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Research Paper

Influence of swelling behavior on the stability of an infinite unsaturated expansive soil slope

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A R T I C L E I N F O

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A B S T R A C T

The influence of the stress regime change and associated softening can be significant on unsaturated expansive soil slope stability due to soil swelling upon wetting, which cannot be considered in conventional hydrological models. In this paper, the shallow expansive soil slope failure mechanism is addressed in the framework of an infinite slope formulation. The unsaturated soil elasto-plastic constitutive relationship is utilized for interpretation of stress regime evolution induced by expansive soil swelling during infiltration. The extended Mohr–Coulomb failure criterion for unsaturated soils is used as the yield surface, under which the nonlinear elastic behavior is considered by quantifying the effect of two stress state variables (net stress and suction) on elasticity parameters. The strain softening behavior in unsaturated soils is accounted for via reducing the material parameters of the yield surface with respect to plastic deviatoric strain. A numerical exercise is performed on a relatively gentle slope in Regina, Canada with highly expansive soil properties, using the developed computer program that implements the constitutive model into infinite slope formulation. The results suggest that neglecting the swelling-induced stress change and associated softening behavior can significantly overestimate the stability of expansive soil shallow layer under infiltration, in terms of both failure occurrence and failure time. Additional parametric study shows that all the considered parameters (including initial stress condition, softening rate and slope angle) have a considerable effect on the failure time and failure depth of the shallow deposit, which have important implications for the engineering design of expansive soil slopes.

1. Introduction

Infiltration (rainfall, ground snow melting or other types) induced shallow failures of expansive (swelling) soil slopes are frequently reported in many countries around the world, including Canada [1], China [2–5], Spain [6,7], and United States [8]. The wetting-induced slope failure in expansive soil advances in a progressive pattern typically initiating at or near the toe of slope. The progressive failures of slopes were observed a long time ago (e.g. [9]), and were usually interpreted using strain softening behavior of soils (e.g. [10,11]). Many investigators have used numerical techniques, such as the Finite Element Method [12–16] and the Material Point Method [17,18], to reproduce and (or) quantify the progressive failures, based on strain softening Mohr–Coulomb elasto-plastic model [12–14,17,18], elasto-viscoplastic model [15] or pragmatic Modified Cam Clay model [16].

Most of the previous numerical analyses were mainly conducted within the framework of saturated soil mechanics. The surficial layer of expansive soil slopes addressed in the present study occurs in a state of unsaturated condition, and are likely to fail before attaining fully saturated condition. There is significant evidence of the strain softening behavior of unsaturated soil specimens in the literature from laboratory test results (e.g. [4,19–22]). Hoyos et al. [19] suggested that the residual shear strength contribution due to suction may be described using models similar to that postulated for peak shear strength of unsaturated soils (e.g. [23,24]). The experimental results of triaxial tests conducted by Miao et al. [20] on expansive soils at several constant suction values showed that the deviator stress gradually decreased with increasing axial strain after reaching peak values. Similar trends of results were also observed from the direct shear tests carried out by Zhan and Ng [21] on expansive soils. In order to simulate stress path within the slope soil subjected to rainfall infiltration, a different loading sequence (i.e. shearing infiltration: reducing the suction after shearing by increasing the net deviator stress to a prescribed level) was applied to unsaturated expansive soil specimens by Zhan et al. [4] and Gui and Wu [22] in a series of triaxial tests. The results from both the shearing infiltration tests also

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indicated a softening behavior as those observed in constant-suction shear tests (e.g. [20]).

The significant swelling of expansive soils upon wetting would be another important factor contributing to infiltration-induced shallow slope failures. This is because the swelling deformation can induce a constant and substantial change in the net stress regime of slope, especially within the surficial layer where the suction in soil element is reduced by water infiltration. The swelling-induced stress exerting on a soil element has the same effect as the external net stress. When the amount of non-uniform stress (in-situ stress plus the swelling-induced stress) state reaches the strength of soil element, local failure starts to occur at that particular point within the slope profile. Expansive soil exhibits swelling potential in any direction, however, the amount of swelling-induced pressure in one direction might be different from another, depending on the deformation allowed in the corresponding direction. The vertical swelling pressure can be high and result in severe distress on lightly loaded buildings constructed on expansive soil ground. Vanapalli and Lu [25] provided a comprehensive summary of these research studies. However, for the shallow layer of expansive soil, the swelling induced stress can be essentially released in the direction perpendicular to the sloping surface since soil is allowed to swell freely. While, a large amount of stress along the sloping direction will be formed due to constraints exerted on the soil deformation. Many previous laboratory measurements on expansive soils suggested that the lateral swelling stress can be several times higher than the vertical stress (e.g. 2 times from [26], up to 10 times from [27], up to 3 times from [28]) under laterally confined condition. In-situ records also showed that the horizontal earth pressures due to soil expansion can be much higher than the vertical stress (e.g. 1.3–5.0 times from [29] and 2–4 times from [30]). For sloping ground, the maximum ratio of stress parallel to the sloping direction to the total vertical stress was observed to be 3 by Ng et al. [31] in an expansive slope in Zaoyang, China during an artificial rainfall period. Under such condition, the passive failures within an unsaturated soil element are likely to occur [32] and initiate the failure of expansive soil slopes.

There is a strong link between the above two phenomena (i.e. swelling-induced stress and softening behavior) observed from experimental results. These phenomena can likely contribute to the shallow sliding in in-situ expansive soils. The effect of these phenomena on stability has not been explicitly considered or well discussed in the most existing numerical seepage analyses and coupled hydro-mechanics analyses (e.g. [33]) extending the principles of unsaturated soils. The main objective of the present study is to investigate the evolution of stress regime, softening behavior, and their effect on expansive soil slope stability upon infiltration in the framework of infinite slope formulation.

The infinite slope formulation has been extensively used in assessing stability of slope shallow layer in the past [34]. One of the main advantages of this infinite slope model is that it provides a numerically cheap and rapid estimation of the factor of safety. The basic assumption of this simplified model is that the sliding mass extends infinitely in the sliding direction (i.e. generally in a downslope direction), which is considered rational for shallow landslides. Milledge et al. [35] tested this assumption by comparing the results from infinite slope formulation against those obtained on 5000 synthetic two dimensional slopes using the finite element strength reduction approach presented by Griffiths and Lane [36]. This study provided quantitatively the errors that the infinite slope formulation may induce, as well as the critical length/depth ratio above which the errors are acceptable (within 5%) for different slope scenarios. In addition to calculation of *FS*, the infinite slope formulation has also been used to analyze stress and strain (displacement) evolution before slope collapse or interpret the shear mechanism responsible for the shallow slides (e.g. [37–40]). More recently, this simplified model has been combined with probabilistic analysis to estimate failure probability of the shallow soil layer under both saturated (e.g. [41]) and unsaturated (e.g. [42,43]) conditions. It is interesting to note that both the deterministic [44,74] and probabilistic [41] analyses revealed that the failure surface does not necessarily occur at the base of shallow layer in either saturated or unsaturated conditions as opposite to the assumption adopted in conventional infinite slope stability analysis.

In this paper, the infinite unsaturated expansive soil slope is addressed through a general elasto-plastic constitutive relationship based on two stress state variables for unsaturated soils. There are some sophisticated constitutive models proposed in the literature, which can describe the double-structure (e.g. [45]) and coupled hydro-mechanical (e.g. [46]) characteristics of expansive soil, but require a number of parameters to be defined for proper application. In this paper, in order to maintain the simplicity as of the nature of infinite slope formulation, the Mohr–Coulomb plasticity model that only needs some common soil parameters is adopted. Specifically, the extended Mohr–Coulomb failure criterion is used as the yielding surface, under which the nonlinear variation of elasticity parameters with respect to both net stress and suction is considered. The possible evolution of stress regime within the infinite slope profile upon infiltration is critically discussed. The numerical exercise conducted on an illustrative example using the developed computer program also illustrates that the critical slip surface may not necessarily be at the base of shallow layer. The results from the parametric analyses highlight some engineering practice implications.

2. Elasto-plastic constitutive matrix for unsaturated soils

For saturated soils, the yield function in stress space, which separates purely elastic from elasto-plastic behavior, can be expressed as

$$F(\{\sigma\},\{k\}) = 0 \tag{1}$$

where $\{\sigma\}$ represents the stress state in stress space, $\{k\}$ are the state parameters. The state parameters define the size of yielding surface, which can be related to hardening (softening) parameters (e.g. plastic strain or plastic work) to describe the hardening and softening behavior of material.

For unsaturated soils, Fredlund et al. [23] suggested using two independent stress state variables to describe the mechanical behavior and establish the constitutive relationships. The best combination of stress state variables for geotechnical applications is net stress and suction, which, respectively, refer to total stress in excess of pore air pressure, $(\sigma - u_a)$, and pore air pressure in excess of pore water pressure $(u_a - u_w)$, where σ is the total stress, u_w and u_a are pore water pressure and pore air pressure, respectively. The net stress and suction should be treated separately to describe the stress state of unsaturated soils in the yield function. For most geotechnical problems, u_a can be assumed to remain constant (usually atmospheric), the net stress is equivalent to the total stress, and suction, s, is equivalent to negative pore water pressure. Thus, the general simplified form of yield function for unsaturated soils, defined in terms of net stress, suction, and state parameters, can be expressed as

$$F(\{\sigma\}, s, \{k\}) = 0 \tag{2}$$

Correspondingly, the plastic potential function for unsaturated soils, which is used to specify the plastic straining direction in the flow rule, is of the form

$$G(\{\sigma\}, s, \{g\}) = 0 \tag{3}$$

where $\{g\}$ is a vector of the state parameters.