A review of excavation damage zones in sedimentary rocks with emphasis on numerical modelling for EDZ definition

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ABSTRACT
In order to assess the safety performance of a DGR, it is necessary to establish the extent of the different degrees of damage to the rockmass created by the excavation process. This must include shaft, adit, room and cut-off excavation processes, throughout the life of the DGR, such that migration of radionuclides through the damaged rockmass can be adequately predicted. Perfectly plastic, strain weakening and brittle models were used to demonstrate the importance of selecting the appropriate yield criteria when using volumetric strain as an EDZ indicator.

RÉSUMÉ
Afin d'évaluer la performance de sécurité d'un DGR, il est nécessaire de prévoir adéquatement la mesure des différents degrés de dommages à la masse rocheuse, créé par le processus d'excavation. Ceci doit inclure l'arbre, galerie, salle et le seuil de processus d'excavation, tout au long de la vie de la DGR, tels que la migration des radionucléides par la masse rocheuse endommagé peut être prédit adéquatement. modèles parfaitement plastique, ce qui affaiblit la souche et fragiles ont été utilisés pour démontrer l'importance de la sélection des critères de rendement appropriés pour l'utilisation de la déformation volumétrique comme un indicateur EDZ.

1 INTRODUCTION

In Canada, the long-term care of used nuclear waste produced by nuclear reactors is governed by the Government of Canada's Nuclear Fuel Waste Act established in 2002. Under this Act, The Nuclear Waste Management Organization (NWMO) has been given the mandate to implement an Adapted Phased Management approach to safe and secure long-term containment and isolation of used nuclear waste involving the licensing, construction, operation and decommissioning of a deep geological repository which could be constructed in a suitable rock formation in either sedimentary or crystalline rock at depth.

The Excavation Damage Zone (EDZ) around underground openings, in particular the Deep Geologic Repository (DGR) for the storage of nuclear waste, may create a preferred pathway for radionuclide migration, particular in low permeability rockmasses. Developing an understanding of EDZ evolution, geometry and properties as they may influence the long-term performance of the DGR is an important aspect of a DGR development. The strategy for assessing the role of the EDZ in the DGR concept is threefold; i) to understand possible role in the possibility of creating discrete pathways along the excavated and backfilled openings for mass transport in rock; ii) to minimize damage extent through excavation methods and geometry of excavated openings based on the knowledge of stress re-distribution and influence on EDZ occurrence; and iii) and evaluate sealing methods.

1.1 Underground Storage

The long-term management of nuclear waste in a deep geological repository is globally the preferred method for the long-term safe keeping of spent nuclear fuel and other nuclear waste. The benefit of a deep geological repository is, in addition to the engineered barriers, there is also a geological barrier which will isolate the repository from the surrounding geological environment, particularly the groundwater system.

Underground long-term management of nuclear waste has been envisioned from the early stages of finding a long-term storage solution. Three broad rockmass types are being investigated globally today for the development of geological repositories to store nuclear waste for the long-term. These are crystalline, salt and argillaceous rockmasses.

With any underground excavation, the surrounding rock will be damaged during excavation. Damage initiation and fracture propagation will occur and the crack intensity decrease with increase in distance from the tunnel wall. The thickness of this excavation damage zone (EDZ) is dependent on the excavation method, excavation size and shape, the fracture potential and properties of the rock material and the stress field.

Understanding the extent of the excavation damage zones and how it may be determined using state of the art numerical modelling methods is necessary to identify the damaged zone in underground cavern design, particularly for the underground nuclear waste facilities where the EDZ is a potential pathway for transporting radionuclides.

2 THE EXCAVATION DAMAGE ZONE

The significance of excavation damage and its impact on nuclear waste long-term management in a geological repository was first studied in the early 1980s at the abandoned Stripa mine in central Sweden (Carlsson 1986). The Stripa project had three main areas of focus (Carlsson 1986);

a. Detection and mapping of fracture zones
b. Groundwater conditions and nuclide migration
c. Bentonite clay as a backfilling and seal material

Since this time other studies have been conducted to determine the extent of damage to the rockmass surrounding underground excavations. Backblom (2008) summarizes this information, with a focus on crystalline rock. Defining the excavation damage zones was originally done for different rock types (Tsang et al. 2005) and also by many authors from different organizations (Kelsall et al. 1984, Fairhurst and Damjanac 1996, Emsley et al. 1997 and Marschall et al. 1999). This has lead to some confusion in the terminology used to describe the different zones of rock response to stress relief and perturbations around an excavation.

2.1 Definitions of the Excavation Damage Zones

Reviewing literature pertaining to disturbed and damaged zones can be confusing due to inconsistent use of the terminology, damaged and disturbed zone. For this reason, alternate terminology and revised definitions are presented here to reflect both the impact of the damage intensity on hydraulic conductivities, as well as, to indicate the more useful numerical indicators for prediction of dimensions. These zones are identified in Figure 1 and are collectively referred to as the excavation damage zones.

2.1.1 Excavation Influence Zone (EIZ)

The EIZ, or generally termed EdZ (Tsang et al. 2005), is a zone of stress change and/or elastic strain influence. The material in question is still elastic and no damage is induced. In more porous rocks the stress/strain influence may result in possible hydromechanical and geochemical modifications, without changes in flow and transport properties due to pore volume changes. EIZ permeabilities will be only affected in high porosity materials due to elastic pore volume changes in response to deviatoric stress changes (Lockner and Stanchits 2002). Large stress changes may alter grain boundaries in low porosity rocks or effective joint apertures in rockmasses but influence is minimal.

2.1.2 Excavation Damage Zone (EDZ)

The EDZ is a zone with hydromechanical and geochemical modifications inducing changes in flow and transport properties. There are many experiments showing results of reducing transmissivity or permeability with distance from openings (Shao et al. 2008 and Bossart et al. 2004). These measurements are punctual measurements of rock permeability, which can be significant to 10^6 x that of the undisturbed rock mass, and should be distinguish from the effective axial permeability of the tunnel, which represents scale dependent enhancement of permeability. These effective axial permeabilities could increase by factors of 10x to 100X of

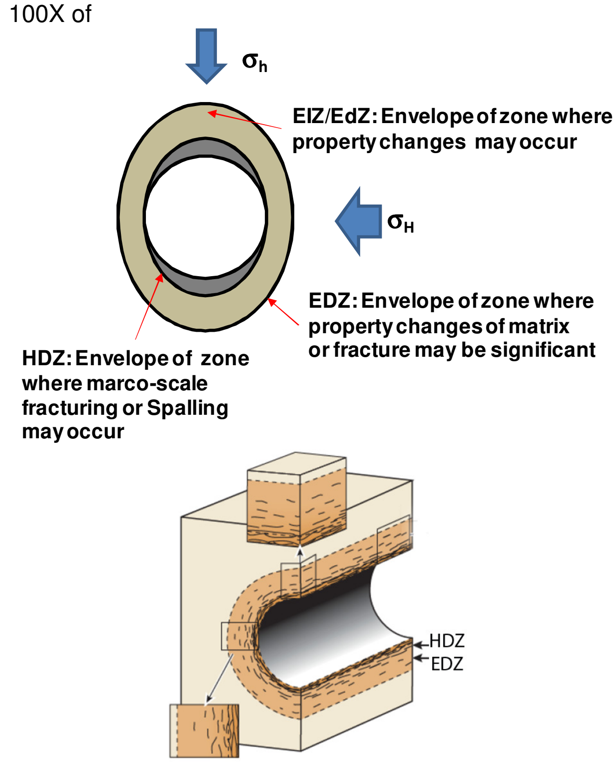

Figure 1: Illustration of the excavation damage zones for massive ground around a circular excavation. (bottom after ANDRA 2005).

the undisturbed rockmass. This zone generally can be sub-divided into, the outer zone (EDZo) and the inner zone (EDZi) to facilitate the hydrogeological modelling of tunnels. NAGRA (2002) treated the two zones by assuming an average factor of 10x permeability increase in the inner zone (EDZi) and 5x in the outer zone (EDZo) in their safety assessment for the Opalinus Clay. The damage in this zone is in the form of grain scale fractures, minor interface dilation, discontinuous internal damage.

Damage in the EDZ is easily identified in modelling by yield indicators accompanied by very limited plastic strain and/or limited internal stress reduction. The analytical boundary with the EIZ is normally sharp however; it is likely to be gradational in nature.

EDZ is a zone which is stress and strain induced and its geometry is highly influenced by i) stress tensor around openings, ii) material anisotropy such as the presence of bedding or fracture planes, iii) opening geometry, and iv) interaction between found and tunnel support (Bluming et al. 2007). In this study, the extent of the EDZ is assumed not to be significantly influenced by excavation activities because of the utilization of controlled drill and blast or mechanical boring techniques in DGR construction. However, blasting operation used in normal construction will likely result in a larger HDZ (see below) which could cause further expansion of the EDZ.

2.1.3 Highly Damaged Zone (HDZ)

The HDZ is a zone where macro-scale fracturing may occur. The effective HDZ permeability is dominated by interconnected fractures and is significantly greater than the undisturbed rockmass. The average permeability in this zone could be in the order of 1000x (ANDRA 2005) or larger than the rockmass permeability. New fractures and bedding slip develops continuously at the excavation scale within this zone, slowing and stopping soon after the excavation reaches a state of equilibrium.

Identified by yield with significant plastic strain, fracture dilation, tensile failure, joint aperture increase and significant drop in internal stresses. The boundary between the HDZ and EDZ will be sharp in brittle rocks and more gradational in ductile rocks.

The HDZ is a highly fractured zone that is generated by the excavation process and is dependent on the excavation method employed. Cautious blasting is needed to minimize the HDZ, although in certain rocks some HDZ may be present regardless of any technique (Jonsson et al. 2009).

Support of HDZ is essential to minimize expansion of both HDZ and EDZ for the excavation. Loss of HDZ material through support failure could lead to EDZ expansion. Strategies should be aimed to remove this high permeability HDZ by means of over-excavation during the sealing of an underground opening in the repository closure stage.

3 INVESTIGATIONS TO DELINEATE THE EDZ

Initially research on damage around underground excavations focused on brittle hard rocks, such as crystalline rockmasses (Carlsson 1986), with some countries also investigating old salt mines in the 1960s (US Department of Energy 2000). Many countries are now studying the EDZ in sedimentary rocks, particularly argillaceous rocks, as potential hosts for the long-term management of nuclear waste (Mont Terri, Touremire, Tono Mine and Horonobe).

3.1 Crystalline Rockmasses

Investigations on the EDZ in Canada originally concentrated on crystalline rocks of the Lac du Bonnet Granite at the URL, southeastern Manitoba, by AECL (Martin 1994).

In 1982 a shaft was excavated into the granite batholite to gain a better understanding of the excavation response (Read 2004). Martino and Chandler (2004) show (Fig. 2) changes in transmissivity extending away from the excavation. Although the micro-velocity probe (MVP) measurements are not conclusively indicative of interconnecting fractures, the hydraulic transmissivity point measurements (SEPPI) agree well with the MVP data in Figure 2. It should be noted however; that the SEPPI packer used in the experiment had seven 0.1 m long test sections (Matino and Chandler 2004) and that this represents a more localized point measurement, not a rockmass measurement. The excavation damage zones were indicated by Martino and Chandler (2004) and re-labelled by the authors with the terminology defined above for consistency.

Extensive EDZ work has been conducted in Sweden on excavation damage. Jonsson et al. (2009) presented

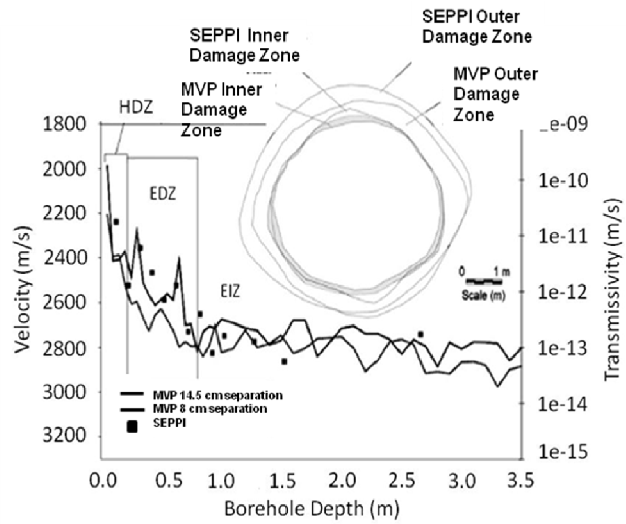

Figure 2: Changes in the velocity (MVP lines) and transmissivity (SEPPI points) with distance from the excavation face. The HDZ, EDZ, and EIZ are delineated at major changes in the slope of the graph (modified from Martino & Chandler 2004).

the main projects relating to mechanical affects and heating of the rockmass on the evolution of EDZ.

A blasting experiment concluded that normal blasting could induced up to 1.7 m thick EDZ and that caution/control blasting can reduce the thickness to 1 m (maximum) (Jonsson et al. 2009) in the granitic rocks. Further reduction of the zone thickness can be achieved by utilizing secondary blasting (slashing).

The ZEDEX project also investigated the evolution of the EIZ, which is referred to by Jonsson et al. (2009) as the disturbance zone. He compared drill and blast methods with tunnel boring machine excavation methods and found that the EDZ in the drill and blast tunnel was larger. The generated fractures by this method seem to propagate in a specific direction for TBM excavation, as shown in Figure 3, comparing to blast fractures which are randomly orientated (Jonsson et al. 2009). Another significant finding by Jonsson et al. (2009) is that there was no difference in the EIZ between the two excavation methods.

The TASQ tunnel was used to collect detailed data on the development of the EDZ and to study the possibility of controlling its development. This project was also used to provide input data for DECOVALEX-THMC project, which was aimed at determining the nature and potential for THMC modelling of the EDZ (Jonsson et al. 2009). Methodical testing, relating THCM parameters to be used in numerical models continues and the reader is referred to Jonsson et al. (2009) for further information and references regarding test details.

3.2 Salt Rockmasses

In 1957, the National Academy of Science, in the United States, stated that the most promising storage option of radioactive waste was in salt deposits (US Department of Energy 2000). Investigations into storage of nuclear waste have predominately been conducted by the US and

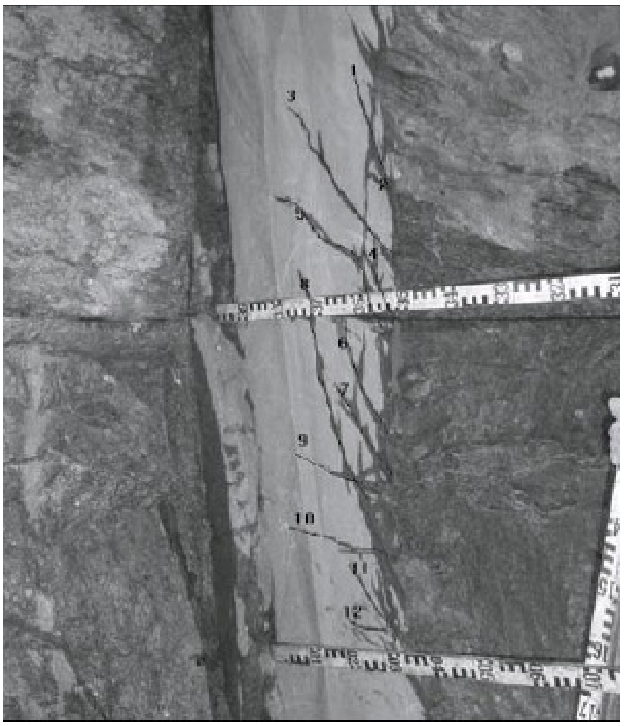

Figure 3: Fractures generated by TBM in cut-away slot at the Aspo HRL, showing upward orientations (Jonsson et al. 2009).

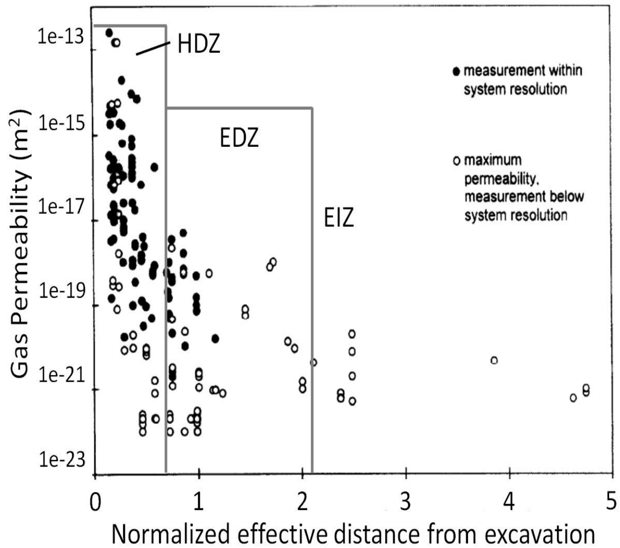

Figure 4: Gas permeabilities, measured at various locations at the WIPP project, normalized to excavation radius dimensions and EDZ dimensions indicated (modified from Stormont 1997).

Germany. In the US, the WIPP site has been a licensed facility since March 1999. Germany started investigations at the Gorleben salt dome in the 1970s (Lidskog and Andersson 2001).

The attractiveness of a salt formation is that there is little water, good heat conduction and self healing capacity (Langer 1999). Salt domes are often associated with oil traps, as the movement of the salt up warps sedimentary beds and the salt itself is impermeable to gas migration (Stormont 1997). Low gas permeability can act as a natural barrier for nuclear waste decay gases.

Using gas permeabilities Stormont (1997) showed that damage within a salt formation could be detected and that an EDZ could be delineated, as shown in Figure 4 from the WIPP site. The results of the permeability tests show a rapid increase in gas permeability within one radius of the excavation, with the measurements coming from a variety of cavern shapes and time durations after excavation (Stormont 1997). The authors have indicated, in Figure 4, the EDZ based on the average curvature of the data points, to illustrate the usefulness of permeability measurements at detecting the EDZ.

Long-term stability of caverns in salt formations, where creep can continue to expand the EIZ and EDZ, is more of a concern for the safe storage of nuclear waste then in crystalline rocks.

3.3 Argillaceous Rockmasses

Sedimentary rocks have been recognized as potential host materials for long-term management of radioactive waste. The geological setting and material properties at these research facilities span a wide spectrum. One aspect of rocks of sedimentary origin is an inherent anisotropy either or both in material strength and stiffness. Extensive studies on cross-anisotropic behaviour of sedimentary rocks from southern Ontario have been carried out by Lo and Hori (1979), Lo et al. (1979) and OPG (1991). The anisotropic behaviour is variable and some rock formations behave more anisotropically than others (Chappell 1990) due to well-defined layering or bedding fabric. Figure 5 shows the ratio of the horizontal and vertical moduli grouped by rock type and plotted versus the ratio of the UCS of horizontally loaded samples of shale and carbonate of southern Ontario (Gartner Lee Ltd. 2008). Aside from some shaley limestone the limestones and dolostones do not exhibit significant stiffness anisotropic behaviour. Conversely, the tested shale specimens do indicate significant mechanical anisotropy.

However; the influence, irrespective of the degree of anisotropy, on fracture propagation will result in a fracture pattern that is more repeatable than that in granitic rocks.

This is the results of fractures propagating nearly parallel and perpendicularly to the plane of anisotropy. Martin and Lanyon (2003) have identified the significant influence of bedding planes slip on the distribution of EDZ in Opalinus Clay at Mont Terri.

In micro scale, fracturing in grantic rocks is focused along grain boundaries, were as in limestone units it has been shown by Hoagland et al. (1973) that fractures can propagated through grains, however; at the macro scale bedding planes within a limestone can dominate the failure process depending on their spacing, where wide spacing will be less dominate There are other significant differences between argillaceous and crystalline rocks which make the development of the EDZ different. This includes anisotropic strength, which results in a less symmetrical EDZ if the bedding planes are not horizontal, as illustrated in Figure 6, where the upper image shows

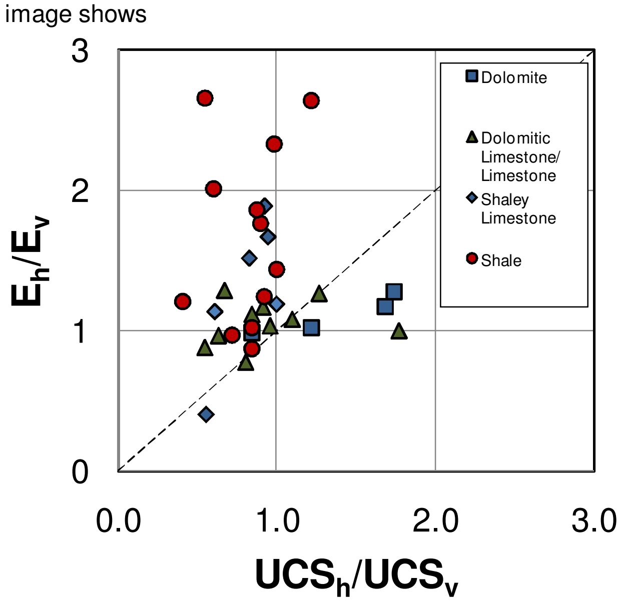

Figure 5: Strength and stiffness anisotropies of rocks of southern Ontario (data after Gartner Lee Ltd. 2008).

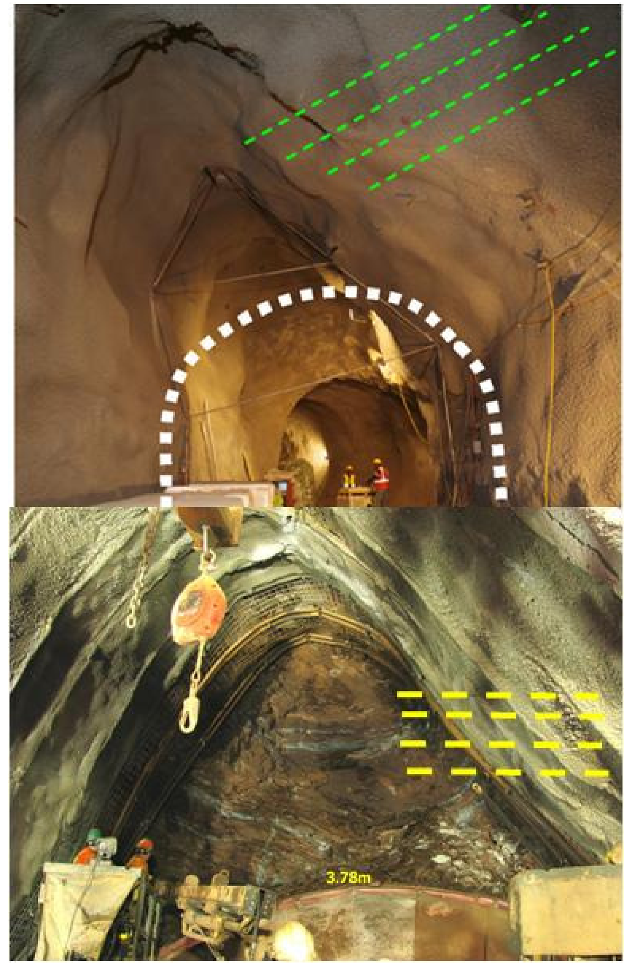

Figure 6: Overbreak pictures from the Mont Terri URL (above) and the Niagara Tunnel Project (below), from Blumling et al. 2007 and Perras 2009 respectively, showing bedding plane orientations.

inclined bedding planes and an asymmetric EDZ and the lower image shows near horizontal bedding planes and a more symmetrical EDZ. Blumling et al. (2007) also observed from the Mont Terri experiments that the stresses at the tunnel walls are independent of the size of the excavation. The stresses measured around a 100 mm diameter borehole are the same as those exist around a 5-m-diameter tunnel.

Argillaceous rocks may have some self-healing capacity, depending on the mineralogical content, to reduce the flow through the EDZ with time. The self-healing results from changes in the clay minerals of the rockmass, which can expand to fill micro fractures in the EDZ. Therefore, the self-healing behaviour of the EDZ in shale formations due to the reduction in fracture transmissivity is an important aspect in characterizing potential host rockmasses. Bock et al. (2009) have conducted a state-of-the-science review on mechanisms that might lead to self-healing in argillaceous rock.

4 PREDICTING THE DAMAGE ZONE DIMENSIONS

Numerical models can be used to predict the size and shape of the various damage zones around an excavation (an example is given in Fig. 7). Several factors will affect the dimensions; including the mechanistic failure criteria used, influence of joints, excavation shape, and the stress field. All these factors are dependent on the rockmass properties and the most representative numerical yield criteria should be employed for prediction.

Wawerik (1968) differentiated between ductile (class I) and brittle (class II) type rocks using servo-controlled testing machines, as illustrated in the stress-strain diagram of Figure 8. This demonstrates the need for different yield criteria for engineering design purposes. Current numerical modelling codes can accommodate various failure criteria and the most commonly used are perfectly plastic, strain weakening and brittle. These failure criteria can be implemented using the m, s, and a parameters introduced by Hoek and Brown in 1980.

4.1 Perfectly Plastic

Since its inception in 1980 (Hoek and Brown 1980) the Hoek-Brown failure criteria has become the standard material model for rock mechanics today and it has been most recently updated by Hoek et al. (2002). It was originally introduced for hard rock which where massive to jointed (Hoek et al. 2002) and has since been adapted to weak rock (Marinos and Hoek 2001).

Utilizing the Hoek-Brown parameters and a perfectly plastic material the plastic yield zone around an excavation can be defined. The volumetric strain represents the expansion of the material and this can be used to determine the beginning of the EDZ as the start of volumetric strain increase. With a perfectly plastic material it is not possible to distinguish numerically the start of the HDZ. Hoek et al. (2008) have modelled the Yacambú-Quibor tunnel, using plastic parameters, where squeezing was a significant issue even though the rockmass did not collapse. Here it maybe argued that a HDZ does not exist, since only the rock support collapsed and the rockmass remains intact.

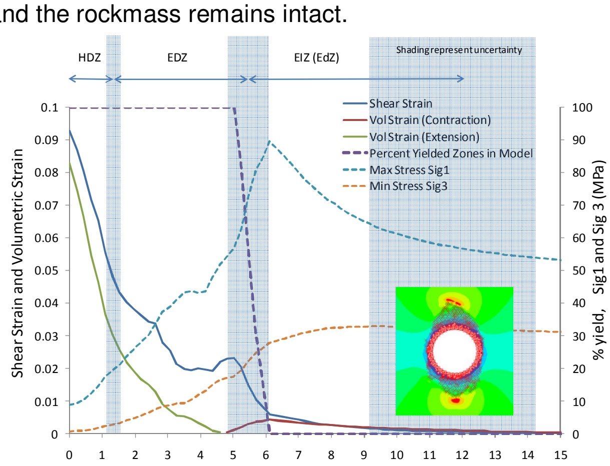

Figure 7: Example of model output using arbitrary loading and material parameters. Various indicators for EDZ and HDZ using a strain weakening model with a stress ratio of 1.7. Results are for a vertical line above the roof. Absolute volumetric and shear strain are shown relative to insitu conditions.

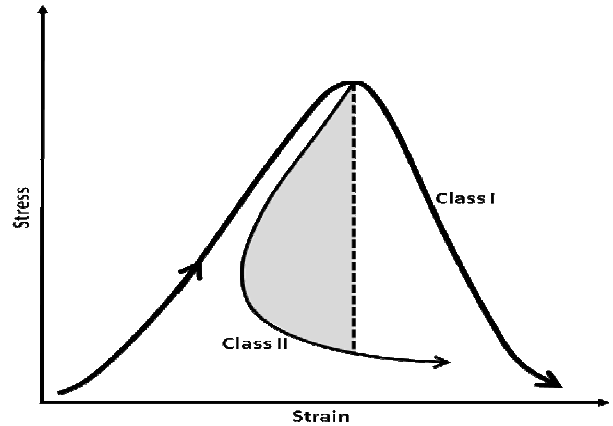

Figure 8: Stress-strain diagram showing class I and class II type post-peak behaviour for laboratory experiments as identified by Wawerik (1968) (modified from Fairhurst and Hudson, 1999).

It should be noted that the plastic yield zone demonstrated around an excavation when using plastic parameters does not necessarily mean that there are open induced fractures, which are interconnected to form a flow path. The plastic yield indicator simply means that the zone stresses have exceeded the strength of the material; however the material may still be capable of carrying stress, especially further from the excavation surface. If this is the case then crack propagation and interaction maybe suppressed near the outer boundary of the plastic yield zone.

4.2 Strain Weakening

Diederichs (1999) concluded that strength reduction is the result of crack interaction and not crack initiation and local weakening. Developments in numerical models which can realistically create fractures at the excavation scale are not readily available for use in standard engineering design; however utilizing strain weakening, it is possible to reduce the strength once the yield threshold has been exceeded, using post peak parameters.

Hoek et al. (1995) suggested reducing the cohesion to 20% of peak and friction to the base angle for brittle materials where there is a rapid decrease in strength after failure. Hoek et al. (2002) provides the equations for conversion of the Mohr-Coulomb, friction and cohesion, to Hoek-Brown (HB), m and s, parameters. The reduction to the post peak values should be less for rockmasses which are relatively weaker, since these rockmasses are already closer to residual strength (Crowder and Bawden 2004). Essentially the HB s can be considered a cohesional term, which Martin (1997) demonstrated, reduces to near zero once failure occurs. The reader is referred to Crowder and Bawden (2004) for a good discussion on post peak parameters. Martin and Chandler (1994) showed that the accumulation of extensional fractures reduces the cohesion and mobilizes friction after only a small amount of damage has occurred. Based on these findings Martin et al. (1999) defined an empirical equation to predict the depth of failure. This helped in developing a brittle failure criterion using Hoek-Brown parameters presented by Diederichs (2007).

4.3 Brittle

For brittle rocks that have a dominant tendency to split or spall near the excavation boundary, the conceptual model of Diederichs (2007), using crack initiation and long-term strength, can be adopted to delineate the three zones around the excavation, as shown in Figure 9.

To model brittle behaviour more accurately using the Hoek-Brown failure criteria an approach was developed to describe the transition from spalling behaviour at low confinement, which is controlled by the crack initiation threshold to shear strength behvaiour as crack extension is suppressed at higher confinements (Diederichs 2007). This is presented in Figure 10, which shows the failure envelops for damage initiation, long-term strength, spalling limit and the combined threshold which more accurately reflects in-situ behaviour of materials at various stress levels. Popp et al. (2008) incorporated this approach (hardening/softening) in combination with a friction model to describe the shear strength of bedding planes for the modeling of the Opalinus Clay at the Mont Terri test site. Shao et al. (2008) used similar models to account for the hydraulic and anisotropic strength properties at the Underground Research Laboratory at Meuse/Haute-Marne (France) to characterize the extent of the EDZ.

5 CONCLUSIONS AND FUTURE WORK

The ability to delineate the excavation damage zones using numerical models will greatly enhance the design process for geological repositories for long-term management of nuclear waste and other applications in tunnelling and mining. Clearly defining the excavation damage zones and how they can be delineated using standard numerical codes will also help to increase confidence in repository safety assessment.

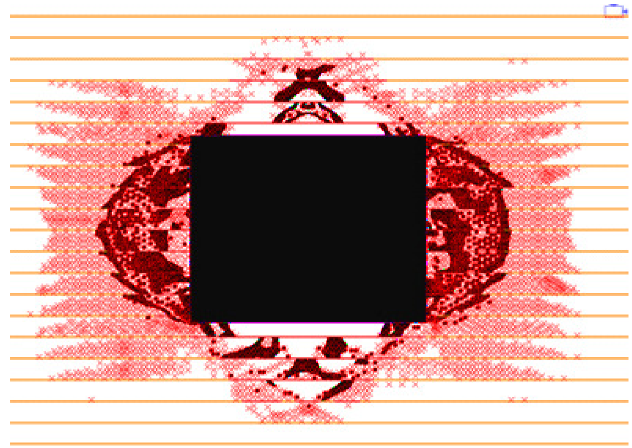

Figure 9: Square tunnel in brittle rock modelled as per Diederichs 2007. Red yield indicators reflect EDZ limits while dark red shading (shear strain) shows HDZ.

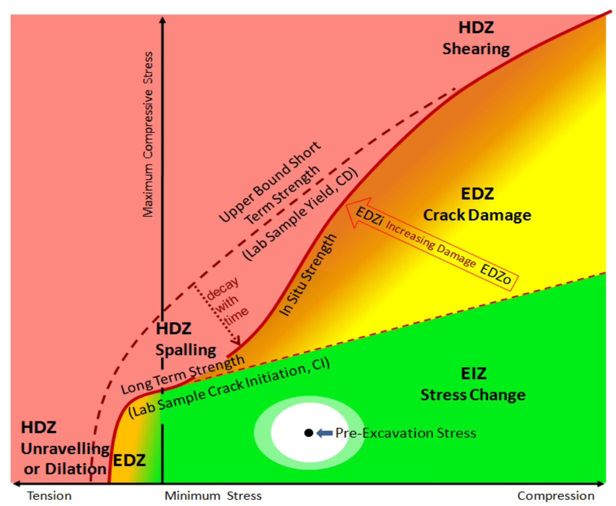

Figure 10: Damage zones mapped to the conceptual model of Diederichs (2007).

This article demonstrated that numerical modeling can provide a means to assess and estimate the time dependent extent of EDZ formation for given site specific rockmass properties and stress tensor around an excavation. The modeling also shows the influence of excavation geometry to the EDZ extent and evolution. Criteria can be established to define damage zones, HDZ, EDZ and EIZ from numerical modeling. Improving the state of knowledge of the formation of EDZ can build confidence in the repository design.

Future study on EDZ research will include the above mentioned modelling utilizing software such as Rocscience's Phase2 and Itasca's FLAC 3D and UDEC as well as new emerging software fracture codes.

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