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Effect of water content and soil texture on consolidation in unsaturated soils

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ABSTRACT

Soil consolidation, involving time-dependent coupling between deformation of a porous medium and interstitial fluid flows within it, is of relevance to many subsurface engineering problems. A comprehensive model of poroelasticity for consolidation in unsaturated soils has been recently developed by Lo et al. (2014), but it still remains elusive how variations in soil texture and water content affect consolidation behavior, and the underlying parameters deriving this behavior.

In the current study, a boundary-value problem is first setup corresponding to two symmetric semi-permeable drainage conditions, and then solved analytically for describing the excess pore air and water pressures along with the total settlement in response to time-invariant external loading using the Laplace transform. These solutions are numerically calculated for unsaturated soils with eleven texture classes as a function of three initial water saturations as representative examples. Our results reveal that the excess pore water pressure and time-dependent total settlement are indeed significantly sensitive to both soil texture and initial water saturation. We demonstrate that the coefficient of consolidation for water and its loading efficiency are two important physical parameters controlling consolidation behavior. With respect to the same soil texture, the coefficient of consolidation for water increases with an increase in initial water saturation, taking a value approximately four to five orders of magnitude greater in saturated soils than that in unsaturated ones. For a given initial water saturation, the rate of dissipation of excess pore water pressure is smallest in clay, followed by silty clay, silty clay loam, sandy clay, clay loam, silt loam, loam, sandy clay loam, sandy loam, loamy sand, and sand. A comparative study shows that in the early stage of consolidation, unsaturated soils bear smaller excess pore water pressure, but its dissipation is completed faster in saturated soils. The loading efficiency for water exhibits a concave upward relationship with initial water saturation in silty clay and clay, whereas a positively-correlated relationship between the efficiency and initial water saturation is observed in other soil textures. Unlike saturated soils, a considerable amount of total settlement is shown to occur immediately after application of external loading.

1. Introduction

Scientific research has long revealed that a strong intimate interaction occurs between deformation of a porous medium and interstitial fluid flows within it as bearing loads [27,34]. Porous medium deformation induces fluid flow due to pore volume changes; the latter affects the former as a result of excess pore pressure gradients created [15]. Such hydromechanical coupling is ubiquitous in subsurface environments of relevance to a rich variety of practical engineering problems, such as land subsidence caused by withdrawal of groundwater or oil [3,10], compaction of soils due to the construction of buildings [17], and groundwater remediation [22]. Soil consolidation that addresses a slow transient phenomenon, leading to time-dependent settlements, involves this coupling in a quasi-static regime; i.e. inertial forces are substantially negligible because the time scale pertinent to the second-order time-derivatives is much smaller than the other process of interest.

The classical theory of one-dimensional consolidation in water-saturated soils was first established by Terzaghi [31], who derived a diffusion equation to describe pore pressure variations in response to time-invariant loading. In attempting to illustrate the transient behavior of soil consolidation, Terzaghi [31] proposed the pioneering notion of effective stress to quantify the vertical stress tending to compact the porous matrix. Despite the significant advance of this theory in capturing the essence of

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consolidation process, the coupling between fluid flow and solid deformation in a water-saturated porous medium is not truly laid on a firm theoretical base. This conceptual breakthrough was achieved later by Biot [4], who brought the role of the solid and fluid constituents on equal footing to formulate a pair of coupled equilibrium equations of motion using the displacement vector of solid and fluid pore pressure as dependent variables, now known as poroelasticity [14]. This generalization makes it possible to realize rigorously the simultaneous representation of coupled three-dimensional fluid flow and solid deformation in a systematic way, wherein external loading is thereby allowed to be a time-varying variable. Over the past decades, a number of other researchers have elaborated and expanded upon Biot's poroelasticity theory. A series of analytical solutions for the Biot [4] poroelasticity equations under various boundary-value problems of engineering interest after reformulating dependent variables in terms of pore fluid pressure and total stress were presented by Rice and Cleary [29]. Detournay and Cheng [9] clarified the physical interpretation of poroelasticity parameters. An appropriate set of thermodynamic relationships was developed by Lewis and Schrefler [17] to describe non-isothermal, multiphase-fluid problems of poroelasticity. Aichi and Tokunaga [1] extended material coefficients in constitutive equations of thermoporoelasticity for anisotropic micro-heterogeneous porous media.

Although a long history of efforts has provided a reasonably comprehensive understanding of the importance of the stress-flow coupling in consolidation behavior of a fluid-saturated porous medium, it has received relatively little emphasis on that for a porous medium containing two immiscible, viscous, compressible fluids. To account for the effect of partial fluid saturation, Bishop and Blight [7] introduced a modified form of Terzaghi's effective stress, which was formulated using two stress-state variables: net stress, a variation between external force and air pressure, and matrix suction, a difference between water and air pressures. In this generic form, a scaling factor, termed the effective stress parameter or Bishop's parameter, was proposed to weight the saturation state, reflecting the configuration that not all matrix suction contributes to effective stress, instead depending on the degree of water saturation [7]. Nikooee et al. [26] have recently discussed various relationships characterizing the functional dependency of Bishop's parameter, which is likely related to water saturation, capillary pressure, air entry pressure, and fluid interfacial area. Fredlund and Morgenstern [11] developed two constitutive mathematical relations for connecting the two stress variables (net stress and matrix suction) with changes in volume of soil matrix and water by postulating the solid phase to be incompressible. With neglect of the compressibility of water and under the simplification of uniaxial strain, Fredlund and Hasan [12] incorporated those relations into continuity equations, yielding two coupled partial differential equations for the excess pore water and air pressures, wherein two recursive formulas were also established to specify their initial values. Using the technique of volume averaging, Tuncay and Corapcioglu [32] obtained two coupled partial differential equations as well, which take the similar form to those in Fredlund and Hasan [12] but with different constitutive coefficients. Conte [8] proposed a theoretical approach toward extending the one-dimensional consolidation model of Fredlund and Hasan [12] to the plane-strain condition. A numerical investigation concerning the effect of boundary drainage conditions on one-dimensional consolidation in unsaturated soils was performed by Shan et al. [30] for various types of external loading. Lo et al. [24] have recently developed the mathematical model of poroelasticity applicable to three-dimensional consolidation in unsaturated soils, which features the displacement vector of the solid phase together with the excess pore water and air pressures as dependent variables.

Despite these long-standing advances, the effect of soil texture and initial water saturation on consolidation behavior in unsaturated soils does not receive much attention. Differences in soil texture are a major cause of variations in matric potential and the degree to which the pores are filled with water, thus leading to distinct elasticity properties and viscous coupling parameters [2,18,23]. This in turn implies that the mechanical response of unsaturated soils to external loading should be considerably sensitive to their texture [2,19,20]. In addition, although an analytical solution for one-dimensional consolidation of unsaturated soils under an entirely permeable boundary drainage condition has been lately given by Lo et al. [24], the closed-form solution involving the semi-permeable boundary drainage conditions is still missing. Most importantly, much also remains unknown as to what physical parameters are crucial in controlling the dissipation rate of the excess pore water and air pressures during consolidation in unsaturated soils.

We shall address these issues in the present study, which consists of theoretical derivation and numerical modeling. In the former part, a boundary-value problem corresponding to two different but symmetric semi-permeable drainage conditions is first developed, as opposed to a completely permeable drainage condition addressed previously by Lo et al. [24]. By application of the Laplace transform, the problem is then solved analytically to obtain the temporal and spatial distributions of the excess pore water and air pressures together with total settlement caused by time-invariant external loading. The solution is then numerically evaluated with elasticity parameters and hydraulic data applicable to eleven different soil textures (sand, loamy sand, sandy loam, loam, silt loam, sandy clay loam, clay loam, silty clay loam, sandy clay, silty clay, and clay) as a function of three initial water saturations (0.7, 0.8, and 0.9) as representative examples. A comparative study is next carried out for unsaturated and water-saturated clays. Our results show that the coefficient of consolidation with respect to water is crucial in defining the rate of dissipation of the excess pore water pressure, whereas the loading efficiency for water is the one to characterize the fraction of changes in external loading initially added to pore water under an undrained response, thereby quantifying the total settlement that occurs immediately after the loading is imposed.

2. Model equations

A set of coupled poroelasticity equations describing one-dimensional consolidation in unsaturated soils, in the absence of body force, were developed by Lo et al. [24], which constitute two diffusion equations with coupling in the time-derivatives:

$$q_1 \frac{\partial p_1}{\partial t} + q_2 \frac{\partial p_2}{\partial t} = b_1 \frac{\partial^2 p_1}{\partial z^2}, \tag{1.1}$$

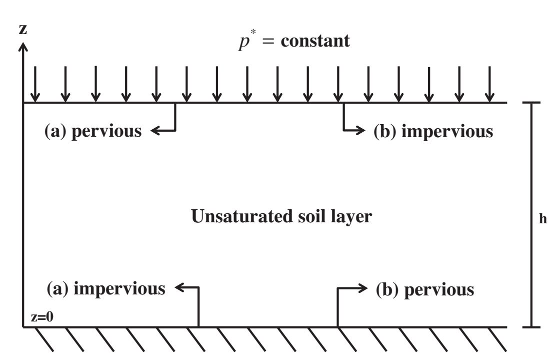

Fig. 1. Schematic diagram of the boundary-value problem.