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**A microstructure-based elastoplastic model to describe the behaviour  
of a compacted clayey silt in isotropic and triaxial compression**

Guido Musso<sup>1</sup>, Arash Azizi<sup>2\*</sup> and Cristina Jommi<sup>3,4</sup>

1. Associate Professor  
Department of Structural, Geotechnical and Building Engineering  
Politecnico di Torino  
Corso Duca degli Abruzzi, 24  
10129 Torino, Italy  
[guido.musso@polito.it](mailto:guido.musso@polito.it)

2. Post-doc Researcher  
Department of Structural, Geotechnical and Building Engineering  
Politecnico di Torino  
Corso Duca degli Abruzzi, 24  
10129 Torino, Italy  
Currently:  
Research Fellow  
Department of Engineering  
Durham University  
Lower Mountjoy, South Rd.  
DH1 3LE Durham, UK  
[arash.azizi@durham.ac.uk](mailto:arash.azizi@durham.ac.uk)

34 3. Professor  
35 Department of Civil and Environmental Engineering,  
36 Politecnico di Milano  
37 Piazza Leonardo da Vinci, 32  
38 20133 Milano, Italy  
39 [cristina.jommi@polimi.it](mailto:cristina.jommi@polimi.it)

40 4. Department of Geosciences and Engineering  
41 Delft University of Technology  
42 Stevin weg 1  
43 2628CN Delft, The Netherlands  
44 [c.jommi@tudelft.nl](mailto:c.jommi@tudelft.nl)

45

46 \*Corresponding author

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48 **A microstructure-based elastoplastic model to describe the behaviour**  
49 **of a compacted clayey silt in isotropic and triaxial compression**

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51

52 **Abstract**

53

54 The paper focuses on the hydro-mechanical behaviour of an unsaturated compacted clayey silt, accounting for fabric  
55 changes induced by drying-wetting cycles occurring at low-stress levels. The response along isotropic compression and  
56 triaxial compression (shear) at constant water content was investigated by laboratory tests on both as compacted and  
57 dried-wetted samples. Compaction induces a micro-structural porosity pertinent to clay peds and a macro-structural  
58 porosity external to the peds. Drying-wetting cycles decrease the micro-porosity and increase the macro-porosity, which  
59 reduces the water retention capacity, increases the compressibility and promotes higher peak strengths with more brittle  
60 behaviour during triaxial compression. A coupled double porosity elastic-plastic model was formulated to simulate the  
61 experimental results. A non-associated flow rule was defined for the macrostructure, modifying a stress-dilatancy  
62 relationship for saturated granular soils to account for the increase in dilatancy with suction observed in the  
63 experiments. The average skeleton stress and suction were adopted as stress variables. Consistently with model  
64 predictions, the shear strength at critical state is not significantly influenced by the degree of saturation or by the  
65 hydraulic history. On the other contrary, the higher peak strength, brittleness and dilatancy of the dried wetted samples  
66 are mostly explained by their reduced water retention capacity.

67

68

69 **Key words: Compacted silt; drying-wetting cycles; hydro-mechanical behaviour; double-porosity formulation;**  
70 **stress-dilatancy relationship**

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## 81 1. Introduction

82

83 According to the standard practice, the engineering requirements for earth constructions are guaranteed by compaction  
84 at optimum density and water content, and the design of the earth construction is based on the properties of the soil  
85 determined immediately after compaction. To reach the desired density, higher stresses than those imposed by service  
86 loads are used, resulting in a material which is highly overconsolidated just after compaction. However, experimental  
87 (Take and Bolton 2011) and numerical studies (Kovacevic et al. 2001) suggest the soil response changes over time  
88 because of seasonal variations in water pressure causing progressive accumulation of volume strains and leading to a  
89 dwindle of dilatancy. Therefore, the maximum shear strength that can be mobilised may reduce from peak values to  
90 critical state values, with the consequence that design approaches based on soil parameters detected after compaction  
91 might not be on the safe side for the long-term serviceability of the geo-structure.

92

93 More reliable design approaches should account for the fact that hydraulic conditions at the boundary of the earthwork  
94 evolve continuously after the end of the construction, due to oscillations of both the water level and the relative  
95 humidity of the air in contact with the embankment. These both cause oscillations of pore water pressure and suction,  
96 which imply periodic drying-wetting cycles for large volumes of the unsaturated portion of the embankment. Daily and  
97 seasonal cycles of relative humidity, associated to different sequences of rainy and dry days, can be relevant in  
98 continental climates (e.g. Calabresi et al. 2013) and, because of global warming, such cycles are expected to become  
99 more severe in the future (Rouainia et al. 2009). Increasing severity of suction oscillations over time, and the previous  
100 experimental evidence on softening in the material response, justify why the effects of drying-wetting cycles on the  
101 hydro-mechanical behaviour of compacted soils for earthworks deserve careful attention. Besides affecting the  
102 maximum strength, drying-wetting cycles are known to increase the permeability and to reduce the water retention  
103 capacity of compacted soils (Benson et al. 2007). These effects are unfavourable for the stability of embankments, since  
104 higher permeability allows for the propagation of pore pressure changes from the surface to deeper layers, increasing  
105 the chances of strain softening and failure (Nyambayo et al. 2004).

106

107 Changes in the hydraulic behaviour of clayey silts have been related to fabric changes, even occurring at constant  
108 volume (Cuisinier and Laloui 2004). The clay fraction of these soils is organized into peds ('aggregates' in Ng et al.  
109 2017) which plastically shrink over suction increase, while the total soil volume remains constant because of the  
110 shielding effect provided by the 'skeleton' of silt particles (Romero et al. 2014). A larger macro-porosity emerges,  
111 justifying the increase in permeability and the decrease in water storage capacity. This evolution of the soil fabric and of

112 the hydraulic behaviour during drying-wetting cycles can be reproduced adequately with double porosity hydro-  
113 mechanical volumetric models such as the one proposed by Azizi et al. (2019). However, to the authors' knowledge,  
114 limited attention has been paid to the influence of cyclic wetting and drying on the triaxial compression behaviour of  
115 unsaturated compacted soils, although it seems reasonable to infer that the fabric changes responsible for the changes in  
116 the hydraulic response will impact also on the mechanical behaviour. Experimental studies by Kemal et al. (2005) (on  
117 sand samples), by Rojas et al. (2010) (on clayey silt samples cored from a river embankment a few years after  
118 construction), and by Zhang et al. (2016) (on a slightly expansive silty soil) remark that drying-wetting cycles tend to  
119 increase the peak soil strength and the post-peak soil brittleness.

120

121 In this work, we aim at broadening the understanding of the effects of previous drying-wetting cycles on the coupled  
122 hydro-mechanical response of compacted clayey silts, including the pre-failure behaviour. The evolution of the  
123 microstructure of a soil used in the construction of river embankments is analysed experimentally over different hydro-  
124 mechanical paths, both immediately after compaction and after exposure to drying-wetting cycles. Stemming from the  
125 premises on the water retention behaviour in Azizi et al. (2019), the comparison between experimental data on as-  
126 compacted and dried-wetted samples is exploited to describe the mechanical response of the soil, within a double-  
127 porosity elastic-plastic framework. The proposed model is used to simulate the results of drying, isotropic compression  
128 and triaxial compression (shear) at constant water content tests on both as-compacted and dried-wetted samples, with  
129 the purpose of showing and start quantifying the influence of natural drying-wetting cycles on the lifetime response of  
130 embankments made of similar compacted clayey silts.

131

132

## 133 2. Soil characterization and sample preparation

134

135 The soil investigated is a clayey silt from Viadana, used in the construction of a full-scale model embankment built for  
136 research purposes nearly twenty years ago (see Calabresi et al. 2013). The construction of the model embankment  
137 promoted a few studies on this type of material, which is typically used in the reinforcement and construction of flood  
138 defences along the Po river (e.g. Nocilla et al. 2006; Vassallo et al. 2007). The clay fraction (particle diameter  $d < 2$   
139  $\mu\text{m}$ ) is 20.40 % and the silt fraction ( $2 \mu\text{m} \leq d < 60 \mu\text{m}$ ) is 79.60 %. The specific gravity is  $G_s = 2.735$ , the liquid limit  
140  $WL$  is 32.6 %, with a plasticity index  $PI$  equal to 8.3 %. According to ASTM D2487 Viadana clayey silt is a low  
141 plasticity silt (ML), with an activity index  $A = 0.4$ .

142

143 The effects of drying-wetting cycles on both the fabric and the hydro-mechanical behaviour were investigated on  
144 samples that were statically compacted at a dry density  $\rho_d = 1650 \text{ kg/m}^3$  and a water content  $w = 20 \%$ . This state  
145 replicates the construction specification for the model embankment (see e.g. Rojas et al. 2010). The fabric resulting  
146 from compaction (Original Fabric, OF) was investigated with Scanning Electron Microscopy (SEM) observations,  
147 which showed different aggregations of silt particles and peds of clay particles (Fig. 1). In the macrostructure, between  
148 silt particles and between silt particles and peds, the radius of the smallest pores appears to be around  $1 \text{ }\mu\text{m}$  or greater.  
149 Within the peds, the pore radii are clearly smaller than  $1 \text{ }\mu\text{m}$ . Eight samples were prepared to investigate how the pore  
150 network changes as a result of different hydraulic and mechanical histories, using Mercury Intrusion Porosimetry  
151 (MIP). Four of them were analysed, respectively, at the compaction state (OF), after first drying (dry-OF) and after  
152 loading in oedometer at two different axial net stresses ( $\sigma_{ax}^{net} = 98 \text{ kPa}$ , LL-OF, and  $\sigma_{ax}^{net} = 1.6 \text{ MPa}$ , HL-OF). The  
153 other four samples were preliminarily exposed to 6 drying-wetting cycles (6Cyc samples). One of them referred to the  
154 dry state (dry-6Cyc), another to the wet one (6Cyc), and other two to loading at  $\sigma_{ax}^{net} = 98 \text{ (LL-6Cyc) kPa}$  and  
155  $\sigma_{ax}^{net} = 1.6 \text{ MPa}$  (HL-6Cyc). The lower stress level,  $98 \text{ kPa}$ , was chosen to represent typical working stresses in the  
156 field, while the higher stress,  $1.6 \text{ MPa}$ , was chosen to investigate whether mechanical loads could (partially) erase the  
157 effects of previous drying-wetting cycles.

158  
159 Full details on sample preparation and on the cyclic hydraulic history simulating drying-wetting in the field are given in  
160 Azizi et al. (2019). In summary, drying was imposed by exposing the samples to the laboratory environment having a  
161 controlled temperature of  $21^\circ\text{C}$  and relative humidity of  $38.5\%$ , corresponding to a suction  $s = 128.8 \text{ MPa}$ , which  
162 brought the water content to a minimum of  $w \approx 0.4\%$ . After each drying stage, the samples were re-wetted by placing  
163 them in the compaction mould and injecting the volume of water needed to bring the water content back to its initial  
164 value ( $w \cong 20\%$ ). After each drying-wetting cycle, the specimens were wrapped up in plastic bags and kept hanging  
165 over distilled water in a closed container for at least 5 days to ensure water content homogenisation. The state of the  
166 samples prepared for MIP analyses is reported in Table 1. Their hydraulic and mechanical histories are sketched in Fig.  
167 2.

168  
169 The volume of the samples decreased along drying and increased along wetting. By convention, volume decrease is  
170 associated to increasing volume strains and vice versa. Volume strains increased during the first three drying-wetting  
171 cycles (Fig. 3) and were about reversible for a larger number of cycles. Consistently, both the hydraulic behaviour

172 (water retention and hydraulic conductivity) and the fabric evolved during the first three cycles while remaining stable  
173 afterwards (see Azizi et al. 2019 for a detailed discussion).

174

175 The hydro-mechanical behaviour of the OF and 6Cyc samples was studied along drying, isotropic and triaxial  
176 compression at constant water content in a triaxial cell allowing for suction control or measurement. Another eight  
177 samples were prepared to this scope, following the same procedure detailed above. The same stress paths were imposed  
178 to the OF and the 6Cyc samples (Table 3) to allow addressing the effects of hydraulic cycles on the following hydro-  
179 mechanical behaviour. According to Blight (1964), the pore pressure distribution within a sample sheared under  
180 unsaturated conditions is uniform when the time to failure  $t_f$  is equal or greater than the time for consolidation  $t_{100}$ . On  
181 the basis of the measured hydraulic conductivity (Azizi et al. 2019) and sample compressibility,  $t_{100}$  is expected to be of  
182 the order of a few hours or less. Assuming that failure occurs when  $\varepsilon_a = 20\%$ , the axial strain rate imposed during  
183 triaxial compression was  $\dot{\varepsilon}_a = 0.25\% / \text{hour}$ , which implies  $t_f = 80$  hours.

184 The values of suction and isotropic net stress imposed during drying and isotropic compression are provided in Table 2.  
185 The main details of the experimental procedures concerning both the microstructural characterization and the triaxial  
186 tests are provided in Appendix 1, while the experimental results, which justify adopting a double porosity model, are  
187 presented in section 4 (microstructural investigation) and 5 (triaxial tests).

188

### 189 **3. Double porosity formulation**

190

191 Given the observed fabric of the soil, a double porosity framework was chosen to simulate the results of the hydro-  
192 mechanical tests. Double porosity formulations have been extensively adopted to reproduce the hydraulic (e.g.  
193 Barenblatt et al. 1960; Gerke and van Genuchten 1993), hydro-mechanical (e.g. Alonso et al. 1999; Choo et al. 2016)  
194 and chemo-hydro-mechanical behaviour (Musso et al. 2013) of geologic materials possessing two dominant families of  
195 voids, such as fissures and matrix in reservoir rocks (Warren and Root 1963), or inter-aggregate and intra-aggregate  
196 pores in compacted soils (e.g. Della Vecchia et al. 2013). Extended reviews of double porosity models are available in  
197 Musso et al. (2013), Mašin (2013) and in Choo et al. (2016).

198

199 The basic concept underlying these models is that the porous medium can be modelled as two overlapping continua, or  
200 structural levels, commonly named “microstructure” and “macrostructure”. The microstructure is identified with the  
201 deformable solid aggregates, containing their “micropores”. The macrostructure is defined by the pore network made of  
202 the voids between the aggregates and it is characterised by the spatial distribution of the aggregates. The two structural



203 levels deform according to independent constitutive laws, and they may exchange fluid masses if the fluid pressures in  
 204 the two domains are different. However, in the following, the assumption is made that sufficiently slow hydro-  
 205 mechanical processes occur. This assumption implies that the air and the water pressure are the same in the two  
 206 structural levels, hence no explicit internal mass transfer conditions are needed for a complete description of the  
 207 response.

208

### 209 **3.1 Volumetric variables**

210 In the definition of the two overlapping continua, porosity and water content – or void ratio and degree of saturation –  
 211 of the soil are split between the two structural levels. The microstructure is made of the solid particles, having volume  
 212  $V_s$ , and of the voids within the clay peds,  $V_{vm}$ . Therefore, the microstructural void ratio  $e_m$  is defined as:

$$213 \quad e_m = \frac{V_{vm}}{V_s} \quad (1)$$

214 Since the peds are deformable,  $e_m$  will evolve with stress or suction (see section 3.3). The macro-structural void ratio  $e_M$   
 215 is the ratio of the volume of voids between peds (inter-peds, or macro-structural volume of voids  $V_{vM}$ ) over the total  
 216 volume of the peds, hence including the micropores:

$$217 \quad e_M = \frac{V_{vM}}{V_s(1 + e_m)} \quad (2)$$

218 The latter definition implies a reference “solid volume” for macroporosity which is not constant over time. Following  
 219 the derivation given and discussed by Mašin (2013), the total void ratio,  $e$ , must be consistently written as:

$$220 \quad e = e_m + e_M + e_m e_M \quad (3)$$

221 where the third term accounts for the change of the volume of the reference solids considered in the definition of the  
 222 macroscopic void ratio.

223 The microstructural degree of saturation  $S_{rm}$  is the ratio between the volume of water within the micro-pores  $V_{wm}$  and  
 224 the volume of the micro-pores:

$$225 \quad S_{rm} = \frac{V_{wm}}{V_{vm}} \quad (4)$$

226 The macrostructural degree of saturation  $S_{rM}$  is:

$$227 \quad S_{rM} = \frac{V_{wM}}{V_{vM}} \quad (5)$$

228 where  $V_{wM}$  is the volume of water held outside the peds. The total degree of saturation  $S_r$  follows:

$$229 \quad S_r = S_{rM} + \frac{e_m}{e}(S_{rm} - S_{rM}) \quad (6)$$

230 The water ratio  $e_w$  expresses the ratio of the volume of water to the volume of solids. The microstructural water ratio  
 231  $e_{wm}$  is:

232 
$$e_{wm} = \frac{V_{wm}}{V_s} = S_{rm}e_m \quad (7)$$

233 the macro-structural water ratio  $e_{wM}$  is:

234 
$$e_{wM} = \frac{V_{wM}}{V_s(1 + e_m)} = S_{rM}e_M \quad (8)$$

235 and the relationship between the total water ratio and the water ratios of the two domains is:

236 
$$e_w = e_{wm} + e_{wM}(1 + e_m) = S_{rm}e_m + S_{rM}e_M(1 + e_m) \quad (9)$$

237

### 238 **3.2 Water retention**

239 The total water ratio (eq. (9)) is a function of both the micro-and macro-degree of saturation and void ratio. Adopting  
 240 two van Genuchten (1980) expressions for the degree of saturation over the main branches of the water retention  
 241 functions of the micro and the macro porosities (e.g. Durner 1994; Casini et al. 2012; Della Vecchia et al. 2015), the  
 242 water ratio can be written explicitly as a function of suction in the form:

243 
$$e_w(s) = \left[ \frac{1}{1 + (\alpha_m s)^{n_m}} \right]^{m_m} e_m + \left[ \frac{1}{1 + (\alpha_M s)^{n_M}} \right]^{m_M} e_M(1 + e_m) \quad (10)$$

244 where  $n_m$ ,  $m_m$ ,  $\alpha_m$  and  $n_M$ ,  $m_M$ ,  $\alpha_M$  are model parameters describing the micro-structure and the macro-structure  
 245 response, respectively. Infinitesimal variations of the total water ratio are given by:

246 
$$de_w = de_{wm} + de_{wM} = [S_{rm}de_m + e_m dS_{rm}] + [S_{rM}(1 + e_m)de_M + e_M(1 + e_m)dS_{rM} + S_{rM}e_M de_m] \quad (11)$$

247 which measures the changes in water content as a function of changes in the void ratios and degree of saturations of the  
 248 two domains. Also, the previous relationship shows that changes in the degree of saturation of the different fabric levels  
 249 may occur even at constant water ratio, together with changes in the micro and macro void ratios. The transition  
 250 between the wetting and the drying branches (and vice versa) is postulated as a linear law between the increment of  
 251 degree of saturation and the increment of suction, independently for each structural level:

252 
$$dS_r = -k_{sc}ds \quad (12)$$

253 where  $k_{sc}$  is a model parameter, describing the hydraulic stiffness of the soil over reversible drying-wetting cycles,  
 254 bounded by the main wetting and drying branches.

255

256 Changes in the micro or macro void ratio impact mostly on the air entry value of the corresponding porous network. To  
 257 account for this evidence, a dependency of the air entry value  $1/\alpha$  on the void ratio is introduced. Simple relationships  
 258 were chosen relating  $1/\alpha_m$  and  $1/\alpha_M$  to the micro-structural void ratio  $e_m$  and to the macro-structural void ratio  $e_M$ :

259 
$$1/\alpha_m = (e_m/e_{m0})^{c_m}/\alpha_{m0} \text{ and } 1/\alpha_M = (e_{M0}/e_M)^{c_M}/\alpha_{M0} \quad (13)$$

260 where  $c_m$  and  $c_M$  are model parameters,  $e_{m0}$  and  $e_{M0}$  are the values of  $e_m$  and  $e_M$  at as-compacted conditions, and  $1/\alpha_{m0}$   
 261 and  $1/\alpha_{M0}$  are the initial air-entry values. The empirical laws described by eq. (13) are assumed to hold for both the  
 262 main drying and the main wetting curves.

263

### 264 3.3 Stress variables

265 Two stress variables are employed. The first one is the average skeleton stress, which depends on net stress ( $\sigma^{net}$ ),  
 266 effective degree of saturation ( $S_e$ ) and matric suction ( $s$ ):

$$\sigma' = \sigma^{net} + S_e s \mathbf{I} \quad (14)$$

267 Equation (14) defines the average skeleton stress for each structural level (macrostructural skeleton stress  $\sigma'_M$  or  
 268 microstructural skeleton stress  $\sigma'_m$ ), by using the corresponding effective degree of saturation. The second stress  
 269 variable is matric suction. Similar stress variables have been adopted by different authors (e.g. Jommi 2000; Tamagnini  
 270 2004; Romero and Jommi 2008; Zhang and Ikariya 2011; Zhou et al. 2012; Della Vecchia et al. 2013).

271 Both thermodynamic and experimental observations (Alonso et al. 2010) consistently show that the effective degree of  
 272 saturation of interest for the macro-structure is given by the free water filling the macro-voids, and thus for the  
 273 macrostructure  $S_{eM} = S_{rM}$ . For the microstructure, the relationship  $S_{em} = S_{rm}$  is assumed to hold.

274

### 275 3.4 Mechanical model for the microstructure

276 The microstructure is assumed to behave isotropically. Many double porosity models formulated for unsaturated soils  
 277 rely on the hypothesis of elastic microstructure (e.g. Gens and Alonso 1992; Alonso et al. 1999; Mašin 2013). However,  
 278 the experimental data in Azizi et al. (2019) suggest that irrecoverable plastic strains of the peds take place during  
 279 drying-wetting cycles, triggering changes in the water retention and permeability. Therefore, the elastoplastic model of  
 280 Azizi et al. (2019) is adopted here. Two yielding mechanisms can be activated, one related to mechanical straining of  
 281 the peds and the other related to irreversible changes of the microstructural water ratio. The former occurs when the  
 282 stress path reaches the loading collapse (LC) curve, whereas the latter is triggered if the stress path reaches the suction  
 283 increase (SI) curve during drying, or the suction decrease (SD) curve during wetting. These yield curves are expressed  
 284 as:

$$\text{LC: } p'_m = p'_m, \text{ SI: } s = s_I, \text{ SD: } s = s_D \quad (15)$$

285

286 Within the elastic domain, the degree of saturation evolves along the scanning curves and the relationship between  
 287 microstructural volume strain  $\varepsilon_m$  and stress increments is:

$$d\varepsilon_m^e = \frac{\kappa_m dp'_m}{(1 + e_m)p'_m} \quad (16)$$

288

289 where  $\kappa_m$  is the elastic compressibility of the microstructure.

290 If yielding occurs directly on the SI, it induces water ratio changes on the main drying WRC accompanied with  
 291 hardening of the LC, whereas direct yielding on the SD induces water ratio changes on the main wetting WRC  
 292 accompanied with softening of the LC. If yielding occurs on the LC, it produces plastic volumetric strains with a  
 293 coupled outward movement of the SI and inward movement of the SD. The SI and the SD evolve together:

$$\frac{ds_I}{s_I} = \frac{ds_D}{s_D} \quad (17)$$

294 When yielding occurs due to SI or SD, the hardening law is:

$$dp'^*_m = h_{lc} p'^*_m \frac{ds_I}{s_I} \quad (18)$$

295  $h_{lc}$  controls the coupled movement of LC due to SI or SD yielding and  $p'^*_m$  is the microstructural mean stress at yield.

296 The plastic volumetric strains ( $d\varepsilon_m^p$ ) due to yielding of the LC curve are

$$d\varepsilon_m^p = \frac{(\lambda_m - \kappa_m) dp'^*_m}{(1 + e_m) p'^*_m} \quad (19)$$

297 where  $\lambda_m$  and  $\kappa_m$  are model parameters. In this case, the hardening law is given by

$$ds_I = h_s s_I \frac{dp'^*_m}{p'^*_m} \quad (20)$$

298 where  $h_s$  controls the coupled movement of SI and SD.

299 The general expression for plastic strain increment can be derived through eqs. (17) and (18):

$$d\varepsilon_m^p = \frac{(\lambda_m - \kappa_m)}{(1 + e_m)(1 - h_s h_{lc})} \left( \frac{dp'^*_m}{p'^*_m} - h_{lc} \frac{ds_I}{s_I} \right) \quad (21)$$

300

301 The flow rule for yielding on the SI and on the SD is:

$$\frac{d\varepsilon_m^p}{de_{wm}} = 0 \quad (22)$$

302 While the flow rule for yielding on the LC curve is:

$$\frac{de_{wm}}{d\varepsilon_m^p} = 0 \quad (23)$$

303

304 Changes of the microstructural void ratio are then written in the form:

$$de_m = -d\varepsilon_m(1 + e_m) = -(d\varepsilon_m^e + d\varepsilon_m^p)(1 + e_m) \quad (24)$$

305

306 When the suction or the effective stress change, the micro-structural void ratio changes and the WRC of the peds  
 307 evolves accordingly with eq. (13). Further details on the model and the implications on the evolution of the WRC can  
 308 be found in Azizi et al. (2019).

309

### 310 **3.5 Mechanical model for the macrostructure**

311 Silty soils show some recurrent specific behavioural trends, which make them different from ideal coarse or fine-  
 312 grained soils (Cui and Delage 1996; Ma et al. 2016; Kim et al. 2016; Ng et al. 2017). While they have a mostly  
 313 volumetric hardening similar to clays, they typically show non associative elasto-plastic response upon triaxial  
 314 compression, which is more similar to those of coarser soils. When the over consolidation ratio, defined as the ratio  
 315 between the maximum and the current net stress, is low (typically smaller than 2.5), shearing is ductile and the soil  
 316 contracts. Shearing is brittle and accompanied by dilation for greater over-consolidation ratios. Peak strength typically  
 317 occurs together with maximum dilatancy, and both the peak strength and dilatancy at failure have been found to  
 318 increase when the degree of saturation decreases (e.g. Cui and Delage 1996; Cattoni et al. 2005), similarly to most types  
 319 of soils (see, e.g., Zhan and Ng 2006; Yao et al. 2014; Zhou and Sheng 2015 on clays; Fern et al. 2016 on sands;  
 320 Alonso et al. 2016 on rockfill). The finding is consistent with the original conclusions by Kohgo et al. (1993), who  
 321 observed that one of the effects of suction is to inhibit sliding between particles.

322 In general, elasto-plastic models formulated for unsaturated silts adopt non-associative flow rules, but hydro-mechanical  
 323 coupling has been either not introduced (Cui and Delage 1996; Chiu and Ng 2003) or introduced neglecting the water  
 324 retention and mechanical role of the clay peds (Ma et al. 2016). Instead, the latter seems to be an important feature to  
 325 understand and model the behaviour of Viadana silt (Azizi et al. 2019).

326 The yield function and the hardening rule adopted in the present formulation stem from the Modified Cam Clay Model  
 327 (Roscoe and Burland 1968) extended to unsaturated states, as described in Jommi (2000), and used among others by  
 328 Romero and Jommi (2008) and Della Vecchia et al. (2015). The yield function is:

$$f = q^2 - M^2 p'_M (p'_{0M} - p'_M) \quad (25)$$

329 where  $p'_{0M}$  is the pre-consolidation pressure of the macrostructure and  $M$  is the slope of the Critical State Line in the  
 330  $(p'_M, q)$  plane, which is assumed not to depend on suction. Following Jommi (2000) and Gallipoli et al. (2003), the  
 331 preconsolidation pressure in unsaturated states is the sum of the saturated preconsolidation mean stress  $p'^*_M$  depending  
 332 on the volumetric plastic strains, and a term which introduces the effects of the degree of saturation:

$$p'_{0M} = p'^*_M + (1 + b_1 (\exp(b_2(1 - S_{rM})) - 1)) \quad (26)$$

333 where  $b_1$  and  $b_2$  are model parameters describing the sensitivity of the pre-consolidation pressure to changes in the  
 334 degree of saturation of the macrostructure.

335 The volumetric hardening law relates  $p_M^*$  to the plastic volume strains  $\varepsilon_{vM}^p$ :

$$\frac{dp_M^*}{d\varepsilon_{vM}^p} = \frac{(1 + e_M)p_M^*}{\lambda_M - \kappa_M} \quad (27)$$

336 where  $\lambda_M$  and  $\kappa_M$  are the elastic-plastic and the elastic volumetric compressibility of the macrostructure.

337

338 The flow rule is an original proposal of this work, which is formulated to take into account explicitly the evidence of  
339 non-associative behaviour of the silt and the constraining effects of suction in the plastic range. The expression stems  
340 from the original contribution of Li and Dafalias (2000) for saturated coarse soils:

$$\frac{\partial \varepsilon_v^p}{\partial \varepsilon_q^p} = d = d_0 \left[ e^{m\psi} - \frac{\eta}{M} \right] \quad (28)$$

341 where  $\varepsilon_v^p$  and  $\varepsilon_q^p$  are the plastic components of the volumetric and deviatoric strains, respectively,  $d_0$  and  $m$  are model  
342 parameters,  $\eta = q/p'$  is the stress ratio and  $\psi$  is the state parameter (Been and Jefferies 1985):

$$\psi = e - e_c(p') \quad (29)$$

343 where  $e$  is the current void ratio and  $e_c$  is the void ratio at critical state for the current mean effective stress.

344

345 As remarked, a few works point out that dilatancy in unsaturated conditions is higher than in saturated ones. However,  
346 assuming dependency on suction only would imply very high (theoretically infinite) dilatancy for dry conditions.  
347 Therefore, dilatancy is assumed to increase with the inner constraint induced by the hydraulic component of the  
348 skeleton stress, through the product of the effective degree of saturation times suction. Li and Dafalias (2000)  
349 expression is also modified so to account for pure volumetric plastic strains occurring along isotropic compression  
350 paths. The proposed extension of eq. (27) to the unsaturated state for the macrostructure reads then:

$$d = \frac{d_0}{\eta^M} (\exp(\gamma S_{rMs})) \left[ e^{m\psi} - \frac{\eta^M}{M} \right] \quad (30)$$

351 where  $\eta_M = q/p'_M$  is the stress ratio of the macrostructure and  $\gamma$  is the additional model parameter weighting the  
352 relevance of suction and degree of saturation on the deviatoric response.

353

354

#### 355 4. Evolution of the pore size density in light of the double porosity framework

356

357 The description of the microstructural and macrostructural void ratio is based on the MIP measurements taken at the  
358 different conditions outlined in Table 1. Bimodal Pore Size Density (PSD) functions were detected in all cases, and  
359 their evolution with drying-wetting cycles and loading is presented in Fig. 4. Drying-wetting cycles affect the soil fabric

360 by shifting the size of the pores corresponding to the dominant peak to a larger pore radius ( $r = 609$  nm for the OF  
 361 sample, while  $r = 917$  nm for the 6Cyc sample), by reducing the frequency of the pores of the dominant mode and by  
 362 increasing the size and frequency of the pores belonging to the minor mode (Fig. 4a, see also Azizi et al. 2019).  
 363 Mechanical loading of both OF and 6Cyc samples (Figs. 4b and 4c) reduces the frequency of the pores having radii  
 364 larger than the one of the peak of the dominant mode. Increasing the load also leads to a progressive decrease of the size  
 365 of the larger pores belonging to the minor mode. Pores on the left of the dominant peak were not affected by loading.  
 366 Upon loading, the radius of the dominant peak of the OF samples remains fixed at  $r = 609$  nm (Fig. 5b), while it  
 367 progressively decreases from  $r = 917$  nm to  $r = 609$  nm for the 6Cyc samples (Fig. 4c). Interestingly, under the axial  
 368 stress of 1.6 MPa the PSDs of the HL-OF and of the HL-6Cyc samples overlap very well (Fig. 4d), which suggests that  
 369 the effects imparted on the fabric by the hydraulic history can be almost erased by high mechanical loads.

370

#### 371 **4.1 Modelling the Pore Size Density data**

372 A criterion discriminating between intra-peds pores and inter-peds pores allows using the PSDs to evaluate the values of  
 373 the microstructural void ratio  $e_m$  and of the macrostructural void ratio  $e_M$ , as observed in various previous work (e.g.  
 374 Delage and Lefebvre 1984; Cuisinier and Laloui 2004; Monroy et al. 2010). Here, the threshold between intra-peds and  
 375 inter-peds pores was set to correspond to the radius of the peak of the dominant mode, consistently with Azizi et al.  
 376 (2019), which allowed reproducing the evolution of the water retention behaviour of compacted Viadana silt.

377 The microstructural void ratio is evaluated as

$$e_m = \int_{3.5r}^{R_t} \frac{PSD(r)}{3.5r \ln(10)} dr + 0.04 \quad (31)$$

378

379 where 3.5 nm is the smallest pore radius intruded by MIP,  $R_t$  is the threshold radius separating intra-peds from inter-  
 380 peds pores and 0.04 is the void ratio corresponding to the very small non intruded pores, assumed to be equal to the  
 381 residual water ratio obtained at very high suctions. The macrostructural void ratio  $e_M$  was evaluated applying eq. (3), by  
 382 subtraction from the known total void ratio,  $e$ . The values of the  $e_m$  and  $e_M$  for each of the samples investigated are  
 383 provided in Table 3.

384

385 The experimental evolution of the total void ratio  $e$ , of the micro-structural void ratio  $e_m$  and of the macro-structural  
 386 void ratio  $e_M$  along the drying-wetting cycles and the mechanical loading is provided in Fig. 5. Drying-wetting cycles  
 387 reduced the micro-structural void ratio leaving the total void ratio substantially unaffected. As a result, the  
 388 macrostructural void ratio increased. Note that the 6Cyc samples were more compressible than the OF samples when

389 loaded to 98 kPa, suggesting that the larger macro-porosity developed during the preliminary drying-wetting cycles was  
 390 prone to collapse under small mechanical loads. However, the void ratio of both types of samples under the stress of 1.6  
 391 MPa is about the same.

392

393

## 394 **5. Hydro-mechanical behaviour of Viadana silt in unsaturated conditions and model predictions**

395

396 The hydro-mechanical behaviour of Viadana silt in unsaturated conditions, as detected through drying, isotropic and  
 397 triaxial compression tests run in a suction controlled triaxial cell, is presented together with the predictions obtained  
 398 with the double-porosity model introduced in Section 3. The calibration of the parameters of the model is described  
 399 first.

400

### 401 **5.1 Calibration of model parameters**

402 The procedure for the calibration of the parameters of the double porosity water retention model and of the mechanical  
 403 model for the micro-structure is explained in detail in Azizi et al. (2019). Water retention parameters for both the  
 404 microstructure and the macrostructure were determined from independent sets of measurements and from back-analysis  
 405 of the water retention curves of the OF and 6Cyc samples.

406 The air entry value of the microstructure was determined by introducing the value of the threshold pore radius  
 407 separating the microstructure from the macrostructure in the Washburn-Laplace equation, which relates the pore size to  
 408 the suction at which their desaturation takes place. Knowing the evolution of the air entry values and of  $e_m$  and  $e_M$  along  
 409 the drying-wetting cycles (see Table 3) allowed calibrating  $c_m$  and  $c_M$  in eq. (13). For the tested soil,  $c_m$  and  $c_M$  were  
 410 found to be 16.5 and 4, respectively, as provided in Tables 4. The parameters  $n_M$ ,  $m_M$ ,  $n_m$ , and  $m_m$  of the van Genuchten  
 411 expression were calibrated upon the data of the first drying. The scanning parameter  $k_{sc}$  was evaluated on the basis of  
 412 suction cycles run in a suction controlled oedometer (Azizi et al. 2017).

413 The compression behaviour of compacted samples of Viadana silt in saturated conditions presented in Nocilla et al.  
 414 (2006) was interpreted to determine  $\lambda_M$  and  $\kappa_M$ , under the assumption that the volume strains of the microstructure can  
 415 be neglected if compared to those of the macrostructure. Data in the same work were also interpreted to determine the  
 416 slope  $M$  of the critical state line in the  $(p'_M, q)$  plane, which was found to be  $M = 1.29$ . The parameters  $b_1$  and  $b_2$  (eq.  
 417 (26)), describing hardening due to the macroscopic degree of saturation  $S_{rM}$ , and the parameters for the flow rule  $\gamma$  and  
 418  $d_0$  (eq. (30)), were calibrated on the results of the tests carried out on the OF samples, while they were used to predict  
 419 the behaviour of the 6Cyc samples.



420 An oedometer test was performed to determine the preconsolidation stress, assuming that this was the same for the  
 421 microstructure and the macrostructure. An OF specimen was compacted, saturated under a net axial stress  
 422  $\sigma_{ax}^{net} = 10\text{kPa}$  and then loaded. The axial preconsolidation stress was found to range about  $\sigma_{ax}^* = 400\text{ kPa}$ . The radial  
 423 stress at preconsolidation was estimated through Jaky's expression  $K_0 = 1 - \sin\varphi'_{cs}$  (with  $\varphi'_{cs}$  as the critical state  
 424 friction angle and  $\sin\varphi'_{cs} = \frac{3M}{6+M}$ ), which provided  $K_0 = 0.47$ , giving  $\sigma_r^* = K_0\sigma_{ax}^* \cong 212\text{ kPa}$ . Eventually, the value of  
 425 the mean preconsolidation stress in saturated conditions resulted in  $p'^* = p'_M = p'_m \cong 360\text{ kPa}$ .

426

## 427 **5.2 Drying**

428 Drying took place in the suction - controlled triaxial cell, where target suction values  $s_\theta = 50\text{ kPa}$  or  $s_\theta = 300\text{ kPa}$  were  
 429 imposed while keeping the mean net stress constant at  $5\text{ kPa}$  (stress path in Fig. 6a). The water ratio of all samples  
 430 decreased as shown in Fig. 6b. When subjected to the same suction, 6Cyc samples expelled more water than OF  
 431 samples. Figures 6c and 6d show the experimental results and the model predictions for the OF and 6Cyc samples in  
 432 terms of  $e-e_w$ . A small contraction occurred when imposing  $s_\theta = 300\text{ kPa}$ , but the effect of the suction increase was  
 433 mostly a decrease of the total degree of saturation. At the end of the drying process the water ratio and degree of  
 434 saturation of the 6Cyc samples was noticeably smaller than the one of the corresponding OF samples.

435

436 The main drying and wetting curves and the predictions of the evolution of the water ratio with suction are presented in  
 437 Fig. 6e. The model allows explaining the different water ratios of the two samples at the end of drying. The hydraulic  
 438 states of the OF samples were initially inside the reversible domain, very close to their main drying curve. Upon suction  
 439 increase, they approached ( $s_\theta = 50\text{ kPa}$ ) or reached ( $s_\theta = 300\text{ kPa}$ ) the main drying curve. The 6Cyc samples were  
 440 initially closer to their main wetting curve than the OF samples, since they had underwent wetting during the last  
 441 preparatory stage. However, they also reached their main drying curve when subjected to increasing suction. According  
 442 to eqs. (10) and (12), the 6Cyc samples ( $e_M = 0.20$ ) have a lower water retention capacity than OF samples ( $e_M = 0.17$ )  
 443 because of their larger macrostructural void ratio.

444

## 445 **5.3 Isotropic Compression**

446 OF and 6Cyc samples were isotropically compressed to mean net stress values  $p^{net} = 100, 200$  and  $400\text{ kPa}$  (samples  
 447 with  $s_\theta = 50\text{ kPa}$ ) or to a mean net stress value  $p^{net} = 100\text{ kPa}$  (samples with  $s_\theta = 300\text{ kPa}$ ) while keeping suction constant  
 448 (Fig. 7a). At  $p^{net} = 100$  and  $200\text{ kPa}$ , the 6Cyc samples were more compressible than the OF samples. However, the void  
 449 ratios of the OF and of the 6Cyc samples were about the same at  $p^{net} = 400\text{ kPa}$ , which is consistent with the

450 microstructural observations in Section 4. For both types of samples, the compressibility reduced with suction and axial  
451 stress.

452

453 The model provides very reasonable predictions of void ratio changes along isotropic compression, considering that the  
454 compressibility parameters of the macrostructure,  $\kappa_M$  and  $\lambda_M$ , used in the simulations, were determined on different  
455 samples tested in saturated conditions. Also, the model correctly predicts that the void ratios of the 6Cyc samples are  
456 smaller than the void ratios of the OF samples at the same mean net stress, although this difference is overestimated at  
457 high stresses.

458

459 Figure 8a shows the changes in void and water ratios during isotropic compression. The water ratio decreased slightly in  
460 all cases, however, changes in the degree of saturation were negligible since the effects of changes in volume and water  
461 content counterbalanced each other. Figures 8b and 8c show the results in terms of  $e_w-s$ . Because of the small decrease  
462 in the water ratio, the hydraulic states of all samples moved slightly towards the corresponding main wetting curve, still  
463 remaining rather close to the main drying curve. According to the model, both the main drying and the main wetting  
464 curves evolved due to the decrease of void ratios during isotropic compression, but the changes in the suction range of  
465 interest were very small (in the figure only the final position of the WRCs is shown).

466

#### 467 **5.4 Triaxial compression**

468 Triaxial compression (shearing) at constant water content started from the conditions achieved after isotropic  
469 compression. The experimental results and model predictions of the triaxial compression phase for the tests performed  
470 at a net confining stress of 100 kPa (OF\_1 and 6Cyc\_1 with initial suction  $s_0 = 50$  kPa; OF\_4 and 6Cyc\_4 with initial  
471 suction  $s_0 = 300$  kPa) are plotted in Fig. 9. The peak strength and the post-peak softening of both OF and 6Cyc samples  
472 were larger at the highest suction (Fig. 9a). However, the 6Cyc samples showed a higher peak strength and a more  
473 pronounced softening than the OF samples when sheared at the same initial suction. The model predicts reasonably well  
474 the peak strength and the brittleness of these samples. Volumetric strains are plotted against deviatoric strains in Fig. 9b.  
475 All samples initially contracted and afterwards dilated. Dilatancy, which was larger in the case of the 6Cyc samples,  
476 increased with suction. The slope of volumetric strains changes with deviatoric strains, as predicted by the model in the  
477 plastic range (i.e. when the volume starts to increase), is quite similar to the experimental one, especially for the OF\_4  
478 and 6Cyc\_4 samples. Suction decreased during all tests, more markedly the higher its initial value, and the decrease in  
479 suction was larger for the OF samples compared to the 6Cyc samples (Fig. 9c). Because of the constant water content

480 condition, the total degree of saturation changed very slightly, increasing when the volume decreased and decreasing  
 481 when the volume increased (Fig. 9d).

482

483 Figure 10 shows the results of the triaxial compression phase of the OF and 6Cyc samples confined at 200 kPa and 400  
 484 kPa net stress and with an initial suction  $s_0 = 50$  kPa (samples OF\_2 and OF\_3 and samples 6Cyc\_2 and 6Cyc\_3). At  
 485 these higher confinement stresses, the deviatoric stress increased monotonically during triaxial compression, and the  
 486 strength of the 6Cyc samples was slightly higher than the one of the OF samples (Fig. 10a). Monotonic compressive  
 487 strains occurred in all tests (Fig. 10b) with the exception of 6Cyc\_2 (the 6Cyc sample confined at 200 kPa radial net  
 488 stress), which showed moderate softening and little dilatancy. The decrease in suction experienced by the OF samples  
 489 was larger than the one of the corresponding 6Cyc samples (Fig. 10c). Because of the constant water content constraint,  
 490 and of contraction during triaxial compression, the total degree of saturation increased for all samples (Fig. 10d).

491

492 Figure 11 shows the evolution of suction during triaxial compression, together with the evolution predicted for the main  
 493 drying and main wetting retention curves. For contracting samples, such as OF2 and 6Cyc\_2 in Fig. 11a, the model  
 494 predicts an increase of the water retention capacity, with the state of both samples remaining inside the reversible  
 495 domain. On the contrary, for dilating samples such as OF\_4 and 6Cyc\_4 in Fig. 11b, the model predicts a decrease of  
 496 the water retention capacity, and the final hydraulic state of these samples lays on the corresponding main drying  
 497 curves.

498

499

## 500 6. Discussion

501

502 The model predictions can be exploited to provide an insight into the hydro-mechanical behaviour of the compacted  
 503 Viadana silt.

504 At the end of the triaxial compression stage, the samples reached or approached (samples OF\_1, OF\_4 and 6Cyc\_1)  
 505 critical state conditions. Figure 12a compares the experimental points at the end of triaxial compression with the stress  
 506 paths predicted by the model, together with results of undrained triaxial compression tests on saturated compacted  
 507 samples from Nocilla et al. (2006), which are used to the sake of comparison. In the  $(p'_M, q)$  plane, the critical state for  
 508 all the compacted samples (both saturated and unsaturated and regardless of the previous hydraulic history) is very well  
 509 fitted with a single line having a slope  $M = 1.29$ . This substantiates the use of the average skeleton stress as stress  
 510 variable, which is made possible by the correct identification of the macro-structural degree of saturation. Also, the

511 results in Fig. 12a validate the assumptions made on both the position of the threshold between the micro and the  
 512 macro-pores, and the coupled hydro-mechanical model governing the water retention behaviour of the two structural  
 513 domains.

514

515 The void ratio at critical state in Fig. 12b appears to be influenced by suction, as previously remarked for instance by  
 516 Gallipoli et al. (2003), suggesting that the locus of the critical state conditions should be fitted by a Critical State  
 517 Surface in the  $(p'_M, q, e, s)$  hyperspace rather than by a line in the traditional  $(p'_M, q, e)$  space. However, for given  
 518 suction, the OF and 6Cyc samples seem to approach the same line, suggesting that the Critical State Surface does not  
 519 depend substantially on the previous hydraulic history.

520

521 Figure 13 introduces the position of the yield curves of the macrostructure at the beginning of triaxial compression for  
 522 the highly overconsolidated samples, tested at 100 kPa confining stress (OF\_1, OF\_4 and 6Cyc\_1, 6Cyc\_4), together  
 523 with the stress paths predicted by the model. All these samples dilated and softened. The preconsolidation pressure  $p'_{0M}$ ,  
 524 which defines the size of the yield curves (eq. (25)), depends on the macrostructural degree of saturation  $S_{rM}$  (eq. (26)):  
 525 thus it increases with suction and, for the same suction, it is larger for the 6Cyc samples compared to the OF samples  
 526 because of the reduced capacity to retain water of the former. This implies the sequence  $p'_{0M}(\text{OF}_1) < p'_{0M}(\text{6Cyc}_1) <$   
 527  $p'_{0M}(\text{OF}_4) < p'_{0M}(\text{6Cyc}_4)$ . The stress paths intercept the yield surface on the dry side, where  $\eta_M/M > 1$ , and the  
 528 model predicts negative  $d$  values (which means volume increase, eq. (30)) for all of them. Since the hardening rule of  
 529 the Modified Cam Clay is used, the interception between the stress paths and the yield surface provides the peak  
 530 deviatoric stress,  $q_{peak}$ . Therefore, the larger the  $p'_{0M}$ , the larger  $q_{peak}$ , which is consistent with the sequence of peak  
 531 strengths detected in the experiments.

532

533 The stress paths of all the samples sheared at 200 kPa and 400 kPa confining stress and suction  $s_0 = 50$  kPa intercepted  
 534 the yield surface on the wet side ( $\eta_M/M < 1$ ), which implied instead positive  $d$  values, and then contraction and  
 535 hardening. Figures 14a and 14b show the experimental data and model predictions of the stress-dilatancy relationships  
 536 for OF and 6Cyc samples, respectively. The state parameter of the samples sheared at 100 kPa confining stress (OF\_1,  
 537 OF\_4, 6Cyc\_1 and 6Cyc\_4) is negative, since their void ratios are smaller than the ones at critical state for the same  
 538 stress conditions (see Fig. 12). These samples yield when  $\eta_M/M > 1$ , with a predicted negative value of  $d$  (hence,  
 539 dilating). The opposite holds for the samples sheared at 200 kPa and 400 kPa of confining stress. Predictions compare  
 540 very reasonably with the experimental data although the dilatancy of sample OF\_4 appears to be underestimated.

541

542 Relevant model predictions of the evolution of suction during triaxial compression are presented in Fig. 15. An air entry  
 543 value of the microstructure higher than 200 kPa (Table 4) ensured that the microstructure remained saturated during all  
 544 the tests performed at  $s_0 = 50$  kPa. In these cases, the evolution of the WRC is governed by the changes occurring in the  
 545 macrostructure. An example is given by the OF\_1 sample (Fig. 15a). At the beginning of triaxial compression, the  
 546 hydraulic state lays in the reversible domain. Here, according to eq. (11), suction decreases when the macrostructural  
 547 degree of saturation  $S_{rM}$  increases and suction increases when  $S_{rM}$  decreases. Along triaxial compression, an elastic  
 548 contraction occurs first, which in light of the constant water content constraint implies an increase in saturation and then  
 549 a decrease in suction. Afterwards, for  $\varepsilon_q > 0.02$ , the sample dilates, thus  $S_{rM}$  decreases and suction increases again. Note  
 550 that this monotonous relationship between suction and volume changes occurs only because the hydraulic state always  
 551 moves within the reversible domain, and not on the main drying curves plotted as grey lines in Fig. 15a. Similarly, the  
 552 hydraulic state moved within the reversible domain also in the other samples tested at  $s_0 = 50$  kPa, for which suction  
 553 changes and volume strains had the opposite sign.

554

555 On the contrary, when  $s_0 = 300$  kPa (as for test OF\_4 in Fig. 15a), very little water is held by the macrostructure. The  
 556 bimodal WRC is then dominated by the microstructure, which reduces its water retention capacity when the  
 557 microstructural void ratio decreases, and the value of suction associated to the given water content on the main branches  
 558 of the WRC reduces (eqs. (10) and (13)). Note that this occurs also along the whole triaxial compression process,  
 559 following eq. (21). As shearing progresses, the main drying curve reaches the hydraulic state of the sample when  $\varepsilon_q =$   
 560 0.02, which constrains the evolution of suction for the rest of the test to the main drying curve.

561

562

## 563 7. Conclusions

564

565 The hydro-mechanical behaviour of a compacted clayey silt in unsaturated conditions, at the as-compacted state and  
 566 after exposure to drying-wetting cycles, was investigated by means of laboratory tests and then interpreted with a  
 567 coupled double-porosity elasto-plastic model. Drying-wetting cycles at low confinement stresses alter the soil fabric  
 568 promoting volumetric shrinkage of the microstructure, made of clay peds, and a consequent increase of the macro-  
 569 porosity. This porosity exchange significantly reduces the capacity of the soil to retain water for values of suction  
 570 smaller than about 400 kPa. Because of its larger macro-porosity, the dried-wetted soil is more compressible than the  
 571 as-compacted soil when small loads are applied. The response to triaxial compression at constant water content

572 conditions is also affected. At the same initial values of mean net stress and suction, the dried-wetted soil shows higher  
573 shear strength and more brittle behaviour than the 'as-compacted' soil. This is a consequence of different effects of the  
574 fabric changes induced by the previous drying-wetting cycles. Firstly, because of the differences in the water retention  
575 behaviour, the suction decrease occurring during triaxial compression is more contained in the dried-wetted material  
576 compared to the as-compacted one, which keeps the stress path on a drier side. Secondly, higher suction implies higher  
577 dilatancy, hence, higher peak strength.

578

579 The proposed elasto-plastic coupled hydro-mechanical double porosity framework allowed reproducing all the relevant  
580 aspects observed during the tests. The model, which adopts the average skeleton stress of the macrostructure as a  
581 constitutive stress for the macro-porosity domain, permits a natural transition from saturated to unsaturated conditions.  
582 The slope of the critical state line in the mean - deviatoric stress plane is clearly the same for the saturated and  
583 unsaturated conditions, and for any of the two fabrics of the unsaturated material, although the void ratio at critical state  
584 depends on the suction. The volumetric and hydraulic behaviour along isotropic compression in unsaturated conditions  
585 is reasonably reproduced using the elastic and elasto-plastic compliance parameters deduced from tests on saturated  
586 samples to characterize the behaviour of the macrostructure.

587

588 The mechanical behaviour of the macrostructure is nicely captured with an elasto-plastic model which adopts the yield  
589 surface of the Modified Cam Clay, where the preconsolidation pressure increases when the degree of saturation  
590 decreases. The different response to triaxial compression is triggered by the different water retention behaviour for the  
591 two fabrics. Since preliminary drying-wetting cycles reduce the volume the water retention capacity of the macro-  
592 structure, the higher peak strength of the dried-wetted samples can be explained accounting for their smaller macro-  
593 structural degree of saturation, which implies a larger preconsolidation pressure. A non-associated flow rule, which  
594 takes into account the role of the state parameter, of the degree of saturation of macropores and of suction, further  
595 contributes to nicely reproducing the increasing dilatancy and higher peak strength of the dried-wetted samples.

596

597

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727 **List of symbols**

- 728 Void ratio:  $e$
- 729 Microscopic void ratio:  $e_m$
- 730 Macroscopic void ratio:  $e_M$
- 731 Degree of saturation:  $S_r$
- 732 Microscopic degree of saturation:  $S_{rm}$
- 733 Macroscopic degree of saturation:  $S_{rM}$
- 734 Water ratio:  $e_w$
- 735 Water ratio of the microstructure:  $e_{wm}$
- 736 Water ratio of the macrostructure:  $e_{wM}$
- 737 Initial value of air entry pressure of the microstructure:  $1/\alpha_{m0}$
- 738 Initial value of the air entry pressure of the macrostructure:  $1/\alpha_{M0}$
- 739 Parameters of the van Genuchten expression of the microstructure:  $n_m$  and  $m_m$
- 740 Parameters of the van Genuchten expression of the macrostructure:  $n_m$  and  $m_m$
- 741 Model parameter controlling the dependency of microstructure on air entry value:  $c_1$
- 742 Model parameter controlling the dependency of macrostructure on air entry value:  $c_2$
- 743 Skeleton stress of the microstructure:  $\sigma'_m$
- 744 Skeleton stress of the macrostructure:  $\sigma'_M$
- 745 Preconsolidation stress of the microstructure:  $p^*_{0m}$
- 746 Saturated preconsolidation stress of the macrostructure:  $p^*_{0M}$
- 747 Suction increase of the microstructure:  $s_I$
- 748 Suction decrease of the microstructure:  $s_D$
- 749 Slope of the critical state line in the  $(p'_M, q)$  plane:  $M$
- 750 Elastic logarithmic compliance of the microstructure:  $\kappa_m$
- 751 Elastic logarithmic compliance of the macrostructure:  $\kappa_M$
- 752 Elasto-plastic logarithmic compliance of the macrostructure:  $\lambda_m$
- 753 Elasto-plastic logarithmic compliance of the macrostructure:  $\lambda_M$
- 754 Poisson coefficient of the macrostructure:  $\nu$
- 755 Parameters of the modified Li and Dafalias flow rule:  $d_0, \gamma, m$
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Table 1. State of the samples for MIP analyses.

Sample	Axial stress $\sigma_{ax}$ (kPa)	Hydraulic state	Void ratio $e$ (–)	Water content $w$ (%)	Degree of saturation $S_r$ (–)
OF	-	-	0.66	20.0	0.83
dry- OF	-	Dry (first drying)	0.64	1.8	0.08
dry-6Cyc	-	Dry (6th drying)	0.63	0.4	0.07
6Cyc	-	Wet (6 <sup>th</sup> drying- wetting cycle)	0.65	19.9	0.83
LL-OF	98	-	0.61	18.9	0.85
HL-OF	1600	-	0.51	18.5	0.93
LL-6Cyc	98	Wet 6 <sup>th</sup> drying- wetting cycles	0.59	18.2	0.86
HL-6Cyc	1600	Wet 6 <sup>th</sup> drying- wetting cycles	0.51	17.5	0.95

Table 2. Samples for hydro-mechanical characterization with values of suction  $s$  and mean net stress  $p^{net}$  applied during drying and isotropic compression in the triaxial tests

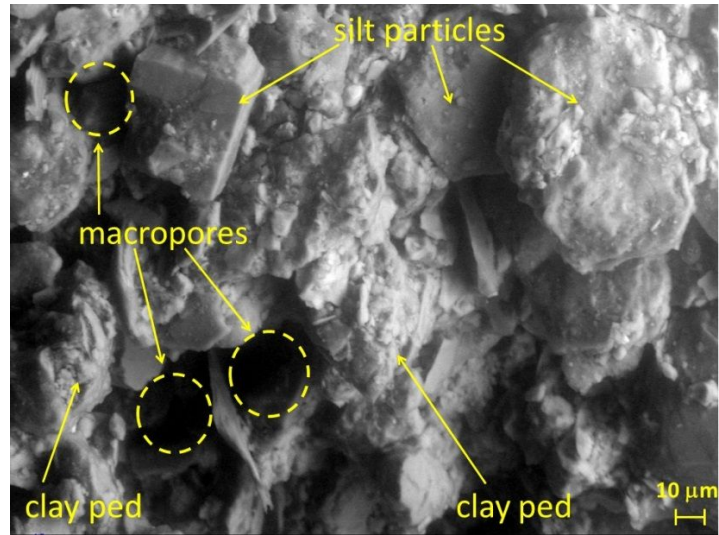
Test	Drying		Isotropic compression	
	Suction, $s$ (kPa)	Mean net stress $p^{net}$ , (kPa)	Suction, $s$ (kPa)	Mean net stress $p^{net}$ , (kPa)
OF_1	50	5-10	50	100
OF_2	50	5-10	50	200
OF_3	50	5-10	50	400
OF_4	300	5-10	300	100
6Cyc_1	50	5-10	50	100
6Cyc_2	50	5-10	50	200
6Cyc_3	50	5-10	50	400
6Cyc_4	300	5-10	300	100

Table 3. Macro-structural, micro-structural and overall void ratios from interpretation of MIP analyses

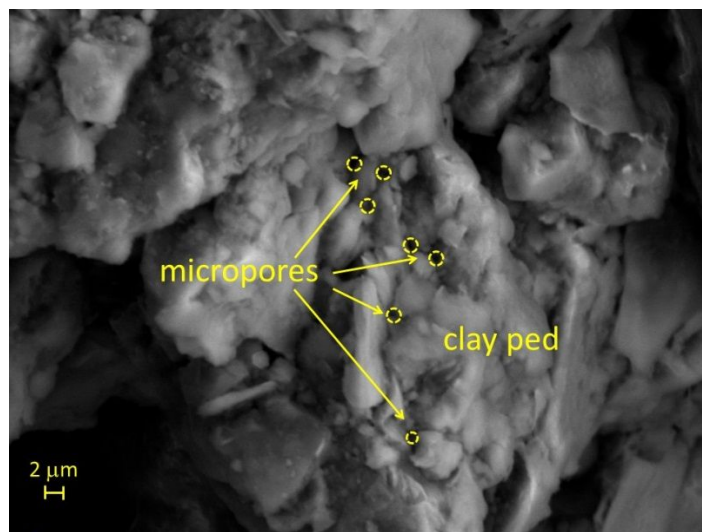
Void ratio	OF	Subjected to hydraulic load			Subjected to mechanical load		Subjected to hydraulic and mechanical load	
		dry-OF	dry-6Cyc	6Cyc	LL-OF	HL-OF	LL-6Cyc	HL-6Cyc
$e$	0.66	0.63	0.63	0.66	0.61	0.51	0.59	0.51
$e_m$	0.42	0.41	0.38	0.38	0.44	0.42	0.40	0.41
$e_M$	0.17	0.16	0.18	0.20	0.12	0.06	0.14	0.07

Table 4. Values of the parameters used in the numerical simulations

Hydraulic Parameters									
Hydraulic path	Micro-structure				Macro-structure				Both domains
	$1/\alpha_{m0}$ (kPa)	$n_m$ (-)	$m_m$ (-)	$c_m$ (-)	$1/\alpha_{M0}$ (kPa)	$n_M$ (-)	$m_M$ (-)	$c_M$ (-)	$k_{sc}$ (kPa <sup>-1</sup> )
Drying	236	2.86	0.14	16.5	64	1.75	0.83	4	$3 \cdot 10^{-4}$
Wetting	34	2.61	0.12		8	2.37	0.97		
Mechanical Parameters, Micro-structure									
$\kappa_m$ (-)	$\lambda_m$ (-)	$h_{IC}$ (-)	$h_s$ (-)	$p'^*_m$ (kPa)	$s_1$ (kPa)	$s_D$ (kPa)			
0.009	0.056	4.3	0.25	360	236	33 (OF) 5 (6Cyc)			
Mechanical Parameters, Macro-structure									
$\kappa_M$ (-)	$\nu$ (-)	$\lambda_M$ (-)	$p'^*_M$ (kPa)	$b_1$ (-)	$b_2$ (-)	$M$ (-)	$d_0$ (-)	$\gamma$ (kPa <sup>-1</sup> )	$m$ (-)
0.025	0.2	0.13	360	0.14	2.2	1.29	1.7	0.03	1.2



(a)



(b)

Fig. 1. SEM images of OF sample: (a) detail with macropores, clay peds and silt particles; (b) detail with micropores within a clay ped.

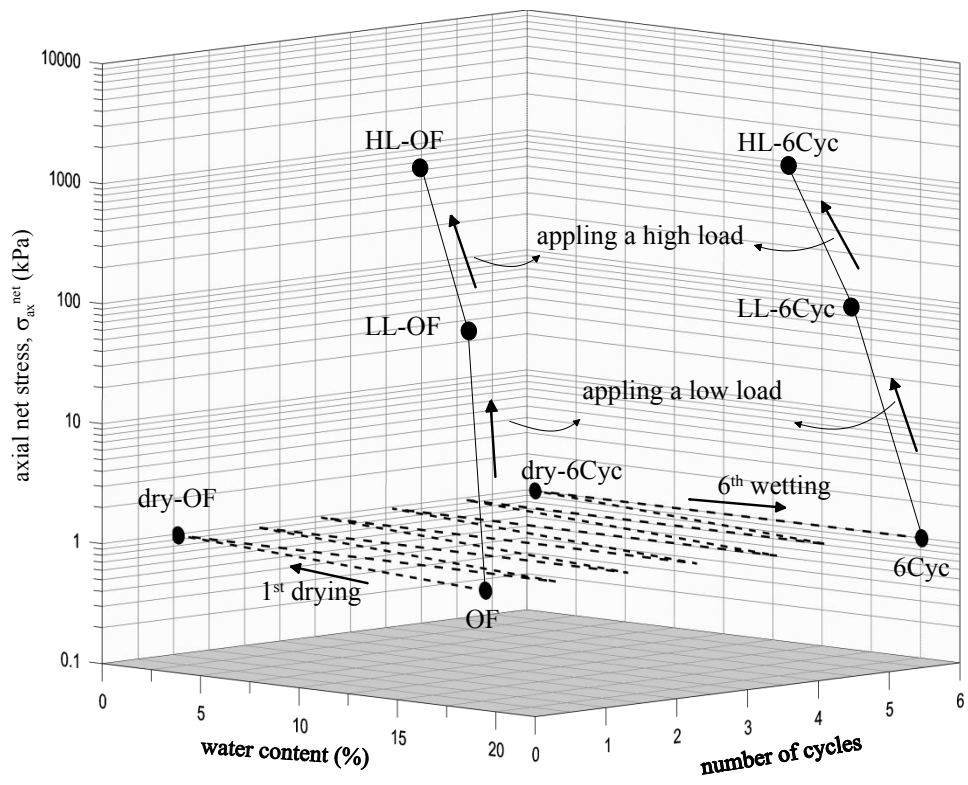


Fig. 2. Hydraulic and mechanical histories of samples prepared for MIP analysis.



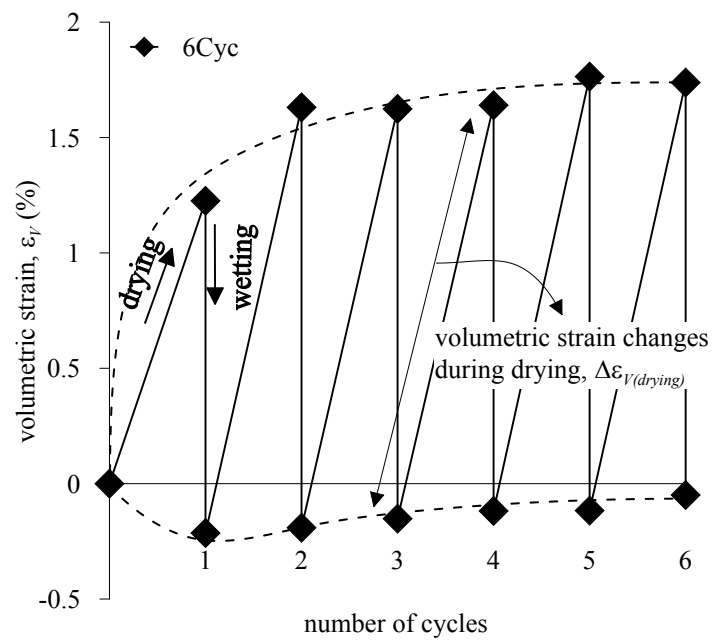
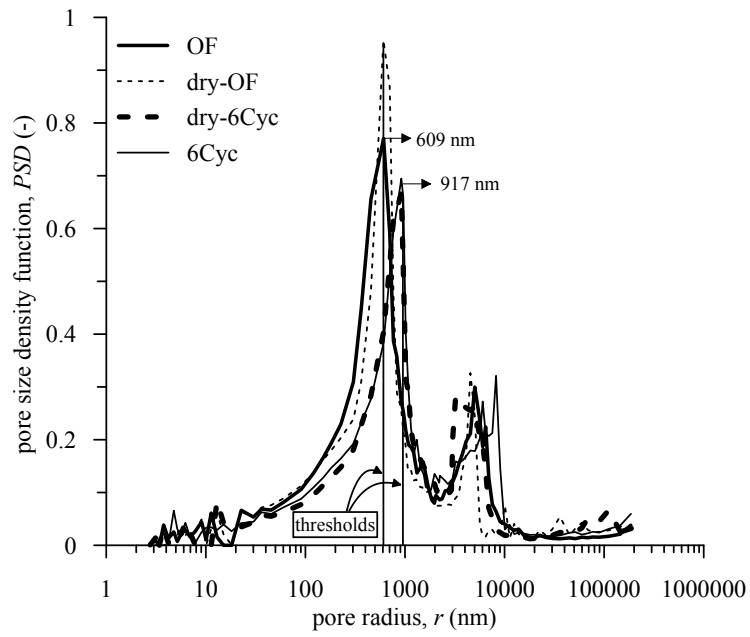
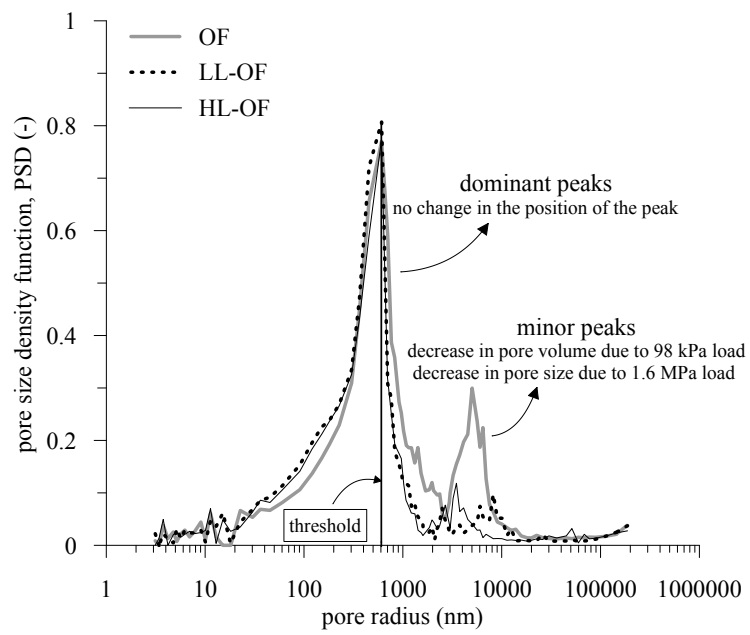


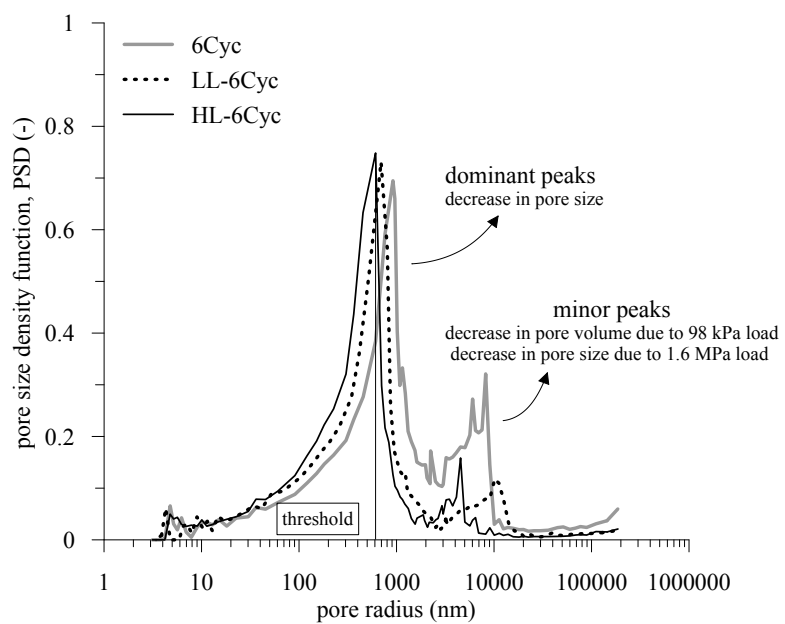
Fig. 3. Volumetric strains during the drying-wetting cycles. Positive volume strains indicate volume decrease, negative volume strains indicate volume increase.



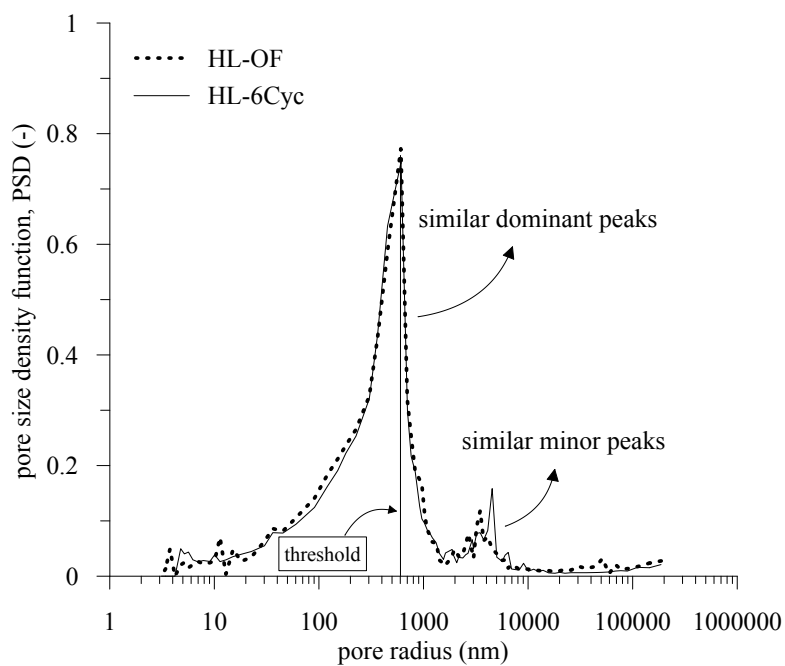
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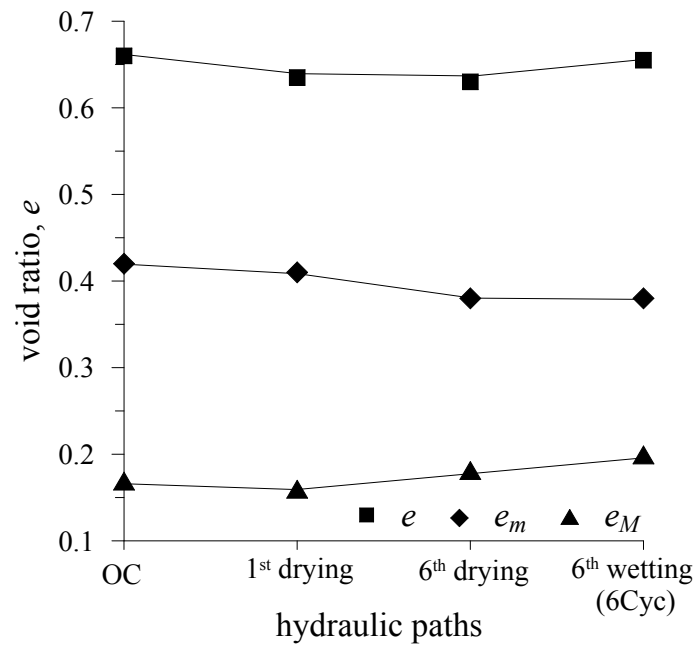


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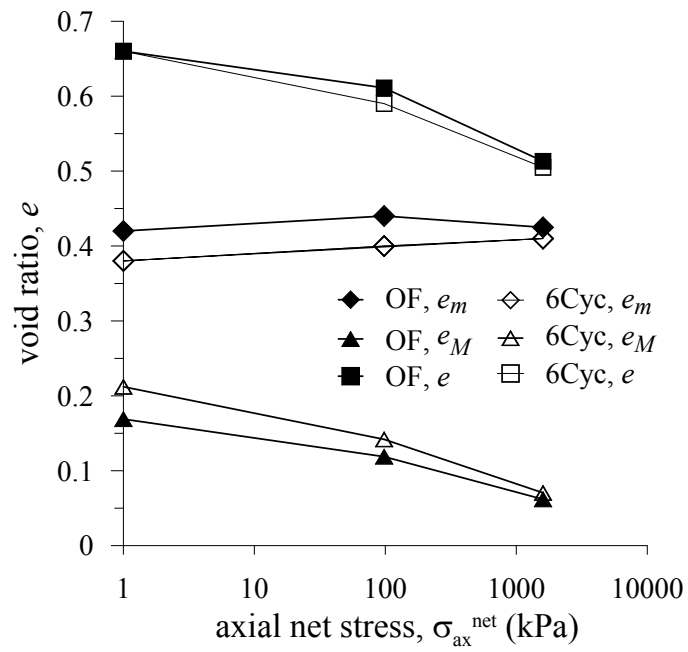


(d)

Fig. 4. Evolution of the PSD with drying-wetting cycles and with mechanical loading: (a) evolving the PSD with drying and wetting; (b) evolving the PSD of OF samples with mechanical loading; (c) evolving the PSD of 6Cyc samples with mechanical loading; (b) the PSDs of OF and 6Cyc samples being subjected to 1.6 MPa.

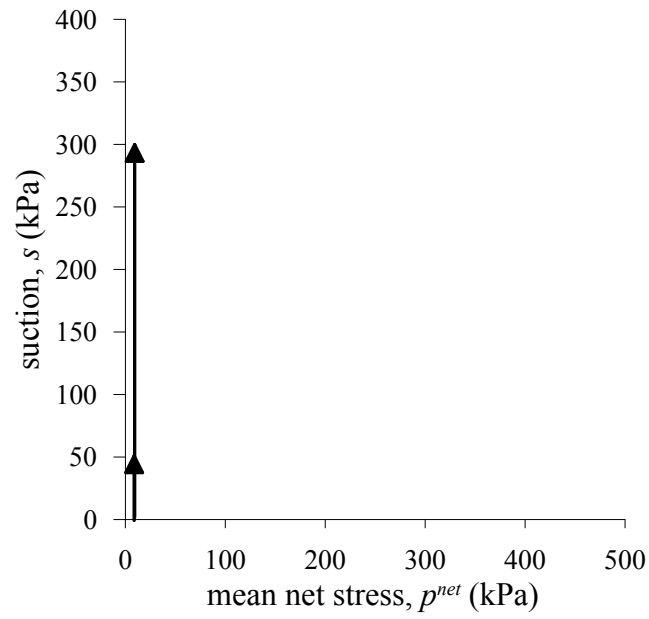


(a)

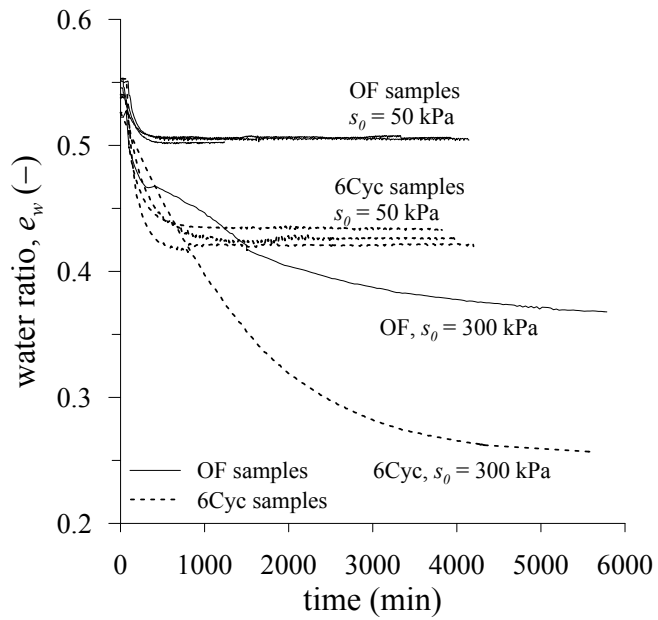


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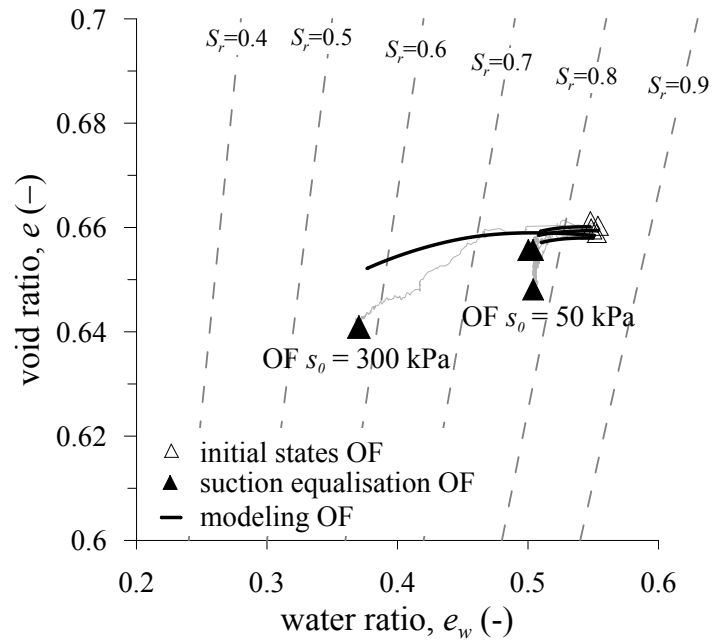
Fig. 5. Evolution of void ratio  $e$ , micro-structural void ratio  $e_m$  and macro-structural void ratio  $e_M$ : (a) with hydraulic loads; (b) with mechanical loads.



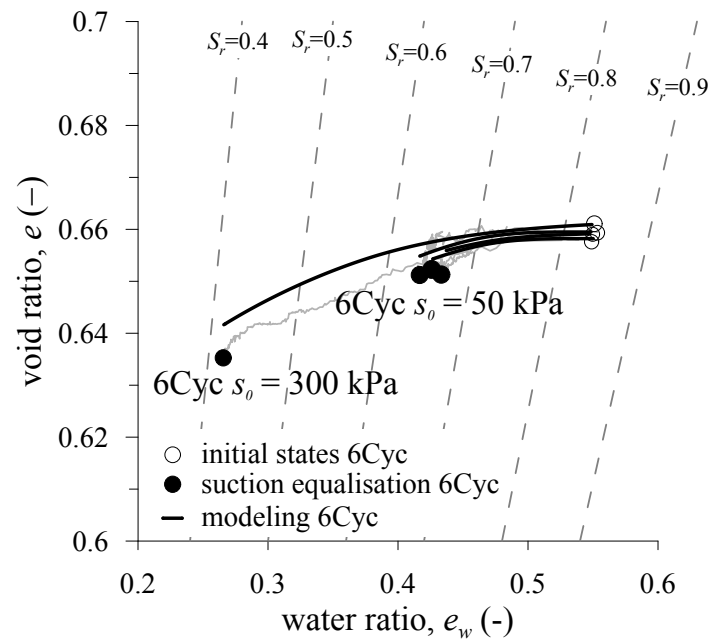
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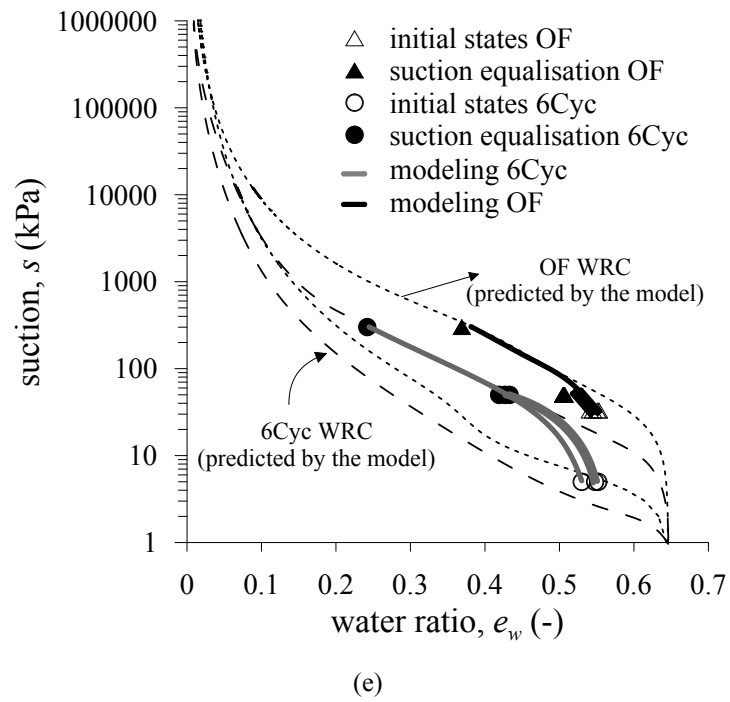
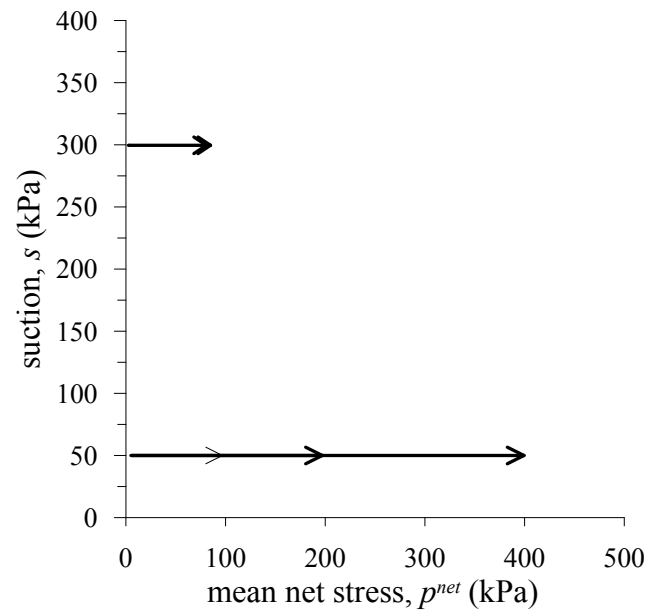
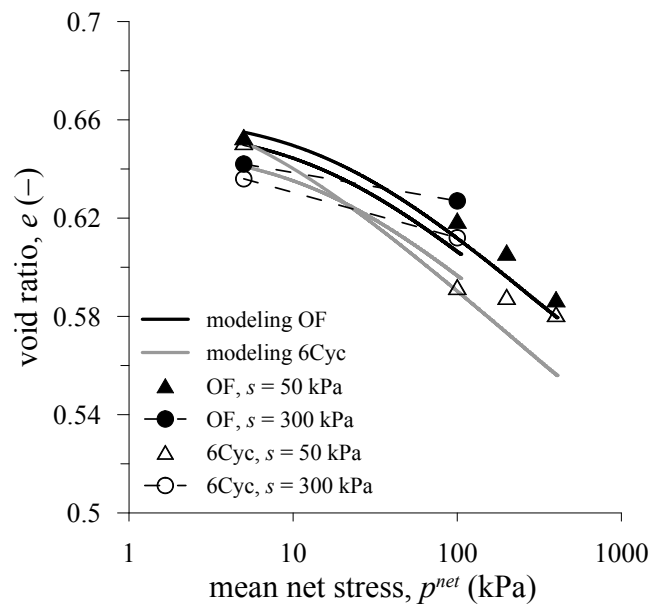


Fig. 6. Behaviour of samples along drying to 50 and 300 kPa of suction: a) stress and hydraulic paths; b) evolution of water ratio with time; c) void ratio-water ratio OF samples; d) void ratio-water ratio 6Cyc samples; e) suction- water ratio.



(a)



(b)

Fig. 7. Isotropic compression at mean net stress  $p^{net} = 100, 200$  and  $400$  kPa; a) stress path; b) void ratio- mean net stress.



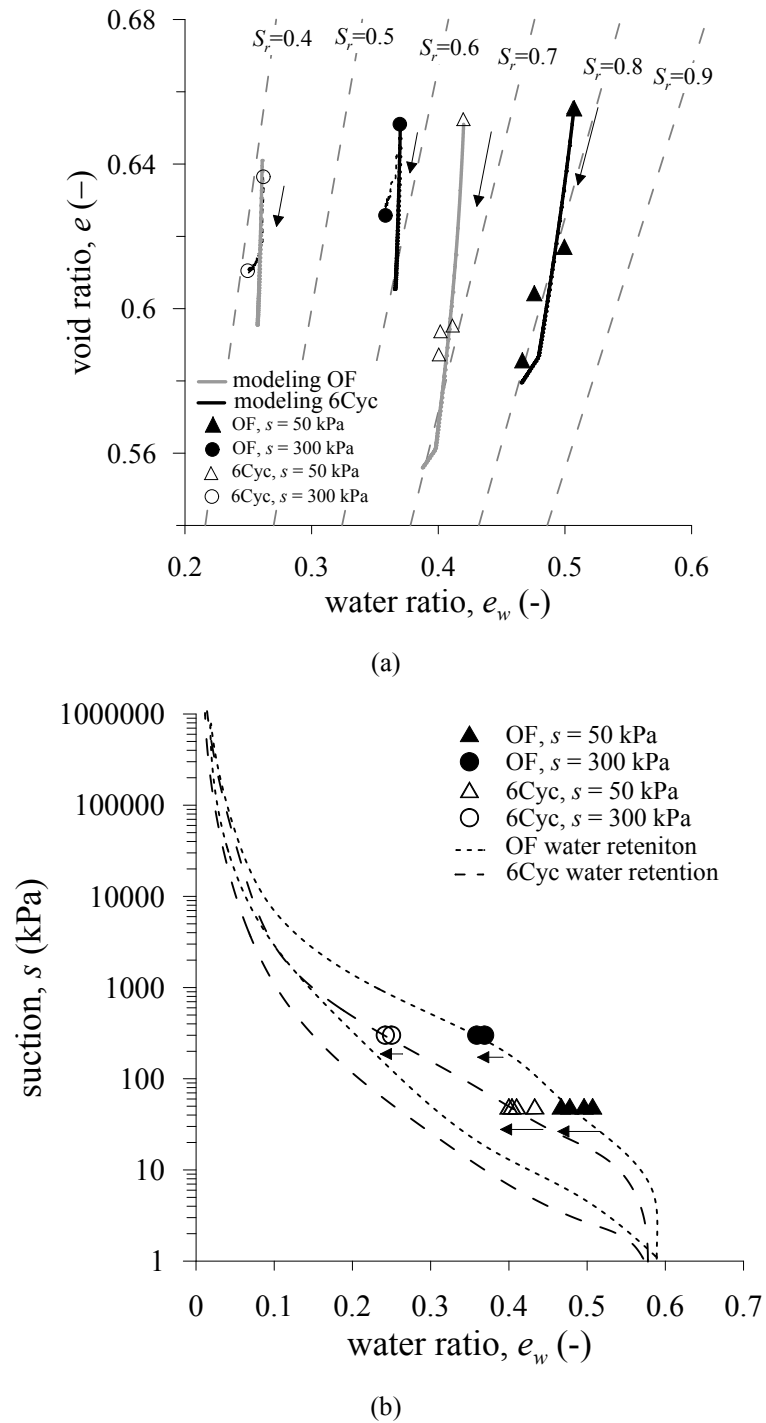


Fig. 8. Behaviour of OF and 6Cyc samples along isotropic compression to mean net stress of  $p^{net} = 100, 200$  and  $400$  kPa: a) void ratio-water ratio; b) suction-water ratio.

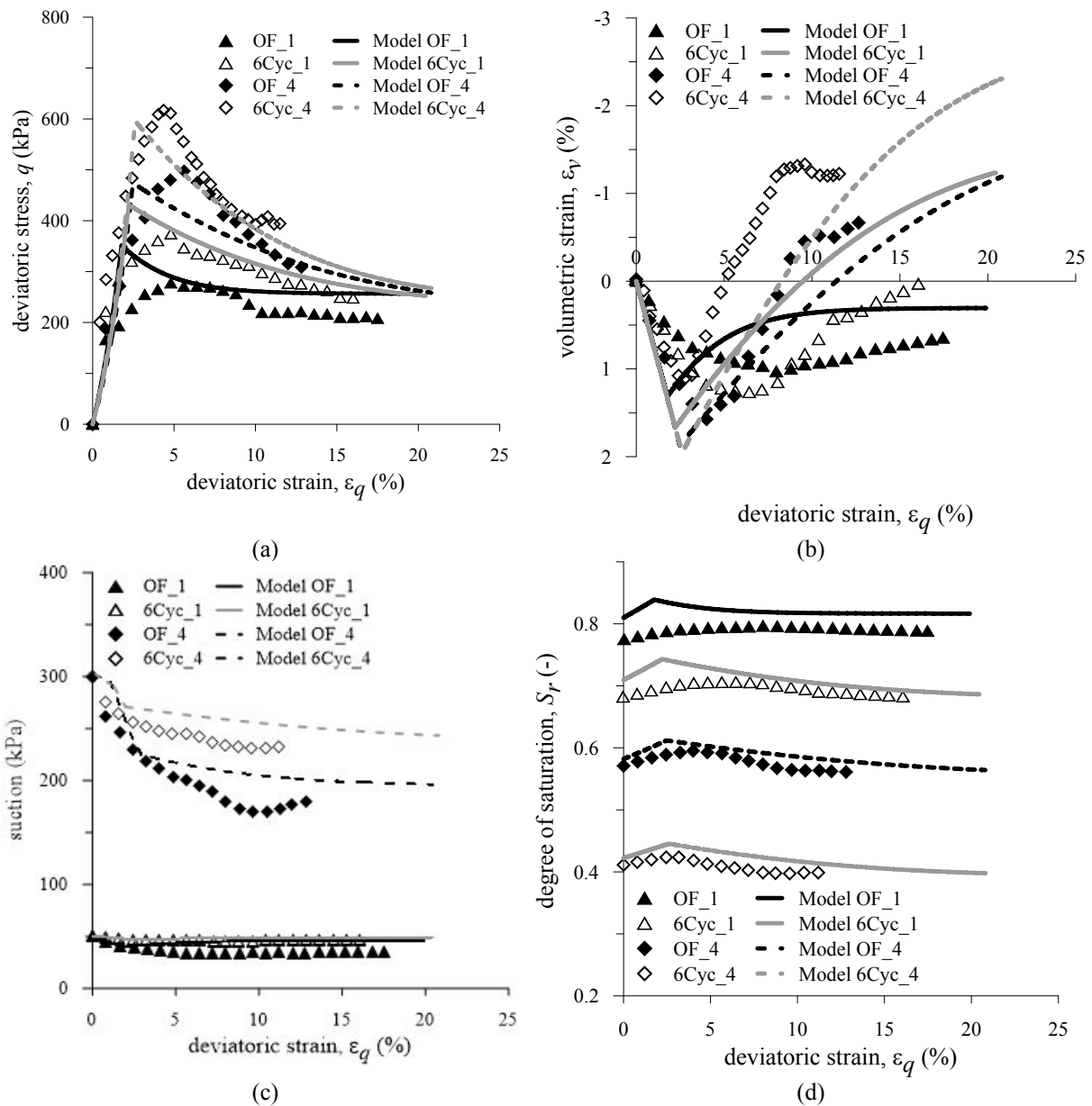


Fig. 9. Behaviour of OF and 6Cyc samples ( $s_0 = 50$  and  $300$  kPa,  $p^{net} = 100$  kPa) along triaxial compression at constant water content: a) deviatoric stress – deviatoric strains; b) volume strain – deviatoric strain; c) suction – deviatoric strain; d) degree of saturation – deviatoric strain.

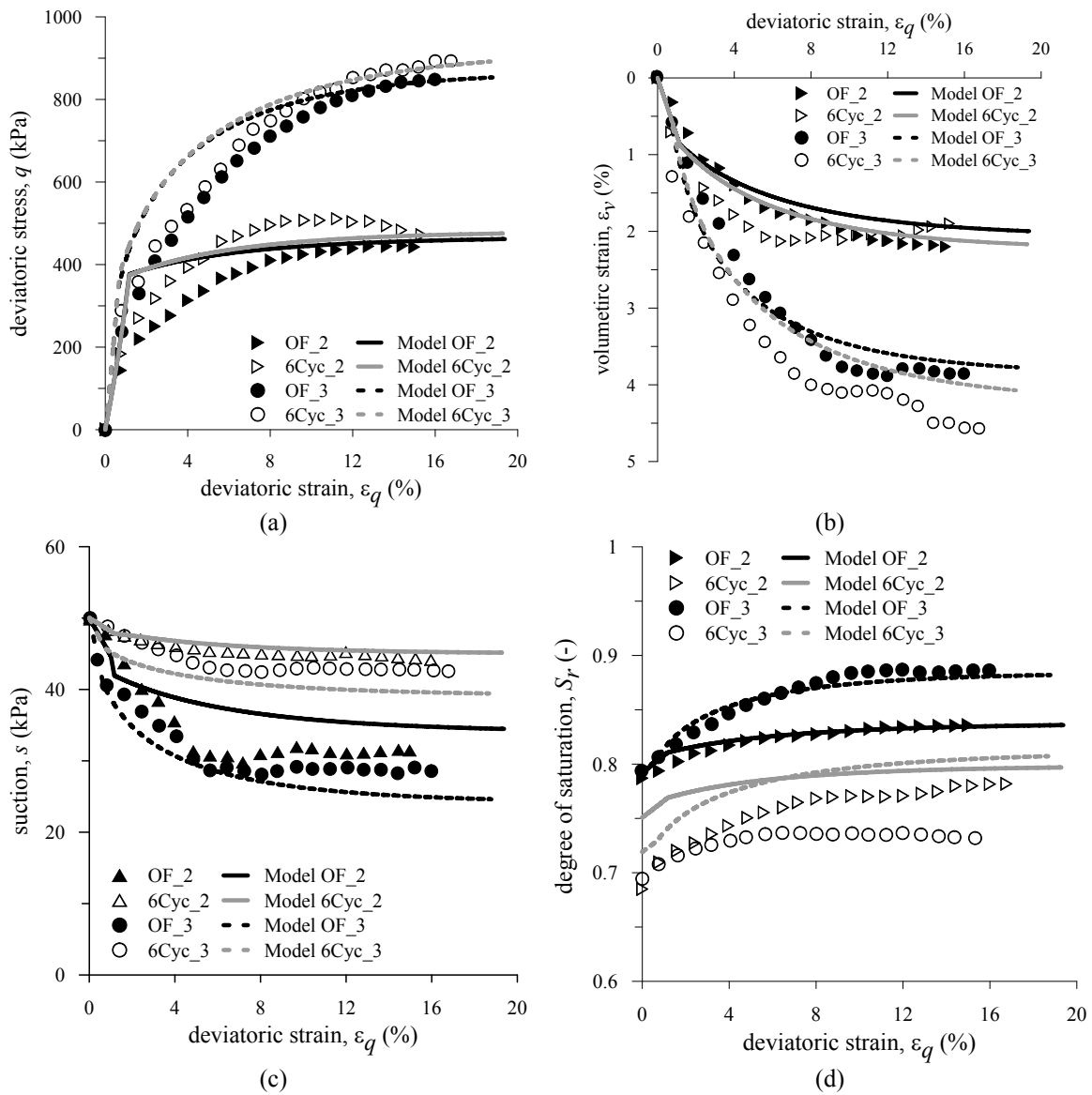
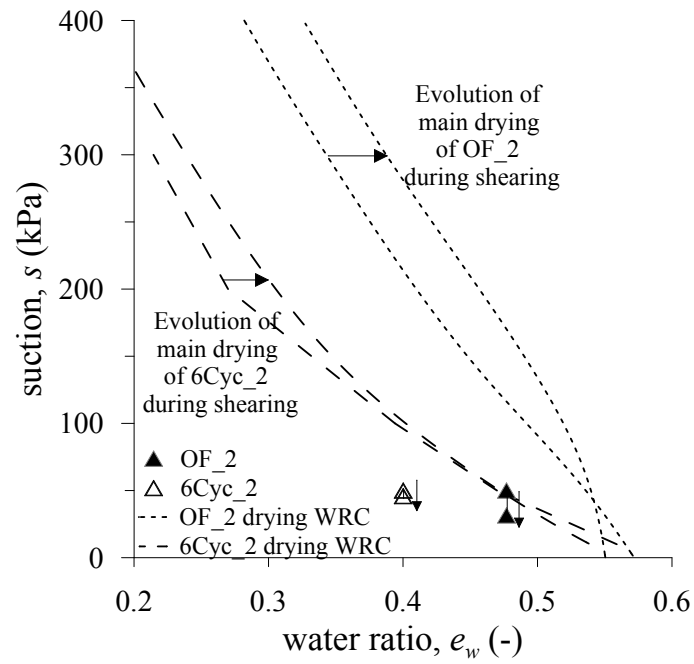
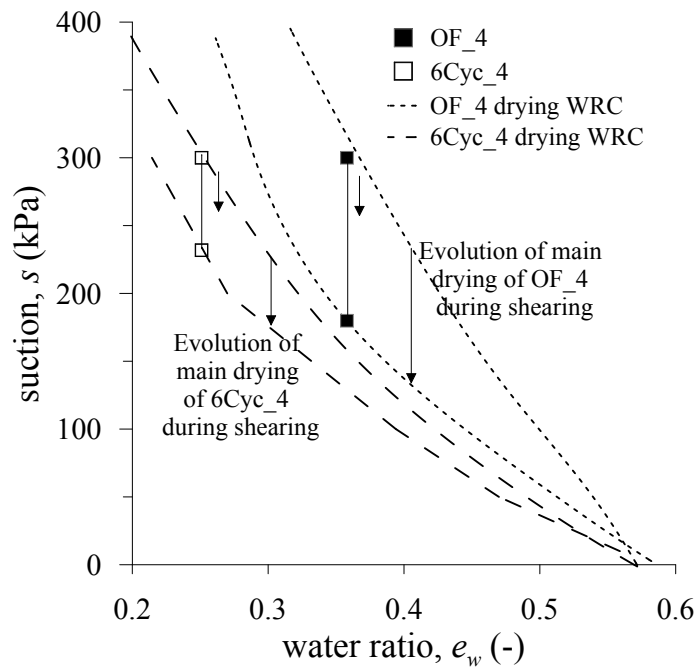


Fig. 10. Behaviour OF and 6Cyc samples ( $s_0 = 50$  kPa,  $p^{net} = 200$  kPa and 400 kPa) along triaxial compression at constant water content: a) deviatoric stress – deviatoric strains; b) volume strain – deviatoric strain; c) suction – deviatoric strain; d) degree of saturation – deviatoric strain.

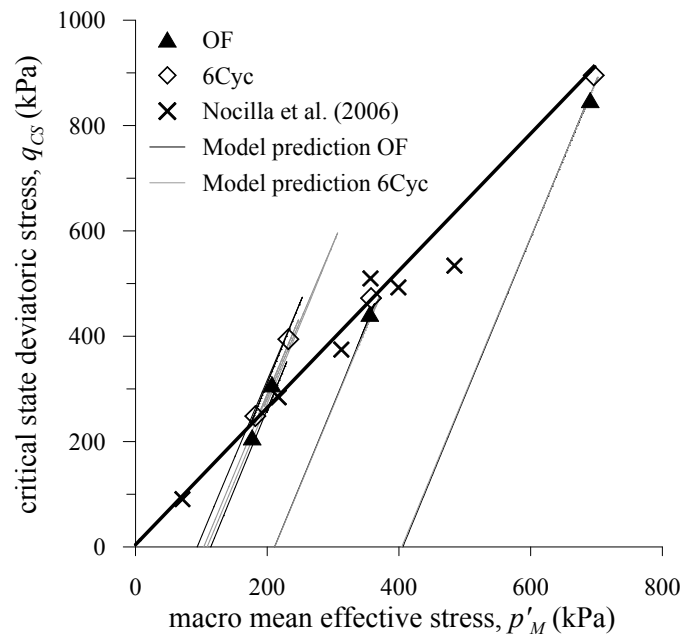


(a)

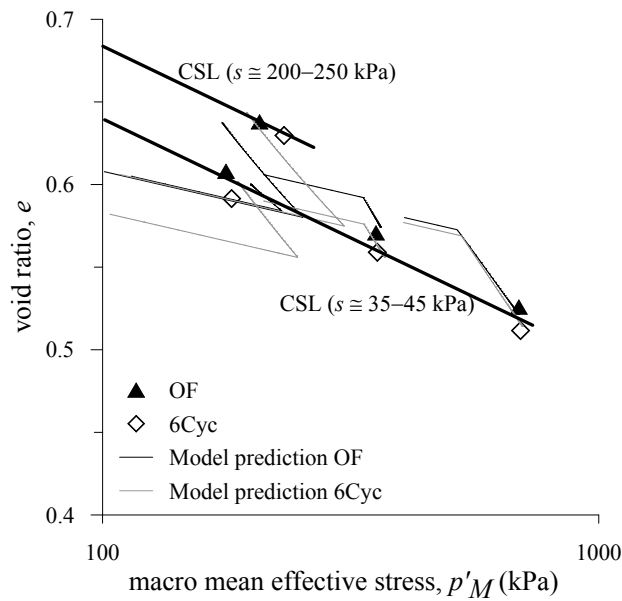


(b)

Fig. 11. Behaviour of OF and 6Cyc samples ( $s_0 = 50$  kPa and  $s_0 = 300$  kPa,  $p_{net} = 100, 200$  and  $400$  kPa) during the triaxial compression phase: (a) void ratio-water ratio for samples with  $s_0 = 50$  kPa; b) suction-water ratio for samples with  $s_0 = 300$  kPa.

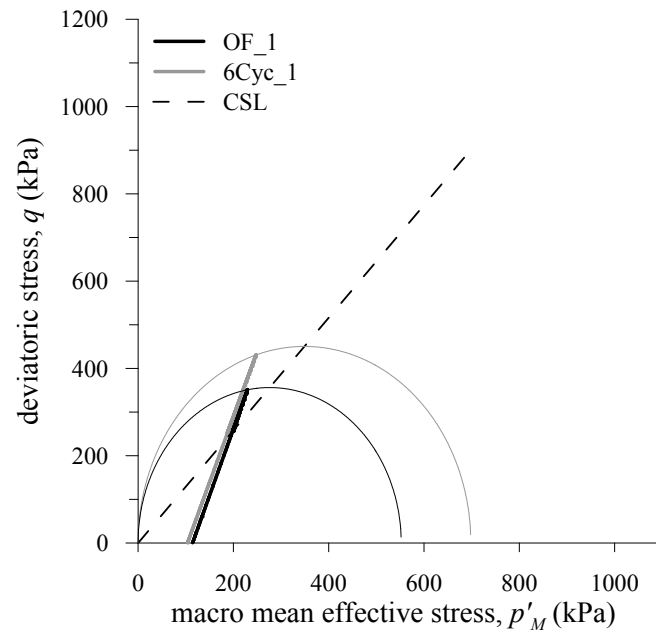


(a)

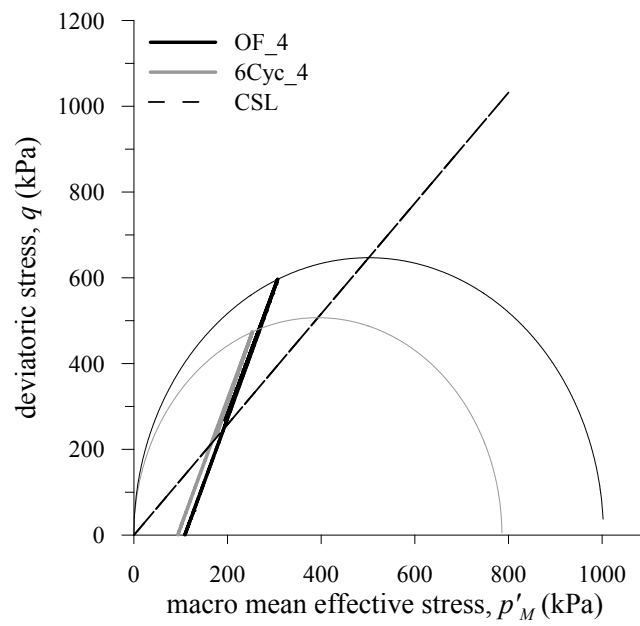


(b)

Fig. 12. Interpretation of final testing conditions and model predictions in terms of macroscopic average skeleton stress of the macrostructure: (a) deviatoric – mean stress plane; (b) compression plane.

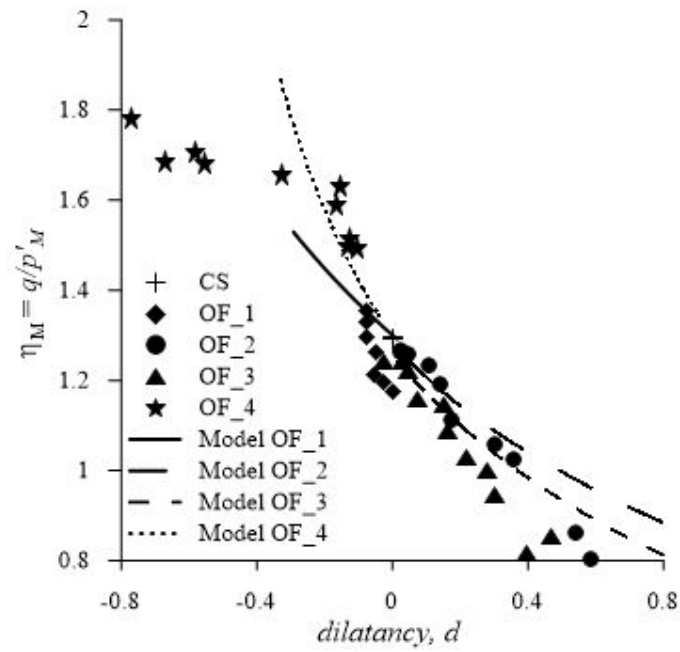


(a)

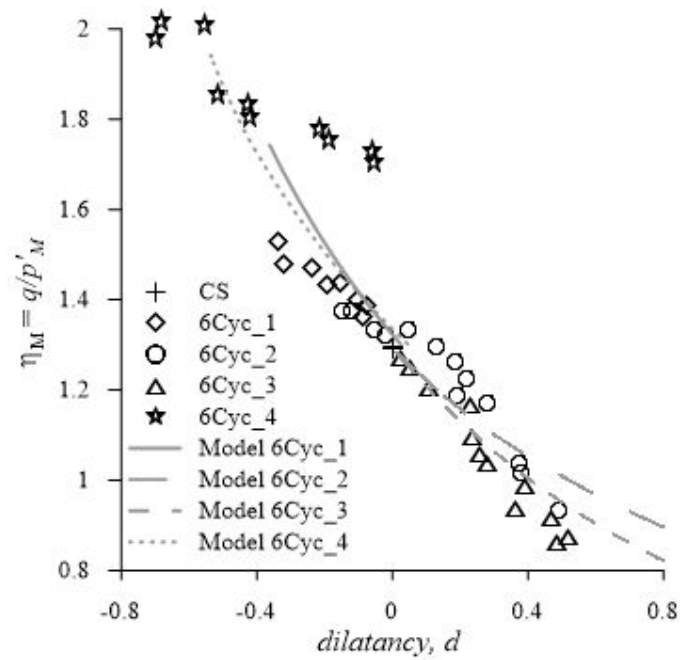


(b)

Fig. 13. Stress paths and initial position of the yield curve: (a) OF\_1 and 6Cyc\_1 ( $s_0 = 50$  kPa); (b) samples OF\_4 and 6Cyc\_4 ( $s_0 = 300$  kPa).

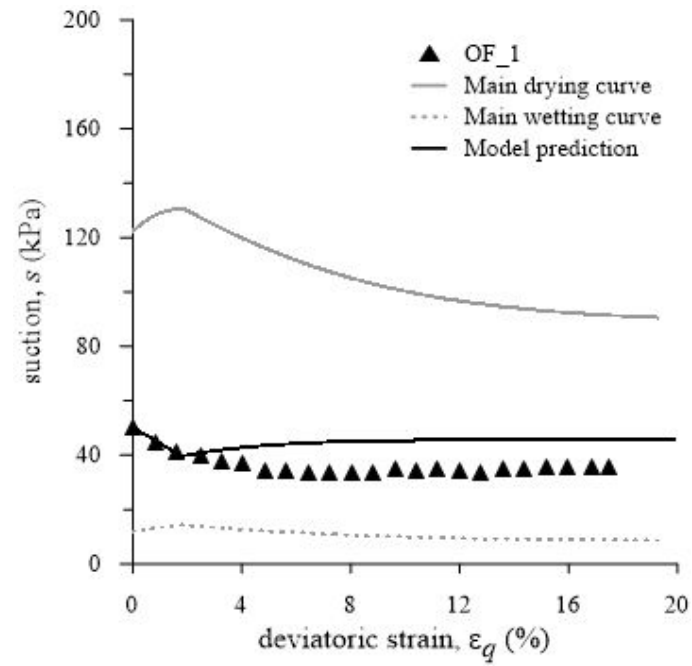


(a)

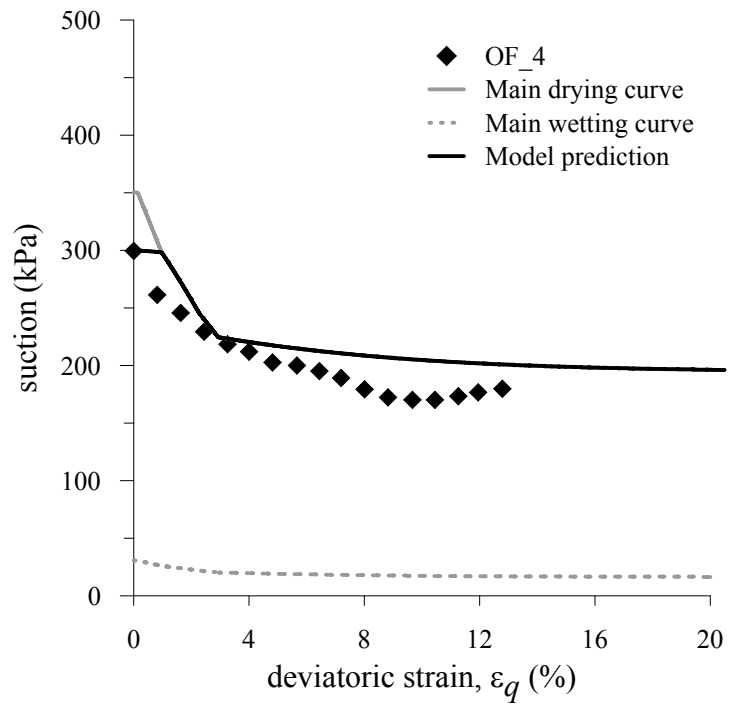


(b)

Fig. 14. Relationship between stress ratio and dilatancy: (a) OF samples; (b) 6Cyc samples.



(a)



(b)

Fig. 15. Changes in suction and evolution of the points lying on the main drying and main wetting curves: (a) test OF\_1 ( $s_0 = 50$  kPa); (b) OF\_4 ( $s_0 = 300$  kPa).



## Appendix 1 - Experimental techniques

Drying was imposed by exposing the samples to the laboratory environment, having a controlled temperature of 21 °C and relative humidity of 38.5% (suction  $s = 128.8$  MPa). The average water content at the end of drying was  $w \approx 0.4\%$ . Wetting was imposed by placing the samples in the compaction mould with a basement having a plastic porous disc and water conduits. The water was injected at a rate of about 500 mm<sup>3</sup>/h to bring the water content back to its initial value ( $w \cong 20\%$ ). Vertical deformations were allowed during wetting while radial ones were constrained by the steel frame. At the end of wetting the samples were dismantled, wrapped up in plastic bags and held in a sealed humid container for at least 5 days to ensure water equalisation.

All the MIP specimens (height and diameter of about 10 mm) were previously freeze-dried to preserve the soil fabric at its natural water content (Delage and Pellerin 1984). A Micromeritics AutoPore IV 9500 was used, injecting mercury into to pore network under vacuum condition. The relationship between the apparent pore radius ( $r$ ) and the absolute injection pressure ( $p$ ) was obtained through Washburn's equation:

$$r = - \frac{2\sigma^{Hg} \cos\theta_{nw}}{p} \quad (\text{A1})$$

where  $\sigma^{Hg} = 0.484$  N/m at 25 °C is the surface tension of the mercury and  $\theta_{nw} = 140^\circ$  is the contact angle between the mercury and the pore wall.

The MIP tests were interpreted in terms of pore size density function (PSD) defined at  $\log r$ :

$$PSD = f(\log r) = \frac{p}{\log e} \frac{d(V_{v0} - V_v)}{V_{v0} dp} \quad (\text{A2})$$

where  $e$  is void ratio,  $V_{v0}$  is the total volume of pores and  $(V_{v0} - V_v)$  is the volume of intruded mercury or the volume of pores with radius equal or greater than  $r$ .

The hydromechanical response along drying, isotropic and triaxial compression was studied with a suction-controlled triaxial cell, adopting the axis translation technique. The top and bottom caps at both sides of the specimen were equipped with two concentric porous stones, one for each fluid of concern (air and water). The inner porous stone, a ceramic disc having an Air Entry Value of 500 kPa in the  $s_\theta = 300$  kPa tests and an Air Entry Value of 100 kPa in the  $s_\theta = 50$  kPa tests, was connected to the water line and it was used to impose the water pressure. The external porous stone, a stainless steel coarse porous ring, was used to impose the air pressure. Local axial displacements were measured on the side of the samples by two miniature LVDTs. An external LVDT contrasted to

the loading ram measured large and necessary displacements. Radial displacements were measured using electro-optical laser sensors mounted outside of the cell, on opposite sides of the sample (as e.g. in Romero 1999).

The triaxial tests consisted of three stages including suction equalization, isotropic and triaxial compression. First the desired suction ( $s_0 = 50$  kPa or  $s_0 = 300$  kPa) was imposed through the axis translation technique while applying a small net mean pressure  $p^{net}$ . The sample was being held to equalize at constant suction until the changes in water content and volume were stabilized.

During isotropic compression, the net mean pressure was increased to the predefined values (100, 200 or 400 kPa) under a free drainage condition while the suction was kept constant. The net pressure was increased at the rate of 50 kPa/h while the deviatoric stress was maintained smaller than 5 kPa, providing isotropic conditions.

During triaxial compression at the constant water content condition, the water drainage was prevented and the pore water pressure was measured by means of a pressure transducer connected to the water porous stone, while the air pressure was kept constant. A constant axial strain rate of 0.25%/h was imparted to ensure that the measured water pressure was in equilibrium with the sample. The cell pressure was kept constant and the axial force was measured.