Method Note/

Influence of Pressure Change during Hydraulic Tests on Fracture Aperture

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Abstract

In a series of field experiments, we evaluate the influence of a small water pressure change on fracture aperture during a hydraulic test. An experimental borehole is instrumented at the Korea Atomic Energy Research Institute (KAERI) Underground Research Tunnel (KURT). The target fracture for testing was found from the analyses of borehole logging and hydraulic tests. A double packer system was developed and installed in the test borehole to directly observe the aperture change due to water pressure change. Using this packer system, both aperture and flow rate are directly observed under various water pressures. Results indicate a slight change in fracture hydraulic head leads to an observable change in aperture. This suggests that aperture change should be considered when analyzing hydraulic test data from a sparsely fractured rock aquifer.

Introduction

Groundwater flow through fractures is a major pathway for radioactive contaminants to migrate from a subsurface waste repository to the biosphere. The cubic law relates transmissivity of a fracture to the cube of its aperture; a relatively small aperture change can lead to a large change in the flow rate and fracture transmissivity. An aperture increase of 50%, for example, is related to a fracture transmissivity increase of 338%. From the field applications of hydro-fracturing and the theoretical studies on the hydromechanical behavior of a fractured rock (NRC 1996; Rutqvist and Stephansson 2003), it is well-known that a large pore pressure change from injecting fluid will increase the aperture and therefore the transmissivity of the fracture. Increasing water pressure in a fracture leads to increased aperture and decreased contact area. When the injected water pressure exceeds some threshold, the fracture suddenly grows and fracture connectivity increases. Water pressures applied in hydro-fracturing are typically in excess of 20 MPa (200 bar) (Walsh 1981; Dvorkin and Nur 1992; NRC 1996), and most laboratory- and field-scale studies on hydromechanical behavior have focused on fracture changes and flow rates at water pressures of 1 ~ 10 MPa (10 ~ 100 bar) where the threshold is located (Alm 1999; Cornet et al. 2003; Rutqvist and Stephansson 2003). Much smaller changes in water pressure are applied while conducting hydrogeologic characterization.

It is plausible that even slight changes in water pressure may affect fracture aperture and well testing results, analogous to the changes observed during hydro-fracturing. There are few attempts to evaluate the hydromechanical response of a fractured rock to a slight change in water pressure (Cappa et al. 2006; Svenson et al. 2008; Schweisinger et al. 2011). They installed the extensometers in a packed-off

71 section of boreholes in highly fractured rock aquifers, and measured the axial
72 displacements and pressures during various well tests such as slug, pulse, and pumping
73 tests. Note that the packed-off sections in their work were mostly fracture zones. By
74 assuming that an ideal fracture was in the test section and displacements occurred at that
75 fracture, they inferred aquifer characteristics from measurements through inverse
76 hydromechanical modeling. However, the observed displacements during the well tests
77 were small enough to ignore their effect on the fracture transmissivity, and the focus of
78 their work was characterization of mechanical properties using the curves for the
79 displacement as a function of water pressure.

80 In this study, we evaluate the influence of relatively small changes in water
81 pressure on fracture aperture with a series of field experiments in a sparsely fractured
82 granite aquifer. An experimental borehole is instrumented at the Korea Atomic Energy
83 Research Institute (KAERI) Underground Research Tunnel (KURT). The target fracture
84 for testing was found from the analyses of borehole logging and hydraulic tests. A
85 double packer system, which is able to directly observe the change of an aperture due to
86 water pressure change, was developed and installed in the test borehole. Using this
87 packer system, both aperture and flow rate were directly observed under various water
88 pressures.

89

90 **Motivation**

91 The KURT facility, which is in Daejeon, in the middle-western area of the
92 Korean peninsula, is a small-scale underground research facility that reaches a
93 maximum depth of 90 m below the ground surface [see Kwon et al. (2011) for site
94 description and characteristics]. Hydraulic tests were conducted in several packed-off

intervals of a 500 m borehole, DB-1 at the KURT (Figure 1). Table 1 shows the number of fractures and estimated transmissivities from the hydraulic testing intervals. In fracture zones, estimated transmissivities from constant head withdrawal tests and the recovery tests are similar. In test intervals with fewer fractures, transmissivities from constant head withdrawal test results are approximately an order of magnitude smaller than those from the recovery, and the difference between the test results becomes larger as the number of fractures in the packed-off interval decreases. Several phenomena are potential causes of this. However, because imposed hydraulic gradients and groundwater flow direction are equal between constant head withdrawal and recovery tests, the cause cannot be the nonlinear groundwater flow in a fracture due to high imposed hydraulic gradients (Ji et al. 2008) or the trapping zone effect from the directional anisotropy of flow (Boutt et al. 2006).

Water pressure is decreasing within the formation during a constant head withdrawal test while it is increasing during a recovery test. We propose that this difference in water pressure causes a small aperture change that explains the differences between estimated transmissivity values from the two types of hydraulic test results. To verify this idea, we directly observe the change in fracture aperture when we change the water pressure in an interval.

Approach

For direct observation of the fracture aperture during a test, we designed and built a special double packer system composed of three parts (Figure 2): an outer pipe, an inner pipe and a clear acrylic pipe. Eight rubber packers are used to mechanically isolate a 90 cm long specific zone in a borehole, and are attached to the outer pipe. A 30

cm long x 13 cm wide observation window is located in the specific zone between the upper and lower packers in the outer pipe (Figures 2a and 2d). The outer pipe has a diameter of 9.8 cm. The inner pipe with a diameter of 8.2 cm is a passage for a borehole camera and cables, and a barrier to shut out the influence of the assigned water pressure to the test zone on the camera (Figure 2b). The inner pipe is coupled with the acrylic pipe for direct observation of a fracture using a borehole camera (Figure 2c), and placed inside the outer pipe. The outer and inner pipes are made of stainless steel and can be extended to the target zone using blank pipe of the same diameter.

Borehole TB-5 at the KURT field site was selected as the test borehole for in-situ experiments (Figure 1). It is 30 m deep and 10.2 cm (4 inches) in diameter, and is completed in massive Jurassic granite. Acoustic televiewing was used to locate the test zone and target fracture. Hydraulic tests (constant-head withdrawal and recovery) were conducted in the test zone to check the suitability of the target fracture for the experiments. The constant-head withdrawal test results were analyzed with the Moye (Batu 1998), Jacob-Lohman (Jacob and Lohman 1952), and straight-line models (Lohman 1972); the recovery test results are analyzed using the Horner model (Horne 1995).

After locating the test zone and target fracture, the water injection tests were conducted. Figure 3 is a schematic of the experimental setup for observation of the aperture under various water pressures. The pressurized water was injected into the test zone through the space between the outer and inner pipes using a constant pressure injection pump, maintaining the desired water pressure. A borehole camera (R-CAM 1000, Laval Underground Survey Inc.) was inserted into the inner pipe to record the aperture change of the target fracture during the experiment. A flow meter and pressure

143 gauge were installed between the injection pump and the injection hole in the outer pipe
144 to measure the established water pressure and the injection rate into the target zone. The
145 tubing that links the injection pump to the injection hole is stainless steel to prevent
146 head loss, and the inner pipe is filled with water to minimize the optical distortion at the
147 acrylic pipe. The imposed water pressures were 2, 3, 4, and 5 bars; the initial water
148 pressure during the all experiments was 0.1 bars. Water injection tests were repeated
149 three times at each pressure. The selected differences between the imposed and initial
150 water pressures are common in hydraulic tests conducted in fractured rock aquifers
151 (Beauheim et al. 2004). The vertical separation distance between two near-planar
152 surfaces, according to some pre-established Cartesian coordinate system, was used as
153 the fracture aperture in the analyses (Konzuk and Kueper 2004).
154

155 **Results and Discussions**

156 Acoustic televiewing results show that the fracture frequency, defined as the
157 number of fractures per unit length of the borehole, is 2.6 m^{-1}, and that fractures are
158 evenly distributed along the borehole. Figure 4 shows the borehole logging result at the
159 section 26.0 – 30.0 m below the top of the casing (TOC). Fractures crossing TB-5
160 borehole were identified from the amplitude distribution of the measured acoustic wave.
161 Based on the borehole logging data, the packed-off section 28.2 – 29.1 m below TOC
162 was selected as the test zone because it has a single fracture, allowing intensive
163 observation and analysis of the target fracture.

164 Figure 5 indicates the results of the hydraulic tests. During constant-head
165 withdrawal tests, the hydraulic head in the test zone was instantaneously decreased from
166 an initial value to the assigned head and was kept constant. The initial outflow rate was

167 at a maximum. During the test the outflow and pressure were monitored as outflow
168 decayed to a steady value. The initial and assigned heads were 22.7 and 11.2 m,
169 respectively, in our constant-head withdrawal test. During the recovery tests the
170 groundwater outflow was stopped; hydraulic head was monitored while it recovered to
171 the original pre-test value. From the constant head withdrawal test, the transmissivity of
172 the test zone is estimated as 3.6×10^{-9}, 4.8×10^{-9} and 5.2×10^{-9} m^2/s with the Moye
173 (Batu 1998), Jacob-Lohman (Jacob and Lohman 1952) and straight line models
174 (Lohman 1972), respectively, which are at least a factor of 0.2 smaller than the
175 estimated transmissivity from the recovery test (2.7×10^{-8} m^2/s). This difference cannot
176 be due to the use of different models for interpreting the data. This result indicates that
177 the proposed test zone and target fracture are suitable for the experiments.

178 To reveal the relation between the water pressure and aperture, water injection
179 tests were conducted, and the aperture and steady-state injection rate of water were
180 measured while various water pressures were imposed. Figure 6a shows the measured
181 hydraulic heads and injection rates during the experiment when we imposed water
182 pressure of 5 bars. The hydraulic head was initially 1.4 m. When the experiment began,
183 it was abruptly increased to 50.5 m, and kept constant, although it oscillated slightly due
184 to the injection pump. The injection rate was greatest at the beginning of the experiment,
185 and stabilized at 1.06×10^{-3} m^3/d. The response of the target fracture was recorded
186 during the test using the borehole camera, and Figures 6b-c are the snapshots of the
187 aperture before the water injection and after reaching steady state flow, at 319 minutes
188 elapsed time. Immediately after a water pressure of 5 bars was imposed, the aperture
189 was on average increased by a factor of 1.25±0.01. Then, as time elapsed from the
190 initial pressurization, the aperture gradually became larger. The aperture stabilized at

about 20 minutes elapsed time. The stabilized aperture was on average about a factor of 1.44±0.03 larger than the initial aperture (Figure 6d).

When water pressures of 2, 3 and 4 bars were applied, changes in aperture were also observed. Changes were similar to the case where the water pressure of 5 bars was imposed: the apertures increased rapidly at the beginning of the experiments, and stabilized after a gradual increase. Figure 7 shows the relation between the applied hydraulic head and the stabilized aperture change. When water pressures of 2, 3 and 4 bars were applied, the hydraulic heads converged to 21.4, 29.2 and 37.5 m, respectively, and the apertures finally increased on average by factors of 1.22±0.02, 1.27±0.03 and 1.29±0.06, respectively, from the initial aperture.

Walsh (1981) reviewed the effect of the confining pressure on fracture permeability during hydro-fracturing, and described the relation between the confining pressure and aperture for a fracture having random fracture surface topography as

$$\frac{de}{dp} = \frac{\sqrt{2}m}{p} \tag{1}$$

where $2e$ is the aperture, p is the confining pressure, and m is the standard deviation of the asperity heights. Hence, it is expected that the aperture increases linearly with the natural log of imposed pressure on a fracture, and our data generally follows this expectation (see Figure 7). From the fitted straight line to our data, the stabilized aperture of the target fracture during the hydraulic tests can be estimated: if the hydraulic heads at the fracture are 11.2 and 22.7 m, the apertures are a factor of 1.05 and 1.21 larger than that at the hydraulic head of 1.4 m, respectively. From this estimation and the cubic law, it can be inferred that the estimated transmissivity of the test zone from the constant head withdrawal test is approximately a factor of 0.6 smaller than that from the recovery test by the aperture changes. This estimated discrepancy

between the transmissivities from the constant head withdrawal and recovery tests is smaller than that observed during the hydraulic tests, which could be a result of ignoring the change in contact area and tortuosity due to aperture change in the estimation (Matsuki et al. 2008).

Summary and Conclusions

Our experimental results indicate that relatively small changes in hydraulic head during a hydraulic test can lead to fracture aperture changes. A small change in aperture induces considerable changes in the estimated fracture hydraulic parameters because the transmissivity is proportional to the cube of the aperture. Additionally, the tortuosity in a fracture is influenced by the aperture. Tortuosity decreases with increasing aperture due to a decrease in asperity contacts between the fracture walls.

Accurate hydrogeological characterization of a radioactive waste disposal site is very important because it provides the input parameters for the safety assessment of a repository and controls the safety assessment results. It is difficult to apply our results directly to improving the quality of a hydraulic test for accurate hydrogeological characterization because there are many factors to be considered (e.g. depth to the test zone, fracture density in the test zone, mechanical properties of the host rock and geometrical properties of the test fractures). Nevertheless, our results show that the effects of water pressure change during a hydraulic test should be considered in test design and analysis. For example, using only constant head withdrawal test data can lead to underestimation of hydraulic parameters, which can potentially lead to overestimation of overall repository safety during ambient pressure conditions. Projection of our results to sparsely-fractured rock aquifer characterization suggests the

pressure-rising hydraulic test is more appropriate than the pressure-decreasing hydraulic test for a conservative safety assessment of a subsurface radioactive waste repository. Then, only a small disturbance of hydraulic heads from the natural condition during a hydraulic test is necessary to estimate the hydraulic parameters close to truly representative values.

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305
306

Figure caption

Figure 1. Layout of the KURT and the location of the test borehole, TB-5.

Figure 2. Designed double packer system. (a) outer pipe with packers; (b) inner pipe for a borehole camera and cables; (c) acrylic pipe for direct observation of fractures; and (d) assembled double packer system.

Figure 3. Schematic of the experimental set up.

Figure 4. Borehole logging result at the section 26.0 – 30.0 m below TOC.

Figure 5. Measured hydraulic heads and flow rates during the constant head withdrawal and recovery tests.

Figure 6. (a) Measured hydraulic heads and injection rates when the water pressure of 5 bars is imposed to the test zone. Snapshots of the target fracture (b) before imposing the pressure; (c) at an elapsed time of 319 minutes from imposing; and (d) changes of apertures during the experiment. The black lines indicate a sketch of the aperture in the white rectangle in Figure 3b before the experiment, and the red, green, and blue ones are after 30 seconds, 10 minutes, and 20 minutes after a pressure of 5 bars is imposed, respectively.

Figure 7. Semi-log relation between the applied hydraulic head and the change of aperture from the initial one at the hydraulic head of 1.4 m. The y-axis values indicate the factor increase in fracture aperture. The dots and bars are the averages and standard deviations of the aperture changes at each applied hydraulic head, respectively. The dashed line in the graph is the fitted straight line to the data.

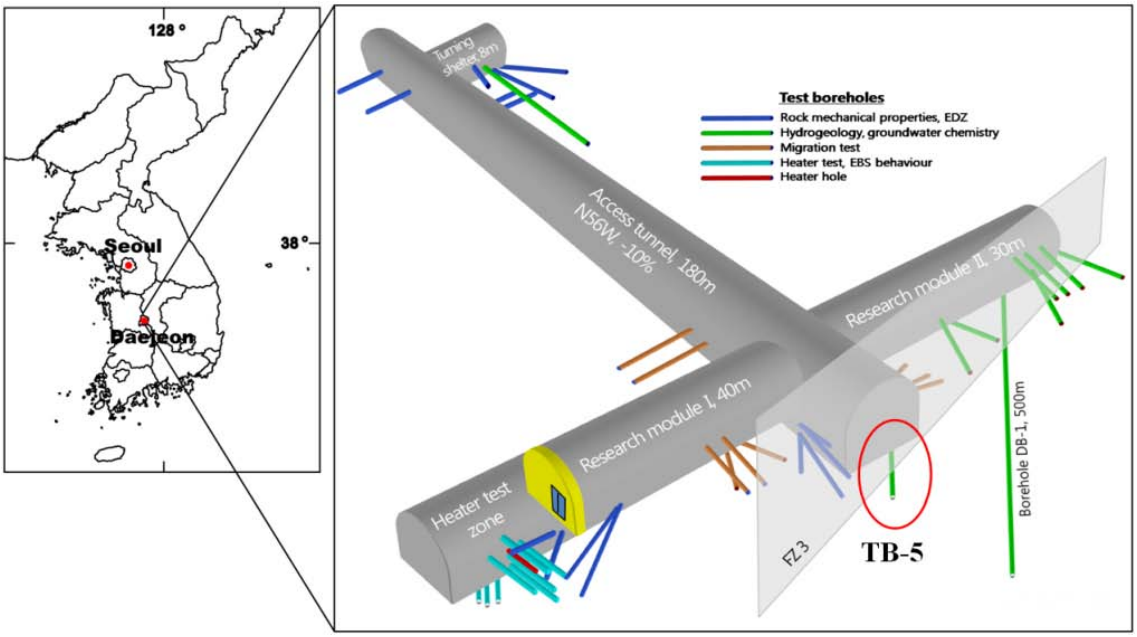
329 **Table 1**. The number of fractures and estimated interval transmissivities from the
330 constant head withdrawal and recovery tests conducted at several packed-off intervals in
331 borehole DB-1 installed at KURT.

Test interval (meters from TOC)	Fracture frequency [m^{-1}]	Estimated interval transmissivity [m^2/sec]			
		Constant head withdrawal test			Recovery test
		Moye	Jacob-Lohman	Straight line	Horner
8 - 23	Fracture zone	$2.8x10^{-5}$	$8.2x10^{-5}$	$3.6x10^{-5}$	$1.2x10^{-5}$
43.5 - 59.5	Fracture zone	$1.5x10^{-6}$	$1.1x10^{-6}$	$1.1x10^{-6}$	$9.4x10^{-7}$
65 - 85	2.75	$1.6x10^{-7}$	$1.3x10^{-7}$	$7.4x10^{-8}$	$1.5x10^{-6}$
92 - 116	Fracture zone	$8.2x10^{-7}$	$6.9x10^{-7}$	$9.7x10^{-7}$	$6.3x10^{-7}$
125 - 145	3.10	$1.1x10^{-7}$	$6.3x10^{-8}$	$4.6x10^{-8}$	$5.7x10^{-7}$
150 - 160.5	Fracture zone	$5.1x10^{-8}$	$3.6x10^{-8}$	$3.8x10^{-8}$	$1.6x10^{-7}$
161 - 181	6.85	$1.1x10^{-7}$	$9.1x10^{-8}$	$8.2x10^{-8}$	$4.0x10^{-7}$
183 - 194	Fracture zone	$1.1x10^{-7}$	$1.3x10^{-7}$	$1.8x10^{-7}$	$1.7x10^{-7}$
201.5 - 226	Fracture zone	$6.7x10^{-6}$	$1.5x10^{-5}$	$2.1x10^{-5}$	$1.0x10^{-4}$
237 - 247	Fracture zone	$2.1x10^{-6}$	$5.4x10^{-6}$	$8.5x10^{-6}$	$4.5x10^{-5}$
251 - 271	0.80	$1.7x10^{-7}$	$5.8x10^{-8}$	$6.3x10^{-8}$	$1.0x10^{-6}$
279 - 293	Fracture zone	$3.9x10^{-8}$	$3.8x10^{-8}$	$5.0x10^{-8}$	$8.8x10^{-7}$
291 - 311	2.45	$5.9x10^{-8}$	$3.0x10^{-8}$	$2.9x10^{-8}$	$5.6x10^{-8}$
311 - 331	0.80	$3.1x10^{-8}$	$1.3x10^{-8}$	$1.5x10^{-8}$	$6.1x10^{-8}$
331 - 351	0.40	$5.7x10^{-8}$	$3.1x10^{-8}$	$3.5x10^{-8}$	$1.5x10^{-7}$
351 - 371	0.75	$5.6x10^{-8}$	$3.3x10^{-8}$	$3.2x10^{-8}$	$3.5x10^{-7}$
371 - 391	0.55	$6.0x10^{-8}$	$4.1x10^{-8}$	$3.4x10^{-8}$	$4.4x10^{-7}$
391 - 411	0.20	$5.9x10^{-8}$	$3.0x10^{-8}$	$3.3x10^{-8}$	$1.8x10^{-7}$
411 - 431	0.40	$4.9x10^{-8}$	$3.0x10^{-8}$	$3.4x10^{-8}$	$3.4x10^{-7}$
431 - 451	0.20	$4.1x10^{-8}$	$5.1x10^{-8}$	$2.5x10^{-8}$	$4.5x10^{-7}$
451 - 471	0.80	$5.5x10^{-8}$	$5.4x10^{-8}$	$3.4x10^{-8}$	$2.8x10^{-7}$
471 - 491	0.10	$5.3x10^{-8}$	$7.6x10^{-8}$	$3.3x10^{-8}$	$3.7x10^{-7}$

332

333

334 Fig. 1.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Seoul
Daejeon
Turning shelter, 8m
Access tunnel, 180m
N56W, -10%
Research module II, 30m
Research module I, 40m
Heater test zone
Test boreholes
Rock mechanical properties, EDZ
Hydrogeology, groundwater chemistry
Migration test
Heater test, EBS behaviour
Heater hole
FZ3
TB-5
Borehole DB-1, 500m

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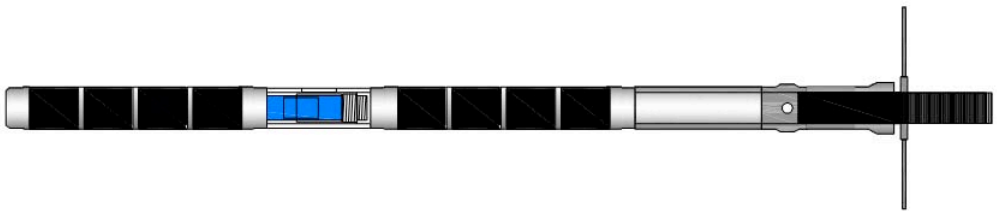
Fig. 2

(a)



(b)

(c)

(d)

346 Fig. 3

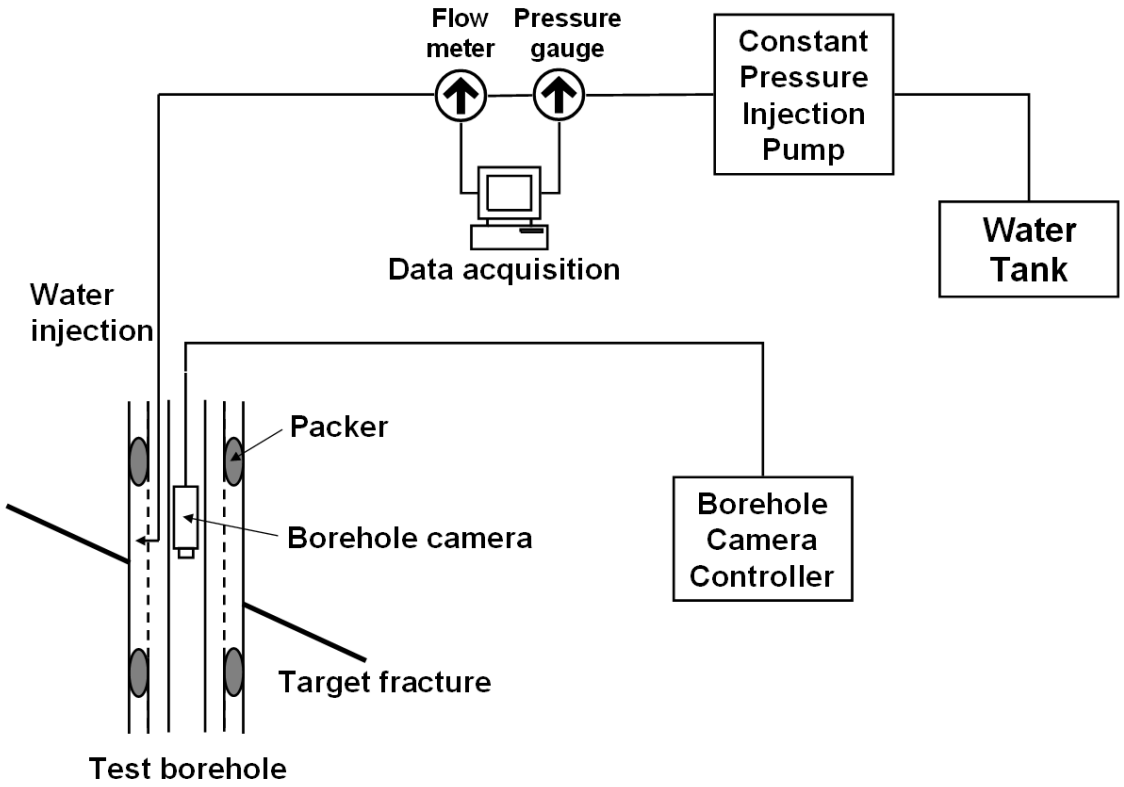


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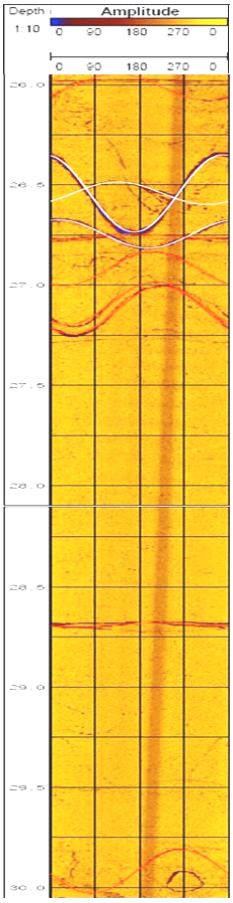
Fig. 4.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Amplitude
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352 Fig. 5.

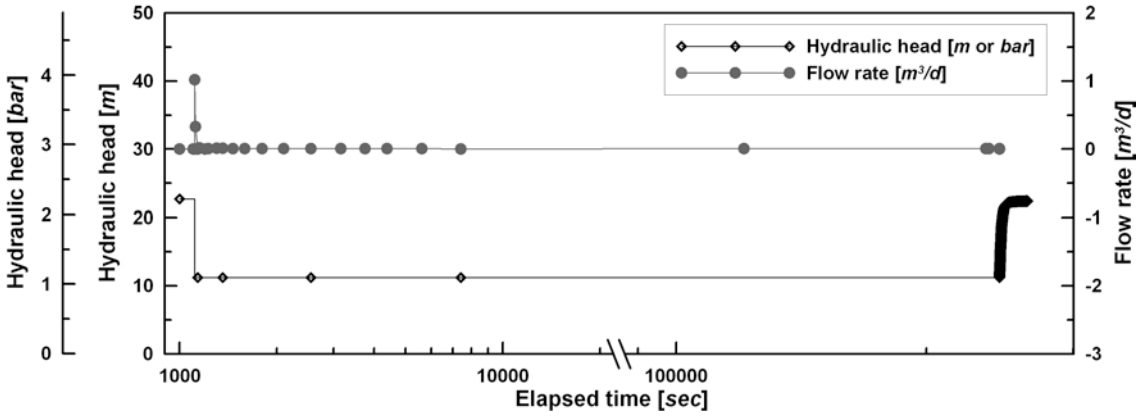

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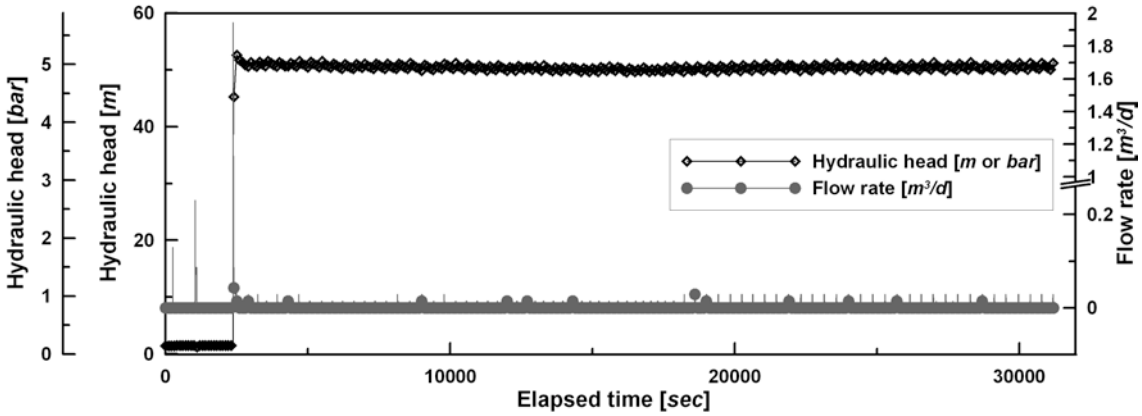
Fig. 6

(a)


Hydraulic head [bar]
Hydraulic head [m]
Flow rate [m³/d]
Elapsed time [sec]
Hydraulic head [m or bar]
Flow rate [m³/d]
0
10000
20000
30000
0
20
40
60
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4
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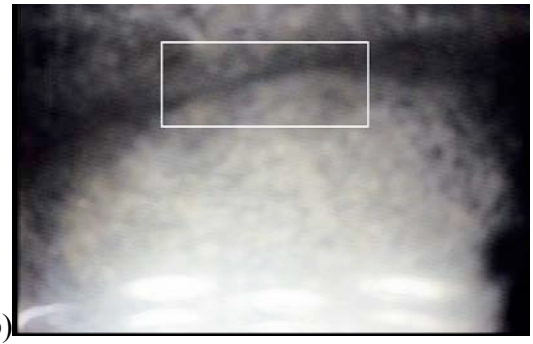
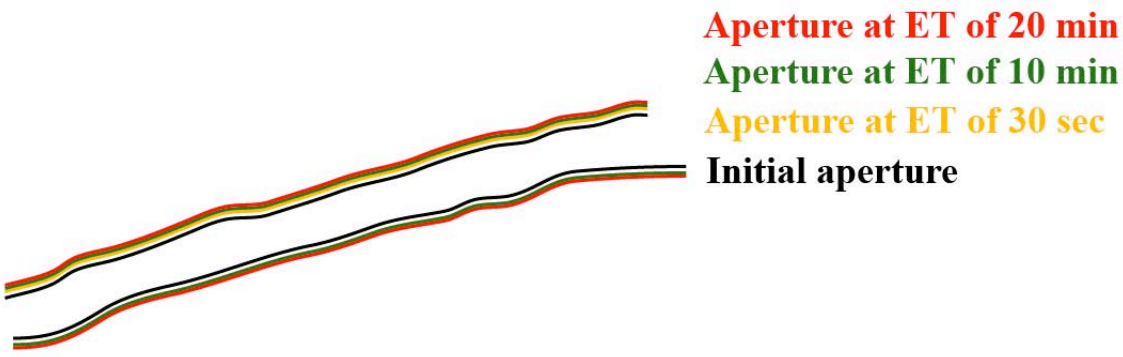
0
0.2
1
1.2
1.4
1.6
1.8
2

(b)

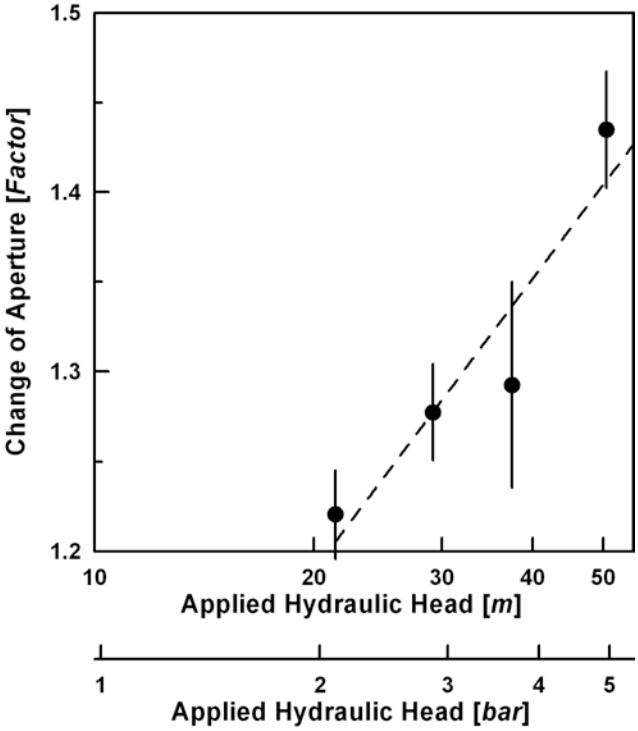


(c)

(d)


Aperture at ET of 20 min
Aperture at ET of 10 min
Aperture at ET of 30 sec
Initial aperture

363 Fig. 7



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