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Effective stress in swelling soils during wetting drying cycles

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ABSTRACT

In this study, the cyclic evolution of an effective stress parameter χ is determined for different swelling soils. This parameter can be modelled using the macro-, meso- and microscales in interaction, stemming from mercury intrusion porosimetry (MIP) tests. The proposed model for χ was calibrated using the experimental results from successive suction cycles for different swelling soils without a vertical stress. Finally, an effective stress model was used to describe the cyclic behaviour of both the loose and dense samples for suction cycles between 8 and 40 MPa. Comparisons between the simulations and the experimental results showed that the effective stress model could be used to accurately describe the cyclic behaviour of the swelling soils over different suction ranges.

1. Introduction

Exposing clay soils to varying climatic conditions can induce soil swelling/shrinkage, thereby affecting the structures built on these soils, including shallow foundations, drainage channels, and radioactive waste disposal buffers. The complex hydro-mechanical behaviour of clay materials depends on the characteristics of their fabric (Pusch, 1982; Alonso et al., 1987; Gens and Alonso, 1992; Alonso et al., 1999) and has been the primary subject of several studies on the micro- and macroscale of soils (Wan et al., 1995; Pusch et al., 1999; Cui et al. 2002; Pusch and Yong, 2003; Lloret et al., 2003; Hoffemann et al., 2007; Nowamooz and Masrouri, 2009a, 2010a). A literature review on hydraulic cycles shows that several wetting-drying cycles (Alonso et al., 2005; Airo Farulla et al., 2007; Nowamooz, 2007; Nowamooz and Masrouri, 2008, 2009b, 2010b; Nowamooz et al., 2013) produce an equilibrium state in which the soil exhibits elastic behaviour. Relatively few models have integrated the coupled hydro-mechanical (monotonic or cyclic) response into a unified framework by considering the multi-scales in clayey soils. Alonso et al. (1999) developed the Barcelona Expansive Model (BExM), which is based on the net stress concept and is often used as a reference model.

The effective stress is an important tool for describing the volumetric and shear behaviour of saturated and unsaturated soils. Many attempts have been made in the literature to quantify an effective stress parameter χ, which appears in the general definition of the effective stress given in Eq. (1) (Bishop, 1959):

$$\sigma' = (\sigma - u_a) + \chi(u_a - u_w), \tag{1}$$

where σ' is the effective stress, σ is the total stress, u_a is the pore air pressure, u_w is the water pore pressure, and $s = (u_a - u_w)$ is the matric suction.

The most widespread approach in the literature estimates χ as being equal to the degree of saturation. Several authors (Houlsby, 1997; Bagherieh et al., 2009; Masin, 2010; Alonso et al., 2010; Khalili and Zargarbashi, 2010; Nuth and Laloui, 2008; Hicher et al., 2012) have studied the validity of the Bishop effective stress model.

Thermodynamic considerations are also important in determining χ. Borja and Koliji (2009) used the first law of thermodynamics to identify energy-conjugate variables and derive an expression for the effective stress as the only stress state variable. Their approach naturally introduced Biot's parameter in the effective stress definition for elastic compressible grains in one dominant porosity. For the case of double porosity the relevant form was introduced by the local suction versus degree of saturation pair and the pore volume fraction versus weighted pore pressure difference pair. Coussy et al. (2010) demonstrated also that the assumption of $\chi = S_r$ is unrealistic because it implies that the pores filled with air experience the same deformation under air pressure as the pores filled with water do under water pressure.

Khalili and Zargarbashi (2010) studied the effect of hydraulic hysteresis on the effective stress. The authors showed that the degree of saturation may not be a good approximation for χ during a wetting-drying

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Table 1
Properties of the studied soils.

Studied soil	Silt/bentonite mixture	Natural E1	Natural E2
Liquid limit (%)	87	86	65
Plasticity index (%)	22	32	25
Specific gravity, G_s	2.67	2.60	2.62
Passing sieve 80 μm (%)	100	99	85
Clay size content (<2 μm) (%)	60	72	52

cycle. The authors also mentioned that very limited information is currently available on the variation in the effective stress along the wetting path, and most of the models in the literature are thus based on drying path results. They concluded that the Bishop model is applicable for granular soils with a single dominant structure.

Khalili and Khabbaz (1998) developed a new equation for χ for suction values greater that the air entry value based on shear strength of unsaturated soil:

$$\chi = \left(\frac{s}{s_e}\right)^{\gamma}, \tag{2}$$

where s is the suction value, s_e is the air entry value for the drying process and the air expulsion value for the wetting condition, and γ is a model parameter.

Khalili et al. (2008) derived the following relationship between the incremental (or time differentiated) effective stress parameter χ and the degree of saturation:

$$\frac{d(\chi s)}{ds} = S_r - n\frac{\partial S_r}{\partial \varepsilon_v}, \tag{3}$$

where S_r is the degree of saturation, n is the porosity of the soil, and ε_v is the volumetric strain. This equation shows degree of saturation may not be taken as the effective stress parameter. S_r becomes equal to the incremental form of the effective stress parameter only when the second term in the equation above is negligible.

Ajdari et al. (2012) used neural network analysis to estimate χ given the air entry value, the volumetric water content, the slope of the soil-water characteristic curve, the net stress, and the suction. The authors validated their model using shear test results.

Plastic soils are characterised by a reduced proportion of free water and a lower contribution from the capillary suction to the effective stress. For the extreme case of high plasticity clays with high suction values, the proportion of free water is negligible and the effective stress reduces to the net stress. The validity of the Bishop model has yet to be extensively examined for fine unsaturated soils. Alonso et al. (2010) have discussed that setting $\chi = S_r$ often results in an overestimate of the effective stress for unsaturated clayey soils that would produce an unrealistic soil compression. They developed an “effective degree of saturation” term based on micro-structural features to describe the proportion of the prevailing suction that actually contributes to the effective stress. This term appears in Eq. (4) and is related to the stored free water quantity, i.e., water that is stored principally in the macropores (degree of saturation of macrostructure):

$$\chi = S_r^e = (S_r)^{\alpha}, \tag{4}$$

where α ($\alpha \geq 1$) is a material parameter. Therefore, $S_r^e \leq S_r$ for $S_r \in [0,1]$.

Accurate modelling of the hydro-mechanical behaviour of swelling soils must account for the multi-scale soil fabric to incorporate interactions between different structural levels. A literature review shows (Alonso et al., 2010; Della Vecchia et al., 2013; Pinyol et al., 2013; Masin, 2013; Nowamooz, 2014) that the χ parameter depends strongly on the soil structure; the evolution of this structure (i.e., the soil fabric) during a wetting-drying cycle implies the concurrent evolution of χ. However, relatively few investigations on the effective stress in multi-scale soils have been reported in the literature and still determining χ for the swelling soils is crucial to be successfully used in constitutive models in soil engineering problems. In this context, this study aims to propose a new effective stress parameter χ by considering the multi-scale evolution of swelling soils during the wetting and drying cycles.

2. Studied material

In this section, we present the studied soils in this study: a mixture of 40% silt and 60% bentonite and two natural soils E1 and E2 of Le Deffend located at about 4 km south-east of Poitiers (France). The characteristics of the studied mixtures are presented in Table 1.

The samples of silt/bentonite mixture were compacted statically at two initial dry densities, 1.27 and 1.55 Mg/m^3, and were designated as loose and dense samples, respectively. The initial water content was fixed at 15% for both samples. Each sample had a diameter of 35 mm and a height of 10 mm. The filter paper method (ASTM D 5298–94, 1995b) was used to estimate the initial total suction of the samples at approximately 20 MPa for both the loose and dense samples.

For the natural soils, two in-situ boreholes were drilled in the same season to a depth of 7 m for geological and geotechnical investigations within the framework of the ANR ARGIC project (Vincent et al., 2009), including one in a pasture (site E1) and the second in a forest (site E2).

The samples of soil E1 were reconstituted to an initial state corresponding to their saturated state (suction = 0 MPa), with an initial water content of 50% and an initial dry density of 1.05 Mg·m^{-3} or a void ratio of 1.47. The soil E2 samples were also reconstituted at their initial state with a water content of 14% and a dry density of 1.84 Mg/m^3 or a void ratio of 0.42 (Table 2). The initial total suction of the natural soils measured by the filter paper technique was about 20 MPa for soil E2.

A series of mercury intrusion porosimetry (MIP) tests was also conducted for all the studied samples. Freeze-drying was selected for our MIP study as an alternative to oven drying to prevent the effects of shrinkage on drying. Soil pieces were quickly frozen with liquid nitrogen (temperature of −196 °C) and then placed in a freeze-drier at least 72 h for the sublimation of the water before the MIP tests.

Fig. 1-a shows the evolution of the pore size density (PSD), i.e., Δ(void ratio)/Δlog (pore radius), as a function of the pore diameter

Table 2
Soil fabric properties of the studied soils.

Soil	Suction (MPa)	Initial dry density (Mg/m^3)	Total void ratio (e_T)	Macro-scale void ratio (e_M)	Meso-scale void ratio (e_m)	Micro-scale void ratio (e_n)
Loose silt/bentonite mixture	20	1.27	1.10	0.59 ± 0.01	0.20 ± 0.01	0.31
Dense silt/bentonite mixture	20	1.55	0.73	0.32 ± 0.01	0.13 ± 0.01	0.28
Natural E1	0	1.05	1.47	0.84 ± 0.01	0.46 ± 0.01	0.17
Natural E2	20	1.84	0.42	0.05 ± 0.01	0.19 ± 0.01	0.18