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The role of the disturbed rock zone in radioactive waste repository safety and performance assessment. A topical discussion and international overview

Anders Winberg

June 1991

SKB-TR--91-25.

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THE ROLE OF THE DISTURBED ROCK ZONE IN RADIOACTIVE WASTE REPOSITORY SAFETY AND PERFORMANCE ASSESSMENT. A TOPICAL DISCUSSION AND INTERNATIONAL OVERVIEW

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Information on SKB technical reports from 1977-1978 (TR 121), 1979 (TR 79-28), 1980 (TR 80-26), 1981 (TR 81-17), 1982 (TR 82-28), 1983 (TR 83-77), 1984 (TR 85-01), 1985 (TR 85-20), 1986 (TR 86-31), 1987 (TR 87-33), 1988 (TR 88-32) and 1989 (TR 89-40) is available through SKB.

The Role of the Disturbed Rock Zone in Radioactive Waste Repository Safety and Performance Assessment

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A Topical Discussion and International Overview

by

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June 1991

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Abstract

A discussion was presented of the role and relative importance of the disturbed rock zone (DRZ) around the underground openings of a repository for nuclear waste in crystalline rock. The term disturbed rock zone was defined and possible criteria to be used to distinguish it from undisturbed rock was suggested.

The processes decisive for the hydraulic characteristics of the DRZ were discussed. With regard to the integral hydraulic characteristics of the DRZ, the effects of the excavation methodology, stress redistribution, thermal changes, chemical changes and backfill were discussed.

A review of in-situ observations of the DRZ was provided. Model analysis where the DRZ has been explicitly or implicitly represented, either from a phenomenological and performance assessment aspect were reviewed.

The implications of the disturbed rock zone for the safe performance of a nuclear waste repository were discussed. Conceptual models for the geometry the DRZ and hydraulic conductivity distribution in the DRZ were suggested.

Key words :

crystalline, disturbed, damage, excavation, international overview, hydraulic conductivity, hydrogeology, modelling, processes, repository, safety and performance assessment, stress.

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Appendices

1. BACKGROUND

The SKB 91 safety and concept assessment program has as one of its principal aims to address a KBS-3 type repository in light of novel know-how, less conservative assumptions and by analyzing the importance of the truly geological parameters (Papp et al 1990). Focus has in this context been put on the Finnsjön site which has been investigated since the late seventies and is still being subject to investigation.

One of the aspects of repository design and performance that will be assessed within the scope of the SKB 91 study is the effect, and relative importance of the Disturbed Rock Zone (DRZ) with regard to enhanced nuclide release and transport from such a repository. The DRZ in the present case pertains to the close environment around access shafts, storage tunnels and individual canister holes.

In previous Swedish repository safety and performance assessment studies, the ALMA and the KBS 1-3 studies, the DRZ was only discussed conceptually without explicitly including it into quantitative analysis. In conjunction with the DRZ, possible means of sealing was discussed. In the safety and performance assessment of the repository for reactor waste, the SFR, the DRZ was however incorporated in the hydraulic modelling.

Internationally, the DRZ has also been given early, mainly conceptual focus of attention, eg. in the US program where its potential impact was part of the background information for Peer Group Review (Golder Associates 1977). During the last decade the study of the DRZ has been given both experimental and modelling attention within the national US, Canadian and Swiss, Swedish, and more recently within the Finnish, programs.

The focus on the impact of the DRZ on repository engineering design and safety performance resulted in a OECD/NEA organized workshop on "Excavation Response in Deep Radioactive Repositories" held in Winnipeg, Canada the Spring of 1988. The workshop brought together experimentalists and modellers analyzing various geological media, including salt, crystalline rock and clay, and addressed the pertinent questions related to excavation inflicted damage in repositories. Among those being to conclude and recommend suitable techniques and instrumentation to assess excavation damage, and to provide a forum for interaction between experimentalists and those developing predictive modelling tools.

The main points and conclusions from the workshop based on the state of the art at the time, were (OECD/NEA 1989);

- that with regard to relevance and importance, the DRZ is most important for the long-term behaviour of repositories in crystalline rock. Further work was identified to demonstrate (the hopefully insignificant) effects on long-term safety, or otherwise provide necessary data for design of sealing of the DRZ. A review of national programs was foreseen to assess the degree of transferability of data, methodology and models from one site to another.

- future excavation response testing and analysis should be focused on the identification of the governing parameters. With regard to crystalline rock the most relevant phenomena are those associated with shafts, storage tunnels and canister holes.

- a need was identified for improved instrumentation and measurement techniques to examine the host rock-excavation interface. In addition the longevity of such instrumentation under in-situ conditions must be prolonged to sustain monitoring periods extending over several years.

- rock mass response to excavation was considered a very useful tool in validating performance assessment models.

- it was also concluded that the DRZ potentially may have a major effect on the design and effectiveness of engineered seals for repository access shafts and storage tunnels. A need for an evaluation of sealing methodology under representative in-situ conditions was identified. More consideration should also be given to a reduction of the DRZ through 1) careful and controlled excavation, 2) optimal positioning, of repository openings, and 3) alternative excavation geometries.

The above conclusions and observations have had bearing on subsequent experimental activities and analysis within the different national radwaste programs. The present report in the light the SKB 91 study constitutes a new state of the art compilation on the DRZ. Special emphasis is given to the flow and transport characteristics of the DRZ.

2. SCOPE

The main objective of the present study provide an overview and discussion of the performance assessment implications of the DRZ, thus providing a base documentation for the modelling of the DRZ in SKB 91. As a general background to this discussion a base documentation is provided on the DRZ. This documentation includes a definition of the term disturbed rock zone and an overview of the physical processes that play a role, either as singular or combined/superimposed processes, in the development of the DRZ around tunnels. An overview of relevant qualitative and quantitative experimental in-situ data on the DRZ is provided. The DRZ around individual canister holes is tentatively discussed.

The implications of the DRZ for repository geometry and siting, safety and performance of repositories in crystalline rock is discussed as is the range of possible material properties and geometry of the DRZ given available data. These values are to be regarded as suggested input values to the modelling of the DRZ in SKB 91.

The source of the information on which the study is based is literature data and oral information obtained from various Swedish and international contacts.

3. DEFINITION OF DISTURBED ROCK ZONE

What we here denote the Disturbed Rock Zone (DRZ) is the zone immediately circumferrent to an underground affected by various processes, including mechanical, thermal, hydraulic and chemical processes, described in Chapter 4. In the literature the DRZ is often called "fracture zone" (Golder Associates 1977) or "excavation damaged zone" (OECD/NEA 1989). With the term disturbed rock zone (DRZ) we dissociate from the purely mechanical aspect and instead emphasise the large number of processes that come into play, either acting alone or coupled and/or as a consequence of one and other.

The disturbed zone has not been uniquely defined in a quantitative manner within the Swedish program. In fact, to the knowledge of the author, the DRZ has not been explicitly defined for any geological media, possibly because of its inherent very site-specific nature. However, a definition of the zone where the rock is disturbed could eg. be based on;

- rock strength/acting stress ratio
- decrease in elastic modulus - seismic velocity
- fracture frequency - RQD or similar index
- permeability change in vicinity of opening
- changes in moisture content (electrical resistivity)
- changes in pore pressure

For each of these parameters one could introduce criteria, setting the limits for undisturbed in-situ conditions, and those imposed by excavation related processes.

It would be presumptuous to introduce definite definitions of DRZ within the scope of this study. It should be borne in mind that the transferability of such definitions from one site to another is not trivial. Observed changes in material properties depend largely on initial conditions and properties.

However, a tentative simplistic definition of the DRZ in a crystalline environment could eg. include the following criteria;

- rock strength/rock stress ratio <= 3
- increase in frequency of open fractures with a factor 5
- 1-2 order of magnitude change in permeability
- decrease in resistivity with a factor 5
- decrease in seismic velocity with a factor 2

4. GOVERNING PARAMETERS AND PROCESSES

4.1 General

When discussing the governing parameters and processes playing a role in the development of the DRZ, a distinction is here made between those decisive for the **short-term** and **long-term** hydraulic characteristics of the DRZ.

The short-term characteristics are in part imposed by the atmospheric conditions prevailing in the opening following excavation. Possible desaturation and invaded excavation gases into the rock mass in the rock close to the opening are pertinent to any type of hydraulic measurement or observation made close to an accessible underground opening. In addition, but probably to a lesser extent, clogging of fractures at the face of the opening due to eg. oxidation of inflowing water may play a role in changing the properties of the DRZ. Thus, any type of prediction-validation exercise of flow and/or coupled mechanical-hydraulic model must take into account the processes giving such characteristics. It should be appreciated that the specific conditions, ie. flow regime, met when studying the above mentioned short-term effects are not necessarily representative of the conditions and reinstated flow-regime of the back-filled repository. The implications of this fact for the usefulness of the predictive tools are yet to be assessed.

The processes providing short-term characteristics are superimposed on the processes deciding the long-term characteristics relevant to the lifetime of a nuclear repository.

The characteristics that are decisive for long-term safety and performance assessment perspective are those which are valid when the repository has been back-filled and fully resaturated. These include the effects of excavation, stress redistribution, thermal load, behaviour and longevity of backfill and changes in the near-field chemistry.

Table 4.1 Processes determining the short- and long term characteristics of the disturbed rock zone in the near-field of a nuclear waste repository in crystalline rock.

<u>Long-term</u>

☐ Mechanical damage due to excavation

☐ Stress redistribution around an underground opening

☐ Thermal loading of the rock mass

☐ Behaviour and longevity of tunnel and canister hole backfill

☐ Chemical reactions in fractures

<u>Short-term</u>

☐ Unsaturated and two-phase flow conditions around the opening

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If we are addressing the flow and transport characteristics of the DRZ, six main processes may be identified, cf. Table 4.1, that all contribute to, or are decisive for changes in the hydraulic properties of the zone closest to a storage tunnel in a high-level nuclear waste repository in crystalline rock.

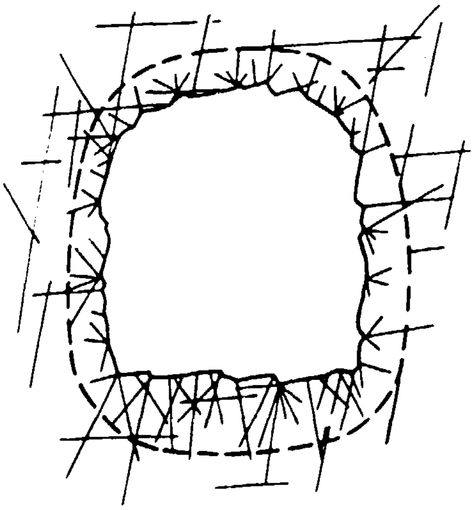


Figure 4.1 Schematic representation of excavation induced fractures around a circular opening in granitic rock (Pusch 1989b).

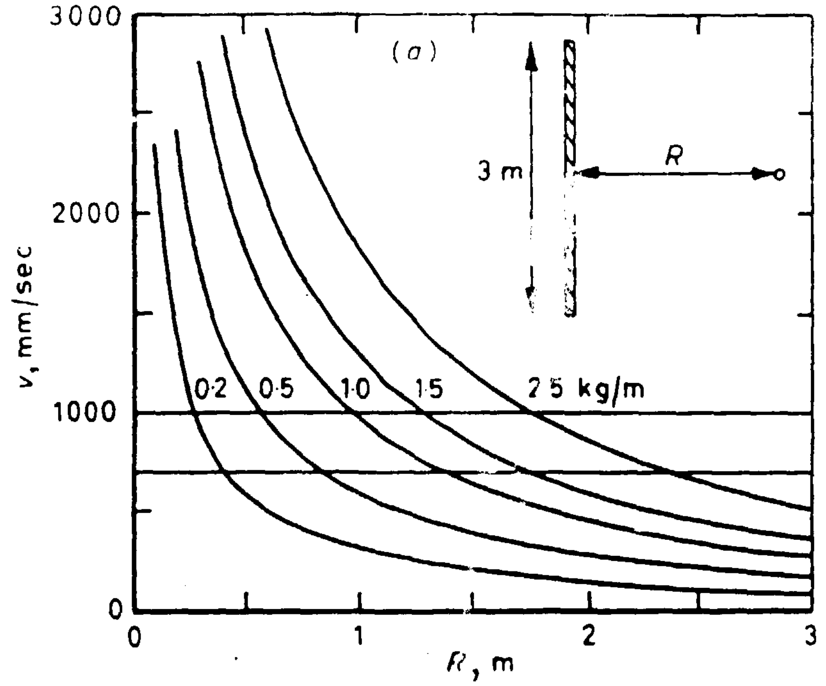


Figure 4.2 Graph showing the extent of the zone affected by peak velocity (damage) due to drill and blast (Holmberg and Persson 1979)

4.2 Mechanical damage due to excavation

Due to excavation alone, mechanical damage is induced in a zone around the opening causing induced fracturing and/or reopening of old and/or elongation of existing fractures, cf. Figure 4.1. As a consequence, a lower RQD (Rock Quality Designation index), lower elastic modulus and lower P and S seismic waves are obtained (Ubbes et al 1989). Of these, all but RQD are dependent on the acting in-situ stress field. The higher the in-situ stress field and the lower the strength of the rock, the higher the amount and focus of energy (of the explosive), the larger the radius of the excavation damaged zone. A mathematical relationship between thickness of excavation damaged zone and explosive charge density has been developed (Holmberg and Persson 1979). The resulting graph is presented in Figure 4.2.

With the aid of careful, controlled drill and blast design techniques based on the theoretical understanding of the excavation process, the damage due to excavation can be minimized. The steps taken include selection of optimal size and spacing between blast holes, charge density and dimension. These techniques have eg. been employed in excavating the Macropermeability drift (Buffer Mass Test site) at Stripa in Sweden (Andersson and Halén 1978), the CSM/OCRD room in the Edgar mine at Idaho Springs (Holmberg 1983, Sperry et al 1984), and at the Canadian Underground Laboratory (URL) near Lac du Bonnet, Manitoba (Kuzyk et al 1986).

It is expected that continuous excavation by tunnel bore machines (TBM) will dramatically reduce the damage due to excavation, more so in magnitude than in spatial extent. An experiment was planned at the NAGRA test facility at Grimsel in Switzerland to compare the damage imposed by controlled drill and blast techniques with that due to continuous excavation by TBM. The continuous excavation was performed and the resulting damage inflicted was assessed (Egger 1986, Lieb et al 1989), but the drill and blast excavation was unfortunately not carried out.

Presently at the AECL Underground Research Laboratory (URL), a new experiment level is excavated at the 420 level. At this level there are plans to compare controlled drill and blast with line-bored excavated tunnels, the latter providing essentially the same result as a TBM (Martin, pers. comm.).

Local heterogeneities in the rock, in terms of variations in bedrock properties, lithology and fracturation, which governs the strength will be decisive for local variations in the radius of excavation damage around an opening.

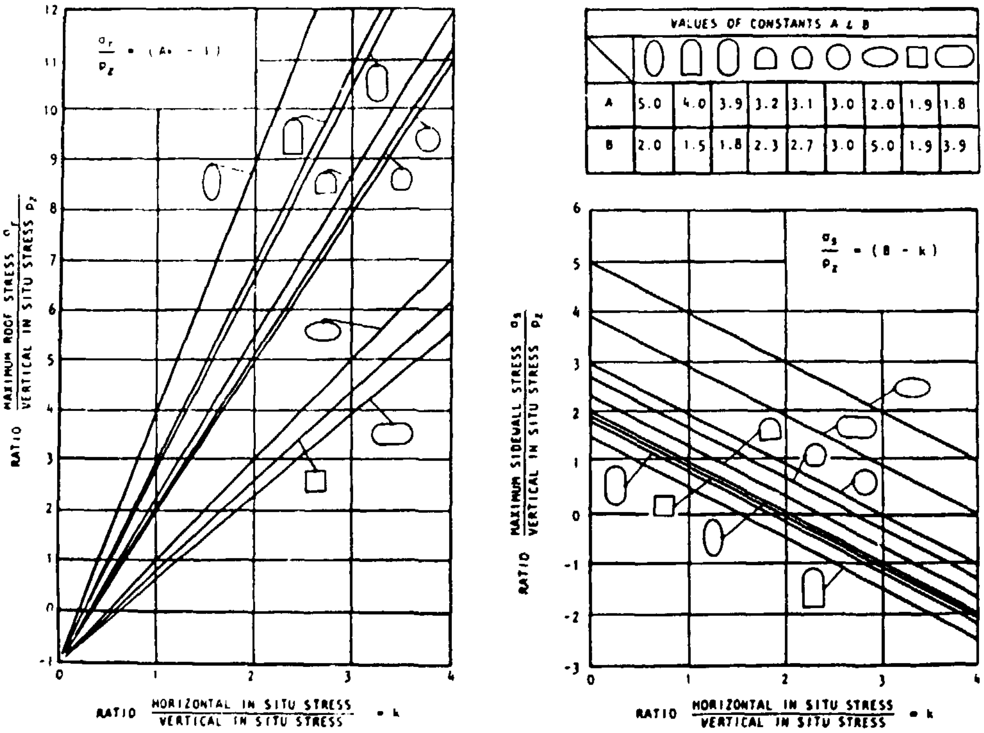
4.3 Stress redistribution around an underground opening

When an opening is excavated in a rock mass under tri-axial stress conditions the constraints on the remaining rock mass is locally removed (Simmons 1989) and the stresses that were previously carried by the rock volume corresponding to the excavated opening are redistributed around the face of the opening (Ubbes et al 1989). In order to reattain equilibrium, existing fractures may displace, new fractures may form or sealed fractures may be reactivated (Simmons 1989).

The extent of disturbance resulting from stress redistribution alone is controlled by the shape of the opening, its size in relation to the fracture spacing of existing fracture sets, its orientation with regard to the stress field, the frequency and properties of fractures, the properties of the rock matrix and finally the magnitude, orientation and magnitudes of the principal in-situ stresses (Kelsall et al 1984, Simmons 1989).

The stress concentrations around an opening, defined as the ratio between resulting radial or tangential stress and the applied stress, are independent of the size of the opening. However, the geometry of the opening and the in-situ stress field are decisive on the magnitude of the stress concentrations. In Figure 4.3 the roof and sidewall boundary stress concentrations for different opening shapes are given for different biaxial in-situ stress situations.

Highly idealized, the induced increase in stresses around an opening will lead to a higher elastic modulus, a higher P and S wave velocity through the closure of existing fractures, and consequently a reduction in permeability (Ubbes et al 1989). The effects of the stress redistribution superimposed on the effects of excavation alone may thus reduce the overall extent of a zone with potentially high permeability, apart from a surficial zone close to the opening.



A	5.0	4.0	3.9	3.2	3.1	3.0	2.0	1.9	1.8
B	2.0	1.5	1.8	2.3	2.7	3.0	5.0	1.9	3.9

Figure 4.3 Boundary stress concentration ($\sigma_{max}/\sigma_{applied}$) as a function of opening shape and biaxial in-situ stress situation (Hoek and Brown 1980).

4.4 Thermal loading of rock mass

The build-up of heat in and around a repository will start after waste emplacement and closure of the repository. The thermal load will constitute yet another cause of rock disturbance, following in succession to damage due to excavation and pure mechanical stress redistribution.

The heating of rock will cause a volume increase in the blocks forming the fractured bedrock. This increase in volume and the given constraints will cause fracture apertures to decrease and thus a net decrease in hydraulic conductivity, if possible aperture changes due to thermally induced shearing are neglected.

Thermal effects were studied during the experiment in the Climax facility in the U.S.A. (Ubbes et al 1989). One of the objectives of this study was to compare the magnitude of displacement following excavation and stress redistribution with those following thermal loading. It was found that the response, in terms of displacement, to excavation and that to thermal load were similar in magnitude, but of fundamentally different nature. The rock mass response due to thermal load was found to be that of a elastic continuum, whereas that due to the excavation and stress relief was controlled by existing joints and shear zones, thus indicating a discontinuum response. It was concluded that response to excavation and stress relief is harder to predict than the response to heating.

At the Yucca mountain site in Nevada, U.S.A., the maximum principal stress in the welded tuff has been found to be near vertical and the minimum horizontal stress is approximately 30 to 80% of the vertical (Bauer et al 1989). Analysis of the thermo-mechanical response of the rock mass in conjunction with the G-tunnel field experiments indicated that 1) the thermal load drives deformations after excavation, and 2) thermal loads results in a 90° rotation of the stress field so that the maximum principal stress in the area of the heat source is near horizontal.

It has also been suggested in a tentative study of a repository placed in shale that when assuming a long-term repository temperature of 190 °C and a temperature of 60 °C some 250 m away, the superimposed effect of the thermally induced stresses will increase the DRZ with 15% (Golder Associates 1977).

To provide perspective, in the Swedish KBS-3 study a repository temperature of 80 °C was considered acceptable. In the SKB 91 study, a maximum repository temperature of 100 °C will be accepted in the analysis.

4.5 Effect of back-fill in deposition hole and storage tunnel

The high grade bentonite back-fill around a canister in a deposition hole will during gradual saturation build up a swelling pressure acting on the walls of the hole. This swelling pressure which may amount to 10 MPa may counteract the effect of the stress redistribution caused by excavation. On the other hand the resulting radial stress close to the wall, which may amount to 15 MPa, may reduce the effective normal stress acting on fractures aligned with the axis of the deposition hole. Rutqvist et al (1991) has shown that such a situation may cause a doubling of a pre-excavation aperture of 60 microns. The swelling bentonite will only penetrate a few millimetres (Pusch 1983), and thus the hydraulic conductivity along the deposition hole will be enhanced.

The swelling pressure in the storage tunnels will only amount to approximately 1% of the swelling pressure in the deposition hole. Thus the counteracting, and possibly deteriorating effect of back-fill swelling in the storage tunnels may be neglected.

Another aspect, rather than a process, which has to be taken into account when discussing the long-term characteristics of the DRZ around a conceived storage tunnel is the stability and longevity of the back-fill. If the backfill is deteriorated due to successive erosion, most possibly initiated in the not so well compacted crown of a storage tunnel, a high-conductive channel may be developed in the upper part of the back-fill along the axis of the tunnel. In addition, the loss of support imposed by the eroded-away back-fill may result in caving in of the crown of the storage tunnel, thus enlarging the high-conductive channel. The implications of such events will discussed further in Chapter 8.

The longevity of back-fill material is studied by Pusch and Börgesson (1989) within the scope of the Stripa project. Conclusions thus far indicate that the longevity of the proposed types of back-fill materials will be acceptable.

4.6 Unsaturated and two-phase flow conditions around the opening

As a natural consequence of the damage inflicted by excavation, stress redistribution, and subsequent thermal loading, the permeability distribution around the storage tunnels of the repository will be altered. The nature and magnitude of these changes will be tentatively discussed in the subsequent Section 4.8.

This section, however, will discuss those processes affecting the permeability and flow conditions around an opening which are related to the effect of 1) the acting atmospheric pressure in the underground openings imposing an artificial extreme boundary condition on whatever hydraulic observation made underground, 2) possible invasion of air and/or explosive gases into the fractures of the DRZ, 3) capillary effects at the interface between gas and fluid in the fractures of the DRZ.

Viewing the problem of the boundary condition in terms of hydraulic head, thus representing any point of the periphery of the opening with a head corresponding to its elevation, most of the water inflow would take place along the tunnel floor and lower part of the ribs even under the assumption of homogeneous material properties. If in addition, a DRZ is introduced a redistribution of water along the DRZ along the roof and ribs to produce an increased inflow in the floor would follow.

An invasion of air and/or explosive gases into the fractures of the rock may potentially create an unsaturated zone in the close proximity of the opening (Jakubick et al 1989). This zone would impose an increased resistance to flow, thus resulting in a lower inflow to drift than anticipated. It has been suggested in excavation technical literature that up to 60% of the produced CO and NO_x gases to 2/3 would be contained in the walls of an excavated wall. However, experimental work by Persson (1983) indicate that < 0.1 % of produced gases were emitted from the fractures of an excavation wall during a 3 hour period. A complete mass balance of produced and recovered gases was not provided.

The invasion of gas could also be associated with invasion of small-size fraction fraction of debris into the DRZ and its fractures which may enhance the resistance to flow.

At the interface between air and fluid at the fractures intercepting underground openings there is a theoretical possibility of creation of capillary forces, particulary so in "good rock" with small aperture fractures. It has recently been suggested by Olsson (pers. comm.) that capillary forces, acting opposite to the direction of flow, as high as 15 m of head may be envisaged (assuming a fracture aperture of 1µm). The smaller the opening (aperture) the stronger the capillary force.

Once the opening is resaturated, and the hydraulic conditions are returned back to their (near) normal state, these effects rapidly dissipate.

4.7 Chemical reactions in fractures of the DRZ

The chemical processes acting in the near proximity of the opening, in relation to the other processes listed above, in most situations play a subordinate role in affecting the groundwater flow conditions close to an underground opening. However, chemical changes, including water-rock interaction is known to play an important role from the radionuclide transport aspect. This latter point is discussed further in Chapter 8.

One of the foreseen reactions is the oxidation of inflowing water at the surface of the opening. The resulting oxidation of Fe^{2+} to Fe^{3+} and the formation of amorphous iron compounds may cause clogging of the fractures in the immediate vicinity of an opening.

Consider a typical Swedish situation with a repository at 500 m depth a typical groundwater of non-saline, HCO_3-dominated composition. Inflowing groundwater towards an opening will be degassed and the initially high partial pressure of CO_2 will be lowered. A fairly rapid equilibrium is foreseen with precipitation of calcite (Tullborg, pers. comm.). The formation of calcite on the fracture surfaces close to the opening will consequently reduce, however probably to a smaller degree, the hydraulic aperture and consequently the permeability of the rock.

The superimposed effect of the increased thermal load from the waste on the formation of calcite is discussed further in Chapter 8.

4.8 Permeability as a function of state of stress

The permeability of fractured crystalline rock is governed by the permeability and interconnection of existing fractures. The fracture permeability is in turn dependent on the effective normal stress ($\sigma' = \sigma_n - P$) acting on the fracture.

Laboratory studies on natural fractures have shown that the an order of magnitude change in σ' results in an order of magnitude change in fracture permeability (Witherspoon and Gale 1977, Makurat et al 1990).

If shearing is added it has been shown (Makurat et al 1990) that even small amount of shearing is sufficient to dilate fractures in hard rock causing joint permeability changes as high as one to two orders of magnitude. If the fractures are mineral coated, implying low JRC values (cf. Section 6.3), small amounts of shear causing formation of gauge may reduce the joint permeability in hard rocks.

Kelsall et al (1984) have analytically investigated the changes in radial and tangential permeability around an idealized circular opening. It was found that the increase in tangential stress, resulting in the formation of "onion skin" fractures, may result in an order of magnitude increase in permeability in the tangential (axial) direction. The permeability in the radial direction, however, will decrease, cf. Figure 4.4.

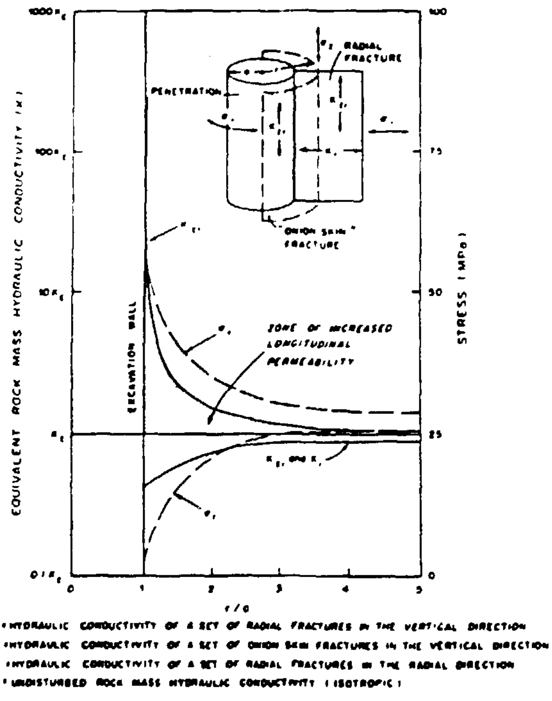


Figure 4.4 Predicted change in rock mass hydraulic conductivity due to state of stress around a circular opening (Kelsall et al 1984)

5. FIELD OBSERVATIONS OF THE DRZ

5.1 General

This chapter constitutes a compilation of qualitative and quantitative studies and observations of the DRZ in crystalline rock. The majority of case histories are for obvious reasons related to radwaste investigations. However, in an introductory section observations of the DRZ are provided from non-radwaste engineering geology and mining applications. The latter are to a large extent related to observations of pure mechanical excavation and stress related damage.

The most extreme observation is one stemming from the study of the effect of a nuclear explosion on bedrock permeability, which for obvious reasons does not reflect any type of "careful blasting". Boardman and Srove (1966) found a two to three order of magnitude increase in air permeability some 25-70 m radially away from the hypocentre of the underground nuclear explosion.

The methodologies used to describe the mechanical and hydraulic characteristics of the DRZ include both indirect and direct methods. To the indirect methods belong various geophysical techniques, measurements of dilation, stress changes, hydraulic pressure. Direct mechanical assessment of the DRZ may be obtained by measurement of induced fracturing (length and intensity). Direct hydraulic assessment of the DRZ may be obtained by various types of permeability measurements.

5.2 Engineering geology and mining experience

The extent of, primarily, the zone damaged by the excavation technique has been given a growing focus of attention during the past three decades. The main reasons being 1) operational safety and 2) safe and successful rock reinforcement of underground structures.

Microseismic studies in the Malmberget Iron mine in northern Sweden and in the Shafts associated with reactor 3 of the Forsmark Nuclear Power station performed by Stephansson et al (1979) indicated an induced fracturation varying between 0.1 and 1 m. The extent of the zone of induced fracturation was collaborated by ocular borehole inspection in the Malmberget mine.

Pukkila (1989) found the damaged zone to be less than 0.2 m in medium grained granite when a 17 mm Forsite pipe charge (0.13 kg/m) was blasted in 45 mm holes.

When using Silosex (1.18 kg/m) in 64 mm holes, Jokinen (1990) found the damaged zone in terms of increased micro fracturing extended 0.8-1 m from the blast holes.

There exist a strong urge from the tunnelling and mining community to reduce the extent of the excavation induced damage around underground openings. The resulting efforts have produced methodologies for blast design that with carefully carried out ordinary drill and blast may keep the excavation damaged zone within 0.1 m. However, the criteria set to delimit such a zone have, to the authors knowledge, not been uniquely defined.

5.3 Stripa (MPT, BMT), OECD/NEA, Sweden

Experience of damage due to excavation has been gained from the smooth blasting of the LBL ventilation drift at Stripa (Andersson and Halén 1978). The drift was used for a macro-permeability test (MPT) aimed to assess the mean rock mass permeability for a large rock volume (Wilson et al 1981, Gale et al 1983). This drift has subsequently been the site of the Buffer Mass Test (Pusch 1985), which have provided additional information of the hydraulic properties of the DRZ (Pusch 1989a, 1990, Pusch and Bergström 1989).

The drift is located at 335 m depth in the Stripa mine in central Sweden. The layout of the drift is given in Figure 5.1. The fracture system as inferred from the drift and surrounding boreholes indicate one north-south and one east- west system with steep dips, one north-south system with intermediate dip to the east and one more or less horizontal system. The axis of the BMT drift is essentially parallel to the north-south and horizontal sets.

The results of rock stress measurements in the Stripa mine indicate a horizontal principal stress σ_1 of c. 20 MPa oriented east-west and σ_2 of c. 10 MPa oriented north-south. The third principal stress σ_3 is 8.8 Mpa corresponding to the load of the overlaying rock mass.

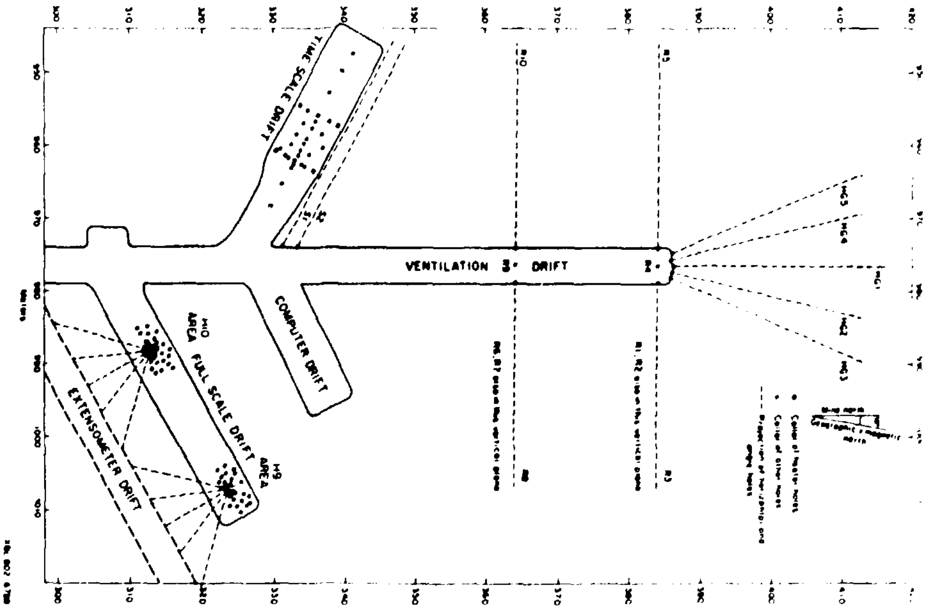


Figure 5.1 Layout of the MPT/BMT tunnel in the Stripa mine.

The excavation effect of twelve blast rounds extending over 45 m of the LBL drift was studied in greater detail (Andersson and Halén 1978). The proportion of remaining halves of contour blast holes that were damaged or blasted away was found to be 2%. A more detailed scrutiny indicated that 10% of the contour holes had undulating fractures along the lengths of the holes. The length of these fractures varied between 0.1 - 1 m. 50% of these fractures were found close to the floor were the primary charge had been placed. Ten short (0.5 m) 52mm diameter core holes were drilled radially, preferably along the plane of identified fractures, to assess fracture extension in the radial direction. The radial extent of these fractures was found to vary between 15 and 30 cm.

On the basis of the collected information the following conclusions were drawn;

- Excavation induced fractures will propagate in the direction of already existing fractures, if they are located less than 40 cm from the contour blast hole.
- The general rule applies which states that the radial extent (from surface of opening) of blast induced fractures corresponds to the charge in kg/m, ie. 0.3 kg/m implies an extent of damage of 0.3 m, cf. Section 4.2.

Pusch (1989) show that increased fracturing as evidenced in boreholes used for grouting is frequent in a zone extending 1m from the periphery.

The rationale of the LBL Macro-permeability Experiment was to assess the bulk permeability of a larger volume of rock on the basis of 1) the net moisture seepage into the (by bulk heads) isolated drift, 2) temperature and hydraulic pressure readings in an array of boreholes around the drift, cf. Figure 5.2 (Wilson et al 1981). Modelling of the experiment set up assuming radial flow

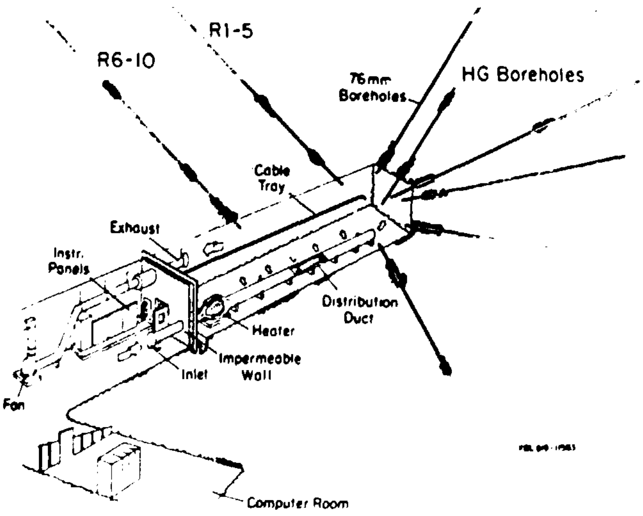


Figure 5.2 Experiment set-up for the LBL Macro-Permeability test (MPT) at Stripa.

indicated an average bulk hydraulic conductivity of approximately 10^{-10} m/s. It was also shown that semi-log plots of the pressure data in terms of head were higher than the actual head when projecting the data to the surface of the drift. This suggested the presence of a skin zone of lower hydraulic conductivity.Assuming a thickness of 2.5m, the skin conductivity was calculated at 3.5 10^{-11} m/s, ie. about one third of the average rock mass conductivity (Gale et al 1983).

The Buffer Mass Test was subsequently performed in the drift used for the Macro-permeability test. The rationale of the BMT was to study water uptake and build-up of swelling pressure in six large diameter holes supplied with heaters embedded in compacted bentonite. The inner part, 12m, of the 35 m long tunnel including 2 heater holes was backfilled using sand-bentonite mixtures, cf. Figure 5.3. Predictions were made of pore pressure build-up at piezometer locations in the rock and at the rock/backfill interface. The water flow from the rock towards the backfill was predicted to increase pore pressures and increase the degree of water saturation in the backfill. Measured pore pressures showed a small increase to 30-50 kPa (corresponding to 30-50 m head) while simultaneously the measured discharge at the rock/backfill interface increased. Using the pressure data along the drift, indicating a gradient towards the outer bulkhead, and the measured discharge, an axial hydraulic conductivity of the DRZ was calculated to be 10^{-8} to 10^{-6} m/s within 0.5 to 1 m from the periphery (Pusch 1989a, 1990, Pusch and Bergström 1989).

Analysis by Kelsall et al (1984) of the Macro-permeability test using their model of stress-permeability relationship indicated that the permeability distribution back-calculated from the test results is consistent with their model that predicts that the increased tangential stresses around the opening will reduce permeabilities in the radial direction towards the drift. They also pointed out, but never pursued an extension of the analysis to predict the change in the axial hydraulic conductivity in the DRZ.

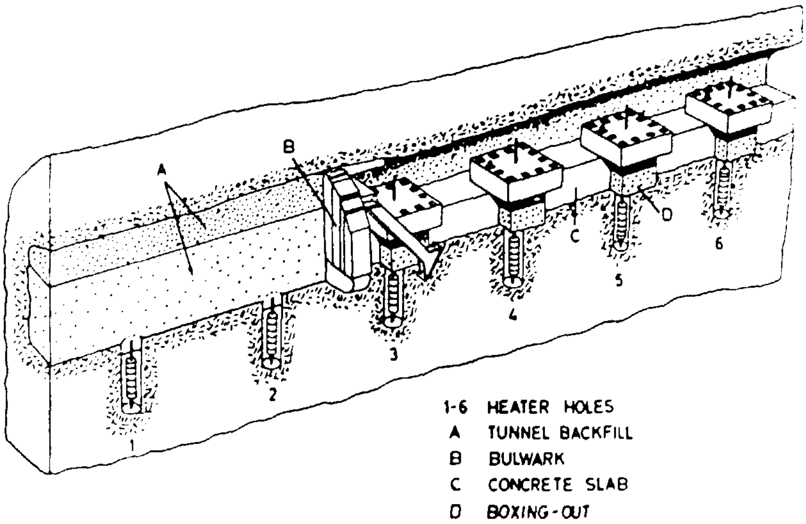


Figure 5.3 Layout of the BMT test at Stripa (Pusch och Bergström 1989).

In conclusion:

- Blast damage assessed from drift walls and radial boreholes. Induced or extended radial fractures propagates on the average 0.3 m into the wall. Increased fracturation with a 1 m zone from drift periphery.

- Evidence from the MPT of a DRZ, 2.5 m deep, with a radial skin permeability reduced to one third of the average rock mass conductivity.

- Increased axial hydraulic conductivity of 10^{-8} to 10^{-6} m/s in 0.5-1m DRZ as evidenced from evaluation of BMT.

5.4 Stripa (SCV), OECD/NEA, Sweden

The ongoing Phase IV at Stripa includes forward predictions of inflow to a drift through the Site Characterization and Validation Site (SCV) (Stripa 87-09), cf. Figure 5.4. One continuum and three discontinuum models have been used to predict the inflow of water to 1) the pilot holes for the SCV drift, and 2) inflow to a certain section of the tunnel, cf. Section 6.3. The inflow to the boreholes were on the order of 0.7 l/min, whereas the inflow to the drift was found to be only 1/8 - 1/7 of the inflow to the boreholes. The SCV experiment thus show definite evidence of decreased inflow to an excavated tunnel compared to observed inflow to the pilot holes. In addition the noted order of magnitude variation in inflow to the six pilot holes (Olsson, pers. comm.) indicate that one single pilot hole observation is not satisfactory for prediction of inflow to a larger opening. The noted lower inflow to the drift was attributed to a skin effect of unknown origin, possibly explained by two-phase flow (incl. capillary) effects (Olsson, pers. comm.). The evaluation of the SCV experiment is an ongoing activity.

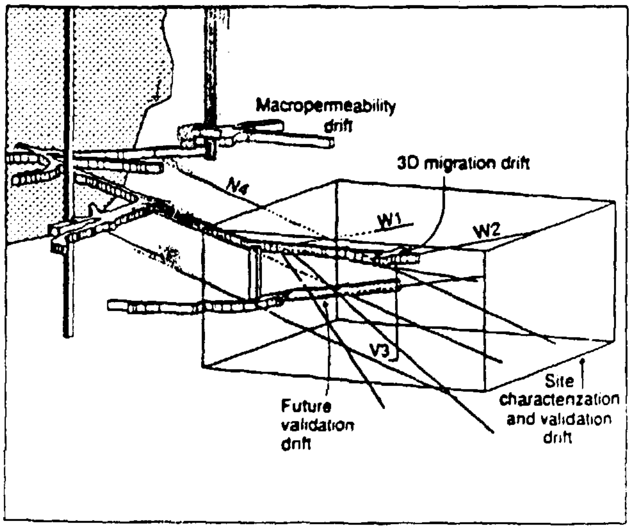


Figure 5.4 Layout of the SCV experiment at Stripa (Long et al 1989).

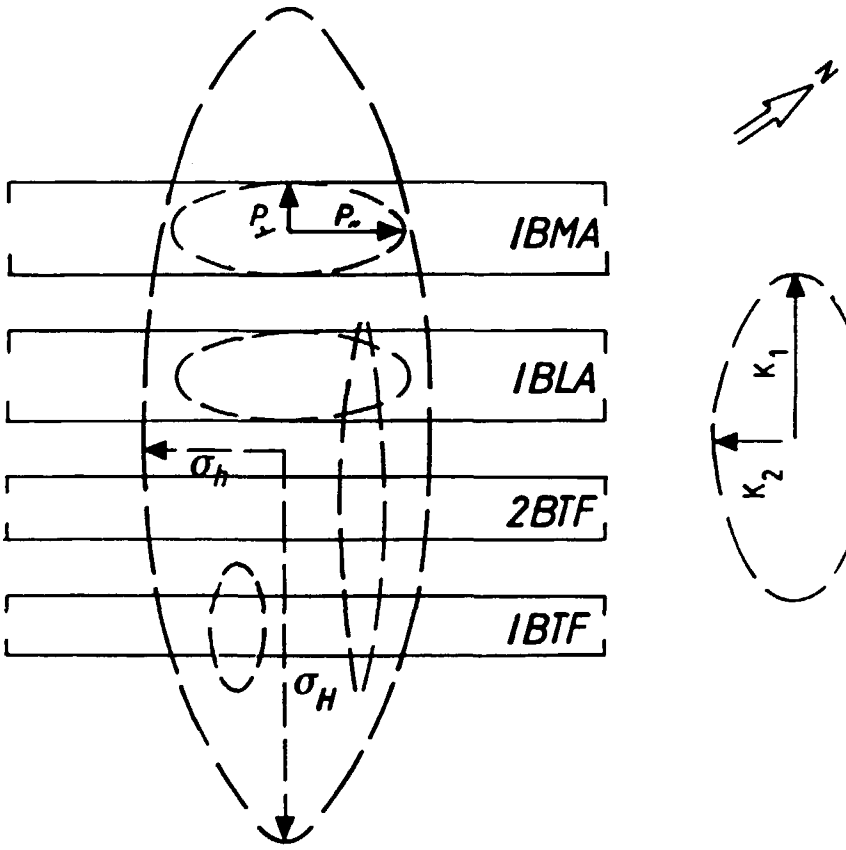


Figure 5.6 SFR Forsmark - Rock cavern area. Schematic of measured in situ pre-excavation principal stresses (σ_H,σ_h), assumed hydraulic pre-excavation hydraulic anisotropy (K_1/K_2) and anisotropy in conductive fracture probabilities ($P_{//}/P_{\perp}$).

5.6 Grimsel test site (GTS), NAGRA, Switzerland

The study of the integrated effects of excavation on the near-field conditions around an underground opening is an integral part of the NAGRA investigations. Apart from specific in-situ tests, also evaluation of existing underground structures, theoretical analysis and modelling has been considered (Lieb et al 1989).

Field studies of effects of excavation have been conducted at the Grimsel test site which is excavated in the granites and granodiorite of the Aar massif in central Switzerland. The Grimsel test facility is located in high strength rock at a depth of 450 m below ground surface. When excavating a tunnel by TBM, 30 m long and 3.5m in diameter, rock mechanical and hydraulic measurements were made before, during, and after excavation to assess the DRZ. The measurements were facilitated by 38 cored boreholes (ϕ 101 mm), parallel and orthogonal to the tunnel, amounting to nearly 600 m in length, cf. Figure 5.7.

The measured mechanical response to excavation included deformability and displacements using sliding micrometers and dilatometers, convergence of the tunnel periphery, P- and S-wave velocities, and changes in rock stresses. The results indicated reductions in P-wave velocities and deformation module on the order of 10-20% near the tunnel wall. However, no reduction in rock strength could be established, not even within a few decimeters of the tunnel wall (Egger 1986).

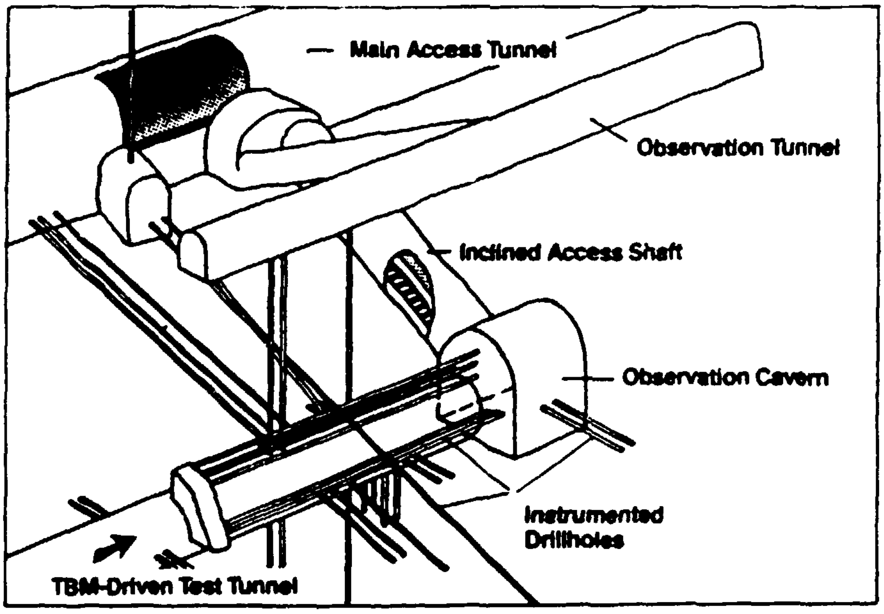


Figure 5.7 Layout of the NAGRA Grimsel test facility in Switzerland.

Single hole injection tests were performed to establish the permeability distribution around the tunnel. The matrix hydraulic conductivity had previously been established to be on the order of less than 10^{-11} m/s. The results of the injection tests indicated that substantial increase in permeability was associated with three steep schistose fracture zones intercepted by the tunnel. No significant increase in permeability could be established in structurally sound rock, not even in the immediate vicinity of the tunnel.

It was concluded that the observed changes in mechanical and hydraulic properties, to a large extent can be explained by elastic deformation and change in the hydraulic boundary conditions due to the tunnel, respectively.

In conclusion:

- No indications of formation of an annular tube of altered rock with increased permeability around the circular tunnel excavated by TBM.
- The investigations at GTS reflects a post-excavation stress situation which did not induce plastic deformation or fracturing of the surrounding rock. This was attributed to the relatively shallow overburden of 450 m and the high rock strength of the granodiorite.

5.7 CSM/OWTD test room, US DOE/CSM, U.S.A.

In order to facilitate an underground thermo-mechanical test facility, a room was excavated in the CSM experimental mine at Idaho Springs, CO. The room which is 30 m long, 3 m high and 5 m wide is positioned some 100 m below ground surface. The room was excavated with careful excavation techniques described by Holmberg (1983) and Perry (1984). The excavation provided an opportunity to test and develop techniques to characterize the nature and extent of the DRZ around the opening. No measurement of permeabilities were performed prior to excavation.

Following excavation, three boreholes were drilled along the room axis at different radial distances from the periphery. In addition six sets of seven 76 mm holes were drilled in a radial fan, cf. Figure 5.8. These holes were air permeability tested and the results were correlated with results from fracture mapping, logging and results of overcoring in-situ stress measurements (Montazer and Hustrulid 1983).

The geology of the rock is migmatized gneiss with a strong foliation striking N70E, dipping 70N. One fracture set with variably opened or closed, closely spaced fractures is developed along the foliation. Four other sets have been identified including one striking N60W, ie. almost parallel to the room, with vertical inclination.

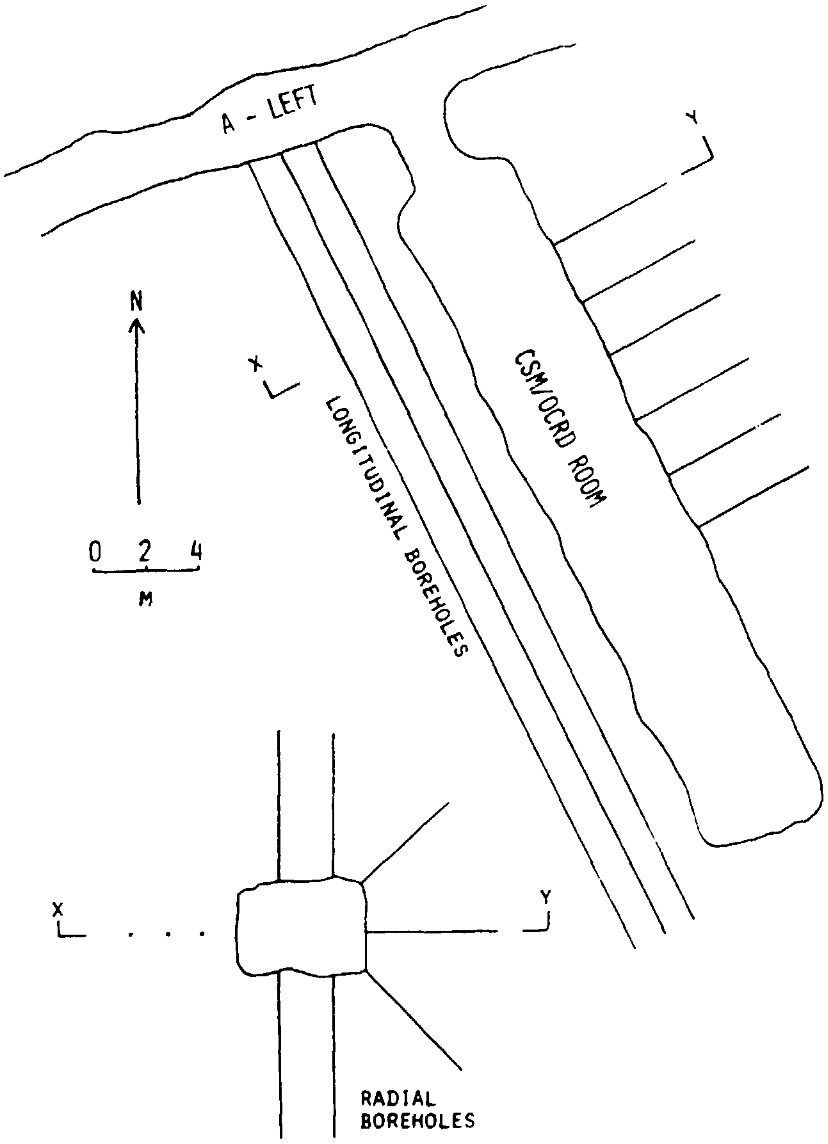


Figure 5.8 Layout of the CSM/OWTD test room, CO, U.S.A.

The results of the air permeability testing in the radial boreholes, though somewhat ambiguous, show a higher air permeability, and consequently a higher disturbance, within the first 0.5 m from the wall (Sour 1987). The results of ultrasonic cross-hole measurements show a zone, approximately 2.5m in from drift wall characterized by high rise times, low amplitudes and low velocities. This zone was considered as "incompetent" due to blasting. Measurements of bulk elastic modulus with CSM triaxial strain cells in radial holes showed a disturbance within an annulus of 0.6 m from the drift wall (Sour 1987).

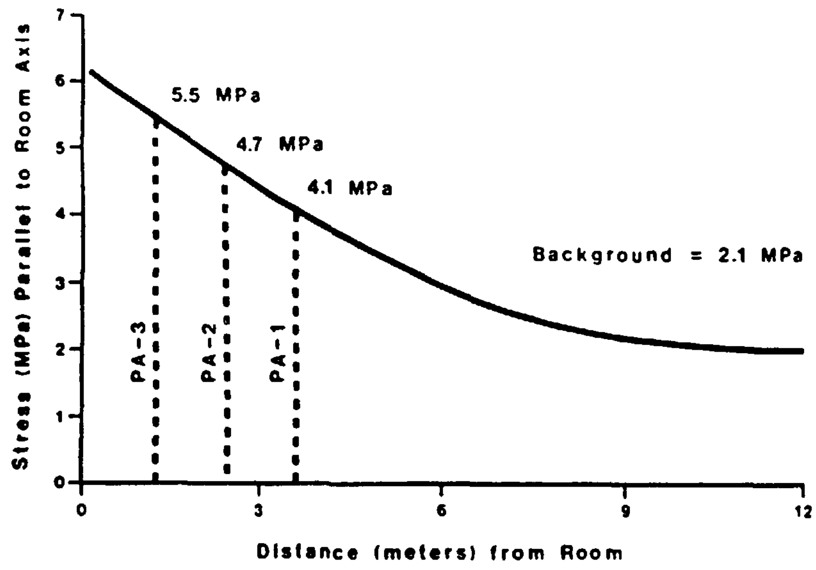


Figure 5.9 CSM/OWTD Room. Horizontal stress parallel to the axis of the room.

Fractures of the main set in the boreholes oriented along the axis of the room were identified and tested to assess the fracture permeability variation with radial distance from the periphery. Of five identified fractures, three showed a decrease in permeability towards the opening. In one case the decrease was approximately two orders of magnitude. In addition, the horizontal stress component acting on the fracture set was found to show a reverse trend, ie. increasing by almost a factor 3 close to the opening from the background 2 MPa some nine room radii away (Montazer and Hustrulid 1983), cf. Figure 5.9.

In conclusion:

- Increase in air permeability within 0.5m and decreased elastic modulus within 0.6m from the walls. Ultra-seismic indication of disturbance within 2.5m from the wall.
- In the metamorphic rocks around the opening a noticeable change in the directional permeability around the opening was noticed.
- The fracture permeability has decreased normal to the direction of the post-excavation maximum principal stress.
- The pre-excavation anisotropic permeability axes around the room have been completely changed in orientation and magnitude. The degree of change is assumed to exponentially increase towards the face of the opening.

- By taking pre-excavation stress and permeability anisotropy into account the shape and orientation of a planned opening can be made in such a manor that the permeability in the radial direction is minimized, thus increasing the effectiveness of the geological barrier.

5.8 Underground Research Laboratory (URL), AECL, Canada

At the AECL Underground Research Laboratory (URL) near Lac du Bonnet, Manitoba, preparations are presently made for an Mine-By Experiment (MBE) to be conducted at the 420 m level (Read and Martin 1990). The MBE is one of many large scale experiments planned to be conducted at URL to study aspects of disposal of nuclear waste at depth in stable granitic rock masses in the Canadian shield.

The objectives of the MBE are to 1) study the effect of excavation with regard to formation of a more permeable DRZ, and permeability changes in pre-existing fractures intercepting the excavation, and 2) help develop procedures for excavation response experiments at a disposal vault to be.

During the excavation of URL, excavation response have so far specifically been subject to investigation during; 1) excavation of the upper part of the access shaft, 2) excavation of the 240m level (Room 209 in particular), and 3) the shaft extension and shaft station at the 300 m level.

Access shaft

Within the upper 15m of the access shaft the excavation disturbance was measured with borehole dilatometer which provide the deformation modulus, which in turn reflect the redistributed in-situ stress levels around an opening (Koopmans and Hughes 1989). Low deformation moduli correspond to the spatial extent of the DRZ. The deformation module was found to increase with distance from the

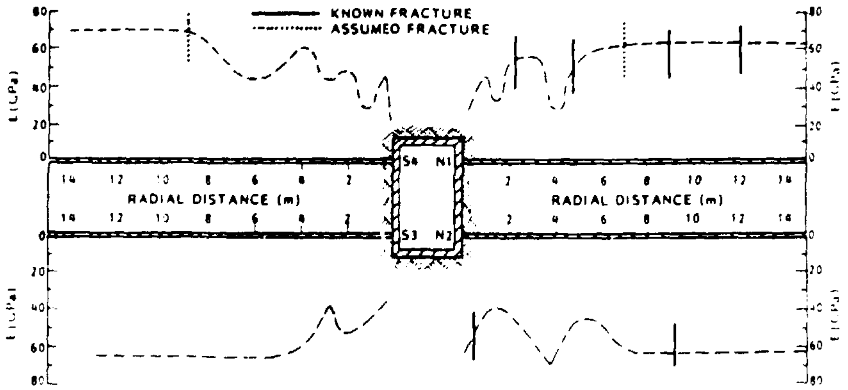


Figure 5.10 Deformation module inferred from dilatometer measurements around upper part of URL access shaft (Koopmans and Hughes 1989).

shaft wall to a constant value (55-65 GPa) at a distance corresponding to 1-2 shaft diameters. The noted high degree of damage was explained to be caused by lack of control and inspection during the initial phase of shaft sinking. The graphical representation of the measurement results, cf. Figure 5.10, show the intricate, complex pattern of stressed and destressed rock around the URL shaft.

The noted high degree of mechanical damage is not collaborated by results from the vacuum permeability method in six radial horizontal boreholes at 15 m depth (Jakubick et al 1989). The study did not detect any continuous zone of increased permeability, only sparsely spaced vertical permeable joints.

With regard to the upper part of the access shaft in general, where a rectangular crossection was used (3x5m), a zone of induced fracturation was detected extending approximately 1.5 m from the shaft wall (Everitt et al 1989).

Room 209

The rationale behind the Room 209 excavation response test is described in detail by Lang (1989). In essence it constituted a trial run to trim methodology and instrumentation to meet the demands of a subsequent large scale ERE. In addition, through its unique geometry, cf. Figure 5.11, including one hydraulically active fracture (or zone of fractures) it has had bearing on the coupled mechanical and hydraulic problem of excavation response in a fracture transecting a carefully excavated tunnel, plus the overall mechanical excavation response in the otherwise unfractured rock mass at the 240 m level.

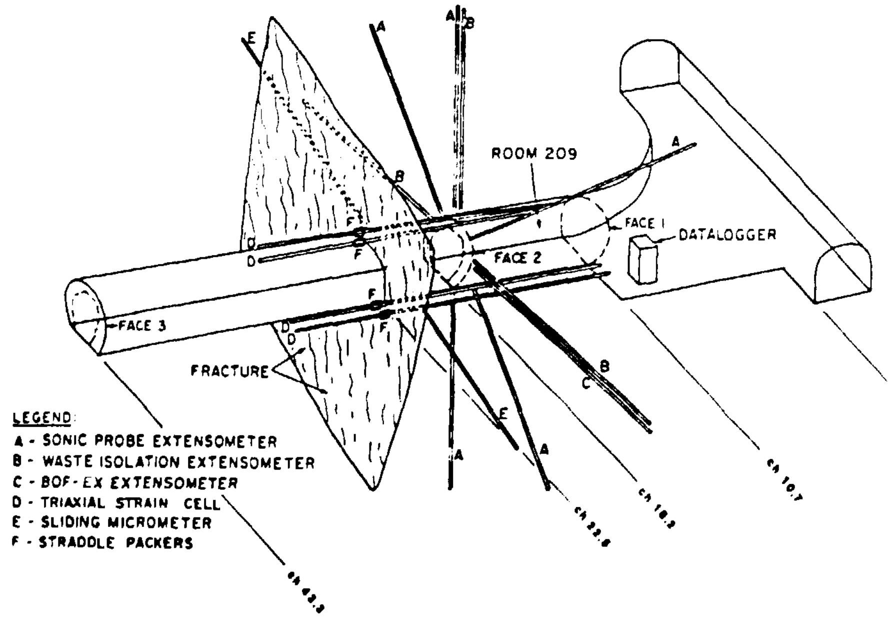


Figure 5.11 Geometry and instrument setup for the AECL Excavation response Test in Room 209 at the 240m level at URL.

The sequencing in the investigations and analysis has been as follows;

1) Pre-characterization, including the installation of an instrumented array close to the noted fracture. Measurement of in-situ response during a short initial excavation section.

2) Pre-excavation model predictions of mechanical and hydraulic responses during complete excavation, based on information collected during previous phase.

3) In-situ monitoring and collection of excavation response data when the tunnel was excavated through the instrumented fracture and rock mass.

4) Post-excavation comparison and analysis of predicted and in-situ measured responses.

5) Post-excavation characterization and additional testing in the rock mass and fracture.

In this section only points 1, 3 and 5 will be discussed and specifically addressing the experimental characterization of DRZ in the intact rock mass and the effect on the hydraulic properties of the fracture. The modelling of the test and comparison with field data is discussed in Section 6.2.

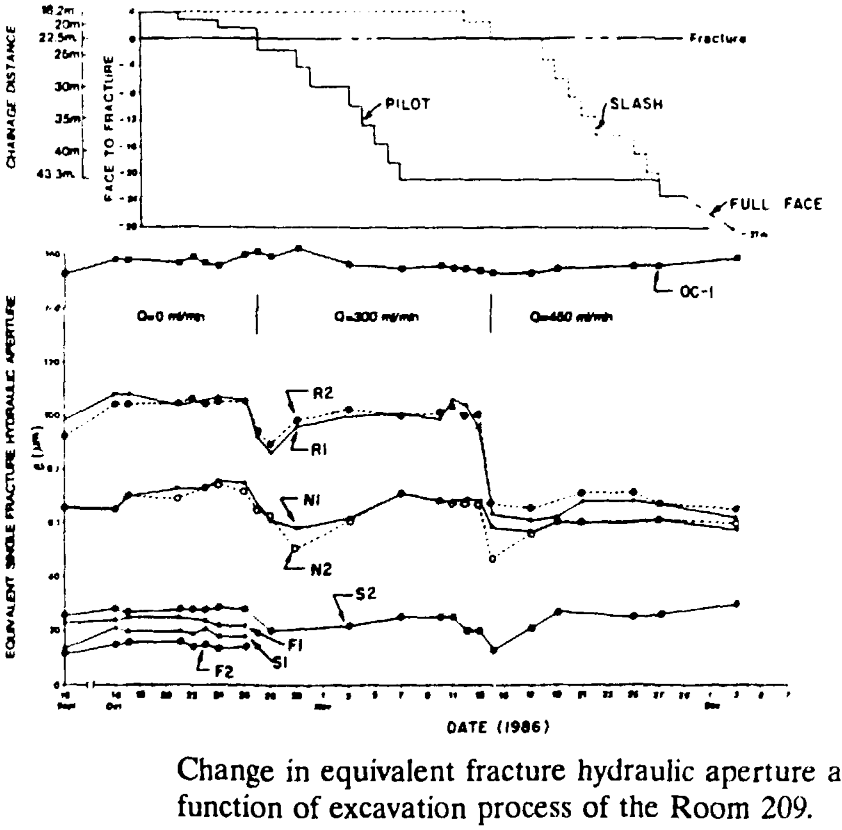


Figure 5.12 Change in equivalent fracture hydraulic aperture as a function of excavation process of the Room 209.

Based on extensometer measurements of displacements it was found that there is a decreasing elastic modulus towards the opening. This fact was attributed to the modulus dependence on confining pressure rather than excavation damage due to blasting, except for the 0.5m closest to the wall of the opening (Lang 1989).

The single fracture hydraulic apertures evaluated from single and multi-step drawdown tests in the nine boreholes circumferrent to the tunnel showed a decrease and a subsequent recovery in the boreholes in the roof and north wall, following excavation of the pilot tunnel through the fracture, cf. Figure 5.12. A far field hole some 13 m away (OC-1) showed no change in aperture. The pressure in the two holes in the floor was lost following pilot intercept. After slashing (excavation to an outer final contour), a similar trend in hydraulic aperture change was observed with exception of the roof piezometers which did not recover (Lang 1989).

The monitoring of hydraulic pressure in the packed off intervals of the fracture is discussed in Section 6.2.

The noted inflow of water to the eight boreholes intercepting the fracture varied between 0.05 and 3 l/min immediately following drilling. The sum of individual inflows from the eight boreholes did not exceed 10 l/min (Lang et al, in prep.).

The inflow of water was monitored from the blast holes, the fracture trace after excavating the pilot tunnel, and after the final slash round. The measured inflow from the blastholes was c. 1 l/min, whereas the inflows from the pilot and slash trace (partly estimated) were 350 ml/min and 450 ml/min, respectively. The latter figures collaborating the noted reduction in the hydraulic aperture of the fracture (Lang 1989).

The fact that the piezometers in the floor were damaged beyond repair indicated that the damage is the largest in the floor extending at least 1 m, depending on a higher charge density and energy used in the floor blast holes. The hydraulic conductivity of the floor has subsequently been measured by large scale constant head tests by pressurizing a part of the tunnel between constructed weirs, and measuring the resulting discharge in the floor. The reporting of this experiment is underway and indicate a hydraulic conductivity on the order of 10^{-6} m/s i the DRZ of the floor (Martin, pers. comm.).

In addition, excavation damage has been assessed using cross-hole radar between radial boreholes, radar surveys in the tunnels, dilatometer testing in boreholes parallel and radial to the tunnel and by comparing measured stress changes and displacements with those predicted by elastic theory. On the basis of these observations Lang (1989) conclude that the DRZ in the walls and crown of Room 209 is less than 0.5m thick. Visual inspection in radial boreholes indicate no apparent fractures beyond 0.2 m, suggesting a low permeability in the walls and crown.

Everitt and Read (1989) discusses the visible (mesoscopic) fractures found on all excavation surfaces. Their origin as induced fractures were sustained by;

- lack of natural infillings.
- symmetry with respect to geometry of opening.
- symmetry with regard to blasting centres.

Fractures mapped along circumpheral scanlines were found to align well with orientation of the axis of the tunnel.

The recorded estimates of extent of the DRZ were based on the difference in damage induced fractures per unit scanline length which was noted for the pilot and final surface mapping of the slash. The average fracture frequency of the pilot surface was 1.2 fractures/m whereas the value for the final surface was 1.8 fr/m. The apparent increase in damage in the latter case was attributed to sampling of a composite population consisting of fractures induced both during pilot and slash excavation.

With the knowledge of the average thickness of the slash (1 m) Everitt concluded that the damaged zone from the pilot extends 0.3-0.6 m from the periphery. A similar extent in damage around the slash is acknowledged, though not sustained.

Shaft extension, 300 m shaft station

The development of a shaft station at the 300 m level at URL, cf. Figure 5.13, provided a unique opportunity to examine the annulus around the circular shaft extension, approximately 5m in diameter. It was found that in a global sense the fractured annulus was concentric, centred on the shaft and extending approximately 0.3 m from the shaft wall.

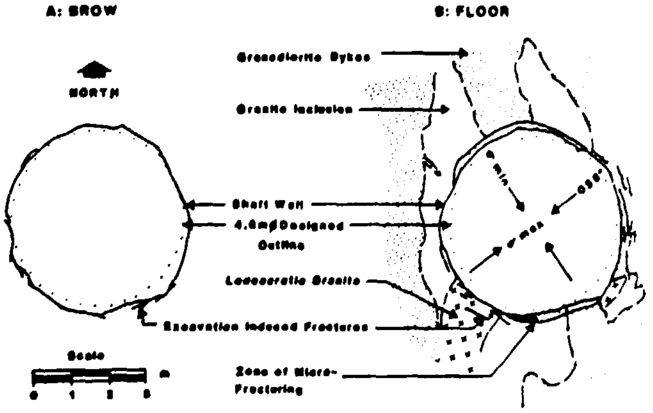


Figure 5.13 URL 300 m shaft station.

Martin (1989) discusses the extension of the shaft in a highly stressed rock with peak in-situ stress magnitudes higher than 100 MPa. He found that despite excellent quality control a significant DRZ will develop around a shaft excavated with full face drill and blast techniques. The DRZ can extend as far as 1 m out from the shaft wall and can propel shaft wall failure. The likely mode of failure is shear and extension.

In conclusion:

- In the upper part of the rectangular access shaft the DRZ extends up to 10m from the shaft wall. Air permeability measurements failed to sustain any zone around the shaft with increased permeability. Around the access shaft in general the DRZ extends some 1.5 m.

- Apparent reduction of permeability of Room 209 fracture following excavation. Monitored inflow of water from fracture trace in tunnel reduced with a factor 2 compared to inflow from blast holes.

- A DRZ in unfractured rock in Room 209 found to extend radially 0.5 m as inferred from available data.

- DRZ around shaft extension in high stress rock believed to create significant DRZ (<1m) even with controlled excavation. Possibly also followed by failure of the rock.

6. MODELLING OF THE DISTURBED ROCK ZONE

6.1 General

This chapter is devoted to description of modelling that in one way or the other take the DRZ into account. Emphasis is laid on the coupled hydraulic-mechanical problem and the purely hydraulic description. In addition, a distinction is made between different objectives of modelling. One can identify two main scopes with regard to modelling including the DRZ. The first addresses the DRZ from a phenomenological aspect with the aim to understand, develop and implement individual or superimposed (coupled) processes that contribute to the formation of the DRZ and its impact on the hydraulic behaviour of the system. This approach is of particular interest and importance when eg. validating set up conceptual hydrogeological models used in geosphere modelling of flow and transport.

The second type does not necessarily require a full understanding of the processes that played a role in the formation of the DRZ. Instead only relevant and representative characteristics in terms of geometry and material properties of the DRZ for the description of flow and transport are needed. These requirements are satisfactory to meet the demands set up from the repository performance and safety assessment aspect.

This chapter will primarily address the first of the mentioned aspects, and primarily the coupling between the mechanical and hydraulic response as reflected by the development of the hydraulic properties of the DRZ. It is not within the scope of the present report to provide a detailed description of the models in use, but rather examples of their application, results obtained, and limitations. The safety and performance assessment aspects will be elaborated upon in a subsequent chapter.

With regard to modelling of the coupled mechanical-hydraulic problem there are presently two conceptually different approaches available; continuum and discontinuum approaches. In the continuum approach the integrated properties of the matrix and fractures of the rock are regarded as a continuum where the material properties are assigned as effective values. Heterogeneities are described as variations in effective values of the material properties. Numerical techniques employed to analyze continuum problems include finite element, finite difference and boundary element methods.

When analyzing fractured (crystalline) rock, special elements may be included to facilitate analysis of discontinuities. Discontinuities may be incorporated as planar discrete-joint or ubiquitous-joint elements upon which normal stress may act, and within which a pore pressure may act.

In the discontinuum approach, the geometry and properties of included discontinuities are the most important features. Introduction of relevant material properties for the matrix and fractures provides the necessary input for the description of the redistributed stress situation around an opening, the associated displacements/block rotations and the subsequent changes in physical/hydraulic fracture aperture. The resulting mechanical situation may be used as input to solve the flow problem.

Hybrid model approaches using continuum description in the far field and discontinuum description in the near field around an opening have been suggested eg. by Fairhurst and Hart (1987).

Lindner (1989) provides a topical discussion of the integrated use of model analysis and the requirements to be met of that analysis in conjunction to an excavation response experiment. The various analysis elements foreseen are also discussed. These include:

- Scoping
- Design
- Code development and refinement
- Demonstration predictions
- Comparison and evaluation
- Back-calculation
- Guideline definition

Lindner (1989) also provides an overview of available analysis tools, cf. Appendix A.

6.2 Continuum modelling

This section focuses on the description of coupled mechanical-hydraulic, and the pure hydraulic description of problems in the vicinity of an underground opening. Though numerous examples exist of forward decoupled analysis, there are to the author's knowledge no reported examples of forward fully coupled prediction of a coupled field situation.

The mechanical and hydraulic modelling of the response of the sinking of the AECL/URL access shaft, cf. Section 5.8, were fully discoupled. The predictions of measured inflow to the shaft as a function of progress of excavation has indicated an overestimation of inflow with a factor three but showed a good trend with time (Chan 1987). Drawdowns of hydraulic head in the rock mass and fracture zones were predicted well. A DRZ was not included around the shaft in the modelling.

The Room 209 excavation response test, Section 5.8, involved three modelling groups using continuum models and one using discontinuum analysis (LBL) to predict the rock mass response to excavation. The details of the models used is provided in Appendix B. Two groups utilized uncoupled planar elements (AECL, UoA) in 3D to describe the hydraulic response in the fracture, and one used a fully coupled joint element (LLNL). A detailed account of the modellers prediction of the mechanical and hydraulic response is provided by Lang et al (1989).

The DRZ was not explicitly described in the 3D models, but AECL performed some preliminary mechanical calculations in 2D including the DRZ with a 50% reduced elastic module, cf. Figure 6.1. It was found that calculated total displacements at the excavation face were 30-55% higher than those obtained with the homogeneous, linear elastic model (Chan et al, in Lang et al 1989).

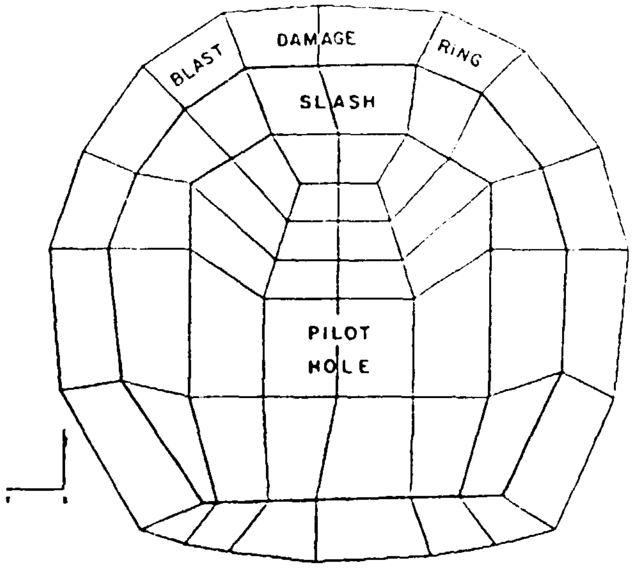


Figure 6.1 Element mesh used by AECL in preliminary 2D modelling of mechanical response including the DRZ.

The two groups using discoupled analysis employed empirical relations between normal stress change and fracture aperture change and the Barton-Bandis model (Barton and Bandis 1990), cf. Section 6.2, to account for shear-roughness induced aperture changes. Both groups predicted negligible changes in equivalent fracture aperture in the near vertical fracture. Thus, none of the groups succeeded in predicting the observed change reported in Section 5.8.

The AECL modelling group (Chan et al, in Lang et al 1989) predicted steady state inflows to the drift amounting to 2.1 and 3.6 l/min after pilot and slash, respectively. Thus an overprediction of a factor 6 and 8, respectively, when compared to the measured quantities, cf. Section 5.6.

The pressure drop in the near field boreholes was predicted to be around 80% (UoA) and 30-70% (AECL). These figures should be compared with the measured drop of 5-45%. The discrepancy was the least in the holes in the floor which are the most affected by excavation damage.

Winberg et al (1989) in a post-excavation analysis of the flow model showed that with more realistic far-field boundary conditions and with the introduction of a skin zone in the fracture close to the opening following the pilot, the resulting hydraulic head drops could be modelled within a factor 4 compared to the measured. The resulting inflow compared remarkably well with the measured in terms of amounts, though not in distribution over the fracture trace.

Development is presently underway at AECL/WNRE to fully couple a planar joint element in their three-dimensional finite-element code MOTIF (Martin, pers. comm.).

As in the case with the LBL Macro-Permeability Test at Stripa, pressure profiles in radial boreholes extending from the access tunnels to the SFR facility off Forsmark indicated the presence of a skin zone circumferrent to the tunnels (Carlsson et al 1986a). Hydraulic modelling in a 2D section perpendicular to the tunnel required a skin zone (arbitrarily attributed a 2m thickness) with a hydraulic conductivity 10 to 100 times lower than the average hydraulic conductivity of approximately 10^{-8} m/s to match the calculated and measured pressure profiles.

6.3 Discontinuum modelling

Discontinuum description of fractured rock has benefitted from the rapid evolution of computing capability. This because of the large amount of memory required to facilitate either a deterministic or stochastic representation of a block of rock with the associated large number of discontinuities.

Discontinuum modelling may be fully hydraulic, not taking the mechanical aspect into account (eg. Long et al 1983, Gale and Rouleau 1986, Andersson and Dverstorp 1987, Dershowitz 1985) or take into account the effective stress normal to existing fractures without allowing block rotations (Herbert et al 1989, Geier et al 1989, Long et al 1989). The latter references pertains to model predictions of inflow to pilot holes for the SCV drift at Stripa. Presently, model calculations of groundwater inflow to the fully excavated SCV drift are being compared to measured quantities. Available results so far indicate an overprediction by the models.

A further development of discontinuum modelling are the more block oriented Discontinuous Deformation Analysis (DDA) Shi (1988) and the Universal Distinct Element Code (UDEC) introduced by Cundall (1980).

DDA was inaugurated in forward analysis in conjunction with predictions of the mechanical response of the Room 209 excavation response test. The model has a fully coupled joint element, however not used in the analysis of Room 209 (Lang et al 1989).

The UDEC code has undergone continuous development since its appearance in the early eighties, this applies both to dimensionality extension to 3D (3DEC) and constitutive models, where at present eg. the Barton-Bandis joint logic (Barton and Bandis 1990) is incorporated in 2D (UDEC-BB).

The general features of UDEC making it especially suited for discontinuum modelling are;

- simulation of the medium as constituted of an assemblage of blocks which interact through corner and edge contact.

- discontinuities are regarded as boundary interactions between these blocks. Discontinuity behaviour is prescribed for these interactions.

- An explicit time-stepping algorithm is used which allows for large displacements and rotations, and general non-linear constitutive behaviour for both the matrix and the discontinuities.

Among the specific features of UDEC-BB (Monsen et al 1991) which makes it specifically applicable to modelling of the disturbed zone are;

- non-linear, non-elastic joint behaviour
- complex joint structures
- fluid flow in fractures

The particular key input parameters required by UDEC-BB are:

- JRC = joint roughness coefficient
- JCS = joint wall strength
- ϕ_r = residual friction angle

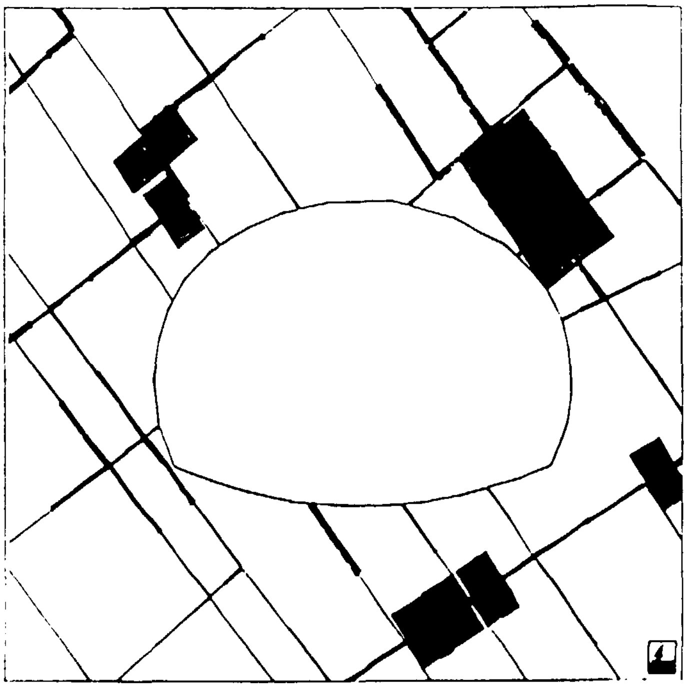
The above listed joint deformation parameters are defined and discussed by Barton and Bandis (1990).

The coupling between the deformation of discontinuities, ie. changes in physical aperture, and changes in joint hydraulic aperture is obtained through an empirical relationship between physical aperture (E) and hydraulic aperture (e) given by:

$$e = JRC_0^{2.5}/(E/e)^2$$

and where $e \leq E$ and $e << E$ at high stress. Thus any change in physical aperture can be coupled to a change in hydraulic aperture, or the reversed. A fracture hydraulic conductivity is provided by:

$$K_j = e^2/12$$



Distribution of conducting apertures around left hand tunnel. One line = 10 µm. Maximum aperture = 1,6 mm.

Figure 6.2 Hydraulic aperture change around twin freeway tunnels in fractured rock near Oslo (Barton and Makurat 1988).

UDEC-BB analysis of disturbed zones around planned twin freeway tunnels in jointed rock near Oslo, Norway has shown that significant zones of joint shear and joint aperture increase can occur (Barton and Makurat 1989), cf. Figure 6.2.

In a recent analysis of reinforcement requirements and stability of a planned 60m span underground icehockey arena near Lillehammer, Norway, it was found that shearing may be significant in the roof of the opening (Barton et al, in press. Figure 6.3 show the successive development of the principal stress field and joint shearing magnitudes assuming $\sigma_h/\sigma_v = 2$ and an overburden of 25 m. It was found that increased hydraulic apertures generally occur along the axis of the arena. The mechanism for increased permeability was identified as block displacement effects at a large number of joint intersections. Small rectangular channels develop at these locations with maximum apertures ranging from 1.2-1.9 mm. These numbers should be compared to an initial mean aperture of c. 24µm. In terms of fracture permeability this implies an increase between three and four orders of magnitude.

Earlier analysis of joint shear around TBM tunnels show that significant shear and hydraulic aperture increase can occur also around circular tunnels in an isotropic stress field. Barton and Makurat (1989) also conclude that the detrimental effects of joint shear on fracture permeability may be reduced if 1) the block size of the rock mass is large, 2) if the associated rock joints have rough

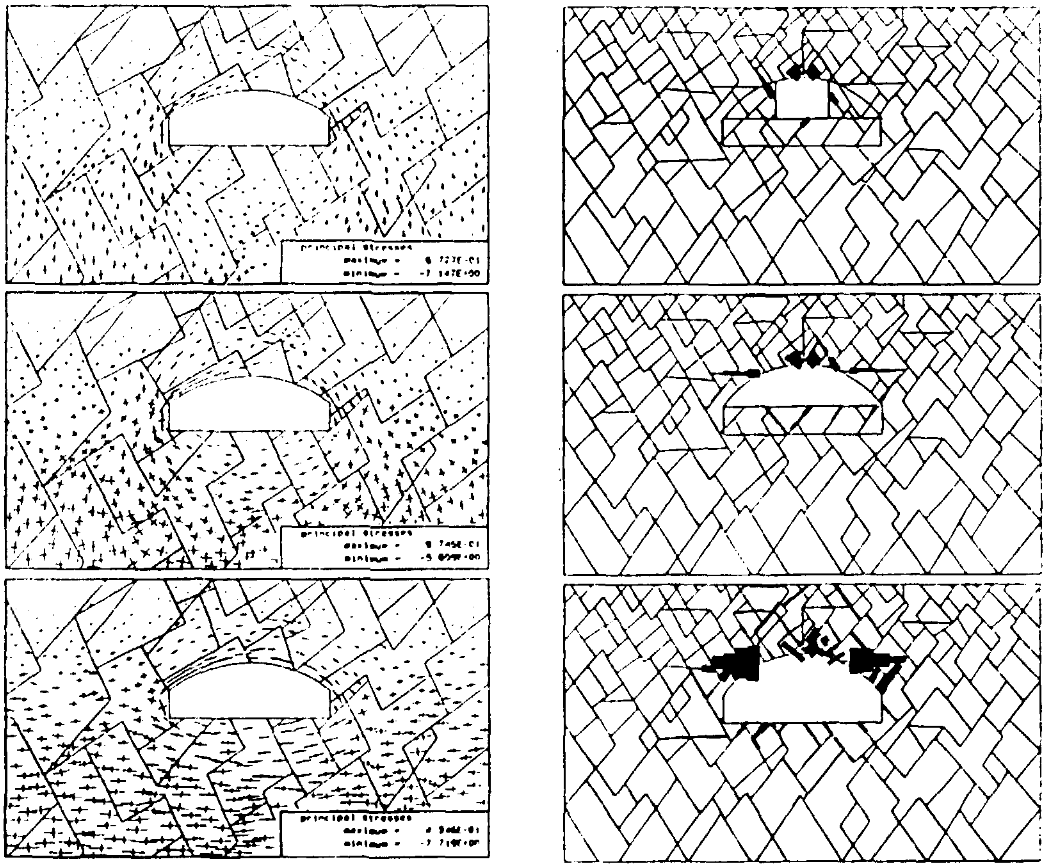


Figure 6.3 Development of principal stress field as a function of excavation for a 60m span underground icehockey rink near Lillehammer (Barton et al, in press).

surfaces. The latter because rough fractures will show the highest resistance to shear when the rock is excavated.

The UDEC-BB code was also used to analyze 2D sections through stochastic 8x8x8m cubes generated by Herbert et al (in press) to characterize the rock mass penetrated by the SCV drift at Stripa. The realizations were loaded with boundary stresses of 10 MPa vertically and 14-18 MPa horizontally. Both length dependent and independent values of input fracture characteristics were used. It was observed that the frequency of aperture changes (+ and -) in the first 0.5 m from the SCV drift is 12 per metre. The persistent (most smooth) fractures had pre-excavation apertures of 1 to 25 µm. Developed channels at joint intersections showed local apertures of 150 to 350 µm, thus indicating increases in fracture permeability parallel to the drift of two to four orders of magnitude. Compared with a performed continuum calculation it was found that peak tangential stresses as obtained from UDEC-BB, 54-74 MPa, were approximately a factor 1.2-1.7 higher.

When assessing the permeability changes in 2D calculated with UDEC one should consider one critical assumption which has strong bearing on the results, namely the assumption of infinite fracture lengths. The axial connectivity is therefore likely to be overestimated and likewise the change in axial hydraulic conductivity.

7. DRZ IN SAFETY ASSESSMENT - AN OVERVIEW

7.1 General

This chapter describes how the disturbed rock zone (DRZ) has been conceptualized and incorporated in the safety and performance assessment and supporting modelling of repositories for high level radionuclide waste. The overview is international with emphasis on the Finnish, Canadian, Swiss, and Swedish national programs which all consider emplacement in deep-seated crystalline bedrock.

This chapter is purely descriptive in terms of concepts, approaches and results. The subsequent chapter will discuss the overall implications and conclusions that may be drawn on the basis of the presented information.

7.2 TVO, Finland

In Finland, Teollisuuden Voima Oy (TVO) is investigating the feasibility of disposal of nuclear waste at depths ranging from 300 to 800 m. A concept and safety and performance assessment study was presented in 1985 (TVO-85), and presently a new more specific study is underway (TVO-92), planned to be finalized in 1992 (Äikäs, pers. comm.).

Some of the aspects being studied in detail in supporting studies is the thermo-mechanical effects on the hydraulics of the near-field (Johansson et al, in press), and the effects of repository tunnel geometry in relation to different groundwater flow directions (Hautojärvi 1990). Both these studies describe, or take the effects of the DRZ into account.

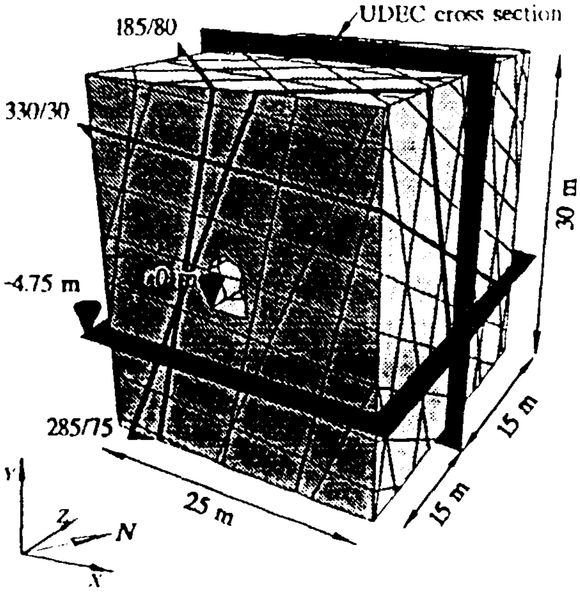


Figure 7.1 Fractured 3D rock block with modelled fracture sets and 2D model sections (Johansson et al, in press)

The study by Johansson et al (in press) provides an analysis and comparison of calculated 2D and 3D thermo-mechanical, and associated hydraulic response around disposal tunnels and canister holes. The analysis performed with 3DEC and UDEC assumes deformable blocks and joints and linear joint normal stiffness. Principal horizontal stresses of 50 and 25 MPa and a vertical stress of 12 MPa were assigned to the model. Backfill swelling pressures were set to 10 MPa (canister holes) and 150 kPa (tunnels). On the basis of available hydraulic injection tests, an average initial hydraulic aperture of 10μm was assigned to the three included joint sets, cf. Figure 7.1. The heat produced by an individual canister was set to 1250 W.

Immediately following excavation of the tunnel and canister holes it was found that the average hydraulic conductivities (obtained by the cubic law) were up to four times higher near the canister holes and 10-40% elsewhere, cf. Figure 7.2a. After 60 years, corresponding to a maximum thermally-induced stress increase, stresses were found to be 20-25 MPa higher. The hydraulic conductivities were found to be 1 to 4% of initial values, cf. Figure 7.2b. After 900 years, corresponding to sufficient cooling to return the stresses and displacements to excavation state, it was found the hydraulic conductivities in the near field were 10-50% of initial in-situ values, cf. Figure 7.2c.

It was concluded that a maximum increase of hydraulic conductivity following excavation is noted within the closest 0.3 m from the canister hole and tunnel. Even though the analysis is made assuming linear joint normal stiffness, its is assumed that the general conclusions would also apply if a non-linear relation is used. The numerical values of the aperture changes would however be different.

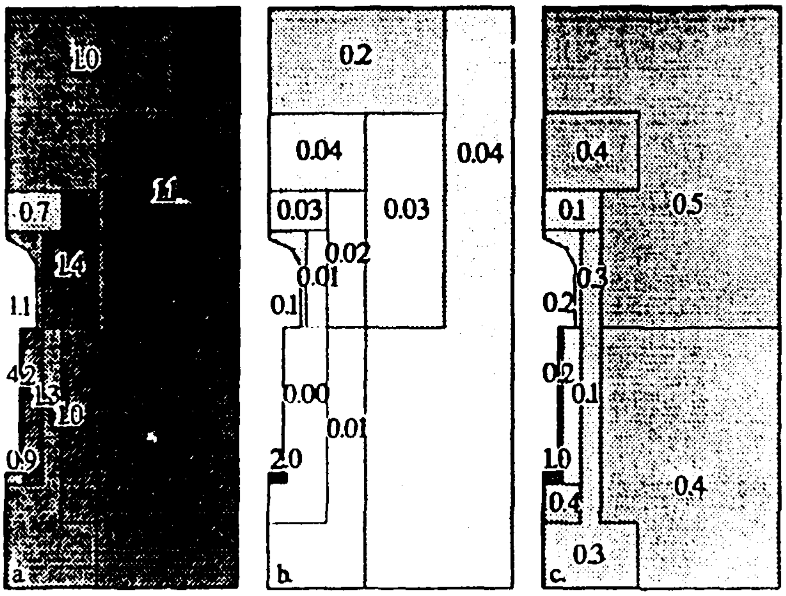
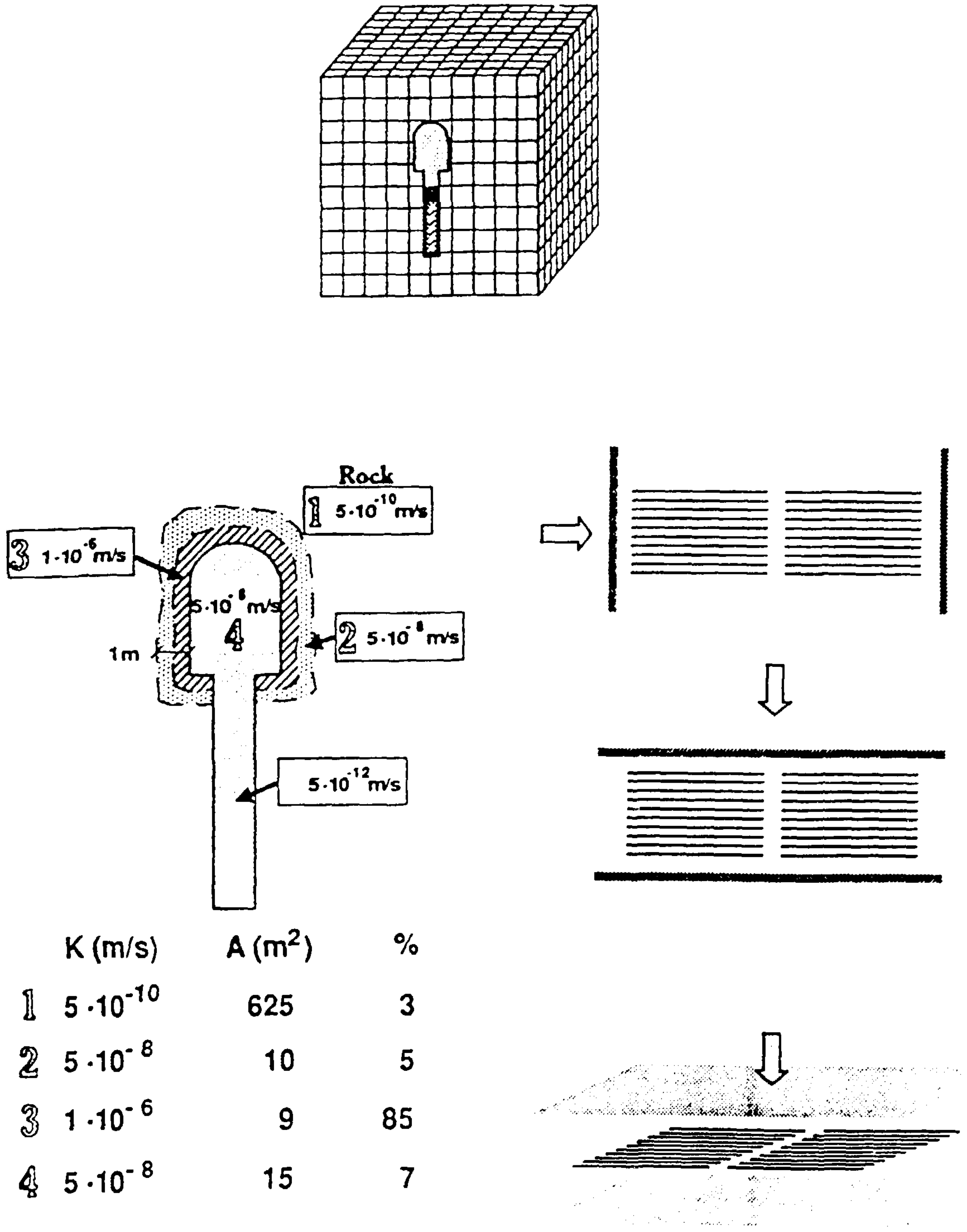


Figure 7.2 Average hydraulic conductivity changes at secondary state (a) at 60 years (b), and at 900 years (c) based on three-dimensional analysis (Johansson et al, in press).

Hautojärvi analyzed mass fluxes associated with tunnels of a repository sited in a in a bedrock with a simplified cubic fracture pattern with a 2m spacing, cf. Figure 7.3a. Around the tunnels, a DRZ of 1m was assumed as a result of excavation and stress redistribution. The material property distribution assigned to the near-field of the concept is illustrated in Figure 7.3b. Figure 7.3c illustrates the different flow conditions coupled to the repository that have been studied.

With a simple 1D estimate it was found that in the case of flow parallel to the tunnel, the DRZ carries close to 90% of the total flow through the tunnel area. When a horizontal flow situation, perpendicular to the tunnel axes, is considered, the impact of the disturbed zone is small because of the intact rock between the tunnels, thus intact rock is regulating the flow. Also in the case with vertical flow the impact of the disturbed zone is small for the same reasons. When studying total mass fluxes from the repository to the far-field, however, there was no significant difference between the three cases.



	K (m/s)	A (m²)	%
1	$5 \cdot 10^{-10}$	625	3
2	$5 \cdot 10^{-8}$	10	5
3	$1 \cdot 10^{-6}$	9	85
4	$5 \cdot 10^{-8}$	15	7

Figure 7.3 a) Simplified fracture system used in analytical calculations. b) Material property distribution used in calculations. c) Groundwater flow conditions in relation to repository considered (Hautojärvi 1990).

7.3 AECL, Canada

The Canadian Nuclear Fuel Waste Management Program uses the SYVAC code based on the systems variability analysis methodology in its safety and performance assessment program (Rosinger and Hancox 1988). The SYVAC code is the key element in the analysis and is modular in construction and contains submodels for description of the physical and chemical processes in the vault, geosphere and biosphere. There is an ongoing activity of improvement of old, and development of new alternative submodels. Among latter, a description of the coupling processes between the vault and the geosphere, where the DRZ may be included.

The SYVAC simplified geosphere (flow and transport) model is built on the assembled output from the three-dimensional MOTIF code (Chan 1987). The geometry of the submodel network is determined by interpretation of output from the MOTIF finite element model calculations. SYVAC uses a Monte-Carlo simulation approach to accommodate uncertainty and variability in the system. Thus, also distribution functions for input parameters to the geosphere model must be provided. This is accomplished by using subroutines of the MOTIF code, solving for 1D elements in 3D space using sampled distributions of hydraulic parameters within the submodel.

Chan and Stanchell (1990a) in a supporting 3D sensitivity analysis based on the Whiteshell Research Area conceptual model, analyzed the effect on repository performance of a 3m DRZ around the openings of a repository at 500m depth. The hydraulic conductivity of the reference rock mass and reference back-fill were 10^{-13} and 10^{-11} m/s, respectively. The hydraulic conductivity of the DRZ was assigned a factor 10, 10^2, and 10^5 higher hydraulic conductivity than the reference rock mass.

On the basis of the distributions of transport times of conservative particles from the repository area it was found that the presence of a DRZ around the openings of the repository has no harmful effect. In fact the shortest travel times increase somewhat compared to cases with no DRZ included. The observed effects were attributed to 1) hydraulic cage effects and 2) the fact that the axes of repository tunnels are oblique to the prevailing hydraulic gradient.

It was concluded that given the premises of the conceptual model, moderate enhancement of the permeability caused by excavation does not necessarily compromise the waste isolation performance of a geological repository.

However, when a water well is drilled above the repository short-circuiting the repository with a subhorizontal fracture zone situated above, the travel times are reduced though the amount of mass transported is small (Chan and Stanchell 1990b).

7.4 NAGRA, Switzerland

The Swiss national program in 1985 presented its equivalent to the Swedish KBS-3, called "Projekt Gewähr 1985". In this safety and performance assessment analysis it was shown how a safe repository system for HLW may be constructed with modern techniques.

The integrated experience from field tests performed at the in situ test facility at Grimsel (Egger 1986, Lieb et al 1989) and additional analysis (Gysel 1985) have formed the basis for conceptualization of the role of the DRZ in repository performance.

The conceptualization of the DRZ in the Projekt Gewähr 1985 assumes an increase in tangential, and decrease in radial stress around a storage tunnel following excavation (NAGRA 1985). Thus, an increased axial hydraulic conductivity in the decompressed zone would follow. Together with the highly permeable kakirite zones, localised increases in groundwater flow were envisaged.

In the DRZ the hydraulic conductivity was assumed to increase with a factor of 3 to two orders of magnitude of the average bedrock hydraulic conductivity ($K=10^{-11}$ m/s) within the first 4 m from the tunnel wall.

It has also been shown that the presence of a DRZ with increased permeability around tunnels has a strong impact on the flow conditions in and around a repository (Lieb et al 1989). The DRZ may have a positive effect in terms of release rates and barrier integrity by forming a hydraulic cage around the repository, diverting the flow around the repository, rather than through it.

It is also shown in the hydraulic modelling of the LLW/ILW site Wellenberg that the DRZ may be used to act as a drain upstream from a repository, thus lowering the hydraulic potential, and the hydraulic gradient and flux through the repository (Lieb et al 1989).

Presently, the data collected on the DRZ are revisited by NAGRA.

7.5 SKB, Sweden

The Swedish national program operated by SKB have produced three concept and safety assessment studies for high level waste (KBS 1-3) and two regarding L/ILW (ALMA and SFR) during the past two decades.

In the case of the high level waste studies, the analysis of the effects of the DRZ has been more of a conceptual one, without incorporating the DRZ explicitly into the actual performance assessment (Papp, pers. comm.).

The code PROPER (SKB 1989) is a key element in the presently ongoing Swedish performance assessment and safety analysis, the SKB 91. As is the case with the Canadian code SYVAC, the Swedish code is highly modular and incorporate process models of varying complexity. The far-field hydrogeological model included is the HYDRASTAR program package which includes capability of three-dimensional conditional stochastic flow modelling where the DRZ can be explicitly represented (Norman, in prep). In HYDRASTAR which includes a finite difference solver of the flow equation, area averaging of material properties is used to assign effective material properties to the nodes associated with the DRZ (Norman, in prep).

In previous analysis of the repository for reactor waste (SFR), the DRZ was explicitly incorporated as a 4 m thick skin zone with hydraulic conductivity 2 times less than that of the average rock mass in the three-dimensional rock cavern model, cf. Figure 7.4, and in the three-dimensional component model of the silo area (Carlsson et al 1986b). In the case of the rock cavern model the calculated inflow, 170 l/min compared well with the measured 150 l/min. A comparison between measured and calculated head, corresponding to piezometer intervals, showed indications of too high calculated head, indicating a too low, though acceptable, skin permeability in the DRZ.

The component analysis of the silo area, however, showed too low calculated head. It was concluded that the contrast in skin hydraulic conductivity should be one order of magnitude rather than a factor of two.

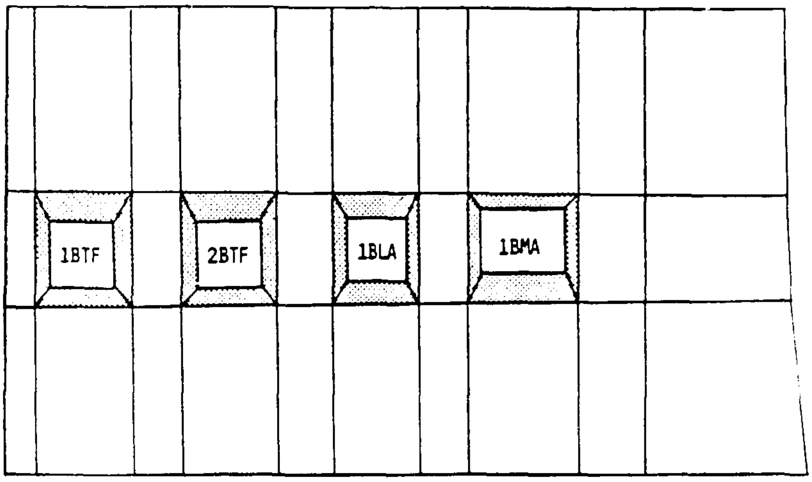


Figure 7.4 Element distribution in a vertical section through the rock cavern area in SFR, cf. Figure 5.3. The shaded elements represent the DRZ around the openings (Carlsson et al 1986b)

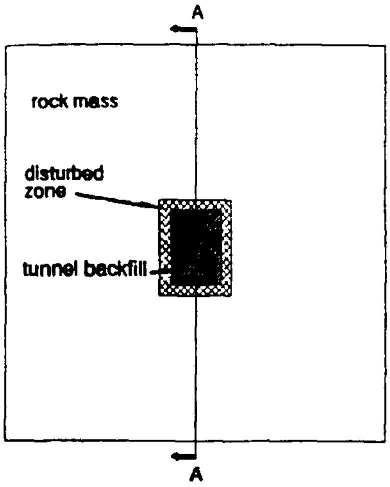


Figure 7.5 Vertical section through the local model (30x30m) with DRZ around storage tunnel (Bengtsson et al 1991)

A recent supporting analytical and numerical study to SKB 91 on the effects the DRZ on repository performance, discusses the influence of an anomalous body of increased permeability in an otherwise uniform media (Bengtsson et al 1991). The converging ability of an ellipsoid body on flow parallel to the body is by analytical analysis shown to be significant and dependent on the contrast in hydraulic conductivity, and the shape of the ellipsoid. In the case when the contrast is a factor 100 and b/a = 0.02, the increase in flow through the ellipsoid is approximately proportional to the contrast in permeability.

The effect of the orientation of the exterior hydraulic gradient on the increase in flow in the ellipsoid was calculated for a body of the same dimension as a conceived repository tunnel, ie. a length of 500 m and a diameter of 10 m (b/a=0.02). It was found that the increase in flow was relatively insensitive to the orientation of exterior gradient for low contrasts in permeability.

A composite repository with multiple tunnels at 25 m interdistance was not addressed explicitly, but it was stated that for flow perpendicular to the axes o tunnels the flow conditions would dissipate to undisturbed between the tunnels. In the case of flow parallel to the tunnels the influence area is larger, resulting in a lower net flow increase for an individual tunnel in a group, than for one single individual tunnel.

Numerical FEM calculations were also conducted to illustrate the effect of the DRZ on a the potential distribution near a repository and an individual storage tunnel at a depth of 500m. A skin zone 1 m thick was included around the tunnel in the local model, cf. Figure 7.5. The sensitivity to the following parameters were addressed;

- different orientations of the hydraulic gradient.
- presence and short-circuiting of DRZ by a set of vertical fracture zones.
- presence of a horizontal fracture zone.
- variations in contrast between the K of DRZ and the rock mass.

The contrast in hydraulic conductivity between the DRZ and the rock mass was allowed to vary between 2 and 4 orders of magnitude.

It was found that the effect on flow at a depth corresponding to the canister positions was limited, within a factor two, when comparing the different cases.

It was shown that the nuclide transport through the DRZ is more rapid than through the intact in situ rock for flow parallel to the tunnels. In the DRZ a frequency of conductive fractures of 3 fractures/m was assigned compared to 0.2 fractures/m in the rock mass. Due to the retention in the DRZ the difference in travel time is less than that solely attributed to difference in velocity (Bengtsson et al 1991).

7.6 SKI, Sweden

Within the scope of the Swedish Nuclear Power Inspectorate's SKI Project 90, a number of supporting studies have been conducted which have addressed coupled phenomena in the near-field of a repository.

Apart from the study by Rutqvist et al (1991) (cf. Section 4.5), Baotang Shen and Stephansson (1990a) analyzed the thermo-mechanical response in the vicinity of a repository due to thermal loading. It was found that for a dual layer repository the thermal loading results in a maximum stress increase of 12 MPa with an associated maximum principal stress rotation of 30°. Thermal expansion leads to closure of fractures in the vicinity of the repository.

In a subsequent more detailed study, Baotang Shen and Stephansson (1990b) analyzed the superimposed effects of excavation, thermal loading and swelling pressure of the backfill on the near-field mechanical situation around caverns and deposition holes. It was found that thermal loading for 200 years and a swelling pressure in the deposition holes of 30 MPa, results in high stresses. Tensile stresses in the wall of the tunnel exceed the strength of the granitic rock modelled. Near perpendicular fractures to the deposition holes exhibit closure.

Project 90 does not incorporate an explicit representation of the DRZ in the actual performance assessment analysis. This since the developed DRZ was not considered a critical element in the analysis. SKI, however, acknowledges the site-specific geological and design importance of the DRZ in the particular case (Johan Andersson, pers. comm.)

8. PERFORMANCE ASSESSMENT IMPLICATIONS

8.1 General

In repository safety and performance assessment studies, the genetical processes behind the creation of the DRZ need not necessarily be explicitly known. Instead only the geometry and integral material property characteristics of the zone governing the groundwater flow and transport of radionuclides are required.

Notwithstanding the fact that the individual processes need not be explicitly incorporated in a performance assessment model, their known integrated effect given the prevailing geological, thermo-mechanical and chemical and hydraulic conditions must be given proper attention.

In the following sections the geometry, hydrogeological, radionuclide transport, chemical and sealing aspects of the DRZ in repository performance assessment are compiled and discussed. A suggested conceptual model of geometry and material property distribution is also presented. The sensitivity in the calculated results, eg. radionuclide transport time, to the geometry and material properties should be further addressed.

8.2 Geometry

Definite criteria for the definition of the geometrical extent of the DRZ have not been stated. This applies to criteria for indirect as well as direct assessments. The reported extent of damage may thus appear arbitrary. However, the mere fact that the reported extent of the DRZ are fairly equal irrespective of origin and geological conditions indicate that inferences are possible.

On the basis of the available field data, and to some extent modelling results, it can be stated that a firm basis and understanding exist with regard to the geometrical extent of the DRZ in crystalline rock, as formed by the integral effects of excavation damage and stress redistribution.

With very careful drill and blast techniques a DRZ circumferrent to the excavated opening will develop mainly affected by the excavation process itself. The radial extent of this zone (Primary DRZ) will vary between 0.1-1 m depending on the site-specific conditions and the drill and blast technique employed. The higher the in-situ stress field, the lower the strength of the rock and the higher the amount and focus of explosive energy, the larger the radius of excavation induced damage.

Depending on the layout and charging of the blast salvos and the orientation and properties of existing fracture sets, the extent of damage due to excavation will vary around the opening. Specifically, experience from the Canadian URL indicate that the more dense charges used in the floor may give rise to a 50% increase in the extent of the DRZ in the floor.

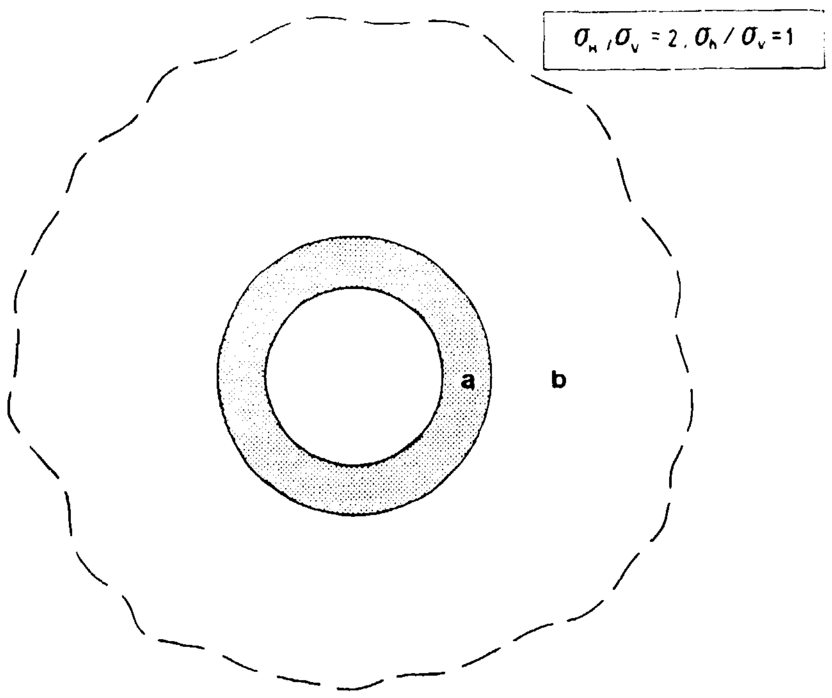


Figure 8.1 Conceptual model of the geometry of the DRZ around a circular storage tunnel (ϕ =3.5m) in a moderate biaxial stress field. a) Primary DRZ (excavation damage +stress redistribution), b) Secondary DRZ (stress redistribution).

It is assumed that a DRZ of similar extent will develop around a TBM tunnel, although with lower magnitude of integrated damage, and consequently affected much less hydraulically.

Beyond the Primary DRZ which is directly affected by blast damage, approximately 1 m, a zone mainly featured by stress redistribution will extend approximately 1-3 tunnel diameters (Secondary DRZ). The impact of stress redistribution is assumed to decrease (near) exponentially in the radial direction from the surface of the opening.

The superimposed impact of a thermal loading from the waste is less well investigated, both by in-situ experiments and analysis. There are indications that the radius of the DRZ would increase by 20% (Golder Associates 1977).

On the basis of available data a suggested geometrical representation of the DRZ has been outlined, cf. Figure 8.1. Around the 3.5m diameter tunnel the conceptual model includes an inner concentric zone (Primary DRZ) affected by excavation and stress redistribution extending 1 m from the excavation wall, and an outer (Secondary DRZ), extending up to 3 tunnel diameters representing a zone affected by stress redistribution alone.

8.3 Hydrogeology

The travel time of radionuclides in the vicinity of, and from the repository and the rate of canister corrosion will be affected by the hydrogeological situation close to the repository.

The groundwater velocity distribution in the vicinity of the resaturated backfilled repository is governed by the hydraulic conductivity distribution, the prevailing magnitude of the hydraulic gradient, and the relative orientation of the hydraulic gradient to the orientation of the storage tunnels of the repository.

The superimposed processes of excavation, stress redistribution and thermal loading from the waste will cause changes in the hydraulic conductivity in the disturbed zone. New fractures will be formed primarily by the excavation process. Stress redistribution of mechanical and thermal origin will induce changes in the effective normal stress perpendicular to existing fractures and lateral displacement along fracture planes (shear), causing changes in aperture. The magnitude of shear displacement and the associated aperture change is dependent on the amplitude and period in fracture surface roughness and the strength of the fracture.

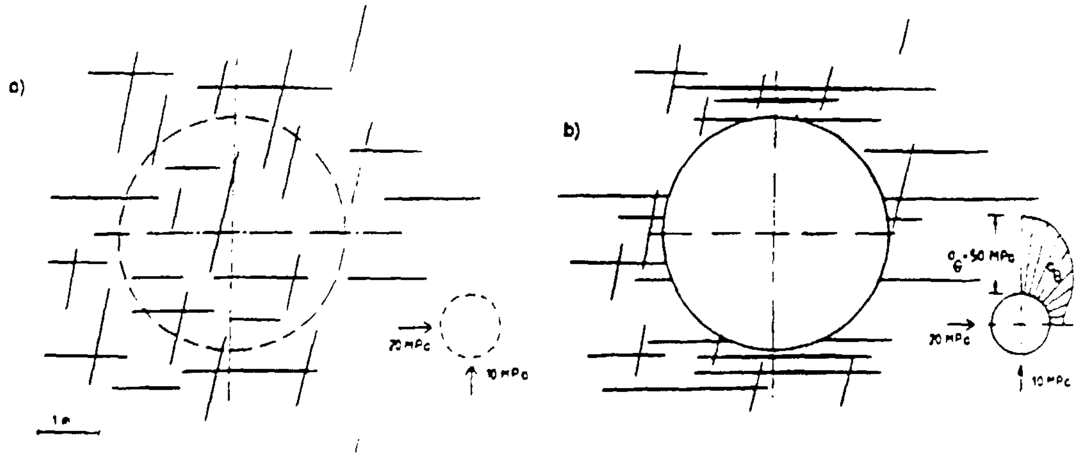


Figure 8.2 Hypothetical stress-induced alteration of granitic fracture geometry following excavation of a circular opening (Pusch 1989b).

The average hydraulic conductivity of crystalline rock, inherent in the parallel-plate conceptualization, is controlled by the equivalent hydraulic aperture (2b) and spacing (S) of existing fractures. Pusch (1989b) provides a generic description of the impact of stress redistribution on the aperture distribution of a cubic fracture system in a granite with an anisotropic stress field following excavation, cf. Figure 8.2. The increase in fracture aperture is obtained in fractures parallel to the principal stress direction.

Since radial block movements following excavation are associated with shear, and shear is often associated with increases in axial fracture hydraulic aperture, an increase in the axial hydraulic conductivity in the Primary DRZ primarily due to excavation is readily envisaged. The magnitude of increase in hydraulic conductivity is also coupled to the block size. The larger the block size, the smaller the potential increase in fracture hydraulic conductivity.

Present understanding on the basis of theoretical and a, unfortunately, limited number of field studies indicates a one to two order of magnitude increase in the axial hydraulic conductivity in the Primary DRZ extending c. 1 m from the wall of an underground opening (Pusch 1990). The increase in hydraulic conductivity in the Primary DRZ is interpreted as being caused by the excavation process itself and subsequent radial displacement of rock blocks towards the centre of the opening associated with shearing along fracture surfaces of the blocks. The magnitude of the increase in axial hydraulic conductivity of the Primary DRZ is dependent on:

- the excavation methodology and design.
- the orientation, spacing, length distribution and material properties of existing and induced fracture sets.
- the magnitude and orientation of the principal in-situ stresses.

In the radial direction, the block displacements towards the opening will result in an increased tangential stress and a decreased radial stress. A local decrease in the radial hydraulic conductivity close to the opening is therefore envisaged.

Thus, the material property of the Primary DRZ may be regarded as anisotropic, with an anisotropy ratio decreasing with radial distance from the wall of the opening. The Secondary DRZ extending beyond 1m will tend to exhibit more isotropic material properties with successively less contrast in hydraulic conductivity to the intact rock as a function of distance from the tunnel wall.

The interdistance between individual storage tunnels either in the plane (single level repository) or between tunnels at different elevations (dual level repository) must be selected in such a way that detrimental superimposed stress effects between tunnels are not achieved, which could increase the extent of the DRZ and associated changes in material properties.

The role the DRZ will play in terms of increase in groundwater flow is dependent on;

- the orientation of the repository tunnels in relation to the orientation of the prevailing hydraulic gradient (disregarding from possible later changes in the magnitude and orientation of the gradient).
- the spatial extent and hydraulic conductivity of the DRZ.
- the contrast in hydraulic conductivity between the DRZ and the intact rock and the competent backfill.
- superimposed events, eg. short-circuiting by fracture zones or boreholes, see below.

In the case of tunnels parallel to the gradient, the flow increase in the DRZ in relation to undisturbed conditions will be nearly proportional to the increase in hydraulic conductivity. If the tunnels are positioned orthogonal to the gradient the increase in flow is significantly less, under the condition that the contrast in hydraulic conductivity is low. If the contrast is high, eg. 1000, an increase in the flow rate in the DRZ on the order of 100 is obtained already at a hydraulic gradient deflection of 10 degrees from the orthogonal.

The flow conditions around the canisters themselves situated some 1.5 m below the extent of the Primary DRZ are moderately affected. However, increases in the vertical component of the gradient together with increases in hydraulic conductivity annular to the canister holes may result in an increase of the flow around the canisters (Bengtsson et al 1991).

The impact of the thermal load of the waste on the near-field hydraulic conductivity distribution is less well established. It has been shown that under certain conditions the orientation of the main principal stress may be rotated 90° (Bauer et al 1989), the consequences of which are still to be evaluated. Pusch and Bergström (1989) attribute the observed radial low-permeability skin ob-served in conjunction to the MPT at Stripa to closure of radial fractures due to thermal loading. Recent analysis by Johansson et al (in press) indicate that, at a time corresponding to peak thermo-mechanically induced stresses, a reduction of pre-excavation hydraulic conductivities on the order of one to two orders of magnitude may be foreseen. After cooling, the hydraulic conductivity distribution returns to the post-excavation state, though still with close to one order of magnitude lower hydraulic conductivity than the initial excavation state.

Use of a careful layout of access drifts to a repository and their associated DRZ:s in relation to the hydraulic regime has been suggested (Lieb et al 1989) to possibly reduce the acting hydraulic gradient across, and thus also reducing the flow through the repository.

Short-circuiting of a repository area and existing DRZ with vertical fracture zones may form a hydraulic U-tube where topographically induced gradients will be conveyed to repository depth, thus potentially increasing the flow through the repository (Hautojärvi 1990, Bengtsson et al 1991). It has been proposed to construct a repository in such a way that the tunnels of the repository will follow individual isopotential lines of hydraulic head, thus inhibiting flow along the tunnels. Though, this scheme is tempting it is not practically feasible. This because there is no guarantee that the present day hydraulic gradient situation will be stable over the time span considered for nuclear waste disposal due to eg. conceived glaciation events and associated erosion of the ground surface.

Hydraulic cage effects caused by the contrast in hydraulic conductivity between the DRZ and the intact bedrock has been suggested as a means of diverting flow around, rather than through a repository (Lieb et al 1989). However, as evidenced by the analysis presented by Bengtsson et al (1991) the effect on the flow rate at canister depth is minimal if any (as noted 2m below the storage tunnel).

In a crystalline bedrock environment a repository may be positioned in relation to a given stress situation, fracture system, and hydraulic anisotropy in such a way that the detrimental increase in hydraulic conductivity in the developed DRZ is minimized. The following assumptions are made with regard to a repository depth of 500 m addressing a possible analysis scenario;

1) maximum horizontal principal stress higher than the vertical stress.

2) horizontal anisotropy in in-situ horizontal stress field (1:2).

3) cubic fracture system.

4) pre-excavation hydraulic anisotropy aligned with fracture system and relative magnitude of stresses (maximum horizontal conductivity parallel with σ_1.

5) regional topographic gradient parallel to main fracture system (maximum principal stress).

In this case, solely on the basis of the orientation of the hydraulic gradient the repository tunnels should be oriented orthogonal to the gradient. The principal stress will cause horizontal fractures to be open and vertical oriented along the axis of the tunnels to close at the floor and crown. Due to stress redistribution vertical fractures along the walls will dilate towards the opening with an increased axial permeability as a result. The permeability of the vertical fracture set orthogonal to the drift is expected to exhibit a small reduction in permeability if any due to a minimal stress change in the axial direction.

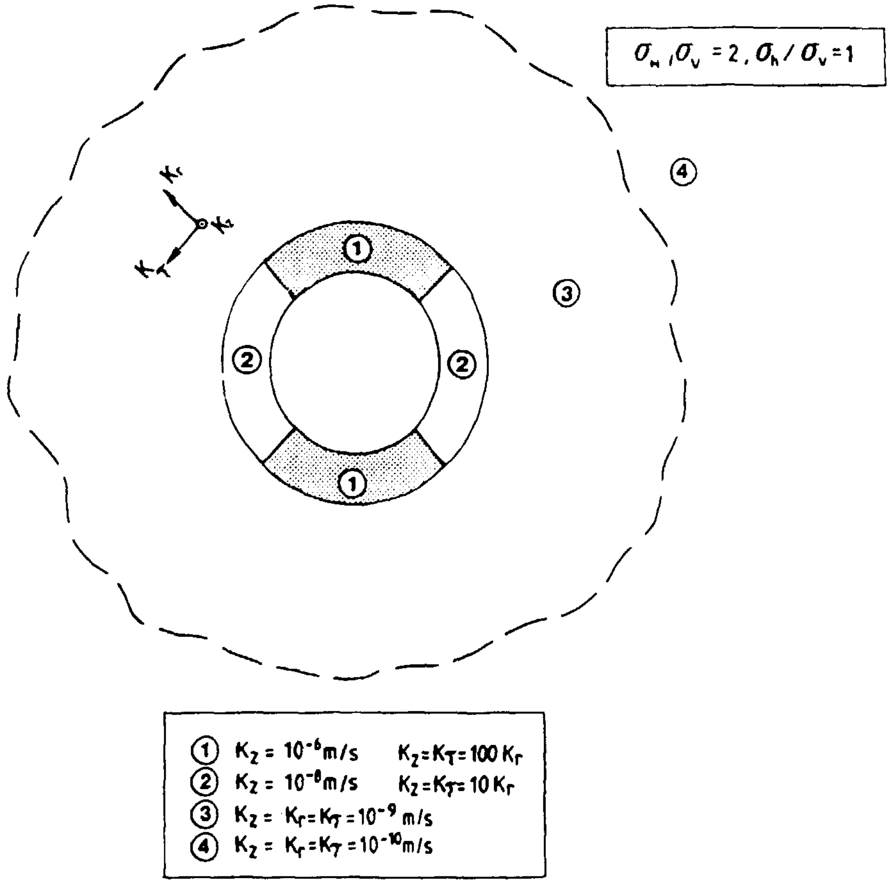


Figure 8.3 Conceptual model of hydraulic conductivity distribution around a circular storage tunnel (ϕ=3.5m) in a moderate biaxial stress field.

The backfill close to the crown may be difficult to compact, and may be subject to successive erosion by groundwater flow and thermo-chemical degradation. Thus, the less compacted backfill in the crown of the tunnel, possibly subject to erosion, together with the existing Primary DRZ in the crown rock may form an enlarged DRZ with an integrated increased hydraulic conductivity. If a more extensive damage in the floor is added, due to drill and blast, a concentric, "life-buoy" like, ring of increased permeability in the Primary DRZ is obtained. The permeability in the crown and floor being higher than in the walls.

On the basis of the above discussion a conceptual model of the material property distribution similar to the one presented by Pusch (1990) may be suggested including a Primary DRZ caused by excavation and to a lesser extent by stress changes. The difference being the added feature of concentric variability and anisotropy in the hydraulic conductivity, cf. Figure 8.3. The axial hydraulic conductivity of the Primary DRZ in the crown and the floor is set to 10^{-6} m/s whereas that of the ribs (walls) is set to 10^{-8} m/s. The corresponding anisotropy ratios governing the radial hydraulic conductivity are 1:100, and 1:10, respectively.

The hydraulic conductivity of the Secondary DRZ extending beyond 1 m is featured by an isotropic hydraulic conductivity of 10^{-9} m/s. Beyond the Secondary DRZ some 1-3 tunnel diameters away, the intact rock has been assigned a hydraulic conductivity of 10^{-10} m/s. The coupling between the magnitude of the hydraulic conductivity of the intact rock and that of the DRZ is difficult to assess on the basis of available data. With a given excavation methodology and design, it is likely that the hydraulic conductivity of the Primary DRZ is fairly independent of the intact rock conductivity, whereas the that of the Secondary DRZ will be more dependent on the pre-existing properties of the intact rock.

It should be noted that no consideration has been taken to any possible thermo-mechanical effects on the hydraulic conductivity when assigning the numbers in Figure 8.3. This fact should be borne in mind when comparing Figure 8.3 with the results of thermo-mechanical effects on hydraulic conductivity reported by Johansson et al (in press), cf. Figure 7.2.

The listed figures on material properties should be regarded as approximative, however conservative, and have to be viewed in light of the limited statistics available. In any model case, including worst case scenarios where the repository is breached, eg. by a water well, the output radionuclide release rates and transport times should also be regarded as conservative.

It should be noted that extension of increased axial hydraulic conductivity in the Primary DRZ over distances corresponding to the lengths of the storage tunnels is unlikely due to finite axial fracture extent. In sensitivity analysis to be performed this feature may be addressed by introducing axial heterogeneity in the hydraulic conductivity of the Primary DRZ.

8.4 Radionuclide transport

Radionuclide transport in bedrock is governed by the following parameters;

1) the velocity of groundwater.

2) the modes of retention.

The groundwater velocity (v) is controlled by the hydraulic conductivity (K) of the rock and the associated magnitude and geometry of kinematic porosity (ϵ_k), where $v \propto K/\epsilon_k$. The retention capability of the rock is controlled by; a) the available surface area to unit volume water ratio **a**, b) the chemistry and complexing capacity of the groundwater, and c) the chemistry of the rock and its fracture coatings.

The kinematic porosity is defined as the portion of the total porosity that is actively involved in the flow of groundwater. The kinematic porosity of fractured rock, based on the simple parallel plate model, is given by $\epsilon_k = 2b/S$.
If one consider the numbers given in Figure 8.3, and assume unit gradient and a spacing between hydraulic fractures of 0.3 m in the DRZ and 5.0 m in the undisturbed rock mass (Bengtsson et al 1991), the coupled increase of hydraulic fracture aperture (2b) and decreased fracture spacing (S) in the DRZ will result in a factor 3 and 70 higher velocity in the walls and crown/floor of the Primary DRZ, respectively, when compared with the undisturbed rock.

The retention of radionuclide transport is, as indicated above, in part governed by the available fracture surface to unit volume water ratio **a**. The chemical aspects of this available surface area is discussed in Section 8.5, whereas the following will discuss the formation of this surface area.

The available surface to unit volume water ratio **a** is defined as 2/2b ($\mathbf{a}=2{*}w{*}l/w{*}l{*}2b$)(Neretnieks 1987), again based on the parallel plate analogy. This implies that **a** would increase inversely proportional to the cubic root of the product K*S. Bengtsson et al (1991) show that, with the input parameters used in their transport calculations, ia. a two order difference in hydraulic conductivity between the DRZ and intact rock, the difference in **a** between the DRZ and the intact rock is within a factor 5. This implies that the impact of the DRZ on **a** is fairly limited with the assumptions made.

The, perhaps surprisingly, noted lower value of **a** in the DRZ compared to the intact rock as reported by Bengtsson et al (1991) is inherent in the parallel plate model and may be conceptualized as being caused by a small number of large flow channels in the DRZ. These may be the result of shear, thus increasing the flow (volume) with a maintained, or even reduced fracture surface area. In addition the developed preferential flow paths may converge flow and leave "old" pre-disturbance flow paths idle.

8.5 Chemistry

As previously noted, the degassing of inflowing waters to an underground opening will, under typical ambient conditions prevailing in a Swedish repository situation, result in precipitation of calcite on existing and fresh fracture surfaces, cf. Section 4.7. This reaction reaches equilibrium very quickly. In addition, the oxidation of iron will result in the formation of amorphous iron compounds in the close proximity of the opening.

The solubility of calcite decreases with temperature (T) whereas the solubility of quartz increases with T. The temperature increase following back-fill and closure of the vault/repository will force the calcite to precipitate, and the quartz to dissolve in the near field. One can envisage the formation of local convection cells where the dissolved quartz is transported from the near-field to a distance far off from the canisters, where the temperature decrease will force quartz to precipitate. In parallel, the calcite in solution will be transported towards the repository and precipitated when the temperature conditions are favourable.

Thus, a developed small scale convection cell could result in self-healing fracture mineral growth in the proximity of the repository during the time of heating of the rock mass, but from two different chemical processes, and at two different locations/distances. The mineral growth in the kinematic porosity of the fractures would lead to a redisposition of the distribution of hydraulic aperture and consequently also of that of the hydraulic conductivity. Whether, the overall hydraulic conductivity of the near-field is reduced through these two processes is difficult to predict. The amount of calcite precipitated will eg. be affected by the rock stabilizing measures, cement and concrete, taken in terms of pre- and post-grouting, cf. Section 8.6.

Trace elements can be incorporated in the calcite lattice during precipitation, or sorbed on the calcite surfaces. Thus, retention of Sr, and to a lesser extent U is likely to occur. Retention of actinides are mimicked by that of retention of rare earth elements.

The relative stability of amorphous iron compounds on the fracture surfaces in the near-field is after closure and heating dependent on the partial pressure of CO_2 which in turn is dependent of the variation in temperature. It has been observed by Bruno et al (1991) that the solubility of Fe(III) oxide/hydroxide decrease with a factor 10-100 with a decrease of the partial pressure of CO_2 with a factor 10. Therefore a sequence of dissolution and precipitation governed by ambient conditions is foreseen intimately coupled to, and interdependent on changes in the hydrogeological regime. The amorphous iron compounds will retenate U, Th and rare earth elements (actinides), but not Cs, Sr, Rb and Ba. Landström and Tullborg (1990) observed an uptake of Cs in Fe-oxy-hydroxides. However, this may be due to the presence of clay minerals, known to selectively sorb Cs, and to a lesser extent Ba and Rb.

8.6 Sealing

The foreseen presence of a disturbed zone of increased permeability, both around individual deposition holes, storage and access tunnels and shafts have initiated efforts to provide methodology and grout material to effectively seal these features, cf. Figure 8.4. Börgesson and Pusch (1989) reports results of pilot and full scale tests at Stripa aimed at such sealing and also the sealing of water-bearing fractures and fracture zones intersecting tunnels and shafts.

Pilot experiments on sealing of deposition holes using dynamic injection indicated that the hydraulic conductivity was decreased to 10^{-10} - 5 10^{-10} m/s irrespective of the initial permeability. Full scale tests including appraisal of the effect of a heat pulse on injection of grout show similar results.

With regard to the disturbed rock zone around tunnels and shafts, sealing at strategically selected positions in a repository is strongly believed to achieve similar successful sealing results. With such seals the waterbearing capability of disturbed zone would be effectively dimished, but would still provide a large available surface area for sorption and/or diffusion.

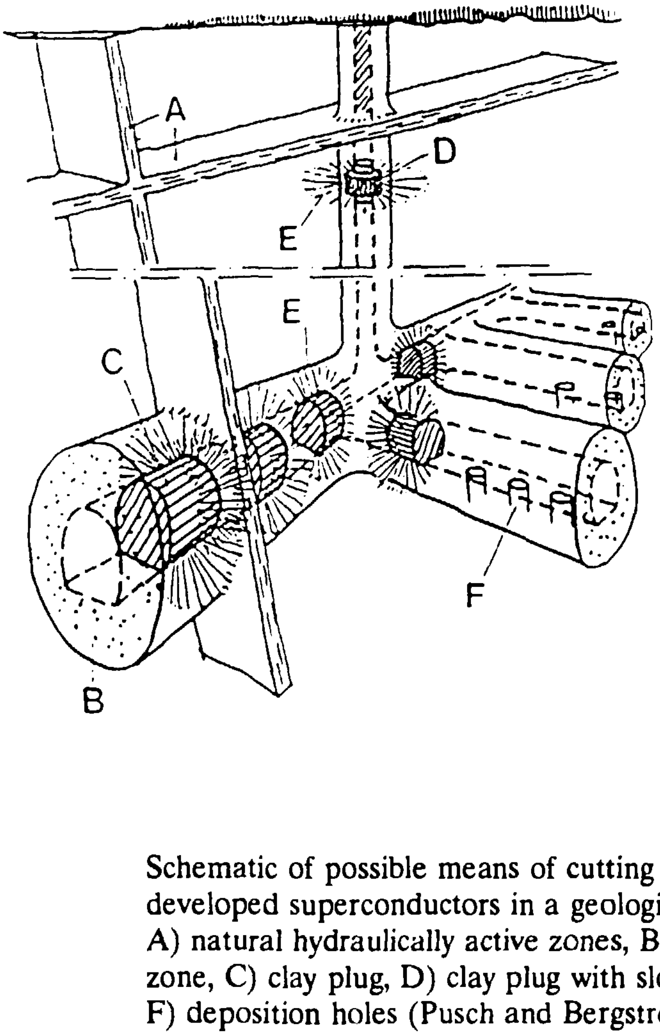


Figure 8.4 Schematic of possible means of cutting off potentially developed superconductors in a geological repository. A) natural hydraulically active zones, B) disturbed rock zone, C) clay plug, D) clay plug with slot, E) grouting, F) deposition holes (Pusch and Bergström 1989).

9. IMPLICATIONS FOR THE FUTURE

Ongoing domestic and international activities, both analytical to asses the relative importance of the DRZ from a safety assessment perspective, and experimental to characterize the geometry and material property distribution in the DRZ, will in the near future provide results that will aid the applicant and licensing agencies in their proper appraisal of role the disturbed rock zone in performance and safety analysis of geological repositories. This joint interest is formulated eg. in the Swedish SKI/SKB scenario development project (Andersson et al 1989).

Though there is a large amount of studies reported on excavation and stress induced damage, there exists a lack of set up criteria for what characteristics feature the DRZ from the undisturbed in-situ rock. Such criteria should be defined in order to uniform observations of the extent of the DRZ. An outline of a set of such criteria are provided in Chapter 3 of this report.

There exist an obvious lack of statistical amounts of observations/data on the hydraulic and transport properties of the DRZ. More field data on the hydraulics of the DRZ will eventually come out of the Swedish Hard Rock Laboratory (HRL) at Äspö and the ongoing large scale Mine-By Experiment (MBE) and other experiments at the Canadian URL. It is believed that the different geological characteristics of these two sites will provide mutually supporting data that will guide in build up of understanding of the physics of the DRZ developed around underground openings in crystalline rock at repository depth.

A list of activities aimed at the characterization and modelling of the DRZ at the Swedish HRL has been devised (Almén 1991). The type of studies planned include geological and structural mapping, in-situ and laboratory mechanical testing, geophysical and hydraulic testing (including tracer tests) and pressure monitoring in boreholes, and finally, assessment of invasion of explosive gases into the rock.

The tools available for coupled thermo-hydro-mechanical analysis, where the analysis and validation of constitutive models of the formation of the DRZ may be one objective, are under constant development. Soon, a project - DECOVALEX - along the directions of the HYDROCOIN and INTRAVAL studies will be launched aimed at setting up an international cooperative project for the development of coupled models and their validation against experiments in nuclear waste isolation.

In parallel, ongoing safety and performance assessment studies, eg. TVO-92 and SKB 91, will be forum for the assessment of the relative importance of the DRZ from a repository safety angle. Given the lack of statistical amounts of experimental data on the hydraulic and transport characteristics of the DRZ, one will at present have to resort to sensitivity analysis within the framework of the available experimental in-situ data and presented conceptual models of the DRZ.

10. CONCLUSIONS

With the disturbed rock zone (DRZ) we imply the zone extending around an underground opening which is affected by the excavation process and subsequent mechanical, thermal and chemical processes.

With regard to the hydraulic characteristics of the DRZ one may identify processes decisive for the short- and long-term hydraulic behaviour of the zone. To the processes deciding the long-term behaviour belong the mechanical stress redistribution following excavation. The thermal load imposed by the waste will moderate the fracture aperture increase imposed by shearing of the rock. In addition the thermal effects will change the distribution of fracture minerals. The longevity of the backfill in the storage tunnels will also be decisive for the long-term hydraulic characteristics near the storage tunnels.

The short-term effects are those acting during the operating phase. The hydraulics of the DRZ are in this case potentially affected by eg. unsaturation, two-phase flow and capillary effects in the fractures of the disturbed rock zone. The exposure to atmospheric conditions will also alter the fracture mineralogy distribution and potentially also the hydraulics around the opening. After repository closure, the hydraulic situation will return to its normal state and the short-term effects will dissipate.

Specific criteria to define the DRZ are difficult to find in the literature, either for direct or indirect assessment. It is believed that site-specific criteria will have to be defined at any given site.

The DRZ have been subject to modelling and in-situ experiments. A few of the modelling studies addresses the hydraulic aspects of the DRZ. In-situ experiments providing hard quantitative hydraulic data are very few. On the basis of available qualitative and quantitative information a conceptual model of the DRZ have been suggested for performance assessment studies (disregarding the thermal effect of the waste).

Around an excavated opening a Primary DRZ is developed extending c. 1m affected by excavation and stress redistribution. The hydraulic conductivity distribution is assumed to be anisotropic and exhibit concentric variability. The axial hydraulic conductivity is set to 10^{-6} m/s in the floor and crown and 10^{-8} m/s in the ribs. The radial hydraulic conductivity is assumed to be 10-100 times less.

Beyond the Primary DRZ a Secondary DRZ is developed, extending some 1-3 tunnel diameters. The zone is primarily affected by stress redistribution. The hydraulic conductivity of the Secondary DRZ is set to 10^{-9} m/s and is assumed to become progressively isotropic with radial distance from the opening.

The given data geometries and material properties should regarded as conservative, and as initial values in a sensitivity analysis.

The relative importance of the DRZ from a performance and safety assessment perspective is dependent the extent of the DRZ and its hydraulic conductivity contrast to the undisturbed rock, and on the orientation of the repository tunnels in relation to the acting hydraulic gradient.

In addition, superimposed events and scenarios, eg. human intrusion, may increase the importance of the DRZ and the steps taken to reduce its impact.

11. ACKNOWLEDGEMENT

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Features of Some Available Mechanical-Analysis Computer Codes

Code Name	Reference	Geometry			Constitutive Behavior/Kinematics																Special Features							Num. Proc.					
		Plane stress/strain	Axisymmetric dimensionality	Rectangular dimensionality	Large rotations	Linear elastic	Nonlinear elastic	Elasto-plastic	Visco-elastic/plastic	Joint/slip model	Crack propagation	Anisotropy	Dilatancy/consolidation	Thermal dependence/coupling	Damage model	Ubiquitous jointing	Work softening	Large displacements	Large strain	Thermal spall	Stochastic processes	Initial stress/strain	Structural components	Material removal/addition	Hydr./chem./radiation coupling	Explosive loading	Pre-/post-processors	Finite difference	Finite element	Boundary element	Distinct element	Explicit	Implicit
ABAQUS	(f)	x	x	3		x	x	x	x	x	x	x	x	x^g	x			x	x			x	x		x		x						
ADINA	SAI 1981	x	x	3		x	x	x	x		x	x		x		●	x	x	x			x	x	x			●		x			x	x
ANSYS	Curtis 1983	x	x	3		x	x	x	x	x		x		x				x				x	x		x		x		x				x
BMINES	Van Dillen 1981	x	x	3		x	x	x	x	x	x	x										x	x	x			x^a		x				x
FLAC	(f)	x		2		x		x				x				x		x	x			x					x	x				x	
JAC	Biffle 1984	x	x	3	x	x	x	x	x	x			x	x		x		x	x			x		x					x			x	
MARC	SAI 1981	x	x	3		x	x	x	x	x^b	x	x	x	x				x											x			x	x
MTNAQ	(e)	x		2		x		x		x				x								x		x			x			x			x
REPOS	(e)			3		x			x^c	x				x								x		x						x			x
ROCMAS	(f)	x	x	2		x								x											x				x				x
SAFE	(f)	x	x	3		x	x	x		x	●	x	x	x			x					x		x			x^d		x			x	
SANCHO	Stone 1985	x	x	2		x		x		x^b								x	x								x^a		x			x	
SPECTROM 32	(e)	x	x	2		x		x	x	x				x								x		x				x				x	
STEALTH	SAI 1981	x	x	3		x	x	x	x	x^b		x		x	x	x	x	x	x			x			x						x	x	
3DEC	(f)	x		3	x	x	x			x	x							x	x					x			x				x	x	
UDEC/MUDEC	(f)	x		2	x	x	x			x	x			x				x	x				x	x	x		x		x			x	
VISCOT	Intera 1983	x	x	2		x	x	x	x					x								x					x		x			x	

x Existing code feature
● Code feature being developed

(a) Mesh generator
(b) Frictional interface only
(c) Only along excavation horizon

(d) Post-processor available
(e) Documentation in draft stage
(f) Software supplier's literature
(g) Fully-coupled, not just forward-coupled

Modified from St. John, 1983

Appendix 2

MODELLING GROUPS AND THEIR APPROACHES

Modelling Group	Atomic Energy of Canada Ltd. Applied Geoscience Branch, Computation and Analysis Section	University of Alberta Department of Civil Engineering	Lawrence Berkley Laboratories, Earth Sciences Division	Lawrence Livermore National Laboratories
Principal Investigator	T. Chan	P. Kaiser	R.E. Goodman	A. Wijesinghe
Name of Numerical Code	ABAQUS (stress and displacements) MOTIF (fracture flow and pressure)	SAFE (stress and displacements) ADINAT (fracture flow and pressure)		GENESIS
Type of Code and Mesh	3-D, finite element, full mesh, continuum (i.e., no joint element). Actual in situ stress and fracture geometry incorporated. Stress changes projected on fracture plane and permeability changes calculated using empirical data.	3-D, finite element half mesh, with joint element. In situ stress and fracture geometry approximated	Discontinuous deformation analysis. 2-D with face advance coefficients to adjust for 3-D effects of tunnel face	3-D, coupled finite element and boundary element
Fracture Hydrogeology Calculations	Uncoupled fluid flow analysis using planar elements in the plane of the fracture. Fracture orientation correctly modelled.	Planar element using uncoupled fluid flow (flow net in plane of fracture). Fracture approximated as normal to tunnel	Fluid flow calculations based on flow net in fracture plane	Fully coupled joint element

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TR 121
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Stockholm, May 1979

1979
TR 79-28
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1981
TR 81-17
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I Puigdomènech[1], J Bruno[2]
[1]Enviromental Services, Studsvik Nuclear, Nyköping, Sweden
[2]MBT Tecnologia Ambiental, CENT, Cerdanyola, Spain
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[1]SGAB, Luleå
[2]SGAB, Uppsala
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[1]Conterra AB
[2]Sveriges Geologiska AB
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[1]Vattenfall HydroPower AB
[2]Golder Geosystem AB
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[2]Chalmers Institute of Technology
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[1]Starprog AB
[2]SKB AB
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