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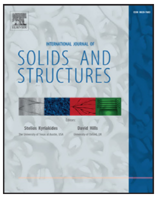

A fully coupled damage-plasticity model for unsaturated geomaterials accounting for the ductile–brittle transition in drying clayey soils

Solenn Le Pense[a,1,*], Chloé Arson[b], Amade Pouya[a]

[a] Laboratoire Navier, UMR 8205, École des Ponts, IFSTTAR, CNRS, UPE, Champs-sur-Marne, France
[b] School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, GA, USA

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ABSTRACT

This paper presents a hydro-mechanical constitutive model for clayey soils accounting for damage-plasticity couplings. Specific features of unsaturated clays such as confining pressure and suction effects on elastic domain and plastic strains are accounted for. A double effective stress incorporating both the effect of suction and damage is defined based on thermodynamical considerations, which results in a unique stress variable being thermodynamically conjugated to elastic strain. Coupling between damage and plasticity phenomena is achieved by following the principle of strain equivalence and incorporating the double effective stress into plasticity equations. Two distinct criteria are defined for damage and plasticity, which can be activated either independently or simultaneously. Their formulation in terms of effective stress and suction allows them to evolve in the total stress space with suction and damage changes. This leads to a direct coupling between damage and plasticity and allows the model to capture the ductile/brittle behaviour transition occurring when clays are drying. Model predictions are compared with experimental data on Boom Clay, and the flexibility of the model is illustrated by presenting results of simulations in which either damage or plasticity dominates the coupled behaviour.

1. Introduction

Pressing needs for sustainable structures and safe geological repositories require the development of reliable models to predict the behaviour of natural geomaterials (e.g., soils, rocks) and engineered materials (e.g. compacted backfill materials, cement-based materials, ceramics etc.). One of the recurring modelling challenges is the prediction of deformation, stiffness and strength of porous media with a solid matrix containing clay minerals.

Experimental evidence show that clayey soils can exhibit either a brittle or a ductile behaviour (Dehandschutter et al., 2005). The transition between both behaviours depends on multiple factors including moisture content (Al-Shayea, 2001). Under deviatoric loading, clayey soils can undergo large permanent strains. Their properties, such as stiffness, strength, or permeability, are also known to be subject to changes after being submitted to hydric or mechanical solicitations. In clayey soils, these changes are related to several physical phenomena, such as the deterioration of cemented bonds, hence the destructuration of the material, or the change in water content, resulting in a decrease of suction-induced bonding.

Sophisticated plasticity models proposed for clayey soils allow capturing suction hardening and wetting collapse. However these models are not suited for stiffer or bonded materials, which can undergo both plastic deformation and stiffness degradation. A phenomenological variable d, called “damage”, can be defined at the continuum scale to quantify the energy dissipated by stiffness degradation. Note that d represents the effects of multiple microscopic dissipative processes that lead to the loss of adhesion between material surfaces, such as micro-crack propagation or debonding due to an increase of water saturation. Coupling damage and plasticity in a thermodynamically consistent framework raises many issues when one wants to ensure thermodynamical consistency while keeping the model simple enough to allow for easy calibration and incorporation into a numerical code. Models coupling damage and plasticity are often material and loading path specific, and difficult to generalise to a broader category of problems related to the coupled effects of mechanical stress and suction in unsaturated clay-bearing porous media. One of the fundamental issues that needs to be addressed is the choice of thermodynamic variables, in particular the stress variable involved in the yield and damage criteria.

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[*] Corresponding author. Tel.: +44 131 451 4243.
E-mail address: s.le_pense@hw.ac.uk (S. Le Pense).

[1] Present address: Heriot-Watt University, United Kingdom.

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State-of-the art models are often designed to fit experimental data for specific materials subjected to specific stress-paths. By contrast, the modelling approach presented in this paper is aimed to predict the transition between brittle and ductile deformation regimes for different fabrics, clay contents and hydro-mechanical stress paths. Model calibration and numerical implementation are facilitated by the low number of constitutive parameters employed in the formulation (14 parameters in total, 8 for the mechanical part of the model and 6 for the hydraulic part). The proposed framework is flexible so that each component can be refined if one wants to adapt it to a specific material. The described model is designed in order to be adaptable to a wide range of geomaterials, ranging from stiff clayey soils to mixtures of clay and sand. To illustrate the versatility of the framework, the model was calibrated against experimental data obtained for a variety of geomaterials including Boom clay and mixtures of clay soil and sand.

The work presented in this paper provides a general method to couple damage and plasticity in porous materials that have a clay-bearing solid matrix. Clay minerals are expected to play a critical role in the deformation and retention properties of the damaged medium. Section 2 reviews the main modelling strategies available to date to model hydro-mechanical plasticity and damage in unsaturated porous media, and introduces the main concepts and states variables used to account for the effect of suction and damage. Then, the concept of double effective stress is introduced in Section 3, and its coupling with damage and plasticity is developed. In Section 4, the behaviour of the mechanical model is analysed, as well as its limits and its sensitivity to the main parameters. Section 5 presents the simulation of different laboratory tests performed on unsaturated clay-bearing geomaterials. The comparison between models predictions and experimental data reported in the literature is used as a basis to assess the performance of the model.

The sign convention used is the one of soil mechanics. Compressive stresses and strains take therefore positive values.

2. Damage in unsaturated clay-bearing porous media

2.1. Pore-scale hydro-mechanical couplings

In this study, we are interested in modelling multiphasic media made of a solid skeleton containing pores filled with a mixture of liquid and gas. The difference between gas and liquid pore pressures, $s = u_a - u_w$, is called suction. In the case in which air remains equal to the atmospheric pressure, water pressure is negative and suction takes a positive value. The air–water interface (called meniscus) starts to curve when suction increases. The radius of the meniscus decreases when suction increases, and once it becomes as small as the pore throats, air can invade the porous structure, which becomes unsaturated. The combination of the water surface tension and the negative pore water pressure results in a force that tends to pull the soil grains towards one another. The resulting force on the solid skeleton is similar to a compressive stress (Santamarina, 2003). An increase in suction will therefore lead to a decrease of the total volume (shrinkage), and wetting soils (i.e. decreasing suction) will usually make them swell. Suction also contributes to stiffen the soil against external loading thanks to grain bonding induced by water menisci in tension. The additional component of normal force at the contact will also prevent slippage between grains and thus increases the external force needed to cause plastic strains (Ridley et al., 2009). However, when wetting a soil under constant mechanical loading, the resaturation destroys the bonds formed by water menisci and may induce an irrecoverable volumetric compression (called collapse) (Muñoz Castelblanco et al., 2011). These main characteristics of unsaturated soils mechanical behaviour are represented in Fig. 1.

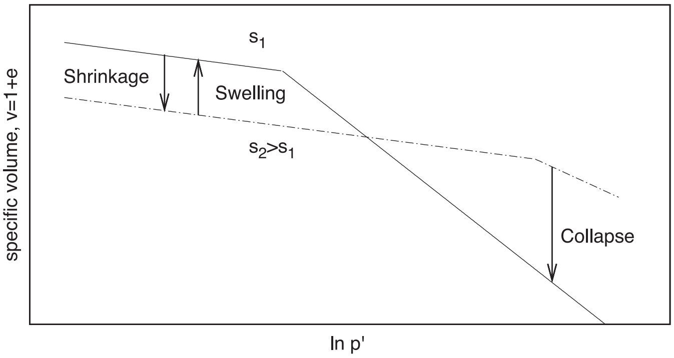

Fig. 1. Influence of suction on volumetric compression and volume changes due to wetting and drying, adapted from Alonso et al. (1990). p' is the net mean stress.

Changes in suction may also induce irreversible processes (plasticity or damage) during a drying process (Alonso et al., 2014; Wang et al., 2014).

2.2. State variables for unsaturated porous media

Unsaturated soil models are usually extensions of saturated soil ones. The most widely used of them is the Cam-clay model, first developed by Roscoe et al. (1958) and later modified by Roscoe and Burland (1968). Extension to unsaturated states requires the definition of specific state variables. A comprehensive review of the existing stress frameworks can be found in the paper of Nuth and Laloui (2008).

Houlsby (1997) demonstrated that, assuming the incompressibility of the solid matrix and the water phase, the work input to an unsaturated soil can be written as:

$$\dot{w} = [\boldsymbol{\sigma} - (S_r u_w + (1 - S_r)u_a)\mathbf{I}] : \dot{\boldsymbol{\varepsilon}} - (u_a - u_w)\phi \dot{S}_r \tag{1}$$

where $\boldsymbol{\sigma}$ is the total stress tensor, $\dot{\boldsymbol{\varepsilon}}$ the total strain rate tensor, u_a and u_w the air and water pore pressures, ϕ the porosity, S_r the degree of saturation, and $\mathbf{I}$ the identity matrix.

This formulation leads to the introduction of two state variables respectively conjugated to the strain rate, $\dot{\boldsymbol{\varepsilon}}$, and to the degree of saturation rate $\dot{S}_r$.

The stress quantity related to the strain increment is,

$$\begin{aligned}\boldsymbol{\sigma}^* &= \boldsymbol{\sigma} - (S_r u_w + (1 - S_r)u_a)\mathbf{I} \\ &= \boldsymbol{\sigma} - u_a\mathbf{I} + (u_a - u_w)S_r\mathbf{I} \\ &= \boldsymbol{\sigma}^{net} + sS_r\mathbf{I}\end{aligned} \tag{2}$$

which is a particular form of Bishop's effective stress (Bishop, 1959) in which the χ factor is taken equal to 1. This stress has been used by many authors and has been attributed different names, such as the average skeleton stress tensor (Jommi, 2000), the constitutive stress (Sheng et al., 2003) or the generalised effective stress (Laloui and Nuth, 2009). In the following, the term *constitutive stress* will be used.

Other expressions have been proposed for this constitutive stress, accounting for the energy of the air–water interface (Nikooee et al., 2012; Pereira et al., 2005), the different levels of porosity (Alonso et al., 2010), or the compressibility of the solid matrix through the Biot's coefficient (Chateau and Dormieux, 2002; Jia et al., 2007). However, for the sake of simplicity, we will keep the simple expression of Eq. (2), although the framework could easily accommodate a different expression for the constitutive stress.

According to Eq. (1), a second suction-related state variable, work-conjugated to the increment of degree of saturation is required. It will be called *modified suction* in the following and is