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Elastoplastic model for hydro-mechanical behavior of unsaturated soils

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Abstract

A coupled elastoplastic constitutive model is presented for describing the hydraulic and mechanical behaviors of unsaturated soils. The model is capable of considering the influence of the irreversible changes in water saturation on the mechanical behavior and in plastic deformation on the hydraulic behavior. The mechanical and hydraulic behaviors are captured using the subloading surface and bounding surface plasticity frameworks, respectively. The coupling between hydraulic and mechanical behaviors is established using the intergranular stress concept in addition to appropriate coupled hardening rules. Attention is also given to the movement of the soil water characteristic curve due to the plastic deformation. Model predictions for some unsaturated soil samples are compared with experimental data, and a reasonable agreement is achieved.

Keywords: Unsaturated soil; Plasticity; Hydro-mechanical coupling; Bounding surface; Sub-loading surface

1. Introduction

The constitutive modeling for the hydraulic and mechanical behaviors of unsaturated soils is a subject of great interest in geotechnical engineering practice. The influence of the degree of saturation on the mechanical behavior and of the influence of volumetric strain on the hydraulic behavior are now demonstrated with experiments (e.g., Sharma, 1998). A description of the hydro-mechanical behavior of unsaturated soils, with the identification of the coupled influence of hydraulic and mechanical behaviors, has become a key area of research in modern geomechanics.

Although several constitutive models for unsaturated soils have been proposed over the last two decades (e.g., Alonso et al., 1990; Dangla et al., 1997; Vaunat et al., 2000; Jommi, 2000; Buisson and Wheeler, 2000; Wheeler et al., 2003; Thu et al., 2007; Sheng et al., 2004; Sun et al., 2007; Li, 2007a; Li, 2007b; Khalili et al., 2008; Della Vecchia et al., 2013; Mašín, 2013; Wong and Mašín, 2014), many fundamental issues, such as the selection of stress-strain variables and the framework of hydro-mechanical coupling, are still under debate. After the pioneering work of Alonso et al. (1990), the concept of two stress-state variables with net stress and matric suction has been widely used to describe the hydro-mechanical behavior of unsaturated soils (Thu et al., 2007; Chiu, 2003; Wheeler and Sivakumar, 1995; Cui and Delage, 1996; Georgiadis et al., 2005). However, Wheeler (1996), Sharma (1998) and Sun et al. (2010) demonstrated that some fundamental coupling effects of hydraulic and

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mechanical behaviors cannot be captured through the use of net stress and matric suction.

Wheeler and his colleagues (Wheeler et al., 2003) employed Bishop's effective stress and modified suction as the stress-state variables to simulate the coupled influences of the degree of saturation and volumetric deformation on the mechanical and hydraulic behaviors of unsaturated soils, respectively. The model proposed by Wheeler et al. (2003) is restricted to isotropic loading conditions. Sheng et al. (2004) and Sun et al. (2007) extended Wheeler et al.'s model to deviatoric loading conditions. However, it seems that they placed more emphasis on the influence of the hydraulic behavior on the stress-strain relation than on the influence of deformation on the hydraulic behavior.

Recently, Muraleetharan et al. (2009) proceeded to use the intergranular stress tensor and matric suction as the stress-state variables to improve Wheeler et al.'s (2003) framework. Although this model can properly simulate problems with multiple cycles of wetting and drying, its ability to simulate problems involving multiple cycles of mechanical loading and unloading is under debate. Ghasemzadeh and Ghoreishian Amiri (2013) extended Muraleetharan et al.'s framework to represent a more realistic model for simulating the coupled hydro-mechanical behavior of unsaturated soils. The model is capable of considering the influence of the water volume fraction on the mechanical behavior, such as irreversible compression during the drying path that does not exceed the maximum value of suction previously experienced by the soil, the coupling effects on the reverse direction, and the variation in the water volume fraction due to mechanical loading or unloading. However, these two models are restricted to isotropic stress states.

Liu and Muraleetharan (2012a) and Liu and Muraleetharan (2012b) extended Muraleetharan et al.'s model (Muraleetharan et al., 2009) for general stress states. The model can successfully capture the mechanical behavior of unsaturated soils under complex mechanical loading conditions. However, assuming fixed wetting and drying bounding curves in suction-volumetric water content space, the model cannot successfully simulate the effects of plastic deformation on the hydraulic behavior of samples involving a decrease in suction as a result of plastic compression. Moreover, the model is restricted to unsaturated silts and sands.

The main objective of this paper is to present a comprehensive, fully coupled hydro-mechanical elastoplastic constitutive model for a wide range of unsaturated soils from silts to collapsible and highly expansive clays. The work is an extension of the model proposed by Ghasemzadeh and Ghoreishian Amiri (2013) covering anisotropic loading conditions. The method of calibration is also described and the ability of the model to capture the coupled hydro-mechanical behavior of unsaturated soils is verified using many laboratory test results.

It should be noted that throughout this paper, compressive stress and strain are assumed to be positive.

2. Hydro-mechanical elastoplastic framework

It is assumed that the water volume fraction and strain increments (dn_w and $d\boldsymbol{\varepsilon}$) are additively decomposed into elastic and plastic parts, as follows:

$$d\boldsymbol{\varepsilon} = d\boldsymbol{\varepsilon}^e + d\boldsymbol{\varepsilon}^p \tag{1}$$

$$dn_w = dn_w^e + dn_w^p \tag{2}$$

where the water volume fraction is defined as the ratio of the volume of water (v_w) over the total volume of soil (v):

$$n_w = \frac{v_w}{v} \tag{3}$$

The selection of appropriate stress and strain variables is an essential step in the development of constitutive models for unsaturated soils. As thermodynamically demonstrated by Wei (2001) and successfully used by other researchers (Muraleetharan et al., 2009; Ghasemzadeh and Ghoreishian Amiri, 2013; Liu and Muraleetharan, 2012a, 2012b), the intergranular stress tensor ($\boldsymbol{\sigma}^*$), the matric suction (s), the plastic strain ($d\varepsilon^p$), and the irrecoverable part of the water volume fraction (dn_w^p) can be selected as the conjugated stress-strain variables. The intergranular stress tensor is defined as

$$\boldsymbol{\sigma}^* = \boldsymbol{\sigma}_{net} + \chi s \mathbf{I} \begin{cases} \chi = n_w & \text{for unsaturated state} \\ \chi = 1 & \text{for saturated state} \end{cases} \tag{4}$$

where $\mathbf{I}$ is the unit tensor and $\boldsymbol{\sigma}_{net}$ is the net stress tensor. In Eq. (4), the intergranular stress tensor should cover Terzaghi's effective stress under fully saturated conditions. This means that a switch is required between saturated and unsaturated states. However, since the value of suction at the moment of transition between saturated and unsaturated conditions is equal to zero, the effective stress and the intergranular stress will not be affected by the value of χ; and thus, the transition between saturated and unsaturated states can be performed without any problem (Muraleetharan et al., 2009).

Based on the work presented by Ghasemzadeh and Ghoreishian Amiri (2013), the process of slippage, widening, and closing between granular medium particles is simulated by introducing a Loading Collapse (LC) normal yield surface (defined later) within the framework of subloading surface plasticity (Hashiguchi, 1989; Hashiguchi et al., 2002). However, the bounding surface plasticity framework (Dafalias and Popov, 1975, 1976) is employed to capture the Soil Water Characteristic Curves (SWCCs) which are associated with Suction Decreased (SD) and Suction Increased (SI) bounding surfaces (defined later). The superiority of employing the subloading and bounding surface frameworks, in contrast to traditional plasticity frameworks, is discussed completely by Ghasemzadeh and Ghoreishian Amiri (2013). Fig. 1 shows the forms and evolutions of the SI and SD bounding and the LC normal yield curves in an isotropic stress space. It is worth noting that according to the argument found in Wheeler et al. (2003), the shapes of the SI and SD bound-