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1 Development of a large-scale infiltration column for studying the hydraulic
2 conductivity of unsaturated fouled ballast

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20 ***Abstract***

21 In order to study the hydraulic behavior of fouled ballast, an infiltration column of 600 mm high and
22 300 mm in diameter was developed. Five TDR sensors and five tensiometers were installed at various
23 levels, allowing the measurement of volumetric water content and matric suction, respectively. The
24 material studied was fouled ballast that was formed in the railway track-bed by penetration of fine-
25 grained soil into the ballast. This material is characterized by a high contrast of size between the largest
26 and the smallest particles. During the test, three stages were followed: saturation, drainage, and
27 evaporation. Based on the test results, the water retention curve and the unsaturated hydraulic
28 conductivity were determined. The quality of the results shows the capacity of this large-scale
29 infiltration column in studying the unsaturated hydraulic properties of such fouled ballast.

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31 Keywords: Infiltration column; fouled ballast; TDR; tensiometer; water retention curve; hydraulic
32 conductivity.

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39 **Introduction**

40 Coarse elements like ballast particles and fine-grained soils co-exist in many geotechnical problems, for
41 instance, in road pavement or railway structures. This is particularly the case for the old railway
42 structures which were initially built by direct emplacement of ballast on sub-soil without separation
43 layer as for the new high-speed lines. After several years of rail traffic, a new layer was developed
44 through the penetration of fine grain soil into the ballast. Sources of fine particles can be train-borne
45 materials (coal, grain, etc), windborne sediments, pumping of subgrade soils, or ballast particle crushing
46 under repeated loading. The phenomenon of filling voids in the ballast layer by fine particles is
47 commonly termed as fouling (Selig and Waters 1994; Indraratna et al. 2011*a*). Indraratna et al. (2011*b*)
48 indicated that highly fouled ballast loses its functions related to water drainage: the permeability of
49 fouled ballast lower than 10^{-4} m/s is considered unacceptable following Selig and Waters (1994).
50 Robinet (2008) investigated the French railway network and observed that 92% of stability problems
51 have been related to insufficient drainage of the platforms. This shows the importance of a good
52 understanding of the hydraulic behavior of soils involved in the platforms, especially fouled ballast.

53 Up to now, there has been quite limited knowledge on the hydro-mechanical behavior of these
54 kinds of soils, even though it is well recognized that these soils can play an important role in the overall
55 behavior of railway platforms. This is probably due to the difficulty of experimentally working on these
56 coarse-grained soils: common experimental devices for soils can no longer be used and large scale
57 columns are needed. The difficulties are obviously much higher when these soils are unsaturated and
58 their densities are high.

59 The hydraulic conductivity of saturated soils is mainly a function of their void ratio, while the
60 hydraulic conductivity of unsaturated soils is not only dependent on the void ratio, but also the degree of
61 saturation (or volumetric water content). Nowadays, there are various methods in the literature allowing

62 the determination of unsaturated hydraulic conductivity. Tarantino et al. (2008) described several field
63 techniques to measure suction, volumetric water content and hydraulic conductivity. In the laboratory
64 condition, according to Masrouri et al. (2008), the hydraulic conductivity of an unsaturated soil can be
65 determined using either direct or indirect techniques, based on Darcy's law. According to the flow mode,
66 direct techniques can be divided into steady and unsteady state methods. In the steady state methods, a
67 constant flow rate is needed under a specified average water pressure head. The steady state methods
68 may be costly, tedious and lengthy for low permeability materials. The unsteady state methods are
69 usually divided into two groups: outflow-inflow methods and instantaneous profile methods. In the first
70 group, it is assumed that during the flow process, the hydraulic conductivity is constant and the
71 relationship between water content and matrix suction is linear. The instantaneous profile methods
72 consist of inducing transient flow in a soil specimen and monitoring the water content and suction
73 profiles changes (Wind 1966; Daniel 1982; Delage and Cui 2001; Cui et al. 2008; Ye et al. 2009). When
74 applying this method, very often, only the suction profile is monitored and the water content profile is
75 obtained indirectly based on the water retention curve that is determined separately. Peters et al. (2011)
76 used a fused quartz (transparent soil) with digital image analysis to monitor the degree of saturation
77 during the test, but this method is not suitable for the fouled ballast studied.

78 Infiltration column is usually used to determine the unsaturated hydraulic conductivity of soils
79 following the instantaneous profile method. In most cases, fine-grained soils are studied and the
80 infiltration columns used were of small diameter: for instance, 150 mm by Bruckler et al. (2002),
81 103 mm by Chapuis et al. (2006). Some authors presented larger infiltration columns allowing
82 embedding volumetric water content sensors in addition to suction sensors (Nützmann et al., 1998;
83 Stormont and Anderson, 1999; Choo and Yanful, 2000; Yang et al., 2004; McCartney and Zornberg,
84 2007; McCartney and Zornberg, 2010). In spite of their larger size (diameter around 200 mm), the
85 columns mentioned above are not adapted to coarse-grained soils or fine-coarse grained soil mixtures

86 where the dimension of the largest particles can reach 60 mm. For these soils, larger infiltration columns
87 are needed. In this regard, Trani and Indraratna (2010) developed a percolation column of 240 mm in
88 diameter and 150 mm in height to investigate the hydraulic behavior of saturated sub-ballast under cyclic
89 loading. The use of large-sized specimens is also specified in the French standard AFNOR (2004): the
90 diameter (D) of the soil specimen for triaxial tests must exceed 5 times the maximum diameter (d_{\max}) of
91 soil grains. This size ratio was more or less respected in various works found in literature: Yasuda et al.
92 (1997) conducted triaxial tests with a D/d_{\max} equal to 4.7 ($D = 300$ mm). A ratio of 5.7 was adopted by
93 Lackenby et al. (2007) in their tests on soil specimen of 300 mm in diameter. The same ratio of 5.7 was
94 adopted by Ekblad (2008) with a specimen diameter D equal to 500 mm. It is obvious that the
95 development of such large columns represents a big challenge because of the technically related
96 difficulties. Note that Tang et al. (2009) developed an infiltration tank of rectangular section (800 mm x
97 1000 mm) with simultaneous suction and volumetric water content monitoring for testing compacted
98 expansive soil. The large size allowed the free swell of soil during wetting but the volumetric sensors
99 used (Thetaprobe) are not suited to the fine-coarse-grained soil mixtures because of the limited
100 dimension of these sensors.

101 In order to investigate the hydraulic conductivity of fouled ballast in both saturated and
102 unsaturated states, a large-sized infiltration column (300 mm in diameter and 600 mm in height) was
103 developed. This column was equipped with both tensiometers and TDRs allowing the simultaneous
104 monitoring of suction and volumetric water content. Note that the water retention curve can be obtained
105 directly from the measurements, and direct application of the simultaneous method can be done for the
106 determination of the hydraulic conductivity of unsaturated fouled ballast.

107 **Materials**

108 The fouled ballast studied was taken from the sub-structure of an ancient railway at S nissiat (North
109 West of Lyon, France) that was constructed in the 1800s. This fouled ballast mainly composed of ballast
110 and sub-soil during the degradation of the railway structures. The sub-soil was also taken at this site.
111 Identification tests were performed in the laboratory on these materials. The results show that the sub-
112 soil is high-plasticity silt with a liquid limit $w_L = 57.8\%$ and a plasticity index $I_p = 24.1$. The fraction of
113 particles smaller than $80 \mu\text{m}$ is 98% and that of particles smaller than $2 \mu\text{m}$ is 50%. The fouled ballast
114 contains 3% to 10% of stones (50-63 mm), 42% to 48% of ballast (25-50 mm), 36 to 42% of micro-
115 ballast, sand, degraded ballast (0.08 to 25 mm), and 16% fines ($<80 \mu\text{m}$). It represents a mixture of fine-
116 coarse-grained soils. Figure 1 shows the grain size distribution curves of both the sub-soil and fouled
117 ballast.

118 The density of particles smaller than 2 mm was determined by the pycnometer method (AFNOR
119 1991) and a value of $\rho_s = 2.67 \text{ Mg/m}^3$ was found. The density of particles larger than 2 mm and those
120 greater than 20 mm was determined using the same method but with a device of larger size (AFNOR
121 2001): $\rho_s = 2.68 \text{ Mg/m}^3$ for both sizes. More details about this fouled ballast can be found in Trinh et al.
122 (2011). The mechanical behavior of this fouled ballast under cyclic loading was investigated by Trinh et
123 al. (2012).

124 **Experimental setup**

125 Figure 2 shows the infiltration column developed to study the hydraulic behavior of the fouled ballast. It
126 has an internal diameter of 300 mm, a wall thickness of 10 mm and a height of 600 mm. The column is
127 equipped with five volumetric water content sensors (TDR1 to TDR5) and five matric suction sensors
128 (T1 to T5) disposed at equal distance along the column ($h = 100, 200, 300, 400$ and 500 mm). On the
129 top, a hole of 50 mm in diameter was drilled allowing installation of a sensor of suction if needed. A
130 second hole in the center allows water drainage or air expulsion. Two valves are installed at the bottom,

131 allowing water injection after expulsion of air in the ducts. Two porous stones are placed for the two
132 valves to avoid any clogging of ducts by soil particles. Geotextiles are placed on the top and at the
133 bottom of the soil specimen. O-rings are used to ensure the waterproofness. A Mariotte bottle is used for
134 water injection. As the area occupied by the sensors is just 6.8% of the total apparatus section area, the
135 sensors installation is expected to not affect the water transfer inside the soil column.

136 The TDR probes used are of waveguides buried (GOE) type, with 3 rods of 3.2 mm diameter and
137 200 mm length. According to Soilmoisture (2000), the influence zone of this TDR is 20-30 mm around
138 the rods. The accuracy of the TDR probes is $\pm 2\%$ of the measured values following the provider. The
139 equipments used (TDR probe and Trase BE) can automatically provide the dielectric constant K_a (which
140 is deduced from the crossing time of electric wave within the surrounding material). Based on the
141 calibration curve (relationship between the dielectric constant and volumetric water content) provided by
142 the producer, the volumetric water content can be then determined. It is thereby an indirect measurement
143 method. Several authors have shown that the calibration curve depends on the texture, density,
144 mineralogical composition, fines content and particle size of the test material (Jacobsen and Schjønning
145 1993; Stolte et al. 1994; Côté and Roy 1998; Hanson and Peters 2000; Gong et al. 2003; Schneider and
146 Fratta 2009; Ekblad and Isacsson 2007). It is therefore necessary to determine the specific calibration
147 curve for each soil studied. Soil matric suction was measured by T8 tensiometer (UMS 2008). The
148 working pressure range of those tensiometers is from 100 kPa to -80 kPa (they measure both positive
149 pressure and suction), with an accuracy of ± 0.5 kPa.

150 **Experimental procedure**

151 The soil studied was firstly dried in an oven at 50°C for 24 h. Water was then added using a large
152 mixer to reach the target water content. After mixing, the wet material was stored in hermetic containers
153 for at least 24 h for moisture homogenization.

154 The soil specimen was then prepared by compaction in six layers of 0.10 m each in the
155 infiltration column using a vibrating hammer. The density of each layer was controlled by fixing the soil
156 weight and the layer height. Before compaction of the subsequent layer, a TDR probe and a metal rod of
157 25 mm diameter were placed on the compacted layer. Once the soil specimen was prepared, the metal
158 rods were removed to install the tensiometers. This protocol was adopted because the tensiometers are
159 fragile and they can't stand the compaction force without being damaged. Considering the influence
160 zone of TDR probes, the distance between the tips of tensiometers and TDR probes was set greater than
161 40 mm. In order to ensure the good contact between tensiometers and soil, a paste made of sub-soil was
162 injected in the holes before introducing the tensiometers.

163 The test was carried out in 3 stages: saturation, drainage and evaporation. The specimen was
164 saturated by injecting water from the bottom. Water was observed at the outlet in less than one hour, and
165 the soil specimen was considered saturated after one day of water flow. Saturated hydraulic conductivity
166 was measured by applying a constant hydraulic head of 0.45 m, using the Mariotte bottle. After
167 completion of the saturation, tensiometers were installed on the column. Note that these sensors were not
168 installed before the saturation stage in order to avoid any cavitations due to possible high suctions in the
169 compacted material. After the installation of tensiometer, the soil column was re-saturated again because
170 the soil was de-saturated when installing the tensiometers. After the saturation stage, water was allowed
171 to flow out through the two bottom valves. After two days, when there was no more water outgoing, it
172 was considered that the drainage stage was completed. The top cover of the column was then removed to
173 allow evaporation. The two bottom valves were closed during this stage. The air conditions in the
174 laboratory during this stage were: a temperature of 22°C and a relative humidity of 50±5%. The
175 evaporation ended after about 160 h when the value given by the tensiometer T5 (h = 500mm) was -50
176 to -60 kPa.

177 Calibration of the TDR was performed within the same soil specimen. After re-saturating the soil
178 inside the column, drainage was performed step-by-step. The drainage valve was opened to let 300 mL
179 of water drained, and then closed again until reaching the equilibrium of the TDR measurement inside
180 the column. This drainage was then repeated 10 times until the full drainage of pore-water inside the soil
181 specimen. For each step, as the TDR measurement reached the equilibrium, hydrostatic water pressure
182 distribution can be expected and the water content can then be estimated for each level of soil column
183 based on the quantity of water drained. These values of water content were then plotted versus the value
184 of K_a given by the TDR in order to determine the calibration curve (Figure 3). The following equation
185 can be then used for the calibration curve of the TDR:

$$186 \quad \theta_{cal} = 0.0221 \times K_a^2 + 0.5118 \times K_a - 3.0677 \quad (1)$$

187 **Experimental results**

188 The soil was compacted in the infiltration column at a density of 2.01 Mg/m^3 (a porosity of 0.25) and a
189 gravimetric water content of 5.5 %, corresponding to a volumetric water content of 10%. Figure 4 shows
190 the measured volumetric water content by TDR probes after compaction (initial state). These values are
191 respectively 4.8, 6.0, 9.7, 8.8 and 10.1% for TDR1 to TDR5. At $t = 80 \text{ h}$, water was injected from the
192 base of the column to saturate the soil. It can be observed that the measured volumetric water content by
193 TDR probes increased quickly and reached a maximum value in less than one hour. The maximum
194 values were 23.4, 23.7, 24.4, 22.4 and 25.0% for TDR5 to TDR1, respectively. Note that at a dry density
195 of 2.01 Mg/m^3 , the volumetric water content in saturated state was 25.0%. These values corresponded to
196 a degree of saturation of 93.6, 94.8, 97.6, 89.6 and 100%, respectively, indicating that the specimen was
197 close to the saturated state.

198 The volume of water injected during the saturation stage is shown in Figure 5. In the beginning,
199 the volume of water increased quickly and the rate decreased with time. Note that after $t = 50$ min, water
200 was observed on the surface of the specimen. The volume of water injected for that time was 4.000×10^{-3}
201 m^3 , while that required to saturate the specimen was $5.795 \times 10^{-3} \text{ m}^3$ (calculated from the density and the
202 initial water content of the specimen). The average degree of saturation at this time was then about 70%.
203 From $t = 50$ min, the relationship between volume of water and time was almost linear. Two tests for
204 measuring hydraulic conductivity at saturated state were performed, 1 day and 3 days respectively after
205 the saturation stage; this delay allowed improving the saturation of the soil. Figure 5 shows that the
206 water volume rates of the two tests are similar. The average value of the hydraulic conductivity
207 estimated is $1.75 \times 10^{-5} \text{ m/s}$.

208 When the specimen was re-saturated, the level of the water surface was maintained at 10 mm
209 above the surface of the specimen. The water pressure values of T1 to T5 were respectively 5.1, 4.1, 3.1,
210 2.1 and 1.2 kPa (Figure 6a) corresponding to water levels of 510, 410, 310, 210 and 120 mm,
211 respectively. This was consistent with the positions of the tensiometers. In the drainage stage, the water
212 pressure decreased. The values became negative five minutes after opening the valves. Then, the
213 changes followed a constant rate for each tensiometer. All tensiometers except T2 ($h = 200\text{mm}$)
214 indicated a lower pressure (higher suction) at a greater elevation (closer position to the evaporation
215 surface).

216 With the same time reference, Figure 6b shows the responses of the five TDR sensors. The
217 responses in volumetric water content were similar to that in water pressure, i.e., the volumetric water
218 content decreased quickly from the maximum value in 10 min. At $t = 90$ min, the measured volumetric
219 water content ranged from 15 to 17% except that by TDR2 (12%).

220 The drainage stage was maintained for 54 h and the water pressure responses are shown in Figure
221 7a. The drainage stage stopped when no more water outflow was observed from the bottom valves ($t =$
222 54 h). The measured pressures were -2.0, -1.9, -1.6, -1.8 and -2.7 kPa for tensiometers T1 to T5,
223 respectively. Figure 7b shows the responses of the five TDR probes. At the end of the drainage stage ($t =$
224 54 h), the volumetric water contents were 11.7, 7.9, 11.8, 10.8 and 10.9% for TDR1 to TDR5,
225 respectively. It can be seen that both the water pressure and volumetric water content did not reach
226 equilibrium.

227 After the drainage stage, the bottom valves were closed, and evaporation was allowed from the
228 top side for 160 h. Figure 8a shows the water pressure changes. The tensiometer close to the surface (T5)
229 shows that the pressure decreased quickly from -2.7 kPa to -61.2 kPa after 160 h of evaporation, while
230 those of other levels decreased much more slowly. The value at $h = 100$ mm remained almost
231 unchanged, around -2.0 kPa.

232 The values of water content are shown in Figure 8b. Due to a technical problem, data are only
233 available for $t = 0$ -120 h. The same trends as for water pressure changes can be observed: the closer the
234 tensiometer to the evaporation surface, the larger the volumetric water content changes. The value at $h =$
235 500 mm (the closest tensiometer to the evaporation surface) decreased from 11% to 7% after 120 h,
236 while those at $h = 100$ mm and 200 mm remained almost constant.

237 **Determination of the hydraulic properties in unsaturated state**

238 As mentioned before, unlike the common infiltration column with only suction profile
239 monitoring (Daniel 1982; Cui et al. 2008; Ye et al. 2009) or only water content monitoring, the column
240 developed in this study is equipped with both tensiometers and TDR sensors, allowing simultaneous
241 measurements of suction and volumetric water content at different levels. The simultaneous profile
242 method can be then directly applied without using the water retention curve. Before determining the

243 unsaturated hydraulic conductivity of the soil, as one of the important hydraulic properties, the water
244 retention curve (WRC) was determined based on the measurements of suction and volumetric water
245 content during the test. In Figure 9 the measured volumetric water content is plotted versus the measured
246 suction for each level. Except the data at $h = 200$ mm, the water retention curves obtained for various
247 depth were similar. The best fit curves obtained from the models of van Genuchten (van Genuchten
248 1980) and Brooks-Corey (Brooks and Corey 1964; Stankovich and Lockington 1995) are also shown.
249 The models formula and parameters are presented in Table 1.

250 Figure 10a shows the values of suction isochrones obtained during the evaporation stage. At the
251 beginning ($t = 0$), suction in the soil was similar and quite low (lower than 2 kPa), then it increased at
252 different rates depending on the position. The closer the tensiometer to the evaporation surface the faster
253 the suction changes. These suction isochrones were used to determine the slope of the total hydraulic
254 head which was in turn used to calculate the hydraulic gradient ($i = \partial h / \partial z$). The measured volumetric
255 water content isochrones are shown in Figure 10b. The isochrones of calculated volumetric water
256 content from the suction measured using van Genuchten's equation (Table 1) are shown in Figure 10c,
257 together with the water content profile at the end of the saturation stage. A general decrease during the
258 evaporation is observed: the curves are shifting leftwards especially for the upper part close to the
259 evaporation surface.

260 McCartney et al. (2007) observed that small variations of suction or volumetric water content in
261 experimental data can result in significant error in hydraulic conductivity. In the present study, the
262 calculation of unsaturated hydraulic conductivity was performed using both the measured water content
263 data (Figure 10b) and the calculated results (Figure 10c), together with the suction profiles (Figure 10a)
264 of the evaporation state. The volume of water passing through a given height for two different times was
265 determined based on the isochrones of volumetric water content. This volume was used to determine the
266 flow rate q . The hydraulic conductivity was calculated using Darcy's law. In the calculation of water

267 volume, three different heights ($h = 400, 450$ and 500mm) were considered. This calculation was
268 relatively easy with the volumetric profiles shown in Figure 10c, but a little difficult for that shown in
269 Figure 10b when considering the height lower than $h = 300$ mm. Indeed, Figure 10b shows that negative
270 values can be obtained when determining the water volume passing through the height $h = 300$ mm. This
271 is mainly because of the little changes in this zone and the accuracy of the measurements. In the
272 calculation, the non physical negative values were not considered for the determination of hydraulic
273 conductivity. Figure 11 shows the relationship between the hydraulic conductivity of soil at a dry density
274 $\rho_d = 2.01 \text{ Mg/m}^3$ and suction, obtained using both Figure 10b and Figure 10c. It can be observed that the
275 two types of volumetric water content profiles gave similar results. A general decrease with increasing
276 suction is observed for the hydraulic conductivity. In this figure the value obtained during the saturation
277 stage is also shown. From the saturated state to an unsaturated state at a suction of 65 kPa , the hydraulic
278 conductivity decreased from $1.75 \times 10^{-5} \text{ m/s}$ to $2 \times 10^{-10} \text{ m/s}$.

279 Figure 12a shows the comparison between the determined hydraulic conductivity and the values
280 calculated from the van Genuchten's model and Brooks-Corey's model. Note that the same parameters
281 as for the water retention curve were used when applying these two models. A general lower hydraulic
282 conductivity was given by the models, especially by the van Genuchten's model. A better agreement
283 between the determined and calculated values (Figure 12b) can be obtained using the models parameters
284 in Table 1. Similar observation was made by Parks et al (2012): the van Genuchten's model, within
285 parameters obtained when fitting the water retention curve, does not provide an adequate prediction of
286 the experimental hydraulic conductivity functions of unsaturated soils in general.

287 **Discussion**

288 The dry density of the soil studied is as high as 2.01 Mg/m^3 . Heavy compaction was needed to reach it.
289 To avoid damage of the tensiometers, metallic rods were used to prepare spaces during compaction for

290 tensiometers installation. For TDR sensors, they were placed between different soil layers and were
291 compacted together with the soil. The good response of these sensors during the test shows that they
292 were not damaged by the compaction. The inconsistent data given by the TDR sensor at $h = 200$ mm
293 (see Figure 4) is rather related to the soil heterogeneity. This observation confirms the difficulty of
294 preparing large-size specimen of fined-coarse grained soils on the one hand, and on the other hand, the
295 necessity of using representative large-size specimen for the investigation of hydraulic behavior of such
296 materials. In figure 9, it was noted that a volumetric water content of 5% corresponds to a degree of
297 saturation of 20%. This can be explained by the presence of the large particles of ballast in the soil.

298 During injection of water, there was a difference between the estimated pore volume and the
299 volume of water injected to reach saturation (Figure 5). This can be explained by the non-uniform flow
300 in the specimen because water flows mainly through the macro-pores. This phenomenon was also
301 reported by Moulton (1980). This means that water outflow from the top valve is not an indicator of full
302 specimen saturation, and longer flow duration is needed (one day in this study). The values of degree of
303 saturation measured by TDR sensors were in the range between 90% and 100% after this stage (see
304 Figure 10*b*).

305 In the present work, the hydraulic conductivity of unsaturated fouled ballast was obtained in the
306 infiltration column during the drainage and evaporation stages. Following ASTM (2010), the hydraulic
307 conductivity of unsaturated soils can be estimated from infiltration column test following four methods:
308 downward infiltration of water onto the surface of an initially unsaturated soil specimen (A1), upward
309 imbibitions of water from the base of an initially unsaturated soil specimen (A2), downward drainage of
310 water from an initially saturated soil specimen (A3), and evaporation of water from an initially saturated
311 soil specimen (A4). Methods A1 and A2 can be used for fine-grained sands and for low-plasticity silts.
312 Method A3 can be used with fine or coarse-grained sands. Method A4 can be used for any soil with the
313 exception of clays of high plasticity. In the work of Moore (1939), unsaturated flow was induced

314 naturally; the water rose from the water table to the surface of the soil column and was evaporated from
315 the surface. This method allowed studying various soils ranging from fine gravel to clay.

316 In the saturated condition, the hydraulic conductivity obtained in the saturated condition is
317 1.75×10^{-5} m/s. According to the classification of Bear (1988) for railway application, the drainage is
318 poor because this value corresponds to the hydraulic conductivity of very fine sand, silt, or loam. Note
319 that in the material studied, there are also clay (5%), fine sand and loam. Thus, from a practical point of
320 view, this soil cannot be used for drainage layer.

321 **Conclusions**

322 A large scale infiltration column was developed to study the hydraulic behavior of a fine-coarse grained
323 mixture from the fouled ballast layer of a railway constructed in the 1800s. The column is equipped with
324 tensiometer and TDRs to monitor the matric suction and volumetric water content, respectively. The
325 results obtained allow the following conclusions to be drawn:

326 The quality of the recorded responses show that the installation protocol adopted for tensiometer
327 probes (using metallic rod) and TDR probes (compacted together with soil) was appropriate when
328 testing fine-coarse-grained soils such as the fouled ballast. In addition, the use of both tensiometer and
329 TDR probes in the test enabled the direct determination of water retention curve and the direct
330 application of the instantaneous method for determining the hydraulic conductivity of the unsaturated
331 soil. The results of hydraulic conductivity obtained by both the measured volumetric water content
332 profiles and those fitted using the van Genuchten's model were found similar. This indicates that fitting
333 curves can be used when determining the hydraulic conductivity of unsaturated fouled ballast without
334 causing significant error.

335 From a practical point of views, the method developed in this study can be used in determining
336 the hydraulic conductivity for fouled ballast in particular and for fine-coarse-grained soil mixtures in
337 general, in both unsaturated and saturated states.

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452

453 **Table 1: Model formula and parameters (θ : volumetric water content, θ_r : residual volumetric water content; θ_s :**
454 **volumetric water content at saturated state; k : hydraulic conductivity; k_s : hydraulic conductivity at saturated state;**
455 **ψ : suction in kPa; ψ_a : air entry value; α , n , m , and λ are constants).**

Model	Formula	Parameters for water retention curve	Parameters for hydraulic conductivity
van Genuchten	$\theta = \theta_r + \frac{\theta_s - \theta_r}{\left[1 + (\alpha\psi)^n\right]^m}$ $k = k_s \Theta^2 \left[1 - (1 - \Theta^{1/m})^m\right]$ <p>with: $\Theta = \frac{\theta - \theta_r}{\theta_s - \theta_r}$</p>	$\theta_s = 25.0\%$ $\theta_r = 0\%$ $\alpha = 0.4 \text{ kPa}^{-1}$; $n = 1.17$; $m = 0.15$	$\theta_s = 25.0 \%$ $\theta_r = 0 \%$ $m = 0.2$
Brooks-Corey	$\theta = \theta_s \quad \text{if } \psi < \psi_a$ $\theta = \theta_s \left(\frac{\psi_a}{\psi}\right)^\lambda \quad \text{if } \psi \geq \psi_a$ $k = k_s \left(\frac{\psi_a}{\psi}\right)^{2+3\lambda}$	$\theta_s = 25.0\%$ $\psi_a = 0.02 \text{ kPa}$ $\lambda = 0.17$	$\psi_a = 0.1 \text{ kPa}$ $\lambda = 0.01$

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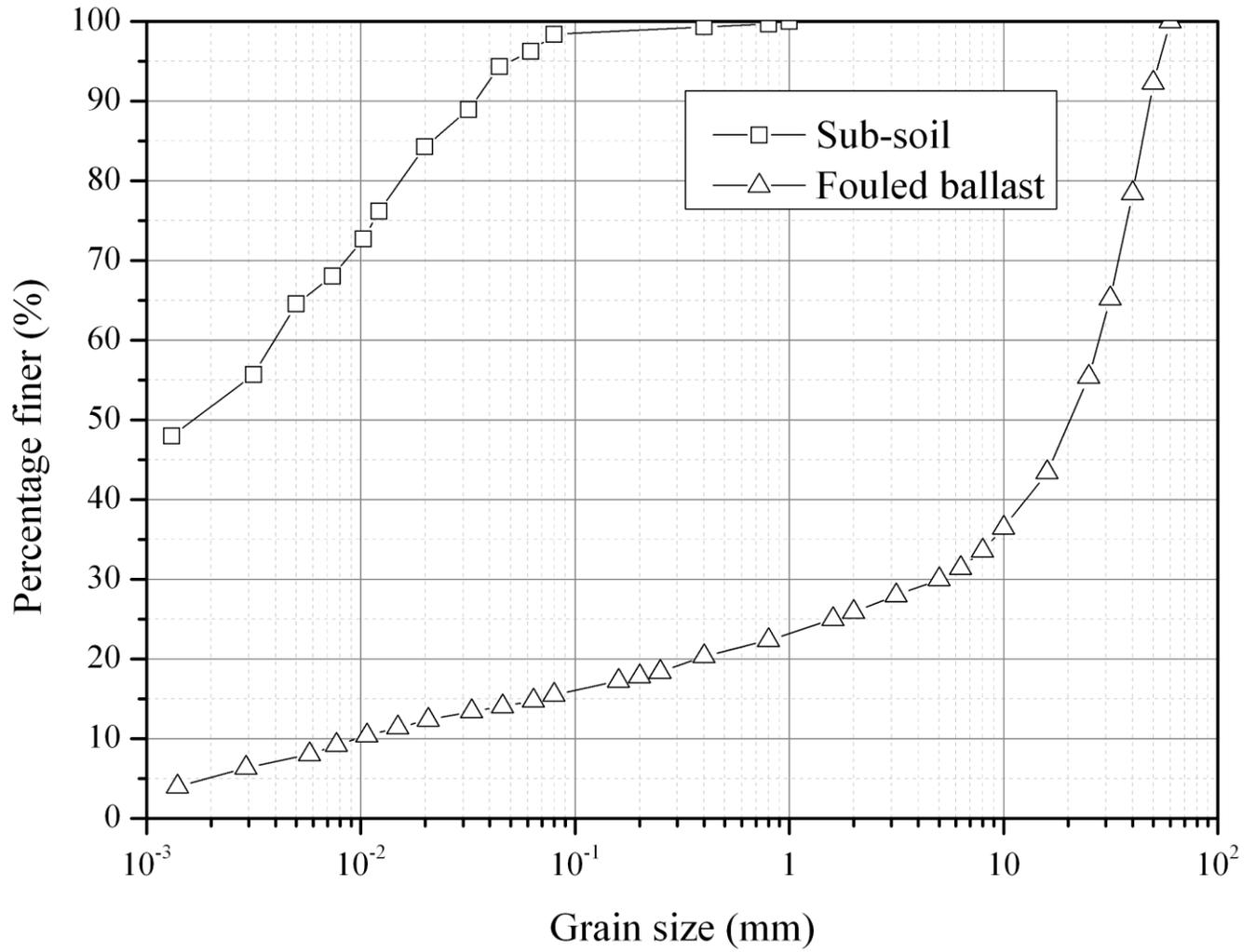
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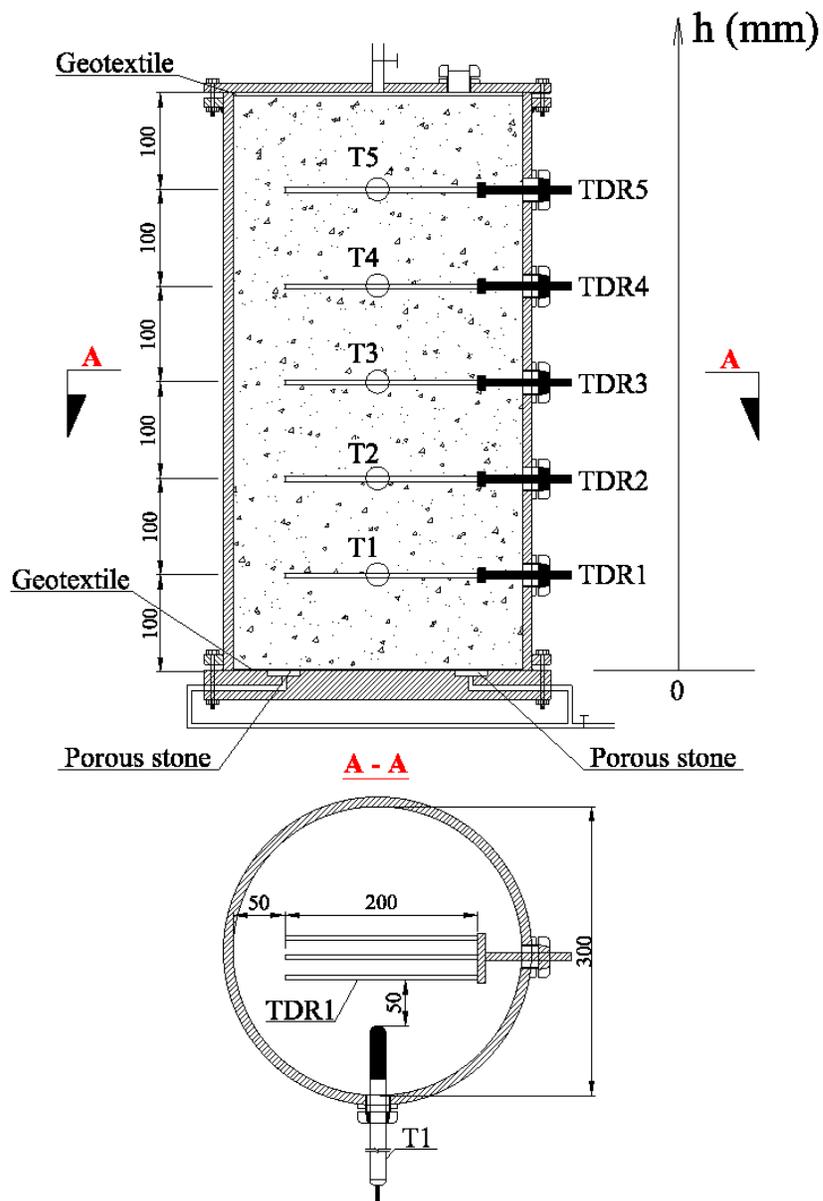
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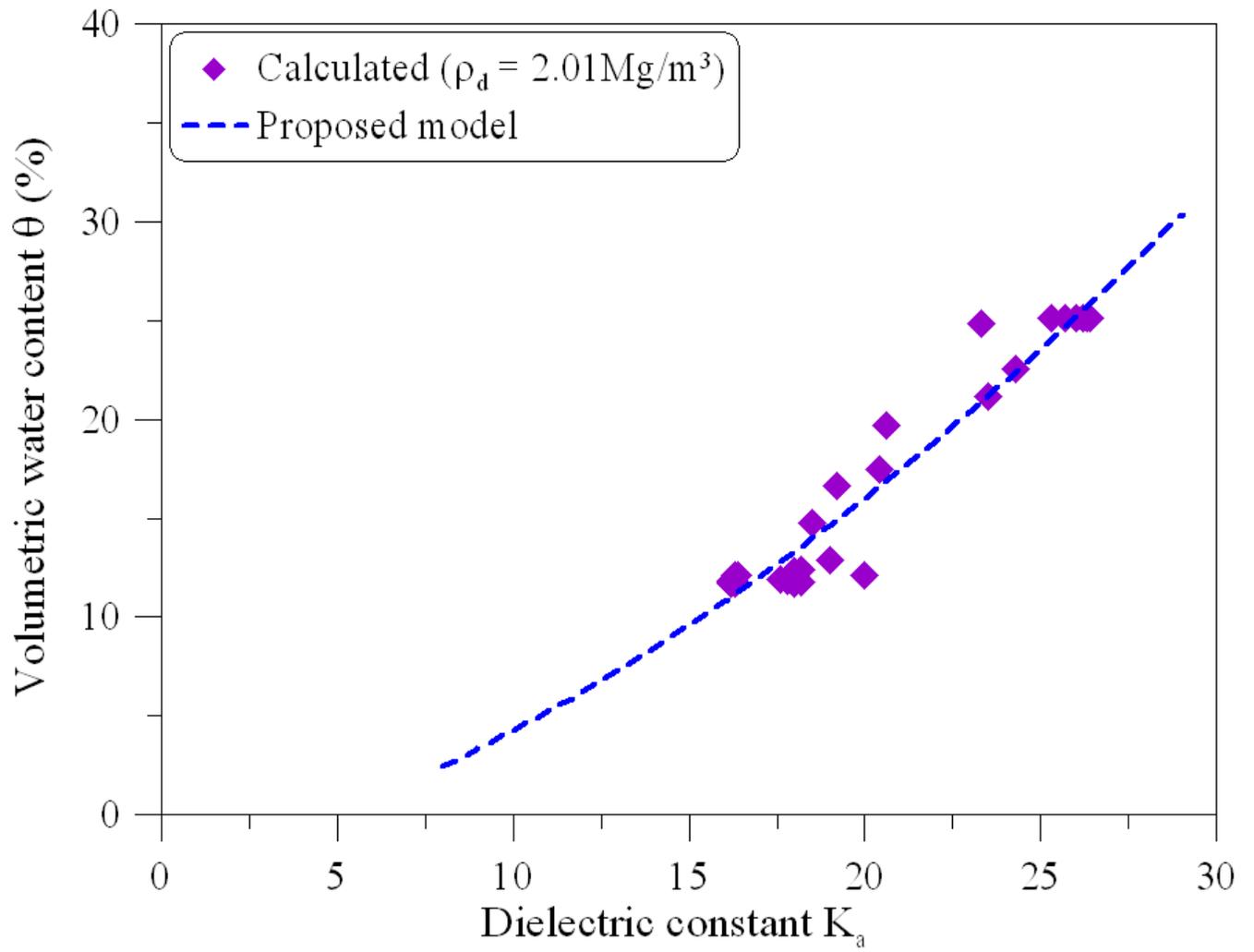
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480 **Figure 1. Grain size distributions of fouled ballast and sub-soil from the S nissiat site**



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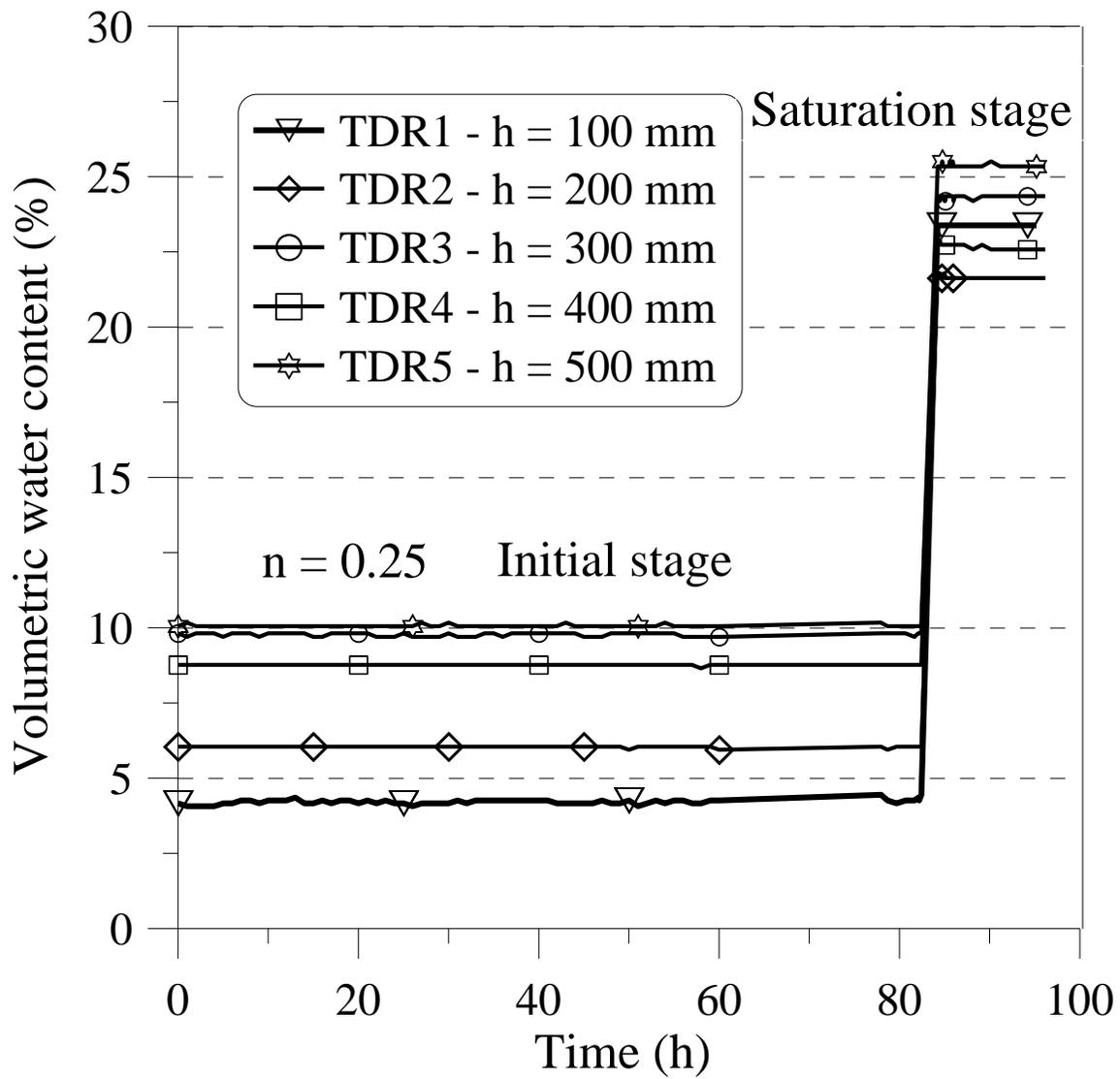
482 Figure 2. Schematic view of the infiltration column



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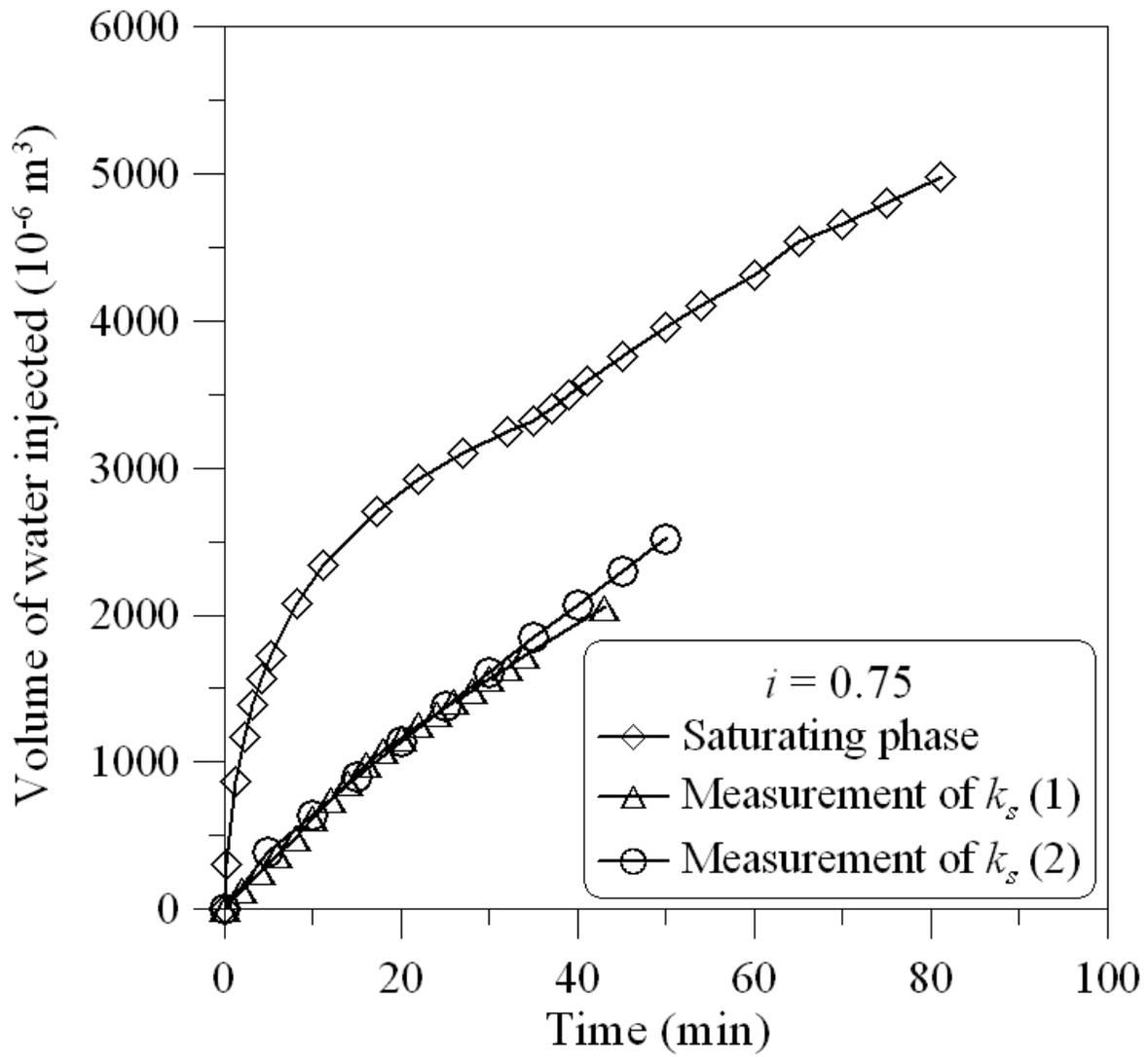
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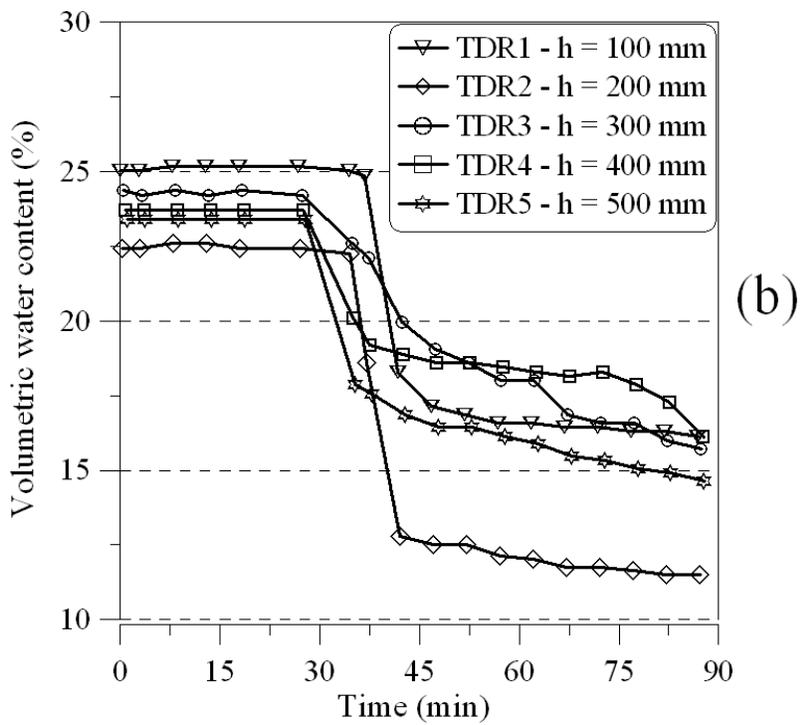
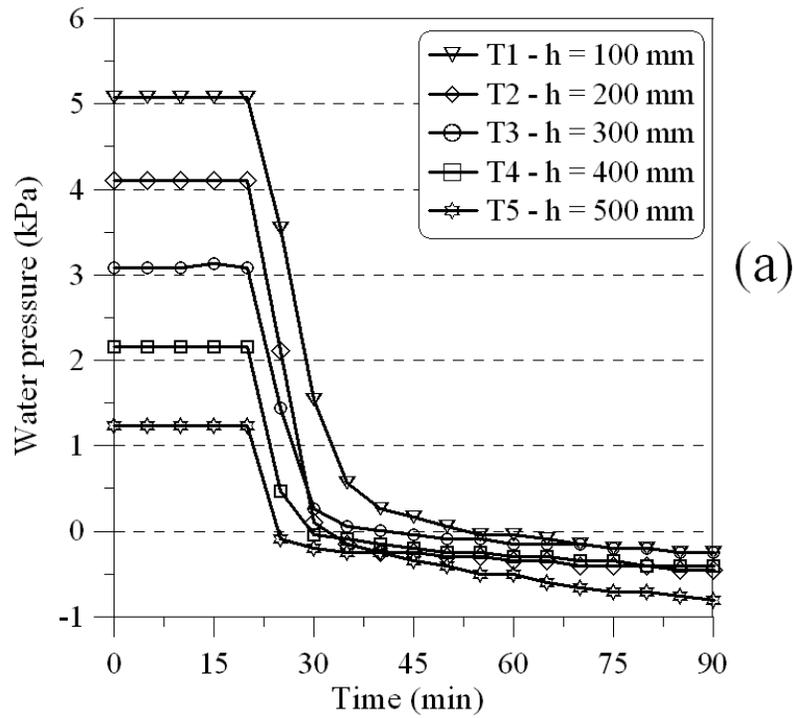


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Figure 4. Volumetric water content – in the initial stage and in the saturation stage



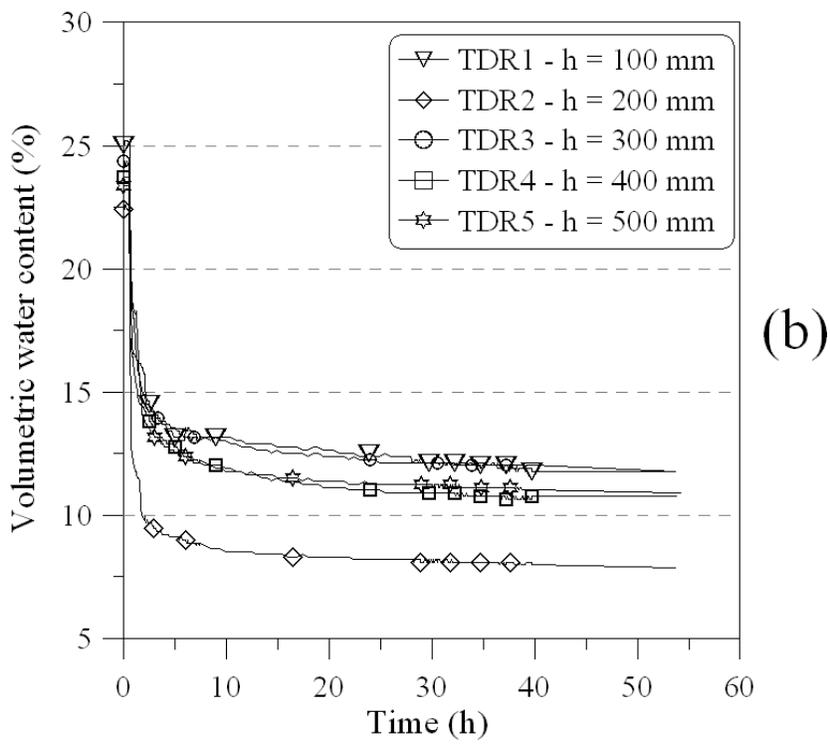
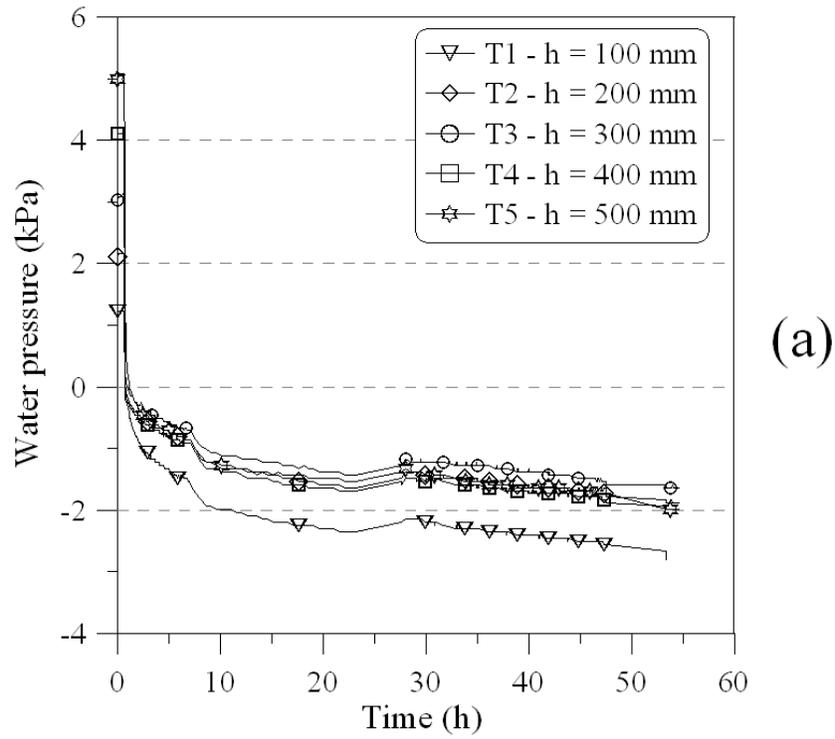
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492 Figure 5. Water volume injected during saturation and hydraulic conductivity measurements



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Figure 6. Water pressure (a) and volumetric water content (b) evolution from 0 to 90 min – drainage stage

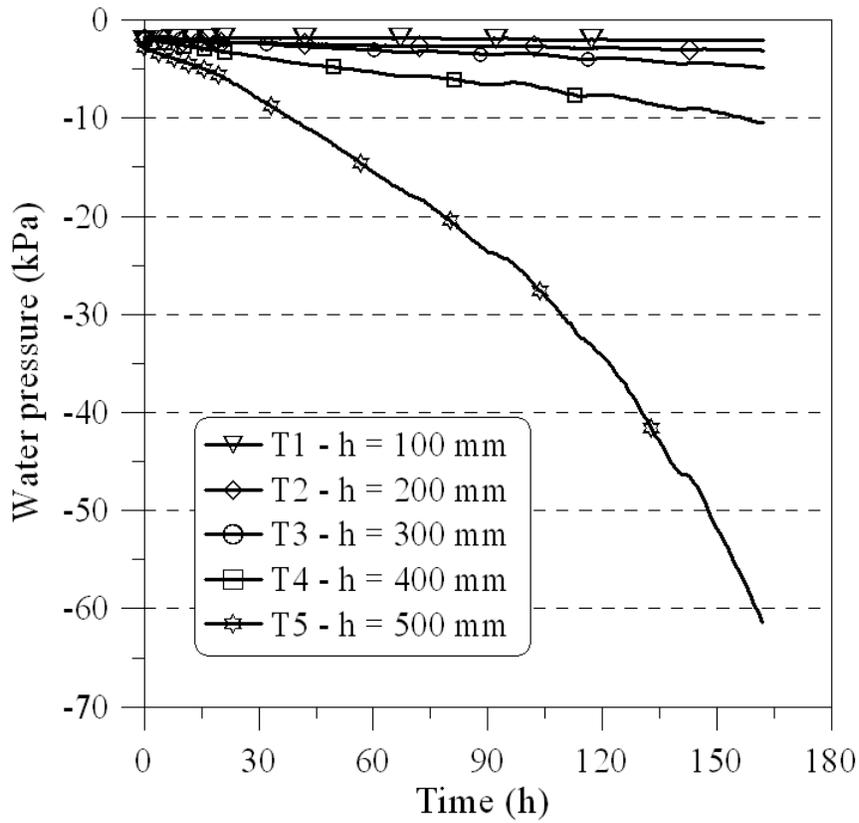


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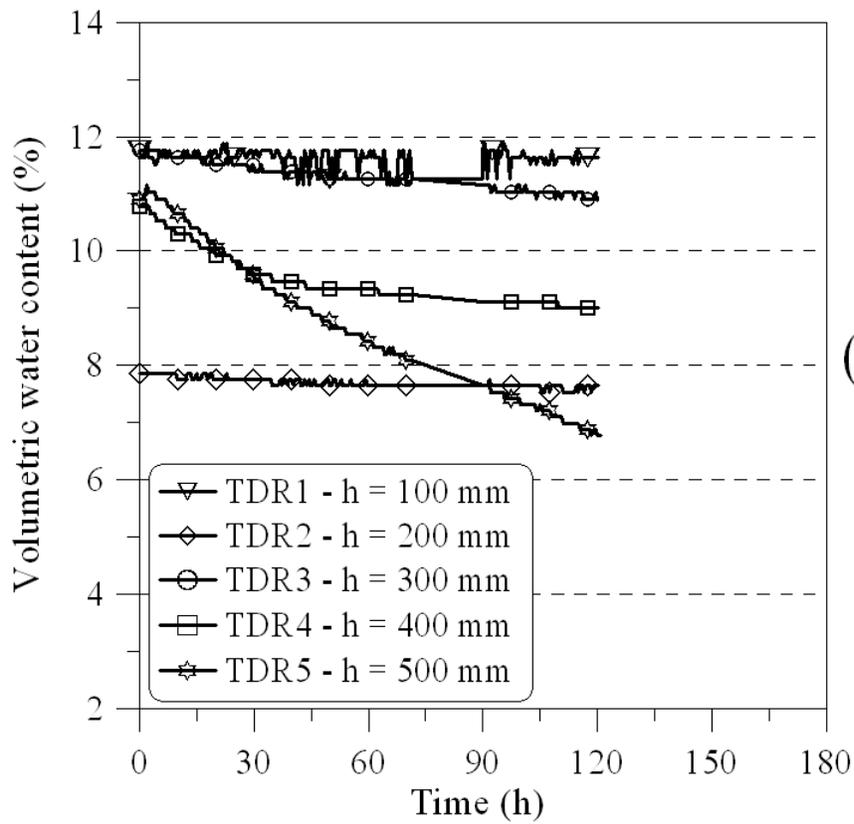
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(a)



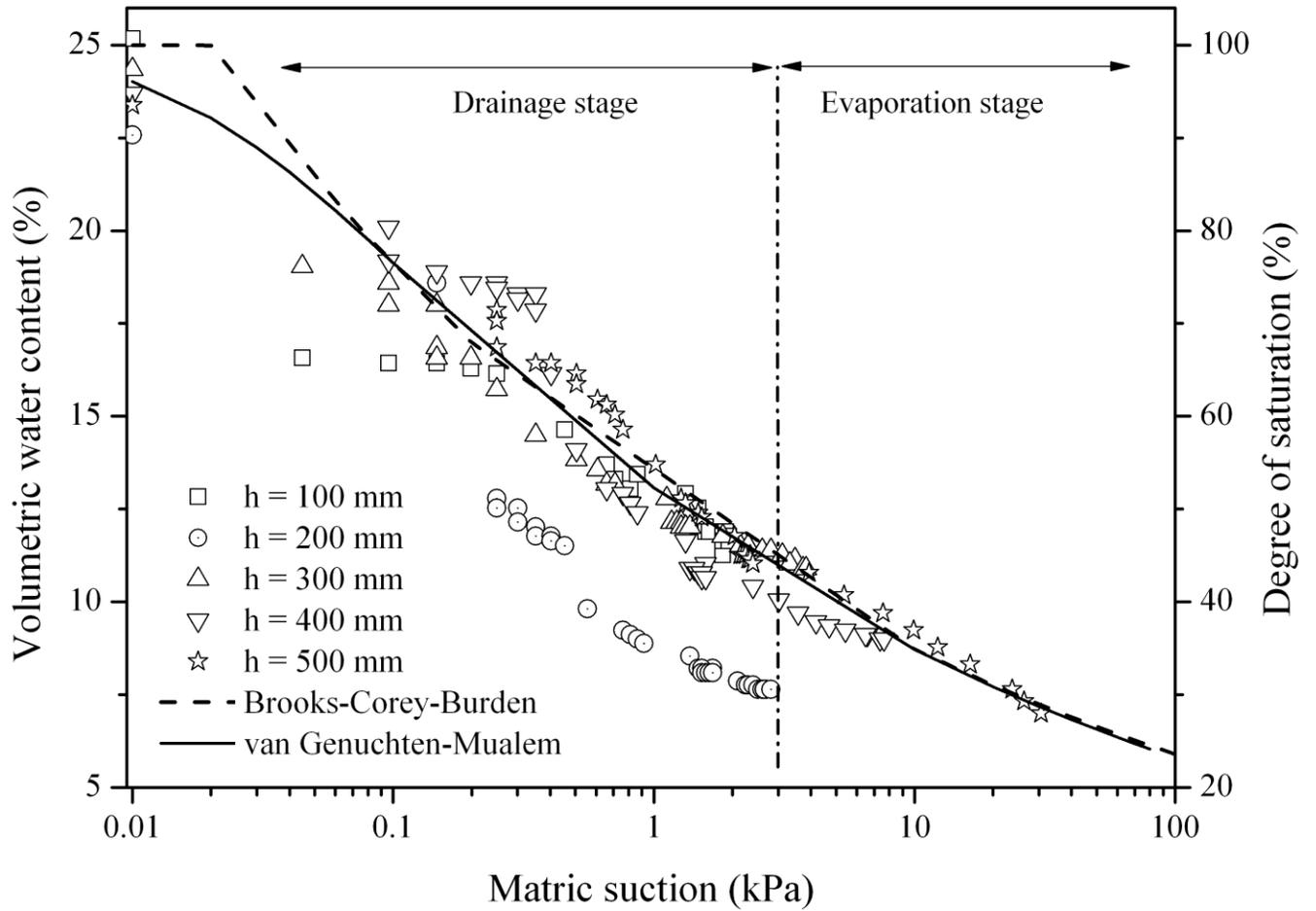
(b)

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Figure 8. Water pressure (a) and volumetric water content (b) evolution – evaporation stage

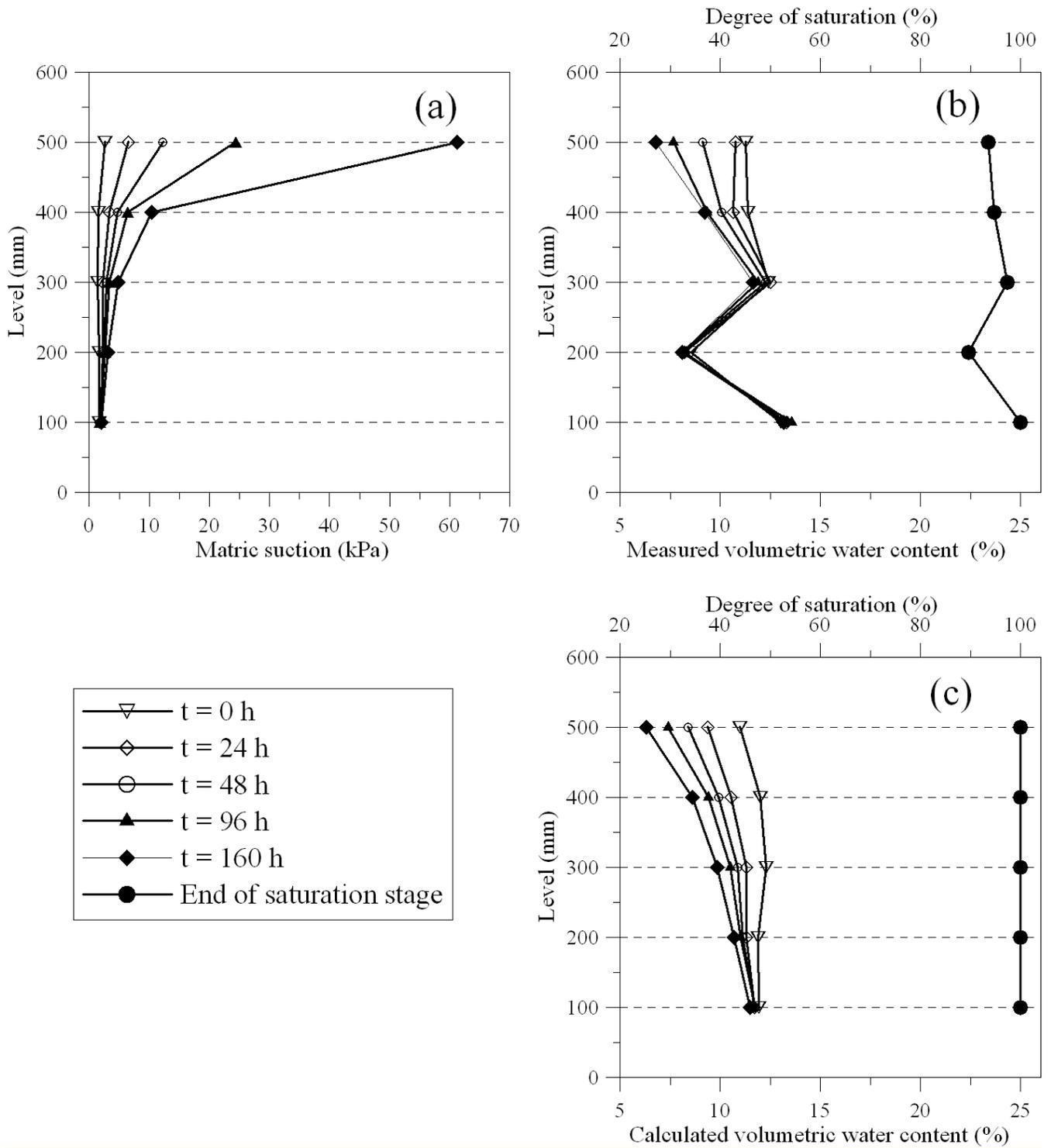
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 504 **fitted to independent data**

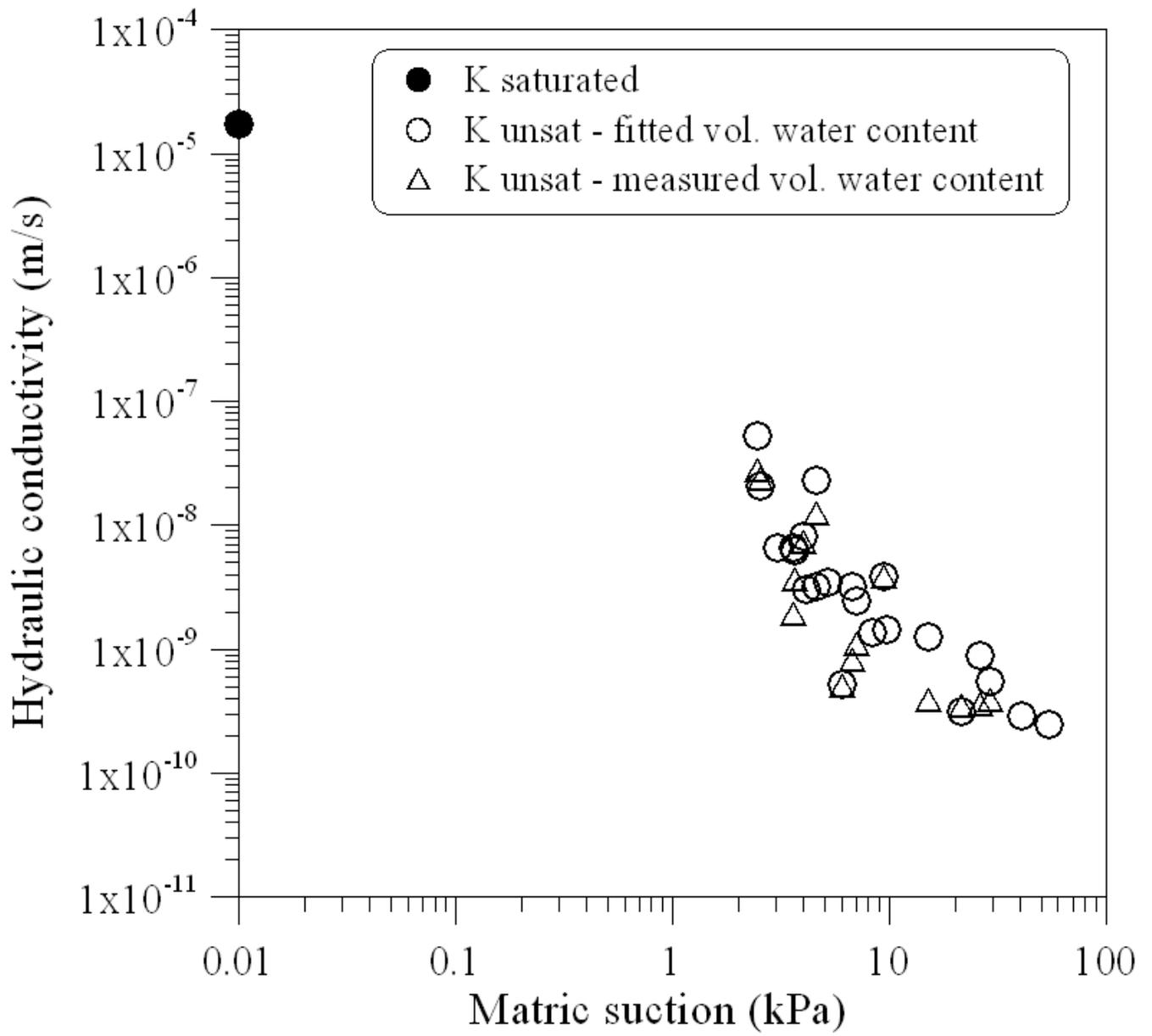
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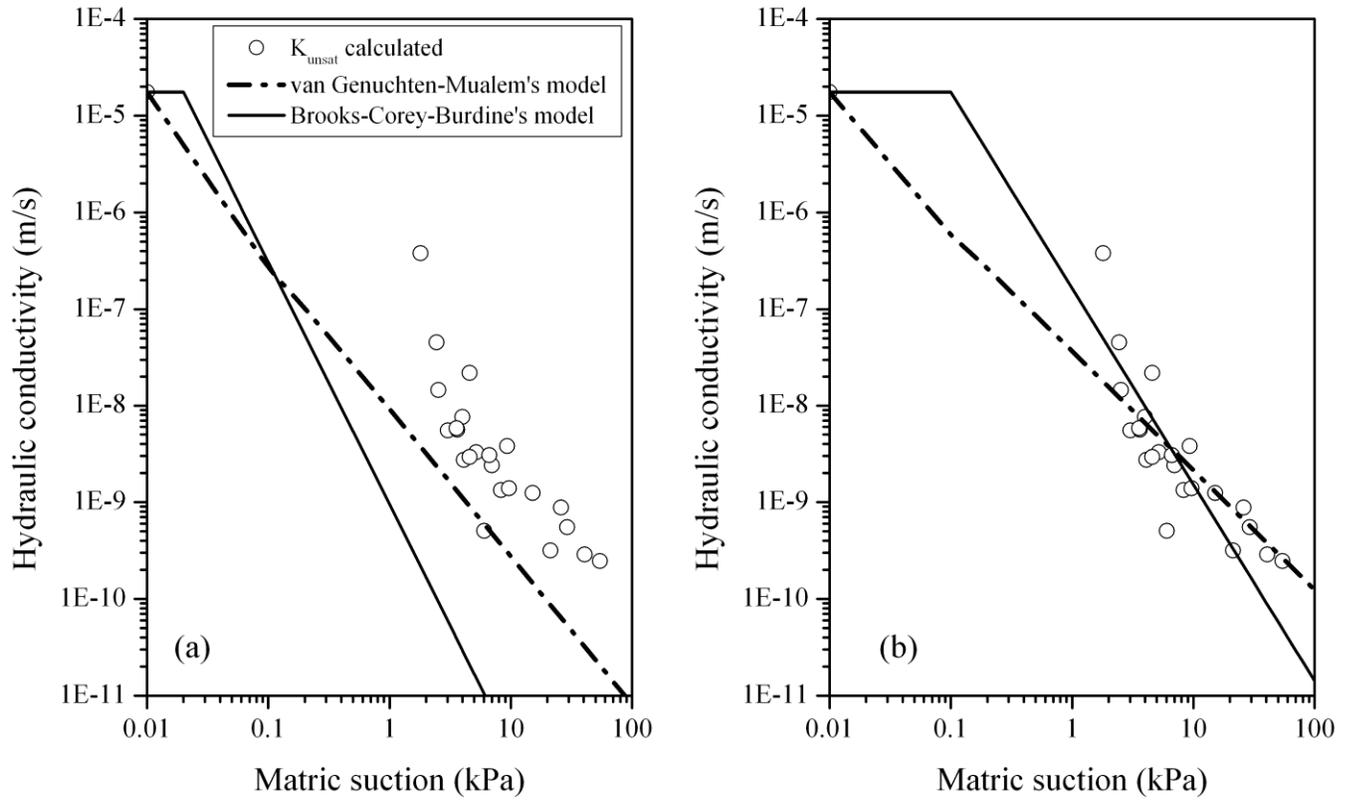
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