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Excavation Damaged Zones Assessment

March 2011

Prepared by: Fracture Systems Ltd.

NWMO DGR-TR-2011-21

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EXECUTIVE SUMMARY

This report summarizes experience from geoscientific studies of the Excavation Damaged and Disturbed Zones in sedimentary rocks. The bulk of these studies have been performed as part of research programs for radioactive waste disposal in argillaceous rocks. In particular, the report draws on in situ experimental studies performed in Underground Research Laboratories (URLs).

The creation of any underground opening creates a zone of disturbed rock around it. Within this disturbed zone there may exist a zone of damaged rock. In the past various definitions of the disturbed and damaged zones have been used. This report uses the definitions of the Damaged and Disturbed Zone proposed by Tsang et al. (2005).

- The Excavation Disturbed Zone (EdZ) is a zone with hydromechanical and geochemical modifications, without major changes in flow and transport properties.
- The Excavation Damaged Zone (EDZ) is a zone with hydromechanical and geochemical modifications inducing significant changes in flow and transport properties. These changes can, for example, include one or more orders of magnitude increase in (effective) flow permeability.

Within the EdZ state variables such as stress, water pressure, temperature, saturation, water chemistry and related properties such as porosity, may be altered by the presence of the opening but these changes are either temporary (e.g., saturation) or do not have a major influence on flow and transport properties (e.g., small changes in porosity due to changes in effective stresses).

In addition, within the study, a Highly Damaged Zone (HDZ) was defined as the part of the EDZ, at the excavated face, where macro-scale fracturing or spalling may occur. The effective permeability of this zone is dominated by the interconnectedness of the discrete fracture system formed and may be orders of magnitude greater than the undisturbed rock mass. An HDZ will only exist where stresses are sufficiently high relative to rock strength or where the excavation method creates a fractured zone (e.g., conventional drill and blast). A wide range of methods have been used to investigate the structure and properties of the EdZ and EDZ. Four types of measurements are considered: geological, hydraulic, geophysical, and geomechanical. The first three relate to characterization during and after excavation, while geomechanical measurements are usually associated with either “mine-by” experiments or monitoring of the evolution of the EdZ and EDZ. One of the most widely used methods is based on interval sonic measurements, which when integrated with geological and hydraulic measurements, have typically provided the basis for determination of EDZ geometry and properties.

The stability of excavations in brittle rocks can be considered under three classes:

- Structurally controlled failure;
- Stress-controlled failure; and
- A combination of structure and stress controlled failure.

In argillaceous rocks additional processes related to wetting can lead to failure:

- Swelling, weakening and softening; and
- Shrinkage during drying and weakening due to repeated wetting/drying cycles.

For excavations in weak sedimentary rocks stress-controlled failure is considered to be the most important and a relationship between damage zone definitions and failure mechanisms based on the work of Diederichs (2000) is presented. The influence of pre-existing structures and excavation method is also considered. A comparison of the structure and extent of the EDZ at four different URLs is presented and related to the maximum stress/strength ratio at each location.

Local measurements of enhanced permeability around excavations have been made in many URLs. There are, however, very few measurements of the axial hydraulic permeability along excavations. Further such measurements have typically been over flowpath lengths of only a few metres. The effective conductance over 10s or 100s of metres is of interest with regard to post-closure repository performance. It is possible that the fracture network within the HDZ may be unconnected over greater length scales. Any interruption to the connectivity of the HDZ fracture system due to local changes in mechanical properties or stresses, influence of pre-existing structures or changes in excavation geometry or method could effectively cut off flow through the fractured HDZ.

The extent and effective permeability of the EDZ can be limited by appropriate excavation design choices. However, it may not be practical to entirely eliminate the EDZ around key locations in a repository, such as, at tunnel or shaft seals. Specific engineering measures to minimize the effects of or cut-off the EDZ have been developed and tested in both sedimentary and crystalline rocks. Possible measures include EDZ cut-offs and design of seal zones including removal of any damaged or altered rock.

In the long-term, in argillaceous rocks, self-sealing processes (Bock et al. 2010) may result in a significant reduction in permeability in the EDZ from that measured after excavation. Such processes will be particularly important in rocks with clay content greater than 40%.

The treatment of the EDZ in safety assessment has typically focussed on its potential role as a preferential flow path and has involved conservative assumptions with regard to the connectivity and effective permeability of the EDZ. Recent studies have shown that even under highly conservative assumptions repository performance in a low conductivity host rock is not significantly affected by the presence of a more permeable EDZ. Some aspects of the EDZ may even be favourable for repository performance, e.g., increase in fracture surface area for sorption, and potential to act as a gas flowpath. This does not; however, eliminate the need for a sound scientific understanding of the EDZ.

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1. INTRODUCTION

1.1 Scope

This report summarizes experience from geoscientific studies of the Excavation Damaged and Disturbed Zones in sedimentary rocks. The report draws on in situ experimental studies performed in Underground Research Laboratories (URLs) focusing on disposal of radioactive wastes. In particular, the report considers results from:

- HADES URL at Mol in Belgium in the Boom Clay (Bastiaens and Bernier 2005);
- Mont Terri Rock Laboratory in Switzerland in the Opalinus Clay (Bossart and Thury 2008);
- Tournemire URL in Aveyron in France in Toarcian argillite/marls (Bonin 1998); and
- Laboratoire Meuse/Haute-Marne at Bure in France in the Callovo-Oxfordian Argillite formation (COX) (Delay et al. 2007, 2010).

Predictive modelling and design studies for deep geological disposal systems for the same host rocks are also discussed.

While the focus is on sedimentary and, in particular, argillaceous rocks, concepts and results from studies in crystalline rocks have been used to supplement this relatively limited database. In addition, experience from drilling in sedimentary rocks is sometimes referenced where borehole failure is used as an analogue for the behaviour around larger cylindrical openings.

One aim of the study is to assess the relevance of experience from rock laboratories and geological disposal programmes to the proposed radioactive waste repository at the Bruce nuclear site in Ontario, Canada (NWMO 2011). This interest concerns not only the damaged and disturbed zones in the Cobourg Limestone (the repository host rock) but primarily the formations that the proposed shafts would intersect (e.g., dolomites, anhydrites and shales). Of particular interest is the possibility of vertical flow through the potential damaged and disturbed zone around the shafts. Thermal aspects are not of significance for the proposed low and intermediate level waste facilities and are only briefly discussed here.

1.2 Experimental Studies of the Damaged and Disturbed Zones

Experimental studies of the tunnel near-field and its relevance to geological disposal of radioactive waste were first performed in fractured granite at the Stripa Mine in Sweden in the 1980s. Results from the “Macro-permeability Test” showed a reduction in radial permeability close to the tunnel wall (Wilson et al. 1983) while subsequent analysis of the “Buffer-Mass Test” (Pusch 1989, Pusch and Stanfors 1992) showed a significant increase in axial permeability. Previously, although the presence of a “disturbed zone” had been considered in theoretical studies of geologic disposal, no experimental studies had been performed. An early assessment of the impact of the disturbed zone on nuclide migration is given in Bengtsson et al. (1991).

Since the first experiments at Stripa further experimental studies on the disturbed zone in crystalline rock have been performed at:

- The Colorado School of Mines Test Site in Colorado, USA;
- The BWIP Near Surface Test Facility, in Washington, USA;
- The Grimsel Test Site in Switzerland;
- The Kamaishi Mine, Japan;
- The AECL Underground Research Laboratory in Manitoba, Canada;

- The Äspö Hard Rock Laboratory in Sweden;
- The KURT Facility in Korea;
- The ONKALO Facility at Olkiluoto in Finland; and
- The MIU URL at Mizunami in Japan.

These experiments were performed in granitic and other crystalline rocks (basalt at BWIP) using different excavation methods in a range of test geometries, depths and stress fields. A recent summary of results from excavation damage experiments in crystalline rock is given in Backblom (2008).

After the first studies at Stripa, the first URL in argillaceous rocks was established at Mol in Belgium and since then additional underground laboratories have been constructed:

- Mont Terri URL in Switzerland;
- Tournemire URL in France;
- Meuse/Haute Marne URL in France;
- Tono Mine in Japan; and
- Horonobe URL in Japan.

Studies of excavation damaged and disturbed zones have been performed at all these laboratories. A table summarizing key aspects of the different sedimentary rock URLs is given in Table 1.1 and host rock properties in Table 1.2. Figure 1.1 to Figure 1.5 show layouts of the different rock laboratories.

Table 1.1: Underground Research Laboratories in Sedimentary Rocks

URL Site	Construction	Host rock	Depth Below Surface (m)	Access
HADES URL	Shafts 1980-1982, 1997-1999 Galleries 1982-1984. 1987, 2001-2002, 2006-2007.	Boom Clay	224	Shafts
Mont Terri Rock Laboratory	Motorway tunnel constructed 1987-1993, experimental niches and galleries from 1996 onwards.	Opalinus Clay (OPA)	~250	Motorway tunnel
Tournemire URL	Main tunnel excavated 1881, experimental galleries 1996, 2003.	Toarcian Argillite/Marl	~250	Tunnel
Laboratoire Meuse Haute Marne	Construction 1999-2006.	Callovo-Oxfordian Argillite (COX)	550	Shafts
Tono Mine	Shafts and drifts excavated in 1972 and 1973. From 1986 geoscientific research on sedimentary environment.	Neogene sediment	135	Shafts
Horonobe URL	Construction from 2005 onwards.	Neogene marine sediments Koetoi, Wakkanai Formations	500 (target)	Shafts

Table 1.2: Properties of the Different URL Host Rocks

URL Site	Material/ Rock Type	In situ Stress (MPa)			UCS (MPa)	Young's Modulus (GPa)	Porosity	Hydraulic Conductivity (m^2)	Age (Ma)
		σ_V	σ_H	σ_h					
HADES URL	Boom Clay	4.5 isotropic			2	0.3	0.39	2/4×10^{-12}	30
Tournemire URL	Toarcian Argillite	4 isotropic			13-32	28/9(5)	0.06-0.09	10^{-13}-10^{-15}	~200
Mont Terri Rock Laboratory	Opalinus Clay	6.5(1)	4.5	2.5	10-16 anisotropic	10/4	0.1-0.16	0.8-2×10^{-13}	180
Laboratoire Meuse Haute Marne	Callovo Oxfordian Argilite	14.8-12.7(2)	12.7	12.4	21 (mean)	13-16	0.11-0.17	<10^{-12}	150
Tono Mine	Tertiary sediments	3	1.7	1.5	6.6	2.8	0.26	10^{-7}-10^{-11} (3)	10
Horonobe URL	Wakkanai				10-35	2-5	0.35-0.5	10^{-5}-10^{-11} (in situ)(4) 10^{-11}-10^{-13}(lab matrix)	3-13
	Koetoi				0-8	0.5-1	0.6-0.62	10^{-7}-10^{-9} (in situ)	3-4

Notes:

(1) From Marschall et al. (2008), but note difficulties in stress measurements as discussed in Martin and Lanyon (2003b).
(2) From Wileveau et al. (2007) for measurements at ~500 m depth.
(3) Pre-excavation measured permeability (Sato et al. 2000).
(4) Reported range from in situ hydraulic testing (JNC 2003).
(5) Modulus values given as a/b refer to parallel and normal to bedding, respectivity.

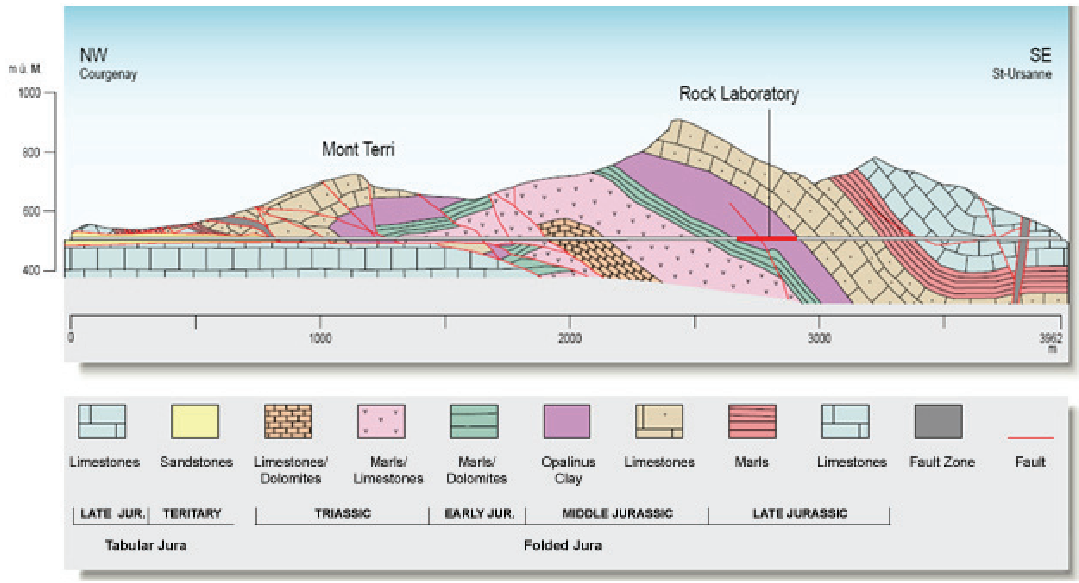
It should be noted, however, that the timescales of investigations at the URLs are only a few years or decades (at Mont Terri) and uniquely over 100 years at Tournemire[1]. The time scales of interest at Bruce are ~100 years (prior to seal emplacement) and ~1,000,000 years (period of assessment) although most of the effects of the time-dependent changes in rock strength are estimated to occur during the first 200 years (ITASCA 2011).

1.3 Other Relevant Literature

Studies of excavation disturbance and damage have also been performed in salt formations at the WIPP site in the USA (Sandia 1996) and Asse Mine in Germany (Bechtold et al. 1999), but are not considered in detail within this report. Studies for the WIPP Shaft did, however address the damage zone in the Rustler Formation (Permian evaporite containing anhydrite, gypsum,

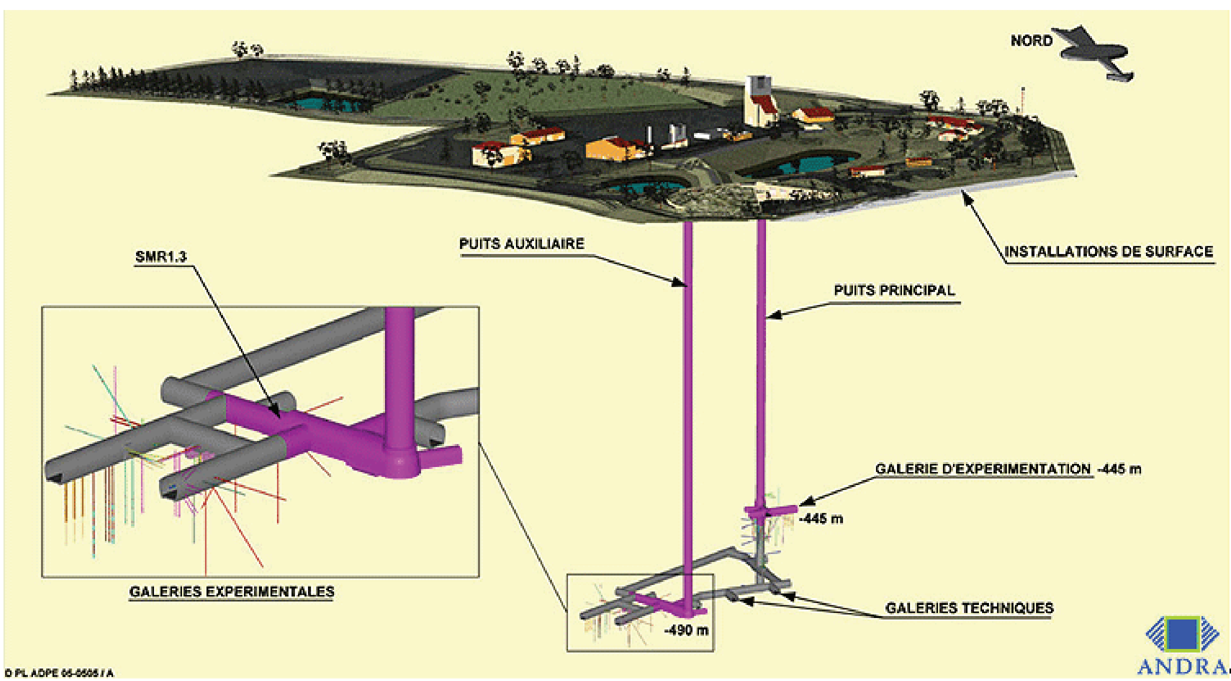
[1] As part of Nagra's investigations of the EDZ in Opalinus clay studies were made of old railway tunnels including the 140 year old Hauenstein tunnel (Mäder and Mazurek 1998).

halite, siltstone, claystone and dolomite) and some discussion is included in later chapters of experimental results and treatment within performance assessment of these rocks.



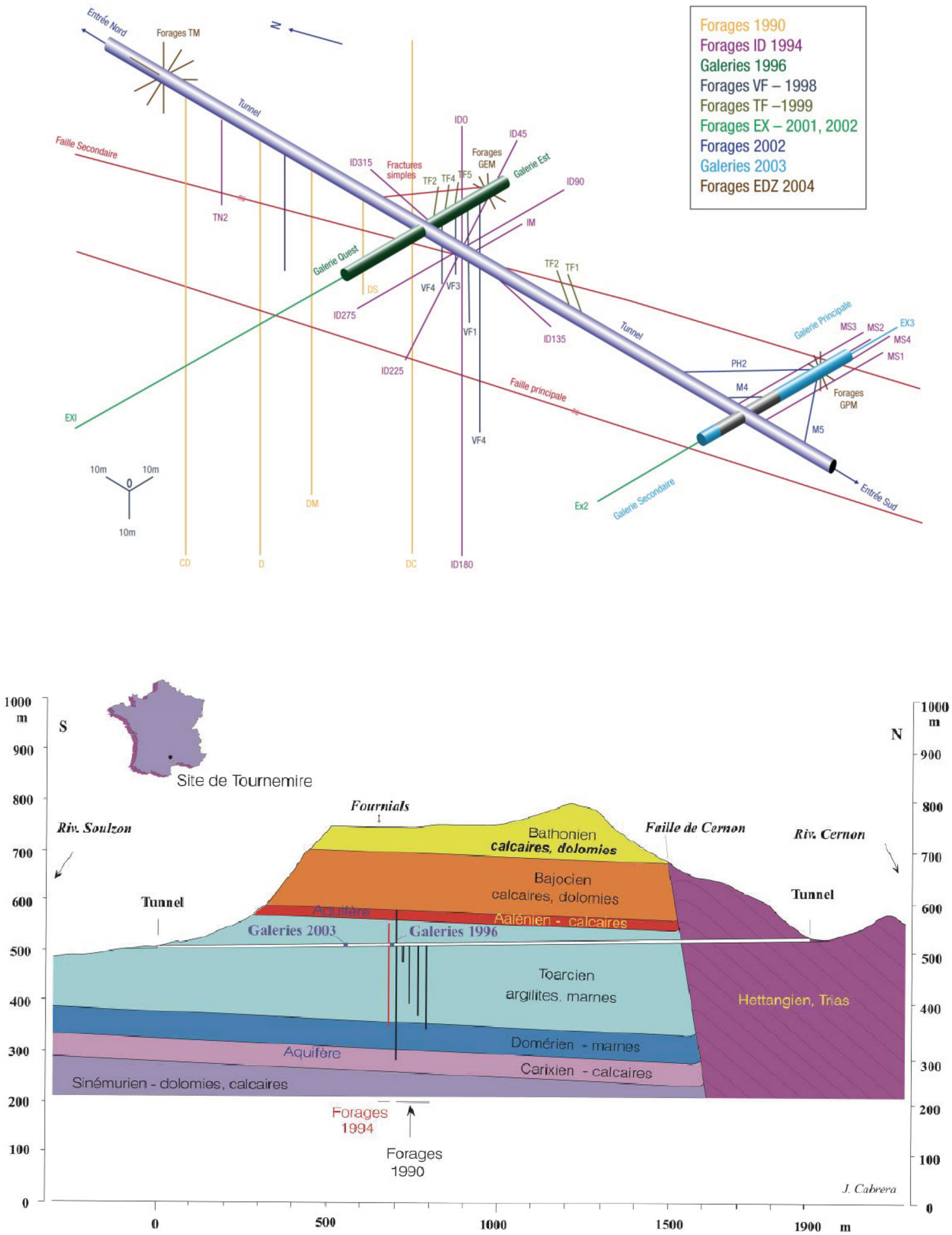
Note: Courtesy Mont Terri Rock Laboratory.

Figure 1.1: Layout of the Mont Terri Rock Laboratory and Geological Cross-section



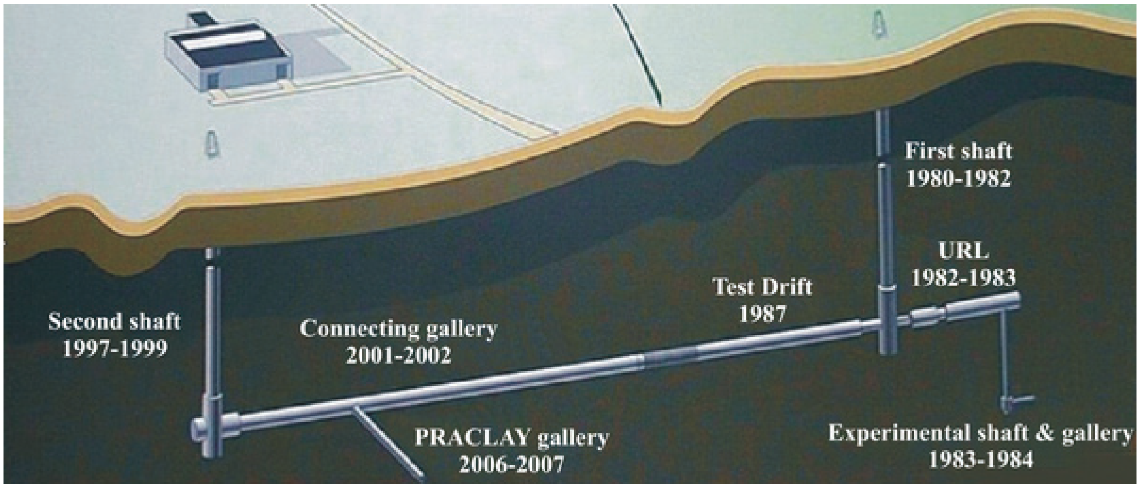
Note: Courtesy ANDRA.

Figure 1.2: Layout of the Laboratoire Meuse Haute Marne



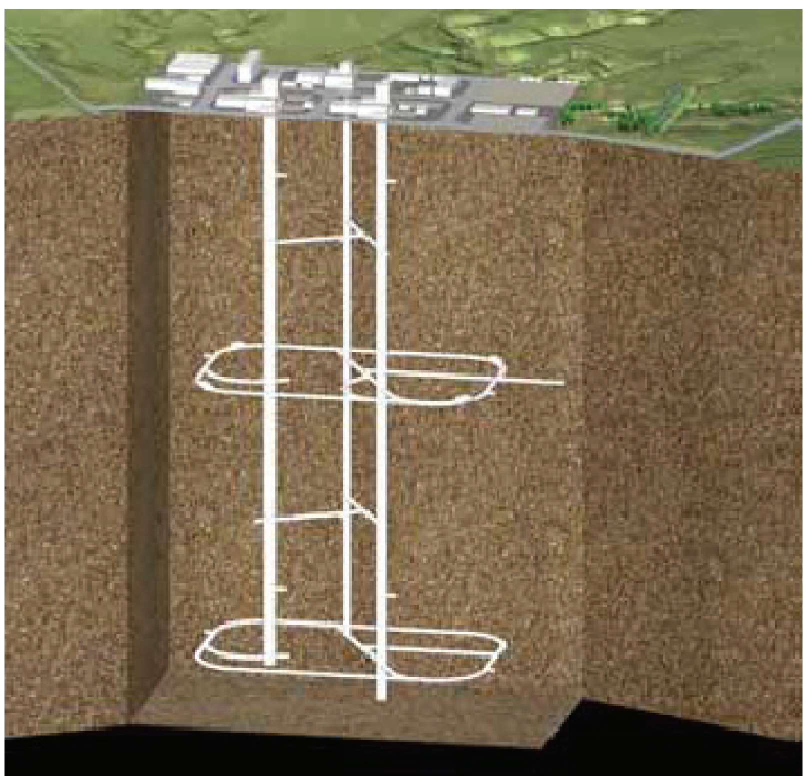
Note: Courtesy IRSN.

Figure 1.3: Layout of Tournemire URL



Note: Courtesy SCK.CEN.

Figure 1.4: Layout of HADES URL



Note: Courtesy JAEA.

Figure 1.5: Layout of Planned Horonobe URL

While studies of excavation damage have largely related to radioactive waste disposal, they are relevant to other applications including: pressure tunnels, gas storage, dam foundations (Wu et al. 2009) and hydrocarbon boreholes (e.g., Økland and Cook 1998, Cook 1999).

This report largely focuses on the results from European rock laboratories and geological disposal programmes. A great deal of this work has been performed within the context of European Commission projects including:

- ESDRED (www.esdred.info): Engineering Studies and Demonstration of Repository Designs;
- NF-PRO (www.nf-pro.org): Understanding and Physical and Numerical Modelling of the Key Processes in the Near-field and their Coupling for Different Host Rocks and Repository Strategies;
- THERESA (www.theresaproject.com): Coupled thermal-hydrological-mechanical-chemical (THMC) processes for application in repository safety assessment; and
- TIMODAZ (www.timodaz.eu): Thermal Impact on the Damaged Zone Around a Radioactive Waste Disposal in Clay Host Rocks.

Studies of gas flow in disturbed rock are also part of the recently started FORGE Project (www.forgeproject.org).

In addition to the results from these projects the proceedings of the following meetings provide useful compilations of relevant literature.

- NEA workshop on Excavation responses in geological repositories for radioactive waste, Winnipeg, April 1988 (NEA 1989).
- EDZ workshop: Designing the Excavation Disturbed Zone for a nuclear repository in hard rock as part of the International Conference on Deep Geological Disposal of Radioactive Waste, Winnipeg 1996 (CNS 1996).
- NEA SEDE Topical Session on Characterisation and Representation of the Excavation Disturbed Zone, Paris, 1998 (NEA 2002).
- The 2002 International EDZ Workshop on the Excavation Damage Zone Effects (Martino 2003).
- EDZ CLUSTER Conference on Impact of the excavation disturbed or damaged zone (EDZ) on the performance of radioactive waste geological repositories, Luxembourg 2003 (EC 2005).
- ANDRA International Meetings on “Clays in natural and engineered barriers for radioactive waste confinement” in Reims (2002), Tours (2005), Lille (2007) and Nantes (2010). Proceedings of these meetings were published in Applied Clay Sciences (selected papers from 2002) and the Journal of Physics and Chemistry of the Earth (selected papers from 2002, 2005 and 2007).

2. DEFINITIONS OF THE DISTURBED AND DAMAGED ZONE

2.1 Previous Definition of Damaged and Disturbed Zone

Different definitions and names for the damaged or disturbed zone have been used within different programmes. Early studies used both "Disturbed Zone" (Kelsall et al. 1984, Pusch and Stanfors 1989) and "Damaged Zone". Fairhurst and Damjanac (1996) noted that "Excavation Damage Zone (EDZ) and Disturbed Rock Zone (DRZ) are used synonymously to describe the region of rock adjacent [sic] to an underground opening that has been significantly damaged or disturbed due to the redistribution of in-situ stresses".

Within the SKB ZEDEX Project (Emsley et al. 1997) a clear distinction between disturbance and damage was made and the Excavation Damage Zone was defined as:

> "a damaged zone closest to the drift wall dominated by changes in material properties which are mainly irreversible"

and the Excavation Disturbed Zone as:

> "a disturbed zone outside the damaged zone dominated by changes in stress state and hydraulic head and where changes in rock properties are small and mainly reversible and it is considered that there are no, or insignificant, material property changes."

Marschall et al. (1999) similarly discriminate between the disturbed and damage zone and note "that the term EDZ has been used ambiguously for both". They also suggest that "The boundary between the two zones is gradational as is the boundary between the disturbed zone and the undisturbed rock. The position of any defined boundary or envelope of the zones may also differ according to the properties of interest and the magnitude of changes that are deemed to be significant in a particular investigation."

Tsang and Bernier (2004) and Tsang et al. (2005), synthesizing discussions from the EDZ Cluster Conference and Workshop held in Luxembourg in November 2003, found that definitions of disturbed and damaged zones varied according to rock type and suggested the following definitions for future usage described below.

- The Excavation Disturbed Zone (EdZ) is a zone with hydromechanical and geochemical modifications, without major changes in flow and transport properties.
- The Excavation Damaged Zone (EDZ) is a zone with hydromechanical and geochemical modifications inducing significant changes in flow and transport properties. These changes can, for example, include one or more orders of magnitude increase in flow permeability.

The notion of reversibility of property changes used in previous definitions of the disturbed zone (largely from crystalline rock studies) is replaced by one based on significant changes in flow and transport properties, relating the definition of the EDZ to processes which are important for the long-term safety of a repository for the geological disposal of radioactive waste. Subsequent revisions to these definitions for argillaceous rocks (e.g., Blümling et al. 2007) added that "within the EdZ there are no negative effects on the long-term safety."

It should be noted that the presence of a hydraulically significant EDZ around an excavation is not necessarily wholly disadvantageous to long-term safety in that it might:

- Reduce hydraulic gradients by forming part of an "hydraulic cage";
- Provide additional fracture surface area (and accessible porosity) for retention of radionuclides;
- Provide low entry-pressure storage or flowpaths for repository-generated gas; and
- Potentially reduce permeability locally.

More recently Backblom (2008), focussing on crystalline rocks, has used the definitions described below.

- Damaged zone is a zone closest to the underground opening that has suffered irreversible deformation and in which shearing of existing fractures, as well as propagation or development of new fractures has occurred. Spalling, with blocks/slabs detached completely from the rock mass, will only occur in high-stress situations, whereas damage and disturbance will always occur due to creation of the underground opening.
- Disturbed zone is a zone dominated by change of state (e.g., stress, hydraulic head). The changes in rock mass properties are insignificant or reversible.

2.2 Definitions of the Disturbed and Damage Zone Used within this Study

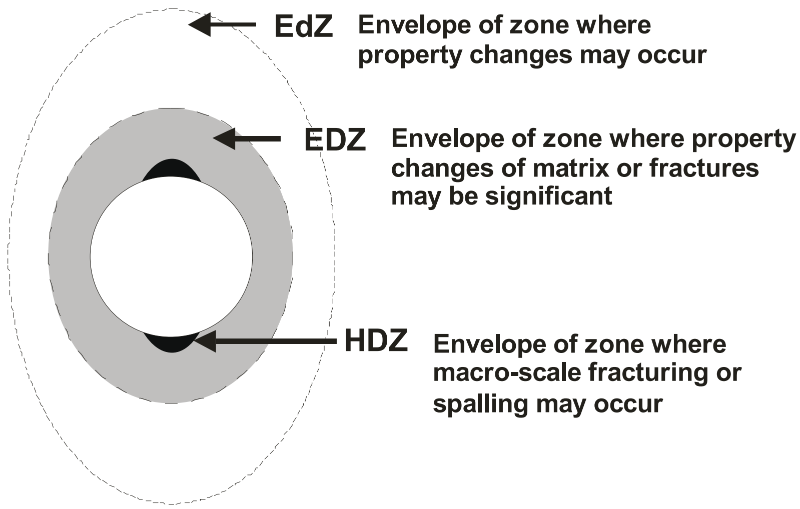
Within this study, given its focus on radioactive waste disposal and sedimentary rocks in particular, the definitions of Tsang et al. (2005) are used.

- The Excavation Disturbed Zone (EdZ) is a zone with hydromechanical and geochemical modifications, without major changes in flow and transport properties.
- The Excavation Damaged Zone (EDZ) is a zone with hydromechanical and geochemical modifications inducing significant changes in flow and transport properties. These changes can, for example, include one or more orders of magnitude increase in (effective) flow permeability.

In addition, within the study, a Highly Damaged Zone (HDZ) is defined as a zone where macro-scale fracturing or spalling may occur. The effective permeability of this zone is dominated by the interconnected fracture system and may be orders of magnitude greater than the undisturbed rock mass.

An HDZ will only exist where stresses are sufficiently high or where the excavation method creates a fractured zone (e.g., conventional drill and blast). The HDZ is part of the EDZ.

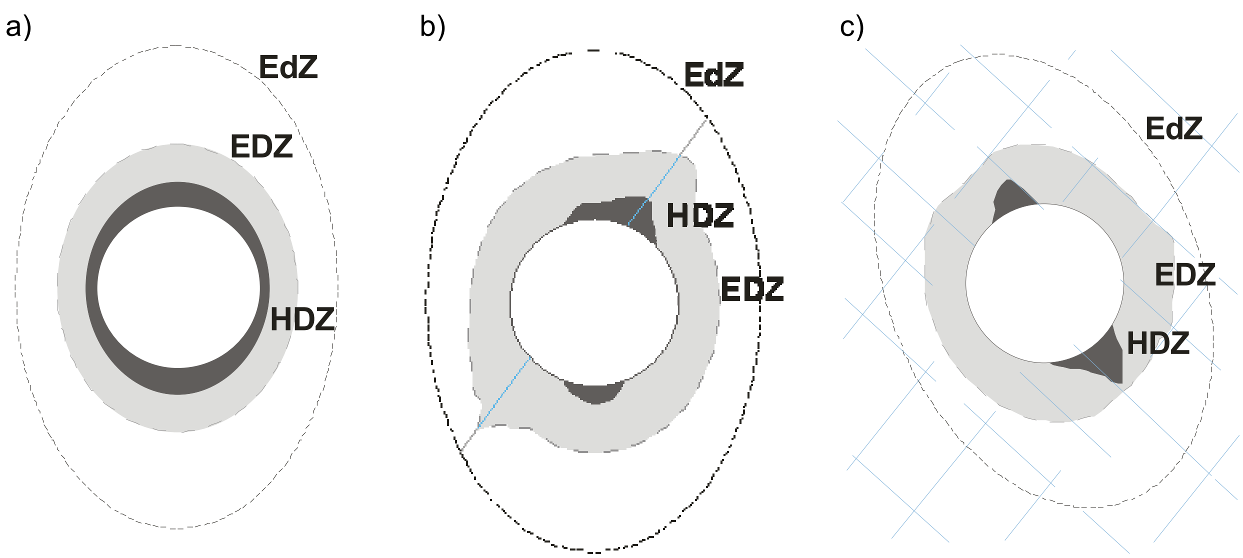
These zones should be treated as "envelopes" encompassing those regions where property changes may occur, but also potentially including regions of unaltered rock properties (just as unaltered rock lenses may occur within a fault damage zone). The definitions are illustrated in Figure 2.1.



Note: Unjointed rock in an anisotropic stress field with mechanical excavation (e.g., roadheader or tunnel boring machine). The HDZ is part of the EDZ.

Figure 2.1: Schematic Illustrating Definitions of EdZ, EDZ and HDZ

The possible influences of excavation method and pre-existing features are illustrated in Figure 2.2. More energetic excavation methods (e.g., conventional drill and blast) may create a local HDZ at the excavation perimeter while in fractured rocks pre-existing features may alter the pattern of matrix damage and may be reactivated, resulting in significant changes in permeability.



Note: a) Extension of HDZ due to local fracturing around blast holes; b) Modification of EDZ and HDZ due to pre-existing fracture; c) Modification of EdZ, EDZ and HDZ in jointed rock.

Figure 2.2: Illustrations of Possible Influence of Excavation Method and Pre-Existing Structures

When identifying the extent of the different zones it is useful to identify particular target properties e.g., permeability or fracture transmissivity. The extent of the EdZ, in particular, may be difficult to define in that small variations in stress and pore pressure due to the excavation may extend large distances but may not be of significance.

It is important to note that the definitions are relative to the properties of the undisturbed rock and so require either well-defined values of the undisturbed properties or demonstration of a stabilisation with distance from the excavation to values consistent with the expected range of undisturbed properties. In fractured rocks variability in fracturing along an excavation may create significant variability in the extent of the different zones and it may be necessary to define upper bounds for the zone extent.

Within this report the definitions set out above have been applied to the results of studies that may have used other definitions. While the definition of the EDZ is relatively consistent, the HDZ has been identified on the basis of the information available and has been taken to be the envelope of fracturing described in the source documents.

In some numerical flow and transport models, the EDZ is represented as an inner and outer ring of altered properties around excavations. Normally these rings indicate only regions of different hydraulic properties and may not correspond to the different zone definitions described here. Within subsequent chapters the extent of the different zones around excavations has been expressed as the normalized radius, r, defined as the radial distance from the excavation centre divided by a radius of the tunnel wall (for non circular tunnel profiles an average radius is used). Thus a ring with outer radius 1.3r corresponds to a zone 0.3r thick around an excavation.

It is also useful to define the Engineered Barrier System (EBS) as “the man-made, engineered materials of a repository, including the waste form, waste canisters, buffer materials, backfill, and seals” (Bennet et al. 2006). While the “near-field” includes the EBS and those parts of the host rock in contact or near the EBS, whose properties have been affected by the presence of the repository (NEA 2003). This definition of near-field therefore explicitly includes the EDZ.

3. CHARACTERIZATION OF THE EDZ

3.1 Introduction

A wide range of methods have been used to investigate the structure and properties of the EdZ and EDZ. The choice of methods depends on:

- Specific aims of the investigation (characterization of structure, extent, properties, monitoring of evolution);
- Excavation method and support;
- Number and geometry of boreholes that can be drilled;
- Formation properties and state (e.g., saturation); and
- Available time and budget.

In this chapter four types of measurements are considered: geological, hydraulic, geophysical and geomechanical. The first three typically relate to characterization during and after excavation, while geomechanical measurements are usually associated with either “mine-by” experiments or monitoring of the evolution of the EdZ and EDZ. Hudson et al. (2008) provide an overview of characterization and modelling of the EDZ in crystalline rocks.

3.2 Geological Characterization

Fractures/damage induced by excavation can be identified from detailed logging of core (fractography) and mapping of excavation walls.

3.2.1 Borehole Core Drilling and Logging

For EDZ studies it is necessary to distinguish between induced fractures, natural fractures/discontinuities and drilling artefacts. Core can be oriented either by mechanical means or by correlation with borehole images. At Mont Terri, good quality core has been recovered using double and triple-core barrel methods (Bossart and Thury 2008). Detailed core logging methods have been developed for the Opalinus Clay (for examples see Yong et al. 2006) and it has been possible to identify:

- Artificial discontinuities caused by drilling or core handling;
- EDZ unloading joints;
- Features showing evidence of shear (striations or fibres); and
- Lithology changes.

Where borehole cores are not available (i.e., when using destructive drilling or due to poor core recovery) borehole images can provide information of fracture location and orientation, together with some limited geological characterization (e.g., categorization into joint, lithological contact, fault).

Testing of borehole cores for geophysical and hydromechanical properties can be used to identify the extent of the EDZ, by showing changes in matrix properties (e.g., porosity and water content Matray et al. 2007) and gas permeability (Autio et al. 1998). Where core samples are taken for subsequent analysis (especially for geomechanical testing) precautions should be taken to minimize sample disturbance by limiting unloading and exposure to the atmosphere (see for example Zhang and Rothfuchs 2004 for treatments of Callovo-Oxfordian Argillite samples from Bure). In general, samples of weak clay rocks are likely to have been disturbed and to demonstrate non-linear behaviour (Blümling et al. 2007). In extreme cases core-disking may occur limiting the ability to take samples. This may either be stress-controlled with disking normal to the borehole axis (as discussed in Blümling et al. 2007) or in shales be bedding parallel (“poker chips”). With regard to the effects of sample disturbance Blümling et al. 2007) comment:

> “Regardless of the amount of confinement, deformation and strength parameters determined from such samples will be significantly less than the properties of undisturbed samples. When dealing with weak, tight rocks with very fine pores and high reactivity with water, environmental conditions (humidity), pore water pressure, drilling fluids (air or oil), and sample storage and handling, can also significantly decrease the quality of drill core.”

Core disturbance will be influenced by the altered stress-state around excavations such that disturbance (either micro-cracking or disking) will be a function of the position of the borehole relative to the excavation and in situ stress direction and the distance from the excavation wall. In the Mol URL in plastic Boom Clay an unusual chevron disking pattern is observed that mimics the large scale fracture pattern observed in tunnels at the site (see Figure 4.13 and Blümling et al. 2007).

3.2.2 Mapping of the Excavation Surfaces

Mapping of excavation surfaces is also a valuable technique, in particular, niche or tunnel crossing excavations that cut into the side-wall of previously excavated tunnels (see Figure 3.1) can be used to study the extent of the EDZ around excavations (Martin and Lanyon 2003a), although the process of excavation may result in enhancement of the existing EDZ fractures in the original tunnel wall.

Note: Figure from Martin and Lanyon (2003a).

Figure 3.1: Stress-induced Extension Fracturing Observed on the Left Side of a Niche

Göbel et al. (2005) provide an example of surface mapping of a short shaft (3 m diameter 7 m deep) at Mont Terri (HE experiment). The maps show “few true EDZ fractures could be identified. Most of them are due to the mechanical reactivation (slip) of bedding planes or of sub-parallel fault planes". It was found that the correlation between surface maps and structural mapping of borehole cores (21 boreholes) from around the shaft was good.

Detailed examination of fracture surfaces is also possible and can provide useful information as to the origin and connectivity of features. At Mont Terri the presence of small gypsum spots on fracture surfaces have been observed in the first metre of the tunnel wall, where the fractures are air-filled and where oxidation reactions have occurred (Bossart et al. 2004). This has been interpreted as indicating the depth of the connected EDZ fracture network.

Surface mapping of shafts can be semi-automated as at the MIU URL at Mizunami where the shaft walls are routinely photographed and thermal imaged followed by surface mapping by geologists. A valuable technique for studying the EDZ around shafts is to map the floor (where possible) of niches or stations as described by Everitt et al. (1988).

3.2.3 Resin Injection and Overcoring

A refined technique for geological characterization of the EDZ has been developed at Mont Terri (Bossart et al. 2002, 2004) and applied elsewhere (Armand et al. 2007) using fluorescence-doped resin injection prior to overcore. This method allows very detailed interpretation and identification of open fractures in the EDZ, estimates of in situ aperture and can provide information on the connectivity of fractures. Injection pressures should be limited to prevent "hydrofracture" or fracture enhancement due to the resin injection (Martin and Lanyon 2003a). Investigations at Mont Terri demonstrated differences in EDZ fracturing between drill and blast and mechanical excavation methods (Bossart et al. 2004). The likelihood that EDZ fracture system geometries will vary according to location (e.g., invert versus side-wall) make it important to plan any programme of overcoring with reference to the controls on EDZ development e.g., excavation method, rock quality, tunnel orientation and location around the tunnel (Armand et al. 2003).

A variant of the resin-injection method can be used to investigate the disturbed and damaged zone around boreholes. At Mont Terri, the stress anisotropy and relatively low strength of the Opalinus results in borehole collapse that can then be overcored. In highly-stressed rock where stress/fabric failure modes are dominant the overcore can be designed to contain the complete Borehole Damage Zone (BDZ) and can be used as an analogue for the EDZ around excavations.

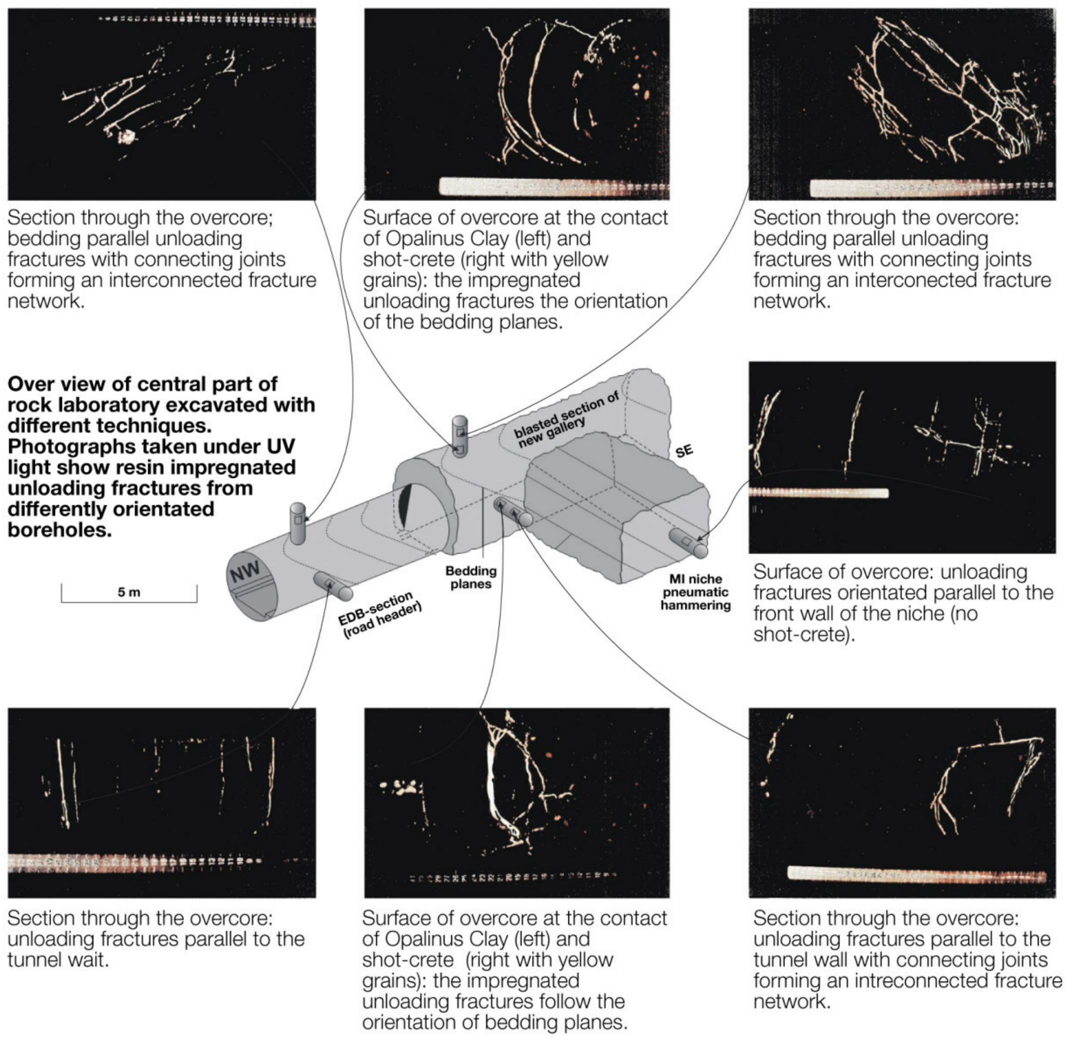
Further sampling of the EDZ is possible via slotting (used at Bure, AECL URL and Äspö) and block extraction. In the Zedex experiment at Äspö slotting was combined with dye penetration tests (Emsley et al. 1997) to determine the hydraulic connectivity of EDZ fractures. Similar studies have been performed at the Onkalo facility in Finland (Mellanen et al. 2008).

3.2.4 Geophysical Characterization

A wide-range of geophysical methods has been used to characterize the EDZ including: ground penetrating radar (GPR), resistivity, sonic/ultrasonic measurements and acoustic emission (AE). Recent studies have also looked at seismo-electrical methods. Measurements can be made as "point/interval" measurements along boreholes or via tomographic approaches.

3.2.4.1 Sonic and Ultrasonic Measurements

Ultrasonic interval velocity measurements probably provide the simplest method of geophysical characterization. These can be stand-alone or integrated with tomographic or reflection surveys. The methods have been applied at both Mont Terri and Bure. Schuster and Alheid (2007) describe the estimation of EDZ and EdZ extent in 43 boreholes from 85 to 504 m depth around the PA-Shaft at the Bure site using the BGR mini-sonic probe. Shao et al. (2008) describe investigations around a test drift at 445 m depth. They detected an elliptical EDZ around the drift by integrating results from ultrasonic, hydraulic and core logging (see Figure 3.3). The different measurement methods correlated well.



Notes: Overview of fracturing in central part of the Mont Terri laboratory excavated using different methods. Photographs taken under UV light show resin-impregnated unloading fractures from differently inclined boreholes. Figure from Bossart et al. (2002).

Figure 3.2: Example of Results from Resin Injection Studies

Similar measurements were made at the Mont Terri URL as discussed in Martin and Lanyon (2003a) and at Tournemire (Contrucci et al. 2007) to delimit the extent of the EDZ.

Tomographic surveys have also provided valuable information. Tomographic surveys have been performed at Bure (Armand et al. 2007, Aranyossy et al. 2006, Balland et al. 2009) and Mont Terri (Damaj et al. 2007). Suzuki et al. (2004) identify a low velocity zone as relating to a highly fractured EDZ around a tunnel in Cretaceous sedimentary rocks at a depth of about 500 m.

Interpretation of the EDZ extent at Mont Terri is complicated by the anisotropic nature of the Opalinus at the rock laboratory (Martin and Lanyon 2003b). Other issues in interpretation relate to pre-existing heterogeneity (e.g., sandy lenses within the Opalinus or healed fractures at Mont Terri and limestone nodules at Tournemire).

3.2.4.2 Acoustic Emission

Acoustic emission surveys require pre-instrumentation with multiple geophones to detect, locate and analyse microseismic and other acoustic events. These systems have been used in crystalline rocks at the AECL URL and Äspö to monitor excavation. They can also be used at the laboratory scale to monitor geomechanical testing (e.g., Eberhardt 1998).

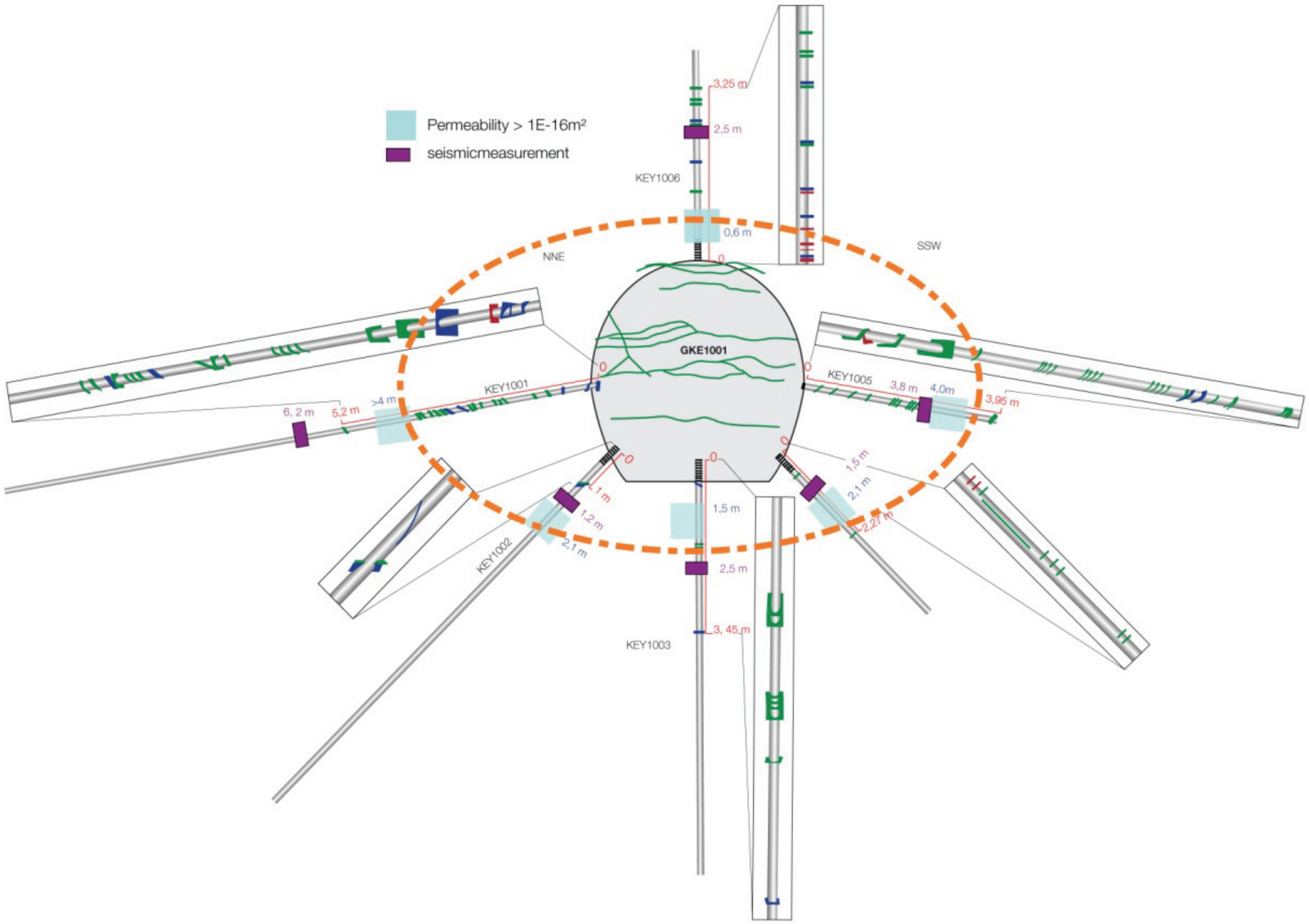
Acoustic emission monitoring was used at Mont Terri within the ED-B experiment, data quality problems were encountered relating to borehole conditions, but some emission events were detected in the side wall of the ED-B section. A permanent monitoring system was also installed for the EB experiment, Schuster et al. (2004) comment that “Acoustic emission events are very rare. During the first 13 months about 100 events could be detected”.

The opening and closure of a borehole at the Hades URL in Boom Clay was also monitored using AE and although events were detected they were “hard to analyse” (Bastiaens et al. 2007).

3.2.4.3 Resistivity/Geo-electrical Measurements

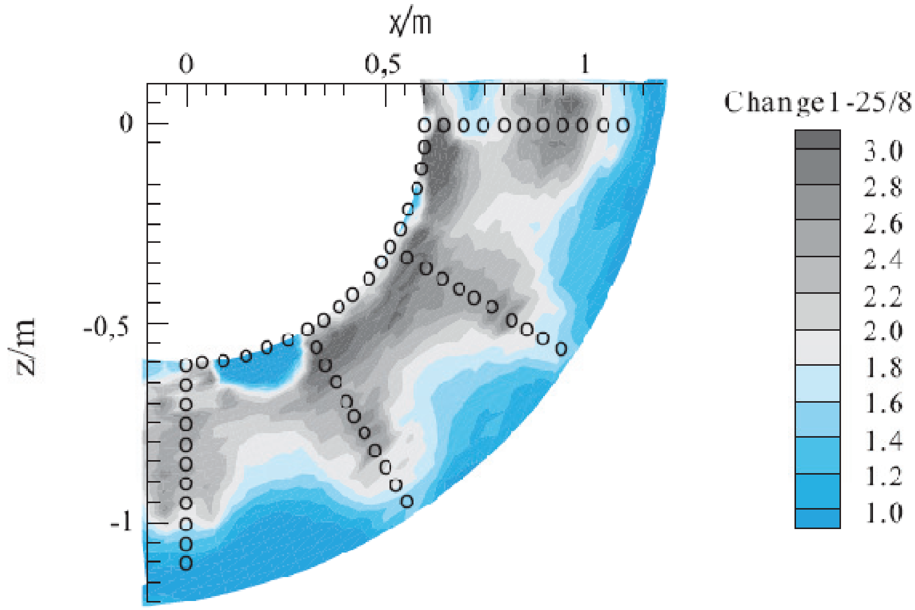
Geo-electrical and resistivity measurements are sensitive to changes in water content/pore saturation, temperature, pore fluid, rock electrical properties and fracturing.

At Mont Terri geo-electrical/resistivity tomographic surveys have been used in several experiments to identify the EdZ and EDZ or to monitor their evolution. In the ED-B tunnel tomographic surveys identified a low-resistivity zone in the tunnel roof, which was believed to relate to unsaturated conditions (Martin and Lanyon 2003a). Around the EB tunnel a variable thickness zone was detected, with the greatest extent again in the roof (Kruschwitz and Yaramanci 2004). Gibert et al. (2006) monitored the evolution of the EdZ and EDZ around the newly excavated Gallery 04. The apparent resistivity was imaged on three different sections of the gallery over a period of 6 months. The results were then successfully correlated with structural models of the EDZ and pre-existing tectonic features. Resistivity measurements were also used to monitor the Heater (Göbel et al. 2005), Ventilation (Mayor et al. 2005a) and Engineered Barrier Experiments (Mayor et al. 2005b) at Mont Terri. Figure 3.4 shows the change in resistivity (as a factor) over 6 months at the Heater Experiment.



Notes: EDZ envelope shown in orange, seismic measurement in brown and permeability in blue. Figure from Shao et al. (2008).

Figure 3.3: Inferred EDZ Around Test Drift at 445 m at Bure



Notes: Saturation in dark grey coloured area ranges around 52%. Increase in resistivity indicates drying/desaturation. Figure from Mayor et al. (2005a).

Figure 3.4: Change in Resistivity (Ratio) Between August 2003 and January 2004

Suzuki et al. (2004) report acoustic and resistivity tomography surveys from two tunnels, one in a hard Cretaceous sedimentary formation containing coarse grain sandstones and conglomerate and the second from a TBM tunnel in Cretaceous cherts and shales. The surveys were repeated on an annual basis for 3 years. Changes in resistivity were largely interpreted as resulting from changes in saturation and fluid properties (possible increase in salinity).

3.2.4.4 Radar Measurements

Radar measurements are sensitive to the electrical conductivity of the rock and structures within it. Changes in electrical conductivity within the EDZ might relate to differences in water content/saturation, fracturing or pore fluid salinity.

Ground penetrating radar has been used extensively in crystalline rocks to image structures around boreholes and has recently been trialled for determining the extent and connectivity of the EDZ in the Onkalo facility in Finland (Silvast and Wiljanen 2008).

At Tournemire Rejeb and Cabrera (2007) report that radar profile measurements clearly showed an EDZ of 1 to 1.5 m in the old tunnel, but did not identify an EDZ around the 1996 gallery.

3.2.5 Hydraulic Characterization

Flow within the EDZ is likely to be localized in the fractured HDZ (if present) and correlation with detailed geological (core or borehole viewer) and geophysical measurements (e.g., interval velocity) requires testing over short intervals. The expected permeability range is also likely to be large between fracture damaged zones and undisturbed low permeability rock requiring relatively small system compressibility. Special hydraulic testing systems for the EDZ have been developed by ANDRA, Nagra and BGR (Bundesanstalt für Geowissenschaften und Rohstoffe) and used to characterize the rock around excavations in crystalline and clay rocks.

- SEPPI System: The SEPPI probe was developed by ANDRA and tested at the AECL URL (Souley et al. 2001), Äspö (Zedex) (Emsley et al. 1997) and Mont Terri Rock (Bossart et al. 2002). The tool is intended as a logging/survey instrument rather than a semi-permanent installation or borehole completion.
- MMPS: The MMPS system developed for Nagra has been used to characterize the EDZ at GTS (Marschall et al. 1999), Mont Terri (Armand et al. 2004, Martin and Lanyon 2003a), Tournemire (Matray et al. 2007) and Bure. An evaluation of its use in sedimentary rocks is described by Nakaoka et al. (2006 - in Japanese). The system is a miniature packer system suitable for hydraulic and pneumatic testing and monitoring.
- BGR have developed “surface packers” that may be applied to the tunnel wall and used for testing and monitoring (Marschall et al. 1999).

The key technical challenge to hydraulic characterization of the EDZ is to provide an efficient method to determine hydraulic properties over short intervals at different locations around the excavation over a wide range of permeability (presence/absence of fractures). Analysis of hydraulic tests in the EDZ may also be complex. Baechler et al. (2010) identified the following problems with the analysis of hydraulic tests in the EDZ at the SUG drift in Bure:

- Difficult to simulate the measurements with a coherent parameter set;
- Unexplained variations in hydraulic properties with time; and
- Inconsistencies in derived parameters with the distribution of fractures in core, observed formation stabilization and estimated discontinuity radius from other measurement methods.

Baechler et al. (2010) reanalyzed previous tests accounting for the partially saturated zone around the drift and the borehole damage zone and derived excellent matches between measurements and simulations that showed permeability estimates consistent with core observation and formation properties together with a consistent evolution with time. The high permeability fractured zone around the SUG drift extended only about 0.5 m into the rock suggesting a smaller HDZ than that identified in the KEY drift (Shao et al. 2008).

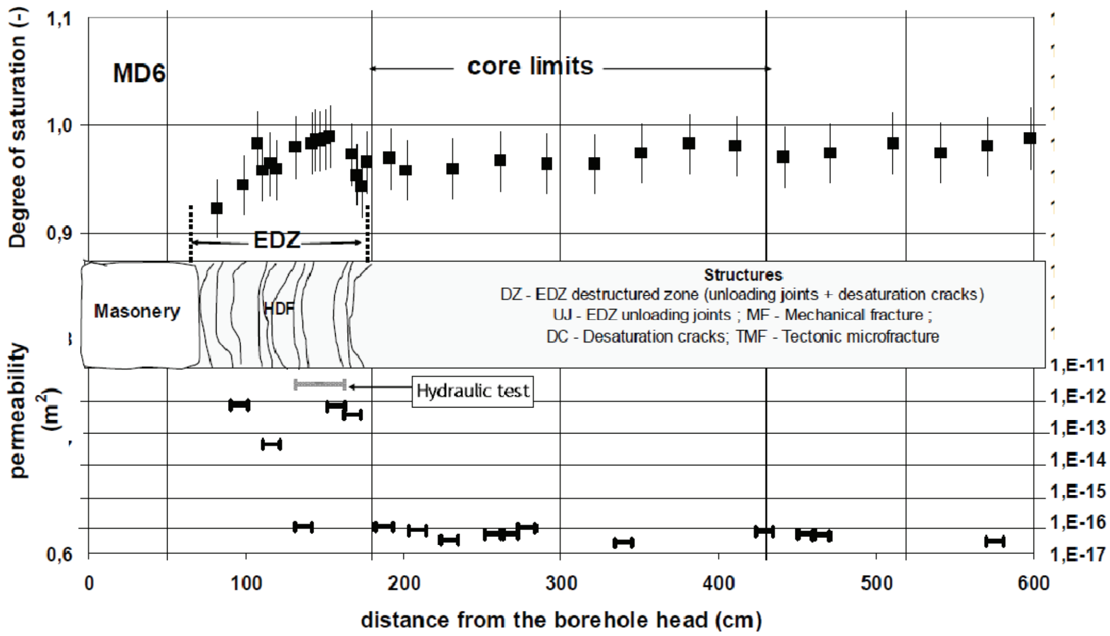
Pneumatic testing is an alternative to hydraulic testing in partially saturated systems (e.g., Matray et al. 2007). In such situations saturation measurements are also possible using Time Domain Reflectometers (TDRs), Relative Humidity (RH) probes or measurements from core samples. Figure 3.5 shows a compilation of different measurements made in boreholes drilled from the Old Tunnel at Tournemire (Matray et al. 2007).

3.2.6 Geomechanical Characterization

Geomechanical measurements typically focus on deformation and stress around the excavation and are most useful in Mine-By and EDZ monitoring applications where time series data can be used to develop an understanding of ongoing changes in the EDZ.

Measurement methods include:

- Deformation: Convergence arrays, deflectometers, inclinometers; and
- Stress: Total pressure cells and borehole stressmeters.



Notes: Saturation from petrophysical measurements on core samples. Permeability from hydraulic and pneumatic tests. Figure from Matray et al. (2007).

Figure 3.5: Borehole Data from Around the Old Tunnel at Tournemire Showing Saturation, Structural Interpretation and Permeability

Fierz et al. (2007) discuss the design and performance of instrumentation for a Mine-By test in the Callovo-Oxfordian Argillite at the URL at Bure and Rejeb (Bure and Rejeb 2003) discusses monitoring EDZ time-dependent behaviour at Tournemire using convergence measurements.

A recent study at Mont Terri (Yong et al. 2006) has provided a very detailed description of response to excavation using point displacement measurements and a panoramic laser scanner to develop 3D profiles. The displacement data have been integrated with:

- Geological mapping, core logging and borehole imaging;
- Refraction, borehole and cross-hole seismic;
- Pore pressure monitoring; and
- Spectral gamma logs.

3.2.7 Geochemical Characterization

Geochemical changes in the tunnel near-field may occur due to:

- The creation of oxidizing conditions through exposure to the air;
- The flow of fluids at the excavation wall or within the rock; and
- Interaction with construction materials.

At Mont Terri mapping of fracture surface minerals (gypsum spots) has been used to identify the extent of the connected fracture system (Mäder and Mazurek 1998, Bossart et al. 2002). Where geochemical disturbance is due to fluid flow, water chemistry within the rock can be monitored by periodic sampling in zones with sufficient permeability.

4. FAILURE MECHANISMS, FORMATION, STRUCTURE AND EVOLUTION OF THE EDZ

4.1 Introduction

This chapter sets out an overview of the mechanisms that lead to failure around excavations and goes on to discuss observations from Underground Research Laboratories. The influence of excavation method and pre-existing structures are also briefly discussed. Evolution of the damaged zone is discussed and a summary of damaged zone observations is provided in terms of shape and extent of the EdZ, EDZ and HDZ.

4.2 Classification of Failure Mechanisms

The stability of excavations in brittle rocks (e.g., Martin et al. 2001) can be considered under three classes:

- Structurally controlled failure;
- Stress-controlled failure; and
- A combination of structure and stress controlled failure.

In clay-rich rocks additional processes related to wetting can lead to failure:

- Swelling, weakening and softening (Steiner 1993, 1996 and Einstein 1996, 2002); and
- Shrinkage during drying and loss of strength due to repeated wetting/drying cycles (Rejeb and Cabrera 2007).

4.2.1 Structurally Controlled Failure

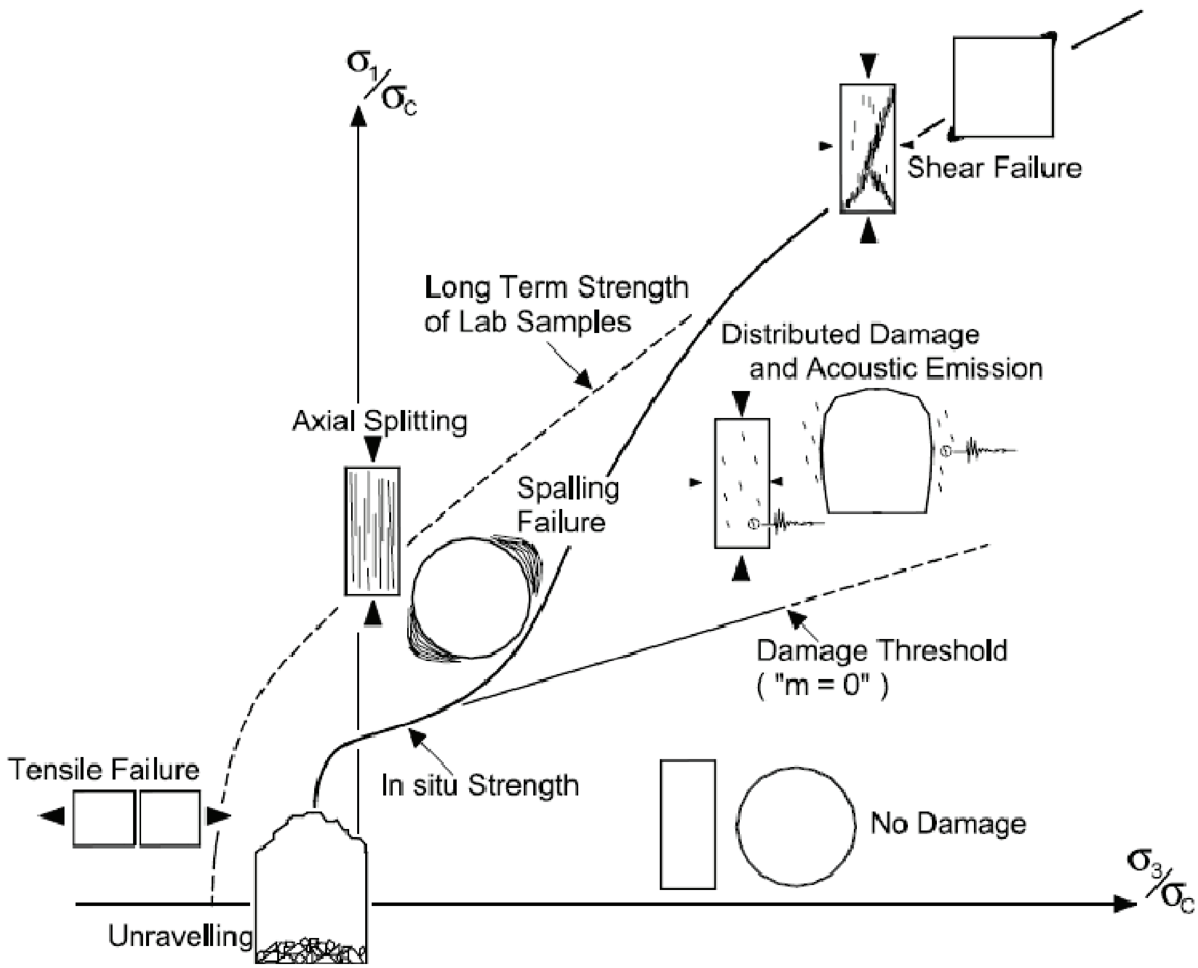
Structurally controlled wedge-type failures caused by loss of confinement and the existence of suitably oriented discontinuities are common in low-stress environments and commonly affect the tunnel roof. Wedge-failures may also occur within shafts where unfavourably oriented discontinuities occur. The key issues here are maintenance of a compressive stress regime (Diederichs and Kaiser 1999) and assessment of the geometry of the relevant discontinuity sets.

Such failure-modes are relatively easily controlled if the discontinuity orientations are known, although problems may occur at excavation intersections or where unexpected discontinuity orientations occur. Given the low likelihood and specific nature of such zones the damage zone around such structurally-controlled failures is not considered further here.

4.2.2 Stress Controlled Failure

Diederichs (2007, 2003) sets out a framework for stress-controlled brittle failure of tunnels identifying five behaviours: no damage, distributed damage, shear failure, spalling and unravelling as shown in Figure 4.1. Compressive failure is associated with either:

- Spalling and unravelling at low confinement where microcracks propagate creating macrofracturing, or
- Macroscopic shear failure at higher confining stress, facilitated by microcrack interaction.



Note: Four zones of distinct rock mass failure mechanisms are shown: no damage, shear failure, spalling and unravelling. Figure from Diederichs (2007).

Figure 4.1: Schematic of Failure Envelope for Brittle Failure

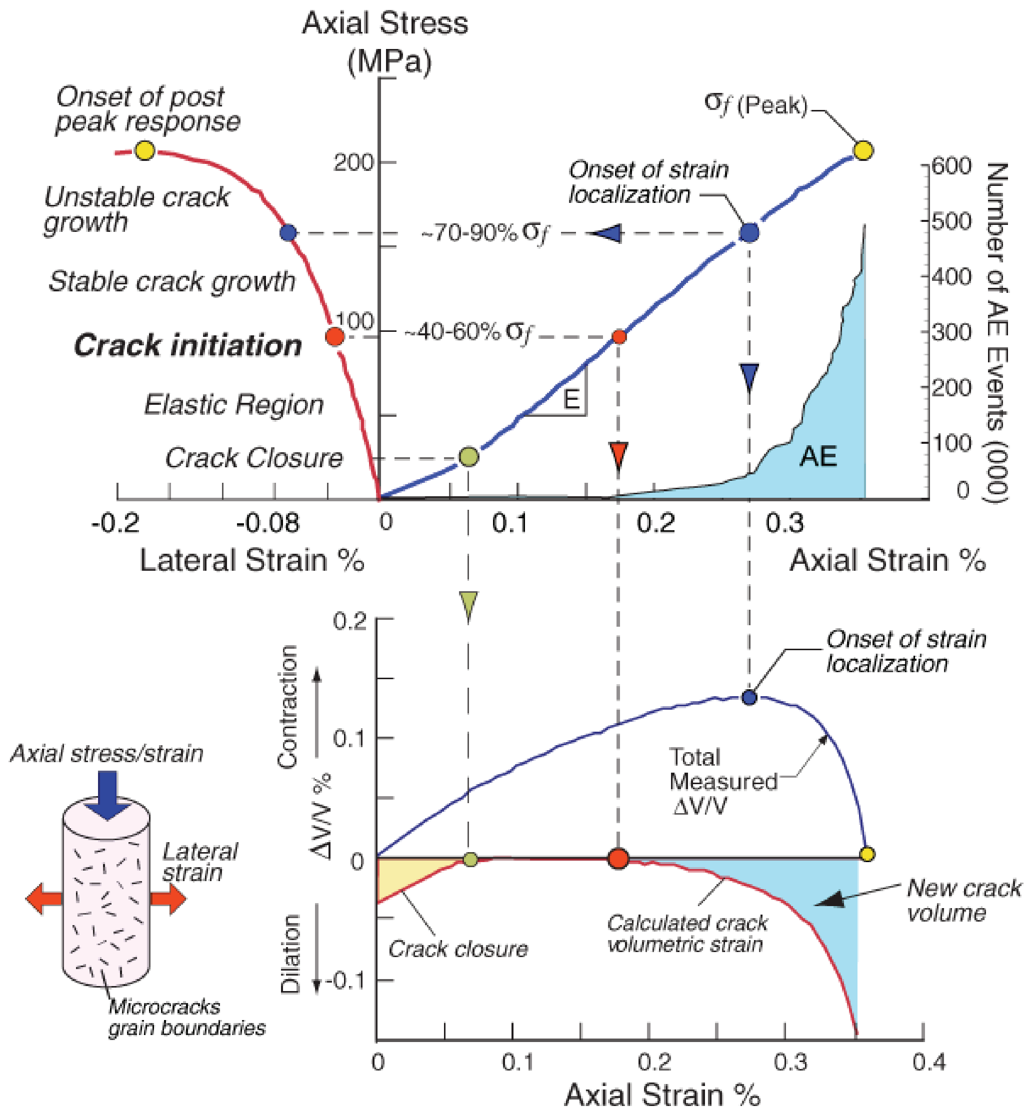
These different mechanisms are described by a trilinear failure envelope and relate to the concepts of Martin and Chandler (1994) shown in Figure 4.2, parameterized by:

σ_{Ci} Crack initiation stress – onset of stable crack growth

σ_{Cd} Crack damage stress – true peak strength or long-term strength

σ_{C} Uniaxial Compressive Strength (UCS) short-term strength

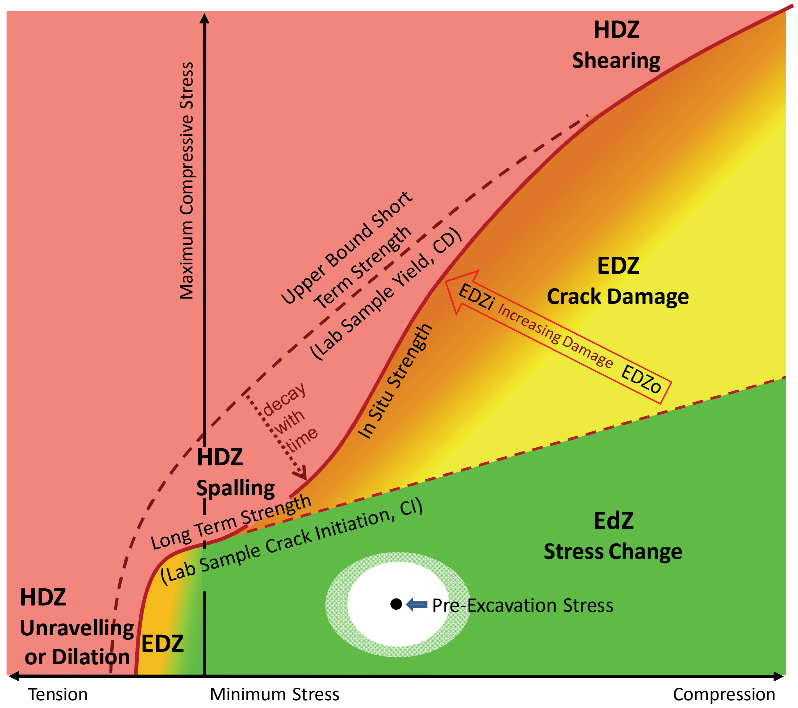
Figure 4.3 relates the brittle failure model of Diederichs (2007) in Figure 4.1 to the definitions of the EDZ and HDZ used here. Note that the EdZ may be defined in terms other than stress change (e.g., temperature, chemistry or pore pressure change). In argillaceous rocks processes related to humidity and desaturation/resaturation cycles are not captured in this diagram and will be discussed later in this chapter.



Note: Figure from Martin and Chandler (1994).

Figure 4.2: The Crack Initiation Stress, Crack Damage Stress, and Peak Stress

While this approach has been developed with reference to crystalline rocks (and in particular the Lac du Bonnet granite), Eberhardt (1998) investigated its applicability to sandstone and potash and found similarities in the behaviour and thresholds. Similar findings of the onset of micro-cracking and damage at stresses significantly below rock strength have been identified by Popp and Salzer (2007) for the Opalinus Clay. They argue that a dilatancy approach (based on concepts of Hunsche and Schulze 2003) can be applied to the Opalinus Clay as shown in Figure 4.4. Subsequent studies (Popp et al. 2008) demonstrated that the influence of “the overlapping effect of matrix compaction” makes detection of dilatancy depend on measurement sensitivity and direction (relative to bedding). They further suggest that a simple correlation between damage and permeability is unlikely and that the application of the “dilatancy concept” to clay rocks is difficult.



Note: Figure from Diederichs and Martin (2010).

Figure 4.3: Schematic of Failure Envelope for Brittle Failure Showing Zones of Distinct Rock Mass Failure Mechanisms and Relationship to EDZ Definitions

Results from observations at URLs are used to illustrate different failure mechanisms in the discussion below. Strong stress and material anisotropy, together with the influence of pre-existing structures and sensitivity to moisture make the tunnel near-field at Mont Terri a particularly rich environment to study induced fracturing and damage.

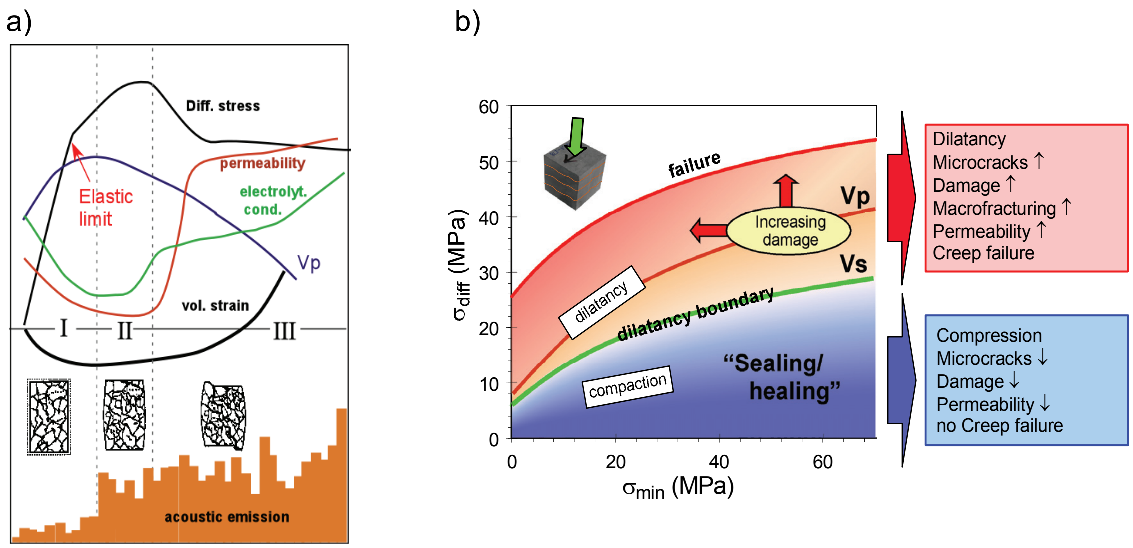
4.2.3 Stress and Structural Failure

4.2.3.1 Bedding Related Failure

Slip on bedding planes (or similar structures) is a common failure mode in anisotropic shales and is often observed in hydrocarbon exploration boreholes (e.g., Økland and Cook 1998, Willson et al. 1999). Martin and Lanyon (2003a) identified bedding slip as an important failure mode at Mont Terri. Where bedding is oblique to the excavation an “en echelon” array of slips developed as shown in Figure 4.5a. This process is exaggerated where swelling and weakening occurs due to humidity as shown in Figure 4.5b. Martin and Lanyon (2003a) identified regions of potential slip using a Mohr-Coulomb criterion:

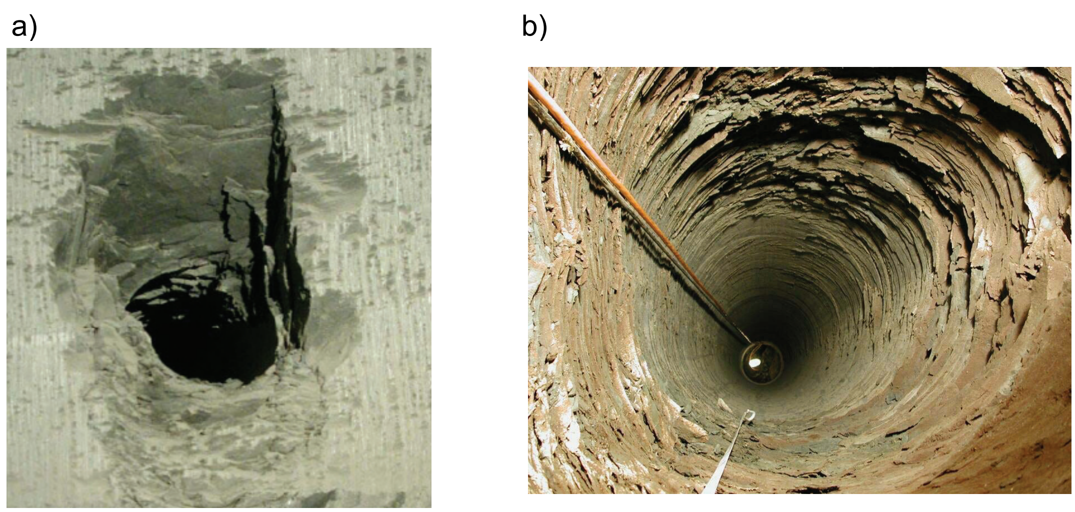
$$\tau = c + \sigma_n' tan\varphi$$

where: τ is the shear stress and σ_n the effective normal stress of the plane, and the strength is captured by a frictional strength, φ, and cohesion, c. They found that using laboratory-derived values for φ and c resulted in an overestimate of the extent of the slip zone. This might either have been due to an underestimate of bedding plane strength or to the partially saturated conditions resulting from ventilation and excavation-induced poroelastic effects. A more complex treatment of bedding plane strength in the Opalinus Clay is given by Popp et al. (2008).



Note: a) Schematic showing changes in physical properties during deformation; b) The Dilatancy Concept in Opalinus Clay referring to various stages of damage as represented by the Stress Dependent Seismic Boundaries of Vs and Vp. Figure from Popp and Salzer (2007).

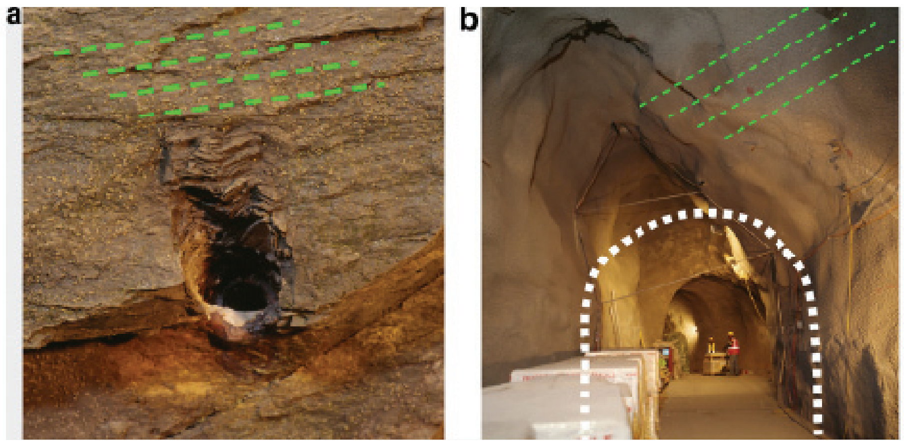
Figure 4.4: Dilatancy Concept



Note: a) As observed from the face of EB niche in the roof of a raise bore pilot hole and b) in a 600 mm-diameter vertical borehole after the borehole was sealed, allowing the air humidity to increase. Figure from Martin and Lanyon (2003a).

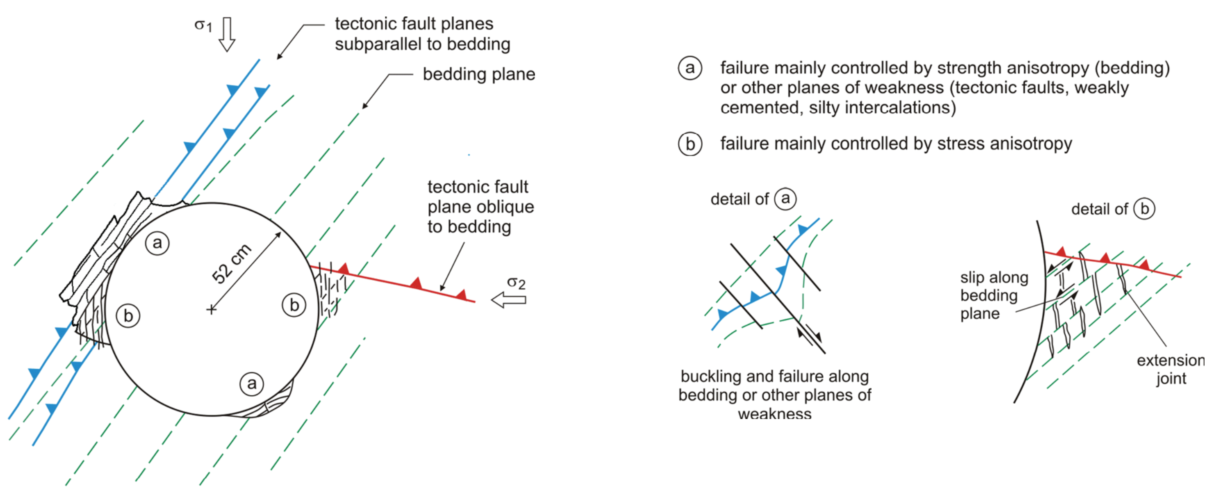
Figure 4.5: Bedding Slip at Mont Terri

Where bedding or other features are near-parallel to the excavation boundary, more extensive slabbing failures may develop (see Figure 4.6). These have been observed in resin-injected borehole over-cores (see Chapter 3) at Mont Terri. A chimney-like buckled zone develops with an internal kink-band structure. These features are most well-developed in collapsed boreholes at the site, but appear more limited in extent around the HG-A micro-tunnel, which was excavated along bedding strike (see Figure 4.7).



Note: Bedding planes in dash green lines. Figure from Blümling et al. (2007).

Figure 4.6: Development of Buckling Zones Around a Borehole and Large Tunnel



Note: Shows the key processes and features that affect excavation stability: slab-like breakouts on the upper left side are due to extensile failure along tectonic fractures. Wedge-like breakouts occur on the right side. Figure from Lanyon et al. 2009, modified after Marschall et al. (2008).

Figure 4.7: Schematic Representation of the Damage Zone Around the HG-A Microtunnel

A similar failure mode was described by Fairhurst and Cook (1966). Diederichs and Kaiser (1999) present an analysis of this failure mode for brittle rocks using the Voussoir beam analogy. The possibility that such mechanisms could create a large EDZ and HDZ in weak laminated highly stressed rocks is illustrated by Bandis (1990) who presents results from model excavations showing displacement to a depth of 3 to 4 diameters (Barton 1993).

4.2.3.2 Influence of Pre-existing Features

The influence of pre-existing features on the development of the tunnel near-field occurs through:

- Local alteration of stress field and redistribution of stresses after excavation and consequent changes in EDZ geometry and extent;
- Reactivation of structures changing transmissivity (e.g., opening a sealed fracture); and
- Creation of additional connectivity in the HDZ fracture network.

Observations from Mont Terri show clear control of the development of unloading fractures by pre-existing tectonic structures.

The pattern of tunnel over-break and fracturing at the HG-A microtunnel (Marschall et al. 2008, Lanyon et al. 2009a) suggests that bedding parallel features and tectonic faults (sealed in undisturbed conditions) result in locally more intense failure and that such features may delineate the failed zone as shown in Figure 4.7. The anisotropy of the rock results in two different breakout modes relating to strength anisotropy (Blümling 1986) and stress anisotropy. These different modes add to the complexity of the EDZ structure.

Yong et al. (2008) show trace-maps (Figure 4.8) indicating the influence of such pre-existing features and perform numerical simulations to show how the pattern of deviatoric stress is influenced by the existence of low stiffness bedding parallel features.

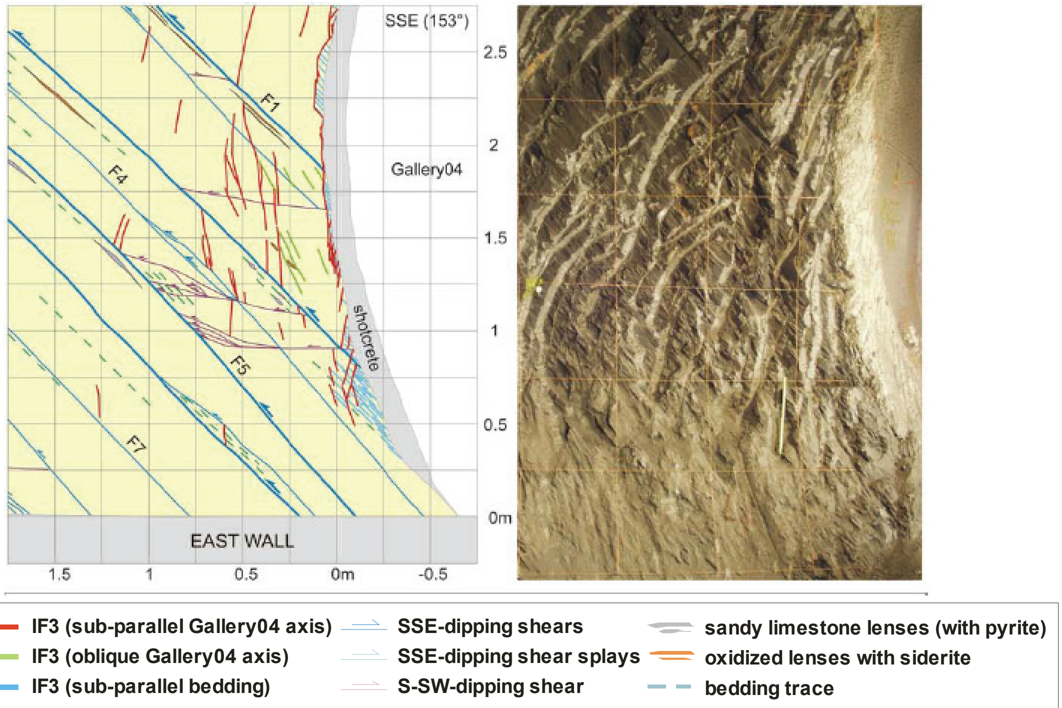
The results from Mont Terri show the potential for pre-existing features to create a more intense but localized HDZ. The structural controls shown in Figure 4.7 and Figure 4.8 indicate that unless such features are axial to the excavation these zones will typically only result in locally enhanced flow and will not form a continuous pathway along the excavation (Olsson and Winberg 1996 come to a similar conclusion).

4.3 Influence of Excavation Method

A limited number of studies have considered the influence of different excavation methods on the extent and properties of the EDZ in sedimentary rocks.

Bossart et al. (2002) compare excavation by drill and blast (data from 10 boreholes) and by road header (data from 8 boreholes) at Mont Terri. They suggest that the "roadheader results in a smaller extent of the EDZ and smaller frequencies of unloading fractures, smaller apertures and a more consistent orientation of fractures." Data from two boreholes in a niche formed using a pneumatic hammer resulted in higher fracture frequency than either the roadheader or drill and blast excavation (Bossart et al. 2002).

Matsui et al. (2003) report a comparison between drill and blast excavation and mechanical excavation using a boom-header for 2.4 m diameter horseshoe cross-section NATM drifts. P-wave velocity surveys showed a significantly greater low velocity zone around the drill and blast tunnel as shown in Figure 4.9. They suggest that the EDZ has a thickness of about 0.8 m and 50 to 60% of the P-wave velocity of intact rock for the drill and blast tunnel, with hydraulic conductivity increased by more than one order of magnitude within a maximum of 1.4 m from the drift wall. Simulations suggest that there should be no significant yield zone around the tunnels, indicating that the fractured HDZ was caused by blasting.



Note: Figure from Yong et al. (2008), Trace-maps originally by Nussbaum.

Figure 4.8: Trace-map and Photograph Showing Induced Fracturing in the East Walls of the EZ-B Niche Entrance

Experience from crystalline rock supports the view that the relative importance of excavation method is dependent on the magnitude of stress relative to rock mass strength.

4.3.1 Low-stress Environments

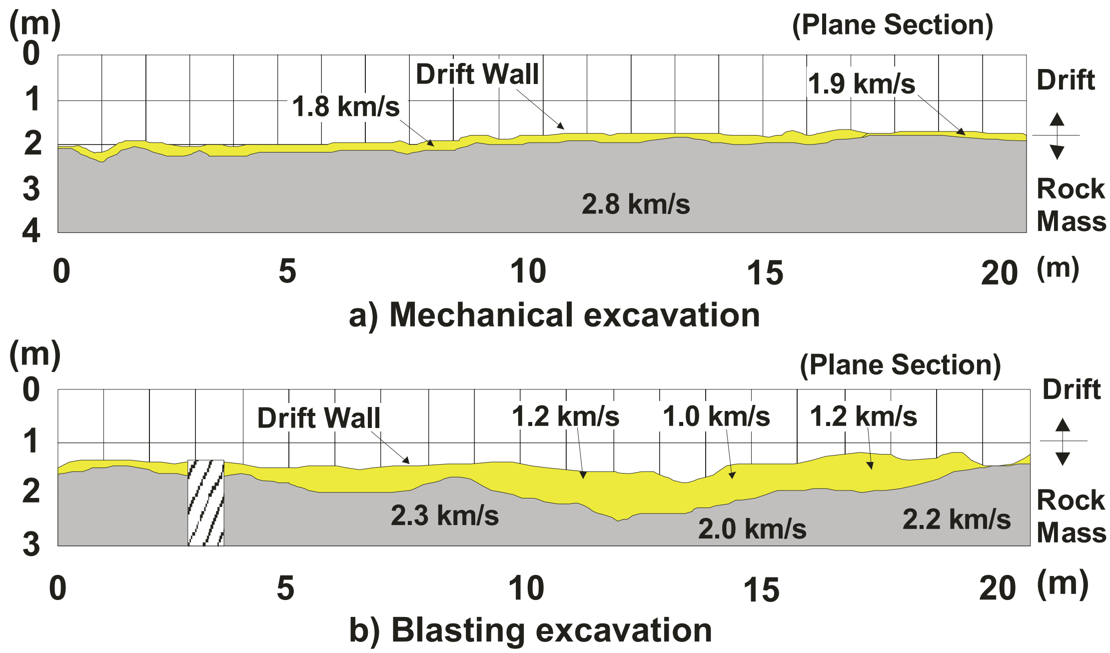
Experience in low-stress environments suggests that the extent of the EDZ and HDZ will be dominated by the influence of excavation method rather than by the creation of the void. In particular drill and blast methods will result in a greater EDZ extent.

<u>Example 1: Tono Mine, Marine Sediments (120 m depth)</u>

At the Tono mine 2 parallel 2.4 m wide, 22 m long drifts were excavated (Sato et al. 2000), one by drill and blast and one by mechanical methods (roadheader). Rock-mechanical, vibration, ultrasonic and hydraulic measurements were performed. Numerical models suggested that there would be no yield zone around the excavation, suggesting that any fracturing is due to the excavation method (Matsui et al. 2003).

Example 2: Zedex, Crystalline Rock (420 m depth)

The damage (i.e., increased fracturing) was concluded to be within 0.3 m in the walls and roof of the drill and blast tunnel and up to 0.8 m in the floor. For the TBM tunnel the damage was within 0.03 m (Backblom 2008).



Note: Figure from Matsui et al. (2003).

Figure 4.9: Distribution of P-wave Velocity Determined by Seismic Refraction Survey in the NATM Drift Evolution of EDZ

Example 3: Olkiluoto, Crystalline Rock (raisebore shafts vs drill and blast tunnel)

Comparison of GPR in drill and blast tunnels and raise-bore shafts at the Olkiluoto showed: The results indicate that there is a different response in GPR results between shafts excavated with raise boring and tunnels excavated with drill and blast method. The results from the GPR have not been calibrated and should therefore be treated with caution, but follow the general trend of differences between drill and blast and mechanical excavation.

Backblom (2008) summarizes the EDZ experience in crystalline rocks as follows.

For rock in a lower stress state, i.e., no spalling environment, the typical damage is dependent on the excavation method. Using mechanical excavation the damage is only a few centimetres and with hydraulic conductivity in the order of 10^{-10} m/s (Äspö) or lower (Olkiluoto and Grimsel, FEBEX).

A typical result for the openings excavated by drill and blast is a damage zone up to several tens of centimetres wide in which the damage progressively diminishes with the distance from the opening. The extent of the damage is dependent on the design and execution of the drill and blast operation, but it is assumed that the damage is insignificant beyond 0.8 m from the periphery (Backblom 2008).

More recent studies relating to the Q and S tunnels at Äspö by Ericsson et al. (2009) indicate that:

- Natural open fractures are the dominating hydraulic features that surround the tunnel if the excavation has been carefully blasted (as at the S-tunnel at Äspö HRL);
- The excavation disturbed zone as indicated by micro cracks has an extension of 250-350 mm into the tunnel wall; and
- There is no significant axial hydraulic connectivity due to the few blast-induced fractures.

4.3.2 High Stress Environments

In high stress environments excavation method may have some effect but is perhaps not the dominant control on EDZ extension as seen in low stress environments.

At Mont Terri, Bossart (2002, 2004) presents a comparison between excavation methods from a study of resin impregnated cores of tunnel walls. The results show greater extent and frequency in the drill and blast tunnels, although these may in part be due to the larger dimension of the excavation (~4.7 m wide, vs 3.5 m).

At the AECL URL Read (2004) comments that "The effects of excavation method were assessed by comparing drill-and blast and mechanically-excavated tunnels. The extent of the failed zone in the compressive regions around the two tunnels was similar, but the drill and blast MBE tunnel showed more damage in the tensile sidewall region, including some evidence of discrete tensile cracking."

A summary of the limited observations is given in Table 4.1.

Table 4.1: Comparison of Influence of Excavation Methods for Sedimentary and Crystalline Rocks

	Sedimentary rocks		Crystalline rock	
	Site	**Comparison**	**Site**	**Comparison**
High stress σ_{max}/σ_c>0.6	Mont Terri	Greater extent and fracture frequency in drill and blast tunnels	AECL URL (420 m)	Extent of failed zone in compressive regions was similar, greater damage in tensile regions in drill and blast tunnels.
Low stress σ_{max}/σ_c <0.6	Tono	Mech r_{EDZ} = 1.3[2] DandB r_{EDZ} =1.7-1.8	Zedex	Mech r_{EDZ} 1.01 DandB r_{EDZ} 1.1-1.2

The evidence from the URL in-situ experiments clearly shows that in hard rock tunnels, if stress-induced spalling is not a factor, the potential size and characteristics of the EDZ is simply related to the excavation method. Mechanical excavation methods will always produce less damage than drill and blast excavation methods. However, as recent findings by Ericsson et al.

[2] EDZ extent from velocity measurements, no significant change in hydraulic properties observed.

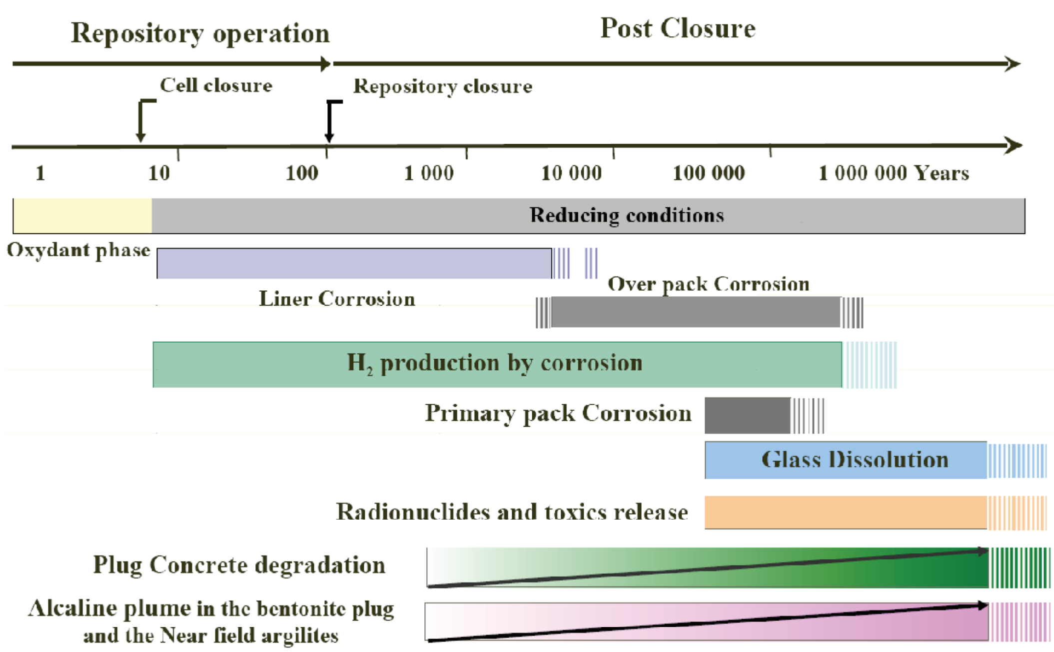
(2009) show, the small number of blast-induced fractures in the EDZ produced by careful blasting techniques, may not significantly increase the axial hydraulic connectivity in the EDZ. When stress magnitudes are sufficient to cause spalling there is a much greater chance for a continuous zone of enhanced axial permeability.

4.4 EDZ Evolution

Time dependent evolution of the EDZ after excavation can be due to:

- Creep, both in compression and shear (transition from control by short-term to long-term rock strength), see for example Kontogianni et al. (2006);
- Relaxation of failed material;
- Pore pressure equilibration in low permeability rock;
- Development of partially saturated zones and cyclic saturation/desaturation and consequent loss of strength; and
- Long-term changes due to the operation of the repository:
  - Thermal stresses;
  - Chemical interaction with the Engineered Barrier System (EBS); and
  - Opening/closure of other excavations causing changes in stress and pore pressure.

Figure 4.10 illustrates the different time-scales relevant to the geochemical evolution of the near-field for a High Level Waste/Spent Fuel repository in COX. The chemical evolution is dependent on the disposal concept (waste forms, buffer, plugs). Heat generating wastes add an additional transient.



Note: Figure from Aranyossy et al. (2006).

Figure 4.10: Geochemical Evolution of the EDZ

Of particular interest in low permeability sedimentary rocks are the effects of pore pressure equilibration and the development of a partially saturated zone.

4.4.1 Pore Pressure Equilibration

In low permeability rocks strain changes couple strongly to pore pressure due to the low hydraulic diffusivity resulting in effectively "undrained" compression of the rock mass (Tsang et al. 2005). The deformation due to excavation therefore results in significant pore pressure changes over several excavation radii. Pore pressure equilibration will occur over characteristic times $\sim\frac{d^2}{\eta}$ where: d is the excavation diameter (m) and η is the hydraulic diffusivity (m^2/s).

At Mont Terri in the ED-B Gallery Martin and Lanyon (2003a) identified regions of pore pressure increase in the tunnel sidewall and decrease in the roof and floor and related them to strain changes due to excavation (see also Bossart et al. 2004). In the tunnel roof and floor pore pressures are initially reduced and subsequently recover resulting in a decrease of effective stress, while in the sidewalls overpressures are initially created at excavation and then reduce. Martin and Lanyon (2003a) suggest that the hydraulic diffusivity of the Opalinus Clay at Mont Terri is between 10^{-8} and 10^{-7} m^2/s resulting in characteristic times for pore pressure equilibration of ~10 years.

Marschall et al. (2006) report similar pore pressure changes around the HG-A micro-tunnel and note that pore pressures continued to increase after excavation, which may be due to an ongoing development of the EDZ around the microtunnel. The induced pore pressure disturbance around HG-A equilibrated over a period of about 2 years. However, the situation is complicated by the response to other activities at and around the site. Ben-Slimane et al. (2003) also report the development of over pressure zones in the REP experiment at Bure due to the anisotropic stress field.

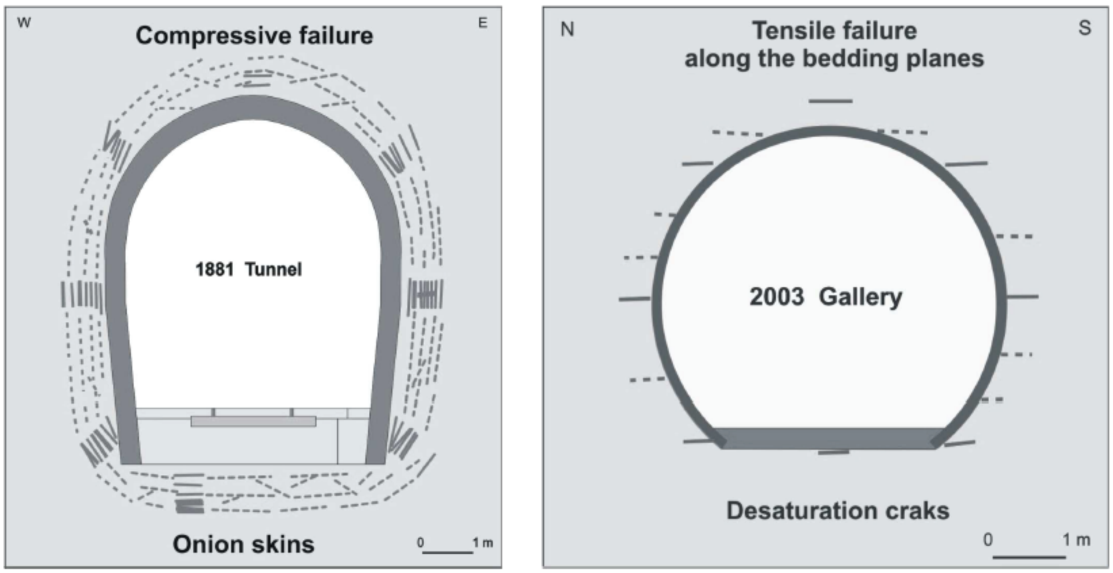
Cook (1999) discusses the effect of pore pressure on the strength of shales (here the term is used as a "catch-all" term for mudrocks) in the context of drilling properties and the effect of strain-rate (Swan et al. 1989 and Cai et al. 2007) on measured strength. Crack growth and coalescence is hindered when permeability is low as the pressure within an extending crack cannot be maintained. Reduced pore pressure and possible desaturation therefore result in effective strengthening of the rock and delayed failure may occur as pore pressure recovers. Martin and Lanyon (2003a) suggest that this may be the cause of ongoing deformation in the roof and floor in the ED-B tunnel at Mont Terri as bedding slip failures occur when effective normal stress on bedding planes reduce.

4.4.2 Desiccation/Desaturation Cracks and Effects of Desaturation/Resaturation Cycles

Desiccation cracks form through shrinkage when a partially saturated zone develops around the excavation. They are sensitive to the humidity within the excavation and may undergo annual cycles. At Tournemire these cracks are horizontal and formed along bedding planes soon after excavation in a zone about 0.4 m thick around the 2003 gallery as shown in Figure 4.11 (Rejeb and Cabrera 2007). Similar features have also been mapped in tunnel walls at Mont Terri (Yong 2008) and around the Mounting Chamber at Mol (Mertens et al. 2004) after an unusually long (several months) exposure to air.

Rejeb and Cabrera (2007) argue that the onion-skin fracturing observed around the 1881 Tunnel at Tournemire (see Figure 4.11) developed over time due to:

- Flaking due to tensile stresses developed from desaturation, which was stabilized by the masonry liner; and
- Long-term desaturation/resaturation phenomena possibly causing decrease in mechanical strength.



Note: Figure from Rejeb and Cabrera (2007).

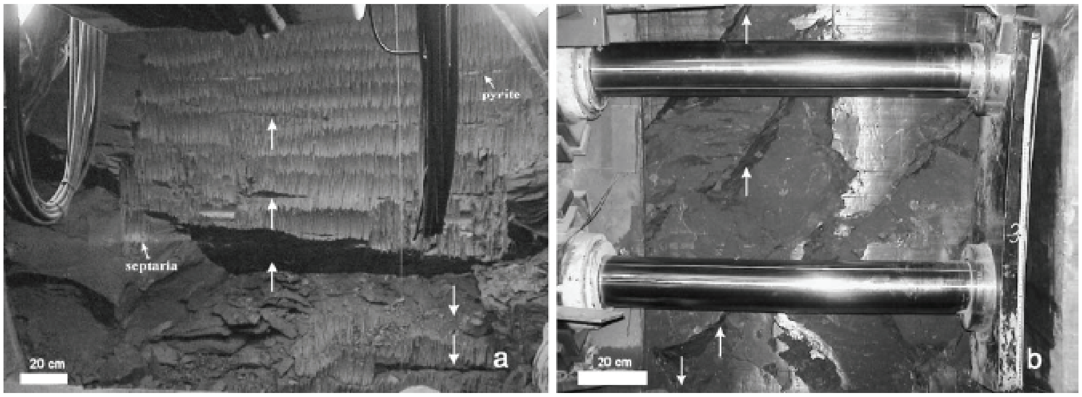
Figure 4.11: Failure Modes in the 1881 Tunnel (Left) and 2003 Gallery at Tournemire

Matray et al. (2007) demonstrated a correlation between the extent of the partially saturated zone and the EDZ extension from core and permeability measurements. Rejeb and Cabrera (2007) suggest that a “deferred failure has occurred around the 1881 tunnel due to a decrease in strength caused by desaturation/resaturation and hydric loading”.

4.5 Tunnel Near-Field in Argillaceous Rocks at Mol, Bure and Mont Terri

4.5.1 Tunnel Near-Field in Drifts at Mol

The tunnel nearfield in plastic clay has been studied at Mol (Mertens et al. 2004, Bastiaens and Mertens 2003). Investigations around the base of the 2nd shaft, performed prior to excavation of the Connecting Gallery in 2002, identified a zone of circular fracturing that extended to 7.5 m into the rock (12 m from the axis of the shaft, approximately 2.7 shaft radii) (Mertens et al. 2004). Investigation in the Connecting Gallery showed a much smaller fractured zone out to a maximum of 1 m from the tunnel wall (1.4 radii from the tunnel axis). The pattern of fracturing in the tunnel face and walls is shown in Figure 4.12.



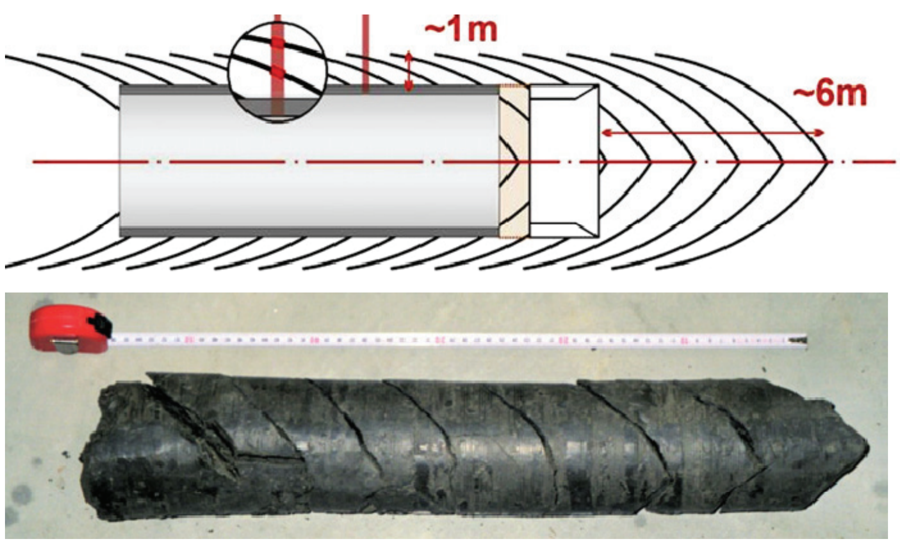
Note: Figure from Mertens et al. (2004).

Figure 4.12: Fracturing a) at the Tunnel Face and b) in the Sidewalls During Excavation of the Connecting Gallery at Mol

The fracturing showed a distinctive chevron pattern similar to that seen in drill-core (see Figure 4.13). In the Connecting Gallery fracture spacing was typically in the decimetre range. More complex fracture patterns were encountered at the ends of the Connecting Gallery due to interaction with the existing fractures. The smaller extent of fracturing (HDZ) was believed to be due to the better control of convergence practised during excavation of the Connecting Gallery with the liner being emplaced as quickly as possible after excavation (Mertens et al. 2004). A similar fracture pattern to that seen in the Connecting Gallery was identified around the Praclay Gallery (2.5 m diameter).

a)

b)



Notes: There is a similarity between the two fracture patterns. Figure from Blümling et al. (2007).

Figure 4.13: Fracture Patterns at Mol a) Around the Connecting Gallery b) Along a Boom Clay Borehole Core Induced by the Drilling Process

4.5.2 Tunnel Near-Field in Drifts at Bure

Delay et al. (2010) report significant differences in the EDZ around tunnels at the -445 m level and those at -490 m at the Bure URL.

At the level of the -445 m drift, in the more carbonated upper levels of the Callovo-Oxfordian layer, observations and measurements show that no fracture occurs and that the thickness of the micro-fissured zone is in the order of 0.1 to 0.2 times the diameter of the structure according to its orientation.

At the level of the -490 m drifts, the most clay-rich level of the Callovo-Oxfordian layer, observations and measurements are carried out during their excavation as described below.

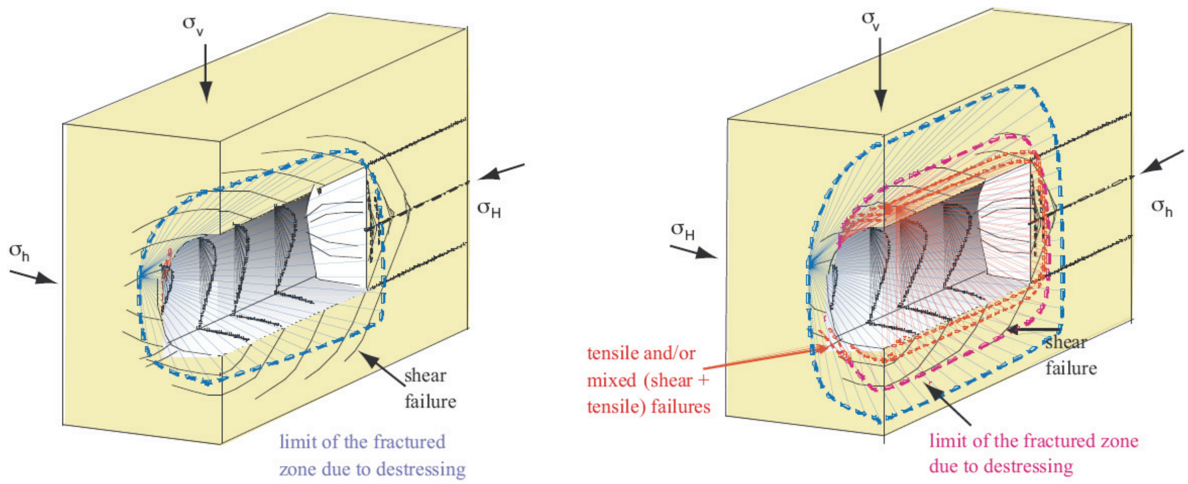
1. Shear fractures are observed at the excavation front face; they develop up to a maximum distance of 2.5 m of the wall face. The formation of these fractures is well reproduced by 3D digital simulations of the drifts excavation taking into account the excavation front face and its excavation speed. Hydraulic conditivity of the shear fractures is below 10^{-12} m/s, more than 0.2 to 0.5 times the radius of the drift. It ranges between 10^{-8} and 10^{-11} m/s near the wall.
2. In the zone fractured by deconfinement, measured hydraulic conductivity values range apoproximately between 10^{-8} m/s and 10^{-10} m/s. These measurements are consistent with the permeability estimated for the fractured argillaceous rocks (5×10^{-9} m/s). The maximum extension of the fractured zone in the vicinity of the laboratory drifts is about 0.2 times their radius, of the same order compared with that obtained through 2D modeling (0.1 times radius).
3. Beyond the fractured zone, values obtained through hydraulic conductivity measurements are less than 10^{-12} m/s and also less than those attributed to the microfissured argillaceous rocks. They indicate a limited or non-existent micro-fissure, as well as a very low permeability of the shear fractures. These values are consistent with the fact that strong mechanical stresses applied to shear fractures greatly restrict an increase in permeability.

These differences between the -445 and -490 m levels relate to the higher in situ stress and lower strength of the rock at -490 m and to possible interactions between excavations at the deeper level.

The shear fractures at the -490 m level discussed by Delay et al. (2010) form chevron fracture patterns (“herringbone” Wileveau and Bernier 2008). Fracture systems observed in drifts oriented in the σ_H direction are dominated by the chevron-shaped shear-failures similar to those observed at Mol. Drifts oriented in the σ_h direction show additional tensile and mixed-mode failures as illustrated in Figure 4.14. These patterns are overlaid by oblique and tensile fracture systems as shown in Figure 4.14 (Dedecker et al. 2006).

Delay et al. (2010) comment that:

“the conditions for the occurrence of shear fractures and their geometries seem to depend on the excavation conditions (speed and regularity of the excavation and installation of the supports of both the drifts and excavation front face). The installation of the first experimental drift at -490 m also highlighted the mechanical interactions among the structures according to their spacings.”



Note: Figure from Bordeau et al. (2007).

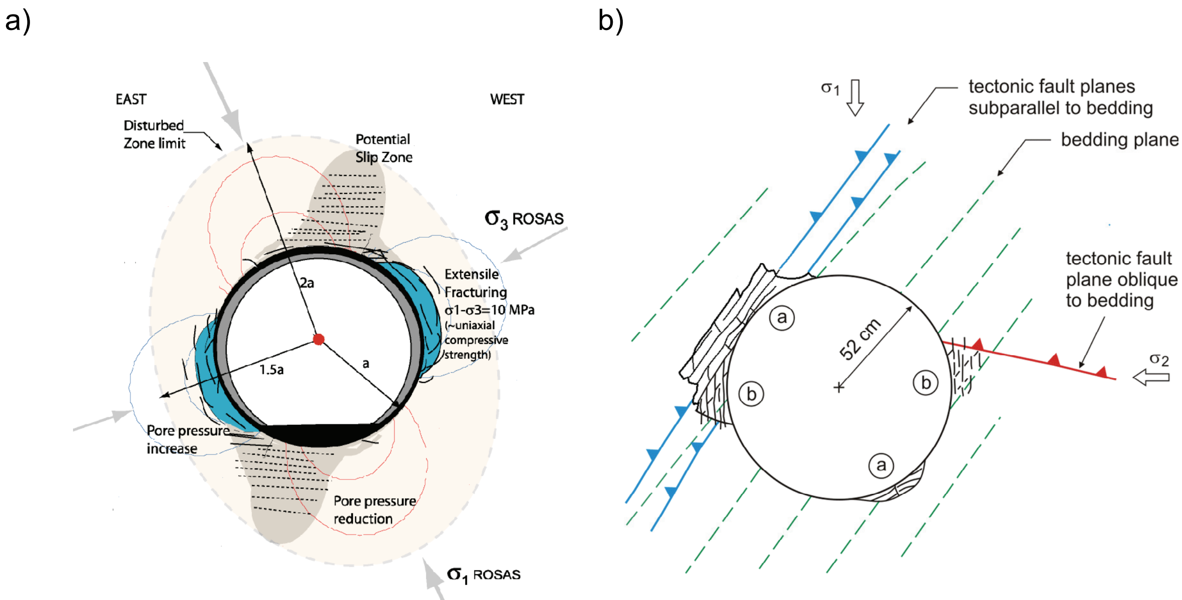
Figure 4.14: Schematic Fracture Patterns from Bure URL for Drifts at the 490 m Level in σH (Left) and σh (Right) Directions

The fracture patterns at the -490 m level in Bure can be considered intermediate between those observed at Mol in plastic clay and relatively isotropic stress field where fracturing is initiated ahead of the face and controlled by the convergence allowed; and those observed at Mont Terri in indurated clay with an anisotropic stress field and rock, where stress control initiates side-wall extension fracturing and bedding slip.

4.5.3 Tunnel Near-Field in Drifts at Mont Terri

The fracture systems around drifts at Mont Terri are shown in Figure 4.15. Fracturing around the lined ED-B, as described by Martin and Lanyon (2003a) comprises extension fracturing in the side walls resulting from the high differential stress (~10 MPa) and zones of bedding slip in the roof and floor, which may develop over time as pore pressures equilibrate (initially pore pressure reduces due to stress relaxation).

The EDZ around the HG-A microtunnel, where the tunnel runs along bedding strike and is approximately in the σ_h direction is described in Lanyon et al. (2009). Fracturing is largely associated with either pre-existing tectonic features or the zones where bedding parallel features are tangential to the excavation and a buckling failure occurs. The depth of the buckling failure appears to develop over time: it may be partially stabilized by the open microtunnel and may subsequently develop further after saturation and pressurisation of the microtunnel.



Note: (a) for the EDB drifts in σ_H direction and (b) for the HG-A microtunel in σ_h direction (along bedding strike). For explanation see Figure 4.7. in Martin and Lanyon (2003a) and Lanyon et al. (2009a).

Figure 4.15: Schematic Fracture Patterns from Mont Terri URL

A comparison of the induced fracturing at the four argillaceous URLs is given in Table 4.2 (for discussion of fracturing at Tournemire see Section 4.3). Fracturing at Mol and Bure (in σ_h direction) show similar herringbone shear-failures, while at Bure (in σ_H direction) and Mont Terri stress anisotropy is sufficient to induce extension fracturing (damage/spalling failure in the terminology of Diederichs (2000). Additionally, strong material anisotropy and pre-existing features are important in determining the geometry of the EDZ at Mont Terri. At Tournemire onion-skin fracturing appears to develop over time due to loss of strength and “hydric” (change in suction or pore pressure) damage leading to a reduction of strength.

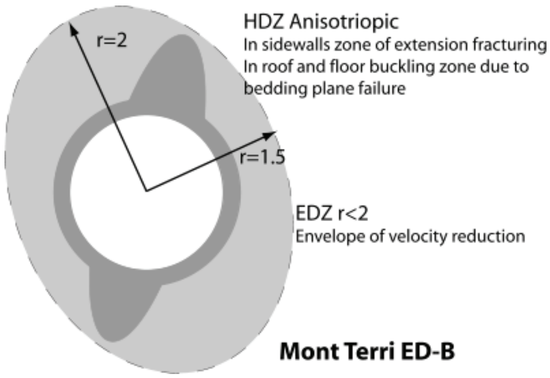
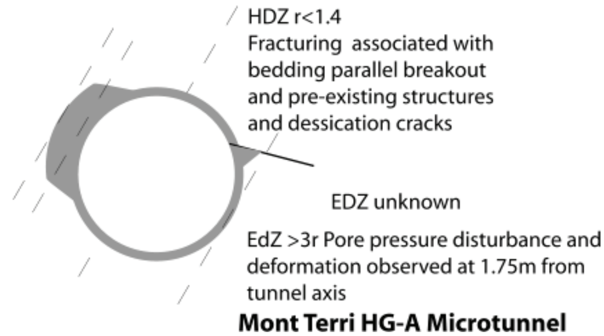
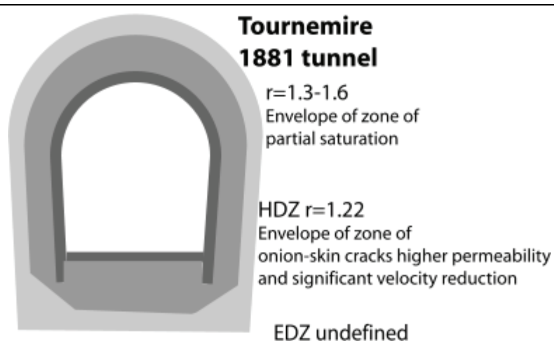
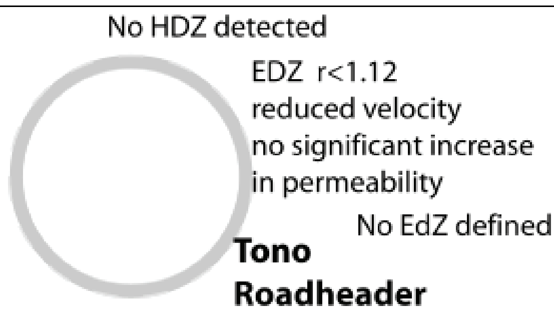
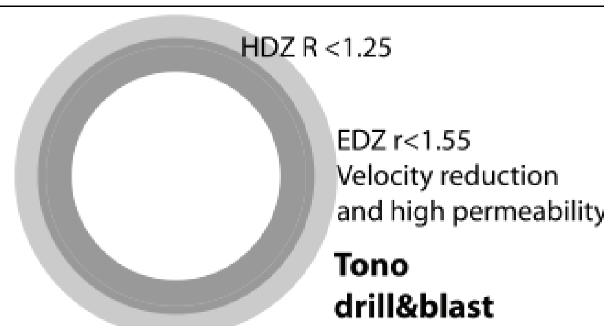
In order to aid the comparison the quantity σ_{max} has been defined as the maximum tangential stress based on elastic analysis around a (circular) opening. For a biaxial stress field (principal stresses σ_1,σ_2) $\sigma_{max}=3\sigma_1-\sigma_2$. The ratio of σ_{max} to Uniaxial Compressive Strength (UCS) has been used by Martin et al. (1999) to estimate the depth of failure around excavations in brittle rocks.

Table 4.3 tabulates the estimates of HDZ and EDZ extent from these URLs and that of Tono Mine. These estimations are expressed effective excavation radius.

Table 4.2: Comparison of Induced Fracturing Around Drifts at Mol, Bure, Mont Terri and Tournemire

	UCS MPa	Excavation Direction	Biaxial Stress (MPa)		Fracturing and Failure Modes	σ_{max}	σ_{max}/ UCS	Observed HDZ	Observed EDZ
			σ_1	σ_2					
Mol	2	Horizontal	4.5	4.5	Herringbone shear failure	9	4.5	<2.7	
Bure -490 m	21	σ_h direction	12	12	Herringbone shear failure	24	1.1	<1.2	<1.5
		σ_H direction	14	12	Herringbone +extension/mixed mode	30	1.4	<1.4	
Mont Terri	10-16	σ_h direction HG-A	6.5	4.5	Buckling failure+extension failure+ influence of existing features	15	0.9-1.5	<1.4	
		σ_H direction ED-B	6.5	2.5	Extension failure +bedding slip	17	1.1-1.7	Anisotropic	<2
Tourne-mire	13-32	Horizontal	4	4	Initial horizontal desiccation cracks (1996,2003 galleries)	8	0.3-0.6	<1.2	<1.2
					Subsequent “onion skin” extension fracturing (1881 tunnel)			1.22	

Table 4.3: Observed HD and EDZ Extents from Selected URLs as Dimensionless Radii

r = radial distance/effective excavation radius	
	
Sidewall extension fracturing and progressive bedding slip and buckling zone development in roof/floor (Martin and Lanyon 2003a, Bossart et al. 2004)	Buckling and failure on bedding parallel features and bedding slip associated with tectonic structures (Marschall et al. 2008, Lanyon et al. 2009a)
	
Delayed onion-skin fracturing caused by initial flaking due to desaturation and hydric loading (Rejeb and Cabrera 2007, Contrucci et al. 2007)	Horizontal desiccation cracks form along bedding planes soon after excavation (Rejeb and Cabrera 2007, Matray et al. 2007, Contrucci et al. 2007)
	
Mechanical excavation No fracturing or permeability increase detected – narrow reduced velocity zone (Matsui et al. 2003)	Drill and blast excavation. Fracturing and permeability increase believed to be solely due to effect of blasting (Matsui et al. 2003)

<table>
<tr><th colspan="2">r = radial distance/effective excavation radius</th></tr>
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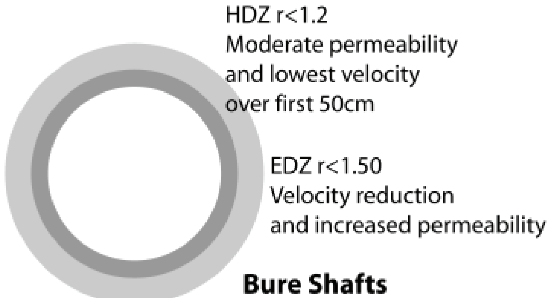
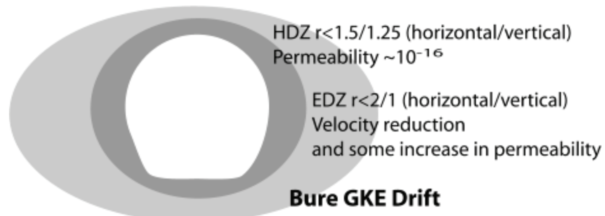
<td>

(Bauer et al. 2003a)</td>
<td>

Chevron fractures together with tensile/oblique features (Shao et al. 2008)</td>
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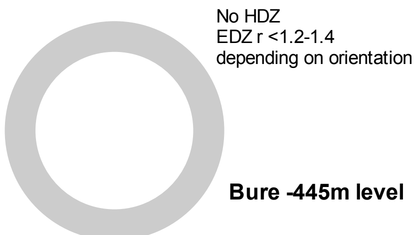
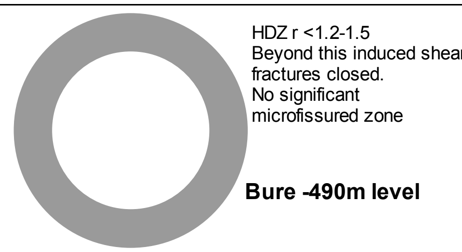
<td>

No fracturing observed Delay et al. (Delay et al. 2010)</td>
<td>

Shear fractures induced ahead of face and deconfinement fractures in drift wall (Delay et al. 2010)</td>
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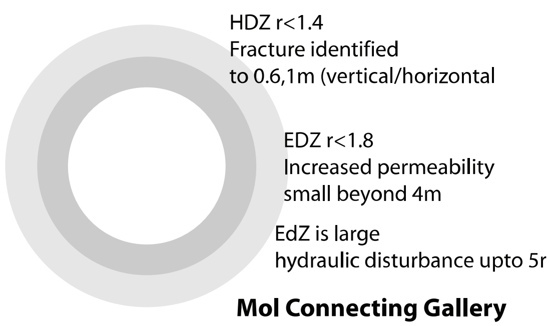
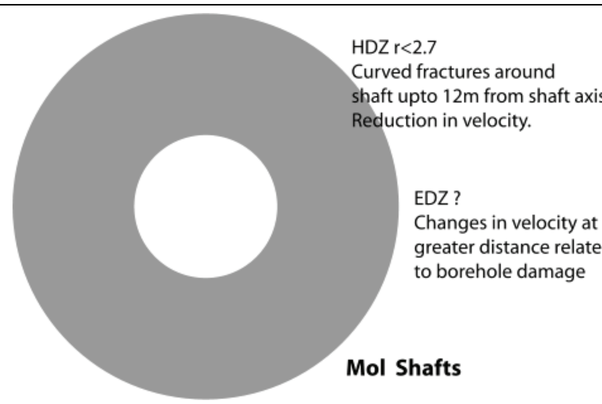
<tr>
<td>

Curved herringbone pattern chevron fractures. Limited convergence due to liner installation (Mertens et al. 2004, Bastiaens and Mertens 2004)</td>
<td>

Large curved shear-failure fractures. Extent of EDZ fractures controlled by convergence (Mertens et al. 2004)</td>
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5. FLOW AND TRANSPORT IN THE EDZ

5.1 Introduction

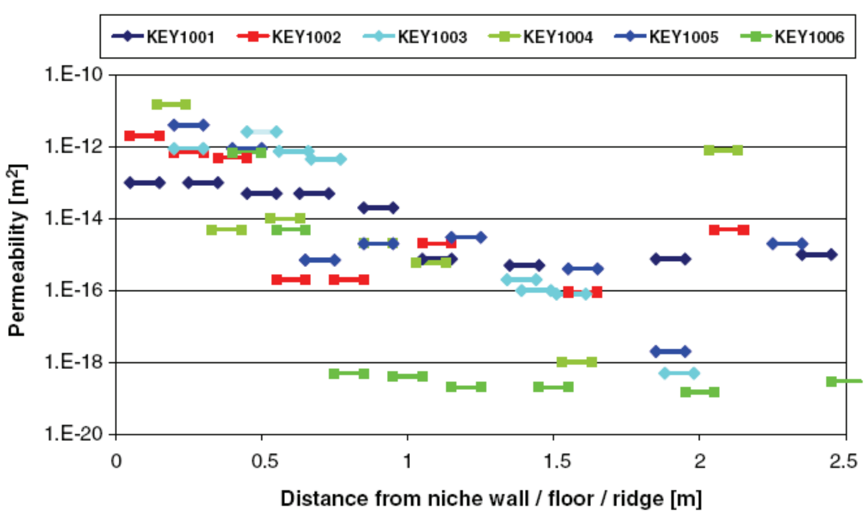
An important issue for the performance of the near-field around repository shafts and tunnels in low permeability sediments is the role of the HDZ and EDZ as a potential preferential flow path for water and gas. In this chapter the evidence for enhanced flow properties from several URLs is presented.

5.2 Observations of Air and Water Flow

5.2.1 Local Flow Measurements

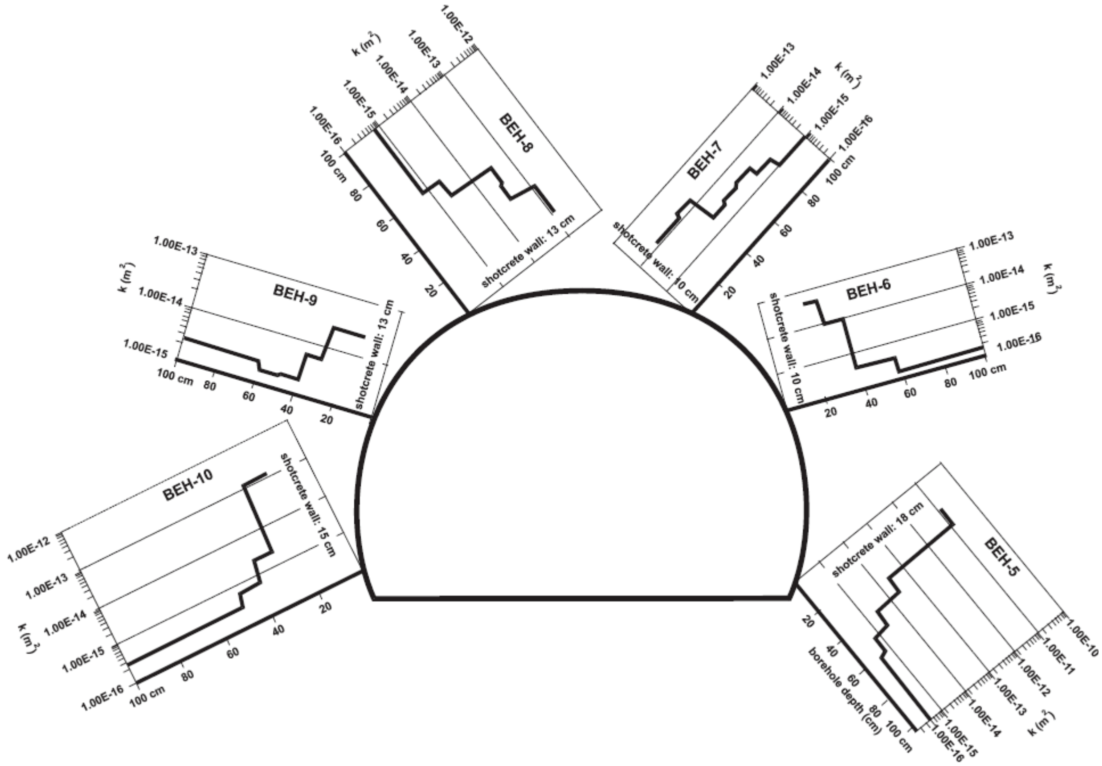
The most common measurements of flow in the EDZ are single borehole pneumatic or hydraulic tests (as discussed in Chapter 3). The expected spatial variability in HDZ and EDZ requires multiple boreholes preferably in different orientations around the tunnel (e.g., floor, sidewall, roof). The proximity to the excavation wall, potentially acting as a constant atmospheric pressure boundary, may limit the radius of investigation of the tests and require detailed analysis (Baechler et al. 2010).

At sites where it is expected that microfracturing in the EDZ is significant (relative to the HDZ), coring and core testing may provide an alternative to borehole testing although problems may occur as a result of sample disturbance and the stress redistribution due to the tunnel presence. Results from many experiments show a reduction in either fracture transmissivity (in HDZ) or permeability (in HDZ/EDZ) with depth from the tunnel wall as shown in Figure 5.1 from the Bure site and Figure 5.2 from Mont Terri (see also the data from Tournemire in Figure 3.5). Note that Baechler et al. (2010) reported significantly increased permeability over only a narrow zone 0.5 m thick around the SUG drift.



Note: Figure from Shao et al. (2008).

Figure 5.1: Distribution of Permeability in the Near-field Around the Drift from Pneumatic Testing at the Bure Site



Note: Figure from Bossart et al. (2004).

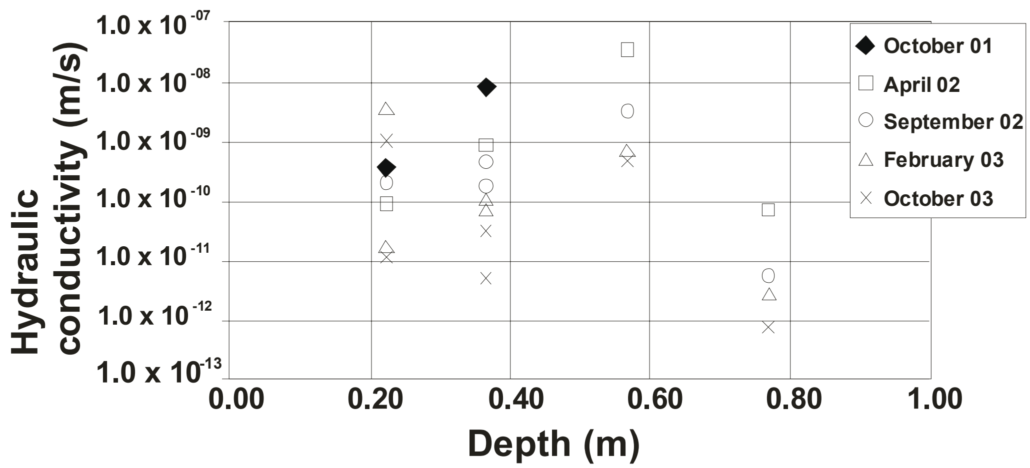
Figure 5.2: Distribution of Permeability in the Near-Field Around the Drift from Pneumatic Testing at Mont Terri

While the general pattern is of reduction in permeability with distance from the excavation, conditions can vary locally by as much as an order of magnitude, as shown in Figure 5.3 from Mont Terri where the most transmissive interval is at 0.6 m. The effect of ongoing permeability reduction (self-sealing) is also clearly seen. Reduced permeability in pneumatic testing may be influenced by saturation conditions possibly resulting in an exaggerated reduction in permeability with depth.

5.2.2 Larger Scale Measurements

In some circumstances it may be possible to detect cross-hole responses in surrounding boreholes if they have been suitably instrumented (e.g., EZ-A experiment at Mont Terri Armand et al. 2004) to give information on the local connectivity. Results were obtained in a 9 borehole array in the floor of a drill and blast tunnel at the EZ-A experiment where cross-hole pneumatic responses were detected over 3.3 m, however permeability and responses were highly varied and the area was thought to have been highly disturbed (Armand et al. 2004). Alternatively, it may be possible to probe the extension of a transmissive feature by drilling multiple boreholes. At Mont Terri tests as part of the EH experiment showed that fracture connectivity was limited to ~1 m (Martin and Lanyon 2003a).

The measurements shown in Figure 5.1 to Figure 5.3 illustrate the local distribution of interval permeability or hydraulic conductivity. Within the HDZ the interval permeability is likely to be dominated by the transmissivity of any fractures rather than enhanced matrix permeability. These local measurements need to be upscaled to derive appropriate estimates of the larger scale permeability along the tunnel. This upscaling has to account for the observed distribution and connectivity of the HDZ fracture system.



Note: Figure from Mayor et al. (2005a).

Figure 5.3: Distribution of Hydraulic Conductivity Around the EB Drift at Mont Terri from Repeat Hydraulic Testing

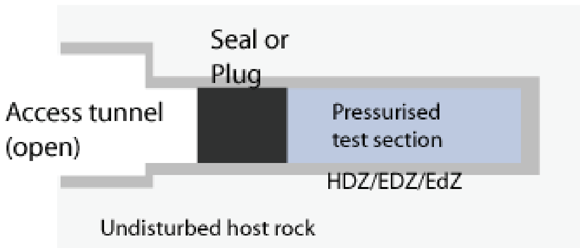
A large-scale ventilation test performed at Mont Terri to determine in situ permeability of the host rock and EDZ found that conventional analyses based on measured pressures and inflow significantly overestimated permeability due to desaturation at the tunnel wall Fernandez-Garcia et al. (2007). Analysis of the test required modelling with a two-phase flow code.

5.2.3 Axial Flow

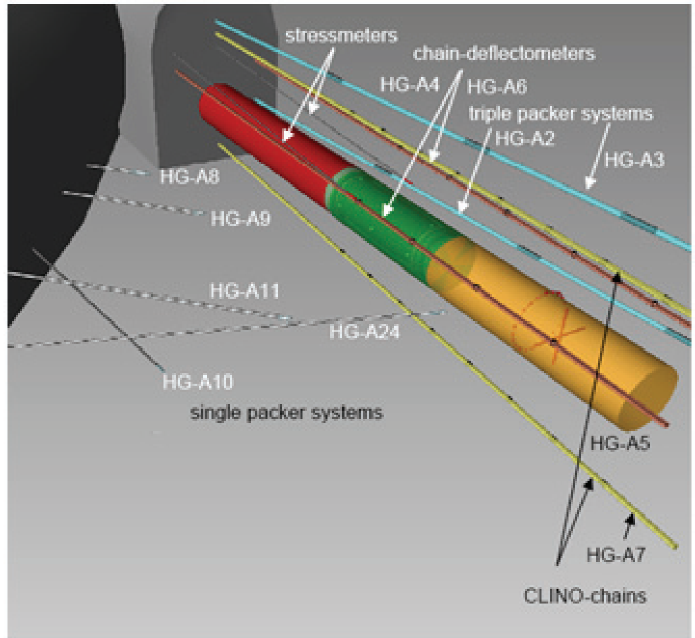
Measurements of flow along the EDZ (parallel to the excavation axis) are very limited due to the difficulty of establishing a head-gradient along an excavation in operational conditions. A typical experimental setup is shown in Figure 5.4 together with the experimental layout of the HG-A experiment at Mont Terri (Marschall et al. 2008). An alternative experimental setup used at the AECL URL is shown in Figure 5.5; this setup was possible due to the localized “notch” shape of the EDZ at the AECL URL.

The layout shown in Figure 5.4 is similar to several experiments focusing on the EBS including the Macro Permeability Test at the Stripa Mine (Wilson et al. 1983); the Plug and Backfill test at Äspö, Gas Migration Test at GTS and the EB experiment at Mont Terri. A key issue is the length of the seal zone which, depending on the nature of the backfill in the test section, determines the length of EDZ tested. In several cases, local leakage around the plug or seal (typically only a few metres in thickness) has required grouting or other measures (e.g., continuous injection) to maintain pressure in the test section due to high local EDZ conductance. In some cases the high conductance was related to the excavation process enhancing the transmissivity of pre-existing natural fractures.

a)

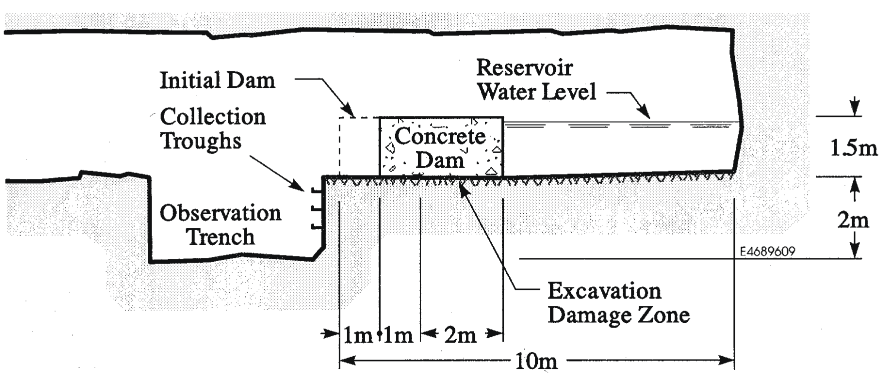


b)



Note: Figure from Marschall et al. (2008).

Figure 5.4: Experimental Setup for EDZ Axial Flow: a) Schematic; b) Layout of HG-A Experiment at Mont Terri



Note: Figure from Frost and Everitt (1997).

Figure 5.5: Experimental Set-up for Connected Permeability Experiment in the Mine-by Tunnel at the AECL Underground Research Laboratory

In the HG-A Experiment performed at Mont Terri, Lanyon et al. (2009) report an EDZ conductance (measured over the 3 m length of the Megapacker seal zone) of ~8×10^{-9} m^3/s, which was observed to be reducing with time (due to self-sealing) by approximately an order of magnitude per year. Alternate layouts for testing the axial conductance of the EDZ include the TSX at the AECL URL (clay bulkhead was 2.5 m long) and the RESEAL Shaft test at Mol (Bentonite seal height 2.24 m) as discussed in Chapter 7.

5.2.4 Gas Flow

With the exception of pneumatic testing of the EDZ during the operational period, only a limited number of experiments have been performed on gas flow through previously saturated EDZ. In crystalline rocks the Gas Migration Test at GTS and the LASGIT test at Äspö focus on gas flow through the EBS with some influence of the EDZ and host rock.

In sedimentary rocks the HG-A experiment at Mont Terri is most relevant (Marschall et al. 2006, Marschall et al. 2008, Lanyon et al. 2009). This experiment is currently (March 2010) entering the start of the gas injection phase. It is expected that gas flow paths may be focussed in the most open features of the EDZ (lowest entry pressure). Tests on gas flow in the borehole damaged zone are under way at Bure and plans for measurement of gas transfer through the seal of a life-size HLW vault are in development (Delay et al. 2010).

5.2.5 Solute Transport

A very limited amount of experimental data is available with regard to solute transport in the EDZ. This is largely because of the difficulty in establishing suitable flow-paths within the EDZ under operational conditions. Hydraulic gradients are normally associated with inflow to the excavations and hence are radial rather than along the EDZ. Further, the fractured nature of the HDZ makes it difficult to identify flow paths and understand their connectivity sufficiently to perform viable experiment in terms of injection volumes, tracer concentrations and sampling arrangements (schedules and locations).

Very few tracer tests have been performed in the EDZ within sedimentary rocks. The RESEAL shaft sealing test described in Chapter 7 is the only example known to the author.[3] In crystalline rocks a tracer experiment has been performed at the AECL URL where the distinctive nature of the HDZ (due to very high stress anisotropy and lack of natural fractures) makes it relatively simple to create a suitable a flowpath within the HDZ. The setup is illustrated in Figure 5.5.

Specific issues relating to transport in the HDZ and EDZ are:

- Connectivity of the fracture system; and
- Chemical reactivity of induced fracture surfaces – due to recent excavation and exposure to air, fracture surfaces may not be in equilibrium with the groundwater.

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[3] Dipole tracer tests were used as part of the KEY experiment at Bure to study the action of EDZ cut-offs (Lavanchy et al. 2007).

6. MODELLING OF THE DAMAGED AND DISTURBED ZONE

6.1 Introduction

This chapter presents a range of numerical model and modelling studies related to the damaged and disturbed zones. The different studies are presented as representative of the "state of the art" in sedimentary (usually argillaceous) rocks and are not an exhaustive summary of current EDZ modelling.

The chapter is organized into four sections:

- Modelling studies of EDZ experiments;
- Numerical tools to model EDZ creation and evolution;
- Modelling of flow within the EDZ; and
- Modelling of transport within the EDZ.

6.2 Modelling EDZ Experiments

The MODEX-REP Project is a hydromechanical coupled modelling benchmark exercise (Lebon et al. 2002). It is presented here as an example of the current state of predictive modelling of rock mass response to excavation and the EDZ.

The modelling and associated experimental work focuses on the sinking of the main shaft at the Bure URL from 460 to 476 m (Armand and Su 2006). Initial studies used two-dimensional models as part of the experimental design process (Ben-Slimane 2003), but the project included development of a range of constitutive models for the Callovo-Oxfordian (Su et al. 2007) as listed in Table 6.1.

Table 6.1: Constitutive Models from MODEX-REP

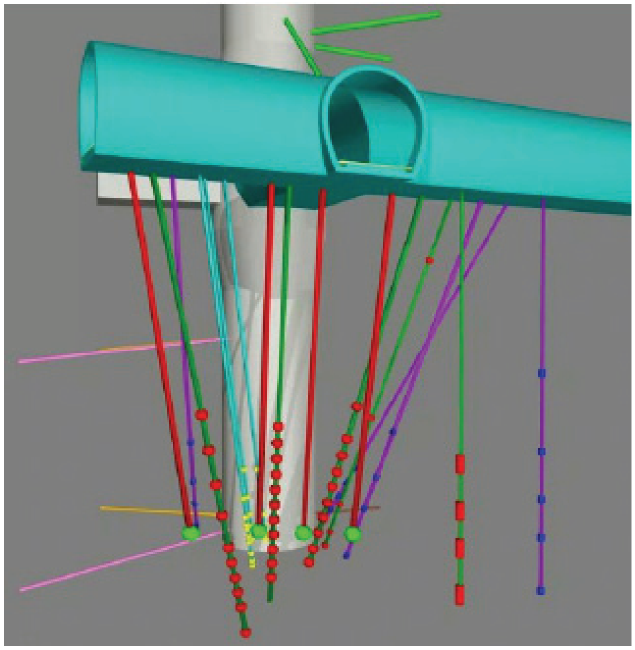
Time Frame	Constitutive Model
Short-term response	• Elastoplastic model with or without softening/hardening • Elastoplastic model with damage • Elastoplastic model with hydro-mechanical-coupling • Discrete model
Long-term response	• Viscoplastic model • Deferred-damage model • Deferred bond failure model

Note: Table from Su (2007).

Blind prediction of the shaft excavation (REP experiment see Figure 6.1) was performed in two phases:

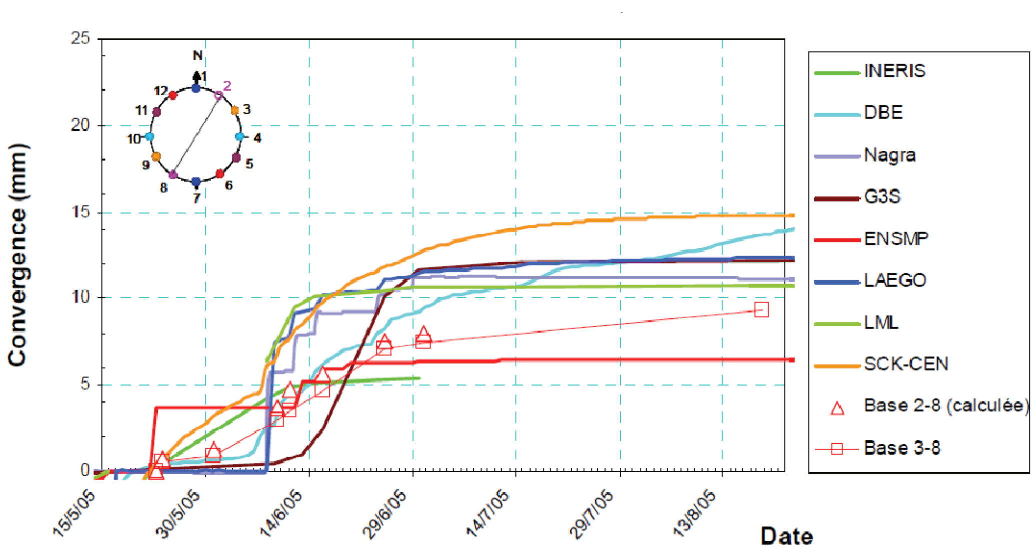
- Phase 1 based on the expected excavation schedule; and
- Phase 2 based on the actual excavation schedule.

In general the models over-estimated convergence, while predicted displacements and pore pressures showed significant variation (Figure 6.2). A further phase of interpretative modelling was performed after the blind predictions. Improved matches were achieved in the interpretative phase.



Note: Figure from Su (2007).

Figure 6.1: REP Experiment Layout



Note: Figure from Su (2007).

Figure 6.2: Comparison of Measurements (Base 2-8, 3-8) and Results from the Different Modeling Groups from MODEX-REP

Su (2007) suggests that "the extension of the very limited fractured zone (HDZ)[4] and of the micro-fractured zone (EDZ) was correctly forecasted by numerical models (using plastic strain criteria). From that point of view, the capability of models for predicting the EDZ extension is good in the case of the argillites located in the section of REP experiment". However further work was needed to understand the short-term pore pressure response and the influence of ventilation. Issues concerning hydromechanical coupling and damage/failure and effective stress in the argillite remained open. This was thought particularly important for understanding the long-term response.

Following on from MODEX-REP, a blind-prediction of excavation response, using a viscoplastic model developed from the previous work, for the GED σ_h-parallel drift is presented by Armand and Souley (2009). The viscoplastic model incorporates a Hoek-Brown failure criterion for short-term response coupled to a modified LeMaitre Creep law to reproduce long-term response. The model couples damage to creep behaviour.

A first comparison of predicted and measured convergence suggests that the model over-estimated horizontal convergence but underestimated vertical convergence while matching convergence rates reasonably well. It is intended to develop the model using the measured results giving particular attention to the treatment of the fractured zone (HDZ).

6.3 Numerical Tools to Model EDZ Creation and Evolution

A range of rock and soil mechanics models have been used to develop understanding of observed behaviour and "predict" EDZ extent and properties in planned repositories. Numerical approaches have included:

- Boundary Elements: (e.g., Examine3D, Map3D);
- Finite Elements: CODE_BRIGHT, CODE_ASTER, Phases;
- Explicit Finite Difference: FLAC, FLAC3D;
- Distinct Elements: UDEC and 3DEC;
- Discontinuous Deformation Analysis (DDA); and
- Granular Particle Assemblies: PFC 2D/3D.

Hybrid models using multiple techniques have also been developed and applied to the EDZ (e.g., ELFEN and AC/DC). While a wide range of tools is available successful application still requires:

- Use of appropriate material models and parameters that account for sample disturbance and upscaling (or calibration to in situ properties); and
- Validation of modelling approaches by comparison with measurement.

An important consideration regarding modelling of the EDZ in low permeability sedimentary rocks (especially clays) is hydromechanical coupling and the influence of partially saturated conditions. The experimental results from Tournemire and Mont Terri both indicate the importance of saturation and pore pressure equilibration on the long–term development of the EDZ.

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[4] In the terminology of this report.

6.3.1 Modelling Damage and Permeability Evolution in the EDZ

A recent study on permeability evolution in the EDZ in granite (Rutqvist et al. 2009) used data from the TSX experiment at the AECL URL. Inner and outer damage zones were defined using transmissivity measurements (data from SEPPI tool, see Chapter 3) and microvelocity probe (MVP) measurements. Borehole cameras showed increased fracturing in this inner damage area and the highest transmissivities were generally recorded where the borehole camera detected fracturing.

Four modelling teams using different Finite Element Method (FEM) codes modelled the damaged zone around the excavation. Permeability and induced pressure responses were simulated. Three different approaches were used to calculate the permeability evolution within the EDZ:

- Permeability as an exponential function of equivalent deviatoric strain;
- Permeability as a cubic function of porosity due to changes in volumetric strain; and
- Permeability as an empirical exponential relationship between effective mean deviatoric stress.

Good agreement was achieved between the measured SEPPI data (interpreted as permeability) and model simulations, however the observation of macrofracturing within the inner damaged zone suggests that the continuum based approaches may not be valid.

The study of Rutqvist et al. (2009) and related work by Nguyen et al. (2009) performed within the Decovalex THMC project provide an example of “state-of the-art” modelling of permeability evolution within the EDZ for crystalline rocks. Similar approaches have been taken in argillaceous rocks and a benchmarking study for hydromechanical simulation is described in Chavant and Fernandes (2005).

6.3.2 Modelling the Fracturing Process

Modelling of fracturing processes in brittle and quasi-brittle materials has developed significantly in the last decade (Owen et al. 2005). Numerical codes that couple damage mechanics (micro-cracking) with fracture initiation and propagation have been developed and applied to the excavation damage zone (Billaux et al. 2004, Klerck et al. 2004). Codes are typically two-dimensional with three-dimensional versions being available or in development. Three codes are discussed below: FRACOD (2D boundary element with linear elastic fracture mechanics), ELFEN and the AC/DC hybrid code.

6.3.2.1 FRACOD Boundary Element Code

2D and 3D fracture propagation codes utilizing boundary elements and linear elastic fracture elements have previously been used to model borehole breakouts (Ewy and Cook 1990a, b). The fracture initiation, propagation and coalescence model FRACOD (Shen 2002) has more recently been applied to the prediction of fracturing and permeability change in the excavation damage zone (Stephansson et al. 2008) in hard rocks. FRACOD is a boundary-element model that includes fracture elements using the displacement discontinuity method. Fracture propagation and coalescence are modelled using linear elastic fracture mechanics and a novel fracture initiation criterion (modified G-criterion Shen and Stephansson 1993).

Fracture transmissivity is calculated from the fracture aperture determined from the calculated normal displacement using the cubic-law. Fracture initiation and effective hydraulic conductivity are calculated on user-determined grid-cells. Stephansson et al. (2008) present the application of FRACOD permeability prediction to the TSX tunnel at AECL and ZEDEX tunnels at Äspö as illustrated in Figure 6.3.

Uncertainties associated with the method and its application to sedimentary rocks include:

- Use of linear-elastic material laws;
- Use of normal displacement as a parallel-plate aperture in the cubic law;
- Potential dependence of grid choices; and
- Uncertainties on fracture initiation and propagation parameters.

6.3.2.2 ELFEN Finite Element/ Discrete Element System

The ELFEN finite element/discrete element code includes facilities for continuum damage mechanics, insertion of discrete fractures and adaptive meshing together with interaction laws for discrete objects (contact laws) for modelling post-failure behaviour. Sellers and Klerck (2000) and Klerck et al. (2004) present 2D models of borehole breakout and tunnel failure using the ELFEN code. The resulting fracture patterns are shown in Figure 6.4.

6.3.2.3 AC/DC Hybrid Code

The 3D hybrid code AC/DC (Billaux et al. 2004) has been developed by ITASCA in the framework of the EU SAFETI Project to capture detailed behaviour in strongly strained zones using a particle flow approach (similar to PFC) and an effective continuum approach for the remainder of the model (low strain regions). The design is based on the idea that high strain regions (e.g., damage zones) make up only a small percentage of the total model volume and so large models can efficiently be split into continuum and particle elements. AC/DC differs from the two codes discussed above by utilising effective continuum elements and super-elements (PBRICKs) made up of periodic assemblies of particles (similar to those in PFC). The PBRICK super elements can be used to replace effective continuum elements when the code detects cracks approaching the continuum element so that particle elements are placed in regions prior to the onset of non-linear mechanics.

The model was initially tested against results from Mont Terri predicting the depth of micro-cracking and range in permeability and has subsequently been used to predict excavation response in the Callovo-Oxfordian argillite at the Bure site shown on Figure 6.5 (Dedecker et al. 2006).

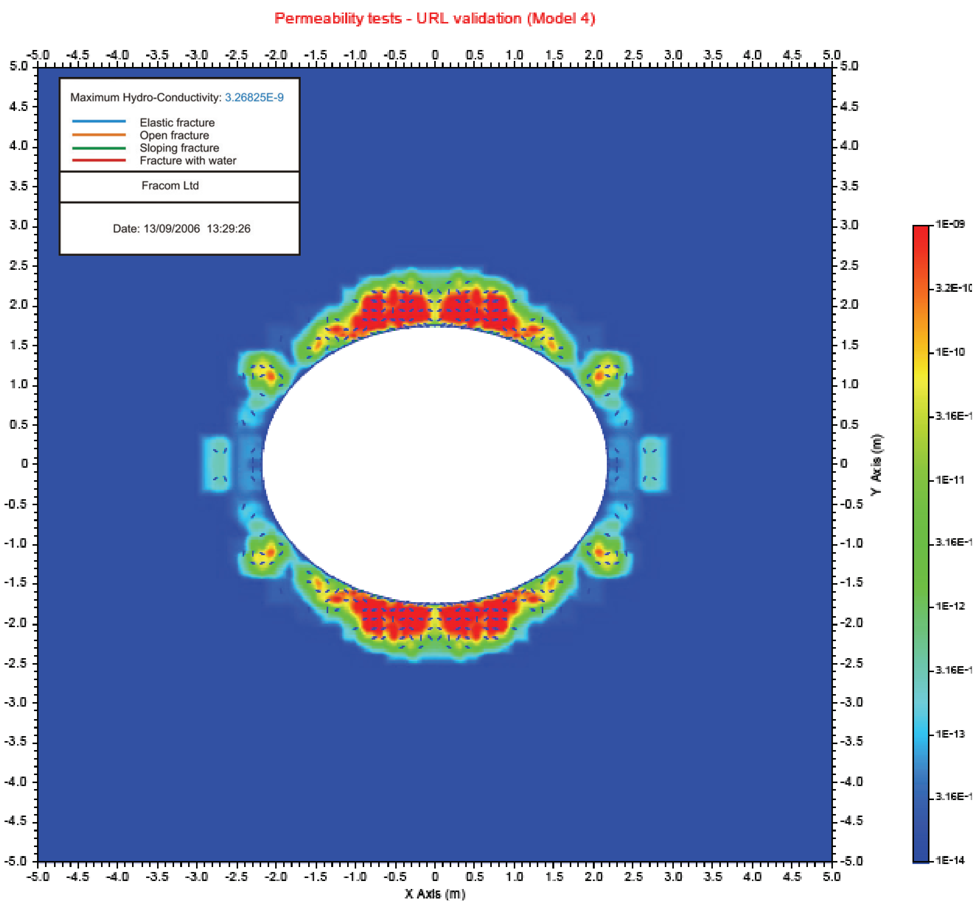
6.4 Modelling Flow in the EDZ

The majority of groundwater flow modelling within the EDZ has been in the context of:

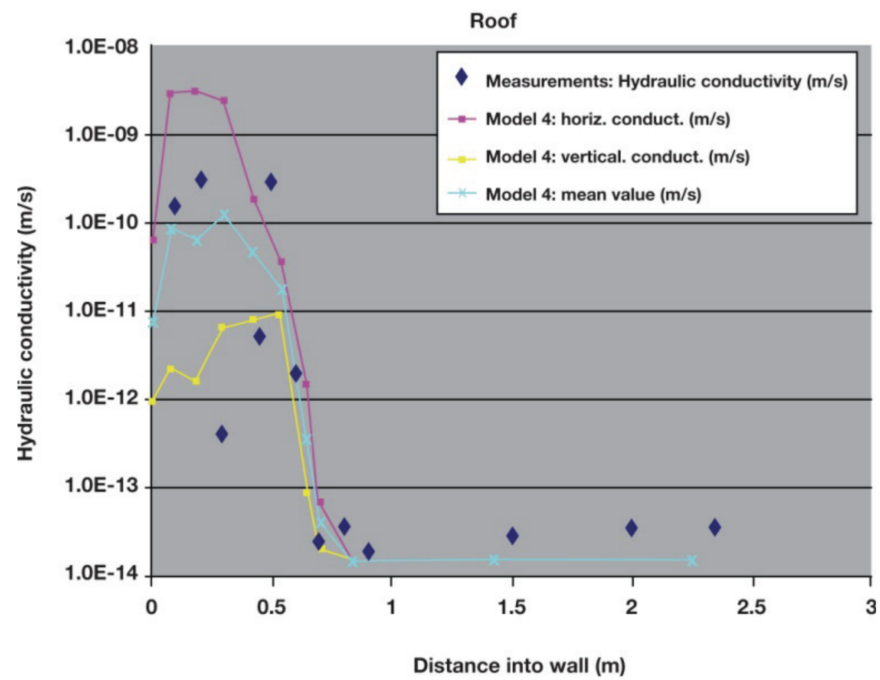
- Modelling of small scale experiments in underground laboratories; and
- Large scale flow simulations of the long-term post-closure groundwater flow, large scale flow simulations of repository resaturation and gas migration (Nagra 2008, Talandier et al. 2006, Ando et al. 2006).

Examples of each approach are given in the following sections.

a)



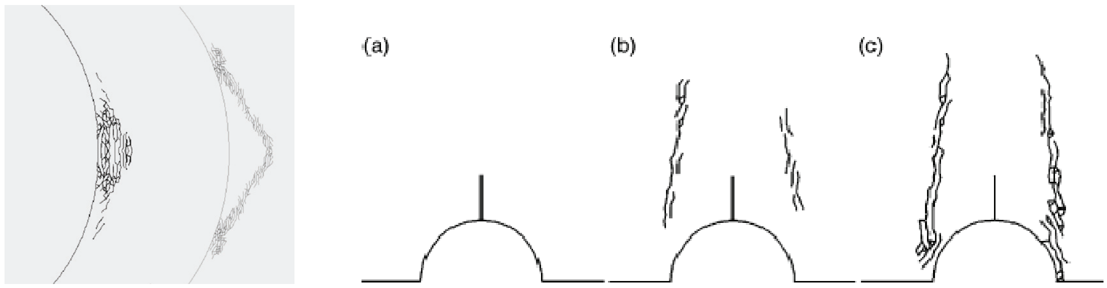
b)



Note: a) Contour of hydraulic conductivity and b) Comparison with measurements form side-wall at TSX.

Figure 6.3: FRACOD Prediction of Damage Zone Permeability Around TSX Tunnel

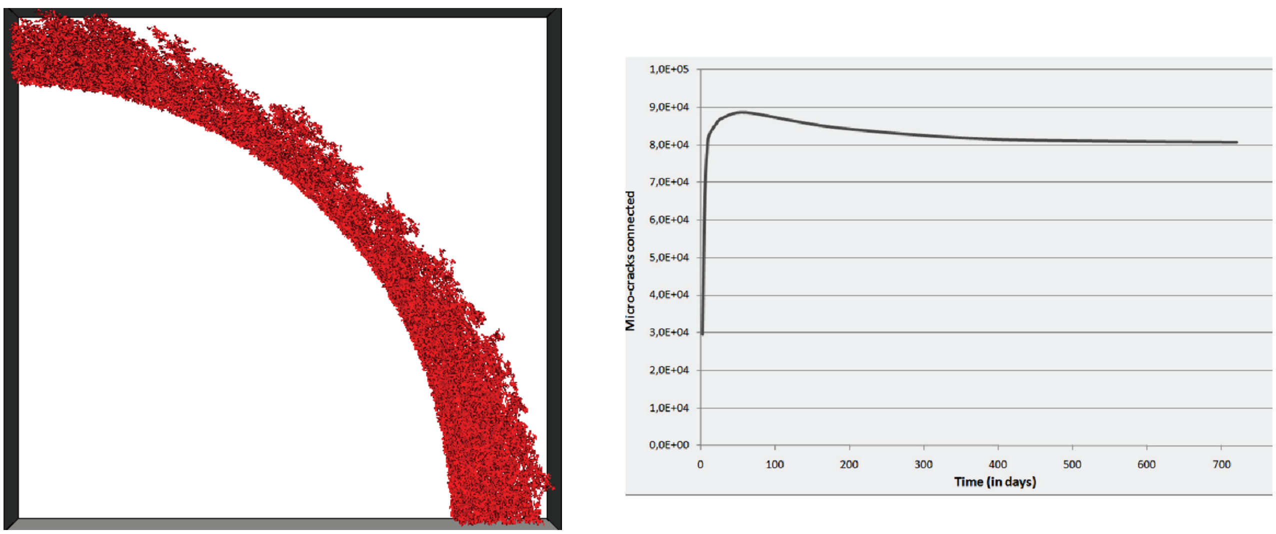
a) b)



Notes: a) Borehole breakouts in Lac du Bonnet Granite and Cardova Cream Limestone; b) Borehole breakout with primary, remote and sidewall fracture imitation. Borehole radius is 25 mm.

Figure 6.4: ELFEN Predictions

a) b)



Notes: a) Distribution of micro-cracking 2 years after shaft opening, b) Number of connected microcracks versus time elapsed (days) since shaft opening. Figure from Dedecker et al. (2006). Tunnel radius is 3 m.

Figure 6.5: AC/DC Modelling of Shaft Excavation at Bure

6.4.1 Modelling Flow in the Small-scale EDZ Models

Small scale models of the EDZ (typically on scales ~10 to 100 m) have been developed to:

- Address the needs of EDZ experiments; and
- Consider heterogeneity and connectivity of the HDZ and EDZ.

Models have used both Discrete Fracture Network (DFN) and heterogeneous Continuum Porous Medium approaches. At small scales equivalent continuum approaches based on establishing a Representative Elementary Volume (REV) for the EDZ fracture network are difficult to justify given the expected strong spatial dependence of fracture network properties and connectivity.

DFN approaches to the EDZ in crystalline rocks were studied in the NEA Stripa Project Simulated Drift and Validation Drift Experiments (Barton et al. 1995, Herbert et al. 1994, Dershowitz 1994, Long 1994 all in OECD 1994) and have been subsequently used to model a range of experiments in Crystalline rocks (see for example Marschall et al. 1999). DFN models are particularly well suited to EDZ problems in crystalline rock because of the very large permeability contrast between fractures and matrix (even when disturbed or damaged). Models generally include families (or “sets”) of induced fractures caused by excavation and sets of natural fractures that may or may not have been disturbed by excavation (both opening and closure of fractures in the EDZ is possible). DFN models have also been used to consider the EDZ in sedimentary rocks such as the Valanginian Marl at Wellenberg (Nagra 1997) and the Opalinus Clay at Mont Terri (Lanyon et al. 2005) and in a hypothetical repository (Lanyon et al. 2009b).

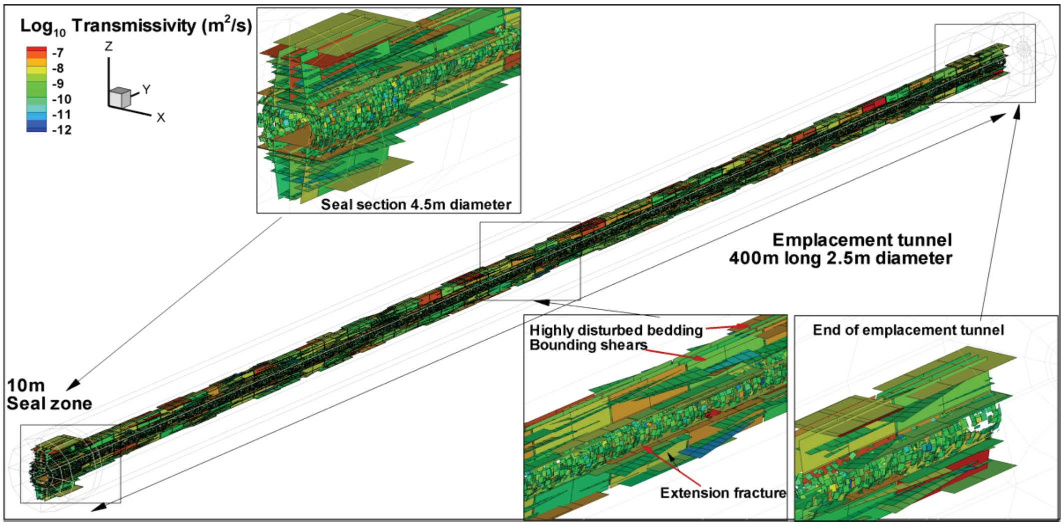
Numerical tools such as Fracman (Dershowitz et al. 1998), CONNECTFLOW (Hartley and Holton 2004) and others provide facilities for modelling water flow and transport in assemblies of millions of fracture elements. As with DFN applications in other areas however, significant issues arise with regard to:

- Identifying appropriate structural models for the EDZ fracture system; and
- Selecting parameter values for distributions of fracture properties such as transmissivity and length scale.

These issues are particularly significant in the EDZ because of the many influences that may control fracture properties in this zone. DFN models are a natural choice for modelling the HDZ and EDZ in situations where fracture properties dominate.

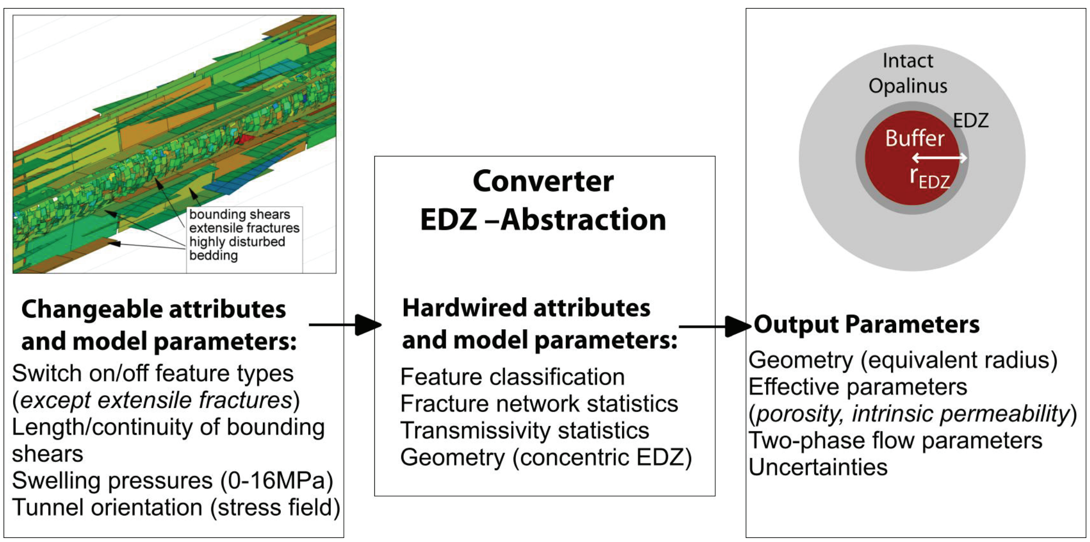
One alternative to DFN models that can represent the observed heterogeneity within the EDZ are heterogeneous continuum models. A comparison of the two methods for unsaturated flow is given in Finsterle et al. (2000). The use of continuum approaches for estimating seepage into drifts in partially saturated rock has been discussed in Or et al. (2005) and subsequent comments by Finsterle (2006).

Lanyon et al. (2009b) present DFN, heterogeneous continuum and simplified homogeneous continuum models of the EDZ around a tunnel in Opalinus Clay as part of the development of an approach to abstraction of geoscientific EDZ models. In this case the abstraction process is from a DFN as shown in Figure 6.6 to models suitable for performance assessment (Johnson et al. 2008), here a homogeneous continuum model. The abstraction process is illustrated in Figure 6.7.



Notes: Fractures coloured by log10 transmissivity (m^2/s). Figure from Lanyon et al. (2009).

Figure 6.6: Realization of One Variant of EDZ DFN Model

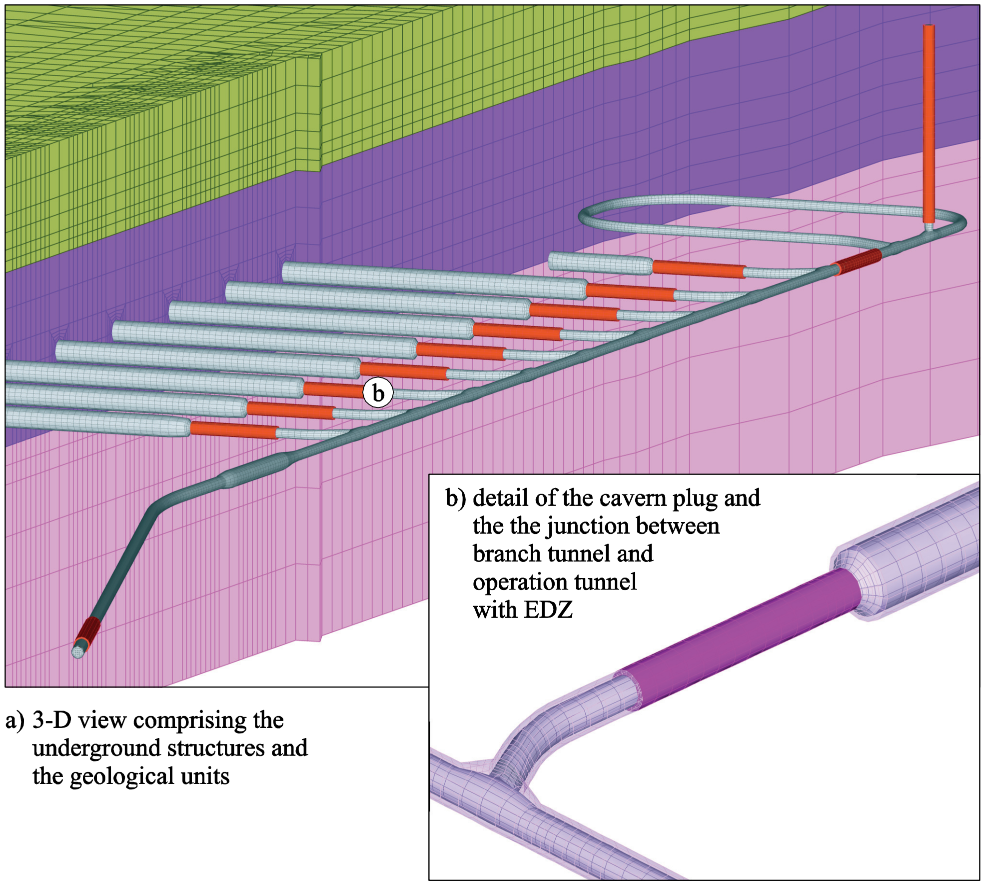


Notes: Input side (definition of changeable attributes/experts), hardwired EDZ abstraction procedure and output for the end users (PSA model). Figure from Lanyon et al. (2009b).

Figure 6.7: Components of the EDZ Converter

6.4.2 Repository Resaturation and Long-term Post Closure Flow

Large-scale flow simulations of resaturation and long-term post-closure flow around a repository including the EDZ have commonly been performed using groundwater modelling codes requiring few special facilities other than large model size capability (in terms of nodes/elements) and flexible mesh generation to include detailed representations of the excavations and EDZ (see Figure 6.8). Typically the EDZ has been represented as one or more concentric rings of altered hydraulic properties around excavations as discussed in Chapter 8.



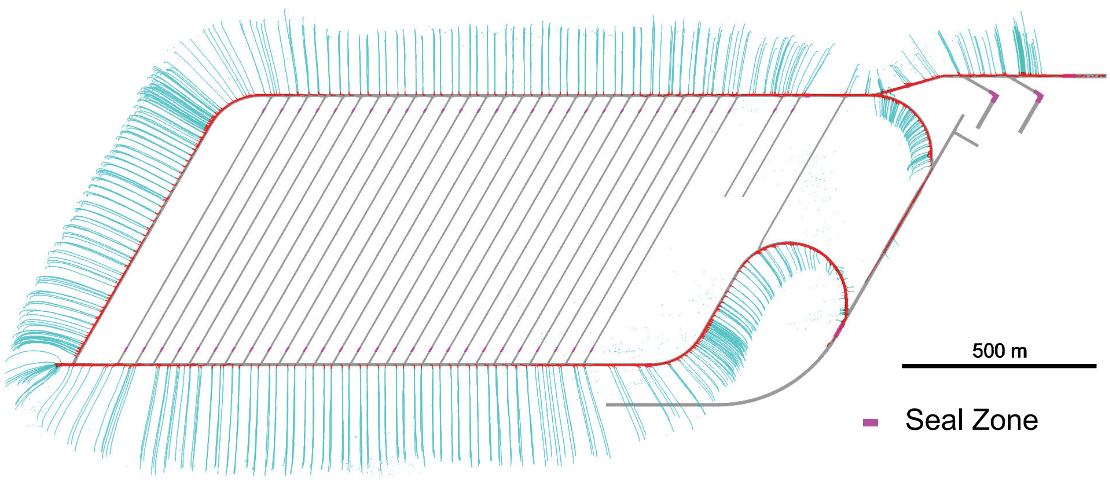
Notes: The EDZ is show as a transparent zone around the excavations but is cut-off at the seal (purple). The model was developed using the CASA groundwater modelling code (Kuhlmann 1995). Figure from Nagra (2008).

Figure 6.8: Details of Hydrodynamic Model Mesh Used for Simulating Resaturation of an L&ILW Repository in Opalinus Clay

Figure 6.9 shows predicted flowpaths from one model variant used within the Nagra Project Opalinus Clay. Flowpaths in the EDZ can be seen along the ventilation tunnel (left of figure) and in the curve leading to the ramp. The action of the seal zones (shown in purple) in cutting off the flow paths in the EDZ can be observed.

6.4.3 Models of Gas Generation and Migration

The effects of gas generation and subsequent pressure build-up may be an important issue in the design of L&ILW repositories (Nagra 2008, Ando et al. 2006, Talandier et al. 2006). Two-phase flow modelling may be required to develop understanding of the consequences for water and gas flow if generation rates are in excess of the capacity of host-rock to transport gas away from the excavations by dissolution. Recent work by Nagra has included 2D and 3D modelling of two-phase flow using the TOUGH2_MP (Zhang et al. 2003) code. The 3D model mesh is shown in Figure 6.10, where again the EDZ is treated as a volume of homogeneous hydraulic properties around the backfilled excavations (here represented as "brick" type elements).

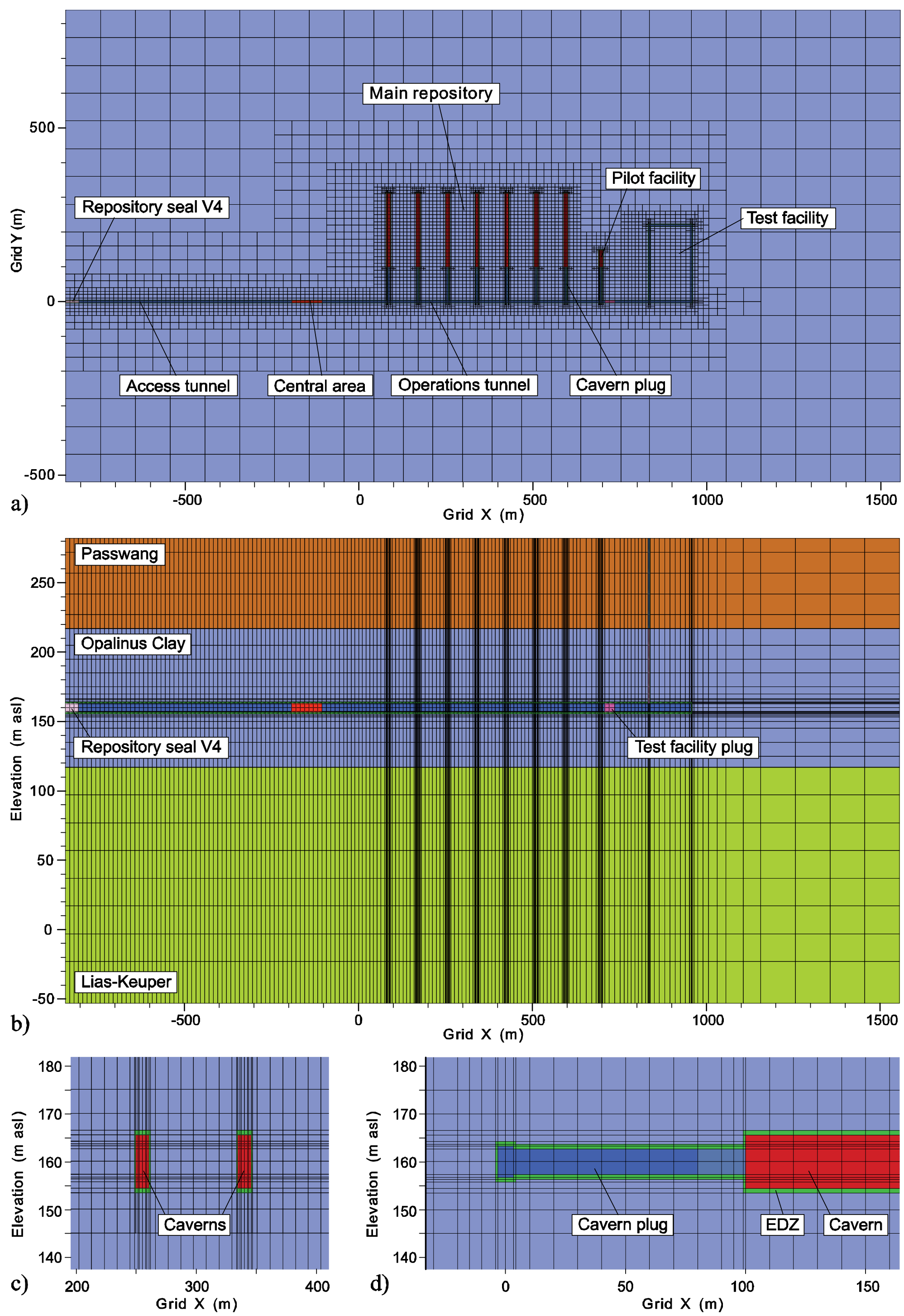


Notes: Flowpaths in EDZ coloured red – flowpaths in host rock coloured blue. Figure from Nagra (2002b).

Figure 6.9: Simulated Flowpaths Through the EDZ and into the Host Rock Driven by an Overpressure Within ILW Storage Tunnels

The modelling demonstrated that, depending on the assumptions made about EDZ, host-rock and seal permeability, the maximum gas pressure in emplacement caverns would remain significantly below the expected lithostatic pressure by use of gas permeable cavern plugs and that dilatancy-controlled gas transport process could therefore be excluded. Even in the case of extremely low permeability of the EDZ and host-rock it was possible to allow gas transport without development of extreme over-pressures, by optimization of the Engineered Gas Transport System (EGTS).

Nagra (2008) also presents a comparison of repository resaturation calculations using the hydrodynamic model (CASA) which used a highly detailed model grid but simplified description of two-phase flow (Richards' equation for unsaturated groundwater flow) and the two-phase flow model (TOUGH2_MP) which uses a simplified representation of the system geometry but includes a more detailed representation of two-phase flow processes.

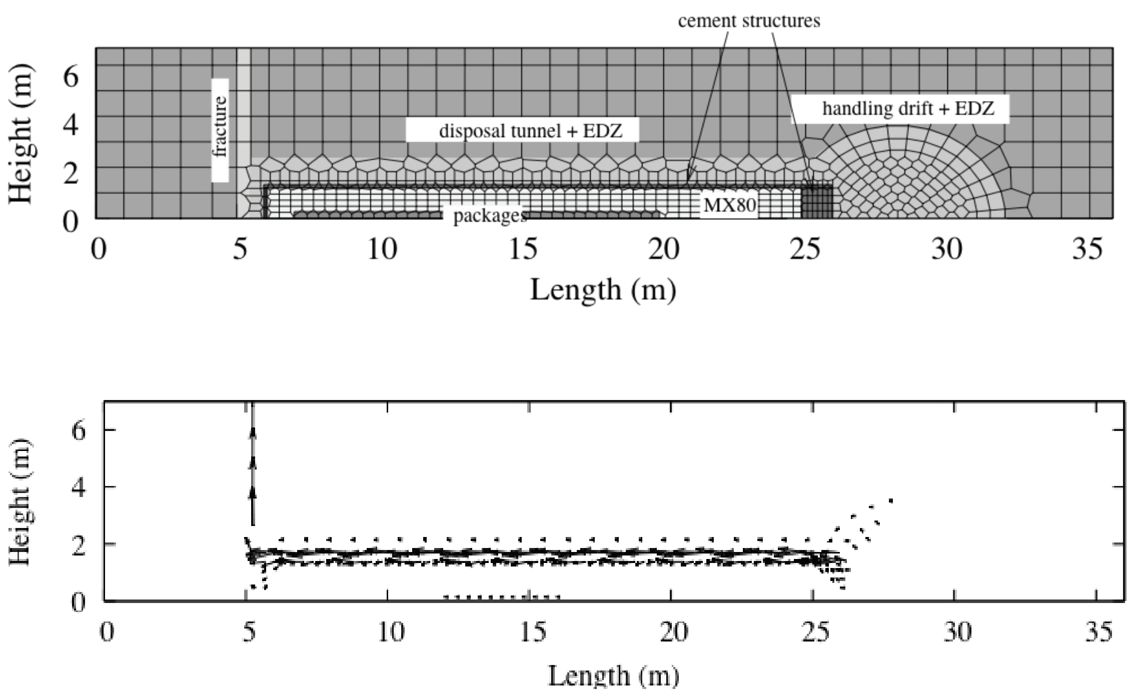


Notes: a) Plane view of the model grid on the repository level; b) Vertical cross section along cavern no. 4; c) Vertical cross section along the access and operation tunnel; d) Vertical cross section along the axis of an emplacement cavern. Note vertical exaggeration.

Figure 6.10: 3-D Model with Repository Structures and Geosphere

6.5 Modelling of EDZ Chemistry

A limited amount of modelling of the hydrochemistry of the EDZ has been performed to examine the transient redox conditions in clay rocks (Bildstein et al. 2007). De Windt et al. (2004) present reactive transport calculations using the code HYTEC (van der Lee et al. 2003) for a simplified EDZ model shown in Figure 6.11. The EDZ was treated as a homogeneous layer around the excavation and uncertainty in EDZ permeability was treated by parameter sensitivity studies. The model considered two scenarios: a base case of diffusive flow and an advective flow scenario where the EDZ is connected to a permeable feature (see Figure 6.11). The advective flow scenario models “illustrate the possibility of preferential pathways through the EDZ for iodine but show almost no effect on the alkaline plume and caesium migration.”



Notes: Calculated stationary flow velocity for test-case B (bottom). The arrows correspond to Darcy velocities: the average Darcy velocity in the EDZ-I zone is about 5 cm/y in case B. Figure from De Windt et al. (2004).

Figure 6.11: Simulation Grid of the Spent Fuel Disposal Tunnel, the Handling Drift and a Main Fracture (top)

7. REPOSITORY ENGINEERING TREATMENT OF THE EDZ

The extent and effective permeability of the EDZ may be minimized by a variety of excavation design choices (Read and Chandler 1996, Bauer et al. 2003b) including:

- Selection of excavation location (e.g., regions of lower stress or higher rock strength, see Delay et al. 2010);
- Selection of excavation orientation to minimize differential stresses that lead to compressive failure (Read and Chandler 1996);
- Selection of excavation geometry to minimize stress concentrations (Read and Chandler 1996);
- Rapid installation of support (e.g., liners) to minimize convergence (Mertens et al. 2004); and
- Management of post-excavation temperature/humidity.

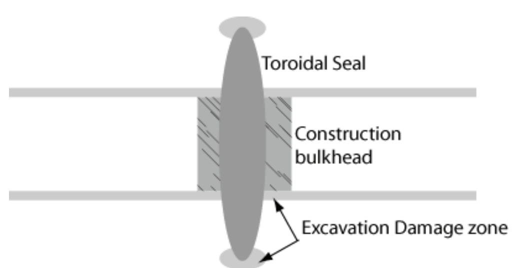
While these choices can reduce the effect of the EDZ, specific engineering measures to counter possible unfavourable EDZ performance include:

- EDZ Cut-offs; and
- Engineering of plugs and seal zones.

These two related Engineered Barrier System (EBS) measures are discussed in the sections below.

7.1 EDZ Cutoffs

Martin et al. (1996) suggested the use of an EDZ cut-off for the high stress environment encountered in the Lac du Bonnet Granite at the AECL URL The proposed cut-off was in the form of a relatively thin toroidal seal of sufficient radius to disconnect the damage zone around the tunnel from that caused by the excavation of the seal (see Figure 7.1). Since then experiments have been performed to test refined designs for EDZ cut-offs in sedimentary rock at Mont Terri and Bure (Delay et al. 2007, Mazurek et al. 2008).

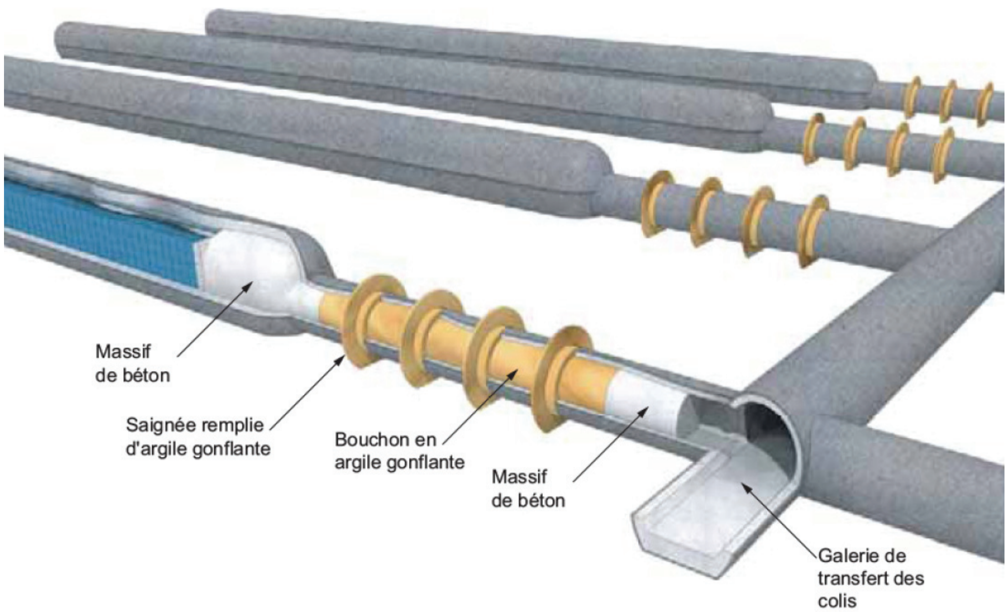


Note: Figure from Martin et al. (1996).

Figure 7.1: Toroidal EDZ Cut-off for High Stress Environment

Within the ANDRA programme the chosen method to interrupt “short-circuit” flow paths in the damaged zone around drifts and shaft seals is to create narrow radial slots (15–30 cm) filled with swelling clay of sufficient depth to completely cut the damaged zones; for example, slots approximately 2.5 m long for a 6 m-diameter drift as shown in Figure 7.2 (Delay et al. 2007).

The use of multiple slots provides an impermeable barrier that interrupts the continuity of the damaged zone. The pressure from the swelling clay tends to recompress the damaged zone and prevents the slot from being bypassed. The feasibility of this concept and the installation of two plugs (one concrete and one swelling clay separated by backfill) was tested in the AECL URL as part of the TSX experiment (see Figure 7.3 and Martino et al. 2007). Further tests and method development have been subsequently performed at Mont Terri and Bure.



Note: Figure from ANDRA (2005).

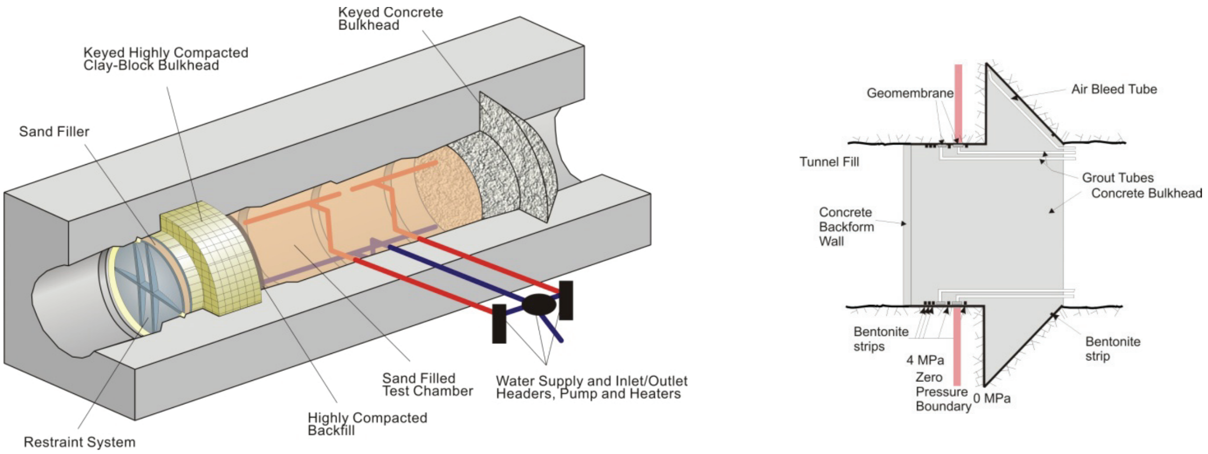
Figure 7.2: EDZ Cut-off Part of ANDRA's Repository Concept

7.1.1 EZ-A Experiment at Mont Terri

The aim of the EZ-A experiment at Mont Terri was to:

- Demonstrate the feasibility of creating radial slots and filling them with bentonite;
- Assess the effectiveness in cutting off hydraulic short-circuits; and
- Verify the effectiveness of applying swelling pressure.

The EZ-A experiment was performed in 2004 and included the cutting of two radial slots in the floor of an existing gallery and filling with a sealing resin to determine the ability of the slots to isolate portions of the EDZ. In a second test the geomechanical response and the feasibility of clay backfilling of the slots were tested (Figure 7.4). Pneumatic and hydraulic testing from EZ-A are discussed in Armand et al. (2004).



Notes: Figure from Backblom (2008) – courtesy of J. Martino.

Figure 7.3: TSX Experiment and Installations

Results from the experiment were useful in providing technical information on the slot-creation and behaviour. The information was used in the detailed design of the KEY experiment at Bure.

Note: Figure from Mazurek et al.(2008).

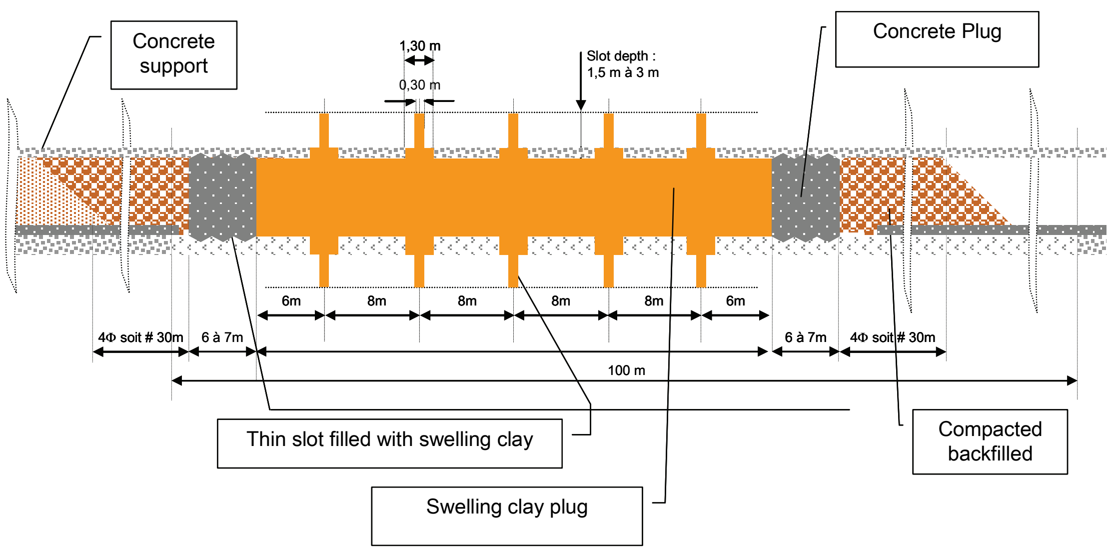
Figure 7.4: Opening and Filling a Trench with Bentonite Bricks

7.1.2 KEY Experiment at Bure

The KEY experiment at Bure focused on the EDZ cut-off concept and was a development of techniques tested in the EZ-A experiment at Mont Terri (Delay et al. 2007). The objectives of the experiment were:

- Characterization of the damaged and disturbed zones;
- Assessment of the effectiveness of radial slots to prevent hydraulic short circuit; and
- To check the effectiveness of applying confinement pressure in the slot.

Three slots were made in the GKE drift, two thin 7 cm slots and one 33 cm thick slot, all with a depth of about 2 m. The radial slots were made as part of the development of a prototype special-purpose saw. All slots remained stable and vertical. Pneumatic tests were performed in the floor of the GKE drift prior to slotting and showed high variability in measured permeability from 10^{-9} to 10^{-14} m^2, with 3 zones showing permeability similar to that of the undisturbed rock of ~10^{-20} m^2. Permeability between 1 and 2 m from the drift wall were similar to that of the undisturbed host rock. After slot-excavation helium tracer tests showed that there was no connection across the radial slots (Delay et al. 2007) although new connections did develop across the tunnel axis in the tunnel floor (Lavanchy et al. 2007).



Note: Figure from Delay et al. (2007).

Figure 7.5: Key Experiment Layout at Bure

7.2 Engineering of Seal Zone and Plugs

Hökmark (1998) performed numerical studies to examine the efficiency of different tunnel plug layouts to limit groundwater flow. He concluded that a plug keyed into the rock mass provided the most effective plug design. Since then various plug designs have been developed for different programmes or have been used in experiments at URLs in crystalline rock (e.g., TSX at AECL URL, Plug and Backfill test at Äspö, Febex, Gas Migration Test and Plug test at GTS (for an overview see Pusch and Börgesson 2005) and clay rocks (e.g., EB experiment at Mont Terri).

The sealing of drifts and shafts in salt host rocks has been investigated at the WIPP Project in New Mexico, USA and in Germany. A detailed description of the backfill and sealing work at the

Asse Mine is given in Bechtold et al. (1999), while sealing studies relating to Morsleben are discussed in Eilers et al. (2003).

Only limited specific testing of plugs/seals has been performed in URLs in clay-rich rocks as discussed below.

7.2.1 RESEAL Shaft at Mol

The RESEAL I and II projects aimed at demonstrating the sealing of a borehole and shaft. RESEAL I started in 1996 with the design and installation of the seals. RESEAL II started in 2000 and continued until 2007 testing the efficiency of the seals. A schematic of the shaft seal is shown in Figure 7.6.

As part of the RESEAL experiment the EDZ around the seal was also instrumented and it was possible to show (van Geet et al. 2007) that:

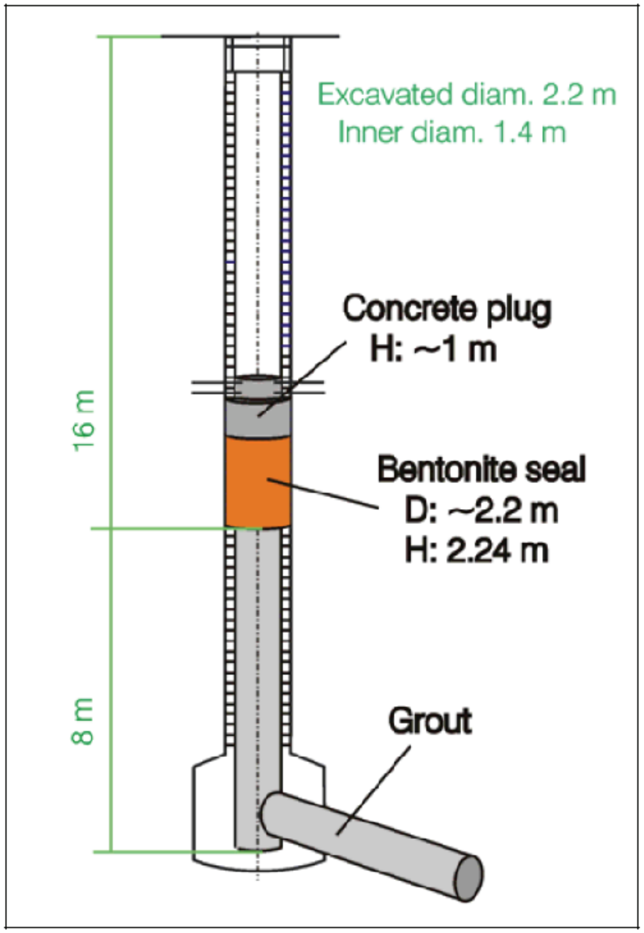
- Fractures are created or re-created during removal of the concrete lining; and
- The induced fractures are limited to a cylindrical zone around the sealed part and extended up to at least one metre inside the surrounding host rock.

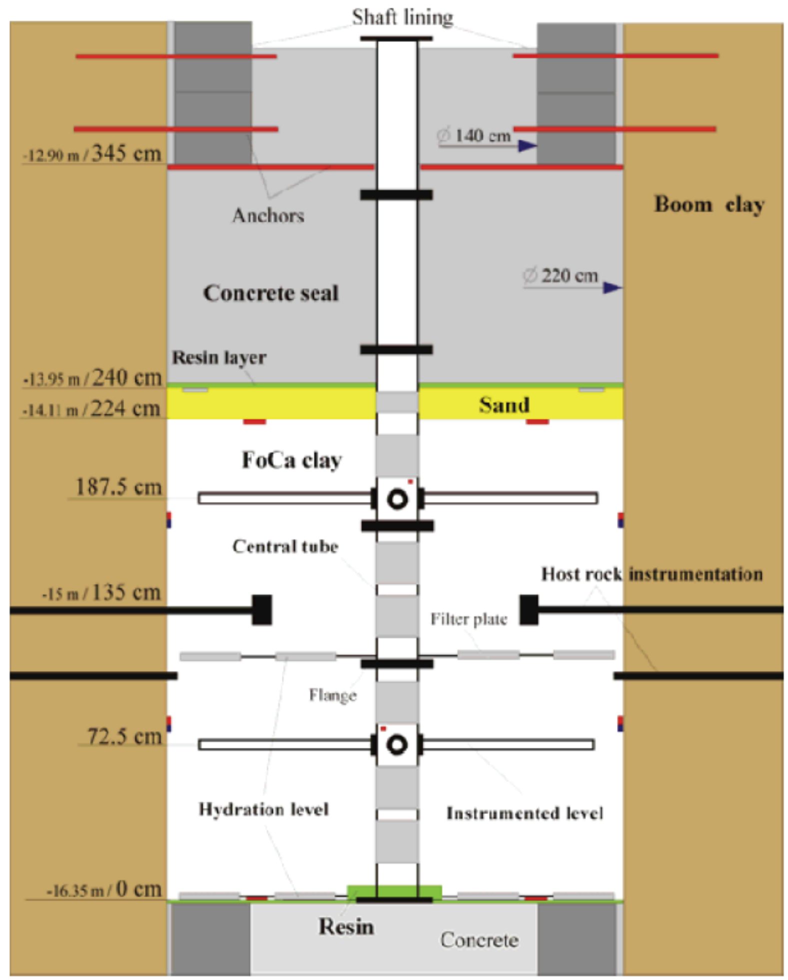
Despite the fast self-sealing of the Boom Clay, there were indications that some fractures remain open during seal hydration and only when full saturation was almost accomplished were the fractures within the host rock sealed. Radionuclide migration tests through the sealed host rock performed after full saturation of the seal showed that the transport is diffusion dominated and no major effects of the sealed fractures was observed on the transport properties.

7.2.2 Praclay Plug-test at Mol

The “PRACLAY Plug Test” aims at demonstrating that it is possible to cut-off hydraulically the EDZ and the engineered barriers of the disposal galleries with a horizontal plug (Figure 7.7). The gallery was constructed in September/October 2007. The plug provides a barrier between the heated zone and the access gallery using an annular seal of compacted bentonite. This seal will be implemented as a ring, assembled with pre-compacted bentonite blocks, taking the place of the concrete gallery lining over a length of 1 m. A stainless steel confining structure encases the bentonite ring. The central section will be closed with a steel plate and is equipped with several flanged holes to allow the feed-through of the instrumentation and heater wiring and tubes (de Bock et al. 2008).

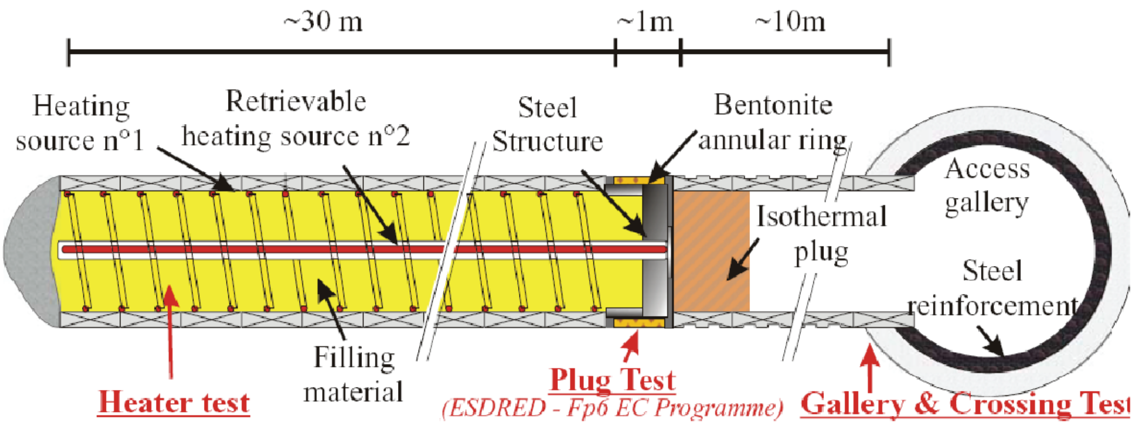
An example of conceptual plans for sealing in a repository context is given by the Nagra Project Opalinus Clay. Figure 7.8 shows the layout for a proposed repository for spent fuel (SF), vitrified high-level waste (HLW) and long-lived intermediate-level waste (ILW), sited in the Opalinus Clay of the Zürcher Weinland in northern Switzerland. The repository is located at a depth of ~650 m (Nagra 2002a).





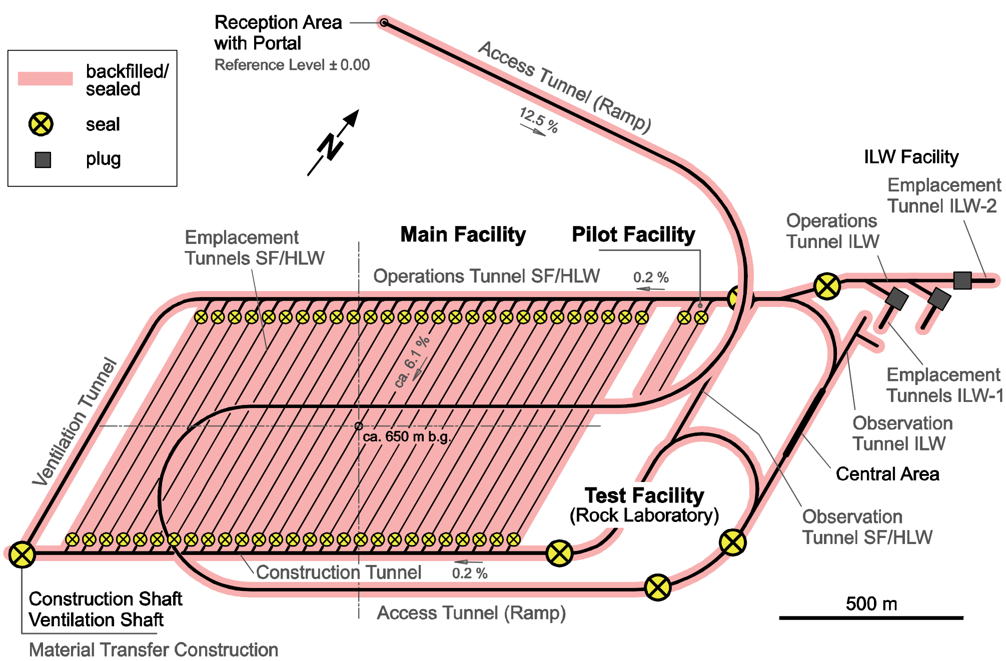
Note: Figure from Van Geet et al. (2009).

Figure 7.6: Reseal Shaft Seal at HADES URL at Mol



Note: Figure from Bernier et al. (2006).

Figure 7.7: PRACLAY Experiments at Mol Nagra's Proposed SF/HLW Repository in Opalinus Clay



Note: Figure from Nagra (2002a).

Figure 7.8: Conceptual Layout of Planned Repository in Opalinus Clay after Final Sealing and Closure

The main repository seals are located in the shaft (at the repository horizon and one at the intersection with a sandstone formation) and in the ramp (again at repository depth and at the intersection with the sandstone). The seals are 40 m long fabricated from highly compacted bentonite. The planned procedure involves:

- Shotcrete liner of tunnel/shaft is removed within the seal section;
- A ring of Opalinus Clay is excavated to a depth of approximately 1 m to remove the Excavation Damaged Zone, which may have been altered by contact with the concrete and with air;
- An abutment is installed across the tunnel;
- An approximately 40 m section of highly-compacted bentonite blocks is installed, keyed into the Opalinus Clay; and
- The second abutment is emplaced; the remaining parts in the adjacent rock formations above the host rock are then backfilled with processed excavated rock.

It is expected that the EDZ will be recompacted by swelling of the highly compacted bentonite blocks, which are designed to give a swelling pressure of 9 MPa. Removal of the 1 m of damaged zone ensures that the contact between the bentonite and the Opalinus is unaffected by exposure to air or concrete.

8. TREATMENT OF EDZ IN SAFETY ANALYSIS

8.1 Introduction

Zuidema (2004) comments that on current understanding the EDZ[5] cannot be avoided but measures can be taken to minimize its effects. He also emphasizes that:

- The phenomena occurring within the EDZ are specific properties of the system and their importance with respect to post-closure behaviour needs to be assessed in the context of the overall repository system behaviour;
- The properties of the EDZ and nature of phenomena in the EDZ may have a strong transient behaviour and results from early-time (short-term) observations need to be translated into information relevant to the post-closure state; and
- The EDZ may have an effect on post-closure performance and therefore needs to be addressed in performance assessment.

In particular the EDZ:

- Is an integral part of the system that evolves with time and may need to be considered in an assessment of the temporal evolution of the overall repository;
- Is a potential pathway for migration of radionuclides; and
- May be of only limited importance to post-closure performance.

8.1.1 EDZ Geometry in Performance Assessment Treatments

For the purposes of assessing long-term safety (i.e., after repository resaturation and any thermal disturbance) the tunnel near-field has typically been treated within safety assessments as one or more zones of altered properties surrounding the excavations. These zones are often treated as concentric rings around the excavation having uniform homogeneous properties. For groundwater flow simulations these rings are specified by their inner and outer radii (as a factor of excavation radius) and permeability (typically as a factor k_{factor} times the permeability of the undisturbed host rock[6]).

Difficulties in establishing the likely extent, transmissivity distribution (after self-sealing) and connectivity of the HDZ fracture network has usually resulted in conservative estimates being made for both radial extent and k_{factor}. Typically, the permeability of the EDZ is assumed to be isotropic, even within host rocks with anisotropic undisturbed permeability.

Discussion here focuses on the treatment of the tunnel near-field within calculations of the long-term safety of radioactive waste repositories. For an overview of tunnel near-field in clay formations and their overall relevance to performance assessment see Blümling et al. (2007) who present results from the Boom Clay, Callovo-Oxfordian Argilite and Opalinus Clay. A brief presentation of some aspects of EDZ treatment within safety assessments for these host rocks is provided in the following sections.

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5 In this case defined as the zone of altered properties relevant to the post-closure performance.

6 For anisotropic undisturbed host rock permeability, the maximum permeability has been used to calculate k_{factor} in this report.

8.1.2 Self Sealing

An important aspect of the transient behaviour of the EDZ in clay formations is the observed self-sealing of fractures resulting in a reduction in fracture transmissivity and hence reduction in the effective EDZ permeability over time during repository resaturation. This sealing of the fractures is a function both of resaturation of the EDZ and saturation and swelling of the buffer. Bock et al. (2010) have recently concluded a review of self-sealing processes and considered seven mechanisms that might lead to self-sealing and assessed the state of knowledge and potential for sealing of each mechanism as set out in Table 8.1.

Table 8.1: Summary of Sealing Mechanisms as Identified by Bock et al. (2010)

	Sealing Mechanism		State of Knowledge	Database	Sealing Potential
M-1	Additional compaction of the rock matrix		Very good		Low
M-2	Increase of the effective normal stress σ_n‘ across the fracture plane		Good		Moderate to high
M-3	Contraction of fracture when subjected to shear		Good		Moderate to very high
M-4	Creep of fracture wall material		Limited	Limited	High to very high
M-5	Swelling of the fracture wall material		Reasonable	Inadequate	Very high
M-6	Slaking:	Body slaking	Limited	Poor	Limited to moderate
		Surface slaking	Non-existent	Non-existent	Unknown (most likely limited)
M-7	Mineral precipitation onto fracture walls		Reasonable	Reasonable	Limited

Bock et al. (2010) suggest that there is likely to be a threshold in clay mineral content (dependent on the fraction of swelling clays such as smectites) below which self-sealing is ineffective. They suggest that this threshold may be as low as 15 to 25% but recommend a threshold of 40% in the absence of dedicated investigations for a specific situation.

8.2 Nagra's Project Opalinus Clay

Within the Nagra Project Opalinus Clay the EDZ is described as a composite structure consisting of two concentric shells (EDZ-i, EDZ-o) the radius of which depends on the local tunnel radius and the orientation of the tunnel axis to the principal horizontal stress direction (Nagra 2002a). The division into two follows the concept of Bossart et al. (2002) as shown in Figure 8.1. A connected fracture system is assumed to exist within the inner zone while any fracturing in the outer zone is assumed to be disconnected. The EDZ-i therefore corresponds to the HDZ as defined in this report, while the EDZ-o contains both the EDZ and some parts of the HDZ where isolated fractures have been induced.

The EDZ-i is assumed to retain an enhanced hydraulic conductivity of up to ~ 10 times that of undisturbed Opalinus Clay if the swelling pressure of the highly compacted bentonite in the seal and the deformation of the EDZ by convergence does not fully reduce its porosity and permeability. Thus for the central case the conductivity of the EDZ-i was taken as 10^{-12} m/s (k_{factor}= 10 relative to bedding parallel hydraulic conductivity of the undisturbed host rock). The hydraulic conductivity of the outer zone was taken as 5×10^{-13} m/s (k_{factor}= 5 relative to bedding parallel hydraulic conductivity). In parameter variations, the hydraulic conductivity of the EDZ-i was increased to 10^{-10} m/s (k_{factor}=1000) applied to emplacement tunnels and sealing sections. Other “what-if“ type calculations varied the hydraulic conductivity of the EDZ-i further (see, for example, Figure 8.2).

Within the Nagra concept, prior to the emplacement of the sealing plugs, the EDZ-i around the seal zone is partially removed. As a consequence, the hydraulic conductivity of the EDZ in sealing sections was expected to be lower than 1×10^{-12} m/s, but this was not taken into account within the performance assessment calculations (Nagra 2002c).

In the absence of any major water conducting features it was found that flow through the damage zone is limited by the inflow into the tunnels and partly by the effectiveness of the seals (Blümling et al. 2007 and Nagra 2002a). Even without effective seals, flow along tunnel levels off at hypothetical effective conductivities of the EDZ-i of about 10^{-8} m/s. Further radionuclide transport is influenced by the retention capability of the host-rock and buffer, and calculations showed that transport along the EDZ associated with emplacement tunnels resulted in diffusion of radionuclides into the matrix Smith et al. (2004) present a sensitivity study evaluating the effect of a highly permeable EDZ-i as a “what-if” study showing that even for an effective EDZ hydraulic conductivity of 10^{-8} m/s the dose stayed well within regulatory guidelines as shown in Figure 8.3.

8.2.1 Gas Migration in the EDZ

When considering gas transport from L&ILW drifts Nagra suggest that the excavation damaged/disturbed zone serves two functions (Nagra 2008):

- Increased porosity, compared to the intact rock, providing additional gas storage capacity; and
- The EDZ fracture network providing a potential gas pathway.

Although it is expected that the EDZ will recompact due to the prevailing rock stress after backfill and resaturation, it may still act as a preferential gas path if the sealed fractures are reactivated in the case of high gas pressure (see Figure 8.4).

The EDZ plays only a subordinate role in transport due to the relatively high conductivity of the backfill. The creation and propagation of gas pathways through the EDZ around cavern plugs may be seen as a favourable process if self-sealing were to occur within the Engineered Gas Transport System (EGTS) and gas pressure builds to a level where pathway dilation occurs resulting in the development of gas-pressure sensitive pathways that would reduce the gas pressure build-up in the emplacement caverns.

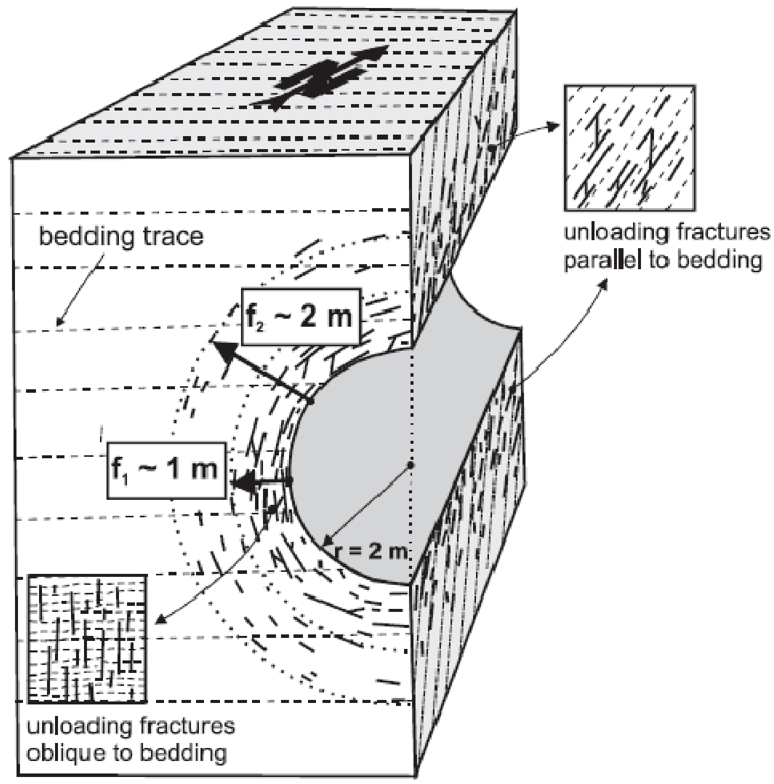
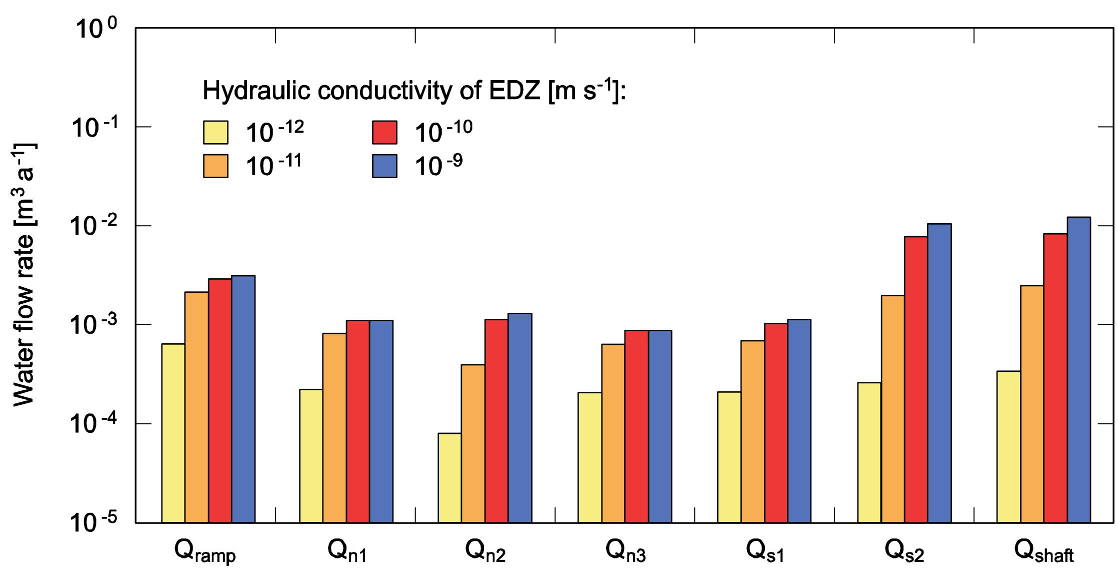
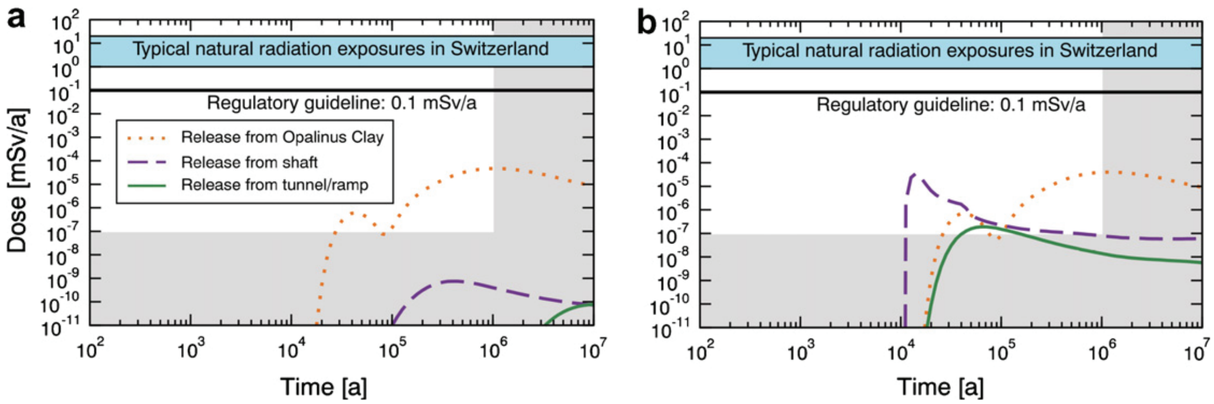


Figure 8.1: Schematic of Tunnel Near-field at Mont Terri Showing Inner (Connected Fractures) and Outer (Isolated Fractures) EDZ



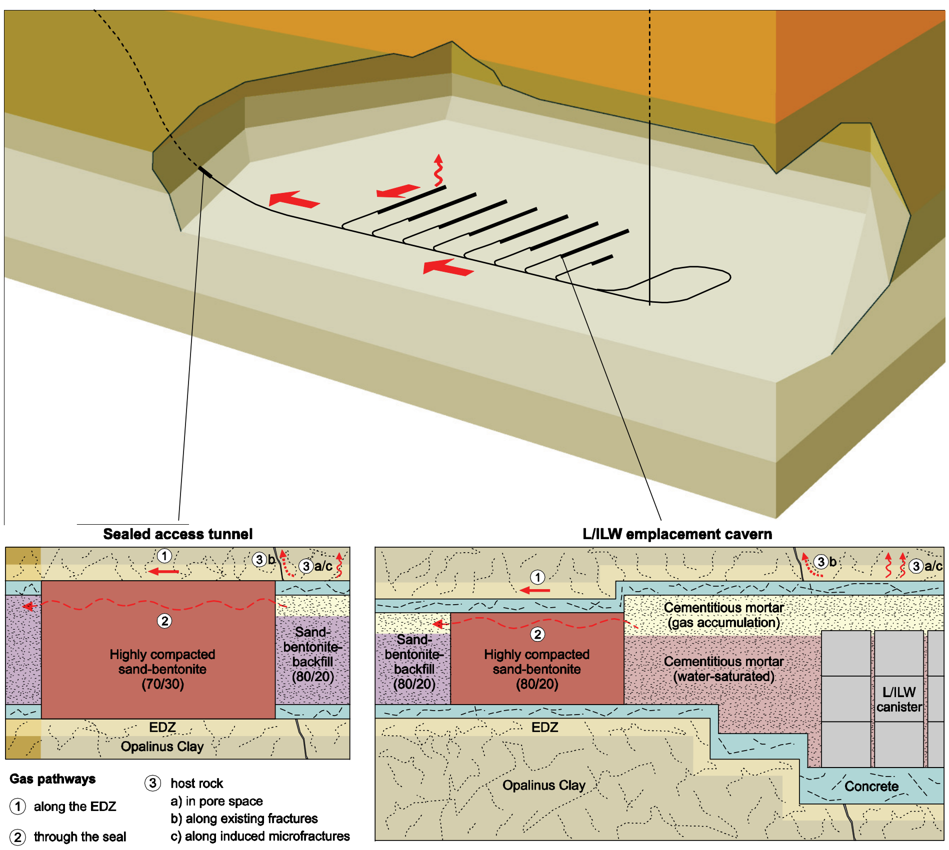
Note: Figure from Nagra(2002c).

Figure 8.2: Comparison of Water Flow Rates Obtained from Resistor Network Model Calculations for Various Values of the Hydraulic Conductivity of the EDZ



Notes: (a) Base case with EDZ-i conductivity of 10^{-12} m/s; (b) ‘‘What if?’’ case with a hypothetical EDZ-i conductivity of 10^{-8} m/s. Figure from Smith et al. (2004).

Figure 8.3: Dose Curves Calculated for a Repository in Opalinus Clay for Spent Fuel



Note: Figure from Nagra (2008).

Figure 8.4: Potential Gas Transport Pathways for Degradation and Corrosion Gases Accumulated

8.2.2 Excavation Damage Zone Geochemistry

Blümling et al. (2007) comment that “transport of radionuclides through engineered barriers and the clay host formation is assumed to be mainly driven by molecular diffusion in the groundwater. Diffusive transport might be facilitated or hindered through the EDZ because of physical and chemical alterations. For instance, the sorption capacity might be affected by oxidation, or the porosity might be different from that of undisturbed clay.”

Project Opalinus Clay documents the possible geochemical effects of the tunnel near-field. In particular oxidation of pyrite on fracture surfaces has been studied and estimates of the extent of oxidation were derived (Nagra 2002c). Results indicated that gypsum formation in the EDZ is limited to open fracture surfaces (Mäder and Mazurek 1998). Using data from Mont Terri and other excavations it was estimated that only about 1% of the pyrite originally present will be altered and that long-term impacts will be insignificant (Mäder 2002).

8.3 Andra’s Dossier Argile

Within Andra’s Dossier Argile (ANDRA 2001, 2005) the EDZ is conceptualized as:

- A “fractured zone” containing a potentially connected network of micro-fractures and fractures; and
- A surrounding micro-fractured or “damaged zone” of “diffuse weakly connected micro-cracks, and with a limited increase of the permeability” (Bauer et al. 2003b).

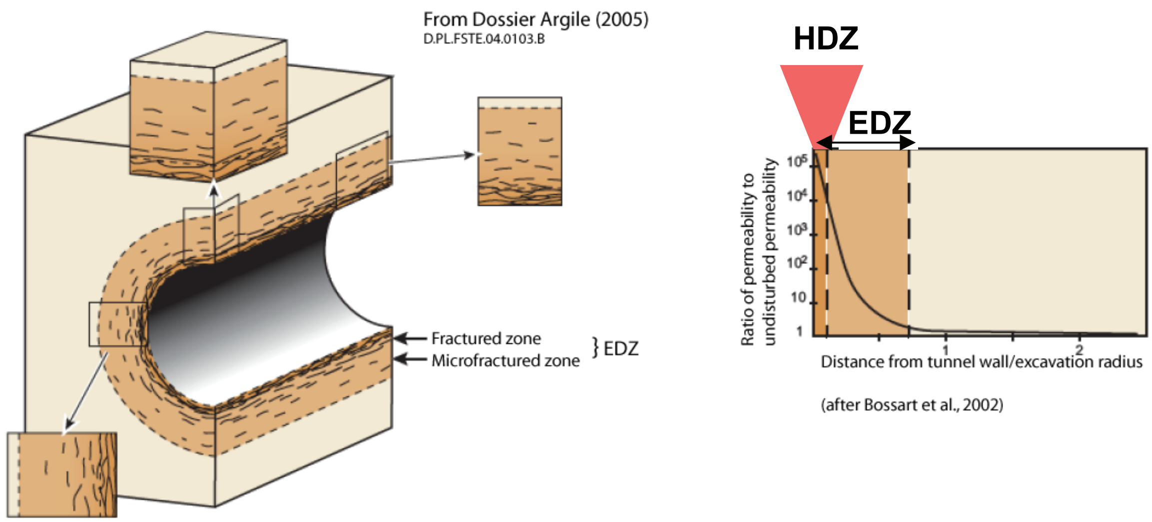
These zones are equivalent to the HDZ and EDZ as defined within this report. The concept is shown in Figure 8.5. Delay et al. (2007) use a slightly different definition with regard to the Bure site where “the damaged zone (EDZ) corresponds to shear fracture or extension fracture zones. The disturbed zone (EdZ) corresponds to a microfissured zone”.

In simulations the fractured zone (HDZ) was conservatively assumed to be 0.1-0.3r thick and the micro-fractured zone (EDZ) 0.5-0.7r at a depth of 630 m. The extension depends on the orientation relative to stress direction and depth (stress magnitudes). For excavations oriented parallel to σ_{Hmax} the fractured zone extent was 0.1r while for excavations oriented parallel to σ_{Hmin} the extent was 0.3r. The extent was also less at smaller depths with no “fractured zone” for tunnels in the σ_{Hmax} direction at 500 m depth.

The micro-fractured zone effective hydraulic conductivity was estimated to be 5×10^{-11} m/s (k_{factor}= 100) and the fractured zone effective hydraulic conductivity 5×10^{-9} m/s (k_{factor}= 10,000). The zones were assumed to extend around all excavations (disposal cell, tunnel, access galleries and shafts), although the “fractured zone” is cut off around seals in “Reference Case” models.

The influence of the fractured and microfractured zones on flow through the repository and on radionuclide transport was examined in the Reference Case where all repository seals are effective and alternate (“Incidental”) simulations where the seals have “failed” and have high permeability. In the Reference Case calculations the tunnel near-field has little effect on flow through the repository and radionuclide transport is dominated by diffusion through the host-rock. In the alternate case flow through the repository became hydraulically disturbed once seal-zone permeability was in excess of 10^{-9} m/s, in which case flow was focussed in the excavations and their associated damaged zones (Bauer et al. 2003b). It was concluded that:

- Considering permeability of sealing systems lower than, or equal to 10^{-10} m/s, and a damaged zone with a permeability no higher than 2 orders of magnitude greater than the sound rock permeability, the geological barrier is the main radionuclide transfer pathway; and
- If the seals do not cut off the fractured zone around the openings and if the latter is continuous with a permeability higher or equal to 10^{-9} m/s the fractured and damaged zone provokes a short circuit of the geological barrier.



Notes: Figure modified from ANDRA (2005). HDZ and EDZ extent added.

Figure 8.5: Schematic of EDZ

8.4 Boom Clay

Blümling et al. (2007) report that the potential role of the EDZ along galleries and shafts as a preferential pathway for advective transport has been considered for the case of a repository in the Boom Clay and that SCK/CEN has investigated several poor sealing scenarios in which the hydraulic conductivity of the galleries and the access shaft was raised to values three to six orders of magnitude above the conductivity of Boom Clay.

Even in such adverse conditions, calculations indicate a rather limited contribution of such a pathway to the overall releases of radionuclides. This is due, in part, to the low conductivity of the host formation, which limits the availability of water for advective transport through the near-field, regardless of the hydraulic conductivity of the Engineered Barrier System (EBS) and EDZ.

Possible mechanical and chemical interactions between the EDZ and components of the EBS may affect the performance of these components. In this sense, at least, knowledge of the behaviour of the EDZ is relevant for understanding the coupled processes within the EBS and thus strengthens the assumptions on which the performance assessment calculations are based.

8.5 Waste Isolation Pilot Plant Shafts

While the EDZ in salt formations is outside the scope of this report it is useful to summarize the treatment of the EDZ around shafts at the WIPP site where they pass through evaporite beds containing shales and anhydrites. The discussion here is based on Sandia (1996).

Hydraulic testing in the Waste Handling Shaft (Saulnier and Avis 1988) in the Rustler (Permian evaporite containing anhydrite, gypsum, halite, siltstone, claystone and dolomite) and Salado (halite containing anhydrite beds) formations failed to identify a more permeable EDZ. At some depths the closest interval to the shaft was located 1 m from the shaft wall, while other testing overlapped the interface between the liner and the rock which may have hindered identification of the EDZ.

Table 8.2: Undisturbed and Peak Disturbed Permeability for Lithologic Units in the Salado and Rustler Formation from Sandia (1996) as Used in Fluid Flow Analyses for Flow Along the WIPP Shafts

Formation	Unit	Undisturbed (m^2)	Disturbed (m^2)	EDZ Ratio K_{factor}
Rustler	Anhydrite	1.00E-19	1.00E-19	1
	Mudstone 4	3.89E-16	3.89E-13	1000
	Magenta	1.49E-15	1.49E-14	10
	Mudstone 3	1.49E-19	1.49E-16	1000
	Culebra	2.09E-14	2.09E-13	10
	Anhydrite 1/ Mudstone 1	1.00E-19	1.00E-19	1
	Transition/bioturbated clastics	2.24E-18	2.24E-15	1000
Salado	Anhydrite > 3 m	1.00E-19	1.00E-19	1
	Anhydrite < 3 m	1.00E-19	1.00E-15	10,000
	Halite	1.00E-21	1.00E-15	1,000,000
	Polyhalite	3.00E-21	1.00E-15	333,333
	Vaca Triste	1.49E-19	1.49E-16	1000

Dale and Hurtado (1996) report gas and brine permeability measurements of the "Disturbed Rock Zone" (DRZ) from the WIPP air-intake shaft (6.1 m diameter) in the Salado formation (predominantly halite interbedded with polyhalite and anhydrite). The DRZ was defined as any rock where the permeability was greater than the maximum permeability of intact (undisturbed) halite approximately 10^{-21} m^2 and so may be viewed as equivalent to the EDZ in the definitions used here. Tests were performed at two depth horizons: 345.9 mbgl and 624.9 mbgl. In both depth horizons permeability reduced with radial distance from the shaft wall and the authors concluded that maximum extent of the DRZ was less than 3.0 m (1 radius). Brine-testing intervals located closest to the shaft wall at both depths had an effective brine permeability of 2 to 3 orders of magnitude higher than the testing interval located further from the shaft wall. The measured increase in gas permeability was greatest and extended further in the deeper horizon indicating greater brine desaturation at this depth.

The extent of the DRZ around a shaft in the Rustler formation was taken to be the boundary of the plastic region and calculated from a Coulomb failure criterion. To account for scale-effects the laboratory derived strength was reduced by a factor of 3-5 to give the in situ strength. A stress ratio σ_H/σ_h of 1.5 was assumed. A maximum extent of 2.6 radii was predicted for mudstones at a depth of 260 m.

The permeability of the DRZ was described by a log-linear relationship with distance from the shaft wall. The undisturbed permeability and peak disturbed permeability (at the shaft wall) for the different units are tabulated in Table 8.2. Within the flow models EDZ permeabilities of combined stratigraphic units were calculated using a thickness-weighted harmonic mean.

Rock-mechanical calculations indicated that the anhydrites within the Rustler and thicker beds in the Salado would not develop a DRZ. However, this did not account for blast damage and because no field data was available, DRZ models assumed either a continuous (i.e., using disturbed permeabilities for all units) or discontinuous DRZ (i.e., using undisturbed permeabilities for units that were predicted not to develop a DRZ).

The behaviour of anhydrite beds within the Solado formation (halite) was assumed to depend on bed thickness. The presence of anhydrite beds was assumed to inhibit creep of the surrounding salt, while salt-creep would promote fracturing of the interbeds. The relative thickness of salt and anhydrite layers would determine which of the two behaviours would dominate.

9. SUMMARY AND CONCLUSIONS

The previous chapters have compiled a large body of information based on experience from geoscientific studies of the Excavation Damaged and Disturbed Zones in sedimentary rocks. The information covers:

- The creation and evolution of the damaged and disturbed zones around excavations;
- The failure mechanisms associated with damage and fracturing around excavations;
- The current status of modeling EDZ creation and evolution;
- The development of engineering treatments to cut off EDZ pathways (seals & EDZ Cut-offs);
- The estimation of the extent and magnitude of permeability change associated with the EDZ and
- The influence of the EDZ on repository evolution and post-closure performance.

To properly delineate different zones of disturbed and damaged rock around an excavation opening, the definitions of the Damaged and Disturbed Zones proposed by Tsang et al. (2005) were adopted together with an additional zone to describe highly damaged rock close to the excavation face.

- The Excavation Disturbed Zone (EdZ) is a zone with hydromechanical and geochemical modifications, without major changes in flow and transport properties.
- The Excavation Damaged Zone (EDZ) is a zone with hydromechanical and geochemical modifications inducing significant changes in flow and transport properties. These changes can, for example, include one or more orders of magnitude increase in (effective) flow permeability.
- The Highly Damaged Zone (HDZ) was defined as the part of the EDZ, close to the excavated face, where macro-scale fracturing or spalling may occur. The effective permeability of this zone is dominated by the interconnectedness of the discrete fracture system formed and may be orders of magnitude greater than the undisturbed rock mass.

Within the EdZ variables such as stress, water pressure, temperature, saturation, water chemistry and related properties such as porosity, may be altered by the presence of the opening but these changes are either temporary (e.g., saturation) or do not have a major influence on flow and transport properties (e.g., small changes in porosity due to changes in effective stresses). As for the HDZ, it will only exist where stresses are sufficiently high relative to rock strength or where the excavation method creates a fractured zone (e.g., conventional drill and blast).

A wide range of techniques have been developed in recent years to characterize the extent and properties of the damaged and disturbed zone. Four types of measurements are generally considered: geological, hydraulic, geophysical and geomechanical. The first three relate to characterization during and after excavation, while geomechanical measurements are usually associated with either “mine-by” experiments or monitoring of the evolution of the zones.

One of the most widely used methods is ultrasonic velocity measurements in radial boreholes to survey the extent of the EDZ. Results from velocity profiles can be integrated with other geological and hydraulic measurements to provide a basis for determining EDZ geometry and properties.

Single-hole pneumatic or hydraulic tests performed from radial boreholes provide local point source measurements on the extent and variability in permeability changes around the excavation. Successful measurements of axial flow are very limited and have only been performed over relatively short distances (<10 m) due to the difficulty of establishing appropriate boundary conditions and in some cases observed lack of continuity along fractures in the damage zones.

Obtaining a good understanding of the failure mechanisms associated with damage and fracturing leading to EDZ creation and its evolution is essential. Such mechanisms can be controlled by geologic structure, in situ stress or a combination of the two. Argillaceous rocks can also be affected by wetting and drying leading to swelling, shrinkage, weakening and softening. New understandings of brittle failure around excavations have been developed in the last two decades and these provide a suitable framework for understanding much of the observed behaviour during excavation. The importance of damage and failure initiation ahead of the face has been demonstrated by Martin (1997) and co-workers and is confirmed by observations from the Mol, Bure and Mont Terri URLs (see Figure 4.13 and Figure 4.14).

For excavations in weak sedimentary rocks stress-controlled failure is considered to be the most important and a relationship between damage zone definitions and failure mechanisms based on the work of Diederichs (2000) is presented.

A comparison of the structure and extent of the EDZ at four different URLs is presented and related to the maximum stress/strength ratio at each location. The influence of pre-existing structures and excavation method is also described.

The recent development of numerical models simulating EDZ creation and evolution can provide helpful analytical tools. There has been significant development in the capability of numerical codes and constitutive models to reproduce the observed shape of the EDZ and the pattern of associated fracturing in the HDZ. Multi-code benchmarks of excavation response at the Bure URL have demonstrated a reasonably good ability to predict the observed convergence and EDZ extent.

New engineering treatments are being developed for seals to cut-off EDZ pathways and limit the EDZ extent and effective permeability. Tests on plugs and seals are under way (e.g., RESEAL) and practical designs for EDZ Cut-offs have been tested at Mont Terri and Bure (Delay et al. 2007, 2010) have been shown to be effective in cutting off flow. The extent and effective permeability of the EDZ can be limited by appropriate excavation design choices. However, it may not be practical to entirely eliminate the EDZ around key locations in a repository, such as at tunnel or shaft seals.

An important consideration for any deep geologic repository is the influence of the EDZ on repository evolution and post-closure performance. Local short-term flow investigations have identified highly permeable intervals (in comparison with very low permeability in undisturbed rock) around excavations in sedimentary rock. These are related to a region of induced fracturing (HDZ). However, a demonstration of the existence of a connected HDZ along the axis of an opening over length scales of interest (10s of metres) for repository seals and emplacement tunnels has not been possible even in the short-term. It is possible that the axial fracture network within the HDZ may be unconnected over greater length scales, particularly for vertical shafts in horizontally layered sedimentary rocks with few oblique or vertical joints.

In the longer term self-sealing processes in argillaceous rocks are likely to significantly reduce the effective permeability in the EDZ from that measured after excavation (Johnson et al. 2008, Bock et al. 2010). Such processes will be particularly important in rocks with clay contents greater than 40% but may also be significant below this threshold (Bock et al. ibid).

The assumption that the HDZ (and more generally the EDZ) can provide high permeability short-circuits for flow and transport, has resulted in treatment of the EDZ within safety assessments focussing on its potential role as a preferential flow path and has involved conservative assumptions with regard to the connectivity and effective permeability of the EDZ. Recent studies have shown that even under highly conservative assumptions repository performance in a low conductivity host rock is unaffected by the presence of a more permeable EDZ. Some aspects of the EDZ may even be favourable for repository performance, e.g., increase in fracture surface area for sorption, and potential to act as a gas flowpath. This does not, however, eliminate the need for a sound scientific understanding of the EDZ.

10. REFERENCES

Ando, K., M. Mihara, M. Noda and M. Yamamoto. 2006. Gas generation and migration analysis for TRU Waste Disposal in Japan. Proceedings 11th International High-Level Radioactive Waste Management Conference. May 2006. Las Vegas.

ANDRA. 2001. Dossier 2001 Argile. Progress Report on Feasibility Studies and Research into Deep Geological Disposal of High-level and Long-lived Waste. Andra Synthesis Report.

ANDRA. 2005. Dossier 2005 Argile. Synthesis: Evaluation of the Feasibility of a Geological Repository in an Argillaceous Formation, Meuse/Haute Marne Site. Paris, France.

Aranyossy, J.F., P Blumling, H.J. Alheid, M. Van Geet, J.C. Mayor, P. Marschall and F. Plas. 2006. Importance of the Excavation Damaged Zone (EDZ) in the General Performance of the Near-Field of a Geological Disposal System: Input of the EDZ Component to the EC Integrated Project on the Near-Field (NF-PRO). Scientific Basis for Nuclear Waste Management XXIX 932, 87-94.

Armand, G. and K. Su. 2006. Hydromechanical coupling phenomena observed during a shaft sinking experiment in a deep argillaceous rock. Proceedings Geoproc 2006. Nanjing, China.

Armand, G., T. Doe, M. Piédevache and G. Chavane. 2004. Permeability measurements in the excavation damaged zone in the Opalinus Clay at Mont Terri Rock Laboratory, Switzerland. Proceedings 57th Canadian Geotechnique Conference. Paper G15-453.

Armand, G., K. Ben-Slimane, Y. Wileveau and J. Delay. 2003. EDZ Characterization in the Meuse/ Haute-Marne Underground Research Laboratory: Experimental Programme. Impact of the Excavation Disturbed or Damaged Zone (EDZ) on the performance of radioactive waste geological repositories. Proceedings European Commission CLUSTER Conference and Workshop on EDZ in Radioactive Waste Geological Repositories, Luxembourg.

Armand, G., P. LeBon; M. Cruchaudet, H. Rebours, J. Morel and Y. Wileveau. 2007. Characterization of the excavation-damaged zone in the Meuse Haute Marne Underground Research Laboratory. Clays in Natural and Engineered Barriers for Radioactive Waste Confinement International Meeting September 17-18, 2007. Lille, France.

Armand, G. and M. Souley. 2009. A Viscoplastic Model including Damage for Deep Argillaceous Rocks: Blind Predictions of Drift Behaviour. EURO: TUN 2009 2nd International Conference on Computational Methods in Tunnelling. Ruhr University Bochum, September 9-11, 2009. Aedificatio Publishers, Bochum, Germany.

Autio, J., M. Siitari-Kauppi, J. Timonen, K. Hartikainen and J. Hartikainen. 1998. Determination of the porosity, permeability and diffusivity of rock in the excavation-disturbed zone around full-scale deposition holes using the 14C-PMMA and He-gas methods. Journal of Contaminant Hydrology 35(1-3), 19-29.

Backblom, G. 2008. Excavation Damage and Disturbance in Crystalline Rock – Results from Experiments and Analyses. SKB Technical Report TR 08-08, SKB Stockholm.

Balland, C., J. Morel, G. Armand and W. Pettitt. 2009. Ultrasonic velocity survey in Callovo-Oxfordian argillaceous rock during shaft excavation. International Journal of Rock Mechanics and Mining Sciences 46(1), 69-79.

Bandis, S. 1990. Fracture modes around tunnels in weak rocks. Proceedings 3rd Conference on Mechanics and Engineering of Rocks, IGA/Univ. of Turin, 1990, 12.1-12.10.

Barton, N. 1993. Physical and discrete element models of excavation and failure in jointed rock. Keynote Lecture on Assessment and Prevention of Failure Phenomena in Rock Engineering: Proceedings of the International Symposium on Assessment and Prevention of Failure Phenomena in Rock Engineering: Istanbul, Turkey, 5-7 April 1993, p.35.

Barton, N., A. Makurat, K. Monsen, G. Vik and L. Tunbridge. 1995. Geotechnical predictions of the excavation disturbed zone at stripa. International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts, 413A-414A.

Bastiaens, W. and F. Bernier. 2005. 25 years of underground engineering in a plastic clay formation: the HADES underground research facility. Proceedings of the 5th international conference of TC28 of the ISSMGE on Geotechnical aspects of underground construction in soft ground, Amsterdam, Netherlands, 15-17.

Bastiaens, W., F. Bernier and X.L. Li. 2007. SELFRAC: Experiments and conclusions on fracturing, self-healing and self-sealing processes in clays. Physics and Chemistry of the Earth 32(8-14), 600-615.

Bastiaens, W. and J. Mertens. 2003. EDZ around an Industrial Excavation in Boom Clay. Impact of the Excavation Disturbed or Damaged Zone (EDZ) on the performance of radioactive waste geological repositories. Proceedings European Commission CLUSTER Conference and Workshop on EDZ in Radioactive Waste Geological Repositories, Luxembourg.

Bauer, C., J.P. Piguet and Y. Wileveau. 2003a. Disturbance Assessment at the Wall of a Vertical Blasted Shaft in Marls. ISRM 2003 – Technology Roadmap for Rock Mechanics, South African Institute of Mining and Metallurgy.

Bauer, C., G. Pepin and P. Lebon. 2003b. EDZ in the Performance Assessment of the Meuse/Haute-Marne Site: Conceptual Model Used and Questions Addressed to the Research Programme. Impact of the Excavation Disturbed or Damaged Zone (EDZ) on the Performance of Radioactive Waste Geological Repositories. Proceedings European Commission CLUSTER Conference and Workshop on EDZ in Radioactive Waste Geological Repositories, Luxembourg.

Bechthold, W., T. Rothfuchs, A. Poley, M. Ghoreychi, S. Heusermann, A. Gens and S. Olivella. 1999. Backfilling and sealing of underground repositories for radioactive waste in salt (BAMBUS Project). Nuclear Science and Technology, EUR 19124.

Bengtsson, A., B. Grundfelt, A. Markstrom and A. Rasmuson. 1991. Impact from the Disturbed Zone on Nuclide Migration – A Radioactive Waste Repository Study. SKB Technical Report 91-11, SKB Stockholm.

Bennett, D.G., A.J. Hooper, S. Voinis and H. Umeki. 2006. The Role of the Engineered Barrier System in Safety Cases for Geological Radioactive Waste Repositories: An NEA Initiative in Co-operation with the EC. Scientific Basis for Nuclear Waste Management XXIX, 932, 43-41.

Ben-Slimane, K., A. Thoraval and O. Ozanam. 2003. The REP Experiment at the Bure Underground Research Laboratory: Objectives, Programme and Design. ISRM 2003– Technology roadmap for rock mechanics, South African Institute of Mining and Metallurgy.

Bernier, F., M. Demarche and B. Johan. 2006. The Belgian Demonstration Programme for the Disposal of High-Level and Long-Lived Radioactive Waste. Scientific Basis for Nuclear Waste Management XXIX, 932, 103-110.

Bildstein, O., C. Pozo, M. Jullien and L. Trotignon. 2007. Modelling oxidising perturbations in argillaceous material. 2nd Meeting on Clays in Natural and Engineered Barriers for Radioactive Waste Confinement, Tours, France.

Billaux, D., F. Dedecker and P. Cundall. 2004. A novel approach to studying rock damage: the three-dimensional Adaptive Continuum/Discontinuum Code. Eurock 2004, and 53rd Geomechanics Colloquium, p.723-728.

Blümling G.P. 1986. In situ Spannungsmessung in Tiefbohrungen mit Hilfe von Bohrlochrandausbrüchen und die Spannungsverteilung in der Kruste MittelEuropas und Australiens. Diss. Fak. Physik University Karlsruhe.

Blümling, P., F. Bernier, P. Lebon and C.D. Martin. 2007. The excavation damaged zone in clay formations time-dependent behaviour and influence on performance assessment. Physics and Chemistry of the Earth 32(8-14), 588-599.

Bock, H., B. Dehandschutter, C.D. Martin, M. Mazurek, A. de Haller, F. Skoczylas and C. Davy. 2010. Self-sealing of fractures in argillaceous formations in context with the geological disposal of radioactive waste review and synthesis. OECD, NEA No. 6184.

Bonin, B. 1998. Deep geological disposal in argillaceous formations: studies at the Tournemire test site. Journal of Contaminant Hydrology 35(1-3), 315-330.

Bordeau, F., C. Dedeckerv and D. Billaux. 2007. Discrete modelling of drift behaviour in the Meuse/Haute-Marne URL (France). International Meeting, September 17-18, 2007, Lille, France, Clays in natural and engineered barriers for radioactive waste confinement.

Bossart, P., P.M. Meier, A. Moeri, T. Trick and J.C. Mayor. 2002. Geological and hydraulic Characterization of the excavation disturbed zone in the Opalinus Clay of the Mont Terri Rock Laboratory. Engineering Geology 66, 19-38.

Bossart, P., T. Trick, P.M. Meierand and J.C. Mayor. 2004. Structural and hydrogeological Characterization of the excavation-disturbed zone in the Opalinus Clay (Mont Terri Project, Switzerland). Applied Clay Science 26, 429– 448.

Bossart, P.and M. Thury (Eds). 2008. Mont Terri Rock Laboratory Project, Programme 1996 to 2007 and Results, Rep. Swiss. Geological Survey 3, Wabern, Switzerland.

Cai, M., P. Kaiser, F. Suorineni and K. Su. 2007. A study on the dynamic behavior of the Meuse/Haute-Marne argillite. Physics and Chemistry of the Earth 32(8-14), 907-916.

Chavant, C. and R. Fernandes. 2005. Evaluating the reliability of hydro-mechanical simulation: A benchmark of numerical techniques carried out by research group of MoMaS. 2nd Meeting on Clays in Natural and Eengineered Barriers for Radioactive Waste Confinement, Tours 2005.

CNS. 1996. Designing the Excavation Disturbed Zone for a nuclear repository in hard rock. Proceedings of the EDZ Workshop, International Conference on Deep Geological Disposal of Radioactive Waste, Winnipeg, Canada, 20 September 1996, Canadian Nuclear Society.

Contrucci, I., J. Cabrera, E. Klein and K. Ben-Slimane. 2007. EDZ investigations by ultrasonic borehole logging in drifts of different ages excavated in argillaceous formations of the Tournemire experimental station (Aveyron, France). International Meeting, September 17-18, 2007, Lille, France, Clays in Natural and Engineered Barriers for Radioactive Waste Confinement.

Cook, J. 1999. The effects of pore pressure on the mechanical and physical properties of shales. Oil and Gas Science and Technology 54 (6), 695-701.

Dale, T. and L.D. Hurtado. 1996. WIPP air-intake shaft disturbed-rock zone study. 4th International Conference on the Mechanical Behavior of Salt, Montreal, Quebec, June 17- 18,1996, SAND96-1327C. Albuquerque, New Mexico, Sandia National Laboratories.

Damaj, J., C. Balland, G. Armand and T. Verdel. 2007. Velocity survey of an excavation damaged zone: influence of excavation and reloading. Rock Physics and Geomechanics in the Study of Reservoirs and Repositories.

De Bock, C., J.M. Bosgiraud, H. Weber, T. Rothfuchs, J. Verstricht, B. Breen and M. Johnson. 2008. Achievements of the ESDRED Project in Buffer Construction Technology. Proceedings Euradwaste 08.

Dedecker, F., P. Cundall, D. Billaux and T. Groeger. 2006. Evaluation of damage-induced permeability using a three-dimensional adaptive continuum model. Physics and Chemistry of the Earth 32 (8-14), 681-690.

Delay, J., A. Vinsot, J.M. Krieguer, H. Rebours and G. Armand. 2007. Making of the underground scientific experimental programme at the Meuse/Haute-Marne underground research laboratory, North Eastern France. Physics and Chemistry of the Earth 32(1-7), 2-18.

Delay, J., P. Lebon and H. Rebours. 2010. Meuse/Haute-Marne centre: next steps towards a deep disposal facility. Journal of Rock Mechanics and Geotechnical Engineering 2 (1), 52–70.

Dershowitz, W. 1992. The Role of the Stripa Phase 3 Project in Development of Practical Discrete Fracture Modelling Techniques. In situ experiments at the Stripa mine. Proceedings of the fourth International NEA/SKB Symposium, Stockholm, Sweden, 14-16 October 1992, OECD, pp. 259.

Dershowitz, W., G. Lee, J. Geier, T. Foxford, P. Lapointe and A. Thomas. 1998. FracMan Interactive Discrete Feature Data Analysis, Geometric Modeling and Exploration Simulation. User Documentation, Version 2.

de Windt, L., D. Pellegrini and J. van der Lee. 2004. Reactive transport modelling of a spent fuel repository in a stiff clay formation considering excavation damaged zone. Radiochim. Acta 92, 841–848.

Diederichs, M.S. 2003. Rock fracture and collapse under low confinement conditions. Rock Mechanics and Rock Engineering 36(5), 339-381.

Diederichs, M.S. 2007. Mechanistic interpretation and practical application of damage and spalling prediction criteria for deep tunnelling. Canadian Geotechnical Journal 44(9) 1082-1116.

Diederichs, M.S. and P.K. Kaiser. 1999. Stability of large excavations in laminated hard rock masses: the Voussoir analogue revisited. International Journal of Rock Mechanics and Mining Sciences 36(1), 97-118.

Diederichs, M.S. and C.D. Martin. 2010. Measurement of spalling parameters from laboratory testing. Proceeding of Eurock 2010, Lausanne, Switzerland. June 15-18, 2010. Paper 263.

Eberhardt, E. 1998. Brittle Rock Fracture and Progressive Damage in Uniaxial Compression. Ph.D. Thesis, University of Saskatchewan, Saskatoon.

Martino, J.B. and C.D. Martin (Eds). 2005. CLUSTER EDZ, Impact of the Excavation Disturbed or Damaged Zone (EDZ) on the performance of radioactive waste geological repositories. Proceedings European Commission CLUSTER Conference and Workshop on EDZ in Radioactive Waste Geological Repositories, Luxembourg.

Eilers, G., R. Mauke, F. Gläß, J. Preuss, W. Fischle, M. Linn, H. Schmidt, N. Müller-Hoeppe and C. Schrimpf. 2003. Sealing of the Morsleben repository, Germany. Proceedings of WM'03 Conference, February 23-27, 2003, Tucson, Arizona.

Einstein, H.H. 1996. Tunnelling in difficult ground—Swelling behaviour and identification of swelling rocks. Rock Mechanics and Rock Engineering 29(3), 113-124.

Einstein, H.H. 2002. Tunnels in Opalinus Clayshale—A Review of Case Histories and New Developments. Geotechnology Compendium 1, 177.

Emsley, S., O. Olsson, L. Stenberg, H.-J. Alheid and S. Falls. 1997. ZEDEX: A Study of Damage and Disturbance from Tunnel Excavation by Blasting and Tunnel Boring. Svensk Kärnbränslehantering AB/Swedish Nuclear Fuel and Waste Management Co.

Ericsson L.O., P. Brinkhoff, G. Gustafson and S.Kvartsberg. 2009. Hydraulic Features of the Excavation Disturbed Zone - Laboratory Investigations of Samples Taken from the Q- and S- Tunnels at Äspö HRL. SKB Report R-09-45, Svensk Kärnbränslehantering AB, Stockholm.

Everitt, R.A., P. Chernis, D. Good, D. and A. Grogan. 1988. Mapping of the excavation damage zone around the circular access shaft at Atomic Energy of Canada Limited's underground research laboratory. Proceedings Workshop on Excavation Response in Deep Radioactive Waste Repositories - Implications for Engineering Design and Safety Performance, Winnipeg, 271–82.

Ewy, R.T. and N.G.W. Cook. 1990a. Deformation and fracture around cylindrical openings in rock—Part I: observation and analysis of deformations. International Journal of Rock Mechanics and Mining Science 27, 387-407.

Ewy, R.T. and N.G.W. Cook. 1990b. Deformation and fracture around cylindrical openings in rock Part II initiation, growth and interaction of fractures. International Journal of Rock Mechanics and Mining Science 27, 409-427.

Fairhurst, C. and N.G.W. Cook. 1966. The phenomenon of rock splitting parallel to the direction of maximum compression in the neighbourhood of a surface. Proceedings of the 1st Congress of the International Society of Rock Mechanics, Lisbon, p.687–692.

Fairhurst, C. and B. Damjanac. 1996. The excavation damaged zone – an international perspective. Proceedings of EDZ Workshop September 1996 Winnipeg - International Conference on Deep Geological Disposal of Radioactive Waste.

Fernàndez-Garcia, D., J. Gómez-Hernández and J.C. Mayor. 2007. Estimating hydraulic conductivity of the Opalinus Clay at the regional scale: Combined effect of desaturation and EDZ. Physics and Chemistry of the Earth 32(8-14), 639-645.

Fierz, T.; M. Piedevache, J. Delay, G. Armand and J. Morel. 2007. Specialized instrumentation for hydromechanical measurements in deep argillaceous rock. Proceedings of the Seventh International Symposium on Field Measurements in Geomechanics (GSP 175).

Finsterle, S. 2000. Using the continuum approach to model unsaturated flow in fractured rock. Water Resources Research 36(8), 2055.

Finsterle, S. 2006. Comment on “Seepage into drifts and tunnels in unsaturated fractured rock” by Dani Or, Markus Tuller and Randall Fedors. Water Resour. Res. 42, W07603.

Frost, L. and R.A. Everitt. 1997. Excavation Damage Zone Tracer Experiments in the Floor of the Room 415 Test Tunnel AECL-11 640, COG-96-321-1. AECL, Manitoba.

Gibert, D., F. Nicollin, B. Kergosien, P. Bossart, C. Nussbaum, A. Grislin-Mouëzy, F. Conil and N. Hoteit. 2006. Electrical tomography monitoring of the excavation damaged zone of the Gallery 04 in the Mont Terri rock laboratory: Field experiments, modelling, and relationship with structural geology. Applied Clay Science 33(1), 21-34.

Göbel, I., H.-J.Alheid, E. Alonso, Ch. Ammon, P. Bossart, Ch. Bühler, K. Emmerich, A.M. Fernandez, J.L. Garcia-Siñeriz, A. Graf, N. Jockwer, St. Kaufhold, M. Kech, G. Klubertanz, A. Lloret, J.C. Mayor, T. Meyer, R. Miehe, J.J. Muñoz, M. Naumann, Ch. Nussbaum, Th. Pletsch, I. Plischke, M. Ploetze, M. Rey, H. Schnier, K. Schuster, K. Sprado, Th. Trick, H. Weber, K. Wieczorek and A. Zingg. 2007. Heater Experiment: Rock and Bentonite Thermo-hydro-mechanical (THM) Processes in the Near-field of a Thermal Source for Development of Deep Underground High Level Radioactive Waste Repositories. Ed. by Bossart & Nussbaum, Rep. Swiss Geol. Surv. 1. Bern.

Hartley L.J. and D. Holton. 2004. CONNECTFLOW (Release 8.0). Technical Summary Document, Serco Assurance.

Herbert, A.W., G.W. Lanyon, J.E. Gale and R. Macleod. 1992. Discrete fracture network modelling for phase 3 of the Stripa project using NAPSAC. In Situ Experiments at the Stripa Mine, OECD Nuclear Energy Agency and Swedish Nuclear Fuel and Waste Management Company, Paris: Organisation for Economic Co-operation and Development, 219–235.

Hökmark, H. 1998. Numerical study of the performance of tunnel plugs. Engineering Geology, 49 (3-4), 327-335.

Hudson, J., A. Bäckström, J. Rutqvist, L. Jing, T. Backer, M. Chijimatsu, X. Feng, A. Kobayashi, T. Koyama, H.-S. Lee, P. Pan, M. Rinne and B. Shen. 2008. Final Report of DECOVALEX THMC Task B (EDZ Guidance Document) Characterising and Modelling the Excavation Damaged Zone (EDZ) in Crystalline Rock in the Context of Radioactive Waste Disposal. SKI Report 2008:43 Svenska Strålskyddsmyndigheten.

Hunsche, U. and O. Schulze. 2003. The Dilatancy Concept – a basis for the modelling of coupled T–M–H processes in rock salt. Proceedings European Commission CLUSTER Conference and Workshop on EDZ in Radioactive Waste Geological Repositories. 3–5 November 2003, Luxembourg.

ITASCA. 2011. Long-term Geomechnical Stability Analysis. Itasca Consulting Group, Inc. report for the Nuclear Waste Management Organization NWMO DGR-TR-2011-17 R000. Toronto, Canada.

Johnson, L., D. Pellegrini, J. Alonso, F. Plas and M. Van Geet. 2008. Near-Field Processes - The Challenge of Integration into Performance Assessment. Proceedings Euradwaste 2008, Luxembourg.

JNC 2003. Horonobe Underground Research Laboratory project plans for surface-based investigations (Phase 1). JNX TN5510 2003-002.

Kelsall, P.C., J.B. Case and C. Chabannes. 1984. Evaluation of excavation induced changes in rock permeability. International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts 21, 121-135.

Klerck, P.A., E.J Sellers and D.R.J. Owen. 2004. Discrete fracture in quasi-brittle materials under compressive and tensile stress states. Computer Methods in Applied Mechanics and Engineering 193, 3035–3056.

Kontogianni, V., P. Psimoulis and S. Stiros. 2006. What is the contribution of time-dependent deformation in tunnel convergence? Engineering Geology 82(4), 264-267.

Kuhlmann, U. 1995. CASA – Calibration and Sensitivity Analysis in steady state and transient groundwater flow –User's Guide. Nagra Internal Report. Wettingen, Switzerland

Kruschwitz, S. and U. Yaramanci. 2004. Detection and characterization of the disturbed rock zone in claystone with the complex resistivity method. Journal of Applied Geophysics 57(1), 63-79.

Kwon, S. and W.J. Cho. 2008. The influence of an excavation damaged zone on the thermal-mechanical and hydro-mechanical behaviors of an underground excavation. Engineering Geology 101(3-4), 110-123.

Lanyon, G.W., P. Marschall and P. Blümling. 2005. Modelling of groundwater flow along the excavation damage zone of a tunnel in the Opalinus Clay. 2nd meeting on Clays in natural and engineered barriers for radioactive waste confinement. Tours, France.

Lanyon, G.W., P. Marschall, T. Trick, R. de la Vaissière, H. Shao and H. Leung. 2009a. Hydromechanical evolution and self-sealing of damage zones around a microtunnel in a claystone formation of the Swiss Jura mountains, 43rd U.S. Rock Mechanics Symposium & 4th U.S. - Canada Rock Mechanics Symposium, paper 09-152, June/July 2009 , Asheville, North Carolina.

Lanyon, G.W., R. Senger and P. Marschall. 2009b. A structured approach to the derivation of effective properties for combined water and gas flow in the EDZ. Proceedings, TOUGH Symposium 2009 Lawrence Berkeley National Laboratory, Berkeley, California, September 14-16, 2009.

Lavanchy, J.M., J. Croisé, R. Schwarz, G. Armand and M. Cruchaudet. 2007. Clay formation at the Meuse/Haute-Marne URL: evaluation of the impact of resin filled slots on flow paths characteristics within the EDZ. International Meeting, September 17-18, 2007, Lille, France, Clays in Natural and Engineered Barriers for Radioactive Waste Confinement.

Lebon, P., J. Delay and K. Su. 2002. Meuse/Haute-Marne URL, Bure (France): The in-situ programme and the MODEX-REP project. EUR (Luxembourg), (19954), 31-41.

Long, J.C.S. 1994. Modeling Flow and Transport for Stripa Phase 3 What did we learn? In situ experiments at the Stripa mine: Proceedings of the fourth International NEA/SKB Symposium, Stockholm, Sweden, 14-16 October 1992, 1994, OECD, pp.259.

Mäder, U.K. and M. Mazurek. 1998. Oxidation phenomena and processes in Opalinus Clay: evidence from the excavation-disturbed zones in Hauenstein and Mont Terri tunnels and Siblingen open clay pit, Materials Research Society Symposium Proceedings, 1998, Materials Research Society 731-740.

Mäder, U.K. 2002. Oxidation of clay-rich host rock during the operational phase of a nuclear waste repository: case studies and quantitative estimates of pyrite oxidation in Opalinus Clay and marl of the Palfris Formation. Nagra Internal Report. Wettingen, Switzerland.

Marschall, P., E. Fein, H. Kull, G.W. Lanyon, L. Liedtke, Müller-Lyda, and H. Shao. 1999. Conclusions of the Tunnel Near-Field Programme (CTN). Nagra Technical Report 99-07, Nagra, Wettingen, Switzerland.

Marschall, P., M. Distinguin, H. Shao, P. Bossart, C. Enachescu and T. Trick. 2006. Creation and evolution of damage zones around a microtunnel in a claystone formation of the Swiss Jura Mountains, International Symposium and Exhibition on Formation Damage Control.

Marschall, P., T. Trick, G.W. Lanyon, J. Delay and H. Shao. 2008. Hydro-Mechanical evolution of damaged zones around a microtunnel in a claystone formation of the Swiss Jura mountains, The 42nd US Rock Mechanics Symposium (USRMS).

Martin, C.D. 1997. Seventeenth Canadian Geotechnical Colloquium: The effect of cohesion loss and stress path on brittle rock strength. Canadian Geotechnical Journal 34(5), 698-725.

Martin, C.D. and N.A. Chandler. 1994. The progressive fracture of Lac du Bonnet granite. International Journal Rock Mechanics Mining Sciences and Geomechanics Abstracts 31(6), 643–659.

Martin, C.D., E.J. Dzik, E.J. and R.S. Read. 1996. Designing an effective EDZ cutoff in high stress environments. Proceedings of EDZ Workshop September 1996 Winnipeg - International Conference on Deep Geological Disposal of Radioactive Waste.

Martin, C.D., P.K. Kaiser and D.R. Mccreath. 1999. Hoek-Brown parameters for predicting the depth of brittle failure around tunnels. Canadian Geotechnical Journal 36(1), 136-151.

Martin, C.D., R. Christiansson and J. Söderhäll. 2001. Rock Stability Considerations for Siting and Constructing a KBS-3 Repository. SKB Technical Report TR-01-38.

Martin, C.D. and G.W. Lanyon. 2003a. EDZ in clay shale: Mont Terri. Mont Terri Techn. Rep.2001, 1. With contributions from P. Bossart and P. Blümling.

Martin, C.D. and G.W. Lanyon. 2003b. Measurement of in-situ stress in weak rocks at Mont Terri Rock Laboratory, Switzerland. International Journal of Rock Mechanics and Mining Sciences 40(7-8), 1077-1088.

Martino J.B. (Ed). 2003. The 2002 International EDZ Workshop on the Excavation Damage – Causes and Effects. Atomic Energy of Canada Ltd. Report 06819-REP-01200-10105-R00.

Martino, J., D. Dixon, E. Kozak, M. Gascoyne, B. Vignal, Y. Sugita, T. Fujita and K. Masumoto, 2007. The tunnel sealing experiment: An international study of full-scale seals. Physics and Chemistry of the Earth 32(1-7), 93-107.

Matray, J., S. Savoye and J. Cabrera. 2007. Desaturation and structures relationships around drifts excavated in the well-compacted Tournemire's argillite and their impact on the hydraulic head profiles. Engineering Geology 90, 1-16.

Matsui, H., K. Sugihara and K. Sato. 2003. In-situ experiments on excavation disturbance in JNC's Geoscientific Research Programme. Impact of the excavation disturbed or damaged zone (EDZ) on the performance of radioactive waste geological repositories. Proceedings European Commission CLUSTER Conference and Workshop on EDZ in Radioactive Waste Geological Repositories, Luxembourg.

Mayor, J.C., J.L. Garcia-Sineriz, E. Alonso, H.J. Alheid and P. Blümling. 2005a. Engineered barrier emplacement experiment in Opalinus Clay for the disposal of radioactive waste in underground repositories. ENRESA.

Mayor, J.C., J.L. García-Siñeriz, M. Velasco, J. Gómez-Hernández, A. Lloret, J.M. Matry, F. Coste, A. Giraud, T. Rothfuchs and P. Marschall. 2005b. Ventilation experiment in Opalinus Clay for the management of radioactive waste. Publicación técnica (Empresa Nacional de Residuos Radiactivos) (7), 1-82.

Mazurek, M., A. Gautschi, P. Marschall, G. Vigneron, P. Lebon and J. Delay. 2008. Transferability of geoscientific information from various sources (study sites, underground rock laboratories, natural analogues) to support safety cases for radioactive waste repositories in argillaceous formations. Physics and Chemistry of the Earth 33, 95-105.

Mellanen, S. ed., L. Koskinen, P. Hellä, J. Löfman, B. Lanyon, A. Öhberg, J. Autio, N. Sacklén, K. Saukkonen, J. Saari, A. Lakio, M. Silvast, B. Wiljanen, J. Vuokko and T. Lyytinen. 2008. EDZ Programme, EDZ Studies in ONKALO 2007-2008. Posiva Working Report 2008-66.

Mertens, J., W. Bastiaens and B. Dehandschutter. 2004. Characterization of induced discontinuities in the Boom Clay around the underground excavations (URF, Mol, Belgium). Applied Clay Science 26(1-4), 413-428.

Nagra. 1997. Geosynthese Wellenberg 1996-Ergebnisse der Untersuchungsphasen I und II; Nagra Technical Report NTB 96-01. Wettingen Switzerland.

Nagra. 2002a. Project Opalinus Clay: Safety Report. Demonstration of Disposal Feasibility for Spent Fuel, Vitrified High-level Waste and Long-lived Intermediate-level Waste (Entsorgungsnachweis). Nagra Technical Report NTB 02-05. Wettingen, Switzerland.

Nagra. 2002b. Projekt Opalinuston – Synthese der geowissenschaftlichen Untersuchungsergebnisse. Entsorgungs-nachweis für abgebrannte Brennelemente, verglaste hochaktive sowie langlebige mittelaktive Abfälle. Nagra Technical Report NTB 02-03. Wettingen, Switzerland.

Nagra. 2002c. Project Opalinus Clay: Models, Codes and Data for Safety Assessment – Demonstration of Disposal Feasibility for Spent Fuel, Vitrified High-level Waste and Long-lived Intermediate-level Waste. Nagra Technical Report NTB 02-06. Wettingen, Switzerland.

Nagra. 2008. Effects of Post-disposal Gas Generation in a Repository for Low- and Intermediate-level Waste Sited in the Opalinus Clay of Northern Switzerland. Nagra Technical Report NTB 08-07. Wettingen, Switzerland.

Nakaoka, K., K. Hata and K. Ando. 2006. A study about availability of mini multi packer system with sedimentary soft rock. Proceedings of the Symposium on Rock Mechanics, 267-270.

NEA. 1989. Excavation Response in Geological Repositories for Radioactive Waste. Proceedings of an NEA Workshop, Winnipeg, Canada, 26-28 April 1988. OECD/NEA, Paris.

NEA. 2002. Characterization and Representation of the Excavation Disturbed or Damaged Zone (EDZ). Lessons learnt from a SEDE Topical Session, September 1998, Paris. NEA Report NEA/RWM(2002)1.

NEA. 2003. Engineered Barrier Systems and the Safety of Deep Geological Repositories. State-of-the-art Report. In co-operation with the European Commission EUR 19964.

Nguyen, T.S., L. Börgesson, M. Chijimatsu, J. Hernelind, L. Jing, A. Kobayashi and J. Rutqvist. 2009. A case study on the influence of THM coupling on the near-field safety of a spent fuel repository in sparsely fractured granite. Environmental Geology 57(6), 1239-1254.

NWMO. 2011. Geosynthesis. Nuclear Waste Management Organization Report NWMO DGR-TR-2011-11 R000. Toronto, Canada.

OECD. 1994. In situ experiments at the Stripa Mine. Proceedings of the 4th NEA/SKB Symposium, Stockholm, Sweden, October 14-16, 1992.

Økland, D. and J.M. Cook. 1998. Bedding-related borehole instability in high-angle wells. SPE/ISRM Rock Mechanics in Petroleum Engineering.

Olsson, O. and A. Winberg. 1996. Current understanding of extent and properties of the excavation disturbed zone and its dependance of excavation method. International Conference on Deep Geological Disposal of Radioactive Waste. Proceedings of the EDZ workshop. Designing the excavation disturbed zone for a nuclear repository in hard rock, September 20, 1996, Winnipeg, Canada, p.101-112.

Or, D., M. Tuller and R. Fedors. 2005. Seepage into drifts and tunnels in unsaturated fractured rock. Water Resour. Res. 41, W05022.

Owen, D.R.J., F.M.A. Pires, E.A. de Souza Neto and Y.T. Feng. 2005. Continuous/discrete strategies for the modelling of fracturing solids. Engineering Structures Under Extreme Conditions: Multi-physics and Multi-scale Computer Models in Non-linear Analysis and Optimal Design. Ibrahimbegovič. A. and B.Bamk (Eds.). IOS Press.

Popp, T. and K. Salzer. 2007. Anisotropy of seismic and mechanical properties of Opalinus Clay during triaxial deformation in a multi-anvil apparatus. Physics and Chemistry of the Earth 32(8-14), 879-888.

Popp, T., K. Salzer and W. Minkley. 2008. Influence of bedding planes to EDZ-evolution and the coupled HM properties of Opalinus Clay. Physics and Chemistry of the Earth 33, 374-387.

Pusch, R. 1989. Alteration of the Hydraulic Conductivity of Rock by Tunnel Excavation. International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts 26(1), 79-83.

Pusch, R. and R. Stanfors. 1992. The zone of disturbance around blasted tunnels at depth. International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts 29(5), 447-456.

Pusch, R. and L. Borgesson. 2005. Examples of the performance of tunnel plugs with and without recesses—theory and practice. Advances in understanding engineered clay barriers: Proceedings of the International Symposium on Large Scale Field Tests in Granite, Sitges, Barcelona, Spain, 12-14th November 2003, p.41.

Read, R.S. 2004. The role of tunnel design in controlling excavation damage development. Proceedings European Commission CLUSTER Conference and Workshop on EDZ in Radioactive Waste Geological Repositories, Luxembourg.

Read, R.S. and N.A. Chandler. 1996. AECL's Excavation Stability Study-summary of Observations. Atomic Energy of Canada Limited Internal Report, AECL-11582.

Rejeb, A. 2003. Time-dependent behaviour of Tournemire argillites, France. Proceedings of the ISRM Conference, South Africa.

Rejeb, A. and J. Cabrera. 2007. Time-dependent evolution of the excavation damaged zone in the argillaceous Tournemire site. Advances on coupled thermohydro-mechanical-chemical processes in geosystems and engineering. Proceedings International Conference GeoProc 2006, Nanjing, China, p.648–657.

Rutqvist, J., L. Börgesson, M. Chijimatsu, J. Hernelind, L. Jing, A. Kobayashi and S. Nguyen. 2009. Modeling of damage, permeability changes and pressure responses during excavation of the TSX tunnel in granitic rock at URL, Canada. Environmental Geology 57(6), 1263-1274.

Sandia. 1996. Waste Isolation Pilot Plant Shaft Sealing System Compliance Submittal Design Report. Sandia Report SAND96-132611 UC-721. Albuquerque, New Mexico

Sato, T., T. Kikuchi and K. Sugihara. 2000. In-situ experiments on an excavation disturbed zone induced by mechanical excavation in Neogene sedimentary rock at Tono mine, central Japan. Engineering Geology 56(1-2), 97-108.

Saulnier, G.J., Jr. and J.D. Avis. 1988. Interpretation of Hydraulic Tests Conducted in the Waste-Handling Shaft at the Waste Isolation Pilot Plant (WIPP) Site. Sandia Report SAND88-7001. Albuquerque, New Mexico.

Schuster, K., H.-J. Alheid and S. Kruschwitz. 2004. Observation of an engineered barrier experiment in the Opalinus Clay of the Mont Terri Rock Laboratory with geophysical and hydraulic methods. Proceedings of EURADWASTE '04.

Schuster K. and H.-J. Alheid. 2007. EDZ Characterization with ultrasonic interval velocity measurements in the URL Meuse/Haute-Marne – performed between depth of 85 m and 504 m. International Meeting, Clays in Natural and Engineered Barriers for Radioactive Waste Confinement, September 17-18, 2007, Lille, France.

Sellers, E.J. and P. Klerck. 2000. Modelling of the effect of discontinuities on the extent of the fracture zone surrounding deep tunnels. Tunnelling and Underground Space Technology, 15(4), 463-469.

Shao, H., K. Schuster, J. Sönnke, and V. Bräuer. 2008. EDZ development in indurated clay formations–In situ borehole measurements and coupled HM modelling. Physics and Chemistry of the Earth 33, 388-395.

Shen, B. 2002. FRACOD Version 1.1, User's Manual. FRACOM Ltd.

Shen, B. and O. Stephansson. 1993. Modification of the G-criterion for crack propagation subjected to compression. International Journal of Engineering Fracture Mechanics 47(2), 177-189.

Silvast, M. and B. Wiljanen. 2008. Onkalo EDZ-measurements using Ground Penetrating Radar (GPR) Method. Working Report 2008-58. Posiva Oy.

Smith, P., P. Gribi, G. Mayer. and J. Schneider. 2004. Project Opalinus Clay (Entsorgungsnachweis): Supplementary Calculations to Illustrate the Influence of EDZ Hydraulic Conductivity on Radionuclide Transport. Nagra Internal Report. Wettingen, Switzerland.

Souley, M., F. Homand, S. Pepa and D. Hoxha. 2001. Damage-induced permeability changes in granite: a case example at the URL in Canada. International Journal of Rock Mechanics and Mining Sciences 38(2), 297-310.

Steiner, W. 1993. Swelling rock in tunnels: rock characterization, effect of horizontal stresses and construction procedures. International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts, 361-380.

Steiner, W. 1996. Tunnelling in squeezing rocks: case histories. Rock Mechanics and Rock Engineering 29(4), 211-246.

Stephansson, O., B. Shen, M. Rinne, K.J. Amemiya, R. Yamashi and S. Toguri. 2008. FRACOD modeling of rock fracturing and permeability change in excavation damaged zones. The 12th International Conference of International Association for Computer Methods and Advances in Geomechanics (IACMAG) 1-6 October, 2008.

Swan, G., J. Cook, S. Bruce and R. Meehan. 1989. Strain rate effects in Kimmeridge Bay shale. International Journal of Rock Mechanics and Mining Sciences 26(2), 135-149.

Su, K., N. Hoteit and O. Ozanam. 2002. Geomechanical investigation programme in the Meuse/Haute-Marne Underground Research Laboratory, Hydromechanical and Thermohydromechanical Behaviour of Deep Argillaceous Rock: Theory and Experiments. Proceedings of the International Workshop on Geomechanics, 11-12 October 2000, Paris, France.

Su, K. 2007. Development and Validation of the Constitutive Hydromechanical Models for Callovo-Oxfordian Argillites: the MODEX-REP Project. Synthesis report of EC MODEX-REP project.

Suzuki, K., E. Nakata, M. Minami, E. Hibino, T. Tani, J. Sakakibara and N.Yamada. 2004. Estimation of the zone of excavation disturbance around tunnels, using resistivity and acoustic tomography. Exploration Geophysics 35, 62-69.

Talandier, J., G. Mayer and J. Croisé. 2006. Simulations of the hydrogen migration out of intermediate-level radioactive waste disposal drifts using TOUGH2. TOUGH Symposium 2006.

Tsang, C.F. and F. Bernier. 2004. Definitions of excavation disturbed zone and excavation damaged zone, in Impact of the excavation disturbed or damaged zone (EDZ) on the performance of radioactive waste geological repositories. Proceedings European Commission CLUSTER Conference and Workshop on EDZ in Radioactive Waste Geological Repositories, Luxembourg.

Tsang, C.F., F. Bernier and C. Davies. 2005. Geohydromechanical processes in the Excavation Damaged Zone in crystalline rock, rock salt, and indurated and plastic clays—in the context of radioactive waste disposal. International Journal of Rock Mechanics and Mining Sciences 42(1), 109-125.

Van Der Lee, J., L. De Windt, V. Lagneau and P. Goblet. 2003. Module-oriented modeling of reactive transport with HYTEC. Computers and Geosciences 29(3), 265-275.

Van Geet, M., G. Volckaert, W. Bastiaens, N. Maes, E. Weetjens, X. Sillen, B. Vallejan and A. Gens. 2007. Efficiency of a borehole seal by means of pre-compacted bentonite blocks. Physics and Chemistry of the Earth 32(1-7), 123-134.

Van Geet, M., W. Bastiaens, G. Volckaert, E. Weetjens, X. Sillen, N. Maes, Ch. Imbert, P. Billaud, G. Touzé, M. Filippi, F. Plas, M.V. Villar, M. García-Gutiérrez, M. Mingarro, A. Gens and B. Vallejan. 2009. RESEAL II A large-scale in situ demonstration test for repository sealing in an argillaceous host rock – Phase II. Final Report. European Commission Report EUR 24161 EN.

Wileveau, Y., F.H. Cornet, J. Desroches and P. Blumling. 2007. Complete in situ stress determination in an argillite sedimentary formation. Physics and Chemistry of the Earth 32(8-14), 866-878.

Wileveau, Y. and Bernier, F. 2008. Similarities in the hydromechanical response of Callovo-Oxfordian clay and Boom Clay during gallery excavation. Physics and Chemistry of the Earth 33, 343-349.

Willson, S.M., N.C. Last, M.D. Zoback and D. Moos. 1999. Drilling in South America: a wellbore stability approach for complex geologic conditions, Latin American and Caribbean Petroleum Engineering Conference.

Wilson, C.R., P.A. Witherspoon, J.C.S. Long, R.M. Galbraith, A.O. DuBois and M.J. McPherson. 1983. Large-scale hydraulic conductivity measurements in fractured granite. International Journal of Rock Mechanics and Mining Sciences and Geomechanics Abstracts 20(6), 269-276.

Wu, F., J. Liu, T. Liu, H. Zhuang and C. Yan. 2009. A method for assessment of excavation damaged zone (EDZ) of a rock mass and its application to a dam foundation case. Engineering Geology 104(3-4), 254-262.

Yong, S., S. Loew, C. Fidelibus, E. Frank, F. Lemy and K. Schuster. 2006. Induced fracturing in the Opalinus Clay: an integrated field experiment, rock mechanics in underground construction: ISRM International Symposium 2006: 4th Asian Rock Mechanics Symposium, 8-10 November 2006, Singapore, p.418.

Yong, S. 2008. A three-dimensional analysis of excavation-induced perturbations in the Opalinus Clay at the Mont Terri Rock Laboratory. ETH Zurich.

Yong, S., P.K. Kaiser, S. Loew and F. Corrado. 2008. The role of heterogeneity on the development of excavation-induced fractures in the Opalinus Clay. Canadian Geotechnical Conference, Edmonton, Canada.

Zhang, K., Y.S. Wu, C. Ding and K. Pruess. 2003. TOUGH2_MP: A parallel version of TOUGH2. Proceedings TOUGH2 Symposium 2003, Lawrence Berkeley National Laboratory, California.

Zhang, C. and T. Rothfuchs. 2004. Experimental study of the hydro-mechanical behaviour of the Callovo-Oxfordian argillite. Applied Clay Science 26(1-4), 325-336.

Zuidema, P. 2004. The importance of the Excavation Damaged Zone for Post-Closure Safety of Deep Geological Repositories: Some Introductory Remarks. Proceedings European Commission CLUSTER Conference and Workshop on EDZ in Radioactive Waste Geological Repositories, Luxembourg.

11. ABBREVIATIONS AND ACRONYMS

AE	Acoustic emission
AECL	Atomic Energy of Canada Limited
ANDRA	Agence Nationale pour la Gestion des Déchets Radioactifs
BDZ	Borehole Damage Zone
BGR	Bundesanstalt für Geowissenschaften und Rohstoffe (Germany)
BWIP	Basalt Waste Isolation Project (State of Washington)
COX	Cavallo-Oxfordian Argillite (France)
DFN	Pore Diffusion Coefficient
DGR	Deep Geologic Repository
EB	Engineered barriers experiment (Mont Terri, Switzerland)
EBS	Engineered Barrier System
ED-B	EDZ evolution, mine-by test (Mont Terri, Switzerland)
EDZ	Excavation Damage Zone
EdZ	Excavation Disturbed Zone
EGTS	Engineered Gas Transport System
FEM	Finite Element Method
GPR	Ground Penetrating Radar
GTS	Grimsel Test Site (Switzerland)
HDZ	Highly Damaged Zone
KURT	KAERI Underground Research Tunnel (South Korea)
LASGIT	Large Scale Gas Injection Test (Sweden)
L&ILW	Low and Intermediate Level Waste
MIU	Mizunami URL (Japan)
MMPS	Modular Mini-Packer System
MPa	megapascal
MVP	Microvelocity probe
Nagra	National Cooperative for the Storage of Radioactive Wastes (Switzerland)

NEA	Nuclear Energy Agency
NWMO	Nuclear Waste Management Organization
ONKALO	Underground research facility in Finland
OPG	Ontario Power Generation Inc.
σ	Compressive stress
PRACLAY	Preliminary demonstration test for CLAY disposal of highly radioactive waste (Belgium)
RESEAL	Large scale shaft sealing test, HADES underground laboratory, Belgium
RH	Relative Humidity
SCK/CEN	Studiecentrum voor Kernenergie, Centre d'étude de l'énergie nucléaire (Belgium)
SEPPI	A probe to measure hydraulic transmissivity in small intervals
SEDE	Co-ordinating Group on Site Evaluation and Design of Experiments for Radioactive Waste Disposal
SKB	Swedish Nuclear Fuel and Waste Management Company
SUG	Geotechnical survey of galleries digging
TDR	Time Domain Reflectometer
THMC	Thermal, hydraulic, mechanical and chemical processes
TSX	Tunnel Sealing Experiment
UCS	Uniaxial Compressive Strength
URL	Underground Research Laboratory
WIPP	Waste Isolation Pilot Plant (USA)
ZEDEX	Zone of Excavation Disturbance EXperiment (Sweden)