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# A Device for the Simultaneous Determination of the Water Retention Properties and the Hydraulic Conductivity Function of an Unsaturated Coarse Material; Application to a Green-Roof Volcanic Substrate

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1 A device for the simultaneous determination of the water retention properties and  
2 the hydraulic conductivity function of an unsaturated coarse material; application to  
3 a green-roof volcanic substrate

4  
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24 **Abstract**

25 The determination of the water retention curve (WRC) and the hydraulic conductivity function  
26 (HCF) of a specific volcanic coarse granular material used as a substrate for urban green roofs in  
27 Europe was carried out on a newly developed specific device in which low suctions, typical of  
28 coarse granular materials, were controlled. Smaller suctions (up to 32 *kPa*) were imposed by  
29 using a hanging column system and larger suctions (between 32 and 50 *kPa*) were imposed by  
30 using the axis translation technique in the same cell. The changes in suction during the tests were  
31 monitored by using a high accuracy differential pressure transducer. They were also used to  
32 determine the hydraulic conductivity function by means of both **Kunze and Kirkham** and  
33 Gardner's method. **The former technique was used at low suctions (< 4 *kPa*) to account for the**  
34 **impedance effects due to the high air entry value ceramic porous disk and the latter was used**  
35 **between 4 and 50 *kPa*.** Good comparability was observed in the data from both methods,  
36 demonstrating the good performance of the device. **The mathematical expressions of the water**  
37 **retention curve of van Genuchten and Brooks and Corey were used, and a good fitting with our**  
38 **experimental data was obtained. Conversely, the hydraulic conductivity functions derived from**  
39 **these expressions appeared to lead to a significant under-estimation, confirming the need of**  
40 **operational and simple device for the experimental determination of the HCF.** Also, this material  
41 proved to be an appropriate material for green urban infrastructures, due to light weight,  
42 **satisfactory water retention capability** and hydraulic conductivity.

43  
44 Key words: Green-roof material; water retention; hydraulic conductivity; hanging column; axis  
45 translation; Gardner's method; Kunze and Kirkham's method

46

## 47 1. Introduction

48 Within the context of global warming, green roofs are considered as an efficient option to reduce  
49 the urban heat island (UHI) effect that characterizes large contemporary urban concentrations,  
50 thanks to the evapo-transpiration of the vegetal (lawn or trees) grown on them. Green roofs are  
51 also interesting to reduce urban run-off. The substrates used in green roofs have to be light  
52 enough and to present satisfactory water retention and transfer properties. Volcanic granular  
53 substrates appear to be relevant in this context, and they are frequently used in green roofs, like  
54 for instance in the case of the “Green Wave” of the Bienvenue building (Versini et al. 2017)  
55 located close to Ecole des Ponts ParisTech in the Descartes campus of Marne la Vallée, 18 km  
56 east of Paris (*Figure 1*). The green roof is covering three waves or 260 m length and 80 m wide,  
57 on which a 20 cm thick layer of substrate has been placed. Actually, the use of substrates in urban  
58 green roofs appears to be rather empirical to date, and very little data on their water retention and  
59 transfer properties are available.

60 In this context, the paper describes the development and use of a specific controlled suction  
61 device, based on both a tensiometry principle, through the hanging column technique, and the  
62 axis translation method. The device is used to determine the water retention and transfer  
63 properties of a volcanic substrate (VulkaTec Riebensahm GmbH 2016, Germany;  
64 [www.vulkatec.de](http://www.vulkatec.de)) used in the Green Wave roof presented in *Figure 1*. Tensiometry controlled  
65 suction was applied by means of the hanging column technique by connecting a tube to a ceramic  
66 porous stone of 50 kPa air entry value on which a sample placed, and by imposing in the tube a  
67 water level lower than that of the sample. The axis translation method was implemented by using  
68 by applying air pressure on the top of the sample. The device was also used to determine the  
69 hydraulic conductivity function during the transient phases resulting from step increases in  
70 suction, by using the method proposed by Gardner (1956), accounting when necessary for the

71 impedance effects due to the permeability of the ceramic porous stone, by using Kunze and  
72 Kirkham (1962)'s method.

73

## 74 2. Material and methods

### 75 2.1. Material

76 The VulkaTec volcanic material is presented in the photo of *Figure 2* and its main characteristics  
77 are presented in *Table 1*. The material is very light with an average dry density of  $1100 \text{ kg/m}^3$  so  
78 as not to load the roof significantly. A percentage of 4 % of organic matter was determined by  
79 using the French standard XPP94-047 1998, that consists in comparing the sample weight before  
80 and after heating during at least 3 hours at temperature between 450 and 500 °C. The grain size  
81 distribution curve of the substrate, determined by sieving following the French standard NFP94-  
82 056 (1996) is presented in *Figure 3* (solid line). The distribution of fine particles ( $< 80 \mu\text{m}$ ) was  
83 obtained by sedimentation according to French standard NFP94-057 (1992). It can be noticed that  
84 50% of the grains are larger than 1.6 mm with 10 % particles between 10 and 20 mm, in the  
85 coarse range and 13 % fine particles smaller than  $80 \mu\text{m}$ . Also represented in *Figure 3* (dashed  
86 curve) is the grain size distribution curve of the material used for the test, with all particles  
87 smaller than 6 mm. Particles larger than 6 mm were discarded because we used a 70 mm diameter  
88 cell. For the same volume, a specimen with large particles discarded will contain more small  
89 particles, resulting in a larger porosity, in more water retained at a given suction, and in a larger  
90 hydraulic conductivity. Given that the proportion of the coarse particles discarded is 20%, a  
91 rough estimation of the over-estimation could be between 10 and 20 %. In *Table 1* are also  
92 presented the curvature coefficient  $C_c$  ( $C_c = (D_{30})^2 / (D_{60} \times D_{10}) = 1.95$ ) and the uniformity

93 coefficient  $C_u$  ( $C_u = D_{60}/D_{10} = 55$ ). According to ASTM D2487-00 (2000), the material can be  
94 regarded as well graded.

95

## 96 **2.2. Methods of controlling suction**

97 The various methods of controlling suction in soils include the hanging column technique  
98 (Buckingham 1907), the axis translation technique (Richards 1941, 1947), the osmotic technique  
99 (Zur 1966) and the vapour equilibrium technique (Esteban 1990). A detailed description of these  
100 techniques and of their adaptation in geotechnical testing can be found in Delage (2002),  
101 Vanapalli et al. (2008), Blatz et al. (2008), Delage and Cui (2008) and Fredlund et al. (2012).

102

103 Given that the volcanic substrate investigated here is granular with rather large grain sizes (see  
104 *Figure 2*), it was initially decided to use the hanging column technique, because of its simplicity  
105 to use and of its good accuracy in both the control of low suctions and the measurement of water  
106 exchanges. However, one realized during the preliminary tests that, at the largest height imposed  
107 in the hanging column technique (3.2 m, corresponding to a suction of 32 kPa), a significant  
108 amount of water still remained in the substrate. It was then decided to impose larger suctions by  
109 using the axis translation technique.

110 In both cases, tests were conducted on a 24 mm high specimen placed into a metal 70 mm  
111 diameter cylindrical cell, in contact at its bottom with a 50 kPa air entry value ceramic porous  
112 disk. A thin metal disk (2 mm thick) was placed on top of the sample, so as to monitor changes in  
113 height by means of a displacement sensor (Mitutoyo Brand).

114

115 *The Hanging column technique*

116 The implementation of the hanging column technique is presented in *Figure 4*. The cell is  
117 connected at its base through valve V2 to an outlet controlled by valve V3 and to a water  
118 reservoir through valve V1. The cell is also connected through a central tube to a mobile device  
119 that allows the imposition of water levels lower than that of the sample, so as to apply suction  
120 defined by the difference in water level between the sample and the mobile part (up to 32 kPa at  
121 the maximum height of 3.2 m).

122  
123 The mobile device contains a smaller inner glass tube of  $d_{inn} = 0.5 \text{ cm}$  and larger outer glass tube  
124 of diameter  $d_{out} = 1.5 \text{ cm}$ . The inner tube is connected to the sample while the differential  
125 pressure transducer is connecting the outer tube with the reference glass tube (*Figure 5*). This  
126 pressure transducer (0.1 mm accuracy in water height) is able to provide high frequency  
127 measurements that are necessary for the determination of the hydraulic conductivity function. A  
128 monitoring rate of 10 s was adopted, chosen small enough to capture the change in the capillary  
129 potential at small times through the change of the water level in the mobile device. This change is  
130 detected as the height difference between the water levels either in the inner (valve V4 opened) or  
131 the outer tube (valve V5 opened), and the water level in the reference tube used to indicate  
132 constant reference water level. Most tubes used in the set-up are semi-rigid tubes made up of  
133 polyamide, except that used in the mobile device (inner and outer tubes) and the reference tube  
134 that are made up of glass.

135  
136 The determination of the WRC along the drying path was carried out as follows:  
137 Saturating the whole system: before starting, all the system has to be saturated, particularly the  
138 tubes connected to the differential pressure transducer, because air bubbles in the tubes can result  
139 in misleading data. Saturation was done by placing the reservoir filled with demineralized de-

140 aird water above the sample (*Figure 4*) and by opening valves V1 and V2 to let water infiltrate  
141 the sample from the bottom to the top. Saturation was considered satisfactory when a thin layer of  
142 water was observed on the sample top. Note that, whereas this procedure was satisfactory to  
143 saturate the large inter-grains pores, the full saturation of the small pores existing within the fine  
144 fraction ( $13\% < 80 \mu m$ ) was less guaranteed. To improve saturation, the water circulation  
145 between the bottom and the top of the specimen was let during one night. Then, valves V1 and  
146 V2 were closed. Prior to running the test, the mobile device was placed in such a position that the  
147 top of the inner tube full of water was at the same level as the top of the sample, resulting in  
148  $h_k = 0$  (*Figure 4*). In order to check whether equilibrium was ensured, valve V2 (*Figure 4*) was  
149 opened. If there was no water movement in the inner tube, the experiment could start. Otherwise,  
150 the saturation procedure was repeated.

151 Imposing suction: two methods were used, according to the value of suction imposed.

152 i) At smaller suctions, starting from saturation, it was observed that suction increases mobilized a  
153 significant volume of extracted water. Suction was then imposed by closing valves V2 and V5,  
154 by filling the inner tube up to the top and by moving down the mobile device at a position  
155 corresponding to the required suction. The water levels in the reference and outer tubes were  
156 carefully adjusted at the starting level in both tubes (*Figure 5a*). The imposed suction was  
157 defined by the difference in height between the top of the sample and the water level at the top of  
158 the inner tube ( $h_k$  in *Figure 4*). Valves V2 and V5 were then opened, resulting in water being  
159 extracted from the sample under the effect of increased suction. The extracted volume of water  
160 ( $\Delta V$  in *Figure 4*) flows from the top of the inner tube into the outer tube. It is monitored by the  
161 differential pressure transducer that measures the height difference between the water levels in  
162 the outer and reference tubes ( $\Delta H_1$  - *Figure 5a*). Once equilibrium is reached (after approximately



163 10 – 12 hours), a point on the WRC is obtained from the pair of values  $(\theta_i, h_{k,i})$  from the  
164 following equation:

$$165 \quad \theta_i = \theta_{i-1} - \Delta V_i / V_{\text{sample},(i-\frac{1}{2})} \quad (1)$$

166 where  $\Delta V_i$  is the volume of water [L<sup>3</sup>] extracted from the sample,  $V_{\text{sample},(i-\frac{1}{2})}$  the average sample  
167 volume [L<sup>3</sup>] between the end and the start of the test, determined from the monitored changes in  
168 height of the sample and  $\theta_i - \theta_{i-1}$  the difference in volumetric water content [-] between the end  
169 and the start of the test. Note however that the monitoring of the changes in sample height during  
170 the tests indicated very small changes smaller than 0.5 mm (2%) along the whole test made up of  
171 13 step increases in suction. The changes in height during each step were hence neglected.

172 ii) At larger suctions, the quantity of extracted water appeared to be much smaller and the  
173 procedure was changed to improve accuracy. The initial water level in the inner tube was no  
174 longer imposed at its top, but adjusted (by means of valve V3) at a lower level, in such a way that  
175 overflow was avoided during water extraction from the sample. The changes in height in the  
176 inner tube were then directly measured by the differential pressure transducer by closing valve  
177 V5 and opening valve V4. The imposed suction was calculated at the end of the measurement  
178 from the difference in height between the final water level in the inner tube and the top of the  
179 sample ( $\Delta H_2$  - Figure 5b).

180 Before each new suction step, water levels in the outer (i) / inner (ii) and reference tubes were  
181 adjusted to the same level by opening the bypass valve (Figure 5), in order to reset the  
182 differential pressure transducer. Water levels in the outer (i) / inner (ii) and reference tubes were  
183 then set to the required initial levels by carefully using valve V3, in order to eliminate extra water  
184 through the outlet.

185

186 In this study, only the drying path was considered. But the apparatus can also be used along  
187 wetting paths, along the following steps:

188 W1. Setting the initial position: the initial position of the mobile part is at the lowest vertical  
189 level, i.e. the final position at highest suction reached during the drying path. The sample is hence  
190 capable to store more water, thus a higher change in water level is expected. The water level  
191 change is recorded in the outer tube while the inner tube is filled up with water to the top, and no  
192 longer used during the test. Initial water levels in the outer and reference tubes should be set at  
193 the top of the inner tube by opening valves V1, V4 and bypass and letting water flow over the top  
194 of the inner tube. After reaching the required position, all valves and bypass should be closed.

195 W2. Imposing suction: by opening valves V5 and V2, water from the outer tube enters the  
196 sample. The resulting decrease in water level in the outer tube is captured by the differential  
197 pressure transducer.

198 W3. Reaching equilibrium: once equilibrium is reached, suction is calculated as the height  
199 difference between the water level in the outer tube and the top of the sample. The corresponding  
200 water content is calculated like during the drying path, but with an opposite sign because water  
201 content is now increasing after each measurement ( $\theta_i = \theta_{i-1} + \Delta V_i / V_{\text{sample},(i-\frac{1}{2})}$ ).

202 W4. Decreasing suction: to impose a lower suction, the mobile device is elevated, the outer  
203 and reference tubes are filled again, as described in step W1, and the W2 procedure is repeated.

204 When a smaller change in water level in the outer tube is expected (lower suctions, higher water  
205 content), the inner tube should be used, by closing valve V5 and using valve V4, unlike in step

206 W2.

207 W5. Final state of the wetting path: in order to saturate the sample, the mobile device should  
208 be located at the initial position of the drying path with the water levels in the inner and reference

209 tubes corresponding to the sample top. In case of a difference in height between the level in the  
210 inner tube and the top of the sample (if  $h_k$  marked in *Figure 4* is higher than zero) after reaching  
211 equilibrium, the tubes should be refilled with water by opening valves V1, V4 and the bypass.  
212 After closing valve V1 and the bypass and opening valve V2, without changing the vertical  
213 position of mobile device, no water movement in the inner tube should occur. If this is not the  
214 case, it means that the sample is not fully saturated and the refilling procedure should be  
215 repeated.

216 As commented above, the hanging column technique was used for heights up to 3.2 *m*  
217 corresponding to a maximum suction of 32 *kPa*. For higher suctions, the axis translation  
218 technique was applied.

219

#### 220 *The axis translation technique*

221 The axis translation technique was carried out by applying increasing air pressure on the top  
222 sample surface. To do so, a cap connected to the air pressure supply source was placed on the top  
223 of the cell, as indicated in *Figure 6*. Tests were carried out while keeping the sample and the  
224 mobile device at the same level, above the differential manometer in order to monitor the changes  
225 in height difference. The imposed suction was calculated as the difference between the air  
226 pressure applied on the sample's upper surface and the change of water level inside the inner  
227 tube.

228 Before each test, the water level in the inner tube should be put at the same level as the top of the  
229 sample, and some space should be left above the water level to allow for some level increase with  
230 no overflow during the measurement. Once the air pressure is imposed, valves V2 and V6 are  
231 simultaneously opened, resulting in an increase of the water level in the inner tube, until  
232 stabilization at equilibrium. The final suction is calculated as the difference between the applied

233 air pressure and the pressure corresponding to the water level increment in the inner tube,  
234 captured by the pressure transducer. The corresponding water content is calculated by using  
235 Equation (1). This methodology was applied for suctions up to 50 *kPa*, the air entry value of the  
236 ceramic disk used. Higher suctions could be obtained with higher pressure and a ceramic disk of  
237 higher air entry value.

238

### 239 **2.3. Determination of the hydraulic conductivity function**

#### 240 *Saturated state*

241 The investigation on the hydraulic conductivity function (HCF) of the material started with the  
242 determination of the saturated one. To do so, the cell containing the sample was disconnected  
243 from the device and connected to a Mariotte's bottle filled with demineralized, de-aired water, so  
244 as to run a constant head permeability test. Once the sample was saturated, the position of the  
245 bottom of the thin tube that goes through the Mariotte's bottle was set in such a way that the  
246 difference in height between the bottom of the thin tube and the top surface of the sample  
247 represented the imposed water head  $\Delta H$  [L]. The water level in the Mariotte's bottle had always  
248 to be above the bottom of the thin tube, in order to ensure a constant imposed water head. By  
249 measuring the water level change in the Mariotte's bottle  $\Delta H$  [L] and the time necessary for  
250 obtaining this change  $\Delta t$  [T], the flux  $q$  [L/T] can be calculated.

$$251 \quad q_n = \frac{\Delta H_n A_{\text{mariotte}}}{\Delta t_n A} \quad n = 1, 2, 3 \quad (2)$$

252 where  $A_{\text{Mariotte}}$  is the cross-section area of the Mariotte's bottle, decreased by the area of the thin  
253 tube. The saturated hydraulic conductivity  $K_s$  is then calculated using Darcy's law.

$$254 \quad K_{s,n} = \frac{q_n}{\Delta H_n} H_{\text{sample}} \quad n = 1, 2, 3 \quad (3)$$

255 The procedure was repeated for three different imposed water heads ( $n = 1, 2, 3$ ), that were  
256 adjusted by changing the altitude of the bottom of the thin tube.

257

258 *Unsaturated states*

259 The various existing methods of measuring the hydraulic conductivity functions in unsaturated  
260 have been described in various papers or textbooks including Masrouri et al. (2008) and Fredlund  
261 et al. (2012). In steady state methods (Corey 1957, Klute 1972, Olsen et al. 1985, among others),  
262 a constant flow is imposed in a specimen put under given values of controlled suction. These  
263 methods are known to be rather long and tedious, due in particular to the need of very precisely  
264 measuring tiny transient flows along rather long periods of time. Alternatively, transient methods,  
265 in which the water outflow from the specimen submitted to suction steps is monitored (Gardner  
266 1956, Miller and Elrick 1958, Kunze and Kirkham 1962), are known to be easier to perform, with  
267 simpler equipment (Masrouri et al. 2008). For these reasons, transient methods were used in this  
268 work.

269 The HCF was hence determined by applying suction steps and monitoring the resulting changes  
270 in water content  $V(t)$  with time until equilibration, by means of the differential pressure  
271 transducer. It was planned to calculate the hydraulic conductivity of the specimen by using  
272 Gardner's method (Gardner 1956). This method assumes that the change in suction for each step  
273 is small, in such a way that the diffusion coefficient  $D(h_k)$  can reasonably be considered constant  
274 during the test:

$$275 \quad D(h_k) = D = \frac{K(h_k)}{C(h_k)} = \frac{K(h_k)\Delta h_k}{\Delta\theta} \quad (4)$$

276 where  $C(h_k)$  is the average slope of the WRC [ $L^{-1}$ ] along the suction step corresponding to  $\Delta h_k$   
277 [L] and  $K(h_k)$  is the hydraulic conductivity [L/T]. Based on the analytical solution of the diffusion

278 equation expressed in terms of a Fourier series, Gardner proposed an estimation of the water  
279 conductivity using the monitored volume  $V(t)$  [L<sup>3</sup>] of water extracted from the sample:

$$280 \quad V(t) = V_{\infty} \left( 1 - \frac{8}{\pi^2} \sum_{n=1,3,5,\dots}^{\infty} \frac{1}{n^2} e^{-\left(\frac{n}{2}\right)^2 \pi^2 \frac{t}{T}} \right) \quad (5)$$

$$281 \quad T = \frac{H_{sample}^2 C(h_k)}{K(h_k)} = \frac{H_{sample}^2}{D} \quad (6)$$

282 where  $V_{\infty}$  is the total amount of water extracted during the suction step [L<sup>3</sup>]. As commented  
283 above, we observed in this work that the sample height  $H_{sample}$  remained reasonably constant, we  
284 hence adopted  $H_{sample} = 2.4 \text{ cm}$ .

285 Gardner's method is based on the fact that only the first member ( $n = 1$ ) of the Fourier series in  
286 Equation (5) can be taken into account as a reasonable approximate solution, acceptable after  $t >$

287  $t_{bound} = \frac{4H_{sample}^2}{3\pi^2 D}$ . In such conditions, the equation corresponding to the first member of

288 Equation (5) can be written as:

$$289 \quad \ln[V_{\infty} - V(t)] = \ln \frac{8V_{\infty}}{\pi^2} - \pi^2 \frac{Dt}{4H_{sample}^2} \quad (7)$$

290 showing that the term  $\ln[V_{\infty} - V(t)]$  becomes a linear function of time  $t$ , with a slope depending  
291 on the diffusion coefficient  $D$ .

292 The hydraulic conductivity  $K(h_k)$  can then be calculated using the following equation:

$$293 \quad K(h_k) = \frac{D\Delta\theta}{\Delta h_k} \quad (8)$$

294 The experimental data obtained in this work indicated that Gardner's method is more relevant at  
295 higher suctions, in which i) less water exchanges occurred, ii) the condition of constant suction is  
296 ensured and iii) the assumption about a constant diffusion coefficient  $D$  is more satisfactorily  
297 fulfilled.

298 However, Gardner's method cannot be directly used when the saturated hydraulic conductivity of  
299 the ceramic disk is smaller than that of the sample. Experimental data showed that this occurred  
300 during the first steps at low suction from the saturated state, during which higher hydraulic  
301 conductivity values are obtained. To cope with the cases in which impedance effects due to the  
302 ceramic disk occur, the method proposed by Kunze and Kirkham (1962) was adopted.

303

#### 304 *Kunze and Kirkham's method*

305 Kunze and Kirkham (1962) considered the solution of the consolidation equation applied for  
306 various layers of soil with different hydraulic conductivities. Their solution is graphically  
307 presented through various curves showing the changes in  $V(t)/V_\infty$  with respect to the variable  
308  $\lambda_1^2 Dt / H_{sample}^2$  (see *Figure 11*), in which the parameter  $\lambda_1$  is the first solution of equation  
309  $a\lambda_n = \cot\lambda_n$  and  $a$  is the ratio between the impedance of the ceramic disk and that of the sample.  
310 The various curves in *Figure 11* correspond to various values of parameter  $a$ .

311 In order to determine the hydraulic conductivity  $K(h_k)$  of the sample, it is required to estimate  
312 parameters  $a$  and  $\lambda_1$ , by fitting the experimental data (presented in the form  $V(t) / V_\infty$  versus  $t$ )  
313 with one of the theoretical curves. Kunze and Kirkham (1962) remarked that only a portion of the  
314 experimental data corresponded to the theoretical curves, so they recommended to rather fit the  
315 curves at small times, for which more accurate values of  $\lambda_1^2$  are obtained. The choice of the  
316 adequate theoretical curve provides the value of parameter  $a$ . It is then possible to determine the  
317 corresponding parameter  $\lambda_1$  from the table presented in the paper of Kunze and Kirkham (1962).  
318 It is also necessary to graphically determine the reference time  $t_{RP}$  that corresponds to  
319  $\lambda_1^2 Dt / H_{soil}^2 = 1$  (vertical arrow in *Figure 11*). Finally, the diffusion coefficient is calculated as  
320  $D = H_{soil}^2 / \lambda_1^2 t_{RP}$  and the hydraulic conductivity as  $K = D\Delta\theta / \Delta h_0$ .

321

322 Another way to explore a possible impedance effect due to the ceramic porous disk is to apply  
323 Darcy's law to the flux going through the saturated ceramic disk, as follows:

$$324 \quad h_{k,top} = h_k + \Delta z_s \frac{\Delta V}{\Delta t} \frac{1}{A_{cs} K_{cs}} \quad (9)$$

325 where  $h_{k,top}$  is the suction [L] at the top of the ceramic disk,  $\Delta z_s$  its thickness [L],  $A_{cs}$  its cross  
326 section area [L<sup>2</sup>] (7 cm diameter), and  $\Delta V$  is the volume [L<sup>3</sup>] extracted from the sample during the  
327 time interval  $\Delta t$  [T].

328 The change in suction at the top of the ceramic disk can hence be derived from the monitoring of  
329 the extracted water volume  $\Delta V$  with respect to time. In the lack of any impedance effect, both  
330 suction values at top and bottom should be equal.

331

### 332 3. Experimental results

#### 333 3.1. Water retention curve

334 *Figure 7* shows the continuous monitoring of the changes in suction with both the hanging  
335 column technique (steps 1 to 10) and the axis translation technique (steps 11 to 13). The outer  
336 tube was used for steps 1 and 2 that mobilized larger water volumes (valve V4 closed, valve V5  
337 opened, see *Figure 5a*), while the subsequent 11 steps (3 – 13) were made by using the inner tube  
338 (valve V4 opened, valve V5 closed, see *Figure 5b*). In the former case, the imposed suction  
339 remains constant (*Figure 8a*, solid line with squares – the dashed line with triangles will be  
340 commented later on), while in the latter case (3 - 13), the initial instantaneous drop in height  $\Delta h_o$   
341 (increase in suction) is followed by a slight progressive increase in height, corresponding to a  
342 slight decrease in suction (see for example steps 11 - 12 in *Figure 8b*).



343 The corresponding drying path of the WRC is presented in *Figure 9*, in which the changes in  
 344 volumetric water content  $\theta$  are plotted with respect to changes in suction. The curve evidences a  
 345 significant decrease in water content for the initial steps at low suctions, with  $\theta$  decreasing from  
 346 the initial value of 0.45 down to 0.29 upon application of the first suction step of 2.1 *kPa*. The  
 347 increment in volumetric water content progressively decreases afterwards, with a decrease in  $\theta$  to  
 348 0.25 at a suction of 4.2 *kPa*. The curve finally becomes almost linear at suction larger than  
 349 14.2 *kPa*, indicating that the further suction increments extract small quantities of water. A final  
 350 value of 0.16 is reached at 49.6 *kPa*. Good compatibility is observed between the section  
 351 obtained with the hanging column technique (1 – 10) and that with the axis translation method  
 352 (11 – 13).

353 *Figure 9* also shows that a good fitting is obtained by using the WRC expressions of Brooks and  
 354 Corey (1964) and van Genuchten (1980), as follows:

355 - van Genuchten (vG):  $\theta = \theta_r + \frac{\theta_s - \theta_r}{[1 + (\alpha h_k)^n]^m}$ ; with  $m = 1 - \frac{1}{n}$  (10)

356 where  $\theta_s$  is the saturated volumetric water content ( $\theta_s = 0.45$ , see *Figure 9*),  $\theta_r$  [-] the residual one,  
 357  $\alpha = 1 / h_a$  [ $L^{-1}$ ] where  $h_a$  [L] is the air entry value expressed in water height, and  $n$  [-] an  
 358 empirical parameter;

359 - Brooks & Corey (BC):  $\theta = \theta_r + (\theta_s - \theta_r) \left(\frac{h_k}{h_a}\right)^{-\lambda}$  (11)

360 where  $\lambda$  [-] is an empirical parameter.

361 The fitting of the parameters of both vG and BC curves were made by first adopting values of  $h_a$   
 362 and  $\theta_r$ , taken equal to 3.2 cm and 0.11, respectively. The best fitting was obtained with  $n = 1.35$   
 363 (vG expression) and  $\lambda = 0.35$  (BC expression).

364

365 **3.2. Hydraulic conductivity function**

366 *Saturated state*

367 *Figure 10* shows the data obtained from the steady-state permeability test, expressed in terms of  
368 changes in fluxes  $q_n$  with respect to the hydraulic gradient ( $i = \Delta\Pi_n / H_{sample}$ , see Equation 3). The  
369 slope of the linear regression corresponding to the three measured points ( $n = 1, 2, 3$ ) and to point  
370  $(0, 0)$  provides a value  $K_s = 8.11 \times 10^{-6} \text{ m/s}$ .

371  
372 The same approach carried out on the ceramic porous stone provided a value  $K_{cs} = 4.02 \times 10^{-8}$   
373  $\text{m/s}$ , confirming that the hydraulic conductivity of the saturated ceramic porous stone is  
374 significantly smaller than that of the saturated material. As a consequence, Kunze and Kirkham's  
375 method was used to interpret the data of the first suction steps (1 and 2) applied from the  
376 saturated state.

377  
378 *Unsaturated states*

379 *Figure 11* presents the experimental data of steps 1 and 2 presented in terms of changes in  
380  $V(t)/V_\infty$  with respect to a log scale of  $\lambda_1^2 D t_{RP} / H_{sample}$ , as proposed by Kunze and Kirkham. For  
381 step 1, *Figure 11* shows excellent agreement of the data with the theoretical curve of parameter  
382  $a = 1$ . The corresponding value of parameter  $\lambda_1^2$  is 0.74, according to Kunze and Kirkham  
383 (1962)'s graph, while the reference time  $t_{RP}$  is 47 min (2800 s). Finally, a hydraulic conductivity  
384  $K(s) = 2.14 \times 10^{-7} \text{ m/s}$  is obtained for a suction of 2.1 kPa. This value is larger than that of the  
385 ceramic disk ( $K_{cs} = 4.02 \times 10^{-8} \text{ m/s}$ ), confirming the necessity of accounting for the impedance  
386 effect of the porous stone.

387 Similarly, a value  $a = 0.142$  is obtained for step 2, with  $\lambda_1^2 = 1.90$  with  $t_{RP} = 24 \text{ min}$  (1440 s),  
388 resulting in a hydraulic conductivity value of  $3.64 \times 10^{-8} \text{ m/s}$ , slightly smaller than that of the  
389 ceramic porous stone.

390 The calculations of the changes with time of the suction imposed on the top of the ceramic disk  
391 according to Equation 10 are presented in *Figure 8a* for step 1 and 2 (dashed line with triangles).  
392 As expected, they confirm the perturbation due to the low permeability of the ceramic disk. This  
393 perturbation is stronger during step 1, in which almost 3 hours are necessary to reach the desired  
394 2.1 kPa suction at the top, compared to step 2 in which the 4.2 kPa imposed suction is reached at  
395 the top after less than 2 hours.

396  
397 Prior to use Gardner's method, the assumption of constant suction during each suction step has to  
398 be checked. Inspection of the suction steps applied for suctions higher than 4.1 kPa (steps 3 – 13,  
399 *Figure 7*) showed that the water level in the inner tube was slightly rising at the start of the step,  
400 hence decreasing the suction. The level changes in the inner tube during steps 3 and 4 are around  
401 7.5 % of the imposed suction and 30 % of the imposed suction increment. These two steps do not  
402 reasonably ensure the constant suction condition, they will not be considered for the  
403 determination of the HCF. For suctions higher than 10 kPa (measurements 5 – 13, *Figure 7*), the  
404 level increase in the tube is smaller (less than 4 % of the imposed suction and less than 12 % of  
405 the imposed suction increment), and suction changes are considered to be reasonably compatible  
406 with the use of Gardner's method (see for example steps 11 and 12 in *Figure 8b*).

407  
408 The application of Gardner's method is presented in *Figure 12*, that shows the changes in  
409  $\ln[V_\infty - V(t)]$  with respect to time for the measurements made during steps 2 and 5 – 13 (see  
410 Equation 7). In all cases, the linearity of the  $\ln[V_\infty - V(t)]$  function is satisfactory. As

411 recommended by Gardner, the fitting is only based on the points corresponding to  $t > t_{bound}$ . The  
412 values of  $t_{bound}$ , calculated for each stage, are given in the graph of each step. Values are included  
413 between 0.2 and 2 h, depending of the value of  $D$ . Note that step 2 was also considered here, so  
414 as to compare the data with that of Kunze and Kirkham's method, that is more appropriate, given  
415 possible impedance effects.

416  
417 *Figure 13* shows the hydraulic conductivities obtained using the three different methods: i)  
418 saturated hydraulic conductivity, using the constant-head permeability test, ii) unsaturated  
419 hydraulic conductivity at lower suctions, using Kunze and Kirkham's method (steps 1 and 2) and  
420 iii) unsaturated hydraulic conductivity at larger suctions, using Gardner's method (steps 2' and 5  
421 to 13).

422  
423 One observes that the hydraulic conductivity at step 2' provided by Gardner's method is  
424 somewhat smaller than that (step 2) given by Kunze and Kirkham's method. This is compatible  
425 with the impedance effect due to the low permeability of the ceramic disk, that indicates that  
426 Gardner's method is not fully satisfactory for step 2. Note however that the difference in  
427 hydraulic conductivity is not that large ( $3.64 \times 10^{-8}$  m/s for Kunze and Kirkham and  $1.64 \times 10^{-8}$   
428 m/s for Gardner's method).

429  
430 All the points obtained by the three methods are in reasonable agreement and provide the  
431 decrease in hydraulic conductivity with increased suction along the drying path. In the first 5  
432 steps, a large decrease of 4 orders of magnitude is observed from  $10^{-5}$  m/s (saturated state) down  
433 to  $10^{-9}$  m/s at a suction of 10.4 kPa, and the hydraulic conductivity then stays between  $10^{-9}$  and  
434  $10^{-10}$  m/s for steps 5 to 13, corresponding to suctions between 10.4 and 49.6 kPa.

435 The results are also compared with the curves obtained by using the mathematical expressions of  
 436 the relative hydraulic conductivity ( $K_r(h_k) = K(h_k) / K_s$ ) derived from the WRC formulations of  
 437 Brooks and Corey (1964) and van Genuchten (1980) according to Mualem (1970)'s approach  
 438 (Equations 10 and 11), as follows:

439 - van Genuchten: 
$$K_r(h_k) = \frac{\{1 - (\alpha h_k)^{n-1} [1 + (\alpha h_k)^n]^{-m}\}^2}{[1 + (\alpha h_k)^n]^{m/2}} \quad (12)$$

440 - Brooks & Corey: 
$$K_r(h_k) = \left(\frac{h_k}{h_a}\right)^{-2-5\lambda/2} \quad (13)$$

441 The curves obtained with the parameters obtained from the WRC curves, also represented in  
 442 *Figure 13*, do not satisfactorily fit with the experimental data. Both formulations underestimate  
 443 the hydraulic conductivity, with a better correspondence observed with the Brooks and Corey  
 444 formulation. Because of this poor correspondence, it was decided to propose a power law, fitted  
 445 by using the root-mean-square-deviation (RMSD) method. This solution can be written in the  
 446 following form:

447 
$$K(s) = a_1 \times s^{b_1} \quad (14)$$

448 with  $a_1 = 5.38 \times 10^{-7}$  and  $b_1 = -2.283$ , giving:

449 
$$K(s) = 5.38 \times 10^{-7} \times s^{-2.283} \quad (15)$$

450 The corresponding expression of the relative permeability is then:

451 
$$\frac{K(s)}{K_s} = a_2 s^{b_1} = 6.63 \times 10^{-2} \times s^{-2.283} \quad (16)$$

452 In order to present the right side of Equation (16) in the relative form as well, coefficient  $a_2$  can  
 453 be written as follows:

454 
$$a_2 = \left(\frac{1}{s_0}\right)^{b_1} \rightarrow s_0 = a_2^{-\frac{1}{b_1}} = 0.305 \quad (17)$$

455 where  $s_0$  is the suction value corresponding to the air entry value, expressed in  $[kPa]$ . The final  
456 form of the equation reads:

$$457 \frac{K(s)}{K_s} = \left(\frac{s}{s_0}\right)^b \quad (18)$$

458 with  $s_0 = 0.305 \text{ kPa}$  and  $b = b_1 = -2.283$ .

459

#### 460 **4. Conclusion**

461 The new device developed in this work allowed to determine the water retention curve and the  
462 hydraulic conductivity function of a light coarse material used as substrate in an urban green roof.

463 In a first estimation, it was estimated than the hanging column technique of controlling suction,  
464 with a maximum height of  $3.2 \text{ m}$  (suction  $32 \text{ kPa}$ ) would have been satisfactory, but it was finally  
465 necessary to impose larger suctions by using the axis translation technique. This adaptation was  
466 rather simple to carry out, finally allowing to run the whole test by using both techniques on the  
467 same specimen in the same cell between the saturated state and a maximum suction of  $49.6 \text{ kPa}$ ,  
468 with a good comparability between the experimental data obtained by the two techniques.

469 The advantage of the hanging column technique is to allow for a very good precision in the  
470 control of both the suction and the water exchanges, made possible by using a differential  
471 pressure sensor with an accuracy of  $0.1 \text{ mm}$  in height. A specific system based on the use of both  
472 an inner and an outer tube was also developed so as to improve the accuracy of the measurements  
473 along the range of the applied suctions. This good accuracy was necessary, given the significant  
474 changes in volumetric water content observed during the first application of a suction as low as  
475  $2.1 \text{ kPa}$ , that resulted in a significant decrease from  $0.45$  to  $0.29$ .

476

477 Starting from a saturated state, the WRC exhibited a drastic decrease under a small suction of  
478 2.1 *kPa*, in link with the coarse nature of the granular substrate, followed by a progressive  
479 decrease down to a water content of 0.16 at 49.6 *kPa*. Both the van Genuchten and Brooks and  
480 Corey mathematical expressions fitted quite nicely with the experimental data.

481  
482 The good accuracy in the measurements of suction and water exchanges also allowed to  
483 simultaneously determine, in a simple fashion, the hydraulic conductivity function from the  
484 monitoring of the water exchanges resulting from the step changes in suction. At lower suctions  
485 (2.1 and 4.2 *kPa*) and higher hydraulic conductivity, it was necessary to account for the  
486 impedance effects due to the 50 *kPa* air entry value ceramic disk by successfully using Kunze  
487 and Kirkham's method. Gardner's method was used at larger suctions, and a good comparability  
488 was observed from the experimental data from each technique. Another advantage of the device  
489 is to simply allow for the determination of both the water retention curve and the hydraulic  
490 conductivity function of the coarse material. Unsurprisingly, the HCF function exhibit a trend  
491 similar to that of the WRC, with a decrease of around 3 orders of magnitude between the  
492 saturated state and that at a suction of 4.2 *kPa*, whereas all the data between 10.4 and 49.6 *kPa*  
493 were comprised between  $10^{-9}$  and  $10^{-10}$  m/s.

494  
495 The experimental HCF data were compared with the analytical expressions derived from the  
496 WRC expressions of van Genuchten and Brooks and Corey, based on Mualem's approach. In  
497 both cases, these expressions appeared to significantly underestimate the experimental HCF, with  
498 however better results with Brooks and Corey's expression, that was less than one order of  
499 magnitude below the experimental data. These expressions of the HCF are often used in the lack  
500 of experimental data, and the difference observed in this work confirm the need of having

501 operational devices for the simultaneous experimental determination of the water retention curve  
502 and the hydraulic conductivity function in granular materials such as the green roof substrate  
503 investigated in this work.

504

## 505 **5. References**

506 ASTM D2487-00: Standard Practice for Classification of Soils for Engineering Purposes (Unified  
507 Soil Classification System), *Annual Book of ASTM Standards*, ASTM International, West  
508 Conshohocken, PA, 2000.

509 Blatz, J., Cui, Y.-J., Oldecop, L.A., 2008, "Vapour equilibrium and osmotic technique for suction  
510 control," *Geotech. Geol. Eng.*, doi:10.1007/s10706-008-9196-1

511 Brooks, R.H, Corey, A. T., 1964, "Hydraulic properties of porous media," *Hydrology papers*,  
512 No.3.

513 Corey, A.T., 1957, "Measurement of water and air permeability in unsaturated soil," *Soil Sci.*  
514 *Soc. Am. Proc.*, Vol. 21, No. 1, pp. 7–10.

515 Buckingham, E., 1907, "Studies on the movement of soil moisture," Bull 38 USDA, Bureau of  
516 Soils, Washington DC.

517 Cui, Y. J., Delage, P., Alzoghbi, P., 2003, "Retention and transport of a hydrocarbon in a silt,"  
518 *Géotechnique*, Vol. 53, No. 1, pp. 83-91.

519 Delage, P., 2002, "Experimental unsaturated soil mechanics: State-of-art-report," 3<sup>rd</sup> International  
520 conference on unsaturated soils, Vol. 3, Recife.

521 Delage, P., Cui, Y.-J., 2008, "An evaluation of the osmotic technique of controlling suction,"



- 522 *Geomech. Geoengin. Int. J.*, Vol. 3, No. 1, pp. 1–11.
- 523 Esteban, F., 1990, “Caracterización de la expansividad de una roca evaporítica. Identificación de  
524 los mecanismos de hinchamiento”, Tesis doctoral de la Universidad de Cantabria, Santander.
- 525 Fredlund, D. G., Rahardjo, H. and Fredlund M. D., 2012, *Unsaturated Soil Mechanics in*  
526 *Engineering practice*, Wiley, New York.
- 527 Fredlund, D. G., and Xing., A., 1994, "Equations for the soil-water characteristic curve," *Can.*  
528 *Geotech. J.*, Vol. 31, pp. 521-532.
- 529 Gardner, W. R., 1956, "Calculation of Capillary Conductivity from Pressure Plate Outflow Data."  
530 *Soil Science Society Proceeding*, Vol. 20, pp. 317 - 320.
- 531 Klute, A., 1972, “The determination of the hydraulic conductivity and diffusivity of unsaturated  
532 soils,” *Soil Sci.*, Vol. 113, No. 4, pp. 264-276.
- 533 Kunze, R. J., and Kirkham, D., 1962, “Simplified Accounting for membrane impedance in  
534 Capillary Conductivity Determinations,” *Soil Sci. Soc. Am. Proc.*, Vol. 26, pp. 421-426.
- 535 Li, Y., and Babcock Jr., R. W., 2016, “A Simplified Model for Modular Green Roof Hydrologic  
536 Analysis and Design,” *Water*, Vol. 8, No. 343, pp. 1 – 13.
- 537 Masrouri, F., Bicalho, K.V., Kawai, K., 2008, “Hydraulic testing in unsaturated soils,” *Geotech.*  
538 *Geol. Eng.*, Vol. 26, pp. 691 – 704, doi:[10.1007/s10706-008-9202-7](https://doi.org/10.1007/s10706-008-9202-7).
- 539 Miller, E., Elrick, D., 1958, “Dynamic determination of capillary conductivity extended for non-  
540 negligible membrane impedance,” *Soil Sci. Soc. Am. Proc.*, Vol. 22, pp. 483–486.
- 541 Mualem, Y., 1976, “A New Model for Predicting the Hydraulic Conductivity of Unsaturated  
542 Porous Media,” *Water Resources Research*, Vol. 12, No. 3, pp. 513-522.

543 NFP94-056, "Analyse granulométrique - Méthode par tamisage à sec après lavage," French  
544 Standard, AFNOR Editions, Paris La Défense Cedex, 1996.

545 NFP94-057, "Analyse granulométrique des sols - Méthode par sédimentation," French Standard,  
546 AFNOR Editions, Paris La Défense Cedex, 1992.

547 Olsen, H.W., Nichols, R.W., Rice, T.L., 1985, "Low gradient permeability methods in a triaxial  
548 system," *Géotechnique*, Vol. 35, No. 2, pp. 145–157.

549 Richards, L.A., 1941, "A pressure-membrane extraction apparatus for soil solution," *Soil Sci.*,  
550 Vol. 51, No. 5, pp. 377–386.

551 Richards, L.A., 1947, "Pressure-membrane apparatus – construction and use," *Agric. Eng.*, Vol.  
552 28, pp. 451–460.

553 Vanapalli, S.K., Sharma, R.S., Nicotera, M.V., 2008, "Axis-translation and negative water  
554 column techniques for suction control," *Geotech. Geol. Eng.*, Vol. 26, pp. 645 – 660,  
555 doi:10.1007/s10706-008-9206-3.

556 van Genuchten, M. Th., 1980, "A Closed-form Equation for Predicting the Hydraulic  
557 Conductivity of Unsaturated Soils," *Soil Sci. Soc. Am. J.*, Vol. 44, pp. 892-898.

558 Versini, P.A., Gires, A., Fitton, G., Tchiguirinskaia, I., Schertzer, D., 2017, "La Vague Verte de  
559 l'ENPC: un site pilote de Blue Green Dream pour évaluer les variabilité spatio-temporelles du  
560 bilan hydrologique d'une infrastructure végétale - ENPC Blue Green Wave: a Blue Green  
561 Dream pilot site to assess spatio-temporal variability of hydrological components in green  
562 infrastructures," *La Houille Blanche*, Accepted for publication.

563 VulkaTec Riebensahm GmbH, "Assurance qualité - Vulkaplus intensiv 0-12,"  
564 GUTEGEMEINSCHAFT SUBSTRATE FUR PFLANZEN E.V., Kretz, Germany, 2016.

565 XPP94-047, "Détermination de la teneur pondérale en matières organiques d'un matériau,"

566 French Standard, AFNOR Editions, Paris La Défense Cedex, 1998.

567 Zur, B., 1966, "Osmotic control the matric soil water potential," *Soil Sci.*, Vol. 102, pp. 394–398

568

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573 *Table 1. Basic characteristics of “Green Wave” substrate*

Dry density	Porosity	Curvature coefficient	Uniformity coefficient	Percentage of organic matter
$\rho_s$ [kg/m <sup>3</sup> ]	n [-]	$C_c$ [-]	$C_u$ [-]	$C_{MOC}$ [%]
1100	0.448	1.95	55	4

574

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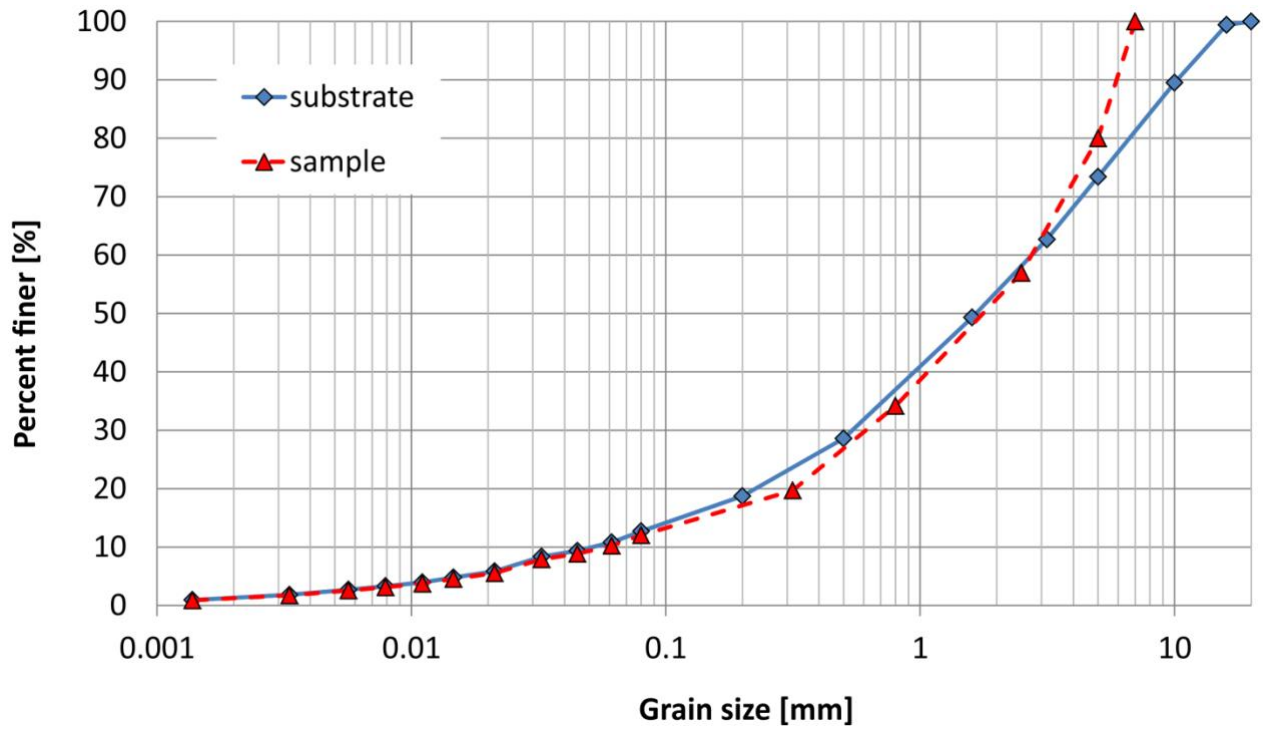
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621 *Figure 3. Grain size distribution curve of the volcanic substrate*

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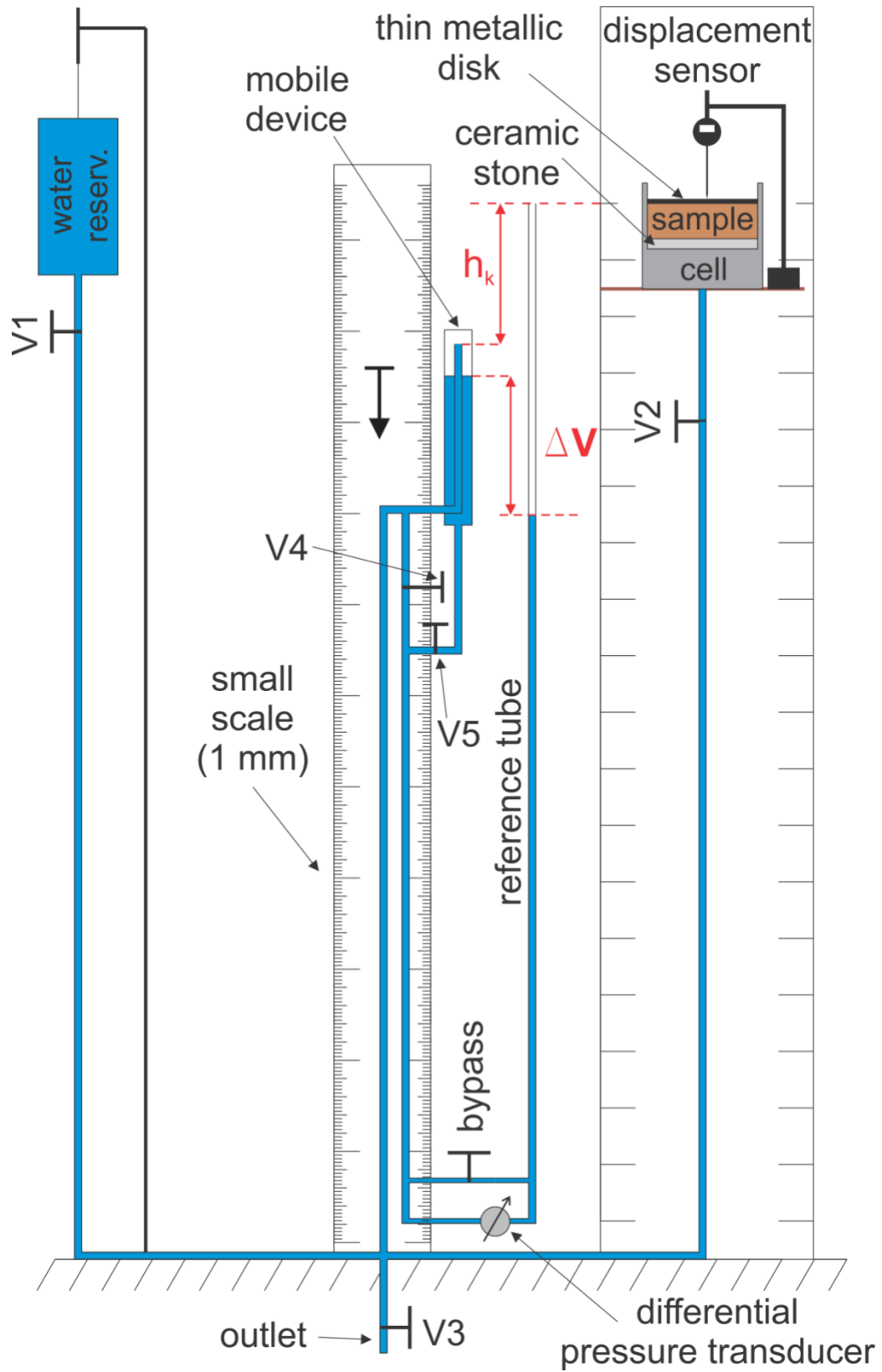
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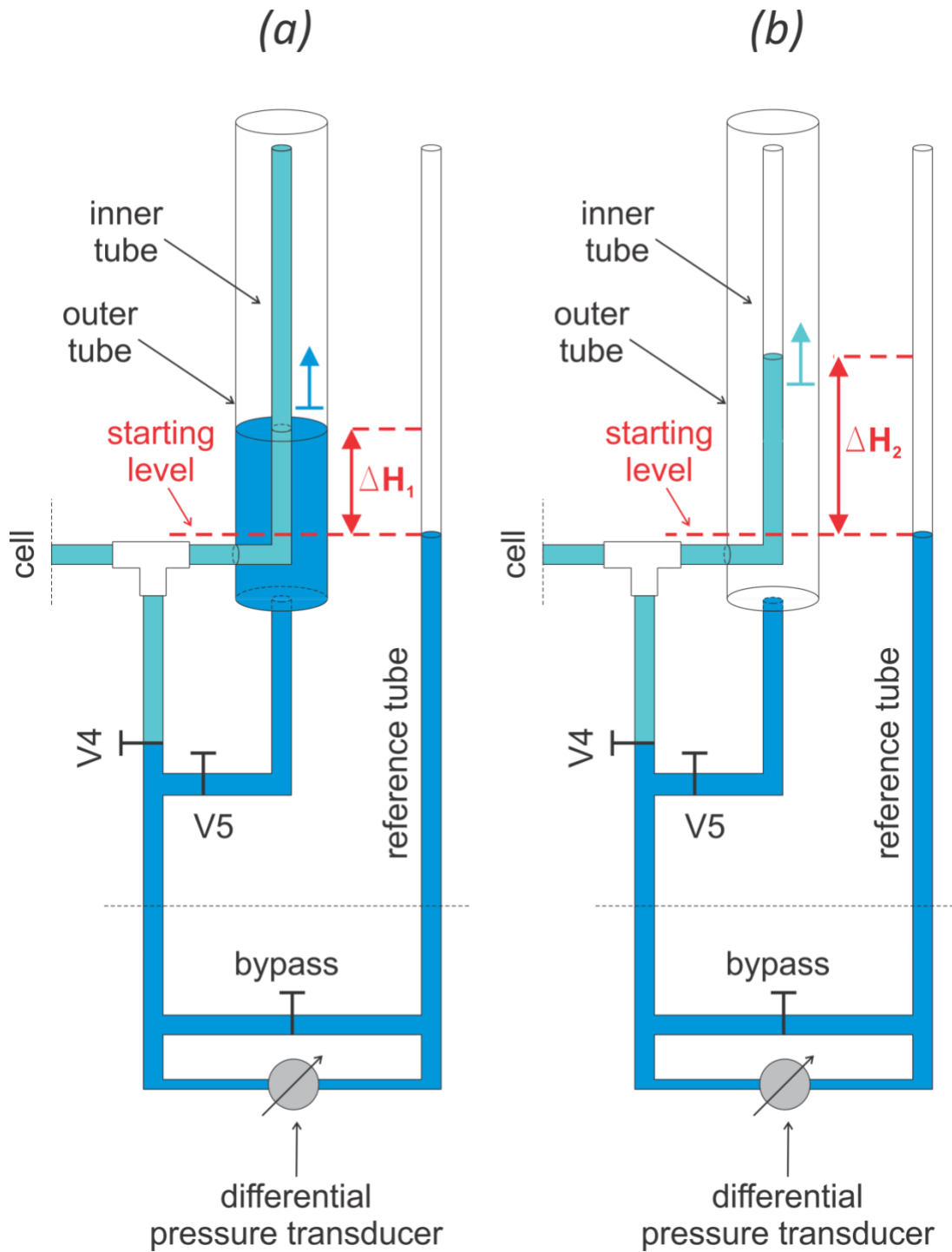
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631 *Figure 4. General lay-out of the hanging column system*



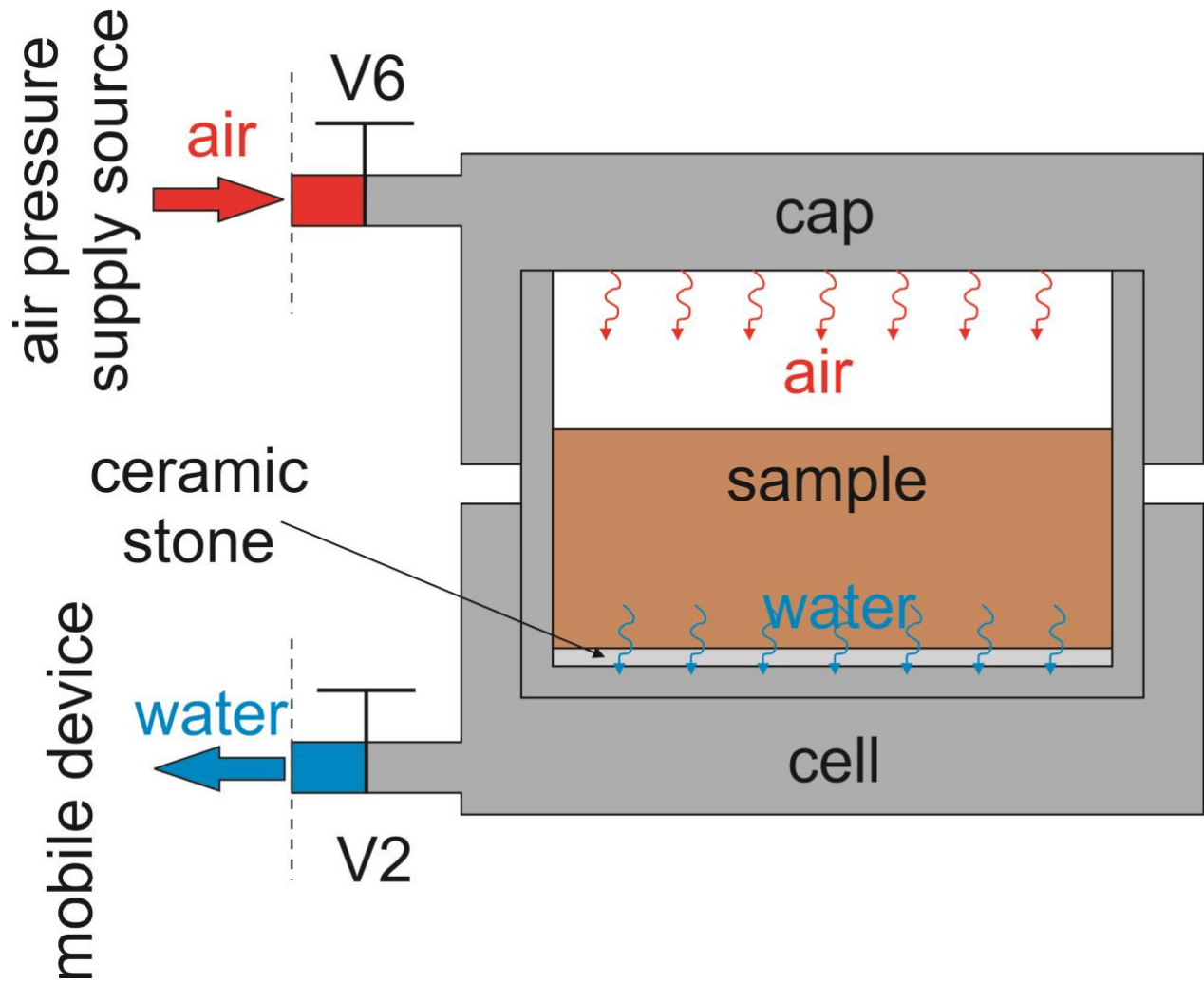


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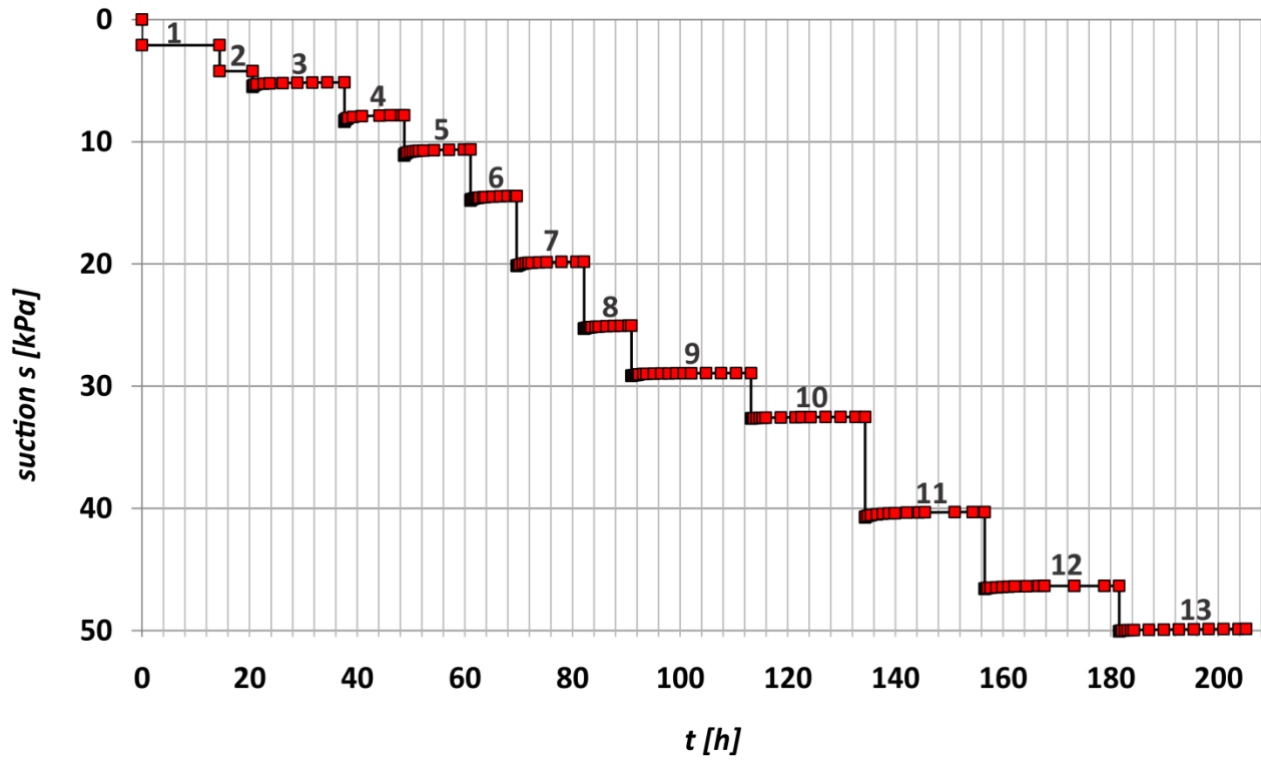
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Figure 6. Application of the axis translation technique



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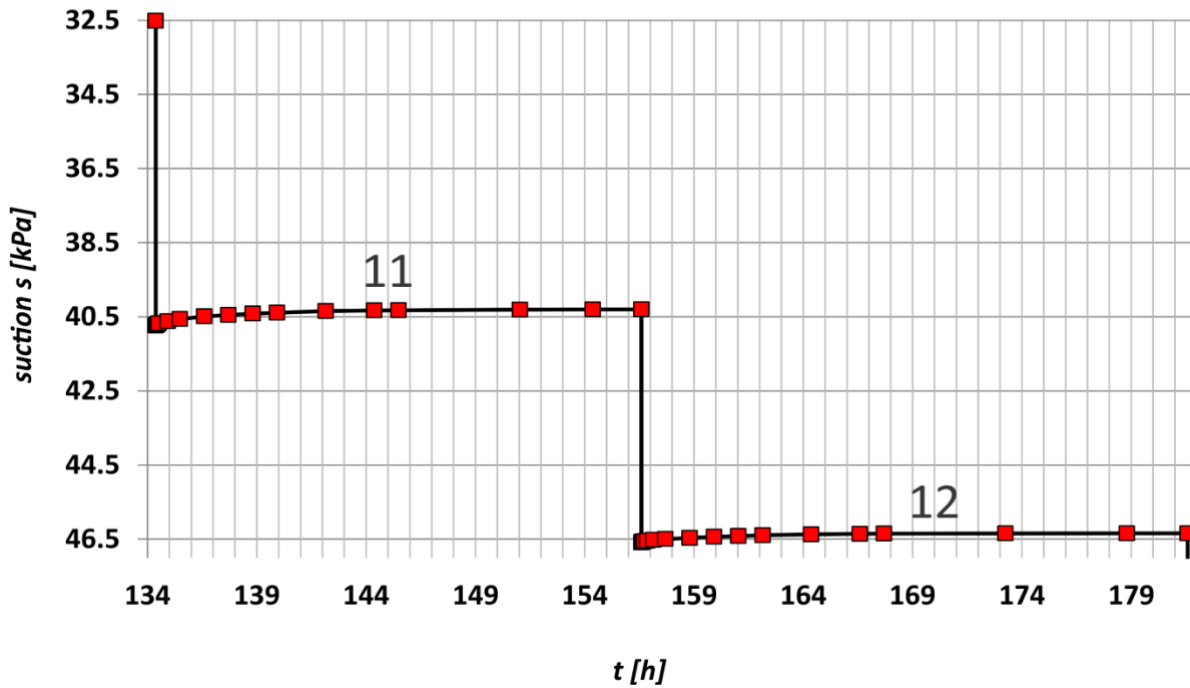
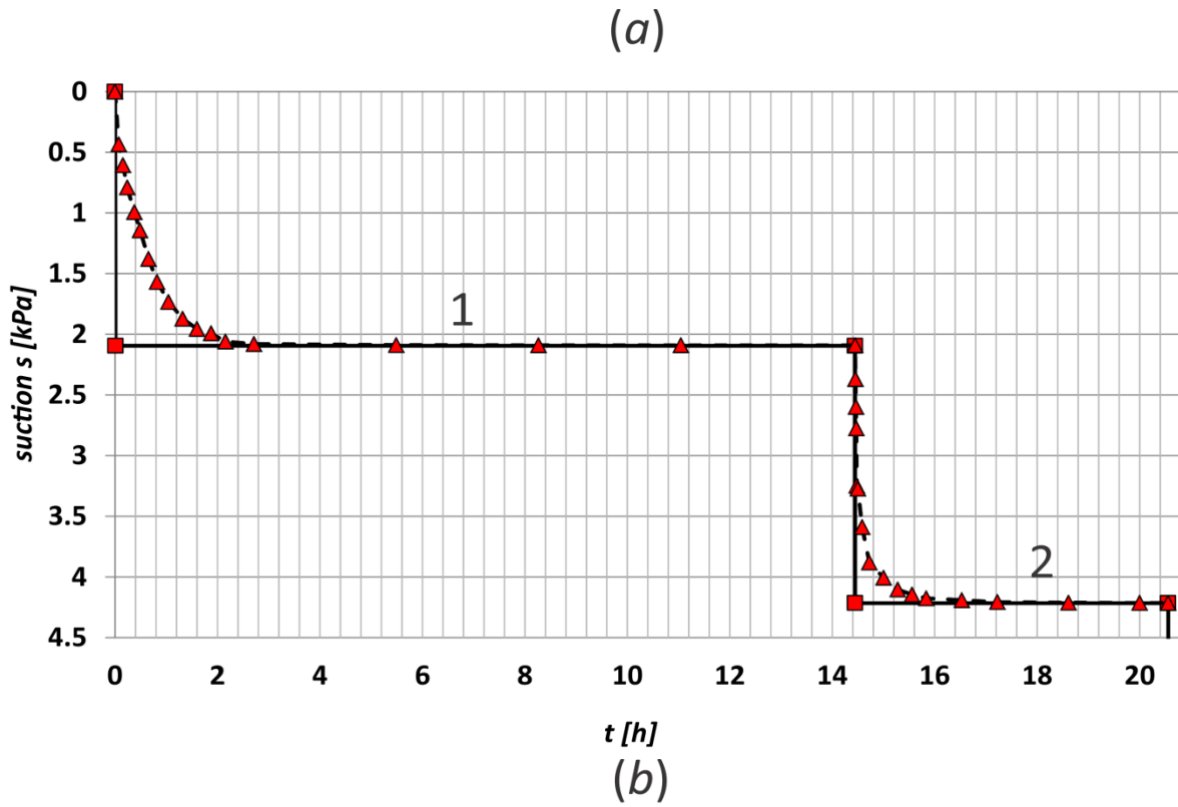
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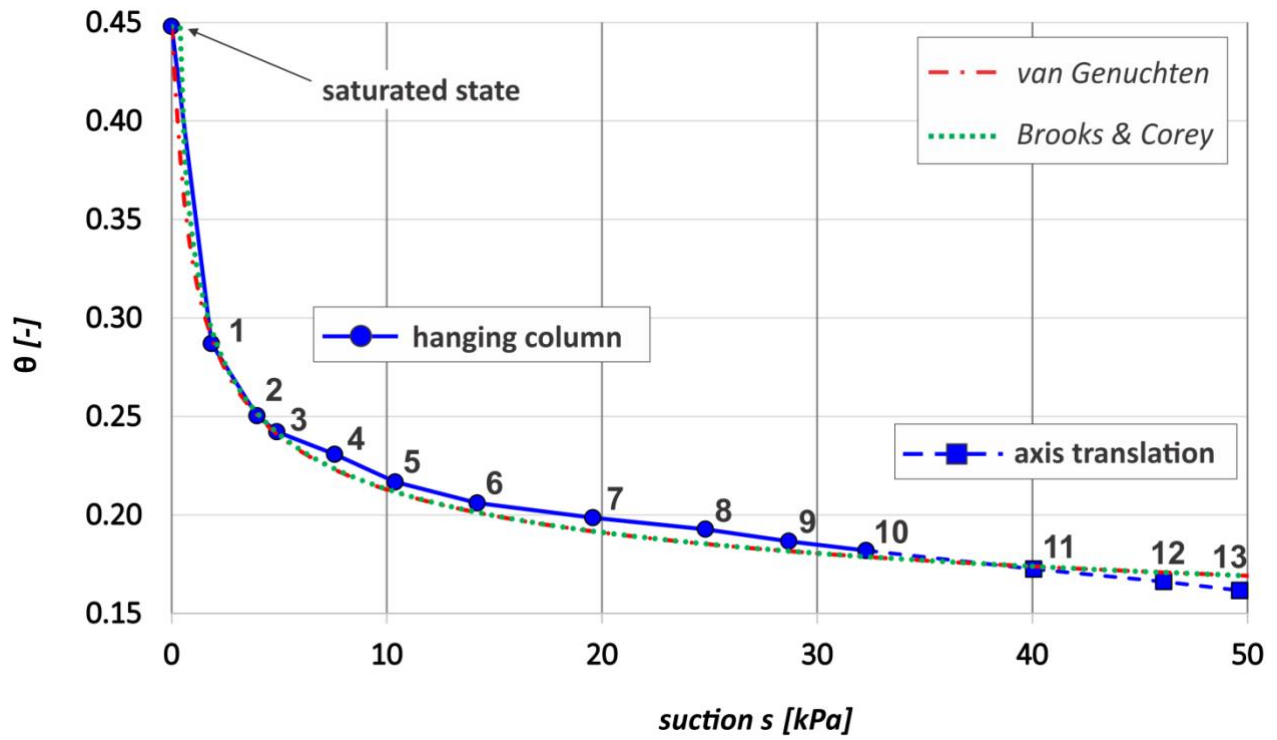
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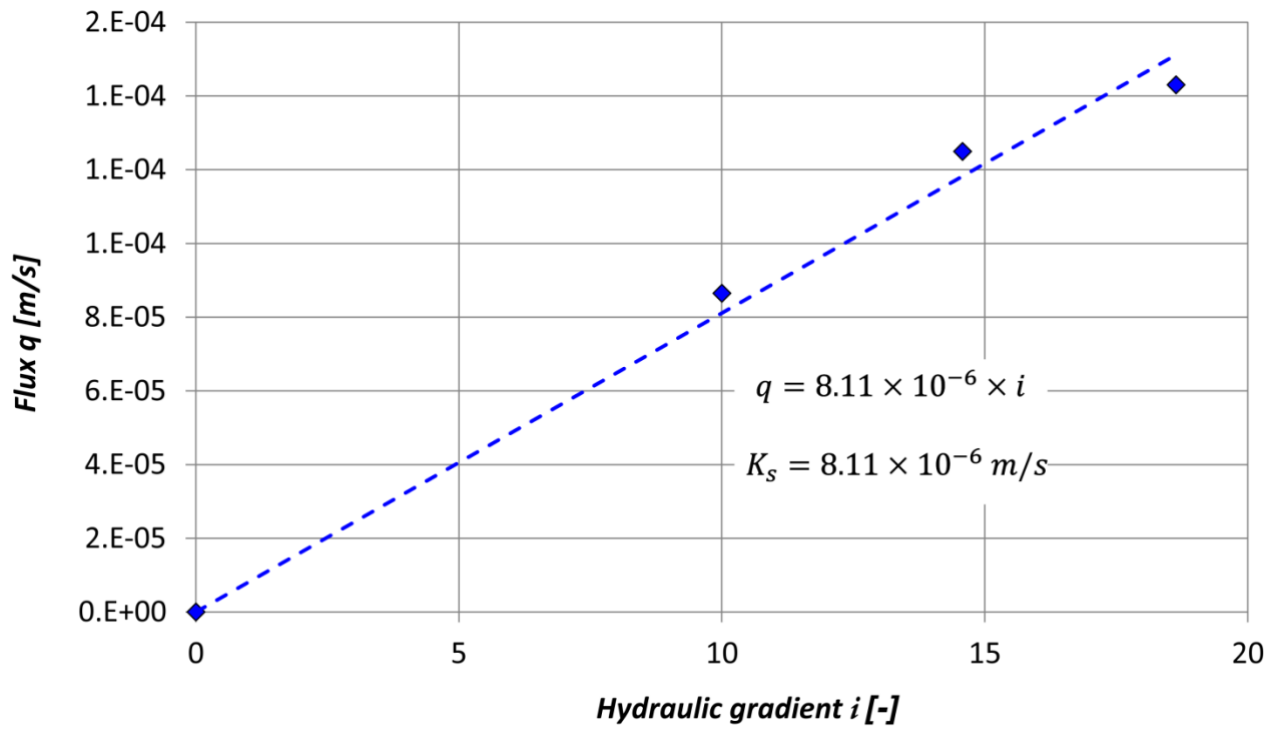
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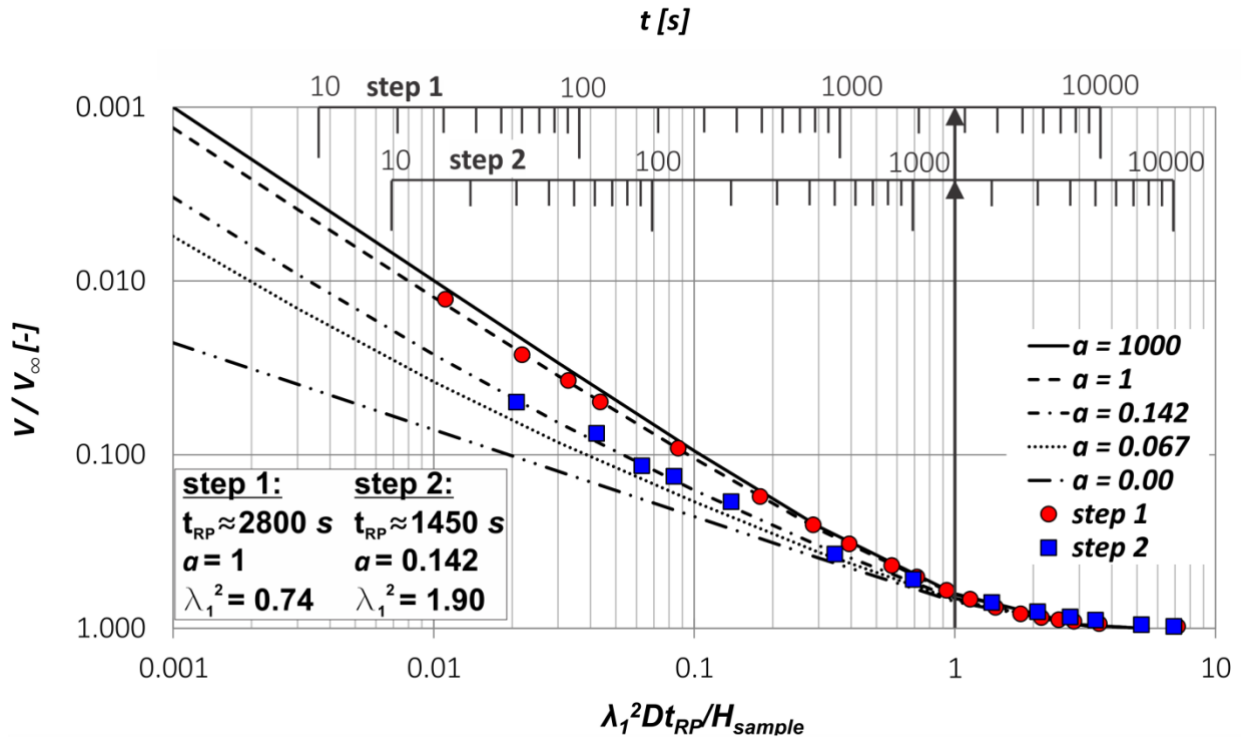
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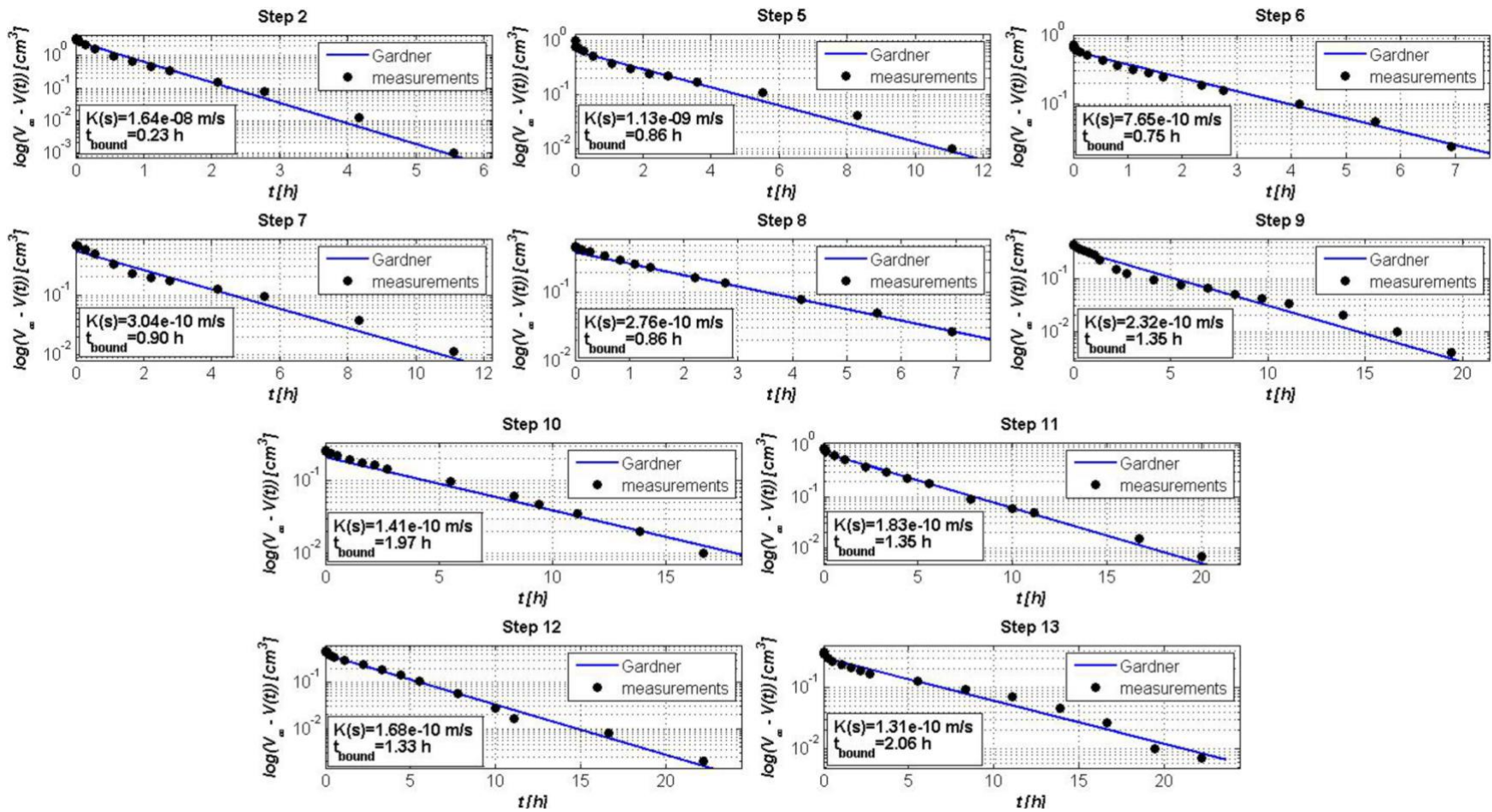
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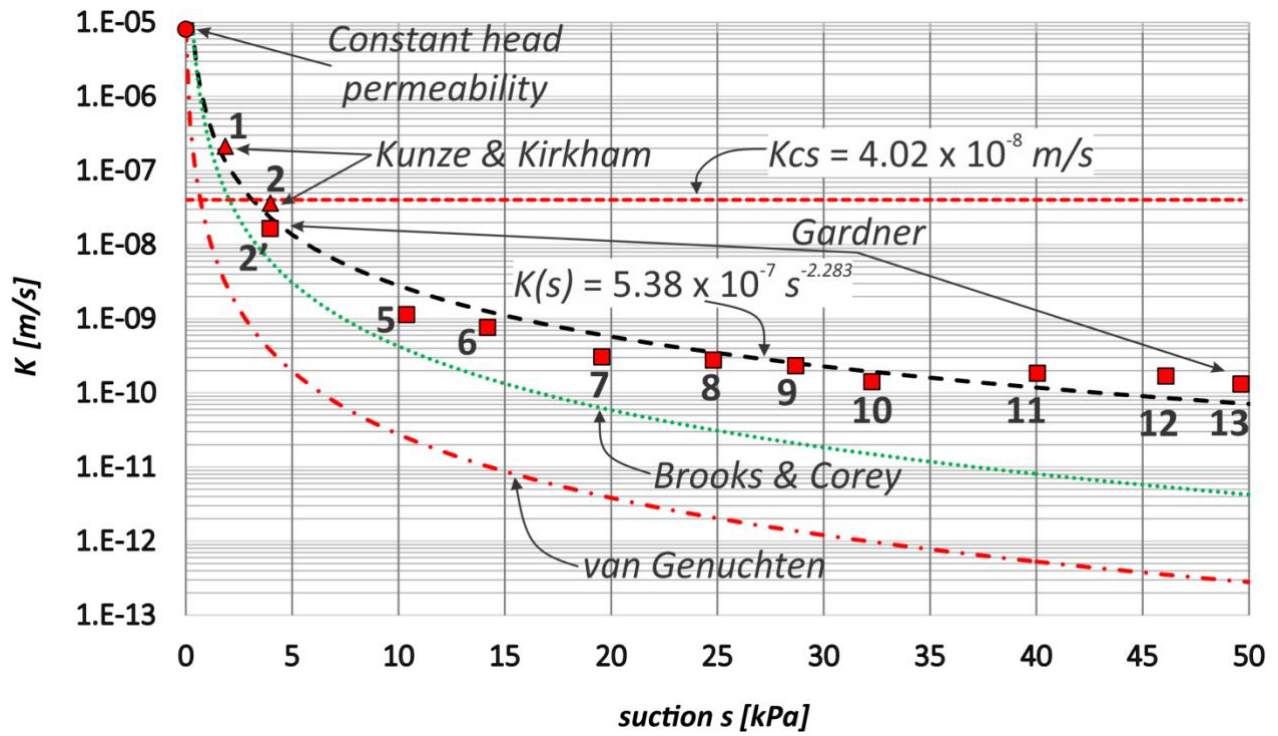


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