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PERMEABILITY MEASUREMENTS IN THE EXCAVATION DAMAGED ZONE IN THE OPALINUS CLAY AT MONT TERRI ROCK LABORATORY, SWITZERLAND

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ABSTRACT

Clay-rich sedimentary rocks, such as argillites, have favourable permeability and chemical retention characteristics for disposal of radioactive wastes. The development of excavation damage zones (EDZ's) around the disposal galleries and access tunnels could compromise these natural characteristics. Minimising the effect of these EDZ's through rock mechanics is a significant research priority for the Andra, the organisation responsible for radioactive waste management in France. Several previous studies for characterising the EDZ's used borehole networks with spacings less than one meter. These studies showed that the fractured zone is confined mostly to less than 0.5 meters from the walls of openings and the fracture networks may be heterogeneously connected. The study presented here extended the range of characterisation to borehole spacings of 1.3 meters or more as part of an effort to demonstrate the constructability of filled slots to disconnect EDZ fractures. The fracture permeabilities vary over three orders of magnitude. These results emphasise the difficulty to give a representative average permeability of the fracture zone at a metric scale.

RÉSUMÉ

La caractérisation de l'EDZ « excavated damage zone » est importante pour la conception des ouvrages de scellement d'un stockage profond de déchets nucléaires. ANDRA (Agence Nationale de gestion des Déchets RAdioactifs) étudie, dans le cadre des ouvrages de scellement, des saignées radiales de faible épaisseur remplies de matériau gonflant de faible perméabilité afin de couper la connectivité de l'EDZ pour éviter que l'EDZ soit un court-circuit des ouvrages de scellement. Ces études nécessitent une bonne compréhension de la connectivité et la perméabilité de l'EDZ. Une expérience montrant la performance hydraulique des saignées radiales a été réalisée dans les argiles à Opalinus du laboratoire Mont Terri (Suisse) et a nécessité la caractérisation initiale de l'EDZ à une échelle supérieure à celle des expériences déjà réalisées. Cet article présente le concept expérimental et les résultats obtenus lors de cette caractérisation. L' EDZ est très hétérogène avec des perméabilités variant de trois ordres de grandeur. Ces résultats montrent la difficulté d'obtenir une perméabilité équivalente représentative à une échelle métrique et à l'échelle d'une galerie.

1. INTRODUCTION

Deep underground repositories require construction of access shaft, drifts and repository chambers. The excavation of underground openings generally causes damage to the rock in the vicinity of the opening. The level of damage depends, among other factors, on the rock properties, the stress field, the geometry of the openings, the excavation method and time. Due to the stress redistribution during the excavation and subsequent rock convergence an EDZ fracture network consisting of unloading joints and shear fractures could appear in the vicinity of the opening. Within such excavation zone the mechanical and hydraulic rock properties are changed. In particular, the hydraulic conductivity of these fracture networks may be orders of magnitude higher than the one of the "virgin" hosted rock. Thus, radionuclide transport from the repository to the biosphere may be possible in the EDZ along galleries and shaft. Safety assessment calculations highlighted the role of EDZ as a possible seal short-cut. However assumption used in the model appeared to be very conservative because uncertainties remain in understanding generation, behaviour and evolution of the EDZ. A proper evaluation of the excavated damage zone is an essential issue for long-term safety and design of high level waste underground repository.

Minimising the effect of these EDZ's through rock mechanics is a significant research priority for ANDRA, the French nuclear waste agency. ANDRA is constructing an underground research laboratory in northern eastern France in clay-rich sedimentary rocks for such studies. Argillaceous formations are widely considered to be suitable as a geological barrier for radioactive waste disposal. Until the French URL is fully completed, ANDRA is participating in co-operative research programs at Mont Terri underground laboratory in northwestern Switzerland, which lies in similar argillite to the one at the URL in France. The Mont Terri rock laboratory is located in the Opalinus Clay, which has an extremely low hydraulic conductivity. The laboratory consists of a part of the security gallery of a motorway tunnel in the Mont Terri (Thury & Bossart, 1999), and a new gallery excavated in 1998. Figure 1 show the layout of the rock laboratory. Several previous studies for characterising the EDZ have been conducted in the Mont Terri laboratory especially in

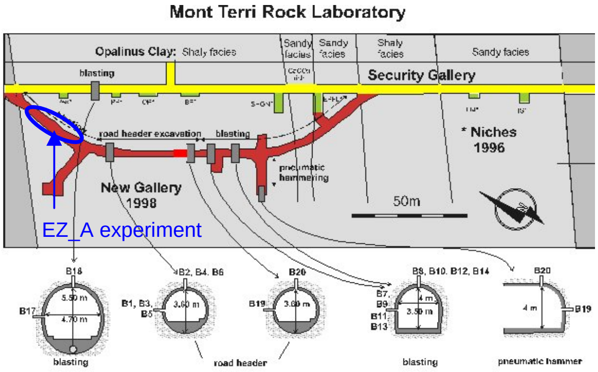

Figure 1. Map of Mont Terri laboratory

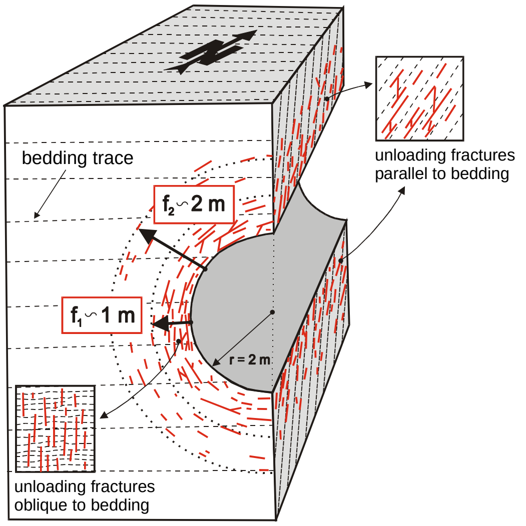

Figure 2. Conceptual model of the excavation disturbed zone. The inner zone (f1 = 1m), the outer zone, which is limited to a zone f2 = 2 m (Bossart et al, 2002)

the so called New Gallery. The permeability was characterised with multipacker system in order to study the permeability evolution with depth or with borehole networks with spacing less than one meter. These studies showed that the fractured zone is confined mostly to less than 0.5 meters from the walls of openings and the fracture networks may be heterogeneously connected.

This article summarizes the conceptual EDZ model developed by Bossart et al (2002) along with previous testing results. Since that study, further testing has been undertaken to evaluate the possibility of sealing the EDZ using cut-off walls. This testing also seeks to expand the testing to a 9-m^2 scale. The new testing uses a cross-hole pneumatic approach of air injection and vacuum withdrawal, in part because EDZ fractures in this material are initially dry. The vacuum withdrawal approach was used previously by Jakubick and Franz (1993). Although air injection can alter the rock by drying, these effects were considered less damaging than clay swelling due to the introduction of water in saturated tests. Such swelling effects could potentially mask other sealing effects introduced by the engineered cut-off system.

2. PREVIOUS RESULTS ON CHARACTERISATION OF THE EXCAVATION DAMAGED ZONE

Bossart et al (2002) summarized the results from field investigations on different scales, mainly the tunnel outcrop mapping, small scale mapping on EDZ fractures on overcores, pneumatic and hydraulic testing in the New Gallery. They used to data to develop a structural-geometrical model of the EDZ. This model is based on for the NW-SE directed galleries in the Opalinus Clay of the Mont Terri rock laboratory. Basically, the model distinguishes two zones, an inner and an outer zone (figure 2). The inner zone, with an average range extent of 1m (range varying between 0.1 and 1.25 m) within the tunnel wall, consists of an interconnected fracture network, which is connected to the tunnel and unsaturated. Less information is available for the outer zone of EDZ. The outer zone appears to extend no more than 2 meters from the tunnel wall and its fractures are generally poorly connected. The outer zone is normally not connected to the tunnel and the fractures may be partially saturated with pore water. The three-dimensional arrangement of the unloading fractures in both the inner and outer zones is strongly influenced by the pronounced bedding plane anisotropy. Pneumatic tests were performed in the inner zone of the EDZ containing an interconnected unloading fracture network which was unsaturated or partially, saturated. The transmissivity of the fractures in the inner zone varies between 10^{-5} m^2/s and 10^{-9} m^2/s, with the highest values found exclusively in the first 40 cm of the wall. The outer zone exhibit much smaller transmissivities between 10^{-9} m^2/s and 10^{-12} m^2/s.

Hydraulic cross hole test have been performed on a selected area in which a fracture has been isolated and saturated (Meier et al, 2000). In the four boreholes surrounding the injection borehole at radial distance from 10 cm to 50 cm, cross hole tests show high to weak connection. Even a borehole at 20 cm shows no connection.

3. CONCEPT OF THE EXPERIMENT

ANDRA is studying the concept of thin radial slot, with a depth larger than the EDZ, filled with swelling clay in order to cut off the EDZ permeability around a sealed gallery. The design of plugging and sealing systems has to consider the geometry and the properties of the EDZ to guaranty proper operation (Fairhurst and Damjanak 1996). The concept of cut-off slots for enhancing repository performance is based on the assumption that the EDZ is a continuous fracture network. This assumption, while conservative, has not been established. Indeed, the site selection work for the fracture healing experiment showed that connectivity of EDZ fracture cannot be assumed, as two of three 0.7-m arrays of three boreholes each failed to establish connectivity between the holes.

A first experiment (EZ_A experiment) was realised at Mont Terri to study the feasibility slot opening and slot backfilling and to assess the performance of the cut off with permeability testing. The objectives of the permeability testing for the EZ_A experiment are the following:

- to provide a characterization of the EDZ in the floor of the drift

- to determine the hydraulic performance of the cut off slot after its emplacement.

The characterization of the EDZ over a larger section of tunnel invert provides baseline information on the hydraulic conductivity and fracture connectivity. Given the lack of previous understanding of connectivity at scale larger than 0.7 m, the initial testing program was a designed as a thorough cross-hole characterization using a 12-hole array. The pressure interference tests in this array would extend our understanding of EDZ geometry to a larger scale than previously tested. Furthermore, the knowledge of the conducting geometry in the EDZ would help to optimize the slot locations to assure a meaningful comparison of pre-slot and post-slot hydraulic behaviors. Due to space limitations in the northern access gallery, the test scale had to be reduced to an array of nine holes.
The EZ-A cut-off area would be characterized using an array of 9 boreholes (Figure 1). The array follows a 3 x 3 grid, where the grid spacing is 1.5 meters along the tunnel axis and 1.3 meter perpendicular to the axis. The holes along the centreline were prepared 2 meters deep, with packers separating the upper and lower 1m sections. The remaining holes were 1 m deep. The expectations based on previous experience at Mont Terri are that EDZ fractures will be sub-parallel to the floor and largely confined to the upper 50 cm of depth. The three deeper holes nonetheless check this hypothesis.
Each borehole and packer interval was tested as a separate injection source while continuously monitoring pressure in the other 11 measurement sections of the borehole array. These short-term tests ran one hour including pressure recovery. Air injection pressures were be limited to 0.1 bar to avoid propagating the EDZ fractures or heaving the floor. The holes were drilled 42 mm in diameter and using coring methods. Due to the small diameter a hand-held, single-tube coring machine was used. As this method does not assure good quality core, the fractures will be studied using an impression packer. An impression packer is packer wrapped in soft, uncured rubber. When inflated or compressed against the borehole wall, the rubber flows into any openings in the wall and creates an impression. The impression can have some advantages over core in that there are no artificial breaks due to drilling and the impression gives an approximate indication of the fracture apertures.

4. IN SITU TEST

4.1 Location of the test

The effect of the slot on EDZ permeability was performed in the new gallery in the northern entrance between the cross section NG 152 to NG 157(figure 1). Figure 4 shows the northern entrance after removing the original concrete slab.

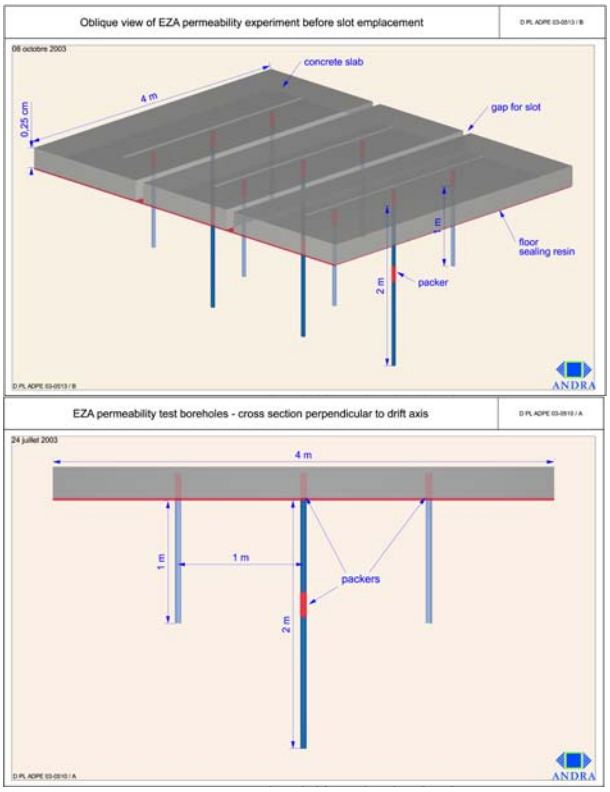

Figure 3. View of the EZ_A experiment concept: (a) 3D view, (b) cross section

4.2 Preparation of the test site

Figure 4. View of the northern entrance gallery after removing the reinforced concrete slab

The drift wall has to be prepared to minimize leakage of injection air back to the tunnel wall. Under the concrete slab, the rock floor was not flat and smooth due to the blasting excavation method. The rock floor was cleaned with a vacuum cleaner and the floor was then coated with an impermeable resin layer. The resin layer was set on the floor and on the lower 0.2 to 0.3 m of the walls. The resin has been overlain by 0.2 m to 0.3 m of concrete to provide a small pressure to the floor from its dead weight and to provide anchoring for the drilling and sawing equipment. Figure 5 illustrates the sealing works and the rock floor which is not smooth due to the blasting excavation in the laboratory northern entrance. Depth and configuration of the test step up boreholes is shown in figure 6.

Figure 5. view of the rock floor sealing

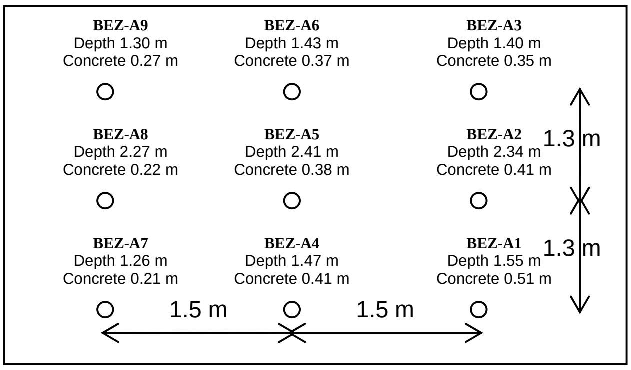

Figure 6. Experiment set up

4.3 Measuring system

Two types of packer systems were prepares: Six single mechanical packer systems for the 1-m holes and three double mechanical packer systems for the 2-m holes.

4.3.1 Packers

The packers have lengths of 15 cm and were inflated by a mechanical piston system. The diameter of each packer was 38 mm (deflated borehole 42 mm). Natural rubber was used for the packer. The other parts of the packer system were made of stainless steel.

The double packer systems had two measuring intervals of 860 mm length. They were equipped with 850 mm long cylindrical polyethylene filters. The outer diameter of these 4 mm thick filters was 40 mm. The diameter of the central tubing of the measuring chambers was 17.5 mm. The porosity of the filter is 30%. All intervals are equipped with 2 polyamide lines (4/2 mm). The interval volume of the 860 mm long interval was 712 ml (if the borehole radius is exactly 42 mm).

The single packer systems had one measuring interval of 890 mm length. They were equipped with 880 mm long cylindrical polyethylene filters. The outer diameter of these 4 mm thick filters was 40 mm. The diameter of the central tubing of the measuring chambers was 17.5 mm. The porosity of the filter is 30%. All intervals are equipped with 2 polyamide lines (4/2 mm). The interval volume of the 890 mm long interval was approximately 737 ml .

4.3.2 Control unit

The system control unit consists of 2 mains parts:

- The flow line control unit: equipped with two way valves. Each interval was equipped with one flow line (polyamide 4/2 mm). All fittings and valves are of stainless steel.
- The pressure lines control unit: equipped with three way valves, manometer and pressure sensors (0 – 5 bar, linearity 0.2% FS). Each interval is equipped with one pressure line (polyamide 4/2 mm). All fittings and valves are of stainless steel.

After the first testing event, 10 pressure sensors were used. The specifications are relative pressure sensors, range 20 mbar, linearity 0.2% FS.

4.3.3 Test equipment specification

For the pneumatic extraction test, an extraction pump and two Brooks gas flowmeters (0.01 to 1 ln/min and 1 to 50 ln/min) were applied. The test series consisted of two test campaigns. Pneumatic injection tests were performed using an air compressor during the first test campaign and a nitrogen bottle as gas source during the second test campaign. The gas supply was controlled using a pressure regulator valve.

The interval pressures were measured with Keller piezo-resistive transducers (0 – 5 bar absolute) during the first testing campaign and with relative high resolution pressure sensors (20 mbar) during the second campaign. The high resolution pressure transducers were applied at the top intervals after the analysis of the first test campaign data, to improve the test results.

5. TESTING RESULTS

5.1 Impression packer

The impression packer system used consists of a packer (ø 38 mm deflated) wrapped with soft rubber. The rubber length is 90 cm, and was inflated with nitrogen through an hydraulic line to a maximal pressure of 12 bars. The rubber was polished between each impression, in order to have always a fresh surface. The packer was oriented at the surface with a compass.

The impressions were taken just after drilling. The packer was inflated on the borehole for 30 - 40 min to allow the soft rubber to flow into the natural opened fractures of the borehole wall. The packer was moved just after pressure release. After removal from the hole, the packer rubber was inspected and the trace of the fracture highlighted with an indelible marker. The packer was then wrapped in a transparent plastic sheet and the lines of the fracture traced onto the sheet, together with the orientation line on the packer. The plastic sheet was then scanned into a computer. An example of the resulting images of the fracture traces as they appeared on the original impression packer wrap of one interval is presented in figure 7. The impression interval depth, referenced to the top of concrete, is indicated on the margins of the image. The impression packer was positioned approximately at the end from concrete. For the 2 m long boreholes, a second impression was taken just below the first impression position. The deepest intervals from boreholes BEZ-A2, BEZ-A5, BEZ-A8 didn't show any fracture.

The impression packer survey yielded excellent results. The fracture extension is not known and was fixed arbitrary to 0.5 m to show emplacement and dip of fractures in the 9 boreholes in figure 9. Most of the fractures traces are in the first 0.5 m under the gallery floor. The number of fractures is between 1 to 10, and the apertures are also very different. One reaches nearly 10 mm. The EDZ is very heterogeneous in the tested area, and exhibit more fractures than in the other part of the new gallery, due to a blasting excavation method.

Figure 7. Original fracture traces on impression packer

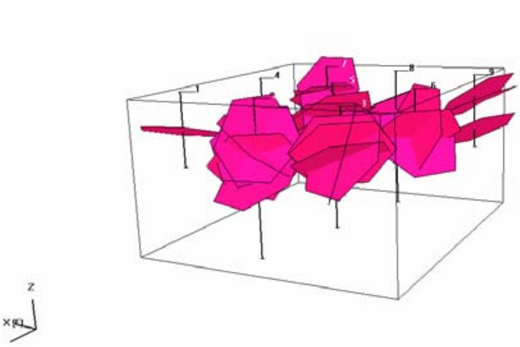

Figure 8. View of fractures crossing the nine boreholes (extension of the fractures was fixed to 0.5 m for the pictures)

5.2 Gas test analysis procedure

The basic equation for radial flow of a single phase fluid in a homogeneous porous media (Darcy 1856) was linearised for liquid assuming that the viscosity μ is independent of the pressure and the compressibility c is constant and small. This assumptions are not available in case of gas. The most successful approach to linearise the basic flow equation for the case of gas flow is that of Ali-Hussainy & Ramey (1966). They introduced the "real gas pseudo pressure function" to compensate the pressure dependence of viscosity and compressibility

$$m(p) = 2\int_{p_0}^{p} \frac{p\,dp}{\mu Z} \qquad [1]$$

where

p: pressure in kPa

μ: viscosity in cP

Z: gas deviation factor

The notion of pseudo-pressure allows to apply standard analysis methods for single-phase liquids to gas test.

Injection pressures were small in these tests, thus the product μZ can be considered as constant and the so-called P-square method is applied (Sabet 1991). The pseudo-pressure is simplified to

$$m(p) = \frac{p^2 - p_0^2}{\mu Z} \qquad [2]$$

where:

p_0: arbitrary low base pressure in kPa

5.2.1 Straight-line analysis (SLA):

After converting the measured pressure to pseudo-pressure, standard test interpretation methods are applied to identify the controlling flow model and to estimate permeability. Infinite-acting radial flow behavior (IARF) can be analyzed by performing a straight-line analysis on a semi-log plot (pressure square versus log time). Permeability, k, can then be calculated using the following equation (Sabet 1991 and Horne, 1995):

$$k = \frac{2.3\, q_{sc} p_{sc} T \mu Z}{2\pi\, m h T_{sc}} \qquad [3]$$

where:

q_{sc}: gas flow rate (m^3/sec)

p_{sc}: pressure at standard conditions (101.325 kPa)

T: reservoir temperature (°K)

T_{sc}: temperature at standard conditions (288.15 °K)

μ: viscosity (0.0175 cP or 1.75E^{-8} kPa sec)

Z: gas deviation factor (0.99 [-])

h: interval length (m)

m: slope of the semi-log straight line (kPa^2/log cycle)

$q_{sc} = (q\ R\ T_{sc}\ Z_{sc})/(\ p_{sc}\ M)$

where:

q: gas mass flow rate [kg/min]

R: 8.31441 kPa l/mol constant factor

Z_{sc}: 1 [-] constant factor

M: 28.0134 g/mol constant factor

Gas density: 1.25 [g/l_n]

5.2.2 Steady-state approximation (SSA):

A steady-state approximation can also be performed using the following equation (Sabet 1991):

$$k = \frac{q_{sc} p_{sc} T \mu Z}{\pi h T_{sc} \, (p_e^2 - p_{wf}^2)} \left[\ln\left(\frac{r_e}{r_w}\right) \right] \qquad [4]$$

where:

p_e: external pressure (kPa)
p_{wf}: well flowing pressure (kPa)
r_e: external radius (m)
r_w: wellbore radius (m)

Steady state approximation is conducted if flow conditions are stables (P and Q constants), and for radial flow, isotropic homogeneous medium. To conduct the interpretation we make the assumption r_e = 10 m, as crosshole response was measured over 4 m.

5.3 Characterisation of gas testing

Tests were conducted in each interval during two field campaigns: First campaign on 5th and 6th November 2003 and second campaign on 26th and 27th November 2003. The tests consisted in pneumatic extraction tests in each interval and pneumatic injection tests in the top intervals. During the first test campaign two longer gas injection tests were performed in interval BEZ-A5i2 (upper interval in Borehole BEZ_A5).

5.3.1 Gas injection and extraction test

After obtaining high permeabilities in the top intervals, a second test campaign was conducted applying gas injection tests to confirm the extraction gas test results and to detect cross-hole responses. During the gas injection tests, we observed an increase in permeability in the intervals BEZ-A5i2, BEZ-A6i1due to rock matrix shrinkage. Figure 9 presents an example of result of injection tat constant flow rate in the borehole BEZ_A5.

Gas permeabilities obtained in the top intervals are relatively high, and those in the bottom intervals are very low and close to flow measurement limit. In the intervals BEZ-A3i1 and BEZ-A7i1 high permeabilities were estimated based on the gas injection tests. However, the pressure recoveries seem to be very slow considering such gas permeability. A summary of the test results is given in Table 1.

5.3.2 Cross-hole responses

No cross-hole responses were observed during extraction tests. Therefore, high flowrate injection tests were performed (second test campaign) with a limited overpressure to avoid possible opening of fractures. The source signal in the injection borehole was very small; consequently the cross-hole responses were very small which required high sensitive pressure transducers. However, it is possible that in some intervals no cross-hole responses were observed because the signal was still below the pressure sensor resolution. In general cross-hole responses followed immediately the source

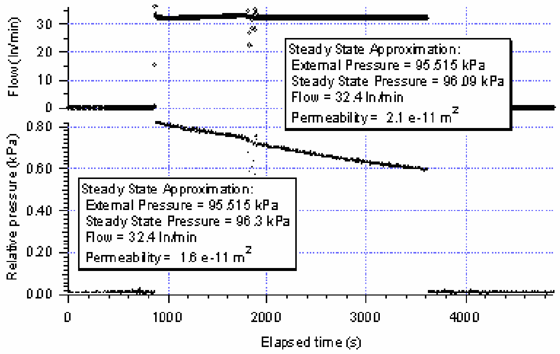

Figure 9. Example of injection test result in borehole BEZ_A5.

Table 1. Results of permeability test (with Steady state approximation SSA)

Interval	Test	Intrinsic permeability (m^2)
BEZ_A1	Extraction Injection	6.4×10^{-14} 5.1×10^{-14}
BEZ_A2i1 (bottom)	Extraction	2.8×10^{-13}
BEZ_A2i2 (top)	Extraction Injection	1.1×10^{-11} 9.8×10^{-12} (SLA)
BEZ_A3	Extraction Injection	5.2×10^{-12} 5.0×10^{-12}
BEZ_A4	Extraction Injection	4.6×10^{-12} 6.1×10^{-12}
BEZ_A5i1 (Bottom)	Extraction	7.7×10^{-14}
BEZ_A5i2 (top)	Extraction Injection Injection Injection	2.9×10^{-11} 1.8×10^{-11} 1.6×10^{-11} 2.5×10^{-11}
BEZ_A6	Extraction Injection Injection	4.4×10^{-12} 8.9×10^{-12} 1.4×10^{-11}
BEZ_A7	Extraction Injection	No pressure 3.6×10^{-11} (SLA)
BEZ_A8i1 (Bottom)	Extraction	$<1.0 \times 10^{-16}$
BEZ_A8i2 (top)	Extraction Injection	8.0×10^{-11} 9.4×10^{-11}
BEZ_A9	Extraction Injection	1.0×10^{-12} 1.5×10^{-12}

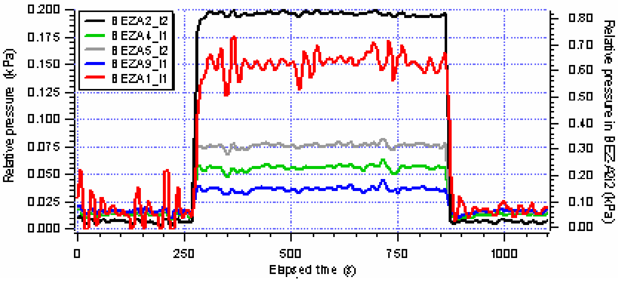

Figure 10. Cross hole test: injection in BEZ_A2

signal, which allowed quite short testing time of about 15 minutes. The cross-hole responses for injection tests in BEZ_A2 (second test campaign) are given in Figure 10.

Figure 11 visualizes the observed connection paths between the intervals. An arrow does not show the real path way between two boreholes, but just shows, when you injected a gas flow at a constant rate, a change of pressure in the observation holes.

All top intervals seem to be connected to interval BEZ-A5i2. Hence, all intervals may be connected together through BEZ-A5i2. However, injection tests in BEZ-A5i2 didn't show cross-hole reactions in all the other intervals.

The boreholes can be divided in two different types of cross hole responses:

- Type 1: Boreholes BEZ-A5i2, BEZ-A2i2, BEZ-A4i1, BEZ-A1i1
- Type 2: Boreholes BEZ-A3i1, BEZ-A6i1, BEZ-A7-i1 and BEZA8i2.

The boreholes from type 1 show cross-hole responses to each borehole intervals, except the borehole intervals BEZ-A1i1 and BEZ-A9i1. The type 2 shows no cross-hole response to any injection tests. A connection between borehole BEZ-A9i1 and the type 1 boreholes was detected after the second injection in BEZ-A5i2.

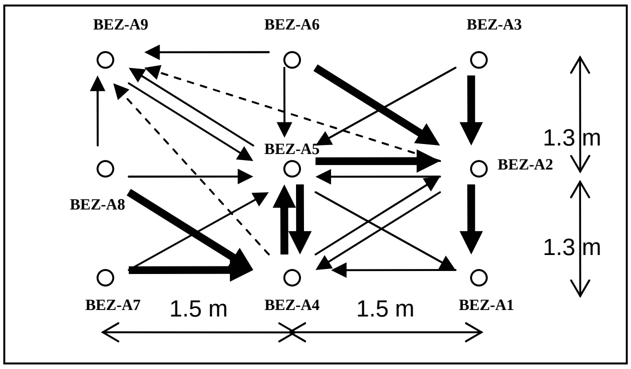

Figure 11. Connected paths derived from all cross-hole injection (the arrow shows the observed response during injection test and the way in which it has been seen, the size of the arrow indicates the type of connection: thick arrow = strong connection, arrow = connection, dash arrow = weak connection)

Pressure measurements in the intervals, BEZ A3i1, BEZ-A6i1, BEZA 7i1, BEZ-A8i2, BEZA9i1, present variations in the course of time. This background noise, which has similar magnitudes to the cross-hole responses, can be explained by the variations of atmospheric pressure due to ventilation, highway traffic, and construction activities in the laboratory. These signals are in the range 10 Pa, which are recorded by the highly sensitive pressure transducers. Not all test intervals observed background noise and were very stable. We interpret the stable zones as having good fracture connections to the tunnel wall thus allowing rapid equilibration of atmospheric pressure changes. The "noisy" sections, appear less well connected to the tunnel as atmospheric load changes on the tunnel wall are transmitted in an undrained fashion the pressure in the EDZ fractures. The lower intervals (depth between 1 m to 2m) are not connected to other intervals, except BEZ-A5i1 which is connected to interval BEZ-A5i2 through a vertical fracture (packer by-pass).

5.3.3 Modular multipacker system test

In addition two parallel boreholes (BEZ_A16 & BEZ_A17), 2.5 meter deep, were equipped with six short testing intervals pneumatically isolated with a modular multi-packer system (MMPS). The distance between parallel holes is approximately 3.3 meters. Figure 12 shows that the borehole BEZ_A17 is located in the section of borehole BEZ_A5. Pneumatic tests in the two boreholes yielded relatively high permeability values close to the tunnel wall and a decrease of the permeability values towards the bottom ends of the boreholes. The permeability values measured in the borehole BEZ-A17 are significantly higher than at comparable depths of the borehole BEZ-A16. Permeability varies from 5.3×10^{-11} to 2.2×10^{-11} m^2 in borehole BEZ_A17 and from 4.6×10^{-11} to 8.7×10^{-17} m^2 in BEZ_A16 (figure 13). These tests confirm the very high permeability in the first 50 cm and heterogeneity of the EDZ. No cross-hole pressure responses between the two boreholes were observed.

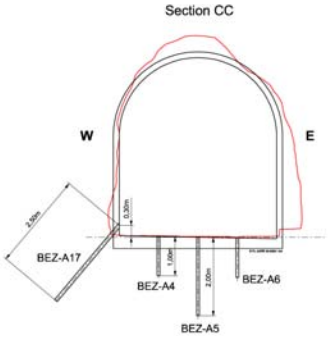

Figure 12. Cross section with borehole BEZ_A17 with MMPS.

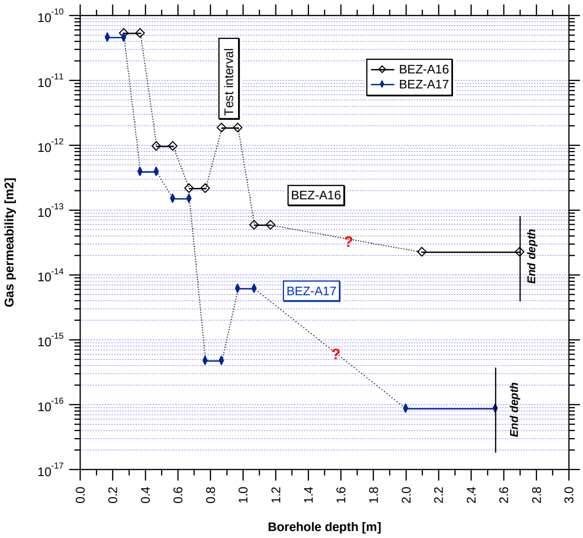

Figure 13. Intrinsic permeability versus depth measured with MMPS in two parallel boreholes

6. CONCLUSIONS

Impression packer survey results emphasized the heterogeneity of the EDZ under the rock floor. The fracture trace (depth and dip) provide valuable information on the geometry of the fracture network. The impressions also confirm previous findings that the major portion of the EDZ lies in the first 0.5 meters of rock from the tunnel wall.

Pneumatic tests were a suitable method to obtain gas permeability estimations of all intervals. Withdrawal tests were not successful in evaluating cross-hole connections due to the extremely small pressure changes in the very high permeability fractures. As a result, the connection mapping was performed using injection tests despite the possibility of fracture opening or dessication. Permeability changes were observed over the course of injection as evidenced by dropping injection pressures with time (for example between BEZ-A5i2 and BEZ-A9i1, or increasing permeability in interval BEZ-A6i1 between extraction and injection test). We believe these are dessication effects rather than deformation effects as the injection pressures were limited to 1.5 kPa well below the overburden weight. The tests confirm the observations obtained by impression packer: the first meter from the tunnel floor can be defined as a zone of relative high permeability (until 9.4×10^{-11} m^2). The permeability decreases towards the lower intervals (2.8×10^{-13} to less than 10^{-16} m^2). Pneumatic tests with mmps confirm this decrease.
The permeability distribution within the upper first “meter” intervals is not homogeneous, where permeabilities vary between 5×10^{-14} and 9.4×10^{-11} m^2.

In general cross-hole responses followed immediately the source signal, which allowed quite short testing time of about 15 minutes. Cross-hole responses were observed in the whole test zone between the intervals located in the first meter. Connections exist over distance of 3.3 meters (BEZ-A8i1 to BEZ-A4i1), which have never been shown in previous experiment at Mont Terri laboratory. The test zone is also more fracture due to the blasting excavation method. The previous experiment were realised in gallery excavated with a round header or pneumatic hammer technique. Cross-hole tests confirm the high heterogeneity of the EDZ at a metric scale, which leads difficulties to estimates the average permeability at a gallery scale.
The lower intervals (depth between 1 m to 2m) are not connected to other intervals.

The results presented here are based on drill and blasted tunnel walls that may be more damaged than mechanically excavated situations. Future testing plans call for saturating the EZ_A area and repeating the tests with water, whose higher viscosity will result in slower , more analysable cross-hole responses. Other tests are also being planned for machine-excavated tunnels.

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