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Thermo-mechanical constitutive modeling of unsaturated clays based on the critical state concepts

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ABSTRACT

A thermo-mechanical constitutive model for unsaturated clays is constructed based on the existing model for saturated clays originally proposed by the authors. The saturated clays model was formulated in the framework of critical state soil mechanics and modified Cam-clay model. The existing model has been generalized to simulate the experimentally observed behavior of unsaturated clays by introducing Bishop's stress and suction as independent stress parameters and modifying the hardening rule and yield criterion to take into account the role of suction. Also, according to previous studies, an increase in temperature causes a reduction in specific volume. A reduction in suction (wetting) for a given confining stress may induce an irreversible volumetric compression (collapse). Thus an increase in suction (drying) raises a specific volume i.e. the movement of normal consolidation line (NCL) to higher values of void ratio. However, some experimental data confirm the assumption that this reduction is dependent on the stress level of soil element. A generalized approach considering the effect of stress level on the magnitude of clays thermal dependency in compression plane is proposed in this study. The number of modeling parameters is kept to a minimum, and they all have clear physical interpretations, to facilitate the usefulness of model for practical applications. A step-by-step procedure used for parameter calibration is also described. The model is finally evaluated using a comprehensive set of experimental data for the thermo-mechanical behavior of unsaturated soils.

1. Introduction

Modeling of the thermo-mechanical behavior of soils, particularly clays, has been the subject of many studies in the past. The possible reason accounting for this attention is the thermal conditions faced in a number of high-priority applications, such as geological storage of nuclear waste, buried high-voltage cables, pavements and geothermal energy.

Geotechnical applications to these problems require a comprehension of the thermo-mechanical behavior of clays. Notwithstanding there is the practical relevance of the thermo-mechanical applications, the effect of high temperatures on soil behavior is not yet completely understood, due to the intricate influence of temperature on the behavior of soils.

Thermo-mechanical models able to simulate most of the observed behaviors of saturated clays at increased temperatures have been developed by several researchers. Unlike some of the advanced models for the thermo-hydromechanical behavior of saturated clays, the models for unsaturated clays are almost based on a Cam-clay elastoplastic approach. Some thermo-hydromechanical models have been proposed for the behavior of unsaturated clays. Philip and de Vries (1957) presented a model for coupled heat and moisture transfer in rigid porous media under the combined gradients of temperature and moisture. Also, de Vries (1958) extended this theory to include moisture and latent heat storage in the vapor phase, and the advection of sensible heat by water. Modified versions of Philip–de Vries model were proposed by Milly (1982), Thomas and King (1991) and Thomas and Sansom (1995), using matric suction rather than volumetric moisture content as the primary variable. The laboratory and field validations of Philip–de Vries model have been reported by Ewen and Thomas (1989) and Thomas and He (1997), amongst others. Reasonable agreement has been found between the theoretical analyses and the laboratory/field results. Furthermore, Geraminegad and Saxena (1986) presented a de-coupled flow deformation model, including the effect of matrix deformation on moisture, heat and gas flow through porous media. A coupled version of this formulation was later presented by Thomas and He (1995, 1997). They introduced the matrix displacement vector as a primary variable, and improved the coupling effects between the temperature and deformation. They also improved the

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energy balance equation by including moisture and latent heat storage in the vapor phase, in addition to the advection of heat by water previously proposed by de Vries (1958). Similar formulations have also been given by Gawin et al. (1995) and Zhou et al. (1998). However, in Gawin et al. (1995), the constitutive laws of the solid phase were introduced in terms of the concept of effective stress. Nevertheless, they used the degree of saturation as the effective stress parameter, which is not fully supported by the experimental evidence. They also retained the degree of saturation as the main coupling element between the air and water flow fields, resulting in the governing differential equations to be strongly non-linear.

In general, a major difficulty in the formulations discussed above is that they either completely ignore the matrix deformation (e.g. Philip and de Vries, 1957; de Vries, 1958; Milly, 1982; Thomas and King, 1991; Thomas and Sansom, 1995) or use the theory of elasticity (Gawin et al., 1995) in conjunction with the "state surfaces" approach (Thomas and He, 1995; Zhou et al., 1998) to account for the strongly non-linear deformation behavior of the soil matrix. Such stress path dependency cannot be modeled using the theory of elasticity and/or the state surfaces approach. An appropriate plasticity model needs to be invoked, in order to take into account the variations of the yield surface with temperature and suction. Furthermore, in these formulations, effect of temperature on state surfaces is not well defined, despite its importance on response of soil (e.g. Hueckel and Baldi, 1990; Lingnau et al., 1995; Hueckel et al., 1998; Cui et al., 2000; Graham et al., 2001).

Also, some researchers simulated the consolidation process and pore-water pressure around hot cylinders buried in saturated clay (e.g. Smith and Booker, 1989; Britto et al., 1989). However, only the reversible volume change of the soil due to a change in temperature was considered in their models. Khalili and Loret (2001) presented an alternative theory for heat and mass transport through deformable unsaturated porous media. The work was an extension of the theoretical developments of Loret and Khalili (2000) dealing with fully coupled isothermal flow and deformation in variably saturated porous media to include thermal coupling effects. Wu et al. (2004) presented a thermo-hydromechanical model for unsaturated soils. The model was based on the four component yield surfaces of the cap plasticity model and on the experimental results obtained for different types of soils. The extension of the model to include temperature effects was embodied through the thermal softening and the suction variation with respect to temperature, as well as the thermal effects to the hydraulic properties. François and Laloui (2008) presented a constitutive model for soils based on a unified thermo-mechanical model for unsaturated conditions. The relevant temperature and suction effects were studied in the light of elastoplasticity. A generalized effective stress framework was adopted that would include a number of intrinsic thermo-hydromechanical connections to represent the state of stress in the soil. Two coupled constitutive aspects were used to fully describe the non-isothermal behavior. The mechanical constitutive part was built on the concepts of bounding surface theory and multi-mechanism plasticity, while water retention characteristics were described using elastoplasticity to reproduce the hysteretic response and the effect of temperature and dry density on retention properties. Mašín and Khalili (2012) presented a model for non-isothermal behavior of unsaturated soils. The model was based on an incrementally non-linear hypoplastic model for saturated clays and could therefore simulate the non-linear behavior of overconsolidated soils. A hypoplastic model for non-isothermal behavior of saturated soils was developed and combined with the existing hypoplastic model for unsaturated soils based on the effective stress principle. The elastoplastic constitutive model developed by Pastor et al. (1990), for fully saturated soils, has been extended to include partially saturated soil behavior by Bolzon et al. (1996). The saturated soil model, formulated in the framework of generalized plasticity, considers volumetric and deviatoric strain hardening and takes into account past stress history and possible limit states.

The generalization of the existing model to simulate the experimentally observed behavior of partially saturated soils is obtained by introducing Bishop's stress and suction as independent stress parameters and by modifying the hardening parameter and the yield condition to take into account the role of suction. Using a similar approach, an isothermal constitutive model is presented for predicting the thermo-elastoplastic behavior of unsaturated clays in triaxial stress space. This model is an extension of the thermo-elastoplastic model for fully saturated clays proposed by Hamidi et al. (2015). Using a non-associated temperature dependent flow rule, the present model can simulate the mechanical behavior of clays with respect to temperature and suction changes.

2. Mechanical behavior and constitutive models for unsaturated soils

The first part in this section reviews the basic features of the mechanical behavior of unsaturated soils. In the second part, constitutive modeling of the mechanical behavior is reviewed.

2.1. Mechanical behavior of unsaturated soils

Generalized effective stress expressions were proposed in order to include unsaturated soils into the conventional soil mechanics framework, the best known being proposed by Bishop (1959):

$$p'_{\rm B} = p - u_{\rm a} + X(u_{\rm a} - u_{\rm w}) = \overline{p} + Xs \quad (1)$$

where $p'_{\rm B}$ is the Bishop's mean effective stress, p is the mean total stress, $\overline{p}$ is the mean effective stress in dry soil, X is a function of the degree of saturation, $u_{\rm a}$ is the pore air pressure, $u_{\rm w}$ is the pore water pressure, and s is the matric suction. In this research, the following equation presented by Khalili and Khabbaz (1998) has been used to calculate the parameter X:

$$X = \begin{cases} [s_{\rm e}(T)/s]^{\Omega} & (s \geq s_{\rm e}(T)) \\ 1 & (s \leq s_{\rm e}(T)) \end{cases} \quad (2)$$

where $s_{\rm e}(T)$ is the bubbling pressure or the air entry value at the temperature T, and $\Omega = 0.5$.

2.2. Constitutive models for unsaturated soils

Elastic models are relatively easy to implement within numerical analysis and to obtain the relevant parameters, but have some major drawbacks. Most importantly, no distinction is made between reversible and irreversible strains. Elastoplastic constitutive models have been developed for both expansive and non-expansive soils. They all fall into two categories depending on the adopted stress variables, i.e. total stress models and effective stress models. Most elastoplastic models are extensions of models for fully saturated soils and are based on the concept of the loading-collapse yield surface. The following elements are usually defined:

(1) A yield function to represent the surface that separates fully elastic from elastoplastic behavior. This surface expands with increasing suction in order to model the increase of shear strength and yield stress with suction. In this way, collapse due to wetting can also be reproduced. The expansion of the yield