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A porous model to simulate the evolution of the soil–water characteristic curve with volumetric strains

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ABSTRACT

Volumetric strains modify the soil–water retention curve. An easy way to take this phenomenon into account is by means of a percolation model based on the pore size distribution of the material. The model proposed herein is able to simulate the retention curves during wetting–drying cycles. As volumetric deformations modify the pore size distribution, its effect on the retention curves can be easily included in the model. The model is validated by comparing some numerical results with experimental results. This procedure represents an option to create fully coupled constitutive models for unsaturated soils.

1. Introduction

It has been well documented that mechanical and hydraulic behavior in unsaturated soils are coupled. An unsaturated soil is a multiphase medium that contains at least three interacting phases. These interactions induce a negative pore water pressure that bonds solid particles to each other. Resistance and volumetric strains depend very much on these water bonds [1]. When water menisci are formed between concurrent solid particles, an additional contact stress appears, bringing them closer and shrinking the porous structure of the material. If suction reduces, two different behaviors may occur. If the soil mass is not loaded further previous to wetting, the volume of the soil suffers an elastic rebound. On the contrary, if the soil is loaded beyond the yield surface previous to wetting, the porous structure of the soil collapses. This volumetric reduction influences the hydraulic behavior of the material.

It is therefore important to understand the relationship between the amount of water in the soil with its corresponding suction. From the point of view of constitutive modeling, it is more important to determine the degree of saturation Sr—the ratio between water volume and volume of voids—because suction and the strain-like variable nSr are both conjugate variables of the soil–air–water system, n being the soil porosity of the material [2,3]. Once plotted in a Cartesian coordinate system, the relationship s–Sr is called soil–water retention curve or soil–water characteristic curve [SWCC]. In addition, suction (s) can be related to the relative humidity of the medium through Kelvin's equation, or to the size of pores through Laplace's equation ($s = 2Ts/R$), where R represents the radius of the pore and Ts is the air–water interface tension coefficient.

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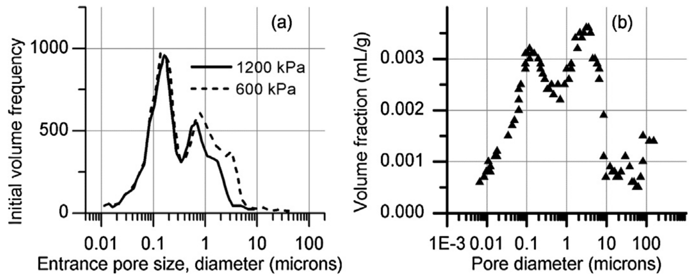

Fig. 1. (a) Comparing intrusion volume frequency ratios of samples compacted at the same water content and different vertical stresses [18], (b) pore-size distributions (PSD) of a clayey till subjected to 840 kPa of suction [19].

Despite its importance, prediction of SWCCs is a complicated task because they are highly dependent on the drying–wetting path. Hence, predictions on SWCCs that include the influence of volumetric deformations are difficult, as it is rather hard to predict how the overall soil structure modifies itself with suction or external stresses. However, this task cannot be avoided when modeling unsaturated soils.

Because internal pore structure and SWCCs are intimately related, there have been some attempts at simulating the hydraulic behavior of soils through equations that introduce some parameters that depend on the pore–size distribution (PSD). Based on Brooks and Corey's equation [4], Khalili [5] proposed a coupled hydromechanical model where the shifting of the SWCCs along the suction axis is a function of the air-entry value. Many models [6–9] modify van Genutchen's equation [10] by incorporating functions that depend on the current void ratio. In that sense, Romero and Vaunat [8] and later Vaunat [9] incorporated the influence of volume changes on the SWCC by quantifying the volume of micropores.

An interesting solution to model internal structural changes has been presented by Koliji et al. [11] who proposed a model to reproduce the evolution of the PSDs during suction increase or loading. Their study is based on experimental observations of PSDs obtained from samples subjected to different suctions. The PSD was obtained from mercury intrusion porosimetry (MIP) tests performed before and after the increment of suction. If this procedure is adapted to a porous model able to reproduce the SWCCs, then it is possible to include the effect of suction or loading on the shifting of the SWCCs. A model of this type is presented herein.

This paper presents a model that has been successfully used to reproduce the PSD of soils from the SWCCs and to correctly interpret the results of MIP tests [12,13]. This model is enhanced to couple volume change and water retention properties focusing on hydraulic hysteresis by proposing a simple yet effective way to simulate the evolution of the PSD.

2. Microstructural volume change

The sizes of pores in soil samples may range between thousandths to hundreds of microns. Coarse clean sands show relatively large pores of uniform size. In comparison, clay particles attract each other by electrochemical forces forming aggregates. This is why clayey soils generally show a double structure with small pores inside the aggregates (intrapores) and large pores between the aggregates (interpores) [14]. This type of structure can be observed through the results of MIP tests performed on these materials. As experimentally demonstrated by Simms and Yanful [15] and later by Romero et al. [16], the PSD modifies during loading or suction increase. Cuisinier and Laloui [17] observed strong modifications of the soil fabric with suction variations.

Fig. 1 shows the variations of volume with the size of pores of a glacial deposit best known as glacial till corresponding to unsorted materials with no apparent stratification commonly including fine grained components such as clay [20]. Notice that both Figs. 1a and 1b clearly show two maximum peaks exhibiting two main structural levels: micro and macroporosity. Here, the pores belonging to the larger sizes are called macropores (denoted by M) and those of smaller sizes are called micropores (denoted by mS site).

Fig. 2 shows the PSD of a soil sample subjected to different values of suction including the saturated conditions ($s = 0$). In this figure, the vertical axis represents the ratio of the volume of injected mercury with the logarithm of the pore radius r, while the horizontal axis represents the pore radius r in logarithmic scale. This figure indicates the contribution of each size to the total volume of pores. The nil suction curve shows a peak at a pore size of about 5 microns (macroporosity). As suction increases, macropores reduce their volume and the peak displaces to a smaller pore size of about 0.45 microns (microporosity). In other words, while the volume of macropores reduces, that of micropores increases.

As aforementioned, suction reduction (wetting) may induce expansion or collapse of the soil structure. Consider a soil subjected to certain suction level. In that case, solid particles are linked by water menisci that induce additional contact forces to these particles. When the soil is soaked, water menisci are destroyed and a general elastic rebound of the material is observed.

Collapse has been frequently related to silty sands subjected to loading while suction is present [21,22]. In this case, relatively large soil grains (sands) are linked by small packets of silt and clay (Fig. 3) which maintain larger grains practically immobile [21,23] when the soil is subjected to further loading. Because the strength of the packets depends on the amount