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

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3 CHEN Yong-Gui^{1, 2}, CUI Yu-Jun^{1, 2}, TANG Anh Minh², WANG Qiong², YE Wei-
4 Min¹

5

6 1. Key Laboratory of Geotechnical and Underground Engineering of Ministry of
7 Education and Department of Geotechnical Engineering, Tongji University, 1239
8 Siping Road, Shanghai 200092, PR China.

9 2. Laboratoire Navier/CERMES, Ecole des Ponts - ParisTech, 6-8 av. Blaise Pascal,
10 Cité Descartes, 77455 Marne-la-Vallée, France.

11

12 **Corresponding author:**

13 Prof. CUI Yu-Jun

14 Laboratoire Navier/CERMES, Ecole des Ponts - ParisTech,

15 6-8 av. Blaise Pascal, Cité Descartes, 77455 Marne-la-Vallée, France.

16 Telephone : +33 1 64 15 35 50

17 Fax : +33 1 64 15 35 62

18 E-mail: yujun.cui@enpc.fr

19

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 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 mm³/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 mm³/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 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

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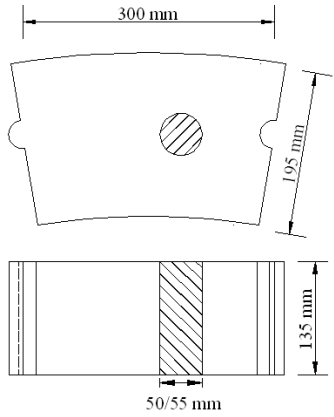
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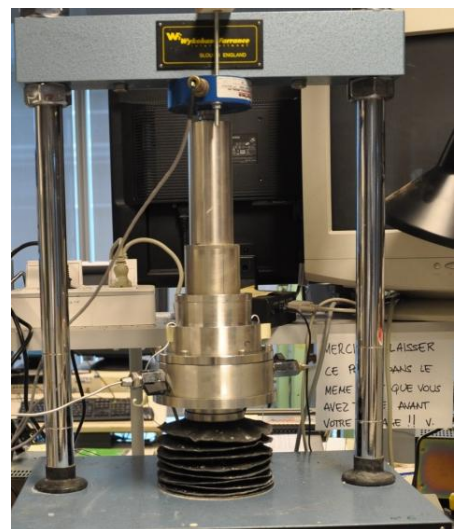
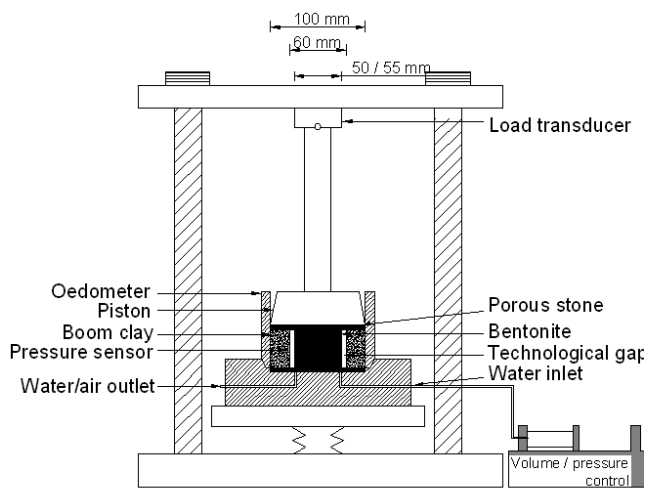
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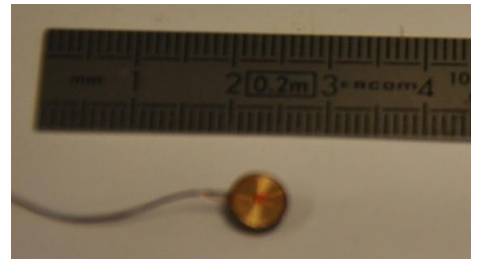


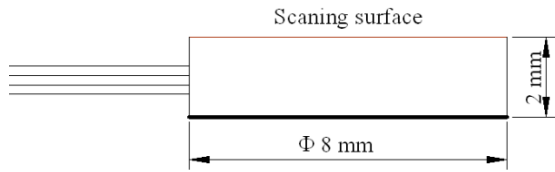
358 Figure 1. Compacted bentonite block and cored sample



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

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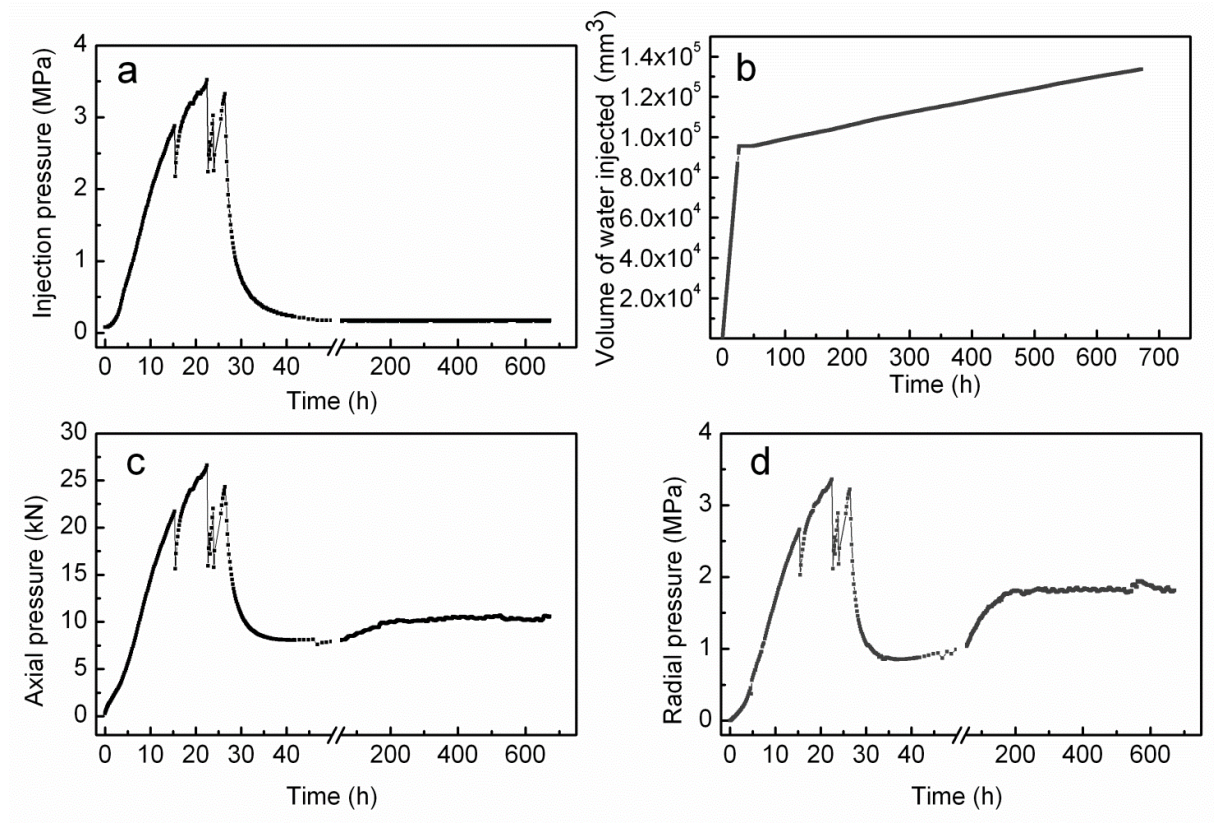
365 Figure 3. Miniature pressure sensor used

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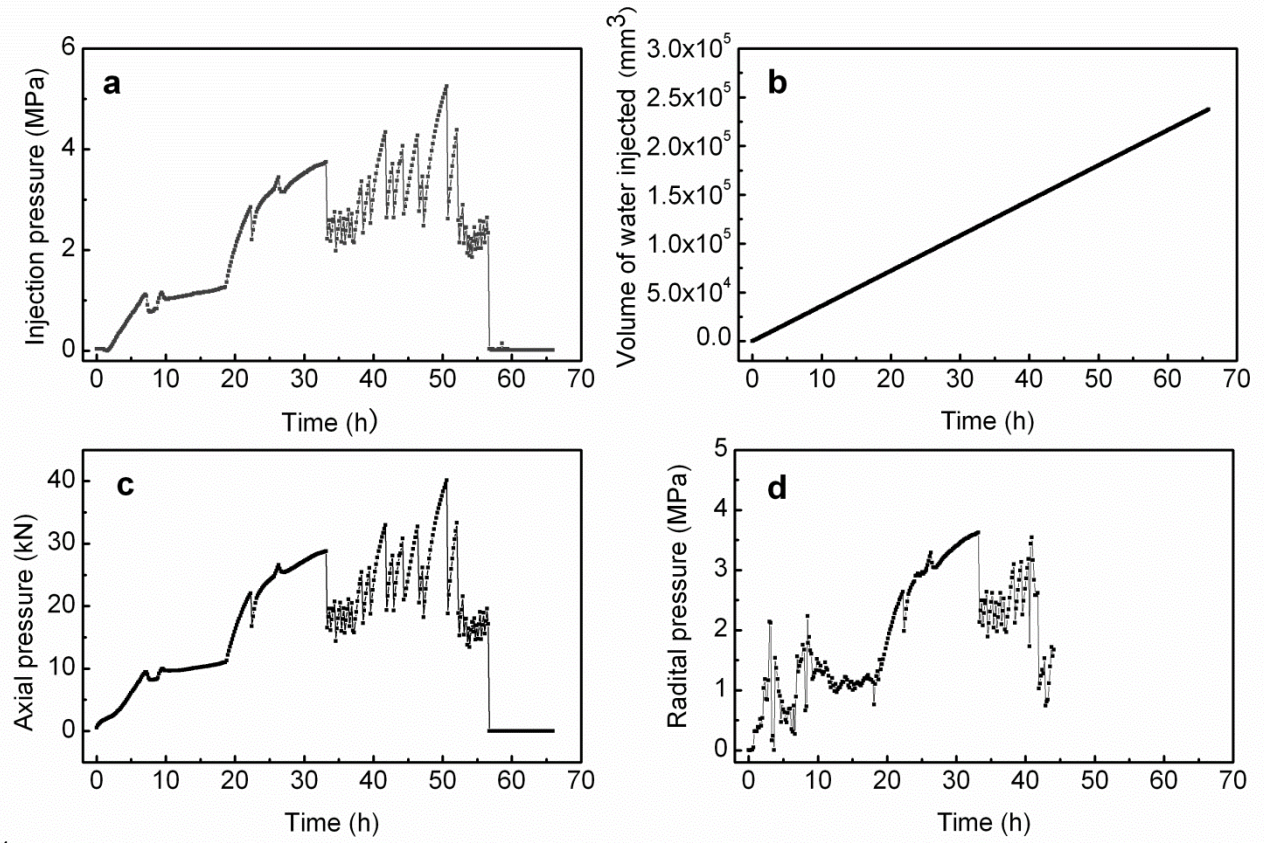


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371 Figure 4. Changes in injection pressure (a), volume of water injected (b), axial (c) and radial

372 (d) pressure in Test A

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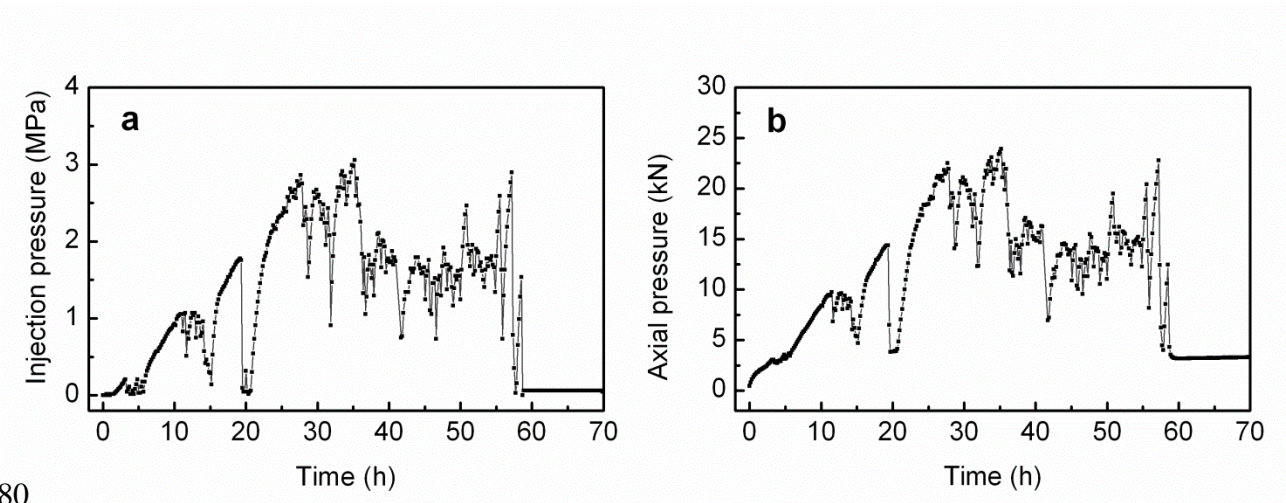
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375 Figure 5. Changes in injection pressure (a), volume of water injected (b), axial

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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395

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 _l (%)	575	59-83
w _p (%)	53	22-28
ρ _s (Mg/m ³)	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)	ρ_d (Mg/m ³)	w (%)	Diameter (mm)	ρ_d (Mg/m ³)	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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400

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

		w (%)				ρ_d (Mg/m ³)				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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