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# Drying response and effective stress in a double porosity aggregated soil

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ABSTRACT

Shrinkage and water retention characteristics of a double porosity compacted soil are studied. Results from a series of suction controlled oedometric drying tests at different net stresses are presented. Water retention curves exhibit a bimodal response which is a characteristic of the double porosity structure of the soil. Validity of the expression proposed by Khalili et al. [Khalili, N., Witt, R., Laloui, L., Vulliet, L., Koliji, A., 2005. Effective stress in double porous media with two immiscible fluids. Geophys. Res. Lett. 32 (15): Art. No. 15309.] for the determination of the effective stress in double porosity media is investigated. It is shown that quantitative predictions of volume change in unsaturated aggregated soils can be made using the effective stress concept.



## 1. Introduction

Natural and made geomaterials frequently exhibit two scales of porosity, with micro pores surrounded by macro pores such as those encountered in fractured rock formations (e.g. see Burger and Shackelford, 2001; Mandique et al., 2007). In soils, double porositiness may arise due to root holes, worm holes and cracks (Jongmans et al., 2003), or the aggregated nature of the medium (Coppola, 2000). Fissuring and cracking are most commonly observed in heavily overconsolidated and desiccated clays (Garga, 1988), whereas aggregation occurs in agricultural soils and compacted soils, particularly when the soil is compacted on the dry side of the optimum moisture content (Romero et al., 1999). In addition to showing two scales of porosity, the void space in natural soils is frequently filled with more than one fluid implying the need for a multi-phase constitutive modelling approach (Khalili, 2008).

A substantial amount of work has been undertaken in the field of double porosity media over the past four decades. Some of the notable contributions include: field and laboratory investigations of Evans (1966), Gringarten et al. (1975), Bawden et al. (1980), Garga (1988), Federico and Musso (1991), Mayo and Koontz (2000), Khalili (2003), Illman and Neuman (2003) and Mandique et al. (2007); theoretical developments of Barrenblatt et al. (1960), Warren and Root (1963) and Kazemi (1969) for fluid flow through rigid double porosity media; coupled flow and deformation models of Aifantis (1977), Khalili-Naghadeh and Valliappan (1991), Auriault and Boutin (1993), Bai et al. (1993), Khalili and Valliappan (1996), Tuncay and Corapcioglu (1996), Wang and Berryman (1996), and Loret and Rizzi (1999); and multi-phase flow and deformation contributions of Lewis and Ghafouri (1997), Bai et al. (1998), Pao and Lewis (2002), Nair et al. (2004) and more recently Khalili (2008).

Nevertheless, all the above contributions have been confined to the study of fluid flow through fissured/fractured porous media, in the context of reservoir engineering. Indeed, there have been very few investigations of the mechanical behaviour of aggregated materials, irrespective of their prevalence in agricultural and geotechnical engineering. Only recently, Romero et al. (1999) and Coppola (2000) reported experimental data on the behaviour of aggregated double porosity soils. However, their investigation was limited to the hydraulic and water retention characteristics of aggregated soils.

In this paper, experimental results are presented on the volume change as well as water retention characteristics of a laboratory prepared aggregated soil. A series of one-dimensional consolidation and drying tests are performed and analysed. The characteristic features of the hydraulic and mechanical response of the soil are investigated, and the effect of net stress on the water retention curve and volume change is highlighted. The application of the effective stress principle (Khalili et al., 2005) to unsaturated aggregated soils is examined, and it is shown that quantitative predictions of volume change in aggregated materials can be made using the effective stress principle. To the authors' knowledge, this is the first reported case of investigating the applicability of the effective stress principle to aggregated soils. By using the effective stress principle, the effect of suction and net stress on the soil response is represented by a single stress variable, thereby simplifying the deformation analysis. Observations are also made as to the existence of suction hardening in unsaturated aggregated soils.

The paper is organised into five sections. Section 2 is devoted to the basic concepts: the effective stress principle and the suction hardening in unsaturated soils. Details of the experimental program including the

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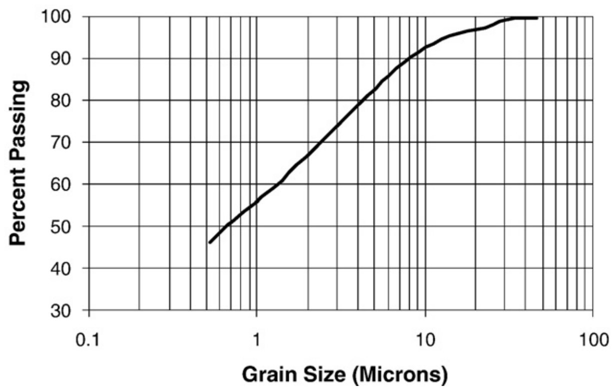


**Fig. 1.** Particle size distribution of kaolin.

index properties of the test soil, sample preparation technique and the testing procedure are presented in Section 3. The interpretation of the results and volume change analysis are presented in Section 4. The findings of the investigation are summarised in Section 5.

## 2. Basic concepts

### 2.1. Effective stress

The effective stress principle is one of the key axioms of soil mechanics. Expressed as, "that function of the externally applied stresses and the internal fluid pressures which controls the mechanical effects of a change in stress, the effective stress converts a multi-phase, multi-porous media to a mechanically equivalent, single-phase, single-stress state continuum" (Khalili et al., 2004, 2005; Nuth and Laloui, 2008). It enters the elastic as well as elasto-plastic constitutive equations of the solid phase, linking a change in stress to straining or any other relevant quantity of the soil skeleton (Khalili et al., 2004).

For saturated soils, the effective stress is expressed as (Skempton, 1961; Nur and Byerlee, 1971),

$$\boldsymbol{\sigma}' = \boldsymbol{\sigma} - \left(1 - \frac{c_s}{c}\right) u_w \boldsymbol{I} \tag{1}$$

in which $\boldsymbol{\sigma}'$ is the effective stress tensor, $\boldsymbol{\sigma}$ is the total stress tensor, $u_w$ is the water pressure, $c_s$ is the compressibility of the solid grains, $c$ is the drained compressibility of the soil, and $\mathbf{I}$ is the second order identity tensor.

For unsaturated soils, the effective stress is defined as (Bishop, 1959),

$$\boldsymbol{\sigma}' = \boldsymbol{\sigma} - \chi u_w \boldsymbol{I} - (1 - \chi) u_a \boldsymbol{I} \tag{2a}$$

or

$$\boldsymbol{\sigma}' = \boldsymbol{\sigma}_{net} + \chi s \boldsymbol{I} \tag{2b}$$

in which $u_a$ is the pore air pressure and $\chi$ is the effective stress parameter, realising a value of 1 for saturated soils and zero for dry soils. $\boldsymbol{\sigma}_{net} \equiv (\boldsymbol{\sigma} - u_a \mathbf{I})$ is the net stress, and $s \equiv (u_a - u_w)$ is the matric suction.

For aggregated soils, saturated with air and water, the effective stress is defined as (Khalili et al., 2005),

$$\begin{aligned} \boldsymbol{\sigma}' = \boldsymbol{\sigma} &- \alpha_m[\chi_m u_{mw} + (1 - \chi_m) u_{ma}]\boldsymbol{I} \\ &- \alpha_M[\chi_M u_{Mw} + (1 - \chi_M) u_{Ma}]\boldsymbol{I} \end{aligned} \tag{3a}$$

or

$$\boldsymbol{\sigma}' = (\boldsymbol{\sigma} - \alpha_m u_{ma} \boldsymbol{I} - \alpha_M u_{Ma} \boldsymbol{I}) + \alpha_m \chi_m s_m \boldsymbol{I} + \alpha_M \chi_M s_M \boldsymbol{I} \tag{3b}$$

in which $u_{mw}$, $u_{ma}$, $u_{Mw}$ and $u_{Ma}$ are the micro pore-water, micro pore-air, macro pore-water and macro pore-air pressures, respectively. $\chi_m$ and $\chi_M$ are the unsaturated effective stress parameters of the micro pores and macro pores, respectively. $s_m \equiv u_{ma} - u_{mw}$ is the matric suction of the micro pores and $s_M \equiv u_{Ma} - u_{Mw}$ is the matric suction of the micro pores. $\alpha_m$ and $\alpha_M$ are the conventional effective stress parameters of saturated double porous media (Khalili and Valliappan, 1996),

$$\alpha_m = \frac{c_g}{c}, \quad \alpha_M = 1 - \frac{c_g}{c} \tag{4}$$

in which $c$ is the drained compressibility of the aggregated soil, and $c_g$ is the drained compressibility of the material forming the aggregates.

The physical interpretation of $\chi_m$, $\chi_M$, $\alpha_m$ and $\alpha_M$ is that $\chi_m$ and $\chi_M$ scale/average air and water pressure in the micro pores and macro pores to *equivalent* pressures of micro pore-fluid and macro pore-fluid. $\alpha_m$ and $\alpha_M$ quantify the contribution of these *equivalent* pressures to the effective stress of the double porosity medium (Khalili et al., 2005).

Khalili and Khabbaz (1998) showed that for single porosity media $\chi_m$ may be estimated as,

$$\chi_m = \begin{cases} \left(\dfrac{s_{m(e)}}{s_m}\right)^{\Omega} & \text{for} \quad s_m \geq s_{m(e)} \\ 1 & \text{for} \quad s_m \leq s_{m(e)} \end{cases} \tag{5}$$

where exponent $\Omega$ is a material parameter, with a best fit value of 0.55. $s_{m(e)}$ is the suction value separating saturated from unsaturated conditions in the micro pores. It is equal to the air entry value, $s_{m(ae)}$, for the main drying path, and the air expulsion value, $s_{m(ex)}$, for the main wetting path (Khalili et al., 2004). For suction values between the main drying and the main wetting paths an interpolation function similar to that in Khalili et al. (2008) may be used.

Extending the observation of Khalili and Khabbaz (1998) for single porosity media to macro pores, we then write,

$$\chi_M = \begin{cases} \left(\dfrac{s_{M(e)}}{s_M}\right)^{\Omega} & \text{for} \quad s_M \geq s_{M(e)} \\ 1 & \text{for} \quad s_M \leq s_{M(e)} \end{cases} \tag{6}$$

in which $s_{M(e)}$ represents the matric suction separating saturated from unsaturated conditions in the macro pores.

### 2.2. Suction hardening

Suction hardening occurs in unsaturated soils as the combined effect of the pore air and pore water pressures affects the soil behaviour in two different ways. Firstly, it increases the effective stress of the soil skeleton through the *equivalent* pore fluid pressures, in the same way that the pore water pressure affects the mechanical behaviour of an equivalent saturated soil. Secondly, it results in the formation of capillary menisci at the particle contact points, which generate inter-particle contact forces normal to the plane of contact. These forces tend to stabilize the contacts and inhibit grain slippage, altering the way the soil experiences plastic (non-reversal) deformation subjected to loading (Loret and Khalili,

**Table 1**
Index and physio-chemical properties of kaolin.

| | |
|---|---|
| Liquid limit, LL (%) | 49 |
| Plastic limit, PL (%) | 29 |
| Plasticity index, PI (%) | 20 |
| >2 μm (%) | 33 |
| <2 μm (%) | 67 |
| Quartz (%) | 8.5 |
| Kalonite (%) | 79.5 |
| Illite (%) | 12 |
| Surface area ($m^2/g$) | 21.1 |
| Specific gravity of solids, *Gs* | 2.63 |
| USCS classification | ML |