Coupled flow-deformation analysis of unsaturated soils including hydraulic and mechanical hystereses effects

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This paper presents the fundamental governing equations for a fully coupled flow-deformation model for unsaturated soils taking into account both mechanical and hydraulic hystereses effects. The governing equations are developed using a systematic macroscopic approach satisfying the equations of balance of mass and momentum. Two separate, yet fully interacting models are identified: one representing the fluid flow, and the other the deformation of the solid matrix. The deformation model is based on theory of elasto-plasticity within a critical state framework. The *mechanical hysteresis* and accumulation of accumulation of permanent deformation during repetitive loading cycles are captured through introducing three zones of elasto-plasticity: an outer yielding zone (the bounding surface), an inner sub-yielding zone, and a zone of pure elasticity with holonomic behaviour. Plasticity occurs when the current effective stress $\boldsymbol{\sigma}'$ lies on the bounding surface or within the inner sub-yielding zone. This is achieved by defining the hardening modulus as a decreasing function of the distance between $\boldsymbol{\sigma}'$ and an "image point" on the bounding surface. The bounding surface is defined in the effective stress space but its size is affected by the plastic volumetric strain as well as matric suction. The constitutive equations in both elastic and plastic regions are written in terms of the effective stresses rather than the independent stress state variables. The advantage of using the effective stress approach is that the elastic deformation of the system can completely be expressed in terms of a single "effective" stress variable rather than two or three independent stress variables. This significantly simplifies the deformation model, and reduces the model parameters. Furthermore, with an effective stress based model, the transition from saturation to unsaturation or vice versa can be readily taken into account using a single set of constitutive equations. The fluid flow model is based on two interacting continua. At every point in space, two pressures are defined: one for the pore water pressure - i.e. at the neighbourhood of the point of interest - and the other for the air pressure. The difference between these two pressures is the matric suction within the system. The interaction between the two flow regions is established through the soil water characteristic curve. The coupling between the flow and the deformation fields is established through the effective stress parameters. The effect of wetting and drying on water retention characteristics of the pores (*hydraulic hysteresis*) is captured though distinguishing between wetting and drying branches of the soil water characteristic curve. The effect of wetting and drying on the *effective stress hysteresis* is captured through distinguishing between air entry and air expulsion suction values in the effective stress equation of the solid skeleton. The governing equations presented enjoy the major symmetry of the constitutive coefficients, a requirement of the elastic strain reversibility within the system. All model parameters are identified in terms of physically measurable entities. The model validation is demonstrated through comparison of simulation results with experimental data for a range of data from the literature.