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# Soil-water retention behaviour of fine/coarse soil mixture with varying coarse grain contents and fine soil dry densities

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1 Soil-water retention behaviour of fine/coarse soil mixture with varying coarse  
2 grain contents and fine soil dry densities

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22 **Abstract**

23 An interlayer soil identified in the French conventional rail track corresponded to a mixture of  
24 fine soil and coarse grains. To investigate the role of fines in the soil-water retention property  
25 of such mixture, different coarse grain contents  $f_v$  and dry densities of fine soil  $\rho_{d-f}$  were  
26 considered. The filter paper method was applied to measure the matric suction. Mercury  
27 intrusion porosimetry tests were performed for the microstructure observation of fine soil. In  
28 terms of gravimetric water content of fine soil  $w_f$  with matric suction  $\psi$ , the soil-water  
29 retention curve (SWRC) was significantly affected by  $\rho_{d-f}$  for  $\psi < 715$  kPa, while independent  
30 of  $\rho_{d-f}$  for  $\psi > 715$  kPa. Interestingly, this threshold  $\psi$  corresponded to a delimiting pore  
31 diameter of bi-modal microstructure of fine soil, which separated micro-pores from macro-  
32 pores. In terms of degree of saturation  $S_r$  with  $\psi$ , the SWRC was significantly affected by  $\rho_{d-f}$   
33 in the full suction range, while independent of  $f_v$ . These findings help better understand the  
34 results on samples with the dry density of mixture  $\rho_d$  kept constant: an increase of  $f_v$  resulted  
35 in a decrease of  $\rho_{d-f}$  and the suction changed accordingly. In that case, both  $f_v$  and  $\psi$  affected  
36 the mechanical behavior.

37 **Keywords:** soil-water retention; matric suction; pore size distribution; dry density; coarse  
38 grain content

39 INTRODUCTION

40 In the French conventional rail track, an interlayer was naturally created in the substructure  
41 under the long-term traffic loading, which corresponded to a mixture of ballast grains and  
42 subgrade fine soil. As its suction can greatly affect its mechanical behavior (see details in Su  
43 et al. 2020a and Wang et al. 2018), it appears important to investigate its water retention  
44 property in-depth.

45 In-situ investigations showed a decrease of ballast grain content with the increasing depth  
46 of interlayer soil (Trinh 2011, Cui et al. 2013). Globally, the interlayer soil was separated into  
47 two parts: the upper part was characterized by a coarse grain skeleton fabric, and the lower  
48 part by a fine matrix macrostructure with dispersed coarse grains. In addition, due to the  
49 different vertical stresses over depths, the dry density of fine soil  $\rho_{d-f}$  was different. Wang et al.  
50 (2017, 2018), Cui (2018) and Qi et al. (2020a) studied the effect of coarse grain content  $f_v$  (the  
51 ratio of the volume of coarse grains  $V_c$  to the volume of total sample  $V$ ) on the mechanical  
52 behavior of interlayer soil at a constant  $\rho_{d-f} = 1.82 \text{ Mg/m}^3$ . They assumed that under a given  
53 water content, the matric suction of mixture was the same at a constant  $\rho_{d-f} = 1.82 \text{ Mg/m}^3$ . Up  
54 to now, this point has not been experimentally examined yet. It seems necessary to verify this  
55 point by investigating the effects of coarse grain content  $f_v$  and dry density of fine soil  $\rho_{d-f}$  on  
56 the soil-water retention property of fine/coarse soil mixture.

57 The effects of dry density and coarse grain content on soil-water retention property were  
58 investigated previously in some studies. The filter paper method (ASTM D5298-10, 2010)  
59 was usually adopted for the measurement of suction (Muñoz-Castelblanco et al. 2010; Kim et  
60 al. 2015; Jing 2017). It appeared that the effect of dry density on soil-water retention behavior

61 was strongly dependent on the microstructure (Simms and Yanful 2002; Romero et al. 2011).  
62 Romero et al. (1999) studied the effect of dry density on water retention and microstructure of  
63 Boom clay by vapor equilibrium technique and mercury intrusion porosimetry tests,  
64 respectively. The results showed that the soil-water retention curve (SWRC) in the low  
65 suction range was governed by the inter-aggregate pores, while that in high suction range was  
66 governed by intra-aggregate pores. Similarly, Salager et al. (2013) and Gao and Sun (2017)  
67 investigated the water retention capacity of clayey soil and found that the SWRCs for  
68 different dry densities was independent of dry density beyond a certain matric suction. It is  
69 worth noting that these studies only involved the effect of dry density without the effect of  
70 coarse grain content. Fiès et al. (2002) studied the soil-water retention property of fine  
71 soil/glass fragments mixture, and found that an increasing glass content led to a reduction of  
72 the amount of water stored in the mixture. Baetens et al. (2009) investigated the effect of rock  
73 fragments on the water retention property of stony soil, and reported that rock fragments could  
74 affect the SWRC when the matric suction was smaller than 30 kPa. Duong et al. (2014)  
75 studied the hydraulic behavior of interlayer soil by infiltration column, and observed that  
76 increasing coarse grain content resulted in a lower SWRC or a lower water retention capacity.  
77 Note that in most of these studies, the effect of coarse grain content on soil-water retention  
78 property of mixture was investigated with a large quantity of coarse grains, which  
79 corresponded to the coarse grain skeleton structure of mixture, without considering the fine  
80 matric macrostructure. In addition, the dry density of mixture  $\rho_d$  was taken constant, leading  
81 to a decrease of dry density of fine soil  $\rho_{d-f}$  with the increase of coarse grain content. That  
82 would increase the difficulty of analysis while studying the effect of suction.

83 This study aims to investigate the effects of coarse grain content  $f_v$  and dry density of fine  
84 soil  $\rho_{d-f}$  on soil-water retention property of fine/coarse soil mixture. Three  $f_v = 0\%$ , 20% and  
85 35% were adopted at the same  $\rho_{d-f} = 1.82 \text{ Mg/m}^3$  for studying the effect of  $f_v$ , and three  $\rho_{d-f}$   
86  $= 1.82, 1.67$  and  $1.52 \text{ Mg/m}^3$  were adopted at the same  $f_v = 0\%$  for studying the effect of  $\rho_{d-f}$ .  
87 The filter paper method was applied to measure the matric suction of soil mixture. The  
88 microstructure of fine soil under varying  $\rho_{d-f}$  values was determined by mercury intrusion  
89 porosimetry tests. The results obtained allowed the effects of  $f_v$  and  $\rho_{d-f}$  on soil-water retention  
90 property of soil mixture to be clarified.

91

## 92 MATERIALS AND METHODS

### 93 *Fine soil and coarse grains*

94 Considering the difficulty of extracting intact interlayer soil from the field, the reconstituted  
95 fine soil and coarse grains were fabricated in the laboratory. For the fine soil fraction, to  
96 obtain a similar grain size distribution of fines from ‘Senissiat site’ (Trinh 2011) (Fig. 1), nine  
97 different mass proportions of commercial soils were mixed (Table 1; see details in Lamas-  
98 Lopez 2016). The liquid limit and plasticity index of the reconstituted fine soil were 32% and  
99 20%, respectively. Consequently, a good agreement between in-situ fine soil and reconstituted  
100 fine soil was observed in terms of grain size distribution, plasticity index and liquid limit (see  
101 details in Wang et al. 2017). Fig. 2 presents the standard Proctor compaction curve of the  
102 reconstituted fine soil, defining an optimum water content  $w_{\text{opt-f}} = 13.7\%$  and a maximum dry  
103 density  $\rho_{\text{dmax-f}} = 1.82 \text{ Mg/m}^3$ . Note that the  $\rho_{\text{dmax-f}} = 1.82 \text{ Mg/m}^3$  of reconstituted fine soil was  
104 consistent with the  $\rho_{d-f} = 1.80 \text{ Mg/m}^3$  of in-situ fine soil measured by Lamas-Lopez (2016).

105 Based on above features, the reconstituted fine soil was considered as representative of the in-  
 106 situ fine soil. For the coarse grains fraction, the micro-ballast was adopted to replace the real  
 107 ballast by following a parallel gradation method adopted by Wang et al. (2017) and Su et al.  
 108 (2020a). The validity of this method was verified by Qi et al. (2020b), who performed  
 109 comparisons between micro-ballast and ballast in terms of mechanical behavior under static  
 110 and cyclic loadings. Note that the scaled fine/coarse soil mixture was used as representative of  
 111 interlayer soil taken from Senissiat (near Lyon, France, Trinh 2011), which was far from the  
 112 coastal. Thus, the salt content-related osmotic suction was ignored and only the matric suction  
 113 was taken into account in this study.

114 Parameter  $f_v$ , widely adopted in previous studies (Seif El Dine et al. 2010; Wang et al.  
 115 2017, 2018; Su et al. 2020a, 2020b), was considered in this study. Based on the definition of  $f_v$   
 116 (Eq.(1)), which only quantified the amount of dry coarse grains in the mixture, all voids and  
 117 water were assumed to be contained in the fine soil (Fig. 3), as in Wang et al. (2018) and Su et  
 118 al. (2020a). Based on this assumption, the degree of saturation  $S_r$  of mixture can be related to  
 119 the fine soil fraction. :

$$120 \quad f_v = \frac{V_c}{V} = \frac{V_c}{V_c + V_f} = \frac{V_c}{V_c + V_{s-f} + V_{w-f} + V_{a-f}} \quad (1)$$

121 where  $V_f$  is the volume of fine soil;  $V_{s-f}$ ,  $V_{w-f}$  and  $V_{a-f}$  are the volume of fine grains, water and  
 122 air in the fine soil.

123 For the soil mixture at varying  $f_v$ ,  $\rho_{d-f}$  and water content  $w_f$  of fine soil, the mass of coarse  
 124 grains  $m_{s-c}$ , fine grains  $m_{s-f}$  and water content of fine soil  $m_{w-f}$  could be determined as follows:

$$125 \quad m_{s-c} = V_c \cdot G_{s-c} \cdot \rho_w = f_v \cdot V \cdot G_{s-c} \cdot \rho_w \quad (2)$$

$$126 \quad m_{s-f} = \rho_{d-f} \cdot V_f = \rho_{d-f} \cdot V \cdot (1 - f_v) \quad (3)$$

127 
$$m_{w-f} = w_f \cdot m_{s-f} \quad (4)$$

128 where  $G_{s-c}$  is the specific gravity of coarse grains;  $\rho_w$  is the water unit mass.

129 For the soil mixture at a given  $\rho_{d-f}$ , the corresponding void ratio of fine soil  $e_f$  could be  
 130 deduced using Eq. (5):

131 
$$e_f = \frac{G_{s-f} \rho_w}{\rho_{d-f}} - 1 \quad (5)$$

132 where  $G_{s-f}$  is the specific gravity of fine soil.

133 Then, the void ratio  $e_m$  of soil mixture can be determined:

134 
$$e_m = \frac{V_{v-f}}{V_c + V_{s-f}} = \frac{V_{v-f}}{V - V_{v-f}} \quad (6)$$

135 
$$V_{v-f} = e_f \cdot V_{s-f} \quad (7)$$

136 
$$V_{s-f} = \frac{m_{s-f}}{G_{s-f} \rho_w} \quad (8)$$

137 where  $V_{v-f}$  is the volume of voids in fine soil;  $V_{s-f}$  is the volume of fine grains.

138 Combining Eqs. (1), (3) and (5)-(8), the void ratio  $e_m$  of soil mixture at varying  $f_v$  and  $\rho_{d-f}$   
 139 was obtained:

140 
$$e_m = -1 + \frac{1}{1 - \frac{(G_{s-f} \rho_w - \rho_{d-f}) \cdot (1 - f_v)}{G_{s-f} \rho_w}} \quad (9)$$

141 Fig. 4 shows the variations of  $e_f$  and  $e_m$  with  $f_v$  at a constant  $\rho_{d-f} = 1.82 \text{ Mg/m}^3$ . The  $e_f$  and  
 142  $e_m$  were obtained by substituting  $\rho_{d-f} = 1.82 \text{ Mg/m}^3$  and  $G_{s-f} = 2.68$  (Duong et al. 2016) into  
 143 Eqs. (5) and (9), respectively:

144 
$$e_f = 0.47 \quad (10)$$

145 
$$e_m = -1 + \frac{1}{1 - 0.32 \cdot (1 - f_v)} \quad (11)$$

146 As mentioned before, all voids and water were assumed to be contained in the fine soil.

147 Thus, the  $S_r$  represented both degree of saturation of soil mixture and that of fine soil:

148 
$$S_r = \frac{V_{w-f}}{V_{v-f}} \quad (12)$$



149 *Filter paper method*

150 The filter paper method (ASTM D5298-10, 2010) was used to measure the matric suction.  
151 Filter paper measurement was generally performed by putting a piece of filter paper between  
152 two soil disks to attain suction equilibrium between filter paper and soil disks (ASTM D5298-  
153 10 2010; Muñoz-Castelblanco et al. 2010; Kim et al. 2015; Jing 2017). Considering the  
154 maximum diameter  $d = 20$  mm of coarse grains (Fig. 1), the soil disk was prepared at 100 mm  
155 diameter and 100 mm height. As for the preparation of soil disks, the fine soil (Fig. 5(a)) was  
156 prepared at a molding water content  $w_{\text{opt-f}} = 13.7\%$ , then stored in a container for at least 24 h,  
157 allowing water homogenization. After that, the fine soil was thoroughly mixed with the coarse  
158 grains (Fig. 5(a)) with their pre-determined masses at target  $f_v$  and  $\rho_{\text{d-f}}$  values (Table 2). Note  
159 that a characteristic coarse grain content  $f_{\text{v-cha}} \approx 27\%$  identified by Wang et al. (2018)  
160 separated the coarse grain skeleton fabric ( $f_v > f_{\text{v-cha}}$ ) and the fine matrix macrostructure ( $f_v <$   
161  $f_{\text{v-cha}}$ ) of mixture. Both fabrics were considered in this study with  $f_v$  ranging from 0% to 35%.  
162 The fine/coarse soil mixture were then compacted in four layers, with an equal amount of fine  
163 soil and coarse grains for each layer (Fig. 5(b)). Table 2 presents the variations of  $e_f$ ,  $S_r$  and the  
164 dry density of soil mixture  $\rho_d$  with  $f_v$  and  $\rho_{\text{d-f}}$  at a molding water content of fine  $w_{\text{opt-f}} = 13.7\%$ .  
165 After compaction, the soil disks at different  $f_v$  and  $\rho_{\text{d-f}}$  values were wetted from the molding  
166 states to the saturated state. The approach proposed by Su et al. (2020c) was adopted during  
167 the wetting process: 10 g water was distributed uniformly on the surface of soil disk by a  
168 sprayer each time. The disk was then covered with plastic film for at least 7 h. Fig. 2 shows  
169 that the wetting process of soil disk from a molding state to a nearly saturated state induced a  
170 slight decrease of  $\rho_{\text{d-f}}$  due to the swelling of fine soil, and consequently a slight increase of  $e_f$

171 and slight decrease of  $\rho_d$  (Table 2). The measured  $w_f$  and the corresponding  $S_r$  of soil disks at  
172 nearly saturated state were also presented in Table 2.

173 To obtain the drying soil-water retention curve of soil mixture at a given  $f_v$  and  $\rho_{d-f}$ , 10  
174 suction measurements were conducted, corresponding to 10 target  $w_f$  values. When a soil disk  
175 reached a target  $w_f$  value, it was covered with plastic film for at least 24 h prior to measuring  
176 its matric suction. A set of three filter paper was prepared, with the middle filter paper  
177 (diameter  $d = 80\text{mm}$ ) slightly smaller than the two outer filter paper ( $d = 90\text{mm}$ ) to avoid  
178 contamination of the middle one. The set of three filter papers was then placed between two  
179 soil disks. The whole set was covered with plastic film, and then sealed with wax. Note that  
180 an initial water content of 4.61% of the filter paper was measured, corresponding to a suction  
181 of 93 MPa. In this case, the filter paper followed a wetting process during the equilibration  
182 process between soil and filter paper. After equilibration, the water content of soil disks and  
183 the middle filter paper were measured, with a balance of 1/10000 g accuracy. The  
184 corresponding matric suction was then determined for varying  $f_v$ ,  $\rho_{d-f}$  and  $w_f$  values. It is worth  
185 noting that the volume of soil disks at different  $w_f$  values was also measured, by means of a  
186 caliper.

187

### 188 *Mercury intrusion porosimetry test (MIP)*

189 For the MIP tests, three soil disks were prepared at varying  $\rho_{d-f} = 1.82, 1.67$  and  $1.52 \text{ Mg/m}^3$   
190 with the same  $f_v = 0\%$ . The freeze-drying method was adopted: fine soil was cut into small  
191 pieces of around 1.5 g each, and then immersed into nitrogen under vacuum; afterwards, the  
192 frozen soil was transferred to the chamber of a freeze dryer for lyophilizing. This method

193 minimized the microstructure disturbance of fine soil, which was widely used in previous  
194 studies (Cui et al. 2002; Delage et al. 2006; Wang et al. 2014).

195

## 196 RESULTS

197 To determine the equilibration time of samples with the filter paper method, three samples  
198 were prepared at the same  $f_v = 0\%$ ,  $\rho_{d-f} = 1.82 \text{ Mg/m}^3$  and  $w_{\text{opt-f}} = 13.7\%$ , with 5, 7 and 9 days  
199 waited, respectively. Fig. 6 depicts the variations of matric suction and water content of filter  
200 paper with time. It appears that with the increase of time from 0 to 5, 7 and 9 days, the water  
201 content of filter paper increased from 4.61% to 30.59%, 32.02% and 32.11%, and the  
202 corresponding matric suction decreased from 93 MPa to 879, 679 and 670 kPa, respectively.  
203 This indicated that at least a time of 7 days was needed for the suction equilibration between  
204 soil and filter paper. Thereby, a duration of 7 days was adopted for all tests.

205 Fig. 7 shows the drying SWRC expressed in terms of  $w_f$  and  $S_r$  with  $\psi$  and the variations  
206 of  $e_f$  with  $\psi$  for different  $f_v$  values (0%, 20% and 35%) and different initial  $\rho_{d-f}$  values (1.82,  
207 1.67 and 1.52  $\text{Mg/m}^3$ ). The retention curves were fitted with the van Genuchten model (1980).  
208 The legends were defined following the rule: ' $f_v$  0%-  $\rho_{d-f}$ 1.82' refers to the  $f_v = 0\%$  and the  
209 initial  $\rho_{d-f} = 1.82 \text{ Mg/m}^3$ . Fig. 7(a) depicts the variations of  $w_f$  with  $\psi$  for various  $f_v$  and  $\rho_{d-f}$   
210 values. It appears clearly that the water retention curves were only dependent on the dry  
211 density of fines  $\rho_{d-f}$ , and independent of the coarse grain content  $f_v$ . In addition, the gaps  
212 between the three curves for different  $\rho_{d-f}$  values decreased with the increase of matric suction  
213  $\psi$ . The curves converged to the same one beyond a threshold suction  $\psi = 715 \text{ kPa}$ . Thus, the  
214 SWRC in low suction range ( $\psi < 715 \text{ kPa}$ ) was sensitive to the variation of  $\rho_{d-f}$ , while

215 independent of  $\rho_{d-f}$  in high suction range ( $\psi > 715$  kPa).

216 Fig. 7(b) depicts the variations of void ratio of fine soil  $e_f$  with  $\psi$  for the fine/coarse soil  
217 mixture at varying  $f_v$  and  $\rho_{d-f}$  values. It appears that such variations were also only dependent  
218 on  $\rho_{d-f}$  and independent of  $f_v$ . In addition, the lower the  $\rho_{d-f}$  value, the larger the decrease of  $e_f$   
219 with increasing  $\psi$ , showing a larger volume change under the effect of suction for the case of  
220 lower  $\rho_{d-f}$ .

221 Fig.7(c) presents the variations of degree of saturation  $S_r$  with  $\psi$  for the fine/coarse soil  
222 mixture at varying  $f_v$  and  $\rho_{d-f}$  values. The curves were found to be independent of  $f_v$ , which  
223 agreed with those in Fig.7 (a)-(b). In addition, the larger the  $\rho_{d-f}$  value the higher the water  
224 retention capacity. With the decrease of  $\rho_{d-f}$  from 1.82 to 1.67 and 1.52 Mg/m<sup>3</sup>, the air entry  
225 value (AEV) decreased from 550 to 96 and 36 kPa respectively.

226 Fig. 8 shows the pore size distributions (PSD) of fine soil at  $\rho_{d-f} = 1.82, 1.67$  and  $1.52$   
227 Mg/m<sup>3</sup>. It can be observed from Fig. 8(a) that a decrease of  $\rho_{d-f}$  resulted in an increase of  
228 intruded mercury void ratio  $e_M$ , which was a little smaller than the corresponding global  $e_f$ .  
229 Fig. 8(b) presents typical bi-modal porosity of fine soil, with a delimiting diameter  $d = 0.65$   
230  $\mu\text{m}$  for micro- and macro-pores. For compacted soils, the micro-pores were generally within  
231 aggregates (intra-aggregate pores), while the macro-pores were between aggregates (inter-  
232 aggregate pores) (Delage et al. 1996). With the increase of  $\rho_{d-f}$ , the volume of inter-aggregate  
233 pores was observed to decrease, while that of intra-aggregate pores was almost constant,  
234 suggesting that the compaction process only affected the macro-pores, in agreement with  
235 Wang et al. (2014).

236

237 DISCUSSIONS

238 *Effect of microstructure of fine soil on SWRC at varying  $\rho_{d-f}$*

239 Fig. 7(a) shows that  $\rho_{d-f}$  affected the SWRC only for  $\psi < 715$  kPa. Correspondingly, Fig. 8(b)  
240 indicates that a decrease of  $\rho_{d-f}$  led to an increase of the volume of inter-aggregate pores ( $d >$   
241  $0.65 \mu\text{m}$ ) without modifying the volume of intra-aggregate pores ( $d < 0.65 \mu\text{m}$ ). The  
242 delimiting  $d = 0.65 \mu\text{m}$  could be associated with an equivalent matric suction based on  
243 Laplace's law under the assumption of cylindrical pore shape:

244 
$$\Psi = \frac{4T_s \cdot \cos \theta}{d} \quad (13)$$

245 where  $T_s$  is the surface tension of water, equal to  $0.073 \text{ N/m}$  at temperature of  $20 \text{ }^\circ\text{C}$ ;  $\theta$  is the  
246 contact angle between the liquid-air interface and the solid, taken equal to  $0^\circ$  in this study.

247 Substituting  $d = 0.65 \mu\text{m}$  into Eq. (13), the corresponding  $\psi$  was obtained:

248 
$$\psi = 449 \text{ kPa} \quad (14)$$

249 It was found that this value was close to the AEV of  $550 \text{ kPa}$  for the mixture at  $\rho_{d-f} = 1.82$   
250  $\text{Mg/m}^3$  (Fig. 7(c)), which was consistent with the findings of Zhang et al. (2018). This value  
251 was smaller than the threshold  $\psi = 715 \text{ kPa}$  in Fig. 7(a). This difference could be explained as  
252 follows: the fine soil with varying  $\rho_{d-f}$  values for MIP tests was compacted at a molding water  
253 content  $w_{\text{opt-f}} = 13.7\%$ , while the fine soil corresponding to the threshold point in Fig. 7(a) was  
254 subjected to a saturation process from the molding water content  $w_{\text{opt-f}} = 13.7\%$ , followed by a  
255 drying process. Li and Zhang (2009) studied the effect of wetting-drying history on bi-modal  
256 porosity of soil, and found that the drying process induced shrinkage of soil, leading to  
257 smaller intra-aggregate pores. Similarly, Sun and Cui (2020) investigated the soil-water  
258 retention curve of reconstituted silt, and reported that the drying process led to a shrinkage of

259 soil and a smaller value of diameter of voids. It could be thus inferred that the larger threshold  
260  $\psi = 715$  kPa in Fig. 7(a) was the consequence of pore size decrease due to soil shrinkage  
261 shown in Fig. 8(b). It could be thus deduced that in low suction range ( $\psi < 715$  kPa) the  
262 SWRC was governed by inter-aggregate pores, while in high suction range ( $\psi > 715$  kPa) the  
263 SWRC was governed by intra-aggregate pores. The similar phenomenon was reported by  
264 Salager et al. (2013) while studying the water retention property of clayey soil. They  
265 identified a threshold suction  $\psi = 5000$  kPa separating the inter-aggregate governing suction  
266 from intra-aggregate governing suction. With the decrease of  $\rho_{d-f}$ , the volume of inter-  
267 aggregate pores increased (Fig. 8(b)), resulting in an increase of water volume in inter-  
268 aggregate pores; thereby, an increase of  $w_f$  was observed (Fig. 7(a)). However, such decrease  
269 of  $\rho_{d-f}$  did not affect the volume of intra-aggregate pores (Fig. 8(b)); thus, a constant  $w_f$  was  
270 observed in high suction range (Fig. 7(a)). This also confirmed that the compaction effort  
271 greatly affected the inter-aggregate pores without touching the intra-aggregate pores (Delage  
272 et al. 1996).

273 Two categories of fine soil in the mixture at  $f_v = 35\%$  were reported by Su et al. (2020c,  
274 2021): a relatively dense fine soil in between coarse grains and a relatively loose fine soil in  
275 macro-pores among coarse grains. In other words, while compacted to  $\rho_{d-f} = 1.82$  Mg/m<sup>3</sup>, the  
276 dense fines had a higher  $\rho_{d-f}$  and the loose fines had a lower  $\rho_{d-f}$ , with the global  $\rho_{d-f}$  being 1.82  
277 Mg/m<sup>3</sup>. Thereby, a higher SWRC was expected for the dense fine soil in between coarse  
278 grains and a lower SWRC for the loose fine soil in macro-pores among coarse grains.  
279 However, as the SWRC at  $f_v = 35\%$  was the same as that at  $f_v = 0\%$  and  $20\%$  for  $\rho_{d-f} = 1.82$   
280 Mg/m<sup>3</sup> (Fig. 7(c)), it could be inferred that in spite of the inhomogeneous distribution of fine

281 soil in the mixture, the SWRC appeared to be controlled by the global dry density of fine soil  
282  $\rho_{d-f}$  only. Similarly, Zeng et al. (2020) studied the axial swelling property of compacted  
283 bentonite/claystone mixture, and found that this behavior was mainly dependent on the global  
284  $\rho_d$  of mixture, irrespective of its heterogeneity.

285

#### 286 *Comparison of present study at constant $\rho_{d-f}$ with previous study at constant $\rho_d$*

287 In present study, the different  $f_v = 0\%$ , 20% and 35% corresponded to the same SWRC under  
288 the constant  $\rho_{d-f} = 1.82 \text{ Mg/m}^3$  (Fig. 7(c)). On the contrary, Duong et al. (2014) investigated  
289 the hydraulic behavior of the upper part interlayer soil with two different  $f_v = 50.3\%$  and  
290 55.5% and a constant dry density of mixture  $\rho_d = 2.01 \text{ Mg/m}^3$  by infiltration column (Table 3).  
291 Fig. 9 shows that an increase of  $f_v$  from 50.3% to 55.5% led to a lower SWRC under the  
292 constant  $\rho_d = 2.01 \text{ Mg/m}^3$ . This phenomenon could be attributed to the effect of  $\rho_{d-f}$  on SWRC.  
293 Fig. 10 shows a constant  $e_m = 0.33$  (corresponding to  $\rho_d = 2.01 \text{ Mg/m}^3$ ) for  $f_v = 50.3\%$  and  
294 55.5% in Duong et al. (2014), which was different from that in Fig. 4 of present study. While  
295 increasing  $f_v$  from 50.3% to 55.5%, the  $e_f$  was increased from 1.01 to 1.28; thereby, a decrease  
296 of  $\rho_{d-f}$  from 1.33 to 1.17  $\text{Mg/m}^3$  (Table 3). As a result, the increase of  $f_v$  from 50.3% to 55.5%  
297 led to a lower SWRC (Fig. 9).

298

#### 299 *The maximum degrees of saturation $S_r$ of samples*

300 It appears from Fig. 7(c) and Fig. 9 that the SWRCs all started at a degree of saturation  $S_r$   
301 lower than 100%. Moreover, the values in Fig. 9 ( $S_r = 91\%$  and 78% for  $f_v = 50.3\%$  and 55.5%  
302 respectively) were smaller than the values around  $S_r = 95\%$  for varying  $f_v = 0\%$ , 20% and 35%

303 at  $\rho_{d-f} = 1.82 \text{ Mg/m}^3$  in Fig. 7(c), showing that the maximum  $S_r$  value reached during the  
304 saturation process decreased with the increase of  $f_v$ . Saba et al. (2014) worked on a  
305 compacted sand/bentonite mixture and found that the fine grains of larger sizes (e.g. the  
306 maximum  $d = 2 \text{ mm}$ ) was preferentially arranged with a large face side in the horizontal  
307 direction. In addition, due to the restriction of mould wall, more macro-pores were formed in  
308 the side part of sample, as evidenced by Zeng et al. (2020) on a compacted  
309 bentonite/claystone mixture. Such preferential presence of macro-pores in the side part was  
310 further confirmed on the mixture of fine soil and micro-ballast by Wang et al. (2018) and Qi et  
311 al. (2020a) through observation at X-ray  $\mu\text{CT}$ . As these macro-pores could not retain water  
312 under the effect of gravity, a maximum value of  $S_r = 95\%$  was obtained. With the increase of  $f_v$ ,  
313 the addition of coarse grains increased the mould wall restriction effect, generating thus more  
314 macro-pores. This led to a decrease of the initial  $S_r$  value of the SWRC with  $f_v$ . It is worth  
315 noting that Duong et al. (2014) adopted the ballast grains of maximum  $d = 60 \text{ mm}$  to prepare  
316 the sample of  $d = 300 \text{ mm}$  and  $h = 600 \text{ mm}$ , while in this study the micro-ballast of maximum  
317  $d = 20 \text{ mm}$  (Fig. 1) was adopted to prepare soil disk of  $d = 100 \text{ mm}$  and  $h = 100 \text{ mm}$ . Much  
318 larger mould wall restriction effect was thus expected in the case of Duong et al. (2014) due to  
319 the larger dimensions of the grains and the sample. Consequently, much lower maximum  
320 degrees of saturation ( $S_r = 91\%$  and  $78\%$  for  $f_v = 50.3\%$  and  $55.5\%$ ) were obtained in their  
321 case.

322

## 323 CONCLUSIONS

324 To investigate the role of fine soil on the soil-water retention property of fine/coarse soil



325 mixture, three  $f_v = 0\%$ , 20% and 35% at the same  $\rho_{d-f} = 1.82 \text{ Mg/m}^3$  and three  $\rho_{d-f} = 1.82, 1.67$   
326 and  $1.52 \text{ Mg/m}^3$  at the same  $f_v = 0\%$  were considered. A filter paper method was applied to  
327 measure the matric suction of soil mixture at different water contents. Mercury intrusion  
328 porosimetry tests were performed for microstructure observation of fine soil at varying  $\rho_{d-f}$ .  
329 The results obtained allowed the following conclusions to be drawn.

330 The drying SWRC of mixture was found to be only dependent on  $\rho_{d-f}$  and independent of  
331  $f_v$ . A typical bi-modal microstructure of fine soil was identified for varying  $\rho_{d-f}$  values,  
332 defining a micro-pore and a macro-pore populations. When expressed in terms of  $w_f$  with  $\psi$ ,  
333 the SWRC was found to be significantly affected by  $\rho_{d-f}$  for the matric suction  $\psi$  lower than  
334 715 kPa. By contrast, when  $\psi$  was higher than 715 kPa, the SWRC kept the same,  
335 independent of  $\rho_{d-f}$ . Interestingly, a delimiting pore diameter  $d = 0.65 \mu\text{m}$  was identified,  
336 separating micro-pores (or intra-aggregate pores) from macro-pores (or inter-aggregate pores).  
337 This delimiting diameter corresponded to a matric suction of 449 kPa, which was smaller than  
338 the threshold  $\psi = 715 \text{ kPa}$  due to the effect of volume change experienced in the course of soil  
339 wetting/drying from the remolded state ( $w_{\text{opt-f}} = 13.7\%$ ). Thus, the SWRC in low suction range  
340 ( $\psi < 715 \text{ kPa}$ ) was governed by macro-pores, while in high suction range ( $\psi > 715 \text{ kPa}$ ) by  
341 micro-pores. In addition, the SWRC of mixture appeared to be controlled by the global fine  
342 soil dry density  $\rho_{d-f}$  only. The effect of the possible heterogeneity of fine soil distribution  
343 inside the mixture seemed to be negligible.

344 When expressed in terms of  $S_r$  with  $\psi$ , the SWRC appeared to be significantly affected by  
345  $\rho_{d-f}$ , while unaffected by  $f_v$ . This helped better understand the observation of Duong et al.  
346 (2014) – the water retention capacity was decreased by the increase of  $f_v$ : in the study of

347 Duong et al. (2014), a constant  $\rho_d = 2.01 \text{ Mg/m}^3$  was adopted instead of a constant  $\rho_{d-f}$ . In this  
348 case, an increase of  $f_v$  resulted in a decrease of  $\rho_{d-f}$ , thereby a decrease of water retention  
349 capacity.

350 The initial  $S_r$  of the SWRC appeared to decrease with the increase of  $f_v$ . At  $f_v = 0\%$ , due to  
351 the effect of mould wall restriction, macro-pores were formed in the side part of sample. As  
352 these macro-pores could not retain water under the effect of gravity, the maximum value of  $S_r$   
353 = 95% smaller than 100% was obtained in the saturation process. With the increase of  $f_v$ , the  
354 addition of coarse grains increased the mould wall restriction effect, generating more macro-  
355 pores and thus lower maximum  $S_r$ . This phenomenon was expected to be more pronounced in  
356 the case of larger grains and larger sample dimensions.

357 From a practical point of view, these findings suggest that when investigating the water-  
358 retention property of interlayer soil, the scaled coarse grains at small size can be used as a  
359 substitute for real ballast grains at large size. With the increasing depth of interlayer soil, the  
360 decrease of  $f_v$  induced no changes on water-retention capacity of interlayer soil, provided that  
361 the  $\rho_{d-f}$  of fine soil kept constant. When the water retention property is determined, it can be  
362 incorporated in the mechanical models to better describe the variation of permanent strain of  
363 unsaturated interlayer soil under the effect of cyclic loadings. In addition, it is worth noting  
364 that to some extent these findings can be helpful in evaluating the effects of  $\rho_{d-f}$  and  $f_v$  on the  
365 water retention property of mixtures with varying types of coarse and fine soil.

366

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370

371

372 NOTATIONS

$e$	void ratio
$e_f$	void ratio of fine soil
$e_m$	void ratio of fine/coarse soil mixture
$f_v$	coarse grain content
$f_{v\text{-cha}}$	characteristic coarse grain content
$G_{s\text{-c}}$	specific gravity of coarse grains
$m_{a\text{-f}}$	mass of air in fine soil
$m_{w\text{-f}}$	mass of water in fine soil
$m_{s\text{-f}}$	mass of fine grains
$m_{s\text{-c}}$	mass of coarse grains
$\rho_d$	dry density of sample
$\rho_{d\text{-f}}$	dry density of fine soil
$\rho_{d\text{max-f}}$	maximum dry density of fine soil
$\rho_w$	water unit mass
$S_r$	degree of saturation
$V$	volume of fine/coarse soil mixture
$V_f$	volume of fine soil
$V_{v\text{-f}}$	volume of voids in fine soil
$V_{a\text{-f}}$	volume of air in fine soil
$V_{w\text{-f}}$	volume of water in fine soil
$V_{s\text{-f}}$	volume of fine grains
$V_c$	volume of coarse grains
$w_{\text{opt-f}}$	optimum water content of fine soil

$w_f$  water content of fine soil

$\psi$  matric suction

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Table 1. Constitution of fine soil

Soil classification	Commercial Soil	Mass proportion (%)	Range of grain size (mm)
Sand	C4	16.7	0.0009 – 0.50
	C10	20	0.0009 – 0.25
	HN34	3.3	0.063 - 0.50
	HN31	3.3	0.16 - 0.63
	HN0.4-0.8	6.7	0.25 - 1
	HN0.6-1.6	6.7	0.32 - 2
	HN1-2.5	13.3	0.32 – 3.20
Clay	Speswhite	23.3	0.0003 – 0.01
	Bentonite	6.7	0.001 – 0.01

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Table 2. As-compacted and saturated states of fine/coarse soil mixture

$f_v$ (%)	As-compacted state					Saturated state				
	$\rho_{d-f}$ (Mg/m <sup>3</sup> )	$e_f$	$w_{opt-f}$ (%)	$S_r$ (%)	$\rho_d$ (Mg/m <sup>3</sup> )	$\rho_{d-f}$ (Mg/m <sup>3</sup> )	$e_f$	Measured $w_f$ (%)	Measured $S_r$ (%)	$\rho_d$ (Mg/m <sup>3</sup> )
	1.82	0.47		78	1.82	1.81	0.48	17.2	95	1.81
0	1.67	0.60		61	1.67	1.65	0.62	22.0	95	1.65
	1.52	0.76	13.7	48	1.52	1.50	0.78	27.3	93	1.50
20	1.82	0.47		78	1.99	1.80	0.49	17.3	95	1.97
35	1.82	0.47		78	2.12	1.80	0.48	17.2	95	2.10

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Note:  $f_v$  represents the volumetric ratio of coarse grains to the fine/coarse soil mixture.  $\rho_{d-f}$ ,  $e_f$ ,  $w_f$ , and  $w_{opt-f}$  represent the dry density, void ratio, water content and optimum water content of fine soil, respectively.  $S_r$  represents the degree of saturation of fine soil, which is also the degree of saturation of the mixture.  $\rho_d$  represents the dry density of soil mixture.

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Table 3. Soil properties of Duong et al. (2014)

$f_v$ (%)	$\rho_d$ (Mg/m <sup>3</sup> )	$e_m$	$\rho_{d-f}$ (Mg/m <sup>3</sup> )	$e_f$
50.3	2.01	0.33	1.33	1.01
55.5			1.17	1.28

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Note:  $e_m$  represents the void ratio of soil mixture.

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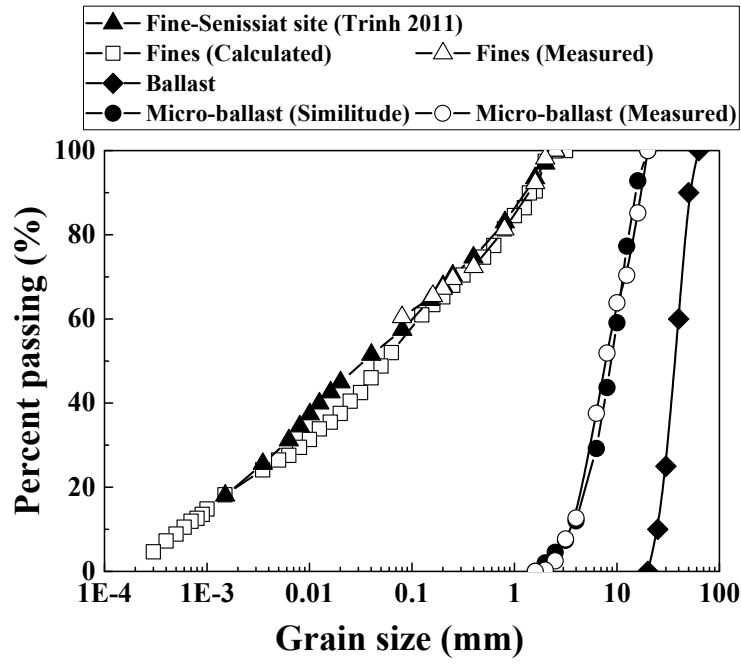
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Fig. 1. Grain size distribution curves of fine soil and micro-ballast (after Wang et al. 2017)

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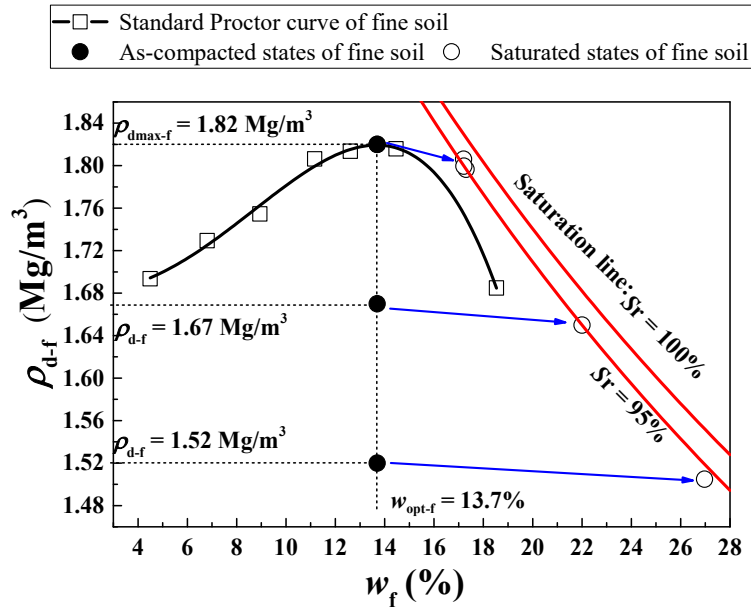
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537 Fig. 2. As-compacted and saturated states of fine soil with respect to its standard Proctor  
 538 compaction curve

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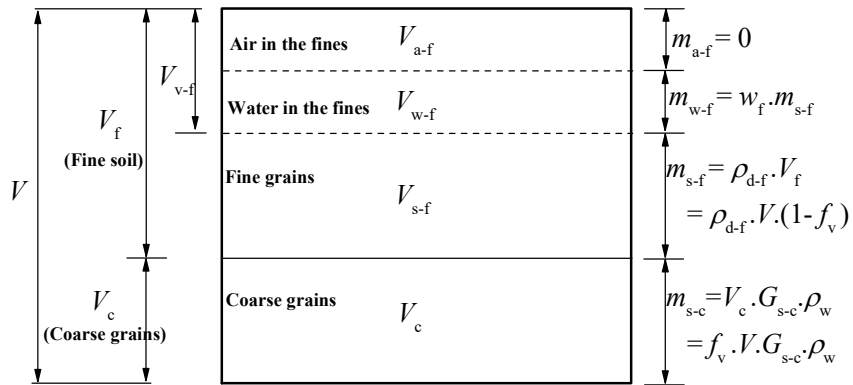
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Fig. 3. Constitution of fine/coarse soil mixture

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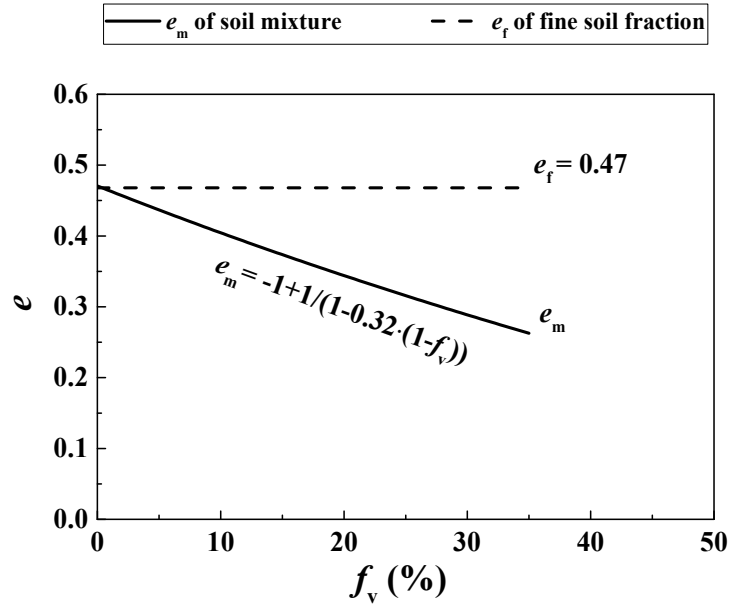
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576 Fig. 4. Variations of void ratios with  $f_v$  at a constant  $\rho_{d-f} = 1.82 \text{ Mg/m}^3$

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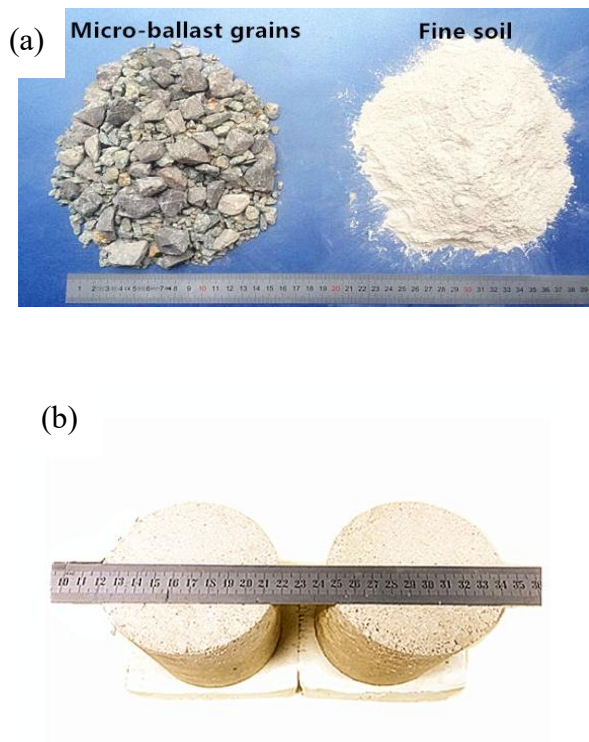
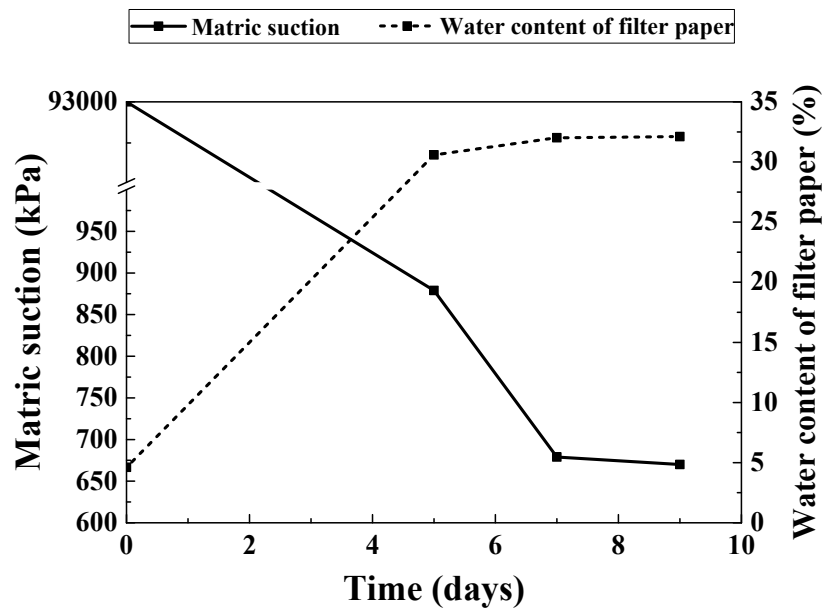


Fig. 5. (a) Preparation of fine soil and micro-ballast and (b) compaction of two soil disks



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Fig. 6. Determination of equilibration time by filter paper method

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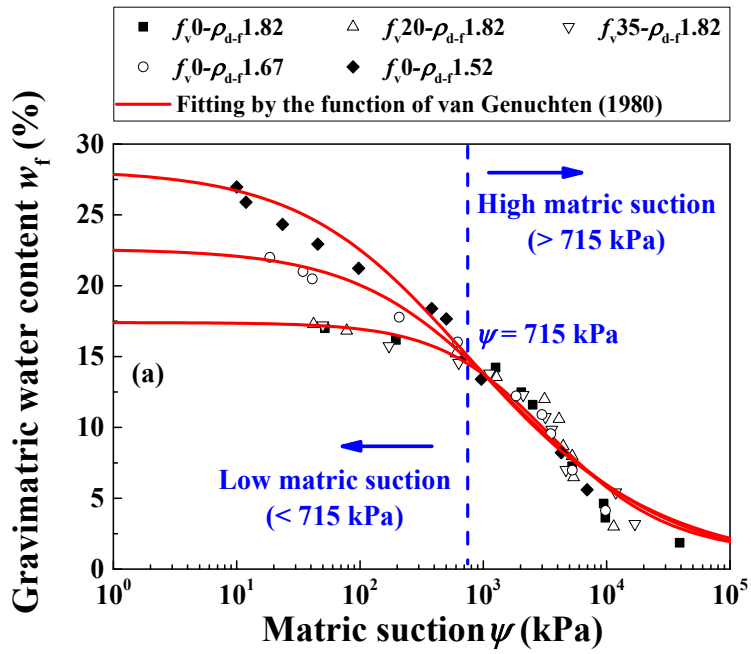
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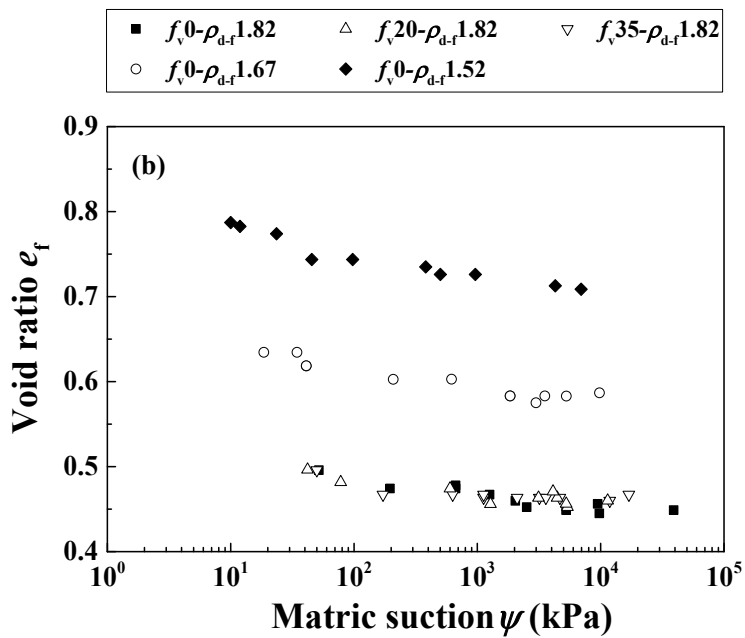
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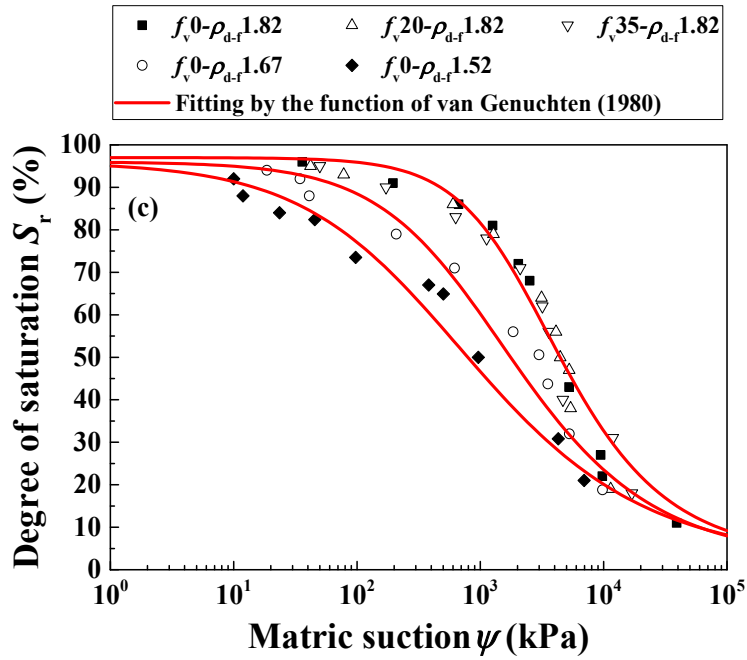


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643 Fig. 7. Drying soil-water retention curves and variations of void ratios of fine soil with matric  
 644 suction for varying  $f_v$  and  $\rho_{d-f}$  values: (a) gravimetric water content of fine soil versus matric  
 645 suction; (b) void ratio of fine soil versus matric suction; (c) degree of saturation versus matric  
 646 suction

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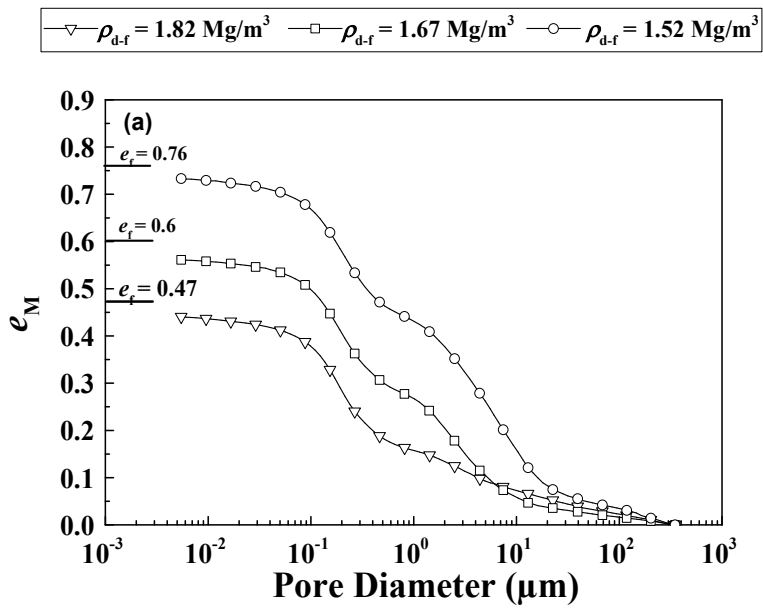
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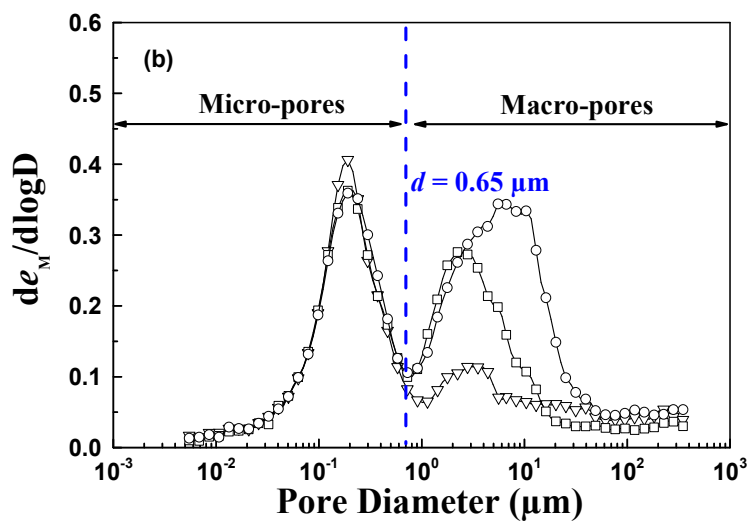
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662 Fig. 8. Pore size distributions of fine soil at  $f_v = 0\%$  and different  $\rho_{d-f}$  values: (a) cumulative

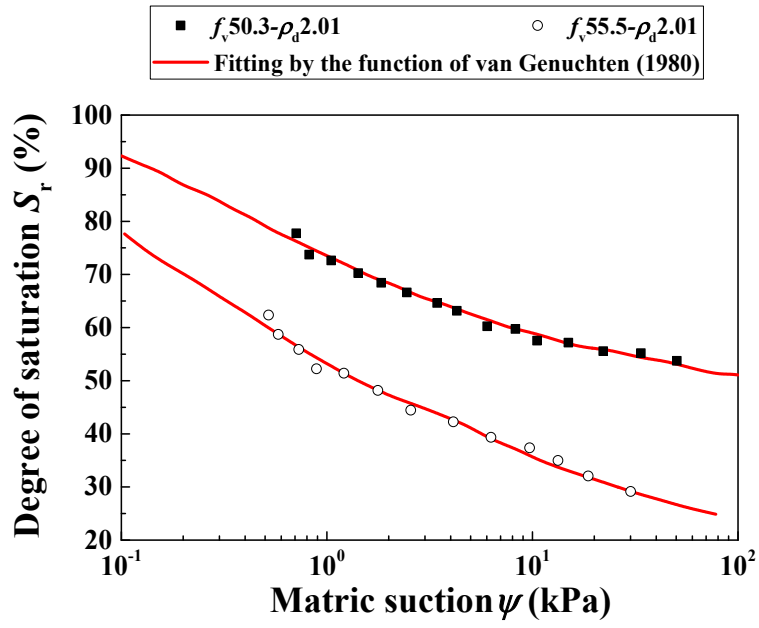
663 curves; (b) density function curves

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Fig. 9. Drying soil-water retention curves in the study of Duong et al. (2014)

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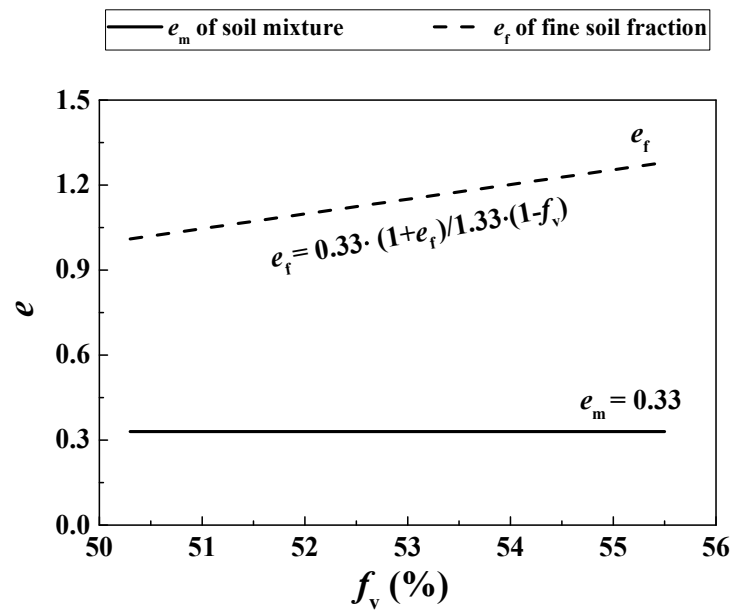
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Fig. 10. Variations of void ratio with  $f_v$  at  $\rho_d = 2.01 \text{ Mg/m}^3$  in Duong et al. (2014)

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