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A structure-based approach to the estimate of the water retention curve of soils

Une approche basée sur la structure pour évaluer la courbe de rétention d'eau des sols

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ABSTRACT
In this work the influence of structure and volumetric straining on the evolution of the water retention curve of fine-grained soils (clays and silts) is discussed. Criteria for the formulation of their water retention curve are then proposed. The study also shows results of prediction of seepage through unsaturated soils, in order to discuss the importance of the above mentioned criteria in the modeling.

RÉSUMÉ
Cet article discute de l'influence de la structure et de la déformation volumétrique plastique sur l'évolution de la courbe de rétention d'eau des sols fins (argile et limon). Conséquemment, des critères sont proposés pour formuler leur courbe de rétention d'eau. Le travail en outre illustre des résultats de calcul de la filtration à travers des sols non saturés, pour déduire l'importance des critères susmentionnés au regard du modelage.

1 INTRODUCTION

Within unsaturated soils, both the changes in suction due to water seepage and the corresponding soil deformations may be modelled through coupled flow-deformation analyses that implement the relations of suction, s (= u_a-u_w, where u_a is the air pressure and u_w the water pressure), with the soil specific volume, v, degree of saturation, S_r, and net mean stress, p (Alonso et al. 1999). From such relations, it follows the soil-water retention curve (SWRC) , θ_w-s, being used in the analysis, that is the relation between the volumetric water content, $\theta_w=nS_r$ (where n is the porosity), and suction. An alternative simulation of the variation of s with θ_w during seepage can be accomplished through analyses using the Richards equation (Richards 1931; IGWMC 1999), which implement directly the SWRC. In this case, though, the analysis is not fully coupled because, where the effects of soil straining due to suction loading can be accounted for if the SWRC is derived from appropriate v-s, S_r-s relations, the effects of soil straining due to mean net stress changes are necessarily neglected. Yet, the reliability of the seepage predictions of either of these analyses depends significantly on how realistic is the SWRC being implemented.

Several formulations used to relate the SWRC basically to the soil physical properties (Arya & Paris 1981; Fredlund & Radardjo 1993), due to the assumption that these control the soil pore diameters that, in turn, control the maximum suction value before cavitation (Haines 1927). More recent formulations account for the variability of the specific volume for a soil of given composition and, therefore, make its retention curve depend explicitely on specific volume (Vanapalli et al. 1999; Fredlund et al. 2000; Kawai et al. 2000; Romero & Vaunat 2000), e.g. according to a single S_r-s-v relation (Gallipoli et al. 2003). However, if accounting for the hydro-mechanical coupling, the suction that the soil can sustain before cavitation should depend on the way the soil deforms under suction loading and the S_r-s-v relation should be related to soil deformability. So far, soil deformability has been shown to depend on the soil state history and structure for saturated conditions, as modelled by elasto-plastic constitutive laws (Kavvadas & Amorosi 2000; Baudet & Stallebrass 2004). The present paper discusses some experimental evidence of the influence of the state history and structure of the soil on its behaviour during unconfined drying and the implications of this influence for both the definition of the SWRC and the modeling of seepage.

2 INFLUENCE OF THE SOIL STATE HISTORY AND STRUCTURE ON THE *SWRC*

During unconfined drying (net mean stress p=0), in the stage when S_r=1, s equals the mean principal effective stress p' (Brady 1988; Klausner 1991). Also, when S_r drops below 1, but stays above 0.95÷0.90 (*quasi-saturated state*), since air forms isolated bubbles in the pore water (Brookes & Corey 1964), the principle of effective stress might be still assumed to apply, so that $s=p'$. It would then follow that, in both the saturated and the quasi-saturated stages, the v-s-S_r relation depends on the bulk deformability of the soil, $d\varepsilon_{vol}/ds= d\varepsilon_{vol}/dp'$, due to suction loading. If the soil is reconstituted, its saturated deformability under external isotropic loading, $d\varepsilon_{vol}/dp'$, depends on both the soil state v-p' and the location of the isotropic normalconsolidation line, *INCL*, thus on the overconsolidation ratio $R=p'_p/p'$ (where p'_p is the preconsolidation pressure). It is then likely that also the deformability of the quasi-saturated soil under suction loading, $d\varepsilon_{vol}/ds$, depends on the location of the soil state v-$s(=p')$ with respect to the *INCL*. If this is the case, the retention curve and corresponding air entry of the reconstituted soil will depend on the distance of the soil state v-s at the start of drying from the *INCL*, differing for the normally consolidated and the overconsolidated soil. Also, since the *INCL* of a given soil depends on the soil current structure, differing for the natural and the reconstituted soil (Burland 1990; Cotecchia & Chandler 2000), the retention curve of a natural soil will depend on its current structure and be related to the corresponding *INCL*.

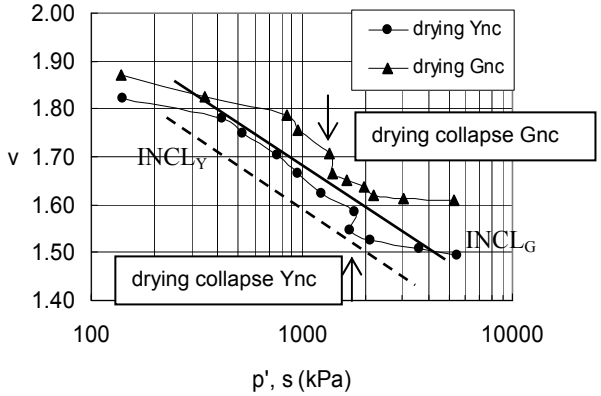
Figure 1 shows the v-lns and S_r-lns paths followed, during unconfined drying, by two samples, G_{NC} and Y_{NC}, of high plasticity clays (PI_G= 27.7%, PI_Y=26.4%) reconstituted and one-dimensionally consolidated from slurry up to p'=160kPa

(Cafaro 1998; Cafaro et al. 2000). In the plot in Figure 1(a) the values of both s and p' are reported on the abscissa and the isotropic normalconsolidation lines of both the samples are also shown. For s>160kPa, the v-s curves represent the virgin drying lines, *VDL* (Toll 1995), of the two normally consolidated samples, which plot to the right of the corresponding *INCL* and have a lower slope than the *INCL* before air entry. For both samples, the offset between the *VDL* and *INCL* reduces at some point, when both the gradients -dv/dln$s$ and -dS_r/dln$s$ suddenly increase. The sudden decrease in specific volume is termed *drying collapse* by Cafaro & Cotecchia (2001) and has been observed also for other clays (Croney & Coleman 1954). It occurs in a small s range, where also the maximum curvature of the S_r-ln$s$ curve ($d^2S_r/dln s^2_{max}$) occurs, generally for S_r between 0.98 and 0.90. Since major desaturation starts in this s range, it may be referred to as *gross air entry*. Just beyond both the drying collapse and the gross air entry the clay specific volume remains almost constant and the desaturation rate dS_r/dln$s$ reaches a top constant value. The data give evidence to a difference in compressibility of the clay when under isotropic external loading (*INCL*), -dv/dln$p'=\lambda$, and under suction loading before gross air entry, -dv/dln$s=\alpha\leq\lambda$. Evidently the fabric changes of the normally consolidated clay with suction loading differ from those resulting from external isotropic loading (Cafaro 2002). The fabric changes due to suction loading pre-gross air entry are likely to cause the contraction of the inter-aggregate pores (Romero & Vaunat 2000). At drying collapse, though, the clay fabric undergoes a sudden further contraction, which seems to trigger a change in the air status within the pores, since the drop of S_r below 0.8 is indicative of the onset of continuous air. The further air entry occurs at constant specific volume (dv/ds=0). For the two normally consolidated clays in Figure 1, the suction values corresponding to the gross air entry are far above the original consolidation pressure and cannot be predicted according to the saturated clay compression behaviour.

In Figures 1(b) and 2 the unconfined drying test on sample G_{NC} can be compared with a similar test on a sample, G_{OC}, of the same reconstituted clay, but preconsolidated one-dimensionally to σ'_v = 1100 kPa and swelled to a much lower stress (Cafaro et al. 2000). Figure 2 shows also the *INCL* of both the samples. The data give evidence to the difference in drying behaviour between the normally consolidated and the overconsolidated sample. Sample G_{OC} exhibits quite a stiff response to drying for S_r>0.9, before a drying collapse which, again, appears to correspond to an acceleration in desaturation, i.e. gross air entry. For sample G_{OC}, the compression index before gross air entry, $-dv/dlns=\alpha$ (defined as κ_s by Alonso et al. 1990), is found to equal the compression index due to isotropic external loading of the overconsolidated clay, $-dv/dlnp'=\kappa=0.01\div0.03$ ($\alpha=\kappa_s=\kappa$). Also, both the drying collapse and the gross air entry are found to occur when the drying path intersects the INCL ($p'_p\cong$1300kPa), that is when the isotropic preconsolidation state of the clay sample is approached. Therefore, the data confirm that the state history of the clay affects its drying behaviour and, thus, its SWRC. In particular, the gross air entry of the overconsolidated clay occurs about its isotropic preconsolidation state.

Overconsolidated natural clays exhibit a response to drying similar to that of sample G_{OC}. Cafaro et al. (2000) and Cafaro & Cotecchia (2001) showed that both a drying collapse and a gross air entry occur when natural clay samples subject to drying reach the *INCL*, that is when s is about the gross yield pressure in isotropic compression, p'_y, which depends on the clay structure (Cotecchia & Chandler 2000).

(a)



(b)

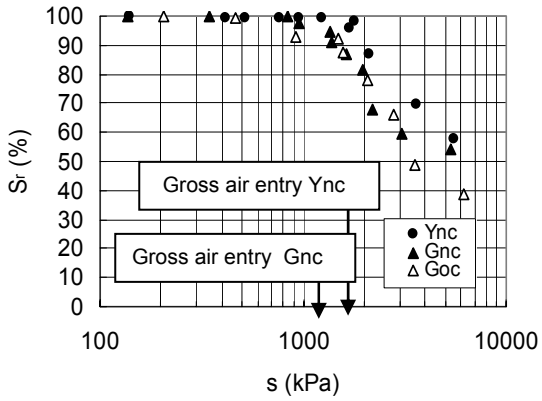


Figure 1. Drying and isotropic compression tests for reconstituted normally consolidated (*a* e *b*) and overconsolidated (*b*) clay samples.

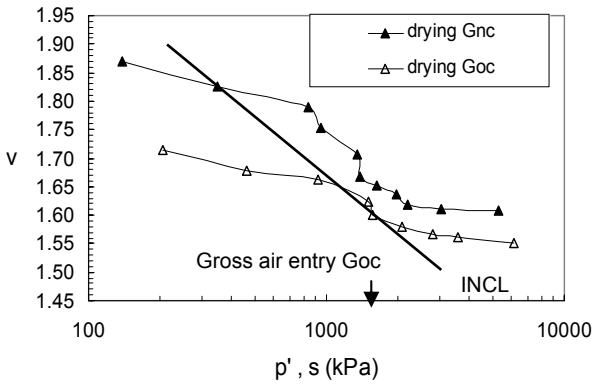


Figure 2. Comparison between normally (Gnc) and overconsolidated (Goc) reconstituted clay sample behaviour.

The natural clay compressibility before gross air entry, α, equals the saturated compressibility due to external isotropic compression, κ. This is demonstrated by the drying response of the overconsolidated natural samples in Figure 3, which have the same composition as the reconstituted samples Y and G. Therefore, with drying, both natural and reconstituted overconsolidated clays are seen to contract along the isotropic compression curve while quasi-saturated, until reaching the INCL, when major air entry starts. Evidence of the dependency of the v-s-S_r relation on either the isotropic preconsolidation state or gross

yield state has been found also for other clays and clayey silts (Cafaro & Cotecchia *in prep.*), although for silts the gross air entry corresponds to a larger decrease of S_r (down to 0.8) within a wider suction range.

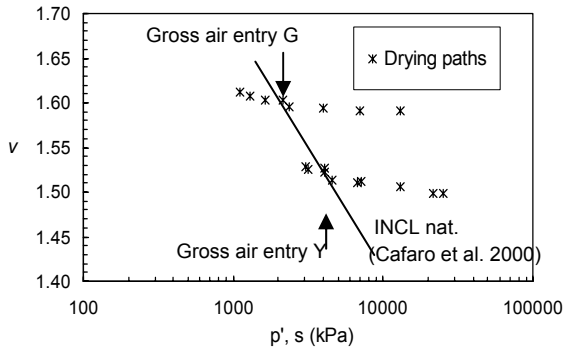


Figure 3. Drying paths of natural clay samples.

3 A CRITERIUM TO FORMULATE THE SWRC OF FINE-GRAINED SOILS

Based upon the observations discussed above, the SWRC for zero net mean stress can be derived from the schematic *v-lns* and S_r-*lns* relations represented in Figure 4. In the first part of the drying process, the changes in volumetric water content, θ_w, are due to the variation of the specific volume, whereas S_r is assumed to be constant. In the second part, the changes in θ_w are due to the variation of S_r, while the specific volume is assumed to remain constant. Therefore, the *v-lns* curve is formed of two segments joining in a point, v_{des}-s_{des}, corresponding to the centre of either the drying collapse or the gross air entry. The slope of the line for $s<s_{des}$ is α. For overconsolidated clays, $\alpha=\kappa_s=\kappa$ and the state v_{des}-s_{des} corresponds to the gross yield state in saturated isotropic compression, v_y-p'_y; for normally consolidated clays, $\alpha \leq \lambda$ and s_{des} cannot be predicted. For $s>s_{des}$, dv/ds=0. The S_r-*lns* curve is formed of three segments, the first and the last of which are horizontal, respectively at S_r=1 until gross air entry, and $S_r=S_{r\ res}$ beyond the suction (s_{res}) at which the degree of saturation reaches its residual value. For $s_{des}<s<s_{res}$, the S_r-*lns* plot is a straight line of gradient β and represents the process of continuous air entry when the soil skeleton has become practically rigid ($v \cong v_{des}$). The values of β recorded in several tests on different clays, which are shown in Table 1, are seen to fluctuate little around 0.3. In the following it will be assumed β=0.3, although further investigation is required to assess the variability of β.

The SWRC in Figure 4 can be formulated as follows:

$$\theta_w = 1 - [v_0 - \alpha \ln(s/s_0)]^{-1} \quad \text{for } s < s_{des}\text{, and}$$
$$\theta_w = (1 - v_{des}^{-1})\,[1 - \beta \ln(s/s_{des})] \quad \text{for } s_{des} < s < s_{res} \qquad (1)$$

where v_0 and v_{des} are the specific volumes at the start of drying and in the middle of the drying collapse respectively, and s_0 is the initial suction. This formulation does not model the hydraulic hysteresis of the soil, which would require the definition of the SWRC upon moisturing (Kazimoglu et al. 2005).

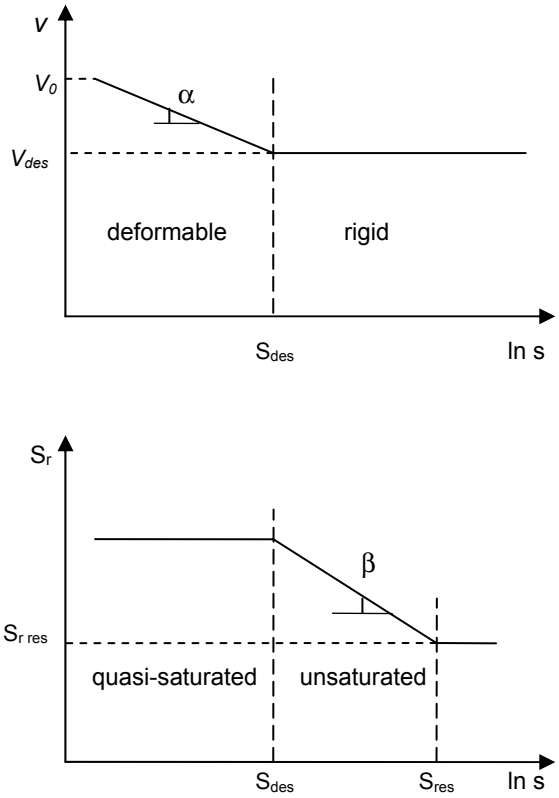


Figure 4. Scheme of the soil response to drying.

Table 1: values of β for different soils.

SOIL	β
Montemesola clays: undisturbed samples (Cafaro 1998)	0.249; 0.320; 0.277; 0.341
Montemesola clays: reconstituted samples (Cafaro 1998)	0.312; 0.318; 0.330
Rendina silts: undisturbed samples (Cafaro and Cotecchia, *in prep.*)	0.316; 0.361
Orvieto clays: undisturbed samples (Cafaro et al., *in prep.*)	0.283; 0.491; 0.266÷0.309

4 EFFECTS ON THE PREDICTION OF SEEPAGE AND CONCLUSIONS

A preliminary evaluation of the impact of the proposed SWRC formulation on the prediction of the suction values during seepage through an unsaturated soil has been done by modeling, by means of the Richards equation, one-dimensional infiltration through a 2 m thick unsaturated soil column (calculation code: SEEPW/Geo-Slope-5). However, two main sources of error apply to this modeling: hydraulic hysteresis is not accounted for and the SWRC applies to unconfined drying. Also, the modeling has been carried out solely with reference to an overconsolidated soil, because only for such soil condition the SWRC in eq.(1) can be predicted without performing any drying test. Rather, the parameter values can be desumed from an isotropic compression test. Though, the model predictions may be representative of what happens in outcropping clayey strata upon infiltration, since these are generally overconsolidated and subjected to negligible external loading ($p \cong 0$).

An initial constant suction profile, s = 800 kPa, has been assumed in the model. A water pressure of 100 kPa has been put as boundary condition at ground level and free drainage has been implemented at the bottom of the stratum. The infiltration process has been first simulated using eq. (1) as SWRC. The soil column has been assumed to be made of the same clay as

the reconstituted sample G_{OC} (Figure 2), therefore the values of the parameters used in the calculations are: $v_0 = 1.71$; $s_0 = 205$ kPa; $s_{des} = p'_y \cong 1100$ kPa; $\alpha = \kappa = 0.03$; $\beta = 0.3$. Then, the simulations have been carried out also using either the SWRC directly deduced from the laboratory measurements (Figures 1(b) and 2), or the SWRC proposed by Aubertin et al. (2003), which is a modified version (MK) of the Kovacs method (1981) and is related basically to the soil physical properties. All the calculations have implemented the same relationship between hydraulic conductivity and S_r, with a coefficient of permeability for the saturated soil: $K_{sat} = 2 \times 10^{-10}$ m/s (Cafaro 1998). The three retention curves are compared in Figure 5.

Figure 6 shows the suction profiles resulting from the three analyses at 5 months since the start of infiltration. It can be seen that the difference between the predictions of the analysis using eq.(1) and those corresponding to the empirical retention curve are not negligible, whereas the use of eq.(1) results in suction predictions very close to those corresponding to the use of the SWRC measured in the laboratory. These preliminary results encourage new research to develope further the formulation of a SWRC accounting for the influence of soil state history and structure. The relevance of the formulation here proposed lies in the important difference between the observed drying behaviour of normally consolidated and highly overconsolidated clays and in the possibility to predict, for the latters, the retention curve on the basis of initial specific volume and isotropic compressibility in saturated conditions.

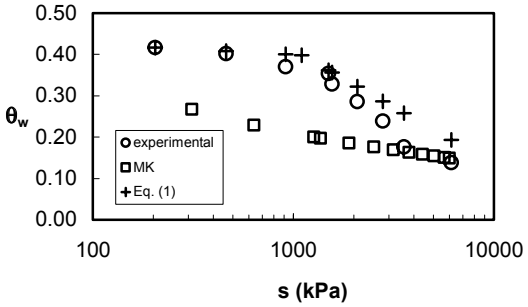


Figure 5. Experimental and theoretical retention curves used in the calculations.

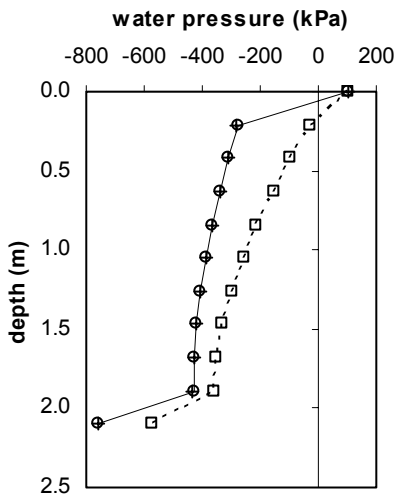


Figure 6. Water pressure profile at 5 months since the start of infiltration (same legend as Figure 5).

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