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Determining the soil-water retention curve using mercury intrusion porosimetry test in consideration of soil volume change

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22 **Abstract:**

23 There is close link between soil water retention curve and pore size distribution.
24 Theoretically, mercury intrusion porosimetry (MIP) test simulates a soil drying path
25 and the soil water retention curve $SWRC_{MIP}$ can be deduced from the MIP results.
26 However, $SWRC_{MIP}$ does not include the volume change effect, as opposed to the
27 [conventional SWRC which is directly determined by suction measurement or suction](#)
28 [control techniques](#). Therefore, for deformable soils, there is significant difference
29 between SWRC and $SWRC_{MIP}$. In this study, drying test was carried out on a
30 reconstituted silty soil, and the volume change, suction and pore size distribution (PSD)
31 were determined on samples at different water contents. [The change of the deduced](#)
32 [SWRC_{MIP} and its](#) relation with the conventional SWRC were analyzed, showing that the
33 volume change of soil is the main reason for the difference between the conventional
34 SWRC and the $SWRC_{MIP}$. Furthermore, based on the test results, a transformation
35 model was proposed for SWRC and $SWRC_{MIP}$, by taking [the soil state with no longer](#)
36 [volume change](#) as a reference. Comparison between the experimental and predicted
37 SWRCs showed that the proposed model can satisfactorily consider the influence of
38 soil volume change on its water retention property.

39

40 **Key words:** Soil-water retention curve; mercury intrusion porosimetry; transform; S_r -
41 $s-e$ plot; deformable soils

42

43

44

45 1. INTRODUCTION

46

47 A soil-water retention curve (SWRC) describes the amount of soil water (in terms of
48 gravimetric water content w or volumetric water content ϑ or degree of saturation S_r)
49 at a given suction s . This curve is essential in analysing water transfer in unsaturated
50 soils. This curve is also of paramount importance when modelling the coupled hydro-
51 mechanical behaviour of unsaturated soils (Wheeler, 1996; Sun et al., 2007; Nuth and
52 Laloui, 2008; Sun and Sun, 2012).

53

54 [Conventional SWRC](#) are usually investigated using either suction measurement or
55 suction control techniques. However, application of these techniques is usually time
56 consuming (Aubertin et al., 2003), especially for clayey soils. As volume change can
57 occur when changing suction, the [conventional](#) SWRC includes the effect of this
58 volume change. There are numerous SWRC models available in the literature, such as
59 [Brooks and Corey model \(Brooks and Corey, 1964\)](#), [van Genuchten model \(Van](#)
60 [Genuchten, 1980\)](#) and [Fredlund and Xing model \(Fredlund and Xing, 1994\)](#), to name
61 only a few. But these models do not account for the volume change effect. [Fredlund](#)
62 [\(2018\) proposed mathematical algorithms combining the shrinkage curve and the](#)
63 [SWRC, allowing for the separation of volume change effect from the effect of degree](#)
64 [of saturation.](#)

65

66 Based on the [pore size distribution \(PSD\)](#) obtained from mercury intrusion
67 porosimetry (MIP) test, the soil water retention curve in the drying path can be
68 obtained by applying Laplace's equation (Prapaharan et al., 1985; Delage et al., 1995;

69 Romero et al., 1999; Aung et al., 2001; Simms and Yanful, 2002, 2005; Muñoz-
70 Castelblanco et al., 2012; Hu et al., 2013). It is worth noting that the SWRC derived by
71 MIP result represents the SWRC under constant void ratio, which is termed as $SWRC_{MIP}$.
72 Accordingly, the derived degree of saturation and suction relationship is termed as
73 S_{rMIP-S} , the derived water content and suction relationship as w_{MIP-S} and the derived
74 void ratio and suction relationship as e_{MIP-S} .

75

76 Delage et al. (1995) analysed the PSDs and the SWRCs of various geomaterials, i.e., a
77 siliceous and a clayey sandstone, an overconsolidated clay and a compacted silt. A
78 good agreement was observed between $SWRC_{MIP}$ and SWRC for sandstones, while this
79 agreement was not observed for fine-grained soils. Muñoz-Castelblanco et al. (2012)
80 also reported a significant difference between $SWRC_{MIP}$ and SWRC for a loess. These
81 differences were discussed in the literature, but no conclusive explanations were given.
82 For example, Romero et al. (1999) thought that the differences could arise from the
83 different effects that water and dissolved salts produce on clay fabric compared to the
84 process in mercury intrusion. While Simms and Yanful (2002) mentioned the possible
85 pore trapping effect; that is, mercury intrusion only gives the entrance pore radius,
86 thus somewhat overestimating the porous volume associated with the estimated
87 diameter.

88

89 Normally, soil microstructure is sensitive to changes in water content, especially for
90 deformable soils. Delage et al. (1995) concluded that soil water retention properties
91 were conditioned by the microstructure changes. Muñoz-Castelblanco et al. (2012)
92 also showed the significant effects of changes in microstructure occurring at the level

93 of clay aggregations and the growing importance of the water adsorption in the clay
94 fraction at high suctions. The hydraulic and mechanical responses of soil take place
95 simultaneously when it is subjected to suction changes. That is to say, the total change
96 in degree of saturation is induced by both changes in suction and void ratio (Simms
97 and Yanful, 2005; Mašín, 2010; Romero et al., 2011; Sun and Sun, 2012; Hu et al., 2013;
98 Sun et al., 2014; Della Vecchia et al., 2015; Vaunat and Casini, 2017; Fredlund, 2018).
99 Therefore, it can be deduced that microstructural changes may be the reason for the
100 difference between the conventional SWRC and SWRC_{MIP}, especially for deformable
101 soils.

102

103 Recently, the coupled hydro-mechanical response due to suction changes was
104 accounted for by several authors (Gallipoli et al., 2003; Simms and Yanful, 2005; Sun
105 et al., 2007; Nuth and Laloui, 2008; Mašín, 2010; Hu et al., 2013; Tsiampousi et al.,
106 2013; Fredlund, 2018). Some of them proposed the approach based on the
107 quantitative information derived from MIP data. Simms and Yanful (2005) developed
108 a deformable pore-network model (DPNM) to predict the SWRC based on the
109 evolution of measured PSDs for a compacted clayey soil under isotropic loading and/or
110 desaturation. While in the DPNM model, pores are randomly mapped in space and
111 idealized as a network. Hu et al. (2013) formulated a hysteretic SWRC model to
112 account for the influence of deformation on the variation of saturation based on the
113 changes in PSD function for deformable soils. In their model, the PSD at a deformed
114 state can be obtained by horizontal shifting and vertical scaling of the PSD function
115 from a reference state - initial state with void ratio e_0 . The premise of the model is that
116 the overall shapes of the various PSDs can be considered to be insignificantly different

117 from each other. This is obviously too strong hypothesis for fine-grained soils as
118 illustrated by Sun and Cui (2018), *testifying that the changes in the aggregate porosity*
119 *were not negligible*. Romero et al. (2011) and Della Vecchia et al. (2015) proposed a
120 physically based conceptual framework for modelling the retention behaviour of
121 compacted clayey soils, which considers the PSD function evolution along hydraulic
122 and mechanical paths. *However, their framework contains a large number of*
123 *parameters to be calibrated, limiting its application.*

124

125 In this paper, drying tests were conducted on a reconstituted silty soil. The volume,
126 suction and PSD were determined on samples at different target water contents.
127 *Based on the obtained results, the difference between the conventional SWRC and*
128 *the SWRC_{MIP} derived from PSD was analysed*. Particular attention was paid to the
129 interrelationship between the SWRC_{MIP} families and the conventional SWRC.
130 Moreover, a transformation model was established between SWRC and SWRC_{MIP},
131 allowing the prediction of SWRC from the SWRC_{MIP} *families*. Through this study, the
132 water retention mechanism associated with the volume change of soil was clearly
133 evidenced.

134

135 **2. MATERIAL, TESTING PROGRAM AND CALCULATING METHOD**

136 *2.1 Material and testing program*

137

138 An aeolian Jossigny silt was used. The liquid limit w_l is 37%, the plastic limit w_p is 19%
139 and the shrinkage limit w_s is 12%. In the Casagrande diagram of plasticity, the soil is

140 located close to the A-line, belonging to low plasticity clay. The clay-size fraction of
141 Jossigny silt is 34 %.

142

143 Soil slurry, with a water content 1.5 times the liquid limit mixed with deionised water,
144 was firstly poured into several small containers. Afterwards, the samples in the
145 containers were air-dried to different target water contents, which were selected
146 around w_l , w_p and w_s . The air-drying intervals were taken short - every 30 minutes - to
147 avoid macro-cracks in samples. After each drying operation, the container was
148 covered for several hours for water homogenisation. By repeating these steps, dried
149 samples at different water contents were obtained.

150

151 After reaching the respective target water content, the sample was divided into 4
152 pieces. One for water content measurement. A second for the volume measurement
153 based on the principle of buoyancy (Delage et al., 2007; Zeng et al., 2017). A third was
154 freeze-dried for MIP investigation (Delage and Lefebvre, 1984; Delage et al., 1996)
155 using an Autopore IV 9500 mercury intrusion porosimeter (Micrometrics), which
156 operated from 3.4 kPa (363.6 μm pore) to 227.5 MPa pressure (5.5 nm pore). The last
157 one was used for suction measurement using a chilled-mirror dew-point
158 psychrometer (WP4C Dewpoint PotentiaMeter). To measure low suction of soil, a test
159 apparatus consisting of an odometer cell with 70 mm inner diameter, a porous
160 ceramic disc with an air-entry pressure of 50 kPa and a graduated tube with 6 mm
161 inner diameter connected to a water tank was used. More details about this apparatus
162 can be found in Feia et al. (2014) and Sun et al. (2017). Table 1 shows the indexes of
163 samples dried to different target states.

164

165 2.2 Calculating method

166

167 The mercury intrusion process is assimilated to a drying process, in which a non-
168 wetting liquid is penetrating into a porous medium full of wetting fluid (Delage et al.,
169 1996; Muñoz-Castelblanco et al., 2012).

170

171 The pore diameter can be deduced from the mercury pressure, as follows (Romero et
172 al., 1999):

$$173 \quad d = -\frac{4T_m \cos \theta_m}{p} \quad (1)$$

174 where T_m is the surface tension of mercury (0.485N/m); d is the pore entrance
175 diameter (μm); θ_m is the mercury-soil contact angle (taken equal to 130° in this study);
176 p is the external applied intrusion pressure ($\times 10^6 \text{ N/m}^2$).

177

178 The cumulative intrusion void ratio (e_{MIP}) is computed as follows:

$$179 \quad e_{MIP} = \frac{V_m}{V_s} = \frac{V_m}{m_s} \cdot G_s \cdot \rho_w \quad (2)$$

180 where V_s is the volume of soil; V_m is the volume of intruded mercury; m_s is the mass of
181 soil; G_s is the specific gravity; ρ_w is the water unit mass.

182

183 From the derivative of the cumulative intrusion curve, the pore size density function
184 is obtained:

$$185 \quad f = -\frac{\delta(e_{MIP})}{\delta(\lg d)} \quad (3)$$

186 Based on the PSD obtained from MIP test, the $SWRC_{MIP}$ can be determined
 187 (Prapaharan et al., 1985; Romero et al., 1999; Aung et al., 2001; Simms and Yanful,
 188 2002). The relationship between matric suction ($u_a - u_w$) and mercury intrusion
 189 pressure p can be deduced from Eq. (4):

$$190 \quad u_a - u_w = -\frac{T_w \cos \theta_w}{T_m \cos \theta_m} p \quad (4)$$

191 where T_w is the surface tension of water (0.073N/m); θ_w is the water-soil contact angle
 192 (taken equal to 0° in this study).

193

194 Romero et al. (1999) suggested that the degree of saturation S_r and water content w
 195 corresponding to the equivalent applied pressure should consider the hygroscopic
 196 water content related to the strongly attracted adsorbed water to the mineral surface
 197 and the equivalent residual water content corresponding to the non-intruded porosity.

198 They can be expressed as follows:

$$199 \quad S_r = (1 - S_{rm}) + \frac{w_{res}}{w_{sat}} S_{rm} \quad (5)$$

$$200 \quad w = (1 - S_{rm})(w_{sat} - w_{res}) + w_{res} \quad (6)$$

201 where w_{sat} stands for the saturated gravimetric water content; S_{rm} stands for the non-
 202 wetting mercury degree of saturation; w_{res} is the equivalent residual water content
 203 corresponding to the maximum mercury intrusion pressure that the mercury
 204 porosimeter can reach.

205

206 S_{rm} and w_{res} can be calculated as follows:

207
$$S_{rm} = \frac{V_m}{V_{mmax}} = \frac{e_{MIP}}{e_{MIPmax}} \quad (7)$$

208
$$w_{res} = \frac{m_{wres}}{m_s} = \frac{\rho_w (V_v - V_{mmax})}{m_s} = \frac{e - e_{MIPmax}}{G_s} \quad (8)$$

209

210 Finally,

211
$$w_{MIP} = \frac{e}{G_s} \left(1 - \frac{e_{MIP}}{e}\right) \quad (9)$$

212
$$S_{rMIP} = 1 - \frac{e_{MIP}}{e} \quad (10)$$

213 where e_{MIP} is the mercury intruded void ratio; e_{MIPmax} is the maximum mercury
 214 intruded void ratio; e is the void ratio corresponding to different target drying states;
 215 S_{rMIP} is the degree of saturation obtained from MIP test; w_{MIP} is the water content
 216 derived from MIP test.

217

218 Based on the above measurements and calculations, the void ratios and degrees of
 219 saturation of soil samples at different target water contents were calculated, and the
 220 conventional SWRC and the SWRC_{MIP} derived from PSD were also determined.

221

222 3 EXPERIMENTAL RESULTS

223

224 3.1 Shrinkage behaviour and conventional SWRC

225

226 Figure 1 shows the results from the drying tests on the reconstituted Jossigny silt
 227 prepared at initial water content $w_i = 1.5 w_l$. Figs. 1 (a) and (c) depict the shrinkage

228 behaviour, e.g., the changes of void ratio with water content ($e - w$), and degree of
229 saturation with water content ($S_r - w$), respectively. Fig. 1(b) depicts the volume
230 change behaviour under the effect of suction, e.g., void ratio with suction ($e-s$). Figs.
231 1(d) shows the conventional S_r -SWRC of Jossigny silt.

232

233 The $e-w$ relationship obeys a typical shrinkage characteristic curve of soils, as shown
234 in Fig. 1(a), which includes normal shrinkage, residual shrinkage and no shrinkage
235 stages. The experimental results firstly started from the stage of normal shrinkage,
236 which coincided with the dashed full saturation line, and the samples kept fully
237 saturated, as shown in Fig. 1(c) for the S_r-w relationship. Afterwards, when water
238 content reached w_{ae} , the slope of the shrinkage curve decreased, and the residual
239 shrinkage began. From the air entry point, the degree of saturation began to decline,
240 as it can be seen from the S_r-w curve in Fig. 1(c). From the S_r -SWRC in Fig. 1(d), the
241 corresponding suction at w_{ae} could be determined of about 180 kPa. When suction s
242 exceeded the air entry value, S_r -SWRC changed from the saturated to the unsaturated
243 domain. After the water content reached the shrinkage limit w_s , the void ratio
244 remained unchanged with further drying, as shown in Fig. 1(a) and (b), starting the no
245 shrinkage stage.

246

247 *3.2 Microstructure investigation*

248 Figure 2 presents the pore size distribution of Jossigny silt during drying. Fig. 2(a) is the
249 cumulative intruded curves. It can be observed that e_{MIP} decreased in the beginning
250 and became almost unchanged after the water content reached the shrinkage limit.

251 The pore size density functions shown in Fig. 2(b) are the derivative of the cumulative

252 intrusion curves of No. (1)-(6) in Fig. 2(a), plotted in terms of $\delta e_{MIP}/\delta \lg d$ as a function
253 of pore entrance diameter d . From Fig. 2(b), all the PSD curves present a typical
254 unimodal pattern (Fiès and Bruand, 1998). When $w > w_s$, significant pore refinement
255 occurred upon drying. However, with further drying, the curves began shifting to
256 larger diameter. Sun and Cui (2018) explained this phenomenon by the development
257 of possible micro-fissures of the clay part. Moreover, when $w < w_s$, the shift trend of
258 PSD curves ceased. Accordingly, the void ratio at this time almost remained
259 unchanged and reached the minimum value, e_{min} .

260

261 3.3 SWRC_{MIP} derived from MIP investigations

262

263 Figure 3 presents the relationship between degree of saturation and suction. The plots
264 star (★) show the conventional SWRC results determined directly by suction
265 measurement, the others corresponding to the samples with different target water
266 contents. It can be noticed that the SWRC_{MIP} significantly differs from the conventional
267 SWRC.

268

269 SWRC_{MIP} can be divided into three segments on a semi-logarithmic plot, that is, a
270 boundary effect zone, a transition zone and a residual zone:

271

272 (i) In the boundary effect zone, S_{rMIP} was almost equal to 100%, where almost no
273 mercury intrusion took place.

274

275 (ii) In the transition zone, sudden drops occurred because of the intrusion of the
276 dominant pore diameters. It was also observed that the S_{rMIP-s} curve shifted towards
277 the S_r-s curve at the beginning, however in the residual shrinkage stage, the S_{rMIP-s}
278 curve began to shift backwards due to the possible presence of drying-induced
279 internal micro-fissures occurred in the clay fractions and in the interface between silt
280 grain and clay particles, more details can be found in Sun and Cui (2018).

281

282 (iii) In the residual zone, the S_{rMIP-s} curves showed a shifting-up with further drying,
283 and got close to the S_r-s curve. The S_{rMIP} represents the volume fraction of the non-
284 intruded space and can be expressed as $S_{rMIP}=(e-e_{MIP})/e$ in Eq.(10). The shifting-up of
285 the S_{rMIP-s} curve in the residual zone was the result of the changes of non-intruded
286 void ratio ($e-e_{MIP}$). The changes of S_{rMIP-s} curves were also related to the
287 microstructure change during drying. Moreover, it could be deduced according to the
288 shifting-up trend that the S_{rMIP-s} curve of sample with the smallest void ratio ($e=e_{min}$)
289 almost reached the S_r-s curve. At this time, the $SWRC_{MIP}$ from MIP test is the same as
290 the conventional SWRC, in agreement with the observation of Delage et al. (1995).

291

292 3.4 S_r-s & S_{rMIP-s} relationships

293

294 Figure 4 shows the sketch of S_r-s relationship (solid line from A to B) and S_{rMIP-s}
295 relationship (dash line from A to C). Point A marks the coordinate (S_{ri}, s_i) with void ratio
296 e_i and water content w_i , and Point B (S_{ri+1}, s_{i+1}) with void ratio e_{i+1} and water content
297 w_{i+1} . From A to B, when the suction increased from s_i to s_{i+1} , the degree of saturation

298 decreased from S_{ri} to S_{ri+1} . The absolute change value in degree of saturation when
299 suction increased from s_i to s_{i+1} is $|dS_r| = |S_{ri+1} - S_{ri}|$.

300

301 The change in degree of saturation at constant void ratio e_i when suction increased
302 from s_i to s_{i+1} followed the S_{rMIP-s} curve from A to C, and could be described as $|dS_r(s)$
303 $e = e_i|$, which could be obtained by the S_{rMIP-s} curve at constant void ratio e_i , i.e., $dS_r(s)$
304 $e = e_i = dS_{rMIP e = e_i}$.

305

306 Therefore, the change in degree of saturation caused by void ratio change under a
307 constant suction ($s = s_i$) could be determined as $|dS_r(e)_{s = s_i}|$, and it could be calculated
308 by $|dS_r(e)_{s = s_i}| = |dS_r(s)_{e = e_i}| - |dS_r|$.

309

310 From the drying tests, the relationships between degree of saturation and suction (S_r -
311 s) and between void ratio and suction (e - s) were obtained. Combined with the MIP
312 results, the changes of $|dS_r(e)| / |dS_r(s)|$ and $|dS_r| / |dS_r(s)|$ with suction were
313 determined, as shown in Fig. 5. It can be seen from the changes in $|dS_r(e)| / |dS_r(s)|$
314 (dash line) that with increasing suction, the value changes from 1 to 0 gradually,
315 indicating that when suction is low, the reduction of degree of saturation is mainly
316 caused by the changes of void ratio. By contrast, when the water content reached the
317 shrinkage limit, the void ratio kept almost unchanged, and the contribution of void
318 ratio to the change of degree of saturation $|dS_r|$ vanished. Conversely, with
319 increasing suction, the value $|dS_r| / |dS_r(s)|$ changed from 0 to 1 gradually, indicating
320 that when suction was low, the degree of saturation almost kept 100%. At higher

321 suction, the void ratio tended to become unchanged and the change of degree of
322 saturation was totally caused by suction change, that is, $|dS_r| = |dS_r(s)|$.

323

324 For non-deformable soils, the S_{rMIP-s} curves are consistent with the S_r-s curve (Delage
325 et al., 1995), the value $|dS_r| / |dS_r(s)|$ can be approximately taken equal to 1. On
326 the contrary, for deformable soils, the shapes of S_{rMIP-s} curve and S_r-s curve differ
327 significantly and the value $|dS_r| / |dS_r(s)|$ changes from 0 to 1 gradually with the
328 increase of suction.

329

330 *3.5 S_r-e-s & $S_{rMIP-e-s}$ three-dimension surfaces*

331

332 In order to better visualise the effect of void ratio on SWRC, two diagrams are
333 proposed: one is the S_r-e-s three-dimension diagram and another is the $S_{rMIP-e-s}$ three-
334 dimension diagram, as shown in Fig. 6. The conventional SWRC is located on the S_r-e-
335 s 3D surface with void ratio changing, while the $SWRC_{MIP}$ with constant void ratio is
336 located on the $S_{rMIP-e-s}$ 3D surface.

337

338 The F-X equation (Fredlund and Xing, 1994), with the applied correction factor for zero
339 water content at 10^6 kPa of suction, was adopted in building the three-dimension
340 surface for further investigation, as shown in equation (11). However, it is worth
341 noting that other suitable models can be also used provided that they allow the
342 description of the data over the full suction range.

$$343 \quad S_r = \left(1 - \frac{\ln(1 + s / s_{res})}{\ln(1 + 10^6 / s_{res})} \right) \left[\frac{1}{\ln(2.718 + (s / a)^n)} \right]^m \quad (11)$$

344 where s is suction; s_{res} is the suction corresponding to the equivalent residual water
345 content; parameters a , n , and m affect the shape of the curve.

346

347 The $S_{rMIP}-e-s$ three-dimension surface can be obtained by the following method: first,
348 the $S_{rMIP}-s$ curve at constant void ratio $e = e_i$ was derived from the PSD curve obtained
349 from MIP test. Second, each $S_{rMIP}-s$ ($e = e_i$) relationship was expressed through the F-
350 X SWRC model, namely formula (11), each curve having its corresponding three
351 parameters $a(e_i)$, $n(e_i)$, $m(e_i)$. Thus, the function of the parameter changing with the
352 void ratio could be determined. Finally, the $S_{rMIP}-e-s$ three-dimension surface was built.

353

354 From the $w-s$ relationship matched by the F-X SWRC model and the equation $e S_r = G_s$
355 w , the S_r-e-s surface was obtained. After that, several SWRCs at constant void ratio
356 were obtained through the F-X SWRC model.

357

358 Figure 7 shows the projection of drying test results in $S_r(S_{rMIP})-e-s$ diagram, the thick
359 solid curve is the conventional SWRC in drying path obtained in this study, and the
360 thick dash curve is the SWRC projection on the $S_{rMIP}-e-s$ surface. The projections of the
361 two thick curves onto $S_r(S_{rMIP})-o-s$, $S_r(S_{rMIP})-o-e$, and $e-o-s$ surfaces are also shown. It
362 is worth noting that, in S_r-o-s coordinate, the projection of the thick solid curve is
363 conventional S_r-s relationship in drying path, with void ratio changing following the
364 projection in $e-o-s$ coordinate.

365

366 The projection of drying test results on $e-o-s$ coordinate is shown in Fig.1(b). It can be
367 observed that the void ratio decreased with increasing suction. Figure 8 shows the

368 sketch of e - s relationship corresponding to the drying test result. It can be seen that
369 each suction s_i had a corresponding relationship with the void ratio e_i . Combing the
370 test results in Fig.1(b) and the sketch of e - s relationship in Fig.8, it is observed that the
371 water content reached the shrinkage limit at $w_s=12\%$, corresponding to suction s_s
372 $=1500$ kPa and void ratio is $e_s=0.52$. Under further drying, the void ratio remained
373 almost unchanged. When suction reached 10^6 kPa, the void ratio reached the
374 minimum value: $e=e_{\min}$ (about 0.49).

375

376 Figure 9 shows the projection of the test results on S_r (S_{rMIP})- o - s coordinate. The plots
377 star (\star) show the conventional SWRC results obtained in this study. Correspondingly,
378 the thick solid curve represents the conventional S_r - s relationship. The dash dot curve
379 represents the S_{rMIP} - s ($e=e_i$) curve, which can be regarded as one of the MIP test results
380 in the study, or as one of the curves selected from the S_{rMIP} - e - s surface at any void
381 ratio e_i . It is to be mentioned that the corresponding S_{rMIP} - s ($e=e_{\min}$) curve, represented
382 by a dash curve, was obtained from the established S_{rMIP} - e - s three-dimension surface
383 at $e=e_{\min}$.

384

385 As observed previously, the S_{rMIP} - s curve moved rightwards with void ratio decreasing
386 under the premise that there are no micro-fissures developed during drying. After the
387 water content reached the shrinkage limit, the void ratio approached the minimum
388 value e_{\min} gradually. It can be reasonably assumed that the S_r - s ($e=e_{\min}$) curve in S_r - e - s
389 3D surface, the S_{rMIP} - s ($e=e_{\min}$) relationship in S_{rMIP} - e - s 3D surface and the projection
390 of the conventional S_r -SWRC on S_r - o - s coordinate coincide in the high suction range.
391 This is testified in Fig. 9. Therefore, the S_{rMIP} - s ($e=e_{\min}$) curve can be taken as the

392 reference curve, which connects the two surfaces, $S_{rMIP-e-s}$ and S_r-e-s .

393

394 4. TRANSFORMATION FROM S_{rMIP-s} CURVES TO CONVENTIONAL S_r-s RELATIONSHIP

395

396 From above analysis, it is noticed that a $SWRC_{MIP}$ corresponds to a fixed pore structure,

397 however, a real SWRC is affected by soil volume changes. It can also be deduced that

398 S_{rMIP-s} curves would move continuously toward the S_r-s curve under the condition of

399 no micro-fissures occurring, i.e., theoretically, a SWRC is the combination of a family

400 of $SWRC_{MIPs}$ at different suctions. Based on the finding that the S_{rMIP-s} ($e=e_{min}$) curve

401 can be taken as a reference curve, connecting the $S_{rMIP-e-s}$ and the S_r-e-s surfaces, a

402 transformation model was established to predict the SWRC from the $SWRC_{MIP}$ families,

403 accounting for the effect of soil volume change on soil water retention property.

404

405 4.1 Transformation model

406

407 As the conventional S_r-SWRC coincides with the S_{rMIP-s} curve at $e=e_{min}$, as shown in Fig.

408 9, namely $S_r(s=s_i, e=e_i) = S_{rMIP}(s=s_i, e=e_{min})$, the difference between S_r on the S_r-e-s

409 surface and S_{rMIP} on the $S_{rMIP-e-s}$ surface when $s=s_i$, combined with Eq.(10), can be

410 expressed as:

$$411 \quad S_r(s=s_i, e=e_i) - S_{rMIP}(s=s_i, e=e_i) \quad (13)$$

$$412 \quad = S_{rMIP}(s=s_i, e=e_{min}) - S_{rMIP}(s=s_i, e=e_i)$$

$$413 \quad = 1 - \frac{e_{MIP}(s=s_i, e=e_{min})}{e_{min}} - 1 + \frac{e_{MIP}(s=s_i, e=e_i)}{e_i}$$

414
$$= \frac{e_{MIP}(s=s_i, e=e_i)}{e_i} - \frac{e_{MIP}(s=s_i, e=e_{min})}{e_{min}}$$

415 where $e_{MIP}(s=s_i, e=e_i)$ represents the amount of mercury intrusion for soil sample with
 416 void ratio equals e_i , and with pore diameter $d \geq d_i$ and corresponding $s \leq s_i$. Figure 10
 417 shows the e_{MIP} - s relationship, the solid curve represents the condition of $e=e_i$, $e_{MIP}(s=s_i,$
 418 $e=e_i)$ is namely the mercury intrusion porosity ratio when $e=e_i$, $s \leq s_i$ and $d \geq d_i$, and the
 419 dash curve represents the condition of $e=e_{min}$, $e_{MIP}(s=s_i, e=e_{min})$ is namely the mercury
 420 intrusion porosity ratio when $e=e_{min}$, $s \leq s_i$ and $d \geq d_i$.

421

422 Figure 11 shows the pore size distribution diagram, which shows the change of PSD
 423 function when e decreases from e_i to e_{min} . $e_{MIP}(s=s_i, e=e_i)$ and $e_{MIP}(s=s_i, e=e_{min})$ can be
 424 expressed as:

425
$$\begin{aligned} e_{MIP}(s=s_i, e=e_i) &= A_{d \geq d_i}(e=e_i) \cdot e_i \\ e_{MIP}(s=s_i, e=e_{min}) &= A_{d \geq d_i}(e=e_{min}) \cdot e_{min} \end{aligned} \quad (14)$$

426 where $A_{d \geq d_i}(e=e_i)$ represents the porosity proportion of $d \geq d_i$, which is the proportion
 427 of the shaded area with cross grain on the PSD curve of $e=e_i$, and $A_{d \geq d_i}(e=e_{min})$
 428 represents the porosity proportion of $d \geq d_i$, which is the proportion of the shaded
 429 area with vertical stripe on the PSD curve of $e=e_{min}$. When the void ratio decreases to
 430 e_{i+n} , the pore entrance diameter decreases to d_{i+n} , and the corresponding suction
 431 increases to s_{i+n} , and $e_{MIP}(s=s_{i+n}, e=e_{i+n})$ and $e_{MIP}(s=s_{i+n}, e=e_{min})$ can be obtained by the
 432 above method, combined with Fig.11.

433

434 Therefore, the difference $(S_r - S_{rMIP})$ at $s=s_i$, in Eq.(13), can be further expressed as:

435
$$S_r (s = s_i, e = e_i) - S_{rMIP} (s = s_i, e = e_i) = A_{d \geq d_i} (e = e_i) - A_{d \geq d_i} (e = e_{min}) \quad (15)$$

436 It appears from Fig. 6 that the variation between S_r and S_{rMIP} , i.e., $(S_r - S_{rMIP})$ at $s=s_i$,
 437 which is simplified as Y_i , represents the distance between Point A on S_r - e - s 3D surface
 438 and Point A_M on S_{rMIP} - e - s 3D surface. When $s=s_{i+1}$, the variation between S_r and S_{rMIP} at
 439 $s= s_{i+1}$, simplified as Y_{i+1} , represents the distance between Point B on S_r - e - s 3D surface
 440 and Point B_M on S_{rMIP} - e - s 3D surface.

441

442 The variation between Y_{i+1} and Y_i , e.g., ΔY represents the change of the value $(S_r -$
 443 $S_{rMIP})$ from point $s=s_i$ to point $s=s_{i+1}$. It can be expressed as:

444
$$\Delta Y = Y_{i+1} - Y_i \quad (16)$$

445
$$= (S_r - S_{rMIP})_{(s=s_{i+1}, e=e_{i+1})} - (S_r - S_{rMIP})_{(s=s_i, e=e_i)}$$

446
$$= (A_{s \leq s_{i+1}} (e = e_{i+1}) - A_{s \leq s_{i+1}} (e = e_{min})) - (A_{s \leq s_i} (e = e_i) - A_{s \leq s_i} (e = e_{min}))$$

447 To summarize, according to Eq.(16), ΔY can be obtained by the following steps:

448

449 First, the S_{rMIP} - e - s surface can be obtained from at least three MIP experiment results
 450 of samples with different void ratios. Second, the S_{rMIP} - s relationship for any void ratio
 451 e_i and the minimum void ratio e_{min} can be obtained from the deduced S_{rMIP} - e - s surface.

452 Then, the relationships of e_{MIP} - s at $e=e_i$ and $e=e_{min}$ can be back deduced by the

453 obtained S_{rMIP} - s relationship. The proportional "A" value in Eq.(16) can be obtained

454 from the e_{MIP} - s curves of $e=e_i$ and $e=e_{min}$ or their pore size distribution curves. Finally,

455 the variation Y_i between S_r and S_{rMIP} at $s=s_i$ in Eq.(15) can be obtained. Given the

456 suction increasing step, and the suction reaches $s=s_{i+1}$, by repeating the above

457 procedures, Y_{i+1} between S_r and S_{rMIP} at $s= s_{i+1}$ can also be obtained.

458

459 Simultaneously, from Fig. 6, ΔY can also be expressed **geometrically** as:

$$460 \quad \Delta Y = (S_{r_{i+1}} - S_{r_{MIP_{i+1}}}) - (S_{r_i} - S_{r_{MIP_i}}) = S_{r_{i+1}} - S_{r_i} - (S_{r_{MIP_{i+1}}} - S_{r_{MIP_i}}) \quad (17)$$

461 where $S_{r_{MIP_{i+1}}} - S_{r_{MIP_i}} = \Delta S_{r_{MIP(i+1)-(i)}}$ corresponds to the variation of degree of saturation

462 on the $S_{r_{MIP}}-e-s$ three-dimension surface, and includes two parts: one caused by

463 changes of suction and the other caused by changes of void ratio, which can be

464 expressed by the following integral:

$$465 \quad dS_{r_{MIP}}(s_i \rightarrow s_{i+1}, e_i \rightarrow e_{i+1}) = \frac{\partial S_{r_{MIP}}}{\partial e} de + \frac{\partial S_{r_{MIP}}}{\partial s} ds \quad (18)$$

466

467 Finally, using the values of the degree of saturation and water content at suction s_i ,

468 combining Eqs. (16)-(18), the $S_{r_{i+1}}$ and w_{i+1} at s_{i+1} can be deduced, as follows:

$$469 \quad S_{r_{i+1}} = Y_{i+1} - Y_i + S_{r_i} + \Delta S_{r_{MIP(i+1)-(i)}} \quad (19)$$

$$470 \quad w_{i+1} = \frac{e_{i+1} \cdot S_{r_{i+1}}}{G_s} \quad (20)$$

471 Subsequently, the conventional SWRC is predicted from the $SWRC_{MIP}$ families

472 according to the transformation model.

473

474 In summary, in the transformation model, the S_r-e-s three-dimension surface where

475 conventional SWRC is located and $S_{r_{MIP}}-e-s$ three-dimension surface where the

476 $SWRC_{MIP}$ with void ratio unchanging is located were defined. Based on the finding that

477 the S_r-s ($e=e_{min}$) curve, the $S_{r_{MIP}}-s$ ($e=e_{min}$) relationship and the conventional S_r -SWRC

478 coincide at high suction, the soil state with no longer volume change is taken as a

479 reference, that is, $S_{r_{MIP}}-s$ ($e=e_{min}$) curve, which connects the two surfaces, $S_{r_{MIP}}-e-s$ and

480 S_r - e - s . After that, based on the evolution of PSD curves due to the porosity changes,
481 and the variation of S_{rMIP} deduced from the S_{rMIP} - e - s three-dimension surface, the
482 degree of saturation can be determined. Finally, the conventional S_r -SWRC is obtained.
483 It is worth noting that the transformation model introduces no more parameters than
484 those in the F-X model.

485

486 The transformation model is suitable for saturated samples undergoing drying test, no
487 matter what stress histories they have before saturation. Upon wetting, the S_{rMIP} - s
488 curve would shift leftwards due to soil swelling (increase of porosity). Theoretically,
489 the same philosophy of analysis can be applied. This is to be verified later when
490 experimental data are available.

491

492 *4.2 Application of the transformation model*

493

494 Applying the proposed approach, the transformation was completed from the
495 $SWRC_{MIP}$ families to the conventional SWRC. Fig. 12 shows the comparison between
496 the experimental and predicted SWRC from the $SWRC_{MIP}$ families of reconstituted
497 Jossigny silt in drying, including S_r - s relationship in Fig. 12(a) and w - s relationship in
498 Fig. 12(b).

499

500 According to the shrinkage curve of reconstituted Jossigny silt, the minimum void ratio
501 e_{min} is 0.49. In Fig. 12(a), the marks of “★” shows the SWRC test results; the solid curve
502 represents the predicted S_r - s relationship curve by the transformation model; the
503 marks “□” represents the S_{rMIP} - s relationship, which is obtained as follows: given the

504 suction increasing step, the corresponding void ratio is obtained by the e - s curve, and
505 each point in e - s curve corresponds to a point on the obtained S_{rMIP} - e - s surface. Then,
506 these points are projected on the S_r (S_{rMIP})- o - s coordinate, and the S_{rMIP} - s relationship
507 can be obtained.

508

509 It can be seen that the S_r - s and the w - s relationship curves predicted by the
510 transformation model are in good agreement with the measured SWRC results,
511 testifying the validity of the proposed model and indicating that the proposed model
512 can satisfactorily account for the influence of soil volume change on its water
513 retention property.

514

515 **5 CONCLUSIONS**

516

517 In order to analysis the difference between the conventional SWRC and $SWRC_{MIP}$
518 derived from PSD due to volume change, drying test was conducted on a reconstituted
519 silty soil, together with the volume, suction and PSD measurements. The changes of
520 the $SWRC_{MIP}$ families and their relation with conventional SWRC were analyzed. It can
521 be concluded that deformation of the soil is the main reason for the difference
522 between the conventional SWRC and $SWRC_{MIP}$.

523

524 A transformation model was proposed further. [The model is based on the finding that](#)
525 [the \$S_r\$ - \$s\$ \(\$e=e_{min}\$ \) curve in \$S_r\$ - \$e\$ - \$s\$ 3D surface, the \$S_{rMIP}\$ - \$s\$ \(\$e=e_{min}\$ \) relationship in the \$S_{rMIP}\$ -](#)
526 [\$e\$ - \$s\$ 3D surface and the projection of the conventional SWRC on \$S_r\$ \(\$S_{rMIP}\$ \)- \$o\$ - \$s\$ coordinate](#)
527 [coincide at high suctions. This model takes the soil state with no longer volume change](#)

528 as a reference, and takes the S_{rMIP-s} ($e=e_{min}$) curve as a reference curve in S_r -SWRC
529 prediction, which connects the $S_{rMIP-e-s}$ and S_r-e-s surfaces. The model is expected to
530 be suitable for undisturbed and compacted-saturated samples undergoing drying
531 path, no matter what stress histories they have before saturation.

532

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534

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541

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636 Table 1. Indexes of samples drying to different target states

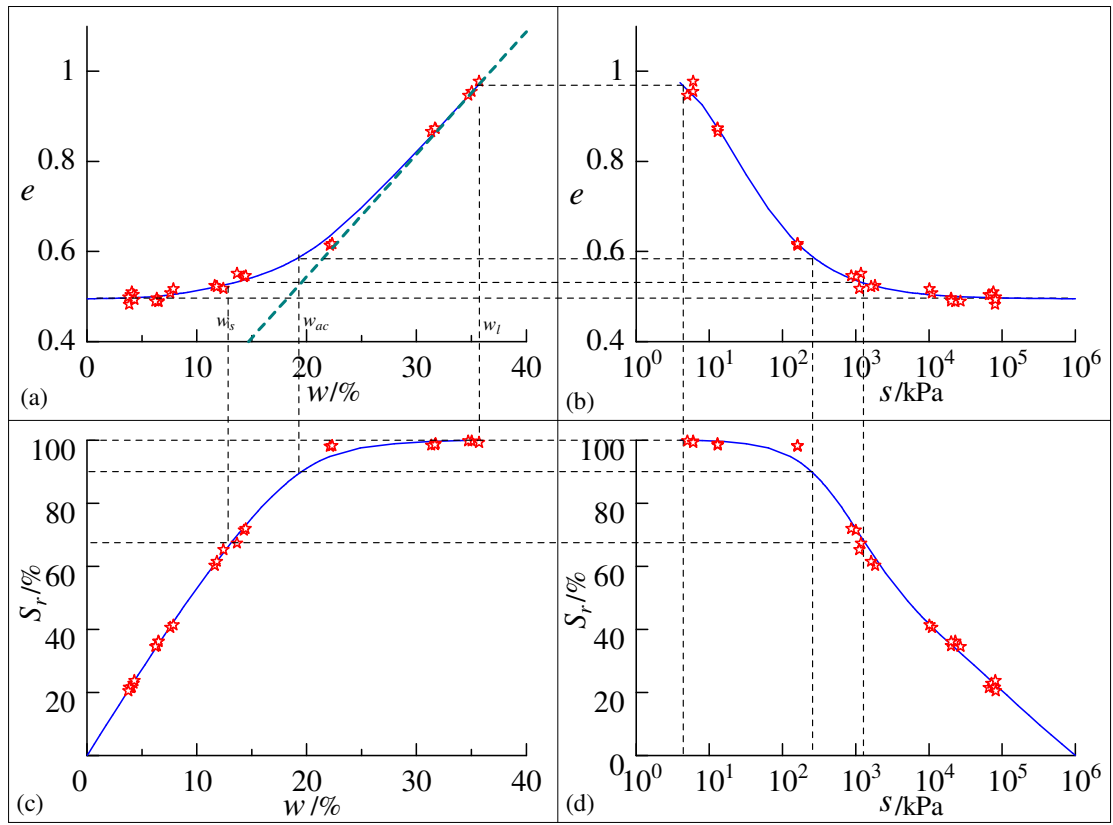
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No.	Sample	s(kPa)	e	w(%)	S _r (%)
	(1)-1	6	0.96	35.02	99.71
(1)	(1)-2	6	0.95	34.71	99.73
	(1)-3	5	0.98	35.70	99.28
	(2)-1	13	0.87	31.75	98.92
(2)	(2)-2	13	0.87	31.34	98.42
	(2)-3	13	0.87	31.68	98.58
	(3)-1	160	0.61	22.12	98.04
(3)	(3)-2	160	0.62	22.31	98.29
	(3)-3	160	0.62	22.31	98.24
	(4)-1	1000	0.54	14.29	71.42
(4)	(4)-2	1180	0.55	13.65	67.33
	(4)-3	870	0.55	14.44	71.92
	(5)-1	11020	0.51	7.58	40.61
(5)	(5)-2	10160	0.52	7.87	41.38
	(5)-3	20000	0.50	6.35	34.80
	(6)-1	65690	0.50	3.98	21.50
(6)	(6)-2	75610	0.51	4.07	21.70
	(6)-3	71510	0.50	4.24	22.89

638

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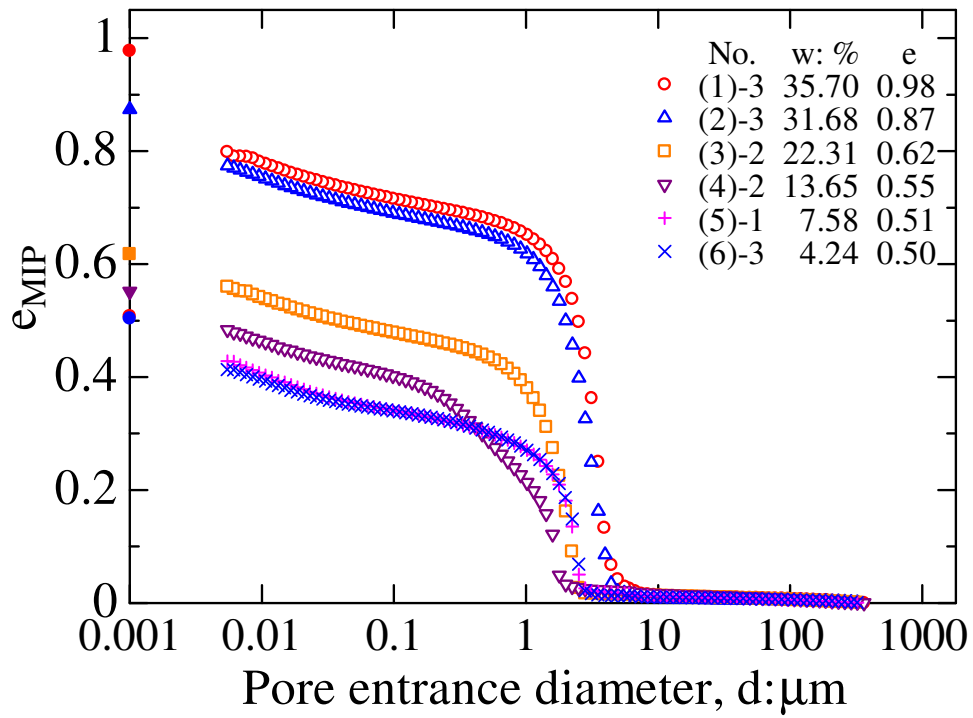
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641

642 **Fig. 1** Results of the drying process of reconstituted Jossigny silt with $w_i = 1.5 w_l$

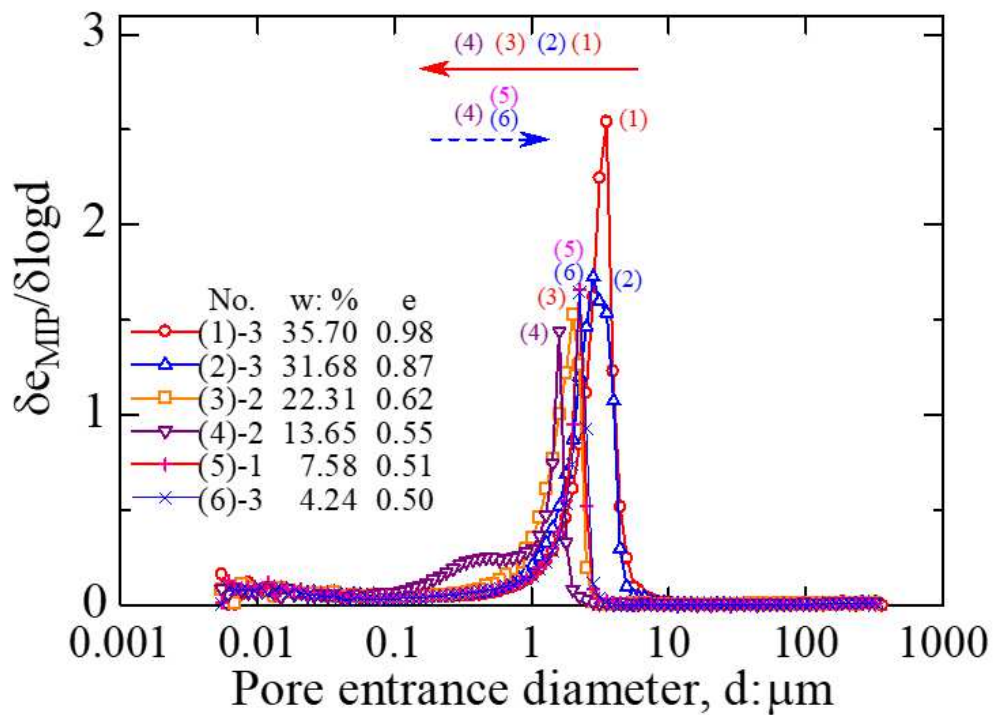
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(a) Cumulative intrusion



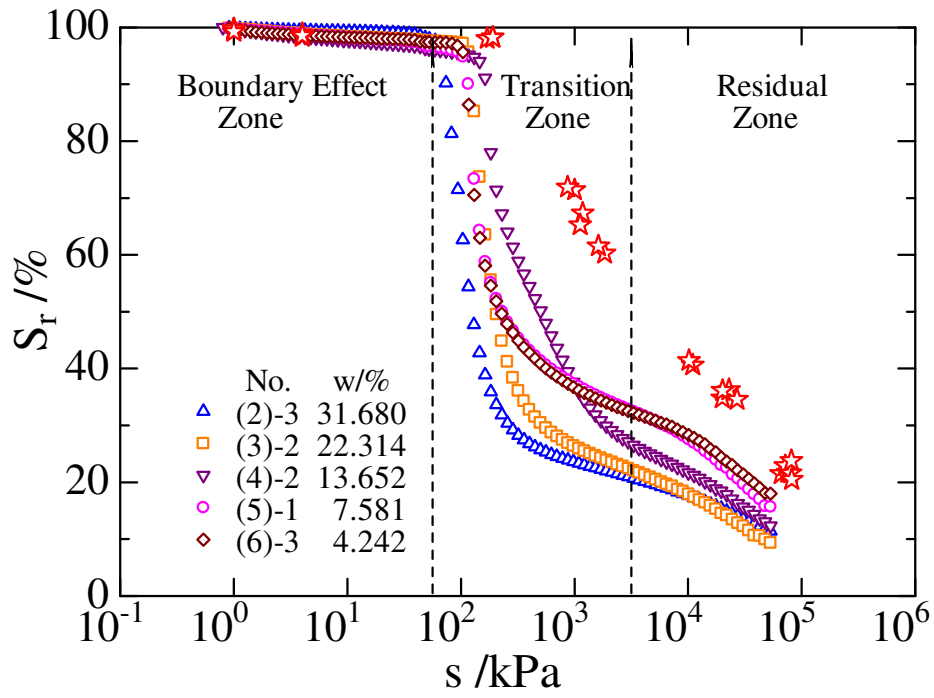
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(b) PSD function

648 **Fig. 2** Pore size distribution of Jossigny silt during drying (data after Sun and Cui,

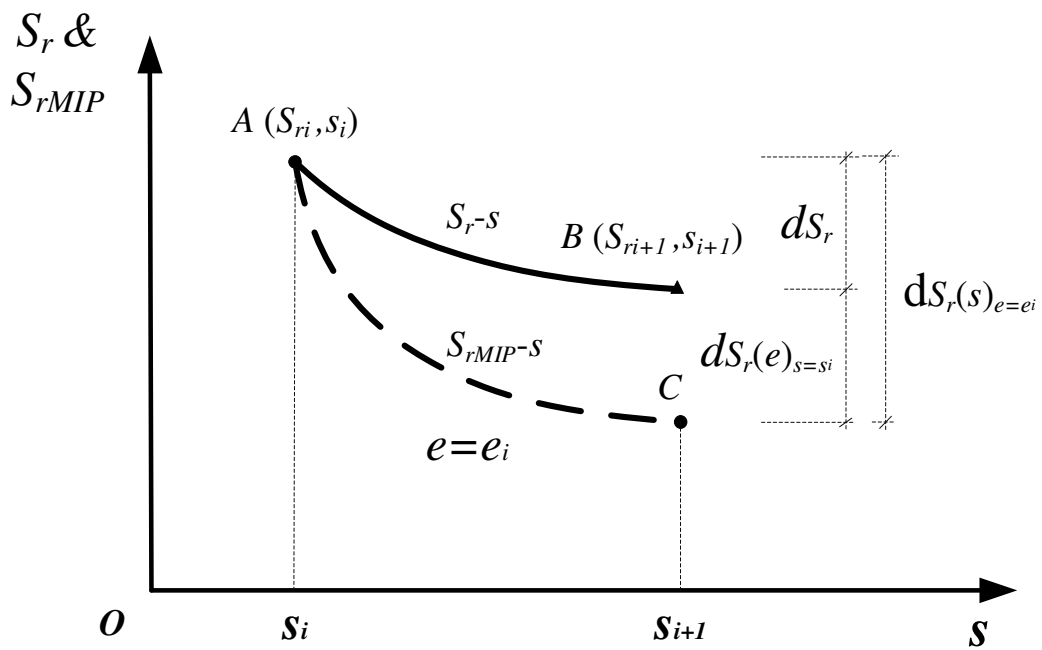
649 2018)



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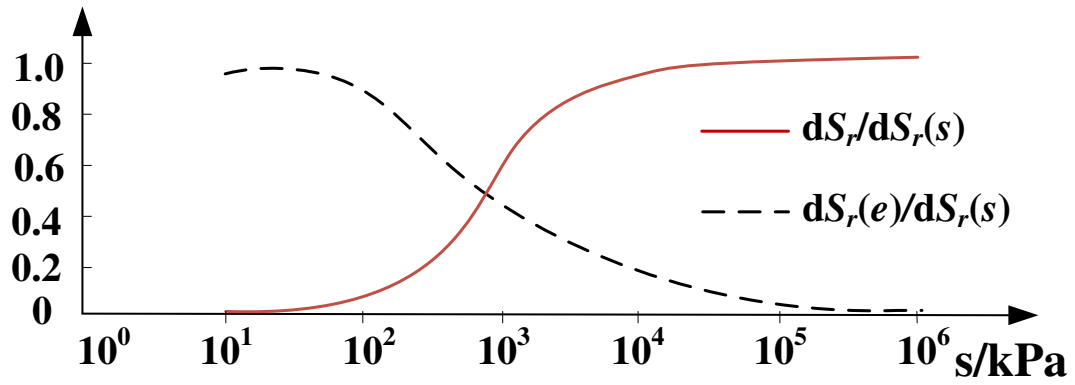
651 **Fig. 3** S_{rMIP} - s relationships and S_r - s relationship

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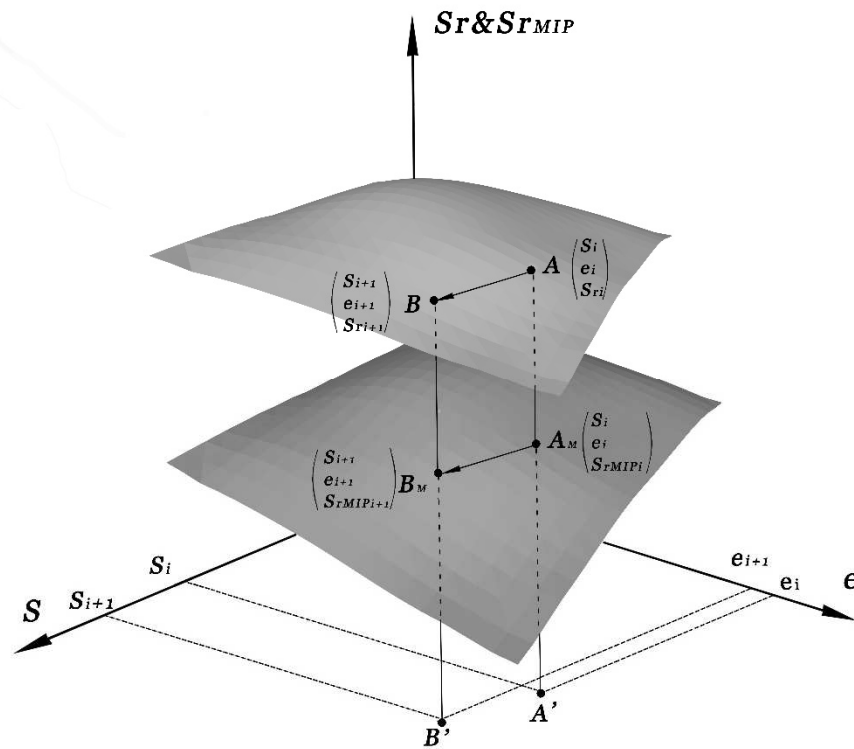
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654 **Fig. 4** $S_r(S_{rMIP})$ - s relationship



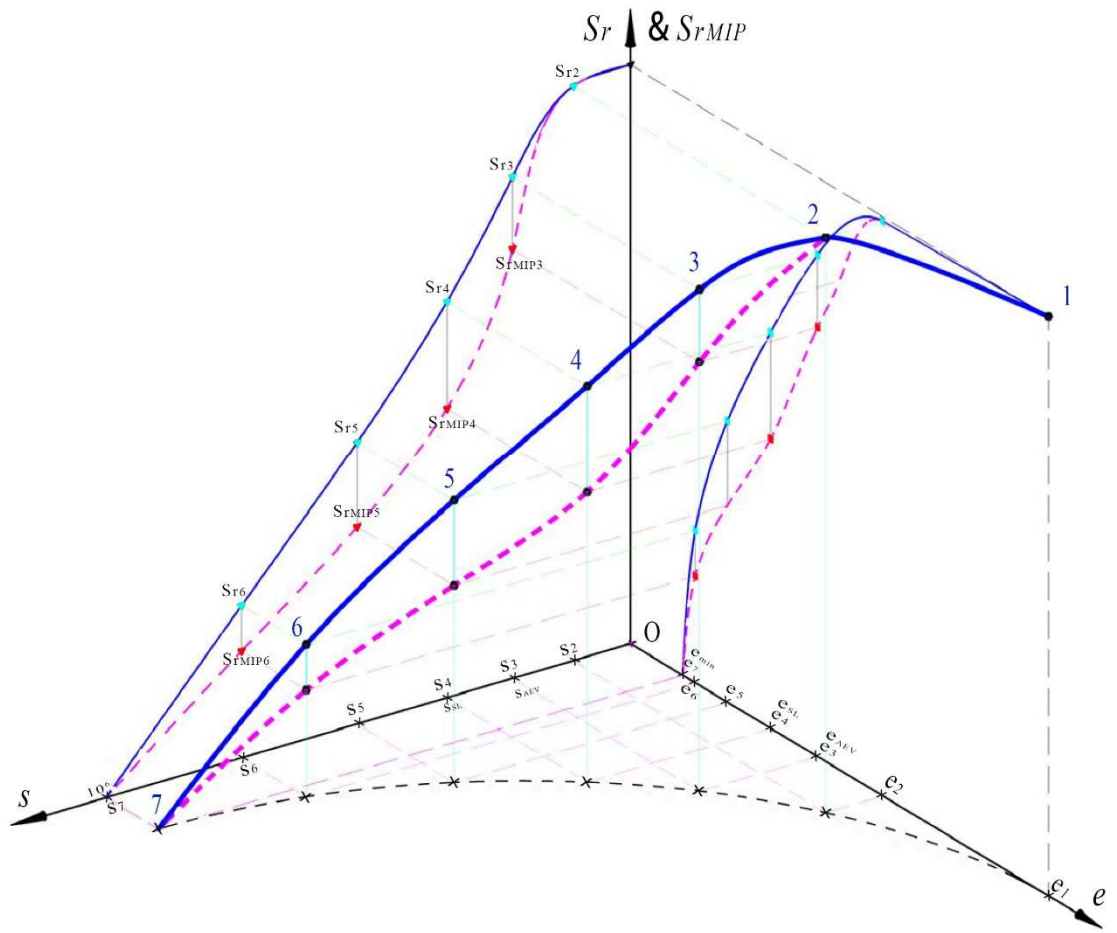
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656 Fig. 5 Changes of $dS_r(e)/dS_r(s)$ & $dS_r/dS_r(s)$ with suction



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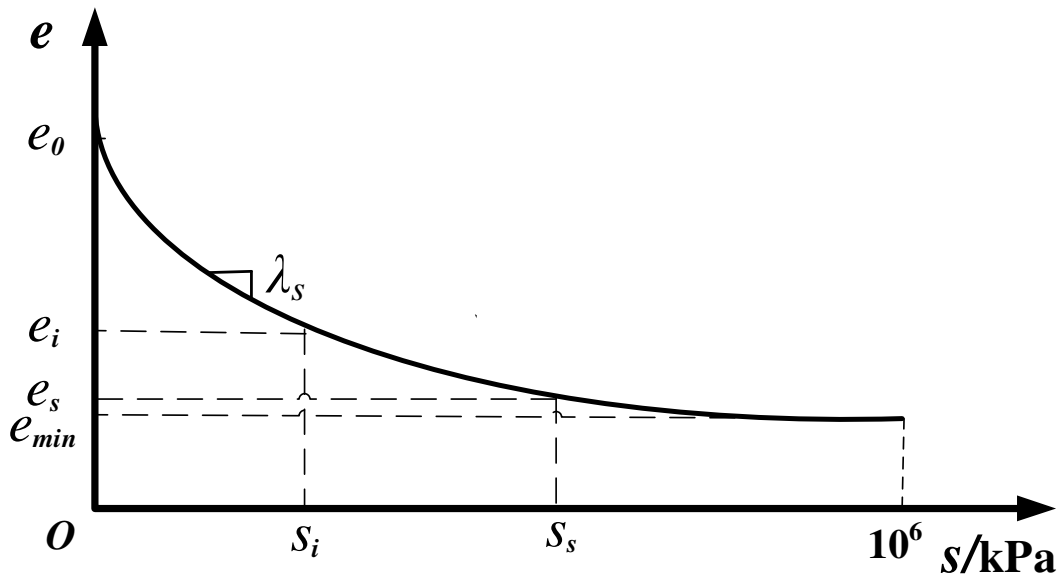
658 Fig. 6 $S_r(S_{rMIP})$ - e - s three-dimension diagram



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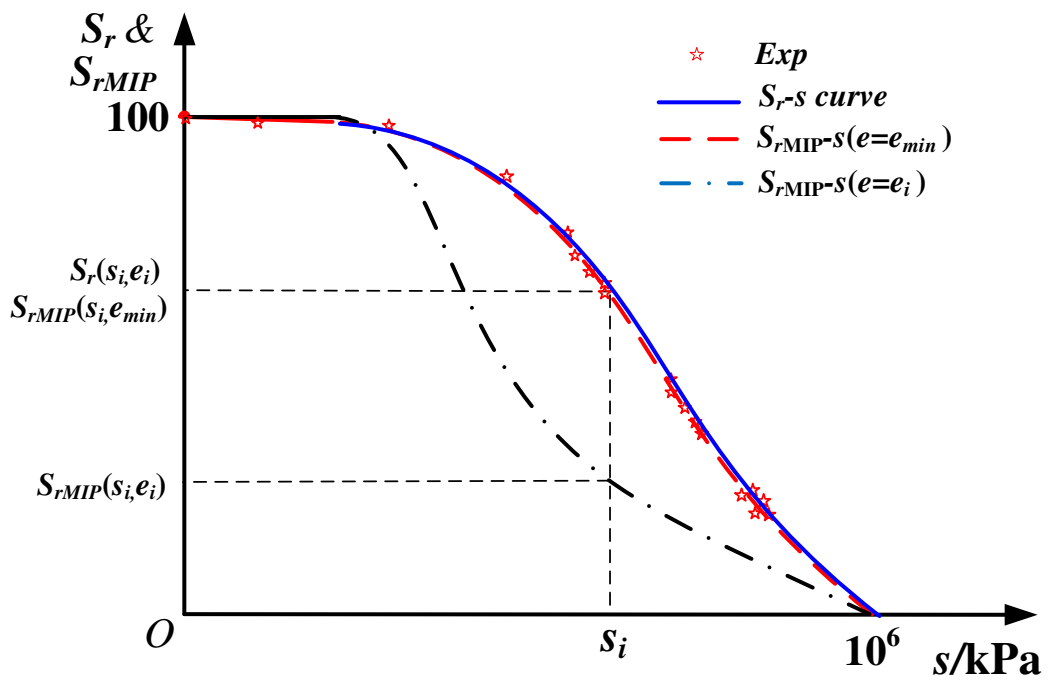
660 **Fig. 7** Projection of drying test results in $S_r(S_{rMIP})$ - e - s three-dimension diagram

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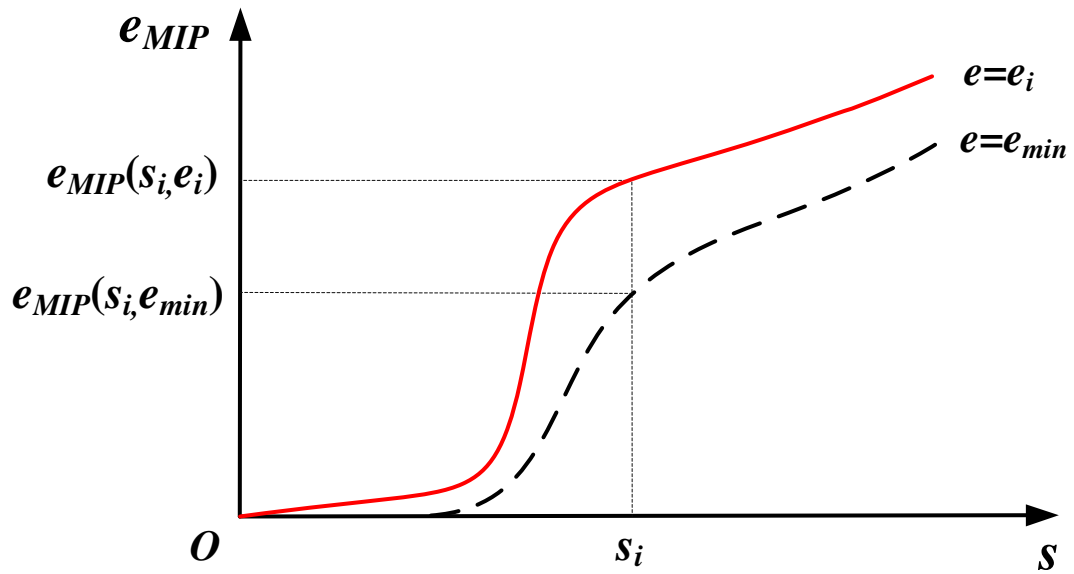
663 Fig. 8 e-s relationship



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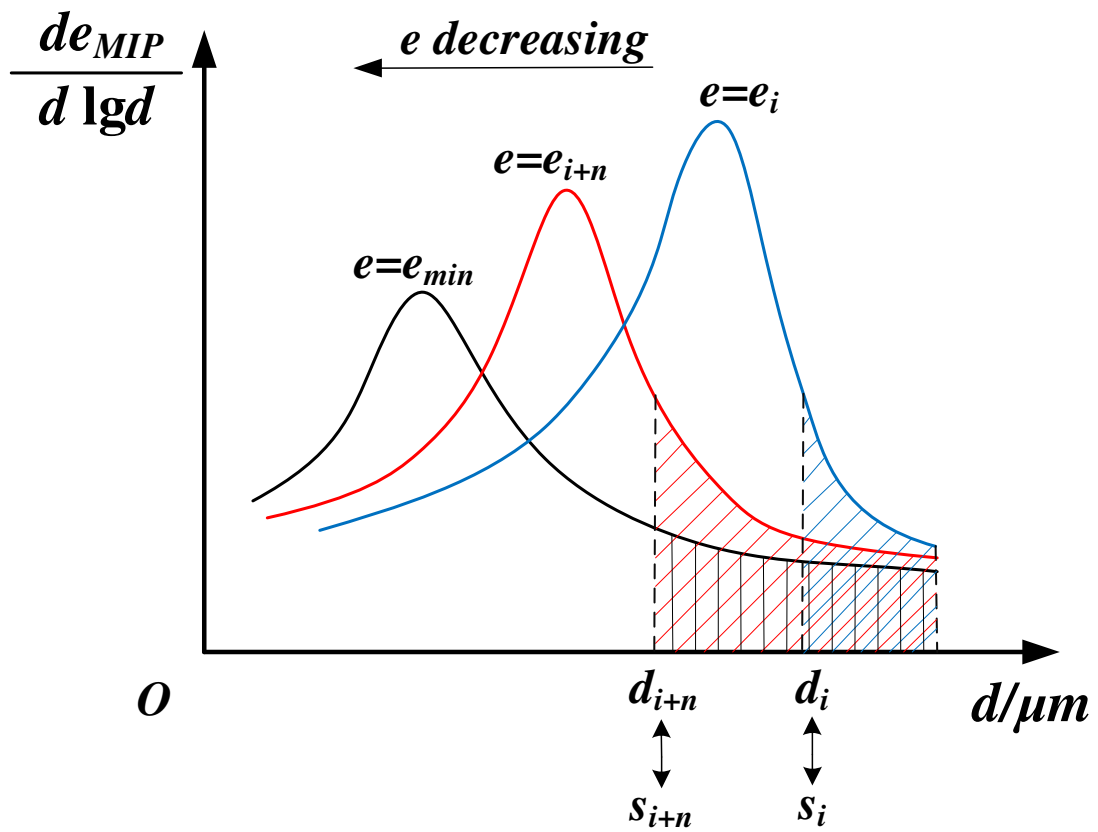
665 Fig. 9 Comparison and connection between S_{rMIP-s} and S_r-s relationship

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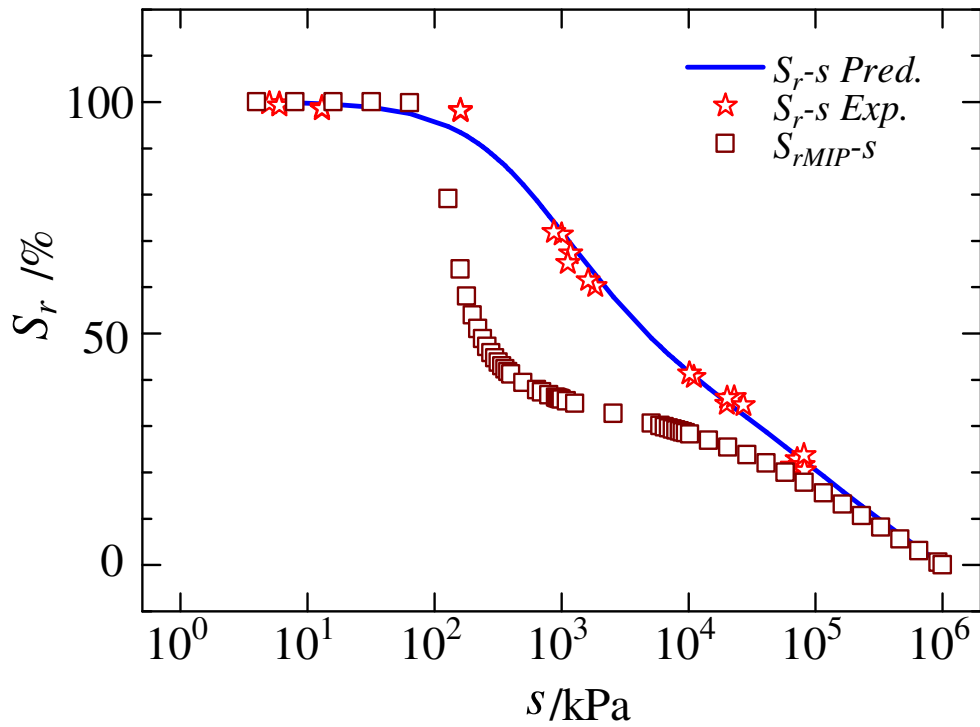
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668 Fig. 10 e_{MIP} - s relationship



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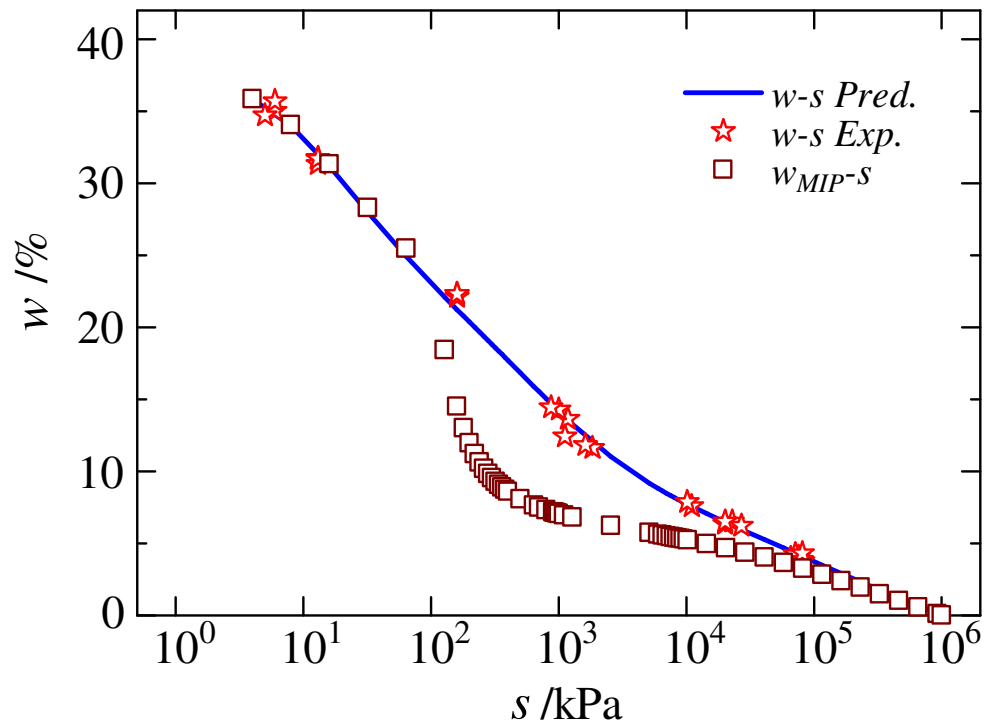
670 Fig. 11 Change of PSD function with void ratio decreasing from $e=e_i$ to e_{min}



671

672

(a) S_r - s



673

674

(b) w - s

675 **Fig. 12** Transformation of $SWRC_{MIP}$ to conventional $SWRC$ in drying of reconstituted

676 Jossigny silt