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Research Paper

Hydro-mechanical coupling effect on surficial layer stability of unsaturated expansive soil slopes

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ABSTRACT

Rain-induced surficial slope failures in expansive soils are frequently reported in the literature. These failures are primarily attributed to the shear strength reduction due to the loss of suction associated with the water infiltration. For this reason, slope stability is conventionally evaluated taking account of the hydraulic response of the soil to infiltration of water. The unsaturated expansive soil swells significantly upon wetting; the associated hydro-mechanical coupling effect on the slope stability of expansive soils is not considered in conventional geotechnical engineering practice. This paper aims to numerically evaluate the coupling effect or swelling on the hydraulic response as well as the stability of surficial layer of a typical expansive soil slope. Both hydro-mechanical (coupled) and hydraulic (uncoupled) responses of the slope to a low intensity prolonged rainfall are modeled using the commercial software SIGMA/W and SEEP/W, respectively. Subsequently, the infinite slope formulation is used to compute the factors of safety (FS) profiles extending both coupled (SIGMA/W) and uncoupled (SEEP/W) analysis. The results of the study presented in this paper show that coupled analysis (considering swelling) leads to different suction (negative pore water pressure (PWP)) and FS profiles within the surficial layer from those resulting from uncoupled analysis at the same elapsed time. The wetting fronts in the PWP profile from coupled analysis advance at a relatively faster rate in comparison to uncoupled analysis contributing to more critical FS values or failure conditions. The study highlights the coupled hydro-mechanical behavior of expansive soil has an adverse effect on the slope stability and hence should be taken into account in practice for estimating reliable values of FS.

1. Introduction

Highly plastic soils that are expansive in nature are widely distributed in many semi-arid and arid areas including some tropical regions of the world. These soils predominantly contain clay mineral montmorillonite that is sensitive to natural moisture content changes and exhibits dramatic swell and shrinkage characteristics. Some expansive soils volume increases up to thirty percent or even more due to an increase in the natural water content. Water content losses and shrinkage in expansive soils are typically associated with evaporation or desiccation. In addition, several cracks and fissures develop during the drying period. The dramatic volume change behavior of expansive soils associated with environmental or manmade changes contribute to damages to the civil infrastructure. The economic losses associated with expansive soils have been reported to be increasing at an alarming rate annually; for example in recent years, losses were estimated to be approximately several hundreds of millions of dollars to several billions of dollars in many countries [2]. The focus of this paper is directed toward suggesting a rational numerical procedure for assessing expansive soil slope surficial layer failures. The proposed methodology is presented using a typical slope in expansive soil from Regina of Saskatchewan province in Canada.

There has been a long history of observations of the rain-induced slope instabilities in cuts and fills near the city of Regina. This city is situated on glacial Lake Regina consisting of over-consolidated expansive clays [60]. Most of the rain-induced failures in this region occur 4–6 years after their construction and exhibit typical shallow and regressive characteristics initiating from the toe of the slope. Similar failure patterns in expansive soil slopes were also reported in many other regions of the world [9].

The suction present within the surficial layer significantly contributes toward the shear strength which in turn enhances the stability of an unsaturated soil layer. Several researchers [16,18,43,48] suggested that the failure mechanisms of this surficial layer during wetting seasons mainly involve rainfall-induced wetting front propagation causing suction losses. In some scenarios it is also

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likely that the formation and rise of the perched ground water table (GWT) will contribute to significant reduction in the shear strength of soils. Many numerical studies have been reported in the literature to investigate the hydraulic response of unsaturated slopes to rainfall infiltration and associated stability. For example, Zhang et al. [64] illustrated the development of various suction profiles within slope soils having different hydraulic properties (i.e. soil–water characteristic curve (SWCC) and hydraulic conductivity) under different rainfall intensities for both steady state and transient conditions. Cai and Ugai [12] first utilized the finite element seepage analysis for predicting the pore-water pressure (PWP) and used this information in the finite element strength reduction technique for computing the factor of safety (FS). This study highlighted the significant influence of initial relative degree of saturation, boundary conditions, and rainfall duration on the predicted PWP and the calculated FS. Based on a numerical analysis on the effect of combined role of saturated hydraulic conductivity and rainfall characteristics and analytically interpretation using infinite slope stability model, Li et al. [35] concluded that propagation of wetting front depth will never result in slope failures when internal frictional angle of soils is greater than the slope angle; unless there is rise of the perched water table which initiate slope failures. More recently, Ali et al. [4] investigated the boundary effects on rain-induced slope failures; the results showed that the hydraulic conductivity of boundary has different effects on the location and the timing of slip surface for slope under different intensity rainfalls. The study also highlights the boundary effects are also dependent of the slope angle, soil effective cohesion and the failure mechanisms (i.e. failures induced by reduction in negative PWP (suction) or generation of water table or positive PWP).

In addition to numerical investigation on hydraulic response of slopes to rainfall outlined above, some research has also been conducted using the coupled hydro-mechanical methods, where the deformation of unsaturated soils is included (e.g. [5,14,17,20,66]). These coupled hydro-mechanical studies are based on different constitutive models for describing the swelling behavior that use different definitions of stress state variables within the framework of unsaturated soil mechanics. For example, the nonlinear elastic stress–strain relationship based on two stress state variables are utilized by some researchers (e.g. [5,17,66]), while, the elasto-viscoplastic and elasto-plastic model considering the plastic strains based on effective stress principle has been used by other researchers (e.g. [11,14,20]). Similar to the uncoupled hydraulic analyses above, the coupled analysis was usually followed by a calculation of FS based on the obtained PWP and/or the stress state within the slope profile. Again, different techniques were extended for calculation of FS, such as the finite element method based on the obtained stress field within the slope (e.g. [5,17,66]), and the traditional limit equilibrium methods (e.g. [5,11,14]). It is worth mentioning that Ehlers et al. [20] obtained the localization of strains using the elasto-viscoplastic analysis directly instead of providing the slope FS.

In spite of the uncoupled and coupled analyses that were carried out within the framework of unsaturated soil mechanics, the effect of soil deformation or coupling behavior on the slope stability has not been clearly interpreted or quantified in the literature. The coupled behavior may be particularly significant in the slope stability analysis of expansive soils. This is because the surficial soils essentially experience substantial swelling during the rainfall period [44]. Cheng et al. [15] from the centrifugal modeling results suggested the instability of expansive soils can be attributed to the influence of swelling or heave within the slope surficial layer.

The key objective of the present study is to investigate the effect of coupling behavior on slope stability of expansive soils. The hydro-mechanical (i.e. coupled) and hydraulic (i.e. uncoupled) responses of a typical representative slope in Regina, subjected to a low intensity prolonged rainfall are modeled using commercial software SIGMA/W [29] and SEEP/W [28]. The hydraulic and mechanical properties measured on Regina clay are used as the input parameters in the Finite Element Analyses (FEA). The infinite (one-dimensional) slope stability analysis formulation that has been regarded as a justifiable method for shallow failure is utilized here for evaluating the stability of surficial layer of unsaturated expansive soil slope. The FS values at three locations (representing the slope toe, mid slope and slope top, respectively) along the slope surface are computed extending both coupled and uncoupled analyses to investigate the effect of coupling behavior of expansive soils. The suction (negative PWP with respect to atmospheric pressure) variation, associated heave amount and FS evolution during the rainfall period from coupled and uncoupled analyses are presented, compared and discussed. The studies show that the FS is significantly lower for coupled analysis in comparison to uncoupled analysis.

2. Slope stability analysis of unsaturated soils

2.1. Coupled and uncoupled analyses

2.1.1. Governing equations

Two sets of basic equations; namely, the partial differential force equilibrium and water continuity equations, form the fundamental equations governing the mechanical behavior for soil structure and flow behavior for water phase of an unsaturated soil element. The two finite element software; namely, SIGMA/W and SEEP/W are programmed based on these two sets of governing equations. Since the third phase (pore air) in the unsaturated soil elements within the slope surficial layer is essentially connected to the atmosphere, the problem was solved assuming constant air pressure.

The partial differential equations of overall static equilibrium with regard to an unsaturated soil element are written as follows:

$$\frac{\partial \sigma_{ij}}{\partial x_j} + b_i = 0 \tag{1}$$

where σ_{ij} are components of the total stress tensor and b_i are components of the body force vector.

Water flow in unsaturated soil is analyzed extending continuity equation assuming water is incompressible and deformations in soils are incrementally infinitesimal. The water continuity equation for an unsaturated soil element can be written as follows:

$$\frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} + \frac{\partial q_z}{\partial z} + \frac{\partial \theta_w}{\partial t} = 0 \tag{2}$$

where q_x, q_y and q_z are the flow velocities in x-, y- and z-directions, respectively, θ_w is volumetric water content, and t is time.

2.1.2. Constitutive relationships

The mechanical behavior of saturated soil can be generally described by an effective stress–strain relationship for soil structure if both the soil particles and water phase are assumed to be incompressible. However, additional relationship between water content and stress variables is required to fully describe the mechanical behavior of an unsaturated soil. Biot [10] was the first investigator who suggested the use of two constitutive equations for both soil structure and water phase of an unsaturated soil containing occluded air bubbles in water phase. These equations are similar in form to the constitutive equations established by Fredlund and Morgenstern [22] based on two stress state variables. The two stress state variables, namely net stress and suction, are also used in the present study to describe the unsaturated soil constitutive relationships. The net stress, $\sigma_{i,j} - u_a$, is the total stress,