DISTURBED ZONE ASSESSMENT WITH PERMEABILITY MEASUREMENTS IN THE ZEDEX TUNNEL

C. BAUER and F. HOMAND
Laboratoire de Géomécanique, 54 501 Vandœuvre-lès-Nancy, France

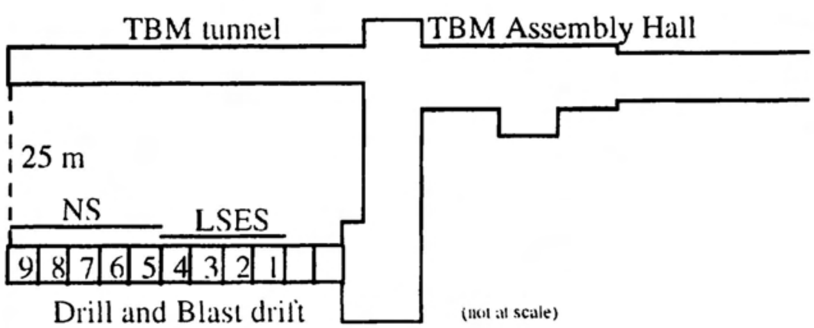
K. BEN SLIMANE
ANDRA, 92 298 Chatenay-Malabry Cedex, France

INTRODUCTION

The construction of deep radioactive waste disposal may generate a disturbed zone around the excavation. Stress redistribution consecutive to excavation, excavation method, rock deformability, and excavation geometry may be responsible of the creation of new fractures and microcracks, and cause movement along existing natural fractures. This disturbance will result in a variation of mechanical and hydraulic properties of the hosting rock which must be considered in the design of a repository and in the assessment of its long-term safety (especially with regard to sealing). Qualitative and quantitative knowledge of this Excavation Disturbed Zone (EDZ) is of prime importance to repository performance and operation.

In order to obtain a better understanding of the properties of the EDZ and its dependence on the excavation method, ANDRA, UK NIREX Ltd. and SKB (*) decided to perform a joint study of the disturbed zone effects. The project named ZEDEX (Zone of Excavation Disturbance EXperiment) comprised investigations before, during, and after completion of two drifts at the Swedish Äspö Hard Rock Laboratory (HRL) using three excavation methods under similar initial conditions (Fig. 1). One tunnel was excavated by a tunnel boring machine (TBM tunnel). Two smooth blasting methods were used for the excavation of the second drift (D&B drift): normal smooth blasting (NS) similar to that used for the excavation of the Äspö tunnel and smooth blasting based on the application of low shock explosives (LSES).

Fig. 1 Experimental configuration



* ANDRA: Agence Nationale pour la Gestion des Déchets Radioactifs (France)
UK NIREX Ltd.: United Kingdom NIREX Limited
SKB: Swedish Nuclear Fuel and Waste Management Co.

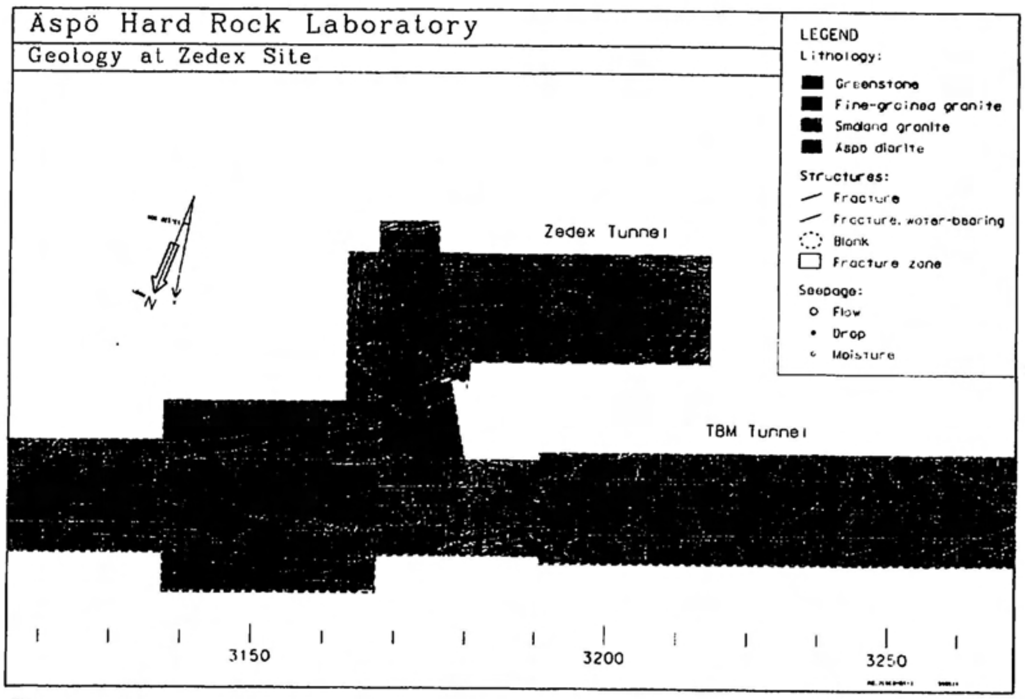
The regional geology of the Äspö HRL has been described by Hermanson *et al.* [1] and the general geology of the ZEDEX site is summarized on Fig. 2. The dominant rock type is grey medium-grained Äspö diorite. Irregular sheets of red fine-grained granite intersect the tunnels in various locations. The geological mapping of the ZEDEX volume showed that the TBM tunnel is relatively fractured compared to the D&B drift which is less fractured. The predominant orientation of water conducting fractures is NW striking and sub-vertical. The Äspö diorite has the following mechanical properties: mean uniaxial compressive strength is 195 MPa; mean Young's modulus is 69 GPa; mean Poisson's ratio is 0.25.

The *in situ* stress field in the vicinity of the ZEDEX volume has been described by Leijon [2]. An estimation of the *in situ* stress is given in Table 1.

Table 1
Estimated virgin rock stresses at the ZEDEX site

Stress component	Magnitude (MPa)	Trend (°)	Plunge (°)
Sigma 1	32	140	0
Sigma 2	17	50	25
Sigma 3	10	240	70

Fig. 2 General geology of the ZEDEX test site



In considering the EDZ, it is common to separate the "near field" and "far field" effects. In the far field the rock is affected by the redistribution of stresses caused by the existence of the voids represented by the drifts. It generally does not induce new fractures but existing fractures may react by dilating, closing or shearing. In the near field the process of excavation causes damage to the rock, changes its properties and may produce microcracks or new fractures.

Hydraulic characterization of the EDZ in the near field requires a testing method which is based on the following criteria: the possibility to measure permeabilities down to 1.0 10^{-21} m^2

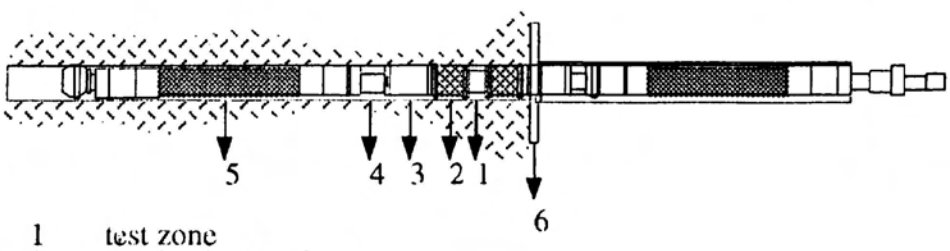
as the candidate rock masses for waste disposal are relatively "non-permeable"; a small testing chamber in order to appreciate the local variations; the measurements should be close to the tunnel walls. As an answer, one can consider a probe with a punctual measurement or a multipacker system. Multipacker probes with 10 centimetres test chambers were developed by AECL [3] and NAGRA [4]. Our objectives were to develop the idea of using a small testing chamber and control possible packer leakage or water/gas arrivals from the rock mass.

EQUIPMENT USED AND INTERPRETATION METHOD: THE SEPPI PROBE

A specific tool for measuring the permeability in boreholes, the SEPPI probe (Système Expérimental de mesure de Perméabilité par Pulse *In situ*) was developed by the Laboratoire de Géomécanique - Nancy and the Laboratoire de Mécanique de Lille (Fig. 3). The concept lies in using a small injection chamber (5 cm) with the ability to measure start from the first 8 cm from the tunnel wall by use of a borehole lengthening tube, enabling control of a possible leakage or water/gas arrivals due to chambers placed behind the packers [5].

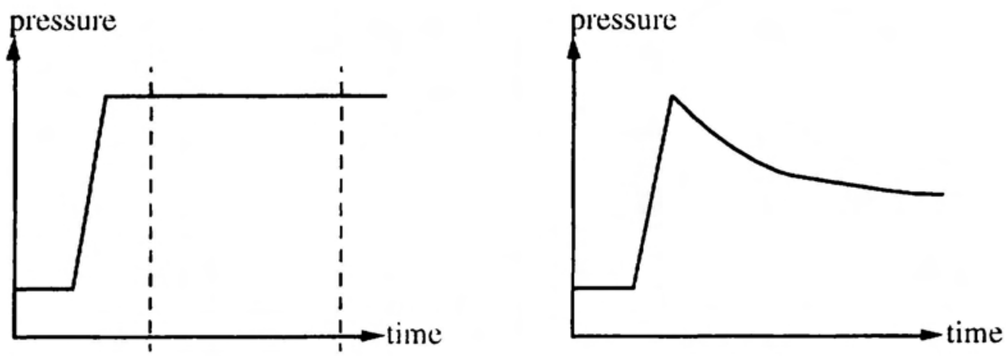
Testing method can be either a steady state conditions test (k, intrinsic permeability, greater than 1.0×10^{-17} m^2) or a pulse test (k less than 1.0×10^{-17} m^2). Usually, permeability values are relatively low in rock masses proposed for waste disposal and the pulse test which is suitable in this case, is mostly performed.

Fig. 3 The SEPPI probe, tool for high resolution permeability measurements



1 test zone
2 mechanical packers
3 jacks
4 leakage control
5 conventional packer
6 borehole lengthening tube

Fig. 4 Two testing methods: the steady state conditions test and the pulse test



steady state conditions test *pulse test*

In steady state conditions, the pressure in the test chamber is maintained at a constant level, and the flow rate is measured. The intrinsic permeability is calculated with the standard relation in steady state flow conditions:

$$k = \frac{\mu Q L}{P S} \tag{1}$$

k intrinsic permeability (L^2)
μ fluid viscosity ($ML^{-1}T^{-1}$)
Q injection rate (L^3T^{-1})
L injection length (L)
P pressure ($ML^{-1}T^{-2}$)
S injection section (L^2)

The pulse tests are conducted by instantaneously increasing the pressure. The pressure time dependent recovery back to the initial hydraulic pressure is interpreted in terms of permeability. The tests can be described by the following equations:

Diffusivity equation:

$$\nabla^2 P = \frac{\mu S}{k}\frac{\partial P}{\partial t} \quad \text{for } R_{bor.} < r < R_{inf.} \tag{2}$$

$R_{bor.}$ borehole radius (L)
$R_{inf.}$ influence radius (L)
P pressure in the test zone ($ML^{-1}T^{-2}$)
r distance from the borehole (L)
(r=0 on the limit of the borehole)
k intrinsic permeability (L^2)
μ fluid viscosity ($ML^{-1}T^{-1}$)
S specific storage of the rock ($M^{-1}LT^2$)
$S = \phi(C_f+C_r)$ with:
C_f fluid compressibility
C_r pore compressibility
ϕ porosity

Mass balance equation:

$$\frac{S_d \mu}{k \gamma_w A}\frac{dP}{dt} = \left(\frac{\partial P}{\partial r}\right)_{r=R_{bor.}} \quad \text{for } t > 0 \tag{3}$$

Sd defined as the change in fluid volume per unit change in pressure (L^2)
γ_w specific weight of the fluid ($ML^{-2}T^{-2}$)
A injection section (L^2)

Initial and limiting conditions:

$$P(r,0) = 0 \quad \text{for } R_{bor.} < r \leq R_{inf.} \tag{4}$$

$$P(R_{bor.},t) = P(t) \quad \text{for } t > 0 \tag{5}$$

$$P(R_{inf.},t) = 0 \quad \text{for } t > 0 \tag{6}$$

The diffusivity equation combined with the mass balance equation, the initial and limiting conditions is approached by a finite difference method and the intrinsic permeability is calculated [5].

In equations (2) and (3), some parameters relative to the tool or the rock mass have to be determined. The injection area (A) was evaluated with a silastenic casting; Sd, which could be called the compressive storage of the system (tool + borehole + fluid), is determined *in situ* by applying a variation of pressure by injection of a volume; Sd is considered non-dependent of the pressure. The pore compressibility C_r is defined by:

$$C_r = \phi\left(\frac{1}{K_B} - \frac{1}{K_M}\right) - \frac{1}{K_M} \tag{7}$$

K_B drained bulk modulus ($ML^{-1}T^{-2}$)
K_M matrix bulk modulus ($ML^{-1}T^{-2}$)

Its determination requires laboratory tests: an isotropic compression test in drained conditions gives the bulk modulus K_B; an isotropic compression test where pore pressure increment remains equal to the hydrostatic pressure increment gives the bulk modulus of the matrix K_M. Ideal conditions for performing these tests are difficult to obtain and the values may be inaccurate. A sensitivity of the interpretation method to K_B and K_M variations showed that a 25% error in determining either parameter did not result in more than 3% variation for the permeability value. The porosity, which is determined by a mercury porosimeter, is often under the apparatus sensitivity (*i.e.* < 2%). A porosity 100% error leads to less than 2% variation for the permeability, a 400% error to less than 7%.

APPLICATION TO ZEDEX: PERMEABILITY MEASUREMENTS IN RADIAL HOLES

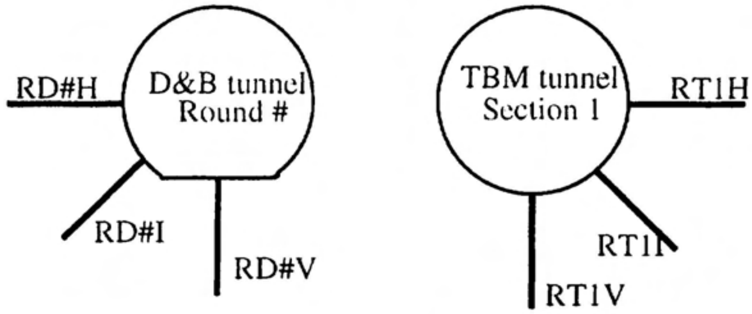
Experimental configuration

After excavation of the drifts, a number of short (3 m) radial boreholes (ϕ 86 mm) with different orientations were drilled in each tunnel to assess the extent of the disturbed zone in the near field. Vertical boreholes were placed on the floor; 45° inclined (down) holes were drilled at the junction of the floor with the walls; horizontal holes were located on the walls. In all twelve boreholes were tested (Fig. 5): three in the TBM tunnel (one of each orientation placed in one section), four in LSES rounds (two inclined, one horizontal and one vertical), and five in NS rounds (two inclined, two vertical and one horizontal).

Pulse tests parameters were the following: initial pressure in the injection chamber was around 1.5 MPa; pulse magnitude was about 0.5 MPa; pressure fall-off was registered during about 300 s. The drained bulk modulus and matrix bulk modulus were taken equal to 48 GPa, and 56 GPa respectively. The porosity was determined to be equal to 1%.

Permeability values were determined as a function of distance from the wall: from 8 to 50 cm depth, the measurements were made at intervals of 5 cm; from 50 to 100 cm, at 10 cm intervals and from 100 cm to the end of the borehole, at 20 cm intervals.

Fig. 5 Tested boreholes layout

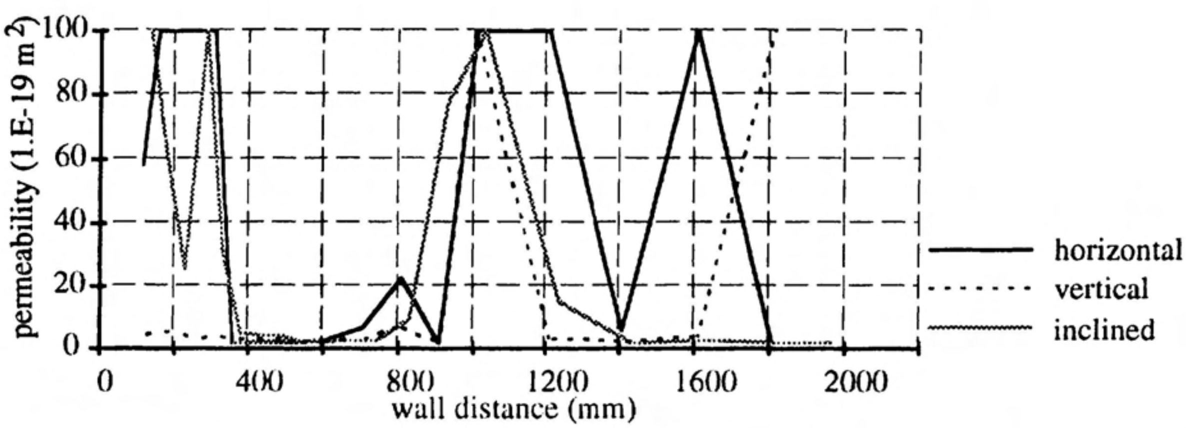


Round 2 (LSES - reblasted): RD2I
Round 3 (LSES): RD3H, RD3I, RD3V
Round 6 (NS - reblasted): RD6I, RD6V
Round 7 (NS): RD7H, RD7I, RD7V

<u>TBM tunnel results</u>

Pulse tests revealed that the undisturbed matrix permeability is about 2.0×10^{-19} - 3.0×10^{-19} m^2 (Fig. 6). The presence of natural fractures, which existed prior to excavation, meant that some sections could not be tested by pulse tests. Such fractures were observed on the cores: their bounding planes were altered or recrystallized. In those zones, the pressure fall-off was nearly instantaneous. When placed near the tunnel wall, these natural fractures obscure the possible damage due to excavation. On that account, damage could not have been observed in the horizontal and inclined boreholes (Fig. 7). For instance, in borehole RT1H, measurements were not possible from 10 to 35 cm. That section coincides with two altered fractures observed on the cores. From 35 to 50 cm, the measured permeability values are low, relatively constant and can be assumed equal to the matrix permeability. At least, rock matrix permeability was retrieved at 40-50 cm in the inclined borehole, at 35 cm in the horizontal borehole. Further natural fractures were readily identified.

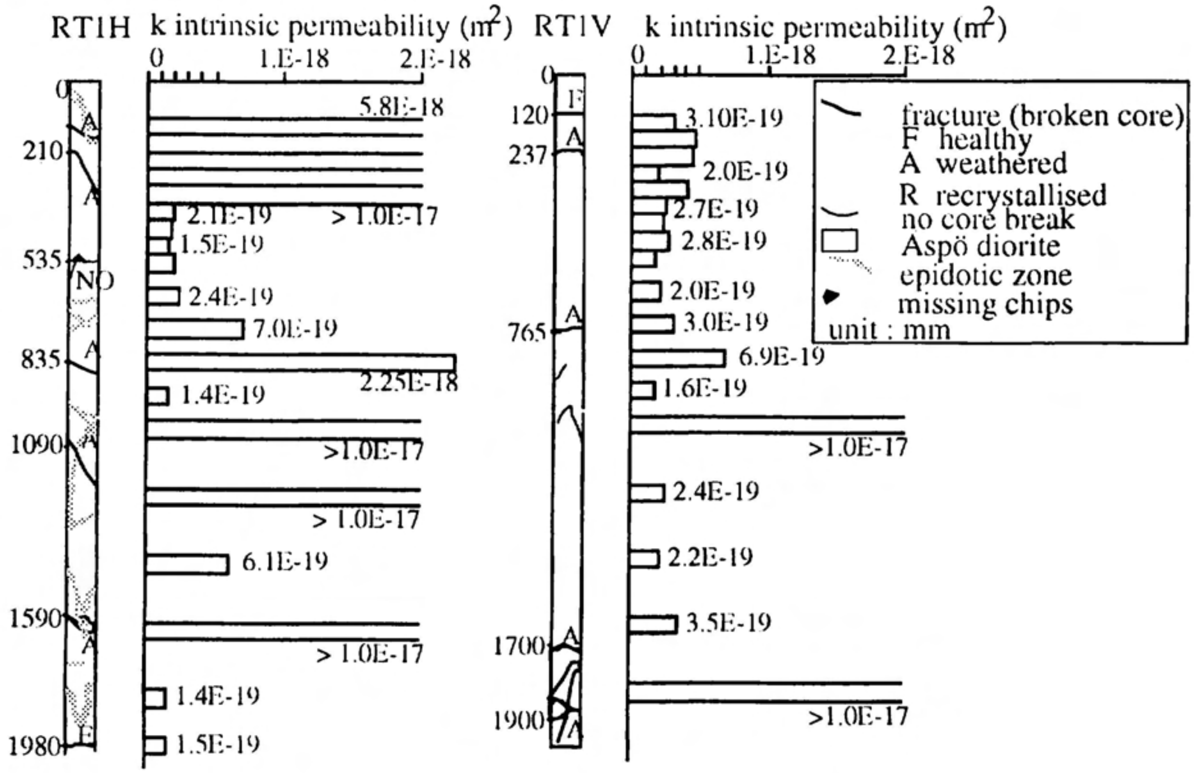
Fig. 6 Permeability results in short radial holes in the TBM tunnel



In the vertical borehole, which does not contain significant natural fractures in the first meter, the permeability tests did not show any notable induced effect: permeability values were not significantly higher near the wall than far from it.

It was considered that the tunnel boring machine did not induce any fractures at distances greater than 20 cm from the tunnel wall. The boring may be responsible of some fractures movements (dilating, shearing), especially when located near the tunnel wall, explaining the high permeability values encountered.

Fig. 7 Core logging superimposed to measured permeability values in RT1H and RT1V



D&B drift results

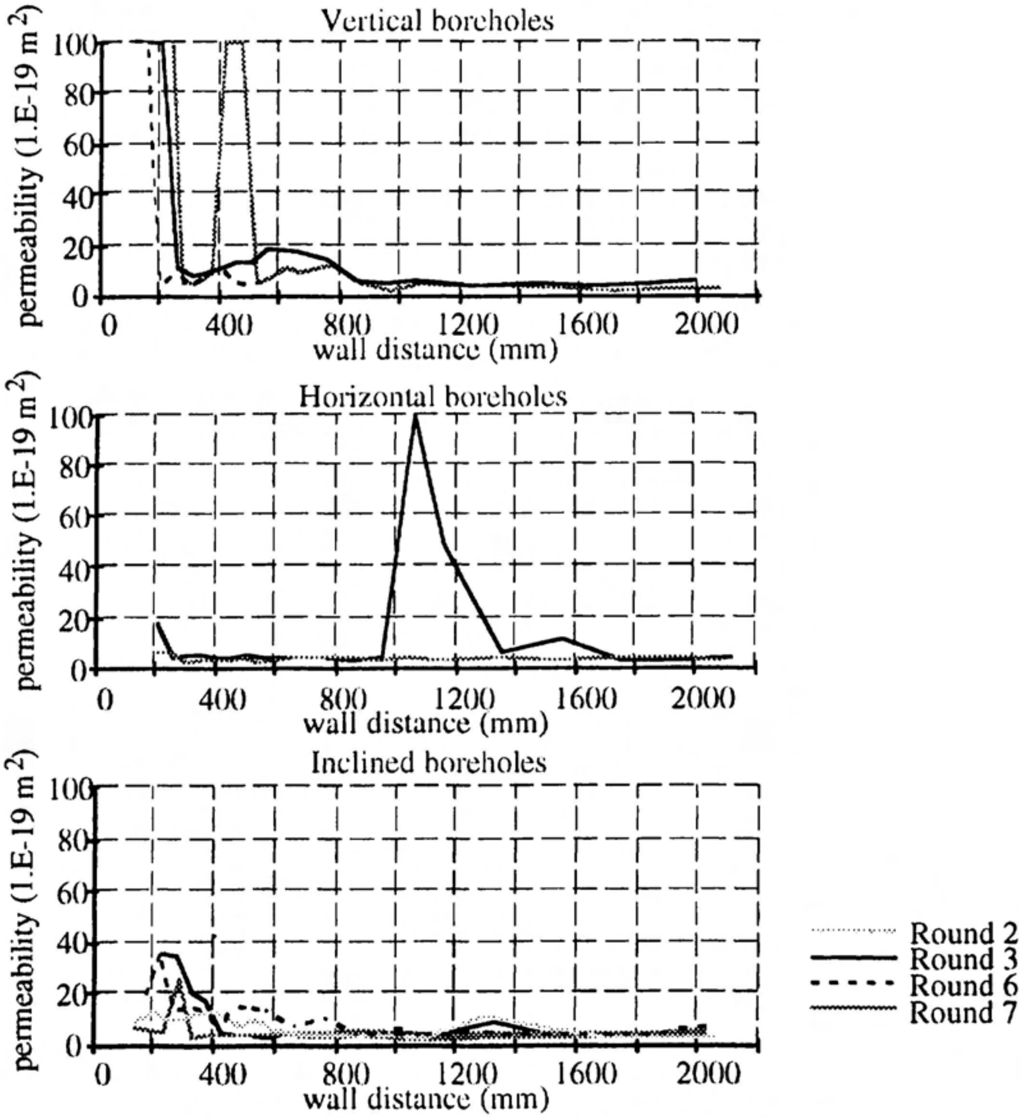
The geological mapping showed that the D&B drift was less fractured than the TBM tunnel. Only two water conducting fractures intersect the drift (one at each end). Excavation effects were more clearly revealed.

In all tested boreholes, the permeability value curves join together: at a more or less important distance from the tunnel wall, the permeability is nearly constant. Consequently, the rock mass matrix permeability in the D&B drift was estimated about 3.0×10^{-19} m^2 (Fig. 8). This is in a good accordance with the TBM results.

EDZ extent as a function of the considered direction. In general, the results from the vertical boreholes were interpreted as showing the greatest induced damage while the horizontal boreholes were interpreted as having suffered the least damage: EDZ extent in the vertical boreholes RD3V and RD7V was estimated to 80 cm; in the horizontal boreholes it did not exceed 25-27 cm (Fig. 8). A high permeability value was observed at approximately 100 cm from the drift wall in the horizontal borehole in LSES round 3 as a consequence of the borehole intersecting a natural fracture (identified in the core).

Close to the drift wall, in the vertical boreholes, the permeability was measured to be up to more than 100 times the matrix permeability value. In the inclined boreholes, it varies between 10 and 40 times. In the horizontal boreholes, it reaches 20 times very selectively.

Fig. 8 Pulse tests results in the radial boreholes from the D&B drift

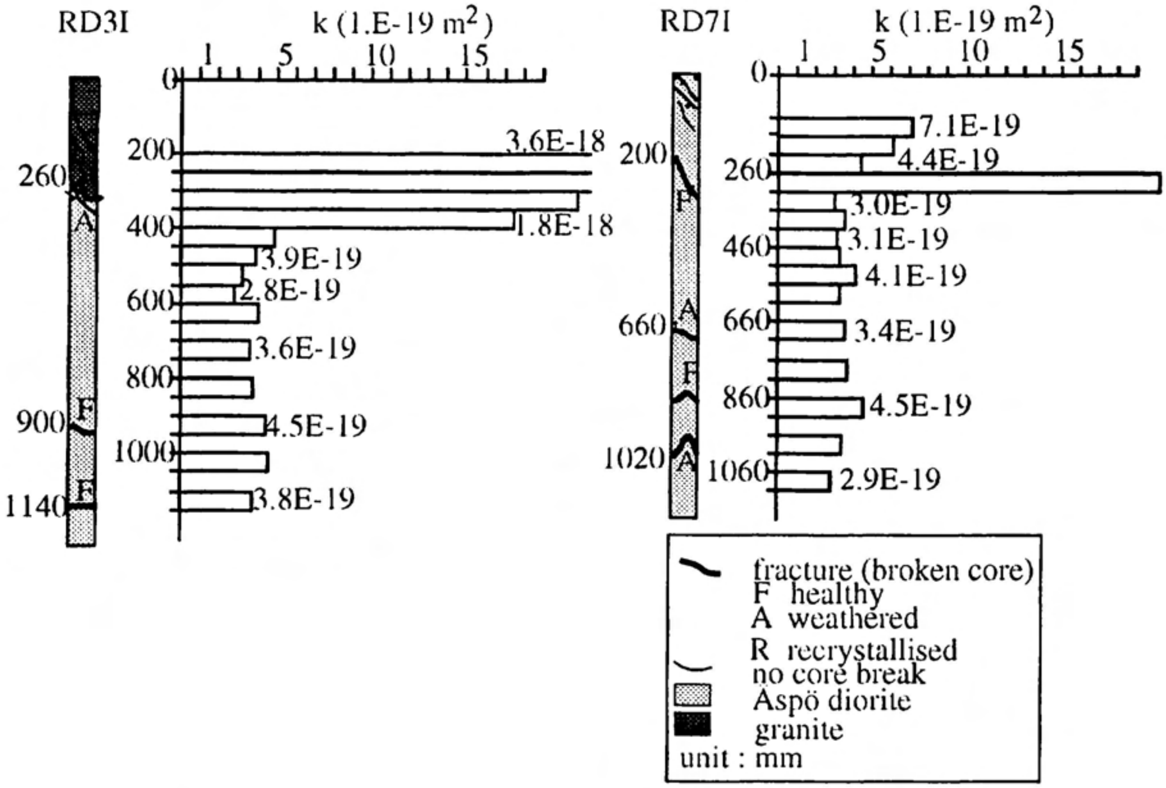


EDZ extent as a function of the blasting parameters. Boreholes in failed and reblasted rounds showed a more extensive EDZ compared to boreholes in successful rounds. For instance, EDZ extent in the inclined direction in reblasted NS round 6 was 80 cm when it was 30 cm in the successful NS round 7. In the reblasted LSES round 2, it was 65 cm and in the successful LSES round 3, it was 40 cm.

Differences between the two blasting methods were not clearly apparent. The data from measurements made in LSES round 3 were generally higher than in NS round 7. This is the inverse of the anticipated result and may not be purely a function of the blasting technique. Indeed, round 3 crosses a relatively important granite vein and granite seems to be more brittle than the Äspö diorite. As a result, the inclined borehole RD3I which intersects grey-red granite at the start presented high permeability values; the borehole RD2I drilled in a reblasted LSES round is located in Äspö diorite and revealed lower permeability values than the borehole RD3I. In a similar manner, the permeability values in borehole RD3I are higher than the values in RD7I as far as granite is concerned. When Äspö diorite is intersected (at about 40 cm), the permeability values are quite similar for both boreholes (Fig. 9). The boreholes RD3V and RD7V are not very different up to 30 cm. From there, the borehole

RD7V is located in diorite and the permeability values are lower than in RD3V, which is still located in granite. These conclusions were confirmed by the cores where induced cracks are observable mainly in granite.

Fig. 9 Core logging superposed to measured permeability values in RD3I and RD7I



CONCLUSIONS

The SEPPI probe is well adapted to evaluate excavation damage by permeability measurements. The results show that a relation between fissuration and permeability is well indicated. The excavation disturbed zone extent in terms of near field damage can accurately be established.

In the ZEDEX project, several radial boreholes bored in drifts excavated by three different methods were tested. The results showed that excavation induced fractures could not easily be separated from the natural fractures. Although the TBM tunnel was relatively fractured, excavation disturbed zone extent was considered to be less or about 20 cm. The D&B drift was less fractured and maximum excavation disturbed zone extent was encountered on the floor (80 cm), minimum extent on the walls (25 cm). The differences between the two blasting methods were not clear. This may not be purely due to the excavation method. Variations in lithology may influence the results. The acoustic emission results also showed that the location of the acoustic emission events extended further into fine-grained granite veins than into diorite [6].

To fully characterize the EDZ, the number of tested boreholes may be inadequate. As part of the ZEDEX extension, additional boreholes drilled surround the drifts and in different orientations will be tested to undertake a full suite of measurements.

Acknowledgments

The authors wish to acknowledge the ZEDEX Steering Committee for the graceful permission to publish the results. We would like to thank the Äspö HRL staff for providing the on-site facilities and logistical support.

REFERENCES

[1] HERMANSON J., LEIJON B., MARKSTRÖM I., MUNIER R., STANFORS R., "Geological interpretation of the ZEDEX rock volume", SKB Technical Note TN 25-95-06z, 1995.

[2] LEIJON B., "Compilation of measured stresses at Äspö HRL", Personnal communication, 1994.

[3] MARTIN C.D., KOZAK E.T., CHANDLER N.A., "Hydraulic properties of the excavation disturbed zone around undergroung opening", Proc. of the 45th Canadian Geotechnical Conference, Toronto, 1992.

[4] ADAMS J., "GTS-EDZ: Multi-packer system for the Excavation Disturbed Zone (EDZ) investigation at the Grimsel Test Site", Internal report NAGRA 95-97, 1995.

[5] BAUER C., HOMAND F., HENRY J.P., "*In situ* low permeability pulse test measurements", Int. J. Rock Mech. Min. Sci. & Geomech. Abstr., Vol.32, N°4, pp. 357-363, 1995.

[6] FALLS S.D., YOUNG R.P., "Acoustic emission monitoring of the Drill and Blast drift", SKB Technical Note TN 25-95-13z, 1995.

[7] BAUER C., HOMAND F., "High resolution permeability measurements in short radial boreholes in the TBM drift", SKB Technical Note TN 25-94-30z, 1994.

[8] BAUER C., HOMAND F., "High resolution permeability measurements in short radial boreholes in the D&B drift", SKB Technical Note TN 25-95-18z, 1995.

[9] C. Bauer, S. Falls, L. Steinberg, S. Emsley, O. Olsson, "A study of the zone of excavation disturbance for blasted and bored tunnels", ZEDEX final report, 1996.