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Yong-Gui Chen, Yu-Jun Cui, Anh Minh A.M. Tang, Qiong Wang, Wei-Min Ye. A preliminary study on hydraulic resistance of bentonite/host-rock seal interface. *Geotechnique*, 2014, 64 (12), pp.997-1002. 10.1680/geot.13.P.209 . hal-01111309

**HAL Id: hal-01111309**

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Submitted on 25 Apr 2018

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1 **A preliminary study on hydraulic resistance of bentonite/host-rock seal interface**

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20 ABSTRACT:

21 Compacted bentonite-based materials are often used as buffer materials in radioactive  
22 waste disposal. When the compacted bentonite blocks are emplaced, technological  
23 voids related to different interfaces involving the buffer material are created, and their  
24 hydro-mechanical behaviour is of primary importance for the disposal safety. In this  
25 study, the hydraulic resistance of the interface between compacted MX80 bentonite  
26 and Boom Clay was investigated in the laboratory using an injection cell. The results  
27 obtained show that when water is injected, the technological gap is quickly reduced  
28 due to the bentonite swelling. When water pressure reached the hydraulic resistance  
29 of the interface, the hydraulic fracturing took place with a drastic pressure decrease.  
30 After fracturing, water injection continued and bentonite continued to swell. A higher  
31 subsequent pressure was needed to produce a new hydraulic fracturing. After a certain  
32 time, the hydraulic resistance becoming high enough no further fracturing occurred,  
33 suggesting that the technological gap was sealed.

34 Keywords : Clays, expansive soils, laboratory test, radioactive waste disposal

35

## 36 INTRODUCTION

37 To safely dispose high-level radioactive waste (HLW), the deep geological repository  
38 concept has been adopted in several countries. For such repository at great depth, the  
39 buffer material employed to seal the waste canisters must have high swelling potential,  
40 low permeability and good adsorption capacity. Blocks made of compacted bentonite-  
41 based material are usually considered for this purpose.

42 When bentonite bricks are placed around the waste canisters in the sealing buffers,  
43 some technological voids either between the bricks themselves or between the bricks,  
44 the canisters and the host rock are created. For instance, 10 mm thick gaps between  
45 the bentonite blocks and canister and 25 mm thick gaps between the bentonite blocks  
46 and the host rock have been considered in the basic design of Finland (Juvankoski,  
47 2010). The joint gaps are limited to 6.6% of the total volume of the confining  
48 structure in the FEBEX mock-up test (Martin et al., 2006). In France, the volume of  
49 the bentonite/rock gaps is estimated at 9% of the volume of the gallery by the French  
50 waste management agency (ANDRA, 2005), while this value reaches 14 % in the  
51 Tournemire Underground Research Laboratory (URL) site (Barnichon & Deleruyelle,  
52 2009).

53 Once placed in the galleries, engineering barriers are progressively hydrated by  
54 pore water infiltration from the host rock. This water infiltration is strongly dependent  
55 on the initial state of the compacted material (Cui et al., 2008) and the imposed  
56 boundary conditions in terms of volume change (Yahia-Aissa et al., 2001). Thereby,  
57 the swell allowed by the technological voids described above has a significant  
58 influence on the hydro-mechanical behavior of the compacted bentonite. Indeed,  
59 swelling results in the decrease of dry density that may lead to the degradation of the

60 hydro-mechanical performance of engineering barriers (Komine et al., 2009; Komine,  
61 2010). Although the compacted bentonite swelling fills the technological gaps, the  
62 filled gaps still represent discontinuities over long time. As a result, the safety  
63 function expected in the design may not be properly ensured. Thereby, a good  
64 understanding of the interface gap behaviour under water pressure is essential.

65 In this study, three laboratory tests were conducted to evaluate the behaviour of the  
66 interface between compacted MX-80 bentonite and natural Boom Clay with different  
67 initial gaps. It is expected to provide useful information for the interface behaviour  
68 between bentonite blocks and host rock in the Praclay heating test conducted in the  
69 URL at Mol, Belgium.

70

## 71 MATERIALS AND METHODS

72 The physical properties of MX80 bentonite and Boom Clay are shown in Table 1.  
73 A compacted MX80 bentonite block as those used in the Praclay heating test was  
74 employed with the dimensions shown in Figure 1. Its dry unit mass is  $1.80 \text{ Mg/m}^3$ ,  
75 and its water content is 15.2%, defining a degree of saturation of 78.4%. The samples  
76 were prepared by coring from the block, and have a diameter of 50 mm or 55 mm and  
77 a height of 40 mm. Boom Clay cores taken from the Mol URL were used. The cores  
78 have a dry unit mass of  $1.65\text{-}1.71 \text{ Mg/m}^3$ , a water content of 21-25% and a degree of  
79 saturation of 91-100%. For the sample preparation, the core was first cut into small  
80 cylindrical pieces of 50 mm high and 100 mm diameter each using a metal saw. A  
81 mould was used to fix the cylindrical pieces, and a machine was employed to prepare

82 a hole of 60 mm diameter. Afterwards, the two ends of the hollow cylinder sample  
83 was cut to have reach 40 mm height.

84 The experimental set-up is shown in Figure 2. The sample is placed inside a cell  
85 that is put in a rigid frame with a load transducer of 50 kN capacity that allows the  
86 measurement of axial stress. The water inlet at the bottom was connected to a  
87 controller of pressure/volume (CPV) for water injection. Inside the cell, a hollow  
88 cylinder of Boom Clay and a cylindrical bentonite specimen were installed. The space  
89 between the bentonite and Boom Clay samples allowed the technological gap to be  
90 simulated. The height of the samples was kept constant by blocking the piston.

91 A miniature total pressure sensor of 8 mm diameter and 2 mm thick was selected to  
92 monitor the radial pressure at the Boom Clay/bentonite interface (see Figure 3).  
93 Firstly, a small flat-bottomed hole with groove was prepared at the internal surface of  
94 Boom clay. Then the sensor was introduced into the hole and its cables were put into  
95 the groove. The scanning surface of the sensor was kept flush with the inner surface of  
96 Boom Clay. After the bentonite specimen was placed in the centre of the hollow  
97 cylinder of Boom Clay, the cables were connected to the data acquisition system.  
98 When water was introduced to the cell, the compacted bentonite was hydrated and  
99 radially swelled. The sensor recorded the generated pressure when the bentonite  
100 contacted Boom Clay.

101 Three tests with two different technological gaps were carried out on samples with  
102 the same initial water content and initial dry density (see Table 2). An initial axial  
103 stress of 0.5 MPa was applied on the specimen before hydration to ensure a good  
104 contact between the piston and the sample (see Figure. 2). When water injection  
105 started, the piston was fixed. In each test, the sample was hydrated by injecting

106 distilled water under constant pressure (0.1 MPa) through a porous disk in contact  
107 with the bottom face, while the top face was put in contact with another porous stone  
108 so as to allow free expulsion of either air or water (see Figure 2). The outlet was  
109 closed when water flowed out of it. Once water was observed on the top of the cell,  
110 the rate of water injection was fixed at  $1 \text{ mm}^3/\text{s}$ . Changes in axial stress, radial  
111 pressures and injected water volume were monitored. When water pressure reached a  
112 certain value under which hydraulic fracturing occurred at the bentonite/Boom Clay  
113 interface, the water pressure decreased drastically. After the fracturing, the water  
114 injection was reset to the initial rate of  $1 \text{ mm}^3/\text{s}$  until the next fracturing. This  
115 operation was repeated until no further hydraulic fracturing occurred. The dry density  
116 and water content of the soil specimen were determined at the end of the test.

117

## 118 RESULTS AND DISCUSSION

119 Figure 4-6 show the changes in pressure, volume of water injected, axial and/or  
120 radial pressure. For all cases, when the injection pressure exceeded a certain level, a  
121 sudden decrease took place. This sharp decrease corresponds to the phenomenon of  
122 hydraulic fracturing, and this pressure level is called herein breakthrough pressure or  
123 hydraulic fracturing pressure.

124 Further examination shows that after starting water injection, the injection pressure  
125 started increasing after 1-2 h. In Test A, the first fracturing was observed at  $t = 15 \text{ h}$   
126 with a sharp pressure decrease from 2.9 MPa to 2.2 MPa. Afterwards, various  
127 hydraulic fracturing occurred with an increase of the hydraulic resistance each time.  
128 When water was injected into the cell, it appeared to flow freely through the gap at  
129 the beginning. The water pressure did not increase before the gap was sealed by

130 hydration that led the compacted bentonite to swell. Once the compacted bentonite  
131 was put in contact with water, it swelled and consequently reduced the gap. This  
132 sealing slowed down the water flow, resulting in an increase of the water pressure  
133 needed to keep a constant injection rate controlled by the CPV. When the water  
134 pressure reached the hydraulic resistance of the interface, hydraulic fracturing took  
135 place, resulting in a drastic pressure decrease. After fracturing, water was continued to  
136 be injected into the cell and bentonite continued to swell, thus, the hydraulic  
137 resistance was increased, resulting in a higher hydraulic fracturing pressure.  
138 Comparing the injection pressure in Test A to those on the two other tests, it appears  
139 clearly that the pressure in Test A increased more quickly than in Tests B and C due  
140 to the smaller gaps.

141 As for the axial pressure, it increased quickly just after starting the injection in  
142 relation to the bentonite swelling. When the fracturing was observed, the axial  
143 pressure also abruptly decreased. The hydraulic fracturings identified through the  
144 changes in injection pressure are thereby observed again. The trend of the axial  
145 pressure – time curves shows that the axial pressure in Test A with 2.5 mm gap  
146 increased more quickly than that in Tests B and C with 5 mm gap. In particular, once  
147 the injection was stopped in Test A, the axial pressure also dropped and a steady final  
148 pressure induced by hydration was observed. However, in Tests B and C, some mud  
149 was observed escaping from the top of the cell during the injection. At that moment,  
150 the axial pressure fluctuated following a similar trend as injection pressure , then they  
151 both decreased to zero. It is supposed that the larger gap resulted in a larger radial  
152 strain (10 mm/50 mm: 20%), and this deformation led to collapse of the compacted  
153 bentonite. As a result, the axial pressure abruptly decreased to zero, the injection



154 water outflowed with the collapsed soil, and the injection pressure did not increase  
155 any more over time.

156 On the whole, the changes in radial pressure are in accordance with those in  
157 injection pressure. When water was injected into the cell, the bentonite swelled and  
158 the gap was reduced. Once the bentonite was in contact with Boom Clay, the radial  
159 pressure increased progressively. The sealing of the gap slowed down the water flow,  
160 resulting in the increase of water pressure. When the water pressure reached the  
161 hydraulic resistance of interface, a fracturing occurred and resulted in a drastic  
162 pressure decrease. If the hydraulic fracturing took place, a sudden decrease of the  
163 radial pressure was also produced.

164 On the other hand, various hydraulic fracturings on the radial pressure were also  
165 observed with the increase of fracturing pressure. This is in agreement with the  
166 observation of Marcial et al. (2006). The increase of radial pressure applied by the  
167 swelling bentonite on the internal surface of Boom Clay evidenced a rapid swelling  
168 rate. Logically, a gap of 2.5 mm in Test A was sealed more quickly than a gap of 5  
169 mm in Tests B and C. In Test A, it was observed that the radial pressure reached 1.8  
170 MPa when the water pressure was controlled at 0.2 MPa. This indicates that the  
171 hydration process was continued even though the water pressure was kept constant.  
172 Komine and Ogata (1999) reported that a necessary condition to demonstrate the self-  
173 sealing capability of buffer material is that the swelling pressure must be greater than  
174 1 MPa once all voids are filled. Consequently, the interface between the Boom Clay  
175 and bentonite has enough swell capacity to seal a technical gap of 2.5 mm.

176 The distribution of water content and dry density of the soil samples after the tests  
177 are shown in Table 3. It appears that for each test the water content at the bottom was

178 higher than that at the top. Moreover, the part near the interface was wetter than the  
179 other part. As for Boom Clay, the water content at the bottom was higher than that at  
180 the top, but the part near the cell was wetter than that near the gap. On the other hand,  
181 the dry density at the bottom and near the interface was lower than that at the top or  
182 far from the interface. This distribution is in good agreement with the wetting path.  
183 The difference between the results of Test A and Test B and C can be explained by  
184 the difference in gap thickness. In Test A, the diameter of the compacted bentonite  
185 was 55 mm and the gap was 2.5 mm, less bentonite was needed to fill the gap, and  
186 thereby a higher final dry density was obtained. Referring to Tests B and C, the  
187 difference in distribution might be due to the different volume of water injected and  
188 the different test durations. The fact that the water content and dry density were not  
189 uniform in the bentonite shows that the swelling of bentonite was not homogeneous.

## 190 CONCLUSION

191 A simple experimental set-up was developed allowing investigation of the  
192 behaviour of the interface between Boom Clay and compacted MX-80 bentonite in  
193 terms of resistance to hydraulic fracturing. The obtained results allow the following  
194 conclusions to be drawn.

195 i) The water pressure did not increase at the first several hours after the start of  
196 injection until the gap was sealed by the compacted bentonite swelling. The axial  
197 pressure increased quickly in relation to the bentonite swelling, and it abruptly  
198 decreased when fracturing occurred.

199 ii) When the gap was sealed, the radial pressure increased progressively. A sudden  
200 decrease of the radial pressure took place when hydraulic fracturing occurred. The  
201 fracturing pressure was found increasing over time.

202 iii) With a 2.5 mm gap, it was observed that fracturing pressure can be as high as  
203 1.8 MPa that can be considered as high enough in the case of Boom Clay/compacted  
204 bentonite interface.

205 ii) The distribution of the water content and dry density of the soil after test  
206 depends on wetting path, gap thickness, injected water volume and elapsed time.

207

## 208 ACKNOWLEDGEMENTS

209 ONDRAF/NIRAS (The Belgian Agency for Radioactive Waste and Enriched Fissile  
210 Materials) is gratefully acknowledged for its financial support. The authors are also  
211 grateful to the National Natural Science Foundation of China (No 41272287,  
212 41030748), Innovation Program of Shanghai Municipal Education Commission  
213 (12ZZ032), Pujiang Program of Shanghai (13PJD029), and Fundamental Research  
214 Funds for the Central Universities.

215

## 216 REFERENCES

217 Alonso E. E., Romero E. 2005. Expansive bentonite-sand mixtures in cyclic  
218 controlled-suction drying and wetting, *Engineering Geology* 81: 213-226.

219 ANDRA 2005. Référentiel des matériaux d'un stockage de déchets à haute activité  
220 et à vie longue – Tome 4: Les matériaux à base d'argilites excavées et remaniées,  
221 Rapport Andra N° CRPASC040015B.

222 Barnichon J. D., Deleruyelle F. 2009. Sealing experiments at the Tournemire URL,  
223 Towards convergence of technical nuclear safety practices in Europe, EUROSAFE.

224 Blanchart P., Faure P., De Craen M., Bruggeman C., Michels R. 2012.  
225 Experimental investigation on the role of kerogen and clay minerals in the formation  
226 of bitumen during the oxidation of Boom Clay, Fuel 97: 344–351.

227 Bradbury M. H., Baeyens B. 2003. Porewater chemistry in compacted re-saturated  
228 MX-80 bentonite, Journal of Contaminant Hydrology 61: 329–338.

229 Chandler N., Dixon D., Gray M., Hara K., Cournut A., Tillerson J. 1998. The  
230 tunnel sealing experiment: an in situ demonstration of technologies for vault sealing,  
231 in Proceedings of the 19th Annual Conference of the Canadian Nuclear Society.

232 Cui Y. J., Tang A. M., Loiseau C., Delage P. 2008. Determining the unsaturated  
233 hydraulic conductivity of a compacted sand–bentonite mixture under constant-volume  
234 and free-swell conditions, Physics and Chemistry of the Earth 33: S462–S471.

235 Cui Y. J., Tang A. M., Qian L. X., Ye W. M., Chen B. 2011. Thermal-mechanical  
236 behavior of compacted GMZ bentonite, Soils and Foundations, 51(6): 1065-1074.

237 Delage P., Howat M., Cui Y. J. 1998. The relationship between suction and  
238 swelling properties in a heavily compacted unsaturated clay, Engineering Geology 50:  
239 31–48.

240 Di Maio C. 1996. Exposure of bentonite to salt solution: Osmotic and mechanical  
241 effects, Geotechnique 46(4): 695-707.

242 Dixon D. A. 2000. Porewater salinity and the development of swelling pressure in  
243 bentonite-based buffer and backfill materials, POSIVA Report 2000-04, Posiva Oy,  
244 Helsinki, Finland.

245 Francois B., Laloui L., Laurent C. 2009. Thermo-hydro-mechanical simulation of  
246 ATLAS in situ large scale test in Boom Clay. *Computers and Geotechnics* 36: 626-  
247 640.

248 Gens A., Sánchez M., Guimarães L Do N, Alonso E E, Lloret A, Olivella S, Villar  
249 M V, Huertas F (2009) A full-scale in situ heating test for high-level nuclear waste  
250 disposal: Observations, analysis and interpretation, *Geotechnique* 59: 377-399.

251 Teachavorasinskun S, Visethrattana K (2006) Local hydraulic resistance of  
252 compacted sand-bentonite mixture, *Geotechnical* 56: 511-516.

253 Herbert H-J, Moog H C (1999) Cation exchange, interlayer spacing, and water  
254 content of MX-80 bentonite in high molar saline solutions, *Engineering Geology* 54,  
255 55-65.

256 Hurel C, Marmier N (2010) Sorption of europium on a MX-80 bentonite sample:  
257 experimental and modelling results, *Journal of Radioanal Nuclear Chemistry* 284:  
258 225–230.

259 Imbert C, Villar M V (2006) Hydro-mechanical response of a bentonite  
260 pellets/powder mixture upon infiltration, *Applied Clay Science* 32: 197-209.

261 Juvankoski M (2009) Description of Basic Design for Buffer, Working Report  
262 2009-131, POSIVA OY.

263 Komine H (2004) Simplified evaluation on hydraulic conductivities of sand-  
264 bentonite mixture backfill, *Applied Clay Science* 26: 13-19.

265 Komine H (2009) Self-sealing capability of some bentonite buffers in artificial  
266 seawater, Proceedings of the 17th International Conference on Soil Mechanics and  
267 Geotechnical Engineering, Hamza M et al.(Eds): 2495-2498.

268 Komine H, Ogata N (1996) Prediction for swelling characteristics of compacted  
269 bentonite, Canadian Geotechnical Journal 33(1): 11-22.

270 Komine H, Ogata N (1999) A Trial Design of Buffer Materials from the Viewpoint  
271 of Self-sealing (Tokyo: Central Research Institute of Electric Power Industry).

272 Lee J O, Lim J G, Kang I M, Kwon S (2012) Swelling pressures of compacted Ca-  
273 bentonite, Engineering Geology 129: 20-26.

274 Li X L, Bastiaens W, Marcke P Van, Verstricht J, Chen G J, Weetjens E, Sillen X  
275 (2010) Design and development of large-scale in-situ PRACLAY heater test and  
276 horizontal high-level radioactive waste disposal gallery seal test in Belgian HADES.  
277 Journal of Rock Mechanics and Geotechnical Engineering 2(2): 103–110.

278 Lloret A, Villar M V (2007) Advances on the knowledge of the therm-hydro-  
279 mechanical behaviour of heavily compacted “FEBEX” bentonite, Physics and  
280 Chemistry of the Earth 32: 701-715.

281 Lloret A, Villar MV, Sanchez M, Gens A, Pintado X, Alonso EE (2003)  
282 Mechanical behaviour of heavily compacted bentonite under high suction changes,  
283 Geotechnique 53(1): 27-40.

284 Marcial D, Delage P, Cui Y J (2006) A laboratory study of the self-sealing  
285 behavior of a compacted sand-bentonite mixture. Geomechanics and Geoengineering:  
286 An International Journal 1: 73-85.

287 Martín P L, Barcala J M, Huertas F (2006) Large-scale and long-term coupled  
288 thermo-hydro-mechanic experiments with bentonite: the FEBEX mock-up test,  
289 Journal of Iberian Geology 32: 259-282.

290 Martino J B, Dixon D A, Kozak E T, Gascoyne M, Vignal B, Sugita Y, Fujita T,  
291 Masumoto K (2007) The tunnel sealing experiment: An international study of full-  
292 scale seals, Physics and Chemistry of the Earth 32: 93-107.

293 Mitachi T (2008) Mechanical behavior of bentonite-sand mixtures as buffer  
294 materials, Soils and Foundations 48(3): 363-374.

295 Montes-H G, Duplay J, Martinez L, Geraud Y, Rousset-Tournier B (2003)  
296 Influence of interlayer cations on the water sorption and swelling-shrinkage of MX-80  
297 bentonite, Applied Clay Science 23: 309-321.

298 Nakashima Y (2006) H<sub>2</sub>O self-diffusion coefficient of water-rich MX-80 bentonite  
299 gels. Clay Minerals 41: 659-668.

300 Niu W J (2008) Study on unsaturated permeability of densely compacted bentonite  
301 under free swelling conditions. Ph.D-thesis, Tongji University, Shanghai.(in Chinese)

302 Tang A M, Cui Y J, Le T T (2008a) A study on the thermal conductivity of  
303 compacted bentonites, Applied Clay Science 41: 181-189.

304 Tang A M, Munoz J J, Cui Y J, Delage P, Li X L (2008b) Experimental evaluation  
305 of the hydraulic resistance of compacted bentonite/Boom clay interface, Proc. of the  
306 International Technical Conference on the Practical Aspects of Deep Geological  
307 Disposal of Radioactive Waste, Prague, 16-18 June 2008, pp. 16.1-16.9.(ISBN: 2-  
308 916162-05-4).

309 Villar M V (2006) Infiltration tests on a granite/Bentonite mixture: influence of  
310 water salinity, Applied Clay Science 31: 96-109.

311 Villar M V, Lloret A (2008) Influence of dry density and water content on the  
312 swelling of a compacted bentonite, *Applied Clay Science* 39: 38-49.

313 Wang Q, Tang A M, Cui YJ, Delage P, Gatmiri, B (2012) Experimental study on  
314 the swelling behaviour of bentonite/claystone mixture, *Engineering Geology* 124: 59-  
315 66.

316 Ye W M, Cui Y J, Qian L X, Chen B (2009) An experimental study of the water  
317 transfer through confined compacted GMZ bentonite, *Engineering Geology* 108: 169-  
318 176.

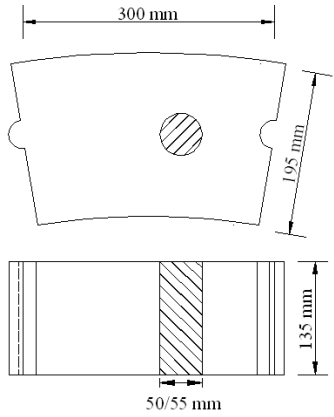
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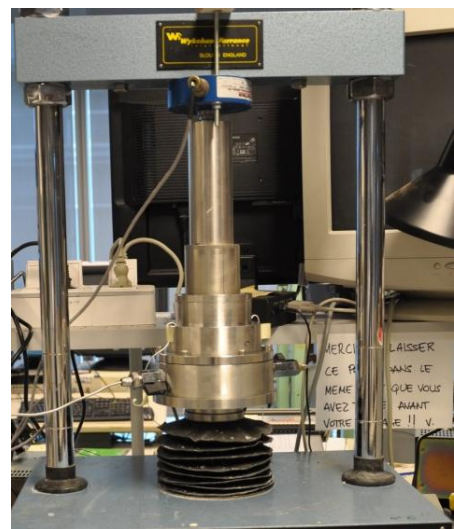
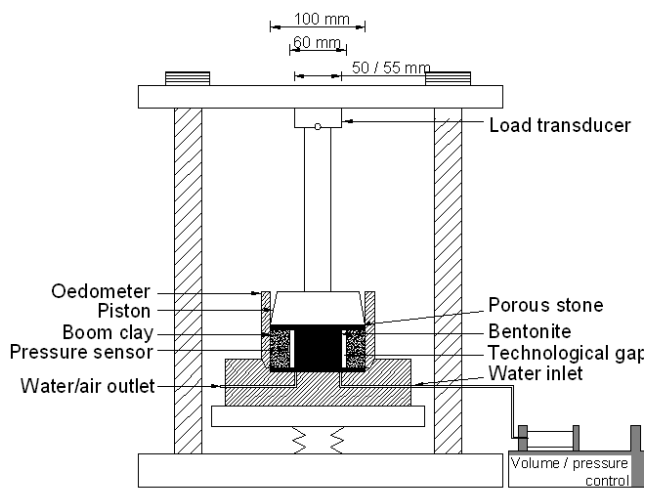
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**List of Figures:**

- Figure 1. Compacted bentonite block and cored sample
- Figure 2. Schematic layout of the experimental set-up
- Figure 3. Miniature pressure sensor used
- Figure 4. Changes in injection pressure (a), volume of water injected (b), axial (c) and radial (d) pressure in Test A
- Figure 5. Changes in injection pressure (a), volume of water injected (b), axial (c) and radial (d) pressure in Test B
- Figure 6. Changes in injection pressure (a) and axial pressure (b) in Test C

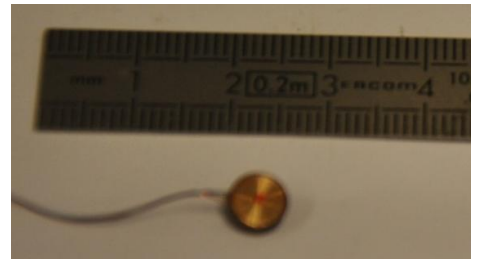


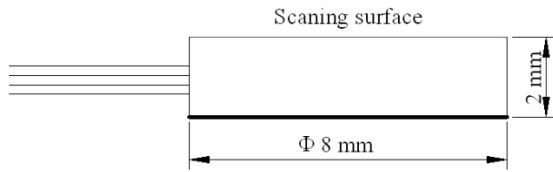
358 Figure 1. Compacted bentonite block and cored sample



359 Figure 2. Schematic layout of the experimental set-up

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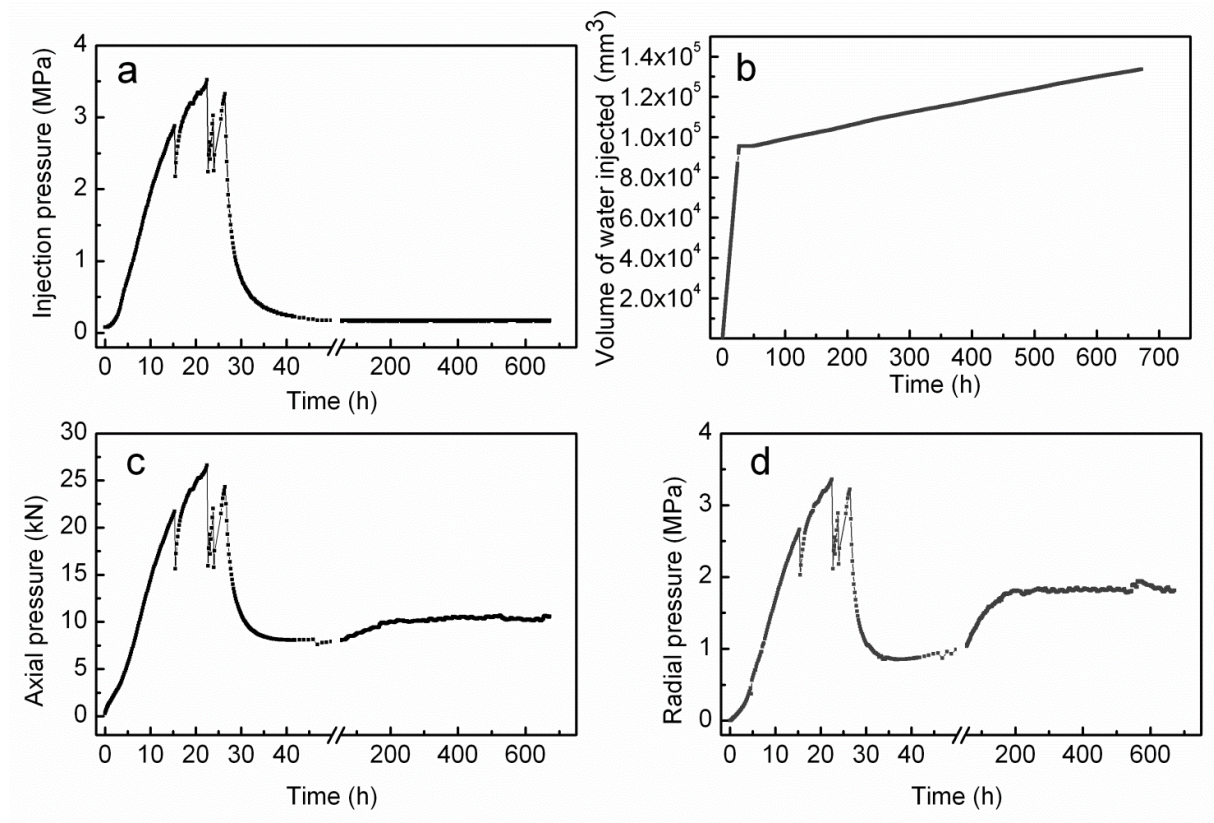
365 Figure 3. Miniature pressure sensor used

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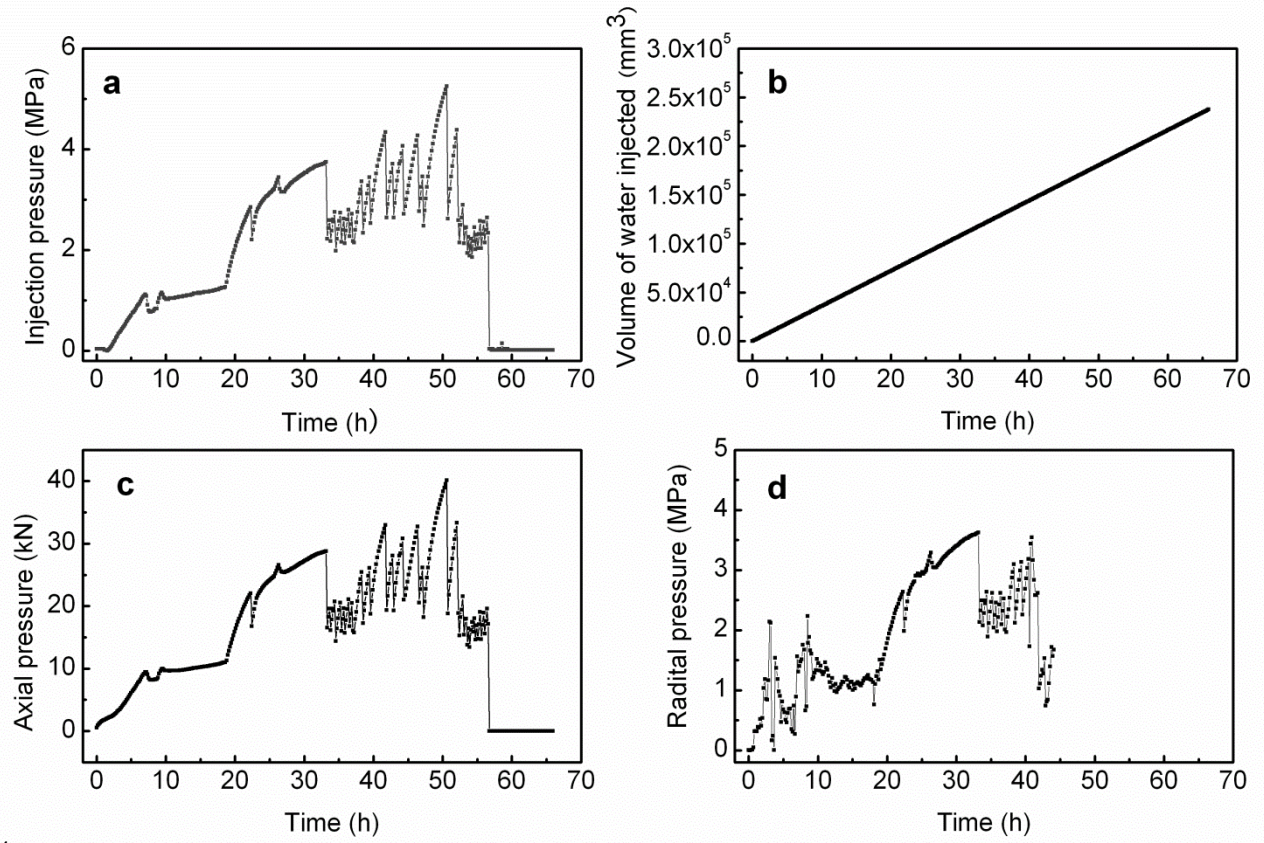


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371 Figure 4. Changes in injection pressure (a), volume of water injected (b), axial (c) and radial

372 (d) pressure in Test A

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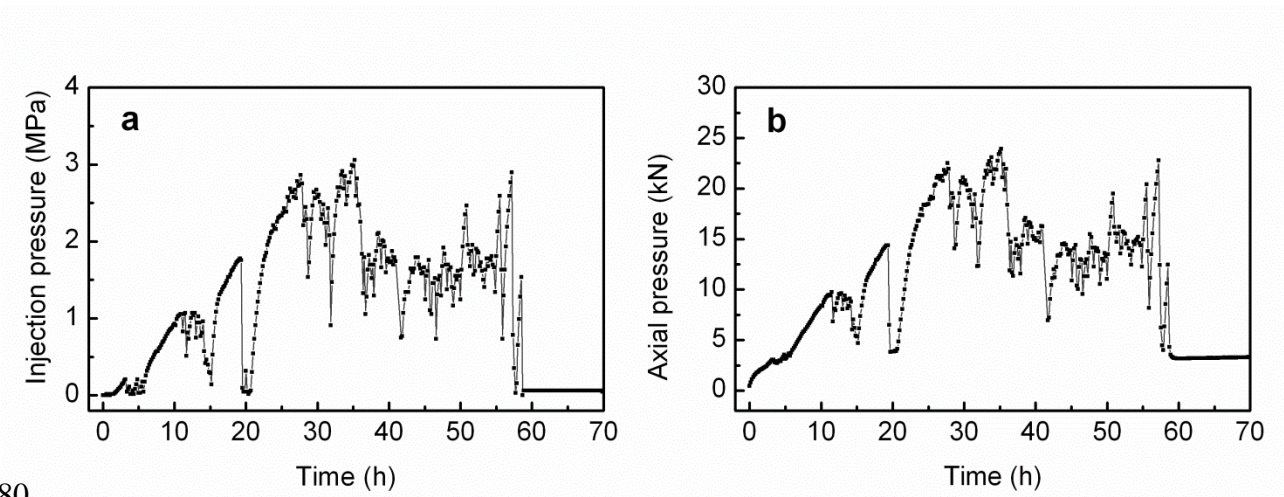
375 Figure 5. Changes in injection pressure (a), volume of water injected (b), axial

376 (d) pressure in Test B

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381 Figure 6. Changes in injection pressure (a) and axial pressure (b) in Test C

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393 Tables

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Table 1. Mineralogical composition of the soils tested

	MX80 bentonite (Wang et al. 2013)	Boom clay (Francois et al. 2009)
Montmorillonite (%)	80	10
Quartz (%)		60
w <sub>l</sub> (%)	575	59-83
w <sub>p</sub> (%)	53	22-28
ρ <sub>s</sub> (Mg/m <sup>3</sup> )	2.77	2.67

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397

398 Table 2. Test conditions

Test No.	Boom clay				MX80 bentonite			Gap	
	Ex-diameter (mm)	Thickness (mm)	$\rho_d$ (Mg/m <sup>3</sup> )	$w$ (%)	Diameter (mm)	$\rho_d$ (Mg/m <sup>3</sup> )	$w$ (%)	Height (mm)	Thickness (mm)
A	100	20	1.65	24	55	1.80	15.2	40	2.5
B	100	20	1.65	24	50	1.80	15.2	40	5
C	100	20	1.65	24	50	1.80	15.2	40	5

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401 Table 3. Water content and dry density of the soil specimens after the tests

		w (%)				$\rho_d$ (Mg/m <sup>3</sup> )				Test duration (hours)
		$r_1$	$r_2$	$r_3$	$r_4$	$r_1$	$r_2$	$r_3$	$r_4$	
Test A	Top	35	35.3	26.2	25.5	1.32	1.32	1.55	1.58	680
	Center	35.1	39.0	26.4	26.3	1.54	1.30	1.54	1.57	
	Bottom	40.1	42.2	28.6	28.2	1.09	1.24	1.48	1.48	
Test B	Top	37.1	44.3	37.0	29.8	1.25	1.21	1.39	1.48	65
	Center	29.9	41.3	33.3	29.3	1.28	1.26	1.39	1.49	
	Bottom	96.4	124.5	69.8	44.8	0.73	0.61	0.91	1.11	
Test C	Top	43.2	45.5	28.5	29.1	1.34	1.22	1.50	1.47	93
	Center	45.2	47.8	29.2	30.5	1.18	1.14	1.47	1.47	
	Bottom	51.1	58.8	32.6	33.6	1.08	0.97	1.39	1.36	

402  $r$ : the distance from the centre of the specimen to the sampling point;  $r_1=7.5\text{mm}$ ,  $r_2=22.5\text{mm}$ ,

403  $r_3=35\text{mm}$ ,  $r_4=45\text{mm}$ .

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