment equilibrium method, an investigation into the critical embedment depth for a rigid retaining wall in unsaturated soils was conducted by Zhang et al. (2016a,b), and the effects of the matric suction distribution patterns on the objectives were illustrated. Tarantino and Mountassir (2013) investigated the stability of geotechnical structures in unsaturated soils, adopting an accessible approach for a hydraulic and strength behavior estimation of unsaturated soils.

It should be noted that investigations into the slope stability of a slope, regardless of under 2D or 3D conditions, have been mainly conducted in dry or saturated soil, even though soil is commonly unsaturated in nature (Fredlund et al., 1978; Lu and Likos, 2004), and only a few investigation into the stability of 3D unsaturated slopes have been applied. Matric suction, which exists in unsaturated soils, makes the physical properties and behavior of unsaturated soils greatly different from those of dry or saturated soils, resulting in different stability conditions of various slopes. As a consequence, the question, which has both theoretical and practical importance, is how to estimate the 3D stability of a slope in various unsaturated soil under different matric suction distributions and pore water levels. In this regard, based on the kinematical approach of limit analysis theorem, a 3D stability analysis of a slope subjected to water level drawdown in unsaturated soils was conducted in this study. External work rates by soil weight, pore water pressure and matric suction as well as the internal energy dissipation were calculated, and expressions of the critical heights of a slope were then derived using an energy equilibrium equation. The effects of matric suction distributions, soil shear strength nonlinearity under diverse SWCC models and water level drawdown on the slope stability were investigated after optimization, and some numerical solutions were presented.

2. Upper bound theorem

The limit analysis method assumes that the soil deforms plastically according to the normality rule. The present method also states that the internal energy dissipations are no less than the work rates by external forces (Pan and Dias, 2017; Yang and Yao, 2018), namely

$$\int_V \sigma^*_{ij}\dot{\varepsilon}^*_{ij}dV \geq \int_S T_i v_i dS + \int_V X_i v_i^* dV \quad (1)$$

where $\dot{\varepsilon}_{ij}^*$ is the strain rate; σ_{ij}^* is the stress rate tensor, S and V are the boundary and volume of a failure block, respectively; T_i is the surcharge load on boundary; X_i is the body force in volume V; and v_i is the velocity along the potential sliding surface.

3. Shear strength of unsaturated soils

Equations for the estimation of unsaturated soils shear strength can be classified into two categories, i.e., linear equations (Fredlund et al., 1978; Zhang et al., 2016a,b) and nonlinear equations (Bao et al., 1998; Fredlund et al., 1996; Vanapalli et al., 1996; Khalili and Khabbaz, 1998; Vilar, 2006). In this study, both linear and nonlinear equations were adopted to demonstrate the effects of matric suction on the stability of a 3D unsaturated slope.

3.1. Linear conditions

For the linear conditions, the uniformly distributed condition of the matric suction and its linearly increased conditions, along with depth, were adopted in this study, as shown in Fig. 1.

3.1.1. Unified shear strength

The equation for the shear strength estimation of unsaturated soils proposed by Fredlund et al. (1978) in the form of the Mohr-Coulomb failure criterion is the most representative function and was adopted in this study to describe the shear strength of unsaturated soils under a linear condition in which the matric suction is uniformly distributed, as shown in Fig. 1(a)