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A new and simple stress-dependent water retention model for unsaturated soil

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ABSTRACT

The water retention curve (WRC) is an important hydraulic property of unsaturated soil needed for seepage analysis. Experimental evidence shows that the WRC is affected by various factors such as net stress and soil type. Many attempts have been made to describe the effects of net stress by including the void ratio in a water retention model. But the void ratio (i.e., soil density) is not the only parameter altered by the application of net stress. The pore structure, including the pore size distribution, pore shape and pore orientation, is also changed. Thus the influence of net stress on the WRC should not be treated as equivalent to density effects. In this study, it is verified that the inclusion of the void ratio cannot adequately capture the effects of net stress on the water retention behaviour. A new and simple water retention model is thus developed by considering the stress effects on the void ratio as well as the pore structure. The model is then applied to simulate the WRCs of three different soils tested over a wide range of stress conditions, including isotropic and anisotropic stress conditions. The results show that better predictions of experimental data can be made by incorporating the effects of net stress on both the void ratio and the pore structure.

1. Introduction

The water retention curve (WRC) is an important hydraulic parameter for seepage analysis in unsaturated soil and has been found to be dependent on many factors [1–3]. Two idealized configurations of unsaturated granular soils having the same void ratio are shown in Fig. 1. Although the particles can be arranged in many configurations that result in the same void ratio, pore structures of the two configurations, including pore size distributions, pore shapes and pore orientations, are almost always different. Thus they should have different water retention abilities, as the experimental results shown in Fig. 2 confirm. In this figure, WRCs of natural and recompacted specimens are compared at two different vertical net stresses (0 and 40 kPa) [3]. The recompacted specimens were purposely prepared to the same initial density and water content as the natural specimens. At each stress level, differences clearly exist in their water retention characteristics, particularly in the air-entry value (AEV). Furthermore, the water retention of both natural and recompacted specimens increases with an increase in vertical net stress.

Ng and Pang [3] found that WRC of unsaturated soil is altered when stress changes. This is because the application of stress affects not only soil density (or void ratio) but also pore structure, as revealed in scanning electronic microscopy tested conducted by Delage and Lefebvre [4]. Through 1D consolidation tests on saturated clay, Delage and Lefebvre [4] found that platy clay particles and hence soil pores show preferential orientations during the loading process. Such rearrangement of the pore structure obviously cannot be completely captured by the soil density (or void ratio) alone. In addition, Ng and Xu [5] carried out a series of suction-controlled triaxial compression tests on unsaturated compacted silt and measured shear modulus reduction curves. They found that the elastic shear range is very small (less than 0.003%). Beyond this very small elastic range, continuous loading induced the rearrangement of soil particles and pore structures (i.e., plastic behaviour). This suggests that even a small increase in net stress would induce plastic deformation and alter the pore structure and hence affect the water retention behaviour. Similarly, Khosravi and McCartney [6] observed plastic changes in shear modulus during drying under constant net stress. This is at least partially because the Bishop's effective stress increases during drying, inducing plastic deformation and a change in pore size distribution. The Bishop's effective stress is defined as $\sigma + S_r(u_a - u_w)$,

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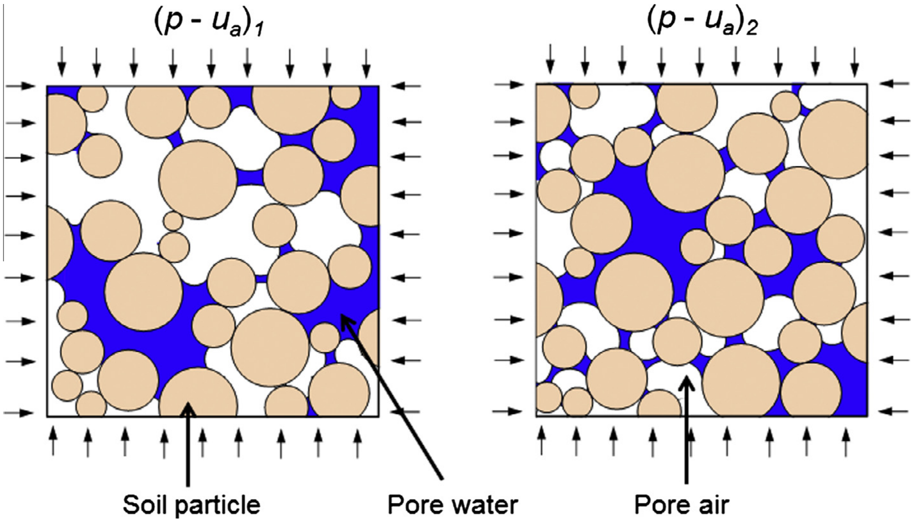

Fig. 1. Idealised configurations of two representative unsaturated soil specimens having the same void ratio but different pore structures.

where σ, S_r, u_a and u_w are net stress, degree of saturation, pore air pressure and pore water pressure. The Bishop's effective stress becomes Terzaghi's effective stress when soil specimen is saturated.

Mathematical formulations have been reported in the literature to describe the relationship between suction (s) and degree of saturation (S_r) on the drying path. These formulations may be classified into four types. The first type assumes a unique relationship between soil moisture and suction [7–10], whereas the second type relates S_r to s and net mean stress (p) [1]. Without explicitly considering the soil density (or void ratio), these two types of formulations may not be able to describe WRCs with different initial densities easily using a single set of parameters. The third type considers S_r as a function of s and the average void ratio (e) [11–19]. The third type of models assumes implicitly that the effects of stress are equivalent to density effects on a WRC. Although this type of formulation is able to capture the density effects, the stress effects are over-simplified. This is because the water retention behaviour is strongly affected by not only the void ratio but also the pore structure [17,20]. Recently, effects of pore structure on water retention behaviour are considered in some coupled hydro-mechanical models for active clays [21,22]. These models focus on aggregated fabric evolution induced by wetting and drying. Stress effects on pore structure and hence on water retention behaviour are not fully understood.

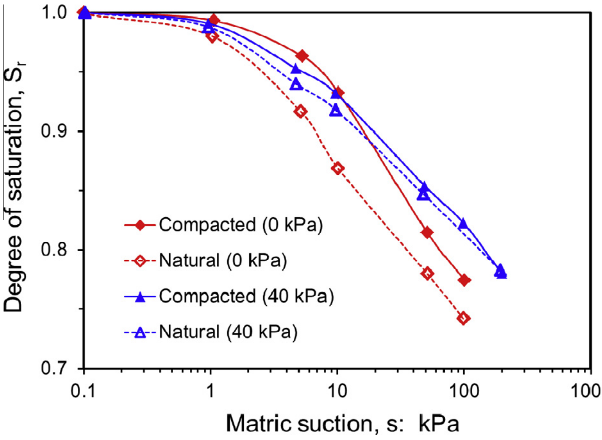

Fig. 2. Influence of pore structure on WRCs of natural and recompacted specimens having the same initial void ratio (data from Ng and Pang [3]).

The main objectives of this study are (1) to clarify that stress effects on water retention behaviour are not equivalent to density effects and (2) to develop a simplified stress-dependent water retention model. For an improved modelling of stress-dependent WRCs, stress effects on void ratio and pore structure are considered. WRCs computed using the new model and existing models are compared with experimental data obtained under a wide range of stress conditions, including isotropic and anisotropic stress paths. The results are reported and discussed. It should be pointed that out soil pore structure would be affected by various factors, such as stress (net stress and Bishop's effective stress), chemical interactions, history of wetting and drying processes, precipitated and dissolved minerals and stress history. For simplicity, this study focuses on stress effects on pore structure as well as an average void ratio, the evolution of which with mean net stress is described by a semi-empirical equation. The new model explicitly incorporates mean net stress rather than microstructural state variable. This is mainly because that microstructural analysis (for example, analyses such as mercury intrusion porosimetry (MIP) and environmental scanning electron microscopy (ESEM)) is not a routine test in geotechnical engineering. Explicit incorporation of microstructural state variable in the model would result in great difficulty in calibrating soil parameters.

2. Development of a new water retention model

van Genuchten [8] proposed a simplified equation to describe the relationship between matric suction and volumetric water content. Assuming that the degree of saturation S_r tends to unity at zero suction, the van Genuchten equation can be expressed as follows:

$$S_r = \left[1 + \left(\frac{s}{a}\right)^{m_2}\right]^{-m_1} \tag{1}$$

where a, m_1 and m_2 are soil parameters. Among these parameters, a is closely related to the AEV of unsaturated soil. It is well recognized that the AEV of unsaturated soil increases with decreasing e. For obtaining the relationship between a and e, Gallipoli et al. [11] proposed the following semi-empirical equation:

$$a = m_3 e^{-m_4} \tag{2}$$

where m_3 and m_4 are soil parameters. S_r can be obtained by combining Eqs. (1) and (2):