A WATER RETENTION MODEL FOR COMPACTED CLAYEY SOILS

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ABSTRACT: *The paper presents a water retention model accounting for the evolution of the aggregated structure of compacted clays along generalized hydromechanical stress paths. In this model, the retention mechanisms of both microstructural and macrostructural levels are described separately using an expression of the type proposed by van Genuchten (1980). From the water retention model, a theoretical pore-size distribution (PSD) can be derived. Experimental PSD data on two compacted clays subjected to various wetting, drying and loading paths are exploited to provide a physical based calibration of the parameters of the water retention model. Not only they emphasize the evolution of some parameters, such as the air-entry pressure, along generalized stress paths but they also provide a quantification of these processes. On this basis, simple evolution laws are proposed. Finally, the water retention model is validated against other experimental data on the same materials compacted at different dry densities. The proposed formulation succeeds in tracking simultaneously the evolution of the fabric pattern and the hydraulic state of compacted clays along generalized stress paths.*

1 INTRODUCTION

In recent years, particular attention has been paid to the behaviour of compacted clays in relation to their use as engineered barriers in deep geological repositories for nuclear waste (Pusch 1992; Komine & Ogata 1994; Delage et al. 1998; Wiebe et al. 1998; Romero et al. 1999; Collin et al. 2002; Lloret et al. 2003; among others). In this context, the engineered barrier experiences a complex behaviour owing to the strong multiphysical processes taking place. Initially unsaturated, the compacted clay experiences hydration from the saturated host rock. During this process, it tends to expand and develops swelling stresses, hence modifying the water transfer properties of the material (see, for instance, Loiseau et al. 2002; Villar & Lloret 2002; Ye et al. 2009).

Because the final effectiveness of the seal is believed to depend on this transient phase, the conceptual understanding of the water retention mechanisms appears as a key issue. It is now admitted that the behaviour of compacted clays is better understood when the effects of the aggregated structure is taken into account, and numerous studies have focused on the evolution of the clay fabric along generalized stress paths (see for instance Romero et al. 1999; Cuisinier & Laloui 2004; Della Vecchia 2009; Monroy et al. 2010; Wang et al. 2012).

Although the influence of structure on the behaviour of compacted clays has been recognized, only a few water retention models have taken it explicitly into account. Indeed classical approaches for modelling the water retention behaviour are based on parameters to be fitted using experimental data.

Durner (1994) modelled successfully the water retention behaviour of a sandy loam, distinguishing explicitly in the formulation the existence of two structural levels. The same approach was later used by Gitirana Jr. & Fredlund (2004) on a pelletized diatomaceous soil and on a residual, highly collapsible clay from Brasilia. Romero & Vaunat (2000) distinguished an intra-aggregate water region and inter-aggregate water region to model the retention behaviour of Boom Clay. However none of these Authors have considered explicitly the evolutionary character of the soil fabric along hydromechanical stress paths. Early attempts to include the evolution of microfabric into a water retention model are the ones proposed by Simms & Yanful (2002, 2004) and by Romero et al. (2011) and Della Vecchia et al. (2013). Simms & Yanful (2002, 2004) proposed indeed water retention models explicitly derived from the pore-size distribution. As Romero et al. (2011) and Della Vecchia et al. (2013) are concerned, they extended the framework of Romero & Vaunat (2000) in order to account for swelling of clay aggregates and identified micro- and macrostructural domains by defining a discriminating pore size.

In this paper, a water retention model, together with a pore-size density model, are proposed to model the behaviour of compacted clayey materials. Micro- and macrostructural domains both cover the whole range of pore sizes, and thus the whole range of suction values. Experimental data on compacted Boom Clay from Della Vecchia (2009) and on compacted London Clay from Monroy et al. (2010) are used to calibrate and later validate the model. Although considered as moderately active, theses clays were selected to grasp the problem of the evolving microstructure along generalized stress paths.

2 WATER RETENTION AND PORE-SIZE DENSITY MODELS

Explicitly accounting for the aggregated structure of compacted clayey materials, the water retention model is written as the superposition of two elementary curves. The retention mechanisms of each structural level are described separately using an expression of the type proposed by van Genuchten (1980). In this way, the total water ratio e_w (defined as the volume of water per unit volume of solid) includes a contribution e_{wm} from the intra-aggregate water and a contribution e_{wM} from the water stored in the macropores. Using the indices (m) and (M) to refer respectively to the microstructural and macrostructural properties, the water retention model writes:

$$e_w(s) = e_{wm} + e_{wM} = e_m \left[1 + \left(\frac{s}{s_0^{(\mathrm{m})}} \right)^{n^{(\mathrm{m})}} \right]^{-m^{(\mathrm{m})}} + (e - e_m) \left[1 + \left(\frac{s}{s_0^{(\mathrm{M})}} \right)^{n^{(\mathrm{M})}} \right]^{-m^{(\mathrm{M})}} \tag{1}$$

where e and e_m are the total and microstructural void ratios, s_0 is a parameter related to the air-entry pressure[1], and n and m are model parameters. The parameter n is associated to the rate

[1] Note that the notion of air-entry value is not defined in van Genuchten's formulation. However, for sake of simplicity, s_0 will be referred as the air-entry pressure in this paper.

of desaturation of the soil while m is linked to the curvature of the water retention curve in the high suction range.

Considering the Washburn equation (Washburn 1921), relating suction s to an equivalent pore diameter x, a theoretical pore-size density (PSD) model can be derived directly from equation (1):

$$PSD \equiv \frac{\partial e_w}{\partial \log x} = -\frac{4\sigma \cos\theta_w}{2.3\, x}\frac{\partial e_w}{\partial s} \tag{2}$$

where $\sigma = 0.07275\ N/m$ is the air/water surface tension and $\theta_w = 0°$ is the water-solid contact angle.

The model parameters s_0, n and m can thus be interpreted linking them to the pore-size density function. The value of s_0 is related to the position, on the x-axis, of maximum value of the PSD function, while n and m are associated to the width and the shape of the pore-size distribution.

3 CALIBRATION OF THE PSD MODEL

3.1 Calibration procedure

Experimental data on compacted Boom Clay from Della Vecchia (2009) and on compacted London Clay from Monroy et al. (2010) are used to calibrate the pore-size distribution model. Mercury intrusion porosimetry data are exploited to this aim. In total, 24 experimental PSD curves are fitted with equation (2) in a systematic way in order to highlight the influence of various hydromechanical stress paths, such as wetting, drying and loading under constant water content, on the model parameters. The calibration procedure includes three main steps:

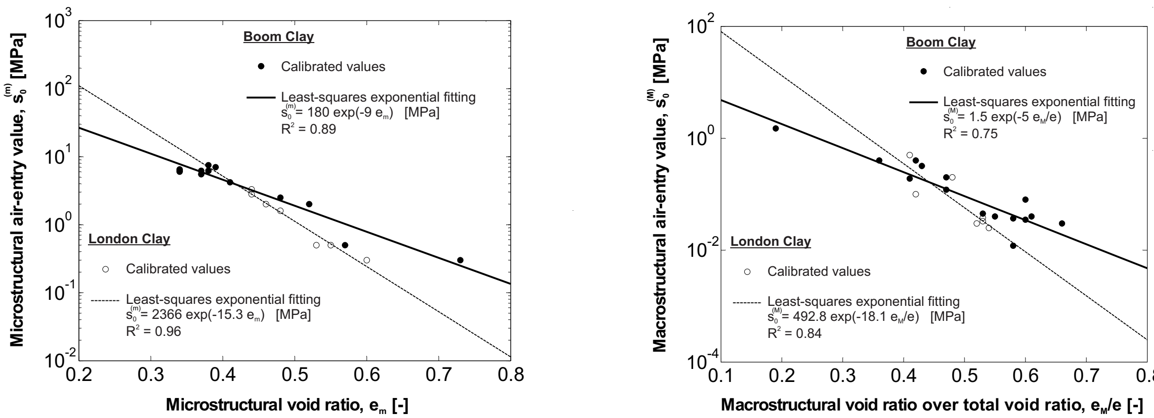
- The definition of a law for the evolution of the microstructural void ratio along generalized hydromechanical paths. In order to achieve this first step, the experimental PSD curves of the as-compacted materials are first calibrated. Their model parameters are then used as starting point for the calibration of the other experimental curves.
  A good correlation is found between the microstructural void ratio e_m and the water content e_w and the following relationship is proposed:

  $$e_m = \beta_0 e_w^2 + \beta_1 e_w + e_{m,0} \tag{3}$$

  where β_0 and β_1 quantifies the swelling tendency of the aggregates and $e_{m,0}$ is the microstructural void ratio of the dry material. Note that this equation is similar to the one proposed by Romero et al. (2011), except that it suggests a continuous evolution of the microstructural void ratio with the water ratio.
  The model parameters for Boom Clay and London Clay are presented in Table 1.
- Basing on the prediction of (3) for e_m, a second calibration is performed, trying to keep fixed the greatest number of parameters. As a result, parameters $n^{(\mathrm{m})}$, $m^{(\mathrm{m})}$ and $m^{(\mathrm{M})}$ are kept almost constant during generalized stress paths.
- A final calibration step, using equation (3) and imposing constant values for $n^{(\mathrm{m})}$, $m^{(\mathrm{m})}$ and $m^{(\mathrm{M})}$. This final calibration highlights the evolution of the microstructural air-entry value $s_0^{(\mathrm{m})}$ with the microstructural void ratio e_m (Fig. 1(a)). Moreover, the macro-structural air-entry pressure is found to change along with the ratio of macrostructural to total void ratios (Fig. 1(b)).

Table 1: Evolution of the microstructural void ratio with the water ratio. Model parameter values for Boom Clay and London Clay.

	β_0	β_1	$e_{m,0}$
Boom Clay	0.2	0.05	0.33
London Clay	0.35	0.08	0.27

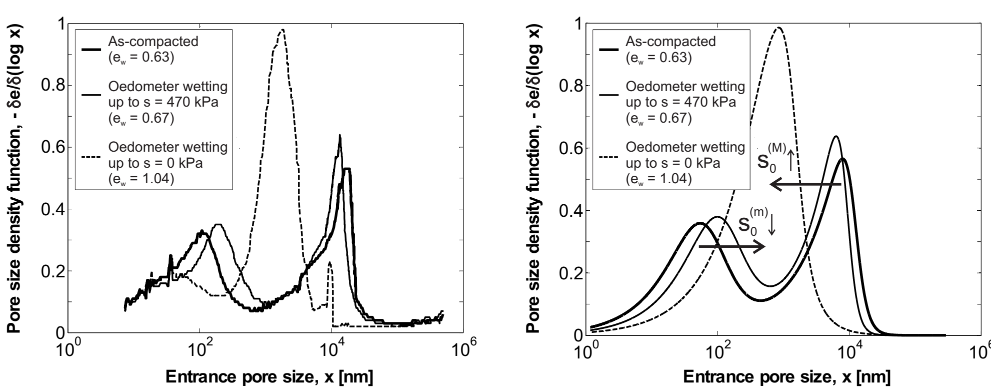


(a) (b)

Fig. 1: Variation of the model parameters along hydromechanical stress paths. (a) Dependence of the microstructural air-entry pressure with the microstructural void ratio. (b) Dependence of the macrostructural air-entry pressure with the ratio of the macrostructural void ratio over the total void ratio.

3.2 Structural changes along wetting paths

Experimental data on London Clay from Monroy et al. (2010) are used to highlight the effects of wetting on the structure. Fig.2(a) presents the evolution of the PSD during a wetting path from the as-compacted material (suction close to 1000 kPa) up to full saturation of the material. Hydration occurred under a nominal load of 7 kPa.



(a) (b)

Fig. 2: Structural changes along wetting paths. (a) Experimental data on London Clay (Monroy et al. 2010). (b) Model fitting.

It can be observed that wetting induces progressive increase of the micropores sizes, hence invasion of the macropores. As the microstructural mode displaces towards larger pore-size values, the microstructural air-entry pressure decreases (Fig.2(b)). On the contrary, invasion of the macropores induces an increase in the macrostructural air-entry pressure as the inter-aggregate volume is decreased.

3.3 Structural changes along drying paths

Data on Boom Clay Della Vecchia (2009) are used to highlight the influence of drying paths on the structure. Samples were prepared by static compaction at a water content of 15%, and then saturated under oedometer conditions at almost null vertical stress.

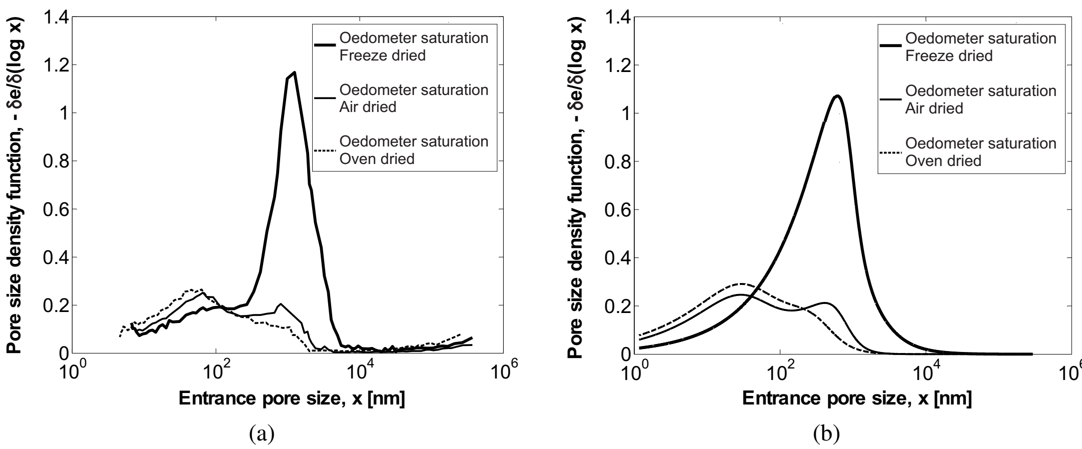


Fig. 3: Structural changes along drying paths. (a) Experimental data on Boom Clay (Della Vecchia 2009). (b) Model fitting.

As shown in Fig. 3, the drying process induces a shrinkage of the material. Assuming that freeze-drying does not induce changes in sample fabric, this shrinkage seems to affect not only the porous volume but also the pore-size distribution. Indeed the decrease in micro- and macrostructural porous volume is associated with a shift of the pores towards smaller sizes. As far air-entry values, this corresponds to an increase in $s_0^{(\mathrm{m})}$ and $s_0^{(\mathrm{M})}$.

3.4 Structural changes along loading paths

Experimental data from Della Vecchia (2009) are used to highlight the influence of loading on the structure. Fig.4 presents the pore-size distributions of the as-compacted material and the material subjected to both triaxial and oedometer compression under constant water content.

It can be observed that loading induces a progressive decrease of the macrostructural pore volume, starting from the largest macropores, while the microstructure is hardly affected.

Similar results are observed on London Clay (Monroy et al. 2010), and over wider ranges of void ratios, on FoCa clay (Lloret et al. 2003), on Spethwhite kaolin (Tarantino & De Col 2008), Barcelona Silty Clay (Buenfil et al. 2005) and on a compacted scaly clay from Italy (Airo Farulla et al. 2011; Della Vecchia et al. 2012), among others.

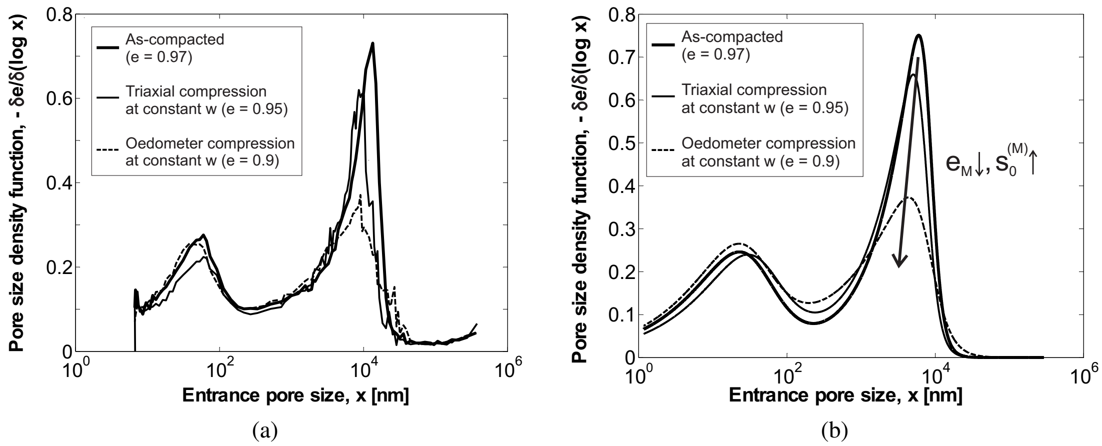


Fig. 4: Structural changes along loading paths. (a) Experimental data on Boom Clay (Della Vecchia 2009). (b) Model fitting.

4 VALIDATION OF THE WATER RETENTION MODEL

The proposed water retention model is validated against experimental data on compacted Boom Clay from Romero et al. (2011). Note that the mercury injection process is assimilated to a desorption path and the model should therefore be used to predict the retention behaviour of the material upon drying. Theoretical predictions of the water retention model are calculated from equations (1). The key issue in the formulation of the model is to assign, when meaningful, evolution laws to the parameters. Exploiting the calibration of the PSD model presented in the previous section, the parameters $s_0^{(\mathrm{m})}$ and $s_0^{(\mathrm{M})}$ are assumed to evolve exponentially (in the considered range of values) respectively with the microstructural void ratio e_m and with the ratio $(e - e_m)/e$, representing the ratio between the macrostructural and the total void ratios:

$$s_0^{(\mathrm{m})} = \alpha_1^{(\mathrm{m})} \exp\left(-\alpha_2^{(\mathrm{m})} e_m\right) \tag{4}$$

$$s_0^{(\mathrm{M})} = \alpha_1^{(\mathrm{M})} \exp\left(-\alpha_2^{(\mathrm{M})} \frac{e - e_m}{e}\right) \tag{5}$$

where e_m is given by equation (3) and α_1 and α_2 are model parameters.

In accordance with the calibration of the PSD model, the parameters $n^{(\mathrm{m})}$, $m^{(\mathrm{m})}$ and $m^{(\mathrm{M})}$ are set constant. Although $n^{(\mathrm{M})}$ is find to vary along generalized stress paths, a constant value is given in the water retention model. All parameter values are presented in Table 2.

Table 2: Model parameter values for Boom Clay.

Microstructural characteristics				Macrostructural characteristics			
$n^{(\mathrm{m})}$	$m^{(\mathrm{m})}$	$\alpha_1^{(\mathrm{m})}$	$\alpha_2^{(\mathrm{m})}$	$n^{(\mathrm{M})}$	$n^{(\mathrm{M})}$	$\alpha_1^{(\mathrm{M})}$	$\alpha_2^{(\mathrm{M})}$
1.65	0.35	180 MPa	9	2.0	0.16	1.5 MPa	5.0

The performance of the model is presented in Fig. 5. It can be observed that the model predictions compare favourably with the experimental data on Boom Clay compacted at different void ratios. The model succeeds in tracking the increase of air entry pressure with decreasing void ratio. Moreover, for high suction values, the model tends to reach a unique relationship between water ratio and suction, regardless of the current value of void ratio. In this domain, the water retention behaviour is indeed dominated by the behaviour of the microstructure. On the contrary, for low values of suction, the water retention curve is sensitive to mechanical actions.

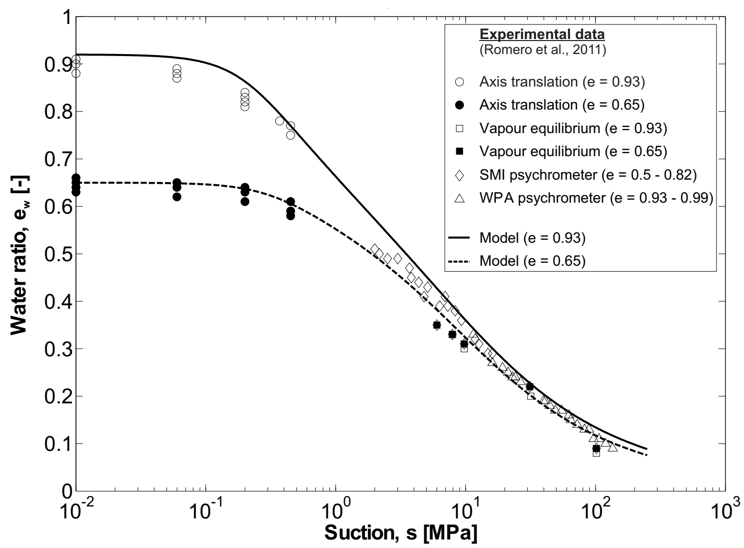


Fig. 5: Comparison between experimental main drying paths for compacted Boom Clay (Romero et al. 2011) and model predictions at different void ratios

5 CONCLUSIONS

The paper presents a water retention model for compacted clayey soils, accounting for the evolution of their aggregated structure along generalized hydromechanical stress paths. Microstructural and macrostructural water retention mechanisms are distinguished and described separately. According to experimental evidence, a law is proposed for the evolution of the microstructural void ratio with the water content.

The water retention model is used to derive a theoretical pore-size distribution which is used to calibrate the model parameters on experimental PSD curves from the literature. As the mercury intrusion process can be assimilated to a drying path, the attention is focussed on the main drying branch of the retention domain. The evolution of some parameters along generalized hydromechanical stress paths is highlighted and quantified. The water retention model is then validated against experimental data on the same materials compacted at different dry densities.

The proposed model captures important features of the retention behaviour of compacted clayey soils, such as:

- The increase in microstructural porous volume with increasing water content;
- The increase in air-entry pressure for decreasing macrostructural voids;
- The existence, in the high suction range, of an intra-aggregate water region which is almost not sensitive to the total void ratio.

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