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## HYDRO-MECHANICAL COUPLING IN UNSATURATED COMPACTED CLAYEY SOILS: MODELLING THE WATER RETENTION BEHAVIOUR

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**ABSTRACT.** Some results of an experimental investigation focused on the study of hydro-mechanical coupling in unsaturated compacted soil, related to the evolution of water retention properties are briefly commented. A model for water retention domain is suggested, that succeeds in tracking the evolution of the retention properties along generalised hydro-mechanical paths. A dependence of intra-aggregate pore space on water content, ruled by clay activity, is introduced. The evolution of inter-aggregate water content, following variations of void ratio, comes naturally from a suitable dependence of the analytical function chosen to describe the complete water retention domain.

### 1. Introduction

Strong coupling between mechanical and hydraulic processes characterises the behaviour of unsaturated soils. Much research was devoted in the last years to analyse both experimentally and theoretically how total stress and suction affect their mechanical response.

It is now recognised that the whole hydraulic state – i.e. both suction and a measure of the amount of water content of the soil – needs to be defined in order to understand and describe the behaviour of unsaturated soils (e.g. Wheeler 1996, Jommi 2000, Gens et al. 2006). More recently, attention was paid to the influence of hydraulic history, besides hydraulic state, on the response of unsaturated soils along generalised hydro-mechanical stress paths (see e.g. Romero & Jommi 2008, Nuth and Laloui, 2008).

The dependence of water retention properties on mechanical state variables and strain history was first underlined by Vanapalli et al. (1999) and Karube & Kawai (2001). Romero & Vaunat (2000), with reference to compacted clays, proposed to distinguish between intra-aggregate pore space, that is not affected by macroscopic void ratio, and inter-aggregate pore space, related to void ratio through a linear scaling law. A model for water retention curve in which air entry value changes with specific volume in the suction - degree of saturation plane was recently proposed by Gallipoli et al. (2003).

Here an extension of the model proposed by Romero & Vaunat (2000) is suggested, that succeeds in modelling the evolution of the retention properties along generalised hydro-mechanical paths. A dependence of intra-aggregate pore space on water content is introduced and ruled by clay activity. The evolution of inter-aggregate water content, following variations of void ratio, comes naturally from a suitable dependence of the analytical function chosen to describe the complete water retention domain.

### 2. Experimental programme and data interpretation

The results presented here are part of a wider experimental investigation focused on different aspects of hydro-mechanical coupling in unsaturated soil behaviour. Tests were carried out with different equipments in order to study the evolution of pore size distribution, water retention properties, elastic behaviour and irreversible behaviour along generalised hydro-mechanical axisymmetric paths. In between the aspects covered, here the results related to the evolution of water retention properties will be briefly summarised.

The soil used in the investigation, Boom clay, is a moderately swelling kaolinitic-illitic clay, with limit liquid  $w_L = 56\%$ , a plastic limit  $w_P = 29\%$ , 50% of particle less than  $2\mu\text{m}$ , specific surface  $S_S = 40\text{m}^2/\text{g}$  and a specific gravity  $G_S = 2.70$ .

Experimental evidence confirms that two regions can be defined in the main retention domain: an intra-aggregate water region and an inter-aggregate water region, where the water ratio is high enough to partially fill the inter-aggregate voids. Following Delage et al. (1996) and Romero et al. (1999), it may be assumed that in the inter-aggregate region a storage mechanism, dependent on void ratio and void structure, therefore sensitive to mechanical actions, predominates. At lower water contents the influence of initial and current dry density is negligible, signifying that the relationship between suction and water content mainly depends on the mineralogical composition of the clay (specific surface) and is controlled

by the intra-aggregate microstructure of the soil. For active clays, the intra-aggregate water content changes following swelling or shrinking of the aggregates. The microscopic water content is no longer constant, and its evolution is governed by the total water mass.

In order to delimit the regions of 'intra-aggregate governing suction' and 'inter-aggregate governing suction', at varying water content, mercury intrusion porosimetry tests were performed. The pore size range corresponding to the intra-aggregate pore space was used to define the 'intra-aggregate governing suction' zone of the retention curve. The criterion to distinguish the diameter separating macro-voids from micro-voids is based on the experimental evidence of the evolution of pore size distribution after isochoric saturation. Starting from an initial bi-modal distribution, increasing water content at constant total volume increases the mean micro-pores diameter while reducing the mean macro-pore diameter. At the end of isochoric wetting, a single peak in the pore size distribution is observed. The diameter corresponding to the resulting peak in the pore size density function – equivalent intruded diameter - has been chosen as the characteristic dimension discriminating 'intra-aggregate governing suction' region from 'inter-aggregate governing suction'.

The data collected in the present investigation seem to suggest a bi-linear envelope between the micro-structural void ratio and the water content. Microscopic void ratio may be considered constant until the water ratio  $e_w = w G_s$  reaches a value  $e_m^*$  which completely saturates the aggregates, leaving dry inter-aggregate pores. Starting from that state, increasing water content partially enters swelling aggregates, that remain saturated, and partially fills macropores, increasing the macroscopic degree of saturation. Literature data on other soils of different activities seem to confirm the proposed conceptual interpretation. The value  $e_m^*$  is related to the specific surface of the soil particles (as already evidenced by Romero and Vaunat, 2000). The linear slope,  $\beta$ , describing the tendency of the aggregates to swell, can be linked to the activity of the clayey soil (Fig. 1).

### 3. A model for soil water retention curve for compacted clayey soils

Different variables may adopted to quantify the amount of water in soil, the more common being volumetric water content  $\theta$  (volume of water over total volume of soil), degree of saturation  $S_r$  (volume of water over volume of voids) and gravimetric water content  $w$  (weight of water over weight of the solid particles). Although useful in certain applications, none of these variables is useful to normalise the role of void ratio on the water retention curve. As the micro-structural void ratio  $e_m$  is linked to the water content  $w$ , a useful normalised variable to describe its evolution is the water ratio,  $e_w$ , defined as the ratio between the volume of water in the pore space and the volume of solid particles:

$$e_w = w G_s = S_r e . \quad (1)$$

Remarkably, the subdivision between water in the intra-aggregate voids and water in the inter-aggregate voids is additive in sense of water ratio:

$$e_w = \frac{V_w}{V_s} = \frac{V_{wm}}{V_s} + \frac{V_{wM}}{V_s} = e_{wm} + e_{wM} , \quad (2)$$

where  $V_s$  is the volume of solid particles,  $V_{wm}$  the volume of water in the micro-voids and  $V_{wM}$  the volume of water in the macro-voids.

The model proposed to describe the water retention domain for active compacted clay is written in terms of the work-conjugate variables water ratio and suction.

#### Microscopic part

The microscopic branch of the water retention curve must fulfill the following requirements:

$$\begin{cases} e_w = 0 & \Rightarrow s = s_{\max} \\ e_w = e_m^* & \Rightarrow s = s_m^* \end{cases} \quad (3)$$

where  $s_{\max} = 1$  GPa is the maximum suction attainable and  $s_m^*$  is the suction corresponding to  $e_m^*$ , i.e. the smallest value of water ratio corresponding to saturated micro-voids and completely dry macro-voids. A suitable function respecting the previous requirements can be written as a function of a single independent parameter,  $b$ , giving the average slope of the curve for high values of suction:

$$e_w = \frac{be_m^*}{\ln\left(\frac{s_{\max}}{s_m^*}\right)} \left[ \frac{b + \ln\left(\frac{s_{\max}}{s_m^*}\right)}{b + \ln\left(\frac{s}{s_m^*}\right)} - 1 \right]. \quad (4)$$

### Macroscopic part

Following the proposal of Romero & Vaunat (2000), the macroscopic part of the water retention curve is scaled in the range  $e \geq e_w \geq e_m$ , with  $e_m$  obtained from the information in figure 1:

$$e_w = e_m + (e - e_m) \left( 1 - \frac{\ln\left[1 + \frac{s}{s_m}\right]}{\ln 2} \right) \left( \frac{1}{1 + (\alpha s)^n} \right)^m, \quad (5)$$

where  $m$  and  $n$  are independent parameters of the model. Imposing that the two analytical expressions (4) and (5) be continuous together with their first derivatives in  $s = s_m$ ,  $e_w = e_{wm}$ , gives a unique dependence of  $\alpha$  on the set of independent parameters, and naturally leads to a correct dependence of the air entry value on void ratio. The micro-structural void ratio may be written as a function of water ratio by means of the two independent parameters,  $e_m^*$  and  $\beta$  (see fig. 1), while the microscopic suction changes following the microscopic branch of the water retention curve.

In figure 2 experimental data of compacted Boom Clay (symbols) are compared with the retention domain modelled following the previous criteria (lines). It is worth noting that all parameters were calibrated on the basis of the drying branch of the curve corresponding to  $e = 0.92$ , except the value of  $s_m^*$ , that was assigned following Romero et al. (1999).

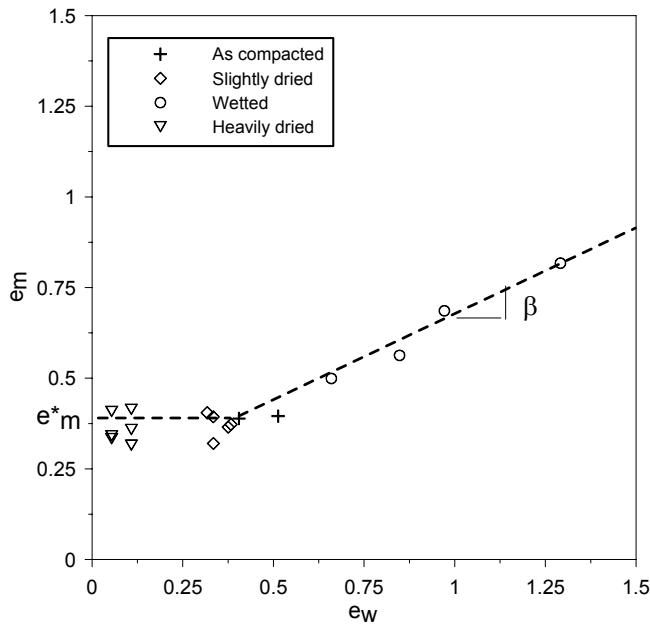


Figure 1. Evolution of microstructural void ratio  $e_m$  with water ratio  $e_w = wGs$

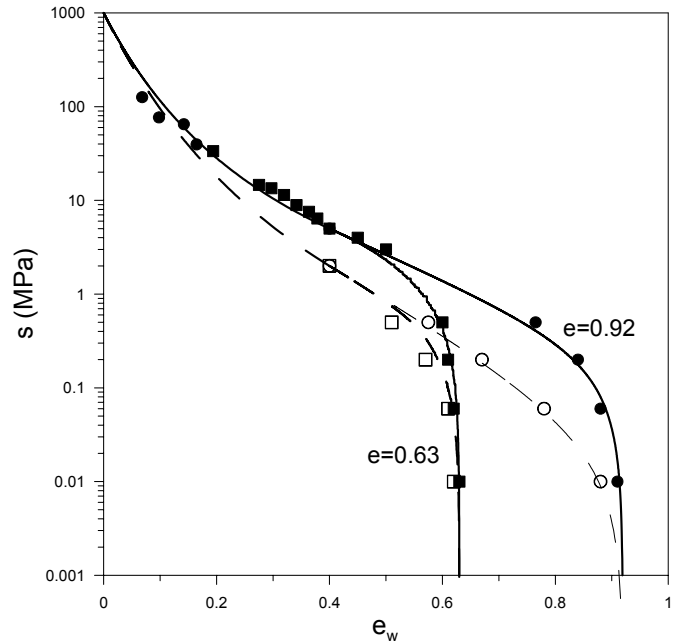


Figure 2. Water retention domain for compacted Boom clay. Parameters calibrated on the drying branch of the curve with  $e=0.92$ .

### 4. Evolution of the retention domain along generalised stress paths: an example

To highlight the capabilities of the proposed model in tracking the evolution of water retention properties of a swelling soil, data coming from an experimental investigation on compacted sand-bentonite 80/20 mixture (Romero et al., 2002) are compared to the numerical simulations along a complex stress path. The mixture was one-dimensionally statically compacted at about  $e_0 = 0.44$  and  $S_{r0} = 0.59$  (point A in figures 3 and 4).

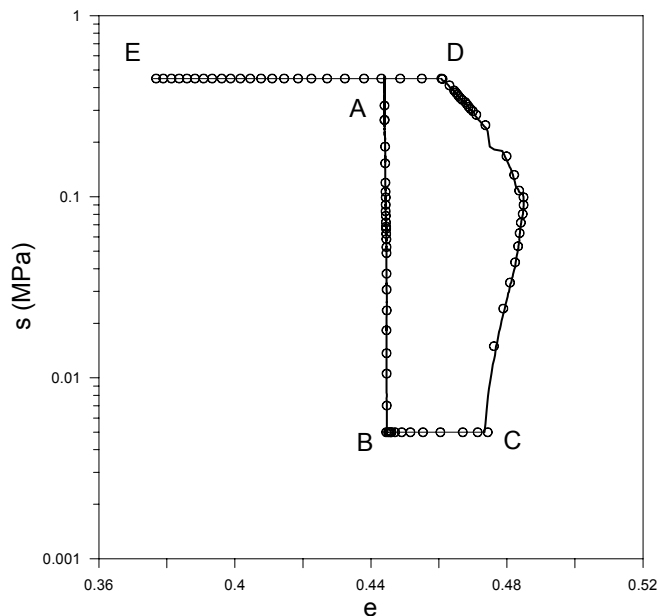


Figure 3. Controlled suction and void ratio along the wetting – unloading – drying – loading path performed on sand-bentonite (80/20)

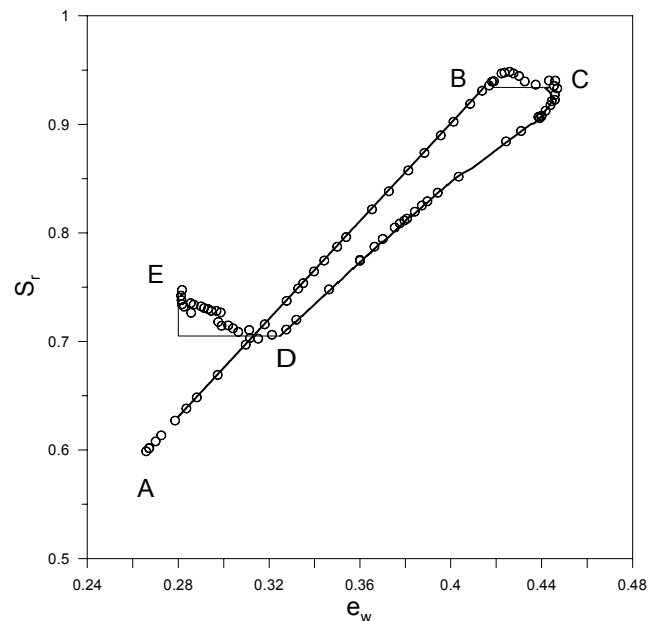


Figure 4. Evolution of degree of saturation and water ratio along the imposed path

Figure 3 describes the path followed in the test. An isochoric wetting (AB), starting from the as compacted condition ( $s_0 = 400$  kPa, point A), was followed by an unloading stage at constant suction ( $s = 5$  kPa), from  $(\sigma_v - u_a) = 95$  kPa to  $(\sigma_v - u_a) = 15$  kPa (path BC). Path CD corresponds to a drying stage at constant net stress, up to suction of 450 kPa. Finally a loading stage at constant suction ( $s = 450$  kPa) was followed up to 725 kPa (path DE).

Good agreement can be observed in figure 4 between the experimental data and the results of the simulations. The model is able to capture the evolution of both water ratio and degree of saturation. It's worth noting that water ratio describes the pure hydraulic response of the material, that depends on swelling and shrinking of aggregates. Degree of saturation better reflects the combined effects of soil water retention capacity and mechanical changes of void ratio.

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