CURRENT UNDERSTANDING OF EXTENT AND PROPERTIES OF THE EXCAVATION DISTURBED ZONE AND ITS DEPENDANCE OF EXCAVATION METHOD

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BACKGROUND

Deep geological disposal of high level radioactive waste is generally based on isolation of the waste from the biosphere by multiple barriers. One of these barriers is the host rock which should provide a stable mechanical and chemical environment for the engineered barriers. It should also reduce and retard transport of radionuclides released from the engineered barriers. Construction of a repository deep underground necessitates construction of underground tunnels, shafts, and vaults. These tunnels and shafts open up transport paths through the host rock which in practically all repository concepts will be blocked by backfilling the underground openings by some impermeable material and/or sealing the tunnels and shafts by plugs placed at strategic locations. The excavation of underground openings will also generate an excavation disturbed zone (EDZ) which could constitute a preferential pathway for radionuclide transport. This paper provides a review of current understanding of the EDZ for crystalline rock environments.

THE EXCAVATION DISTURBED ZONE AND PERFORMANCE ASSESSMENT

The Excavation Disturbed Zone (EDZ) plays an important role in many performance assessments of nuclear waste repositories as a potential pathway for transport of radionuclides. In some cases the EDZ is even considered to be the critical pathway. In considering the role of the EDZ for the performance of a repository there are several aspects that have to be considered.

The repository tunnels and access shafts would constitute major transport paths if they were not backfilled by some impermeable material or sealed by plugs at strategic locations. Most repository concepts include back-filling of underground openings to reduce the hydraulic conductivity to a level comparable to that of the surrounding rock. There is of course only a need to consider the EDZ as a potential pathway for radionuclide transport if it is expected to have a significantly higher hydraulic conductivity than the undisturbed host rock or the backfilled tunnels and shafts. The properties and extent of the EDZ also has to be considered in relation to its effect on the efficiency of plugs made to block transport paths along tunnels or shafts.

A special case which needs to be considered, for example in the Swedish KBS-3 concept, is the disturbed zone around the deposition holes for the waste canisters which constitute one of the important transport paths in the near field [1].

In many performance assessments the EDZ is modelled as a zone of significantly increased permeability (two orders of magnitude) around tunnels and shafts.

Observations in tunnels and shafts are expected to be used for assessing the properties of the host rock as part of detailed characterization of a repository site in conjunction with excavation of the repository. In this context it essential to understand what types of data can be considered representative of undisturbed host rock conditions and what types of data include artifacts introduced by the EDZ. Artifacts introduced by the EDZ must also be considered for proper interpretation of experiments performed close to underground openings. From the performance assessment perspective, the possible artifacts on the hydraulic and transport properties are most important.

The extent and properties of the EDZ is also important for the construction and operation of the repository before closure as it may affect the stability of the underground openings and the possibility to successfully apply the engineered barriers.

The requirements on EDZ properties and extent imposed by performance assessors will have influence on the selection of excavation methods, repository layout, and techniques for application of engineered barriers in the repository.

OVERVIEW OF RESULTS FROM RELEVANT EXPERIMENTS ON THE EDZ

Experiments to study the properties of the EDZ and to test models of its performance have been performed at several underground laboratories during the last two decades, e.g. the Climax and Edgar mines, Stripa, URL, Grimsel, and the Äspö HRL. The main results from these experiments are reviewed below including comments on predicted vs. observed responses, proposed mechanisms, assessment of model agreement, and evidence made in support of proposed mechanisms.

Spent Fuel Test - Climax

The main objective of the Spent Fuel Test at Climax was to experimentally assess the suitability of granite for retrievable storage of spent nuclear fuel and to assess rock mass response to thermal load [2]. Unlike other experiments presented here the Climax Mine is located in the unsaturated zone above the water table. Hence, hydrogeological investigations were limited in scope. Measurements were made of the mechanical response to a central mine-by between two previously excavated drifts. The response was observed in two radial borehole fences instrumented with borehole extensometers, convergence pins, and vibrating wire stress meters [3]. Model calculations of rock mass thermal and mechanical response was performed for each stage of the experiment; excavation, heating, and cooling. Calculations of the mechanical response were initially made with continuum models and later with discrete joint models. Whereas the models predicted expansion of the pillars between the rooms, contraction was measured *in situ*. Results of modelling of the temperature field as a function of time showed good correspondence with *in situ* data.

Edgar Mine OWTD experiment

The experiments carried out by the Colorado School of Mines at the Edgar Mine, CO, had the objectives to develop and evaluate blast rounds in order to minimize damage to the rock around the underground openings, and to develop techniques for characterizing the nature and extent of excavation response [4]. A room (20x5x3 m) was excavated using carefully designed blast rounds. Vertical extensometers were installed in the roof next to the new face following each round. Subsequent to excavation, six sets of seven 5 m boreholes were drilled radially outward from the room to characterize blast damage and excavation response. The characterization showed that the controlled blasting limited the extent of blast damage to within 0.5-1 m from the wall. CSM stress cells, ultrasonic velocity measurements, and permeability measurements generally showed good agreement in delineating the extent and degree of disturbance of the EDZ. Stress models applied adequately predicted the trend and magnitude of measured stresses, but could not account for the variability in the measured data. Predicted and measured displacements did not agree as well as the stress data. This was attributed to non-elastic movements. In a post-analysis, discontinuous deformation analysis techniques were employed to fit distinct block movements to account for measured displacement vectors.

Experience from the Stripa Mine

At Stripa a number of experiments have been performed over the years which did not necessarily have the EDZ as a primary experimental objective but required address of the EDZ in order to explain experimental results.

Macro-permeability test. The objective of the Macro-permeability test was to assess the bulk permeability of a large volume of rock through measurements of water inflow to a drift. Analysis with a radial flow model showed that to match the pressure data a skin zone had to be assigned with hydraulic conductivity decreased by a factor of three relative to the bulk rock conductivity.

Buffer Mass Test and Rock Sealing Project. The Buffer Mass Test was performed to study water uptake in highly compacted bentonite in six large diameter boreholes supplied with heaters [5]. Later, the Rock Sealing Project was carried out in an enclosed part of the same drift to evaluate the hydraulic properties of the EDZ and the ability to seal the EDZ by grouting [6]. The results of this experiment and the associated modelling indicated that the hydraulic conductivity of the part of the EDZ directly affected by blasting (0-0.8 m from the wall) was about two orders of magnitude higher than in the surrounding rock. The hydraulic conductivity in the floor was estimated to be twice as high as in the walls due to the higher density of explosive charges used in the floor.

Site Characterization and Validation Project. The principal aims of the SCV project were to develop and apply 1) an advanced site characterization methodology and 2) to validate models used to describe groundwater flow and transport in fractured rock. The primary experiment within the SCV project was to predict the distribution of water flow and transport through a volume of rock, before and after excavation of a sub-horizontal drift, and to compare model predictions with actual field measurements [7]. In the Simulated Drift Experiment, performed as part of the SCV Project, the inflow distribution to a circular array of 6 boreholes simulating a drift was first measured. Then a drift was excavated within the perimeter outlined by the boreholes and the inflows measured again (Figure 1). The results showed that the inflow to the drift was only 12% of the inflow to the corresponding length of the boreholes. Results also showed that inflow to the drift was more channeled (concentrated to a few inflow points) than the inflow to the boreholes [8].

In the case of the SCV Project a number of predictive modelling exercises were undertaken by four different modelling teams using different approaches [7]. All modelling teams produced predictions of inflow to the borehole array in agreement with measurements. In case of the inflow to the drift, all modelling teams, although taking excavation disturbance effects into account, overpredicted the total inflow by a factor between 3 to 8. The inflow to the averagely fractured rock outside of the fracture zone producing the bulk of the inflow was overpredicted by a factor of 20-30.

Experience from the URL, Canada

At the AECL Underground Research Laboratory (URL) research directed at understanding the factors and the mechanisms controlling rock mass response to excavation has been the focus of two major experiments.

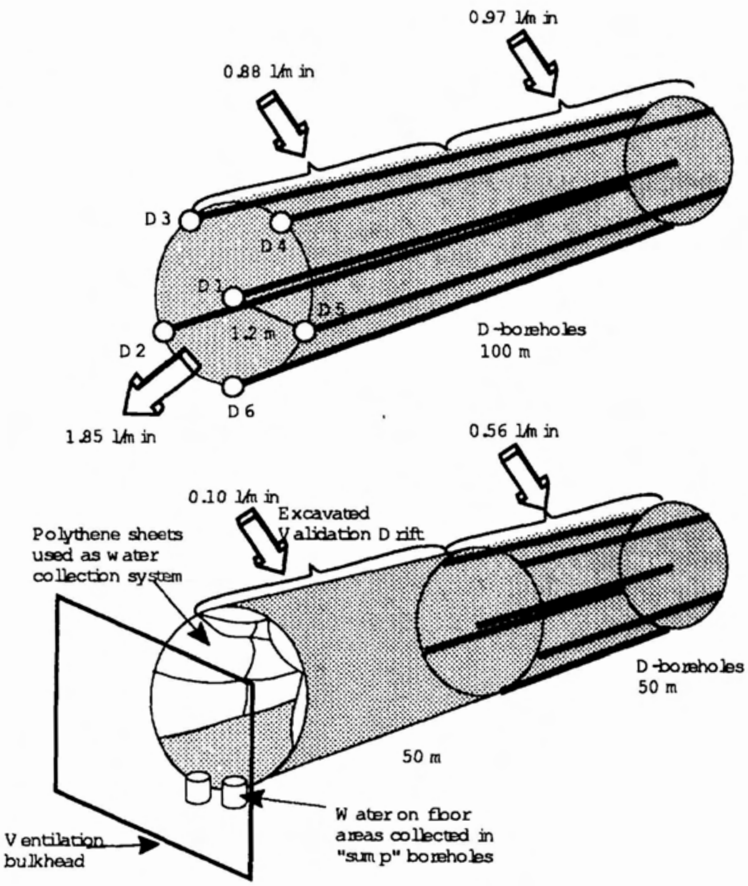

Figure 1 In the Simulated Drift Experiment the inflow distribution to six 100 m long boreholes held at the same head was measured. Later a 50 m long drift was excavated along the boreholes and the inflow measured to the drift.

Room 209 Excavation Response Test. The objective of the Room 209 test was to determine the hydraulic and mechanical response of the rock mass containing a narrow zone of permeable fractures, to estimate the mechanical and hydraulic properties of the rock mass, and to assess the ability to model the hydraulic and mechanical response of the rock mass [9]. The layout of the experiment is shown in Figure 2.

Based on measurements of displacements it was found that there is a decreasing elastic modulus towards the opening. This was attributed to the dependance of modulus on confining pressure rather than excavation damage, except for the 0.5 m closest to the wall of the opening [10]. The transmissivity evaluated from single and multi-step drawdown tests in the nine boreholes circumferent to the tunnel showed a decrease and subsequent increase following excavation of the pilot tunnel through the fracture. In two of the boreholes, transmissivity was reduced permanently by roughly a factor of 5 following passage of the slash. Inflow to the circumferential boreholes prior to excavation was almost 10 l/min, while the inflows from the blast holes, the pilot, and the slash were 1 l/min, 0.35 l/min, and 0.45 l/min, respectively. Hence, a flow reduction to the tunnel similar to that observed at Stripa.

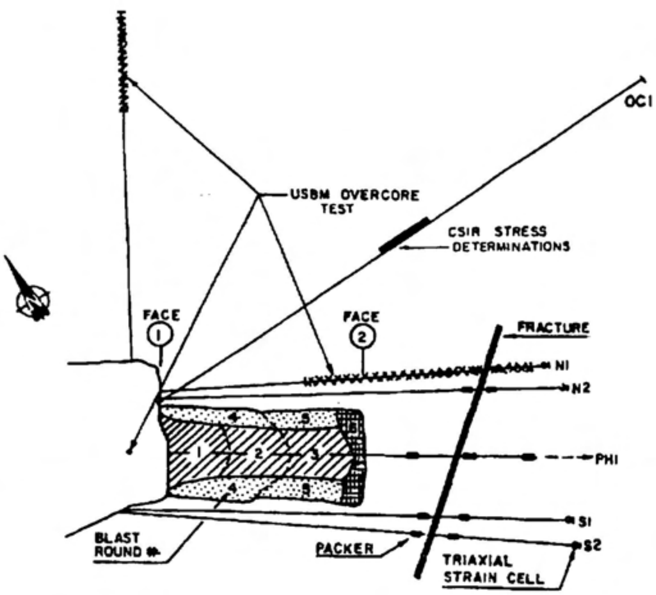

Figure 2 Horizontal view of the experimental array of the Room 209 Excavation response test [9].

It was found that the tunnel floor was more damaged than the rock in the wall and the roof. The extent of damage in the floor was found to be at least 1 m, which was attributed to a higher charge density and explosive energy used in the floor blast holes. The axial hydraulic conductivity of the floor has subsequently been measured by large scale constant head tests by pressurizing a part of the tunnel between weirs and measuring the resulting discharge in measuring slots. The results indicated that the blast-induced fractures were not hydraulically connected and that there was no significant axial conductivity along the tunnel [11]. Subsequent to the constant head tests, short boreholes were drilled to assess the vertical extent of the EDZ. The transient hydraulic tests performed indicated an extent of the EDZ of approximately 0.3 m below the floor.

Modelling of the rock mass response was performed by three different groups. It was concluded that the mechanical response of the rock mass (without the fractured zone) was adequately simulated by the elastic two- and three-dimensional models used [9]. The hydraulic response of the fractured zone were not well simulated by the models used in predictions of the response to tunnel advance.

The Mine-by Experiment. The main objective of the Mine-by Experiment performed at the 420 m level of the URL was to show safe constructability at this depth in highly stressed granitic plutons [12]. Specific objectives were to improve understanding of *in situ* rock mass behavior and failure mechanisms, to evaluate the excavation damage around underground openings, and to contribute to studies on the viability of the borehole alternative for emplacement of waste containers. The first phase of the experiment, the Excavation Response test has recently been completed. The basic idea was to excavate a circular test tunnel in an orientation selected to maximize the in-plane stress ratio in order to promote development of excavation damage. Two of the principal stresses at the test drift location were near horizontal with magnitudes of about 55 and 48 MPa, respectively. The third principal stress, about 14 MPa, was near vertical. The excavation, performed using line-drilling of the complete perimeter of the tunnel, was preceded by excavation of three instrument galleries.

Micro-seismic monitoring of the test tunnel revealed considerable cracking at the face of the advancing tunnel [13]. Stress modelling revealed that the stress magnitudes at the location of these microseismic events agreed well with the crack initiation stress obtained from laboratory tests (70 MPa). Rotation of the compressive stress direction was observed and it is proposed that this rotation contributes to loss of cohesion. Hence, it is believed that the complex loading path at the face is largely responsible for the damage. A notch, i.e. a prismal void, has developed in the crown and floor of the tunnel by progressive failure. A phenomenological understanding of the failure process has been reached.

Investigations of the unsaturated zone at Grimsel

At the Grimsel Test Site the detailed distribution of inflow to a drift has been measured in the so-called ventilation drift. The water balance in the drift and water potentials up to 25 m from the drift were monitored as the climatic conditions in the drift were changed [14]. In a ventilated tunnel with evaporation exceeding the water flow from the surrounding rock matrix, the near field will desaturate and negative water potentials will develop. Negative water potentials could be observed up to a distance of 1.6 m beyond the tunnel wall. Successive, desaturation and resaturation experiments showed no irreversible effects.

A project with the objective to study the hydraulic properties of the EDZ has recently been initiated at the Grimsel Test Site.

The ZEDEX experiment at the Äspö HRL

Most EDZ experiments have been performed in tunnels excavated by blasting. In 1994 ANDRA, Nirex, and SKB decided to jointly perform the ZEDEX experiment at the Äspö Hard Rock Laboratory, Sweden, in order to improve the understanding of the extent and properties of the EDZ for different excavation methods, i.e. drill and blast excavation and tunnel boring (TBM). The main objective was to study the mechanical behavior of the EDZ with respect to its origin, character, magnitude of property change, extent, and its dependance of excavation method. The project also included tests of equipment and methodology for quantifying the EDZ. The development of the EDZ was studied by measurements in axial boreholes before, during, and after excavation and measurements in radial holes made after excavation (Figure 3) [15].

In the near-field, there was little evidence of damage around the drift excavated by Tunnel Boring Machine (TBM) except within a few centimeters of the drift perimeter. AE results from drifts showed micro-cracking occurring predominantly tightly clustered at the drift face and walls, with only scattered cracking further from the drift. The measured extent of the damaged zone for the Drill & Blast (D&B) drift, reached a maximum depth of about 80 centimeters in the floor of the drift, where higher energy explosives were used and was less well developed in the walls (extent about 30 cm). The damaged zone surrounding the drift exhibited by induced fracturing, increased permeability, and reduced seismic

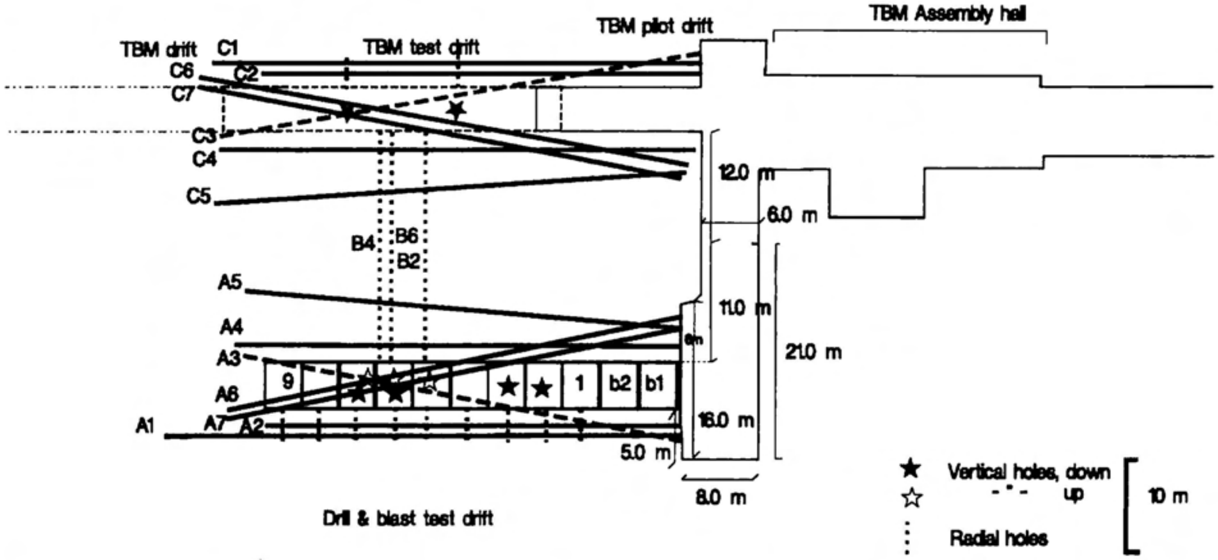

Figure 3 Horizontal view of the layout of the ZEDEX experiment.

velocities. The AE event rate was up to 10 times larger around the D&B drift compared to the TBM drift but there was little difference in AE rate between the two drill and blast designs used. There was no difference observed in EDZ extent and magnitude between the two blast designs used.

The far-field measurements showed no evidence of damage for any of the excavation techniques. Seismic measurements showed no measurable change in seismic velocities and there was sparse AE activity observed beyond about 2 meters from the drift perimeter. Thorough analysis of hydraulic pressure build-up tests in boreholes A4 and A5 showed a general tendency of decreased transmissivity after excavation. Of the nine 3.5 m long intervals measured in borehole A4, located 2 m from the drift wall, three intervals showed decreased transmissivity by half an order to an order of magnitude. The remaining six sections showed no significant change. Of the ten intervals measured in borehole A5, located 6 m from the drift wall, two intervals exhibited decreased transmissivity by two orders of magnitude or more and in one interval the transmissivity increased by more than an order of magnitude. The remaining intervals showed no significant change. The large changes in A5 are associated with a fracture zone intersecting the borehole.

CURRENT UNDERSTANDING OF MECHANISMS FOR EDZ-RELATED RESPONSES

Based on results from experiments at these sites the following main processes or mechanisms have been identified and considered important for the transport related characteristics of the EDZ; mechanical damage due to excavation, stress redistribution around the underground openings, thermal loading, chemical reactions in fractures, and unsaturated conditions around underground openings.

In discussing the consequences on the rock surrounding an excavation it is essential to distinguish between damage and disturbance. We consider it appropriate to define damage as a change in physical properties of the rock due to induced micro- and macro-fracturing (caused by excavation or stress concentrations), e.g. changed elastic modulus, seismic velocities, or permeability. Disturbance would consequently be defined as a change in state (e.g. state of stress, hydraulic head, or displacements) or properties without creation of new fractures. With this definition a change in hydraulic permeability due to aperture change on fractures existing prior to excavation would be classified as disturbance while increased permeability due to new fractures would be a consequence of damage.

Mechanical and thermal responses

In general, the ability to model and predict excavation response related mechanical changes such as stress and displacements can be considered satisfactory. Elastic continuum models generally provide adequate predictions of the trend and overall magnitude of stress changes and displacements. To reproduce the detailed behavior in a fractured rock environment, three-dimensional discrete fracture models, e.g. 3-DEC, are available and can be considered to produce adequate results in most cases. However, in a complex fracture setting there is a problem to include a sufficient number of fractures in the model and to provide representative parameters for the fractures to realistically represent actual conditions.

The ability to produce relatively accurate predictions of the thermal response of the rock mass is also satisfactorily developed [2, 16].

The ability to predict and control the extent of the damaged zone due to excavation by blasting seems to be adequate. Considerable empirical data and experience exist from mining, tunnelling, and EDZ experiments performed as part of research for radioactive waste disposal [17, 18, 19]. Currently available smooth blasting techniques makes it possible to perform excavations where the extent of the damaged zone becomes less than 0.3 m in the walls and about 1 m in the floor [10, 15].

The extent of the damaged zone for mechanically excavated tunnels have recently been investigated as part of the ZEDEX experiment [15] and the Mine-by Experiment at URL. Preliminary results from ZEDEX indicate considerably less damage in the bored tunnel compared to the blasted test tunnel. In this experiment the extent of the damaged zone has been shown to be less than 20 cm but it is estimated to be only a few centimeters (the actual extent has not been possible to quantify due to lack of resolution of the methods used). Recently, the extent of micro-fracturing caused by drilling of deposition holes has been investigated in the TVO Research Tunnel and found to be about 10-15 mm [20].

In the Mine-by Experiment at URL, the high stress concentrations at the crown and the floor caused rock failure and the development of a notch. Recent studies of thermal effects has shown additional failure due to thermally induced stresses. A phenomenological understanding has been obtained of the failure processes.

Hydraulic responses

Predictions of hydraulic responses in EDZ experiments have generally not been successful. In both the Stripa SCV and URL Room 209 experiments the inflows to the drifts were overpredicted by roughly an order of magnitude. In both cases, models were applied which for the prediction of the hydraulic response used a constitutive link between change in transmissivity and normal stress change. However, in both cases the majority of the fractures were nearly perpendicular to the axis of the drift. As the excavation induced normal stress changes parallel to a drift are small the predicted changes in inflow caused by the drifts were small [7]. Hence, the assumed relation between transmissivity and normal stress does not appear explain the smaller than expected inflows observed. It should be noted that results from the ZEDEX project also have indicated a decrease in transmissivity in the disturbed zone (measured at a distance of 2 to 6 m from the drift wall).

Shear displacements in combination with high normal stresses have been suggested as a possible cause for the observed permeability reduction [21]. An analysis of the Room 209 data based on a phenomenological relationship between shear displacement and transmissivity change resulted in good correspondence between measured and modelled responses [22]. However, results from Stripa showed that the reduction in inflow from the dominating fracture zone took place when the drift face was 17 m away from the zone, a distance significantly larger than the distance at which stress induced changes would be expected from a 2.4 m diameter drift [7]. This lead to suggestions of other possible processes which could lead to a reduction of inflow. The most likely ones being: 1) dynamic loading acting on the rock as a consequence of the blasting and 2) degassing of gasses dissolved in the groundwater due to reduced pressure around the drift and subsequent two-phase flow effects. Attempts to verify the second hypothesis *in situ* at Äspö has so far been inconclusive [23] but the effects have been demonstrated in laboratory measurements.

Changes in permeability due to chemical precipitation or dissolution has also been suggested as a possibility near drifts. Potential effects mainly involve the Fe(II)/Fe(III) system and the calcite system. Such effects have rarely been considered in EDZ experiments. For the Stripa SCV experiment it was argued that calcite precipitation was not important because, if effective, it should also have reduced the inflow the boreholes when the pressure was lowered [7].

The Stripa BMT/Rock Sealing, the ZEDEX, and the Room 209 experiments have all shown an increased permeability in the floor of the blasted drifts due to blast induced fractures. The axial permeability tests performed in Room 209 indicated that the blast induced fractures were not connected and that there was no significant axial hydraulic conductivity [11]. In the BMT/Rock Sealing projects indications of increased axial conductivity were inferred from modelling [6]. No axial conductivity tests have yet been performed in ZEDEX.

CONCLUSIONS

Generally, the EDZ experiments that have been performed have shown that the thermal and mechanical responses of the rock mass can be satisfactorily modelled. The understanding of deformation behavior and failure of highly stressed brittle rock masses has been significantly improved by work performed within the Mine-by experiment at URL. However, our understanding of the hydraulic changes caused by excavation are still limited. There appears to be limited evidence in support of the commonly adopted hypothesis that the axial hydraulic conductivity of the EDZ is substantially higher than that of the surrounding rock. There is some experimental evidence for increased permeability in the floor of blasted drifts but the zone of increased permeability does not appear to extend more than 1 m from the floor. The extent of the zone and its axial conductivity, which is largely due to the connectivity of the blast induced fractures, can most likely be reduced by appropriate blasting techniques and form of the tunnel profile.

There appears to be no experimental evidence in support of an increased permeability in the disturbed zone affected by the stress redistribution caused by the void. The stress redistribution will of course lead to changes in fracture aperture, both opening and closure. In a general three-dimensional fracture network it is unlikely that fractures would open and connect is such a way that a permeable path opened along the drift. The risk of a connected pathway is of course greater if drifts are oriented parallel to one of the main fracture sets.

Hence, based on currently available experimental data it appears that the significance of the disturbed zone as a potential pathway has been greatly overestimated, both with respect to the magnitude of permeability increase and extent, in most performance assessments. Moreover, the limited extent of the damaged zone, which is the hydraulically significant part, should make it feasible to block pathways in the damaged zone by plugs placed at strategic locations.

Our relatively poor understanding of the hydraulic properties of the disturbed zone, which generally tend to yield lower permeabilities than the undisturbed rock, should make us reluctant in using drift inflows for estimation of bulk permeabilities and flow path distributions (channeling effects).

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