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Research Paper

Poroelastic behaviour of fine compacted soils in the unsaturated to saturated transition zone

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ABSTRACT

The behaviour of quasi-saturated materials is important to consider when designing cuttings and embankments in which earthwork materials are compacted to the optimum proctor density. Under this condition, the in-pore gaseous phase takes the form of air pockets and bubbles embedded within the liquid phase, which significantly affects the overall behaviour of the soil. The assessment of highly saturated soils thus requires a precise understanding of hydro-chemo-mechanical couplings between the entrapped air, the in-pore liquid and the solid skeleton. This paper presents a fully coupled poromechanical model that separates the kinematics and the mechanical behaviours of the phases in their interactions with each other (e.g., liquid water, dissolved air, gaseous air and solid matrix). The assumptions about the entrapped air behaviour are defined from a bibliographic study, and linear elastic behaviour is used for both the liquid phase and the solid skeleton. The model is implemented in the FEM code COMSOL and is subsequently used to simulate oedometric tests under different loading paths: undrained compression or imposed liquid pressure variation at constant stress. The behaviour, which shows a continuous transition from unsaturated to saturated, is logical and consistent with available experimental data.

1. Introduction

The analysis of the problems encountered by geotechnical structures involving fine soils shows that the majority of disorders are due to inaccurate estimations of the impact of water on their behaviour. Soil can be considered a tri-phasic medium composed of solid grains, liquid water and gas. The interactions between various components within these phases are responsible for the complex behaviour of these materials. In particular, the surface tension phenomenon leads to a difference between in-pore water and gas pressures, known as capillary suction, which creates an apparent attraction between the soil particles, leading to higher stiffness and shear strength [22].

Earthwork materials are usually compacted to the optimum proctor density. Under this condition, the saturation degree is close to 80%, and the gaseous phase, which is no longer continuous, takes the form of air pockets and bubbles entrapped within the liquid phase [9,32]. The presence of this entrapped air seems to significantly influence the behaviour of the soil. Several studies indicate that the entrapped air affects the soil's hydraulic and mechanical properties [40,17,36,6]. However, at the particular degree of saturation mentioned above, it appears that neither unsaturated nor saturated formalisms can accurately reproduce the behaviour of fine compacted soils.

Over the past three decades, a fair amount of theoretical and experimental studies have explored the behaviour of unsaturated soils (e.g., [1,2,26,13,19,34,18,43,3,33,28]). These works resulted in the development of advanced elastoplastic models that allow one to correctly predict the responses of both saturated and unsaturated soil. However, the domain of transition between unsaturated and fully saturated states, namely the "quasi-saturated state" [17] (e.g., when the gaseous phase is entrapped within the pore network), was almost never considered. In particular and to the best of our knowledge, no existing numerical code (such as BRIGHT [30]) takes into account the presence of entrapped air within the soil skeleton at high saturation ratios.

It was not until recently that some groups attempted to develop a constitutive model that could accurately reproduce the behaviours of quasi-saturated soils by accounting for the air entrapped within the pore network [5,27,24]. However, the above studies are based on two major assumptions in the quasi-saturated domain: a linear relationship between the degree of saturation and suction and a constant mass proportion between the gas and the liquid

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phases. Even if these assumptions allow simplifying the mathematical equations, they are not consistent with the chemical equilibrium and kinematics of the in-pore fluid phases. In addition, these models assume that when the in-pore liquid pressure goes beyond the atmospheric pressure, the remaining pockets of entrapped air abruptly become air bubbles, which leads to a pressure discontinuity in the gaseous phase.

In our opinion, a rigorous theoretical framework that is well-adapted to the formulation of coupled multi-physics problems in porous media would be necessary to account for the simultaneous existence of different regimes of saturation, as well as the evolution relative to space and time of the corresponding physical domains. To this end, an original model is proposed in this paper, and its development is based on a rigorous thermodynamic framework. It is part of an ongoing research project named Terredurable, which aims to provide a clearer understanding of coupled hydromechanical responses of civil engineering structures at close-to-saturation states. This requires a good understanding of the dissolution/bubbling processes of entrapped air, as well as its migration kinematics within the pore network.

The first part of this paper is dedicated to the physical description of the air trapping and dissolution phenomena. The theoretical development of the poromechanical model is presented in Section 3. In this model, the liquid water, the entrapped air and the dissolved air have their own kinematics. The model is then illustrated through simple one-dimensional simulations using the FEM code COMSOL. After validation of the model predictions for deformability of a fine-grained quasi-saturated homogeneous soil sample subjected to an undrained oedometric test, other more complicated configurations involving heterogeneous spatial variations are simulated. These simulations show that the model can correctly represent the coexistence of highly unsaturated, quasi-saturated and fully saturated domains that are evolving continuously in space and time.

2. Physical description of the unsaturated to saturated porous medium

We consider an unsaturated porous medium composed of a solid skeleton (S) and a pore space partially saturated by a liquid phase (L). The remaining pore space is filled by a gaseous phase (G). At a local scale and relative to a representative elementary volume (REV) $d\Omega$ of the solid skeleton, the Lagrangian porosity of the medium (ϕ) is defined as the ratio between the actual volume of the pore space and the initial overall volume of the porous medium, and the amount of liquid within the pore space is quantified by the saturation degree (S_L), which is the ratio between the actual volume of liquid and that of the pore space

$$\phi = \frac{d\Omega_L + d\Omega_G}{d\Omega_0}, \quad S_L = \frac{d\Omega_L}{d\Omega_L + d\Omega_G}, \tag{1}$$

where $d\Omega_L$ and $d\Omega_G$ are the actual volumes of, respectively liquid and gas inside the REV in its current position, and $d\Omega_0$ is the overall volume of the same REV at the initial state.

It is sometimes more practical to use the void ratio e, defined as the ratio between actual porous volume $d\Omega_L + d\Omega_G$ and the actual volume occupied by the solid skeleton $d\Omega_S = d\Omega - d\Omega_L - d\Omega_G$ instead of the porosity. Assuming that $d\Omega_S$ remains constant (e.g., negligible volumetric deformation of the solid matrix), the link between the two values is

$$\phi = \frac{Je}{1+e} = \frac{e}{1+e_0}, \tag{2}$$

where $J = d\Omega_0/d\Omega$ is the Jacobian of the movement of the solid skeleton, and $e_0 = (d\Omega_L^0 + d\Omega_G^0)/d\Omega_S$ is the initial void ratio.

In this paper, the in-pore liquid is only composed of liquid water and dissolved air, which we represent symbolically by $L = \{wL, aL\}$. In this notation, the first (small) letter represents the species, and the second (capital) letter represents the phase to which the species belongs. The influence of the other dissolved species is neglected. For the sake of simplicity, we assume that the gaseous phase is only composed of dry air. In other words: $G = \{aG\}$.

The solid phase, S, is primarily composed of the solid matrix. The entrapped air has the same kinematics as the solid skeleton and would therefore be considered part of the same phase. There is, however, no satisfactory symbol to represent the solid matrix; we propose the notation $S = \{mS, aS\}$ to denote the solid particles and the entrapped air. Note also that we limit ourselves to the case of infinitesimal displacements and strains for the solid skeleton. The Jacobian differs from unity only by an infinitesimal amount, so the Lagrangian porosity ϕ can be identified by its Eulerian counterpart. We will therefore use the symbol ϕ to denote the porosity.

Note that, due to the process of dissolution and bubbling, mass exchange can take place between the dissolved air, aL, and the gaseous air phases, namely aS and aG.

2.1. Mechanisms of air trapping and dissolution

During wetting of an initially partially saturated soil, the pore network is invaded by the liquid phase, which forces the evacuation of the gaseous phase out of the medium (e.g., [35,16]). The increase of liquid quantity in the pore space leads to an increase of r_{LG}, the radius of curvature of the liquid/gas interface. The latter is commonly assumed to be close to the entry radius of the pores. Following Laplace's Law, the capillary suction, s, defined as the difference between the gas pressure and the liquid pressure, decreases. Assuming that the gas pressure remains equal to the atmospheric pressure p_0

$$s = p_0 - p_L = \frac{2\gamma}{r_{LG}} = f(S_L), \tag{3}$$

where p_L is the liquid pressure, γ is the interfacial tension between the liquid and the gas, and $f(S_L)$ is a decreasing function of the saturation ratio that depends on the characteristics of the pore network. According to this definition, an increase in p_L causes an increase in the water content at constant gas pressure p_0.

When the saturation ratio increases above a certain threshold, S_e, the volume fraction that remains filled by the gaseous phase may split into several air pockets, which tend to attach themselves to the solid skeleton. At that stage, the gas relative permeability reaches zero, and the volume of entrapped air within an REV is equal to $\phi(1 - S_e)d\Omega_0$. Many experimental studies have been performed to estimate the order of magnitude of S_e. They show that this parameter can vary from 3% to 22%, according to the type of soil [39,32,14]. However, based on data reported by Faybishenko [17] and Sakaguchi [36] on silts and fine soils, an average value close to 10% seems to be a good first approximation for S_e.

The capillary suction needed to reach the saturation S_e is denoted by s_e; this latter quantity behaves like the air-entry suction in classical unsaturated soil mechanics, in that below this value, the porous space is "saturated" by a bubbly liquid (with a reduced bulk modulus). From the theoretical point of view it could also be called "percolation suction" because it marks the transition between a continuous and a discontinuous gas phase. From experimental results, many authors [41,20,8] have observed that this latter decreases when the void ratio increases. As it is illustrated in Fig. 1, at first order, this relationship is linear. Thus, in the following we assume that

$$s_e(e) = s_{e0} - k_1 e, \tag{4}$$