An effective stress based shear strength criterion for unsaturated compacted double-porosity clays

M. Rosone*1, C. Airò Farulla1, A. Ferrari2

1 Department of Civil, Aerospace, Environmental and Materials Engineering (DICAM) - University of Palermo, Palermo, Italy
2 Laboratory for Soil Mechanics (LMS), School of Architecture, Civil and Environmental Engineering (ENAC), Ecole Polytechnique Fédérale de Lausanne (EPFL), Lausanne, Switzerland
* Corresponding Author. E mail: marco.rosone@unipa.it

ABSTRACT An effective stress based shear strength criterion is proposed taking into account the fundamental effects of microstructure characteristics on retention properties of compacted double-porosity clays and their overall coupled hydro-mechanical behaviour. Results of triaxial compression tests carried out on saturated and unsaturated samples of a compacted scaly clay show that points representative of failure conditions depict a unique failure envelope when the macropore degree of saturation is used in the definition of the effective stress and its evolution with the suction is taken into account. Furthermore, the proposed criterion is very effective to consider the most relevant aspects of suction influence on the shear strength of double porosity unsaturated soils.

1 INTRODUCTION

Effective stress approaches are widely used in order to interpret and model experimental data related to shear strength of unsaturated soils (Khalili et al., 2004; Nuth & Laloui, 2008; Alonso et al., 2010). Among the advantages of these approaches, it is worth mentioning the smooth transition from saturated to unsaturated conditions and the possibility to evaluate shear strength of an unsaturated soil by using the parameters that characterize its behaviour when in a saturated state. Nevertheless, failure criterion based on effective stress, as derived from the initial Bishop’s proposal, by assuming the degree of saturation \( S_r \) for the \( \chi \) parameter, can overestimate the shear strength because the quantity \( S_r (u_a - u_w) \), where \( u_a \) is the pore air pressure and \( u_w \) is the pore water pressure, assumes unrealistic high values leading to erroneous evaluations in contrast with experimental data (Alonso et al., 2010).

Limited evidence is available for the shear strength of double structured soils in unsaturated conditions even though a deep understanding on the effects of suction on the shear strength is a fundamental requirement in order to predict the stability of the constructions. In particular, it should be considered that in earthworks, the soils are compacted in an unsaturated state and will be subjected to variations in the degree of saturation of different intensities depending on the environmental boundary conditions.

In the paper, the applicability of a single shear strength criterion is discussed considering an appropriate effective stress definition for unsaturated soils. Relevant considerations on this topic are clarified on the basis of the fundamental effects of microstructure characteristics on retention properties of compacted double-structured clays and their overall coupled hydro-mechanical behaviour. Indeed, results of triaxial compression tests carried out on saturated and unsaturated samples of a compacted scaly clay are used to discuss the choice of the shear strength parameters.

Complementary investigation on the microstructural features (Airò Farulla & Rosone, 2012) and their evolution with the amount of water stored into the material are also presented in order to shed light
on the evolution of the micro and macroporosity with suction. Analysis of the water retention behaviour of the compacted scaly clay (Airò et al., 2011) highlights the different mechanisms which regulate the water content change, the corresponding volumetric strains and the macroscopic degree of saturation evolution on the basis of the microstructure characteristics of the material.

2 PHYSICAL PROPERTIES AND MICROSTRUCTURE OF TESTED MATERIAL

Tested samples were prepared using a stiff and highly fissured clay outcropping near Palermo (Sicily), used for core construction in earth dams. The tested material is a silty clay having liquid and plastic limits within the range of \( w_l = 60-64\% \), \( w_p = 20-26\% \), mean specific gravity \( G_s = 2.76 \), and natural water content \( w_n = 20\% \). The material was excavated at depth of 3-4 m from soil surface and air-dried at laboratory conditions (temperature \( T = 20^\circ C \) and relative humidity \( RH \approx 45\% \)). Partially disaggregated material was moistened to the water content \( w = 15\% \) and dynamically compacted to the target dry density \( \gamma_d = 17.4 \text{ kN/m}^3 \) (Rosone et al., 2015). All specimens were prepared on the left side of the optimum (\( w_{opt} = 17\% \), \( \gamma_{d,max} = 17.5 \text{ kN/m}^3 \)).

A vertical total stress of about 1 MPa was required to prepare specimens with the similar characteristics by static compaction. Initial total suction of the as-compacted material was measured by means of a dew-point chilled mirror psychrometer (Leong et al., 2003; Cardoso et al., 2007) and was approximately 2 MPa; the air entry value for the corresponding void ratio was about 100 kPa (Airò Farulla et al., 2011).

The hydro-mechanical behaviour of scaly clays is influenced deeply by the fabric arrangement at the microstructural level. Mercury Intrusion Porosimetry (MIP) tests results (Rosone et al. 2015), reported in Fig. 1, shows that the structure at microscopic level of as-compacted unsaturated scaly clay presents a clear double porosity network where two main levels of porosity are identified: the largest pores (macropores) can be associated with the inter-assemblage porosity between assemblages composed of scaly fragments and clay aggregates, while the lowest pores (micropores, \( d < 1 \mu m \)) are located inside particle assemblages (intra-assemblage porosity). The prevalent macropore entrance diameters decrease from 50 to 30 \( \mu m \) as \( \gamma_d \) increases from 16 to 18 \( \text{kN/m}^3 \), while the prevalent micropore diameter coincides with the prevalent pore diameter (0.09 \( \mu m \)) of the intact scale. Besides, only minor differences are detected between intruded volume and PSD distribution in the micropore domain of the compacted material and the intact stiff clay scale. There is clear evidence that the microstructure of the as-compacted unsaturated scaly clay depends mainly on the microstructure of intact stiff clay fragments (scales) which survive irrespective of the intensity of compaction stress (Airò Farulla & Rosone, 2012).

![Figure 1. Cumulative intruded void ratio (a) and pore size density function (b) on intact scale, as-compacted samples (\( \gamma_d = 16-18 \text{ kN/m}^3 \)) and samples saturated after compaction](image-url)

Saturation modifies the structure of as-compacted scaly clay. Starting from the clear bimodal pore size distribution of the as-compacted clay specimen, saturation leads to a prevalent monomodal pore size distribution by means of swelling of assemblages and reduction of the inter-assemblage pore volume (Fig. 1). As a consequence, intra-assemblage and inter-assemblage pores are not distinguishable and the single pore mode can be assigned to one or other group.
of pores. So, the dominant peak of the PSD function, determined by MIP after wetting in free swelling conditions, can be assumed as the reference diameter to separate micro and macro pore domains (Romero et al., 2011). This pore entrance diameter is assumed equal to \( d = 1 \) μm, very close to the prevalent mono-modal pore diameter \( d = 0.91 \) μm of the free swelling saturated sample. Swelling of assemblages depends on mechanical boundary conditions; the characteristic mono-modal pore diameter of constant volume saturated samples is significantly lower (0.45 μm) than the one observed in free swelling conditions.

To quantify the evolution of the microstructure of compacted clay upon suction changes, Romero et al. (2011) proposed a linear evolution of the microstructural void ratio \( e_m \) (accounting for intra-assemblage porosity) with the amount of water stored in the material (expressed as the water ratio, \( e_w = w / G_s \), the ratio of the volume of water to the volume of solid):

\[
e_m = e_m^* + \beta \cdot (e_w - e_m^*) \quad \text{for} \quad e_w > e_m^* \tag{1}
\]

where the parameter \( \beta \) accounts for the swelling tendency of the assemblages and \( e_m^* \) represents the intra-assemblage void ratio corresponding to saturated micropores and empty macropores. When the water ratio is higher than \( e_m^* \), water starts to fill the macropores and the micropores start to swell significantly.

This approach is used here to quantify the swelling potential of the assemblages resulting from the compaction of the scaly clay. In this sense, the results of MIP tests are plotted in Fig. 2, after calculation of the microstructural void ratio on the base of intruded void ratio in the range of diameter lower than 1 μm; in the same plot data from an ESEM microphotography campaign to quantify the swelling/shrinkage behaviour of scaly clay assemblages are also reported (Airò Farulla et al., 2010). In this campaign a clay aggregate was selected and subjected to suction controlled wetting/drying cycles by modifying relative humidity and temperature in the ESEM chamber and the induced volumetric behaviour was monitored. The data are plotted in Fig. 2 converting suction into water ratio by means of the main wetting and main drying retention curves of the compacted scaly clay (Airò Farulla et al., 2011), and calculating corresponding microstructural void ratio values on the base of volumetric strain and the initial void ratio, \( e_{m0} = 0.29 \).

With reference to Equation (1), data represented in Fig. 2 suggest a value of \( e_m^* = 0.31 \) and an interpolating slope \( \beta = 0.19 \) to calculate the evolution of the intra-assemblage void ratio at increasing water ratio in the domain \( e_w > e_m^* \).
Analysis of water retention curves suggest that the water ratio \( e_w = 0.30 \) can be assumed to subdivide the plots in two regions in which a different evolution of main retention curves with void ratio can be observed. For water ratio lower than 0.30, independently of the void ratio considered, water retention curves converge along two linear (semilog plot) envelopes related to drying and wetting paths respectively, stemming from the point at hygroscopic water ratio \( e_{wh} \) (where drying paths end and wetting paths start). This behaviour may be interpreted considering the double porosity features of the material structure. Finally, it is not trivial to observe that the different values of \( e_m^* \), determined by the different independent procedures outlined before, are in very good agreement.

3 THE EFFECTIVE STRESS BASED SHEAR STRENGTH CRITERION

As previously discussed, the double porosity affects deeply the water retention features of these materials, owing to the different retention mechanisms operating within micropores and macropores, respectively (Romero and Vaunat, 2000). At high suction values, when water is present in the micropores and macropores are dry, void ratio changes are due mainly to a variation of macropore volume and they do not induce any variation of the retention properties. Adsorption mechanisms depend on mineralogical clay properties such as specific surface and plasticity. At low suction values, when water content is high enough to partly fill the inter-assemblages voids and to form menisci at assemblage contacts, the dominant mechanism of water storage in the macropores is capillarity (Salager et al., 2013).

Analysis of the compacted scaly clay retention curves, reported in Fig. 3, suggested that the water ratio \( e_w = 0.30 \) (corresponding to \( w = 11\% \)) can be assumed to distinguish regions in which the two different evolutions of main retention properties with void ratio can be observed. When the water ratio is higher than \( e_m^* \), the macroporosity degree of saturation \( S_{M} \), is higher than zero and water is starting to fill the macropores. Capillary mechanism is dependent on prevalent macropore entrance diameters that are linked to the void ratio. Menisci, formed at assemblage contacts, mechanically act as a skeleton stress governing stiffness and shear strength of the aggregated material. According to this point of view, capillarity or suction effects should be considered linked only to the amount of water partially filling the macropores. This observation seems well applicable to the case of scaly clays in which the shear strength behaviour is highly influenced by the mutual interactions among the scales.

In order to consider in an appropriate way the effects of suction on the shear strength of the unsaturated scaly clay, the effective stress can be modified taking into account only the macropore degree of saturation, defined as the volume of water inside the inter-aggregate pores over the macropore volume, as follows:

\[
\sigma'_{ij} = \sigma_{ij} - u_n \delta_{ij} + S_M (u_w - u_n) \cdot \delta_{ij}
\]  

(2)

Therefore, a shear strength criterion for unsaturated double structure soil can be defined as:

\[
q = q_c + \left( p_{net} + s \cdot S_M \right) M
\]  

(3)

\[
q = q_c + \left( p_{net} + s \frac{e_w - e_m}{e - e_m} \right) M
\]  

(4)

where \( q_c \) and \( M \) are respectively the intercept and the slope of the saturated envelope on the plane \((q, p')\). This relation is similar to the one suggested by Tarantino & Tombolato (2005). However, the new proposal takes into account the interaction between the two main porosity networks, considering micropore volume variations when calculating macro pore degree of saturation. To this aim, in order to evaluate the evolution of the saturated intra-aggregate pore volume when water ratio is higher than \( e_m^* \), the linear relationship between \( e_m^* \) and \( e_w \) reported in Eq. (1) and depicted in Fig. 2 can be used.

Diagrams in Fig. 4 represent the stress paths of the triaxial compression tests on unsaturated and saturated compacted scaly clay (Rosone et al. 2015) obtained by representing measured deviatoric stress \( q \) values versus mean effective stress \( p' \) values, calculated according to the definition:

\[
p' = (p - u_n) + s \frac{e_w - e_m}{e - e_m}.
\]  

(5)

Because macropore degree of saturation presents very low variations during drained compression, for the range of applied matric suction values, stress paths relative to the unsaturated compression tests are approximately linear with slope \((\partial q / \partial p') \) close to 3. Points representing void and water ratios of tested
samples at the end of equalization, isotropic compression and deviatoric steps, as shown in Fig. 3, collect on (or very near) the corresponding main wetting retention curves (with reference to the current void ratio). As evident from Fig. 4, stress paths of unsaturated tests terminate, with only minor scatters, on the same failure envelope recovered from triaxial tests on saturated samples. Parameters of this unique failure envelope are: \( q_c = 28.4 \text{ kPa} \) and \( M = 0.902 \).

![Figure 4. Stress paths on the plane \((p', q)\) of triaxial compression test.](image)

In order to stress the importance of considering the macropore degree of saturation when using a shear strength criterion in terms of effective stress for unsaturated soils, failure stress points are computed with Eq. 5 and plotted in Fig. 5 for three alternative choices of the Bishop’s parameter \( \chi \); the points were obtained assuming \( \chi \) equal to: (i) the evolving macropore degree of saturation (calculated by assuming \( \beta = 0.19 \), as it was the case in Fig. 2), (ii) a constant macropore degree of saturation (\( \epsilon_m = 0.31 \), \( \beta = 0 \)), (iii) the total degree of saturation. Data represented in Fig. 4 highlight that the best representation is obtained when the macropore degree of saturation is used and the evolution of the microstructural void ratio is taken into account. The fitting is still good also when a constant microstructural void ratio is assumed but clearly unsatisfactory, especially for higher suction values, when the total degree of saturation is considered. The choice of macropore degree of saturation as Bishop’s parameter \( \chi \) is very effective to consider the most relevant aspects of suction influence on the shear strength of double porosity unsaturated soils. To this aim, considering the shear strength angle constant as applied suction varies, values of intercept cohesion \( c = c' + s S_M \tan \phi' \) (where \( c' \) is the intercept cohesion of the saturated envelope) in the full range of the macropore degree of saturation, \( S_M = 0-1 \), for constant void ratio values (0.55 - 0.65) were calculated and represented in Fig. 6.

![Figure 5. Failure stress points for different definition of Bishop’s parameter.](image)

![Figure 6. Intercept cohesion modelled considering the macropore degree of saturation.](image)

As suction increases (or \( S_M \) decreases) \( c \) initially increases, reaches a maximum value and then decreases. When macropores are empty and \( S_M \) becomes equal to zero, \( c \) is again equal to intercept cohesion of saturated envelope \( c' \). However, for suction values in the order of some hundreds of kPa, as
shown in Fig. 7, experimental data (Rosone et al., 2015) and calculated values can be fitted very well by segment of hyperbola (Gens, 1993), having equation:

\[ c = c' + s / (\cot \varphi' + s / c^*) \]  

(6)

where the saturated intercept cohesion \( c' \) is equal to 15 kPa and \( c^* \) is a fitting parameter (calculated by least squares method) equal to \( c^* = 256 \) kPa.

As shown in Fig. 7, at equal suction values, \( c \) values in drying paths are greater than corresponding value in wetting paths; \( c \) values also increase as void ratio \( e \) decreases.

![Figure 7](image.png)

**Figure 7.** Hyperbolic envelopes of intercept cohesion modelled considering the macropore degree of saturation in the range of suction \( s = 0-600 \) kPa.

4 CONCLUSIONS

The paper highlights the importance of assuming the Bishop’s parameter \( \chi \) equal to macropore degree of saturation when using a shear strength criterion in terms of effective stress for unsaturated soils. A proper choice for the quantification of the water stored into the material is a crucial component to define the shear strength criterion and for this aim the paper shows that the evolution of the microstructural void ratio, and hence the macropore degree of saturation, with suction (or water ratio) must be taken into account when compacted double-porosity clays are considered. Results of the triaxial tests carried out on saturated and unsaturated samples give further support to the suitability of the effective stress based shear strength criterion and show that points representative of failure conditions, expressed in terms of effective stresses, depict a unique failure envelope.

Furthermore, the proposed criterion enables to give insight into the evolution of intercept cohesion as a function of suction. According to this approach cohesion vanishes when the interaction of menisci, formed at assemblage contacts, disappears due to the desaturation of the macropores. Then, the criterion highlights that hydraulic hysteresis induces, at the same suction value, different contribution to the shear strength.

REFERENCES


