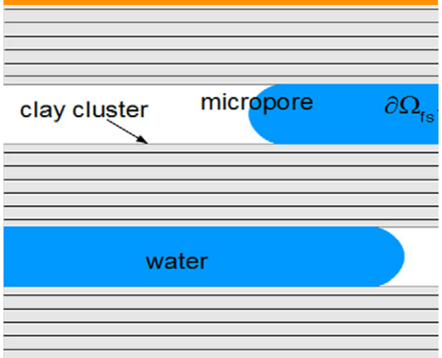
Special section: Principle of Effective Stress




We present an extension of the effective stress principle to unsaturated expansive clays characterized by two porosity levels (micro- and nanopores) including generalizations of the Bishop parameter, equivalent pore pressure, and swelling stress. Such new quantities aim at capturing the coupled phenomena arising from the additional nanopore level.

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# A Modified Effective Stress Principle for Unsaturated Swelling Clays Derived from Microstructure

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A three-scale model is proposed to describe electro-chemo-mechanical couplings in unsaturated swelling clays characterized by two porosity levels and three separate length scales. The nanoscale portrait consists of charged clay particles separated by a nanoporous network saturated by a binary monovalent aqueous electrolyte solution. Local ion distribution and electric potential are governed by the Poisson–Boltzmann problem. At the microscale, the system is represented by swollen clay clusters separated from each other by a network of micropores filled with a mixture of bulk water and air. Under mechanical equilibrium characterized by the competition between disjoining forces of electrochemical nature and capillary attraction effects, we derived a novel form of the effective stress principle in the asymptotic limit of scale separation. Such form includes a new macroscopic equivalent pore pressure weighted by a two-scale effective Bishop coefficient that incorporates the effects of the adsorbed water at the secondary nanopore level in addition to the contributions of the water–air interfaces at the micropore level. Within the thermodynamic context for constructing macroscopic constitutive laws based on stress–strain variables, the three-scale model leads to a set of three work-conjugated state variables. In addition to the contact stress between particles and the new effective Bishop-type component, the novel form includes salinity as an additional stress-conjugated variable and a three-scale version of the electrochemical swelling stress. The potential of the multiscale approach in capturing the complex features of unsaturated expansive clays is illustrated by numerical reconstruction of the effective coefficients in a simplified isotropic microstructure.

Abbreviations: EDL. electric double layer.

Since the seminal works of Terzaghi and Biot, who constructed the foundations of the effective stress principle for fully saturated porous media, several extensions with various degrees of sophistication have been proposed for unsaturated geomaterials (Alonso et al.,1990, 1999, 2010; Gens and Alonso, 1992; Sheng et al., 2004, 2008a, 2008b; Borja and Koliji, 2009; Coussy et al., 2010; Nuth and Laloui, 2008; Laloui and Nuth, 2009; Khalili et al., 2004; Gallipoli et al., 2003; Coussy and Brisard, 2009; Vlahinic et al., 2011). The necessity of proper extensions to unsaturated states became a great challenge for the geotechnical community. Pioneer works put substantial efforts toward the proper identification of a single effective stress, commonly referred to as *Bishop-type effective stress* (Bishop, 1959; Sheng et al., 2008b; Laloui and Nuth, 2009), where the Bishop parameter incorporates information regarding the microstructure of the deformable medium and can be mainly envisioned as a scaling factor that captures the weight of the contribution of each fluid pressure to the effective stress. Subsequently, it was recognized that the choice of the stress space to thermodynamically describe volume changes in unsaturated media was more complex. More precisely, an improved characterization of the mechanics was accomplished by the use of two independent sets of stress variables, namely the net stress and matric suction (Fredlund and Morgenstern, 1977) work-conjugated with the soil skeleton strain and the degree of saturation. The flexibility in the choice of the independent stress state