DESIGNING AN EFFECTIVE EXCAVATION DAMAGED ZONE CUT-OFF IN HIGH STRESS ENVIRONMENTS

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1 ABSTRACT

Practical experience indicates that the initiation of stress-induced damage occurs when the damage index (D_i) expressed as ratio of the maximum tangential boundary stress to the unconfined compressive strength of the rock mass exceeds 0.4. For the Mine-by test tunnel the extent of this damaged zone can be approximated by a constant deviatoric stress criterion, ($\sigma_1 - \sigma_3 = 70$ MPa). Numerical analyses, using the constant deviatoric stress criterion, and observations, indicate that a torus-shaped seal is effective in providing a cut-off to the continuous zone of stress-induced damage that formed around the Mine-by test tunnel.

2 INTRODUCTION

The excavation of a repository at a depth of several hundred metres will result in the creation of an excavation disturbed zone (EDZ), a portion of which will be damaged where damage is defined as permanent deformations which involve microcracking and/or spalling (in this paper macroscopic spalling is synonymous with failure). Sealing systems will be required to reduce the groundwater flow through this excavation-induced damaged zone to acceptable design limits. The term sealing system is introduced to highlight that the design of these seals requires more than an understanding of the longevity of the sealing materials. The sealing system must also be designed for the unique characteristics of the rock mass and the damaged zone, e.g., the rock mass fracture frequency and fracture aperture, the rock mass strength and *in situ* stress magnitudes. The sealing system must also be designed for possible local changes to the rock mass and damaged zone quality in the vicinity of the seal long after the seal is constructed.

Given the variability of a rock mass, it is likely that any one of these rock mass characteristics could dominate the formation of the damaged zone around a tunnel and hence the design of the sealing system. Rock mass conditions encountered at depth in the Underground Research Laboratory (URL) in the Lac du Bonnet granitic batholith are considered representative of similar plutonic rock bodies found across the Canadian Shield. The frequency and persistence of fractures in such rock are expected to be very low, with rock mass qualities ranging from good (RMR: 60-80) to very good (RMR: 80-100) using the classification system of Bieniawski [1]. It is unlikely that fracture frequency or fracture aperture will be the dominating factor in the formation of the damaged zone in these good quality rock masses. However, in these rock masses the *in situ* stress magnitudes can increase significantly and it is suggested that *in situ* stress magnitudes will be the dominating rock mass characteristic in the design of sealing systems.

The stress-induced damage that forms along a tunnel in a high stress environment is meta-stable and continuous. A positive cut-off is recognized as the most efficient sealing system to reduce the axial flow in the EDZ in a low stress environment. However, it is not obvious what approach should be used for constructing a sealing system in a high stress environment. This paper will focus on the

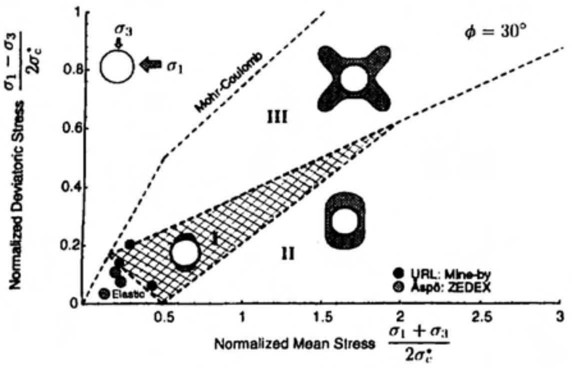


Figure 1: Relationship between failure modes and stress state for an unsupported circular opening, after Detournay and St. John [6].

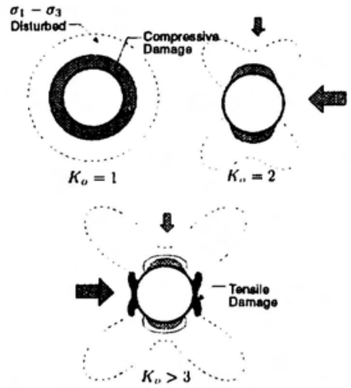


Figure 2: Relationship between damage and the disturbed zone for an unsupported circular opening in Region I in Figure 1.

geomechanical factors that could affect the design of a sealing system in high stress environments and presents a possible design alternative.

3 DAMAGE AND FAILURE ZONE

The failure zone that forms around an underground opening is a function of the geometry of the opening, the far-field stresses and the strength of the rock mass. Detournay and St. John [6] categorized possible failure modes around a circular unsupported tunnel according to Figure 1. The mean and deviatoric stress in Figure 1 is normalized to the uniaxial compressive field strength ($\sigma_c^\star$) which is approximately $0.5\sigma_c$ where σ_c is the laboratory uniaxial compressive strength. The rock mass properties for the Underground Research Laboratory (URL: Mine-by Experiment) and Äspö Laboratory (ZEDEX Experiment), which are currently being used for nuclear repository research, fall either in the elastic region or Region I of Figure 1. Note that for Region I failure mode, the extent of the failure zone is quite localized. The damage that forms around an opening also follows the general shapes given in Figure 1 as there is a gradual transition from damage (microcracking) through to failure (spalling and slabbing). While the damaged zone in Region I will also tend to be quite localized, the disturbed zone, (i.e., the zone of redistributed stress due to the opening) can take on quite different shapes depending on the ratio (K_o) of the horizontal to vertical stress (Figure 2). Each excavation has its unique excavation-induced disturbed zone due to unique *in situ* stress conditions, rock mass properties, tunnel shape and orientation. When two or more excavations approach each other, the stress changes resulting from each of the multiple openings are superimposed and the potential for stress-induced damage increases. In this section, an empirical relationship is proposed to define the stress magnitudes corresponding to the initiation of damage and failure.

A simple method to consider the effect of multiple openings on stress concentrations is the tributary area analysis of pillar support [2]. The average pillar stress (σ_p) is given as:

$$\sigma_p = p_z \left(\frac{1}{1-r}\right) \tag{1}$$

where p_z is the vertical component of the pre-mining stress field and r is the area extraction ratio defined by (area mined)/(total area). Figure 3 shows the stress concentration factor for a typical room and pillar operation as a function of extraction ratio. Practical experience indicates that severe stress-induced damage in Canadian mines occurs when the extraction ratio is greater than

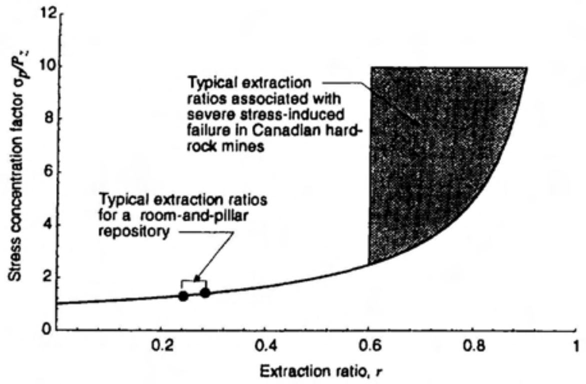


Figure 3: Stress concentrations in a pillar due to extraction ratio.

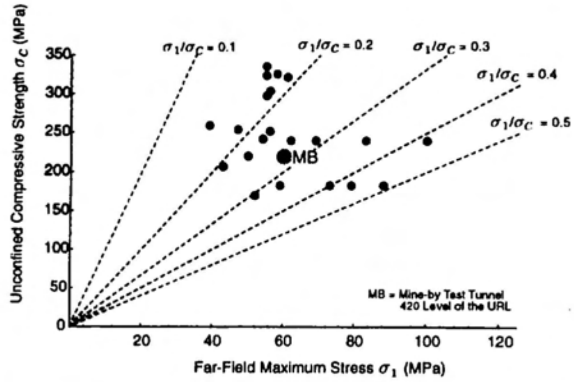


Figure 4: Empirical stability classification developed for square tunnels in South Africa.

0.60. The extraction ratios for the pillars between the rooms for the proposed repository design in the Nuclear Fuel Waste Management Program (NFWMP), with either borehole emplacement or in-room emplacement, varies between 0.27 and 0.25, respectively. Thus it is anticipated that a stress concentration factor of approximately 1.3 to 1.5, for the pillars between the rooms, will not significantly increase the potential for stress-induced damage. While this approach is useful in establishing the stress concentration due to extraction there is no direct correlation of extraction ratio with damage for the extraction ratios of interest.

Hoek and Brown [9] used South African observations from underground mining in massive brittle rocks to classify the effect of stress-induced damage on the stability of square tunnels. They found that the stability of a square tunnel can be estimated by considering the ratio of σ_1/σ_c, where σ_1 is the maximum far-field stress magnitude and σ_c is the laboratory short-term unconfined compressive strength (Figure 4). The stability classification in Figure 4 ranges from 0.1 through 0.5 and can be briefly described as follows: ($\sigma_1/\sigma_c \leq 0.1$) a stable unsupported opening, i.e., no damage; ($\sigma_1/\sigma_c = 0.2$) minor spalling (failure) can be observed, requiring light support; ($\sigma_1/\sigma_c = 0.3$) severe spalling (failure), requiring moderate support; ($\sigma_1/\sigma_c = 0.4$) heavy support required to stabilize the opening; and ($\sigma_1/\sigma_c = 0.5$) stability of the opening may be very difficult to achieve, extreme support required. It is important to note that this classification was developed from mining experience. The *in situ* stress conditions required for stability classes greater than 0.3 are not likely to be encountered at a nuclear repository built in Canada because the depth is specified as between 500 and 1000 m and the extraction ratio for the tunnels of a typical repository will be less than 0.40. The stress conditions required for stability classes greater than $\sigma_1/\sigma_c = 0.3$ are only found at depths of > 1000 m or when extraction ratios are greater than 0.70. Thus the stability classification applicable to a Canadian nuclear repository lies between 0.1 and 0.3.

The stability classification developed by Hoek and Brown [9] is not directly transferable to other tunnel shapes as it only considers the far-field stress under a constant $K_o = 0.5$. The stress-induced damage process initiates at the stress concentrations near the boundary of the tunnel and therefore the maximum tangential stress at the boundary of the tunnel, which is a function of tunnel shape, must be considered. In order to apply the empirical stability classification developed by Hoek and Brown [9] to other sites, the effect of the tunnel geometry and varying stress ratios on the maximum tangential stress at the boundary of the tunnel must be evaluated. Numerical programs can readily be used to assess these effects on the boundary stress. Alternatively, the closed form solution developed by Greenspan [7] can be used for tunnel geometries that can be expressed in the parametric form given by

$$x = p\cos\beta + r\cos 3\beta, \;\; y = q\sin\beta - r\sin 3\beta \tag{2}$$

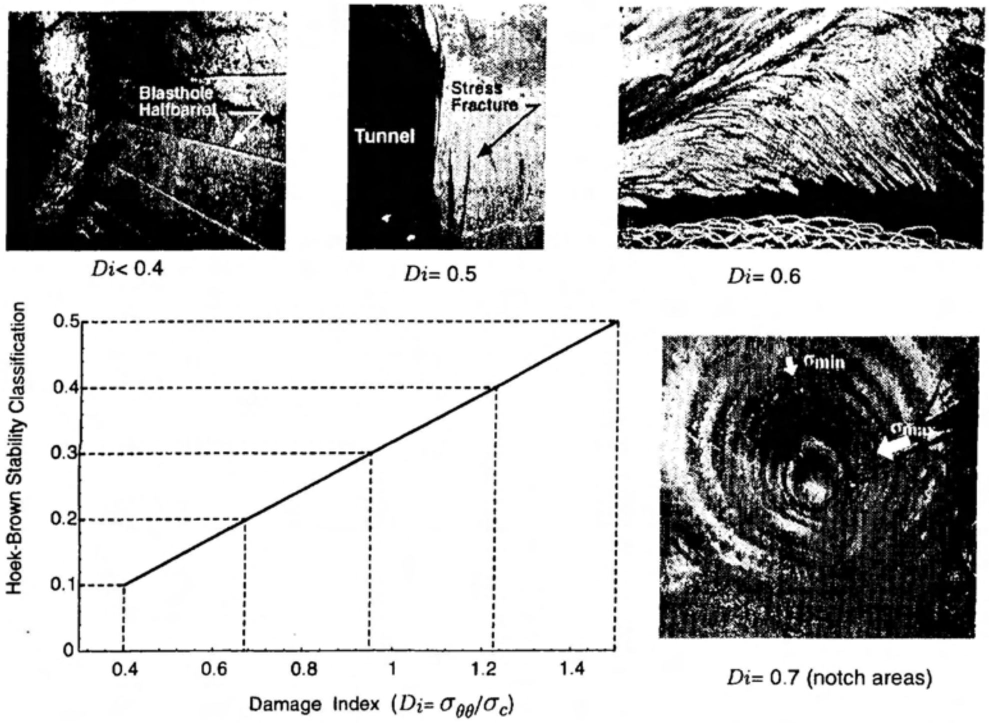


Figure 5: Damage index expressed as a function of the ratio between the maximum tangential boundary stress ($\sigma_{\theta\theta}$) and the unconfined compressive strength (σ_c).

where p, q and r are parameters and β is an angle. Through the appropriate choice of p, q and r, near-rectangular openings can be analyzed and this approach has been used to determine the maximum tangential stress for the case histories used by Hoek and Brown [9].

The conversion of the classification expressed in Figure 4 in terms of the maximum tangential boundary stress ($\sigma_{\theta\theta}$) is given in Figure 5. The ratio of $\sigma_{\theta\theta}$ to the unconfined compressive strength (σ_c) will be referred to as the damage index (D_i). Also given in Figure 5 are photos of the damage recorded at the URL for various D_i. It is interesting to note that for $D_i \leq 0.4$ the rock mass is basically elastic and no damage is recorded.

At $D_i \approx 0.5$ some cracking will occur close to the excavation wall, as a result of either the removal of the confining stresses or the loading by stress concentrations, thus creating a permanent damaged zone near the opening. This crack-induced damage weakens the rock by reducing its cohesive strength component; the largest reductions occur at the tunnel wall, where the damage is the greatest. Outside this damaged zone, the peak cohesive strength of the rockmass is unaffected.

At a $D_i \approx 0.6$, the rockmass is severely damaged and near the opening the maximum load-bearing capacity of the rockmass is exceeded. The accumulated strains in the damaged zone are large and crack coalescence will lead to rock mass disintegration, e.g., by slabbing of the excavation walls. However, even if slabbing occurs, the shape of the opening eventually will stabilize and the surface instability mechanisms will disappear. The opening will remain stable unless further disturbed, e.g., by a disturbance from a nearby opening or by stress changes caused by thermal gradients. Figure 5 shows the stability of the Mine-by test tunnel after excavation even though $D_i = 0.7$.

The damage index developed in the preceding discussion assumes that the excavation method is carefully controlled. Figure 6 illustrates the extent of damage that can be created for an intact rock mass that would otherwise have a $D_i < 0.4$. Hence, the excavation-method can initiate damage at lower stress magnitudes than that indicated by the damage index. However, once the damage index

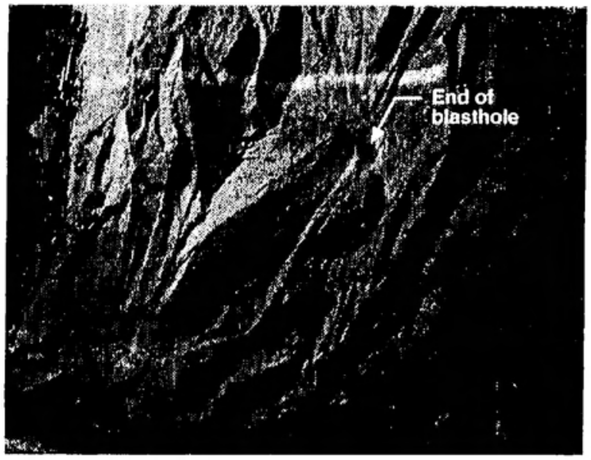


Figure 6: Blast-induced fractures in an otherwise intact rock mass.

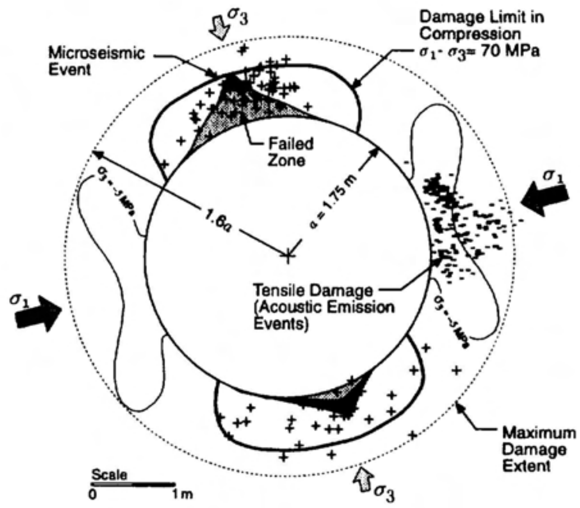


Figure 7: Extent and characteristics of excavation-induced damage around the Mine-by Experiment test tunnel ($D_i = 0.7$ and $K_o \approx 5$).

is greater than 0.4, the effect of the excavation method on the extent of damage around an opening is essentially insignificant as the extent of damage is stress controlled. This has been supported by findings at the URL. There, two parallel tunnels, one excavated by the drill-and-blast method and the other excavated by line drilling and mechanical rock splitters, and both with $D_i > 0.4$, showed nearly identical stress-induced damage.

4 EXTENT OF DAMAGE

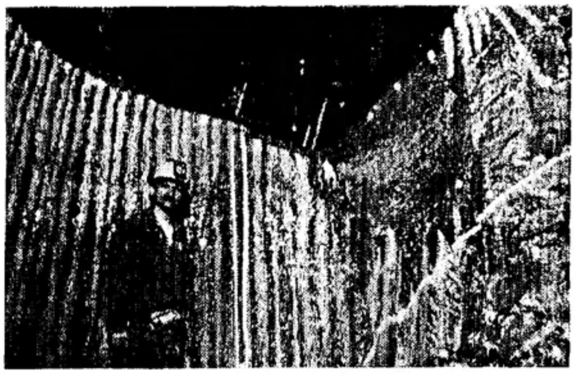
The previous section discussed damage initiation and the effects of this damage on the stability of the openings. However, there is little documented evidence that relates the depth of damage to the damage index. In this section the characteristics and extent of the damage around the Mine-by Experiment test tunnel are investigated. The details pertaining to the Mine-by Experiment and the measured excavation response are given by Read and Martin [15]. Only the results pertaining to the extent of the excavation-induced damage are describe here.

The characterization studies and the numerical modelling indicate that the excavation-induced damage around the Mine-by Experiment tunnel occurs in the regions of compressive stress concentrations in the roof and floor, and in the regions of tensile stress concentration in the sidewalls. The extent and characteristics of these damaged zones are shown schematically in Figure 7. The damaged zone in the roof and floor is the most obvious visually, and the outer limit of this damaged zone is defined by a constant deviatoric stress criterion, given as:

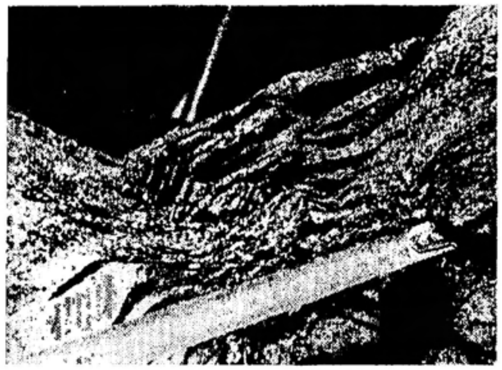
$$\sigma_1 - \sigma_3 \approx 70 \text{ MPa} \tag{3}$$

The contour defined by Equation 3 extends approximately 0.7 m beyond the original tunnel perimeter or $1.5a$ from the tunnel centre, where a is the radius of the tunnel. The failed zone within this damaged region is v-shaped and at the tip of each v-shaped notch is a localized process zone where the rock is crushed (see Figure 8b). The crushed material at the notch tip is no longer part of the far-field elastic continuum around the tunnel and provides a continuous damaged zone with increased hydraulic conductivity [4].

In contrast, the damaged zone in the sidewall (tensile) regions of the tunnel is not visually obvious like that in the roof and floor. In this region the tensile damage has been identified by acoustic



(*a*) Notch shape



(*b*) Process zone at the notch tip

Figure 8: Shape of the notch after stability is achieved. At the notch tip various stages of failure in the process zone are visible, giving an indication of mechanisms involved, and that the hydraulic conductivity of this zone would be increased.

emission surveys. These geophysical surveys indicate that in this zone most of the damage occurs within 0.35 m of the tunnel wall. However, there is also evidence that the damage in this tensile-region tends to expand into the tensile stress concentration defined by the $\sigma_3 \approx -5$ MPa contour shown in Figure 7. Regardless of the origin of the damage (compressive or tensile), there is no evidence to suggest that the stress-induced damage exceeds 1.0 m beyond the Mine-by test tunnel wall or $1.6a$ from the tunnel centre, where a is the tunnel radius.

Damage mechanisms are very sensitive to relatively minor stress changes. Thus, once a damaged zone begins and stabilizes, relatively minor stress changes (i.e., 1-5 MPa) will increase the intensity of the cracking which could promote slabbing. These processes will increase the hydraulic conductivity of the rockmass in the damaged zone, particularly if cracks coalesce and open up in areas of low confinement. Cracks in the compression zone propagate predominantly parallel to the excavation surface and could link to form a continuous axial pathway. However, the potential for a connected conductive pathway decreases rapidly with increasing distance from the tunnel wall. Outside the damaged zone, the background permeability of the rockmass is unchanged. This is supported by the findings of the Mine-by Experiment characterization program. A slot was excavated in the floor of the test tunnel to expose the extent of damage around the test tunnel and to determine the hydraulic characteristics of the damaged rock [4]. Figure 8 shows the shape of the stable notch that developed around the test tunnel and the fracture coalescence that occurred at the tip of the notch when overall tunnel stability was achieved (Figure 8*b*).

5 CRACK DAMAGE AND CONFINING STRESS

The preceding discussion indicates that the stress-induced damage forms in a limited region next to the boundary of the tunnel. The process causing this damage is one involving crack growth parallel to the direction of the maximum principal stress. Experience from the URL indicates that this damage process is sensitive to confining stress. Hoek [8] carried out a series of tests on plates of glass to examine the relationship between crack growth and confining stress, expressed as the ratio of σ_3/σ_1 (Figure 9). Figure 9 implies that as the ratio of σ_3/σ_1 approaches zero the length of the wing cracks are infinite. This can only occur if the crack-opening force is held constant. The inclined surface in Hoek's experiment serves as a crack-opening force to propagate Mode I (opening mode) cracks. Usually the crack-opening force will be associated with a finite stiffness and hence the crack-opening force will decrease as the crack lengthens. Thus, the length of the crack will be

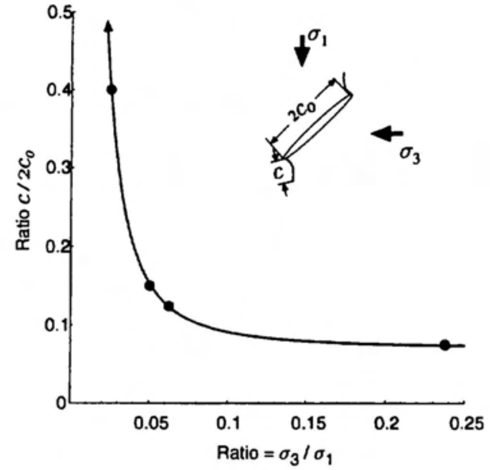


Figure 9: Relationship between crack propagation and the ratio of σ_3/σ_1, data from Hoek [8].

finite.

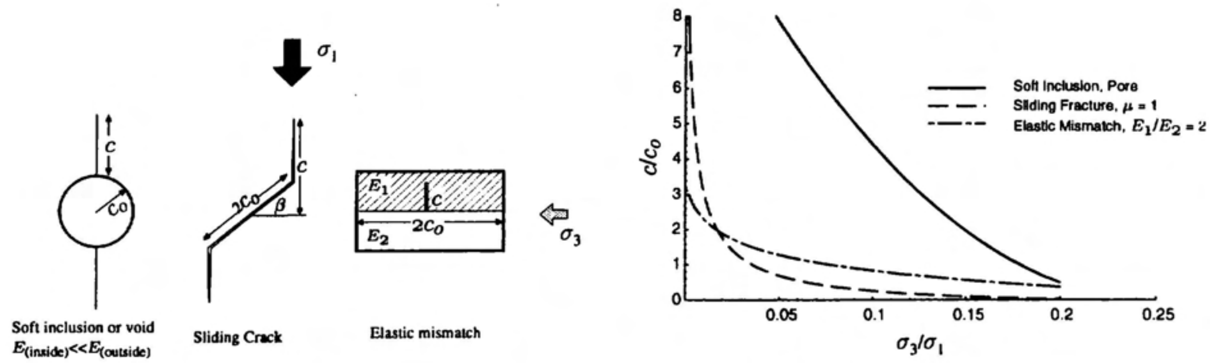
Kemeny and Cook [11] also investigated the propagation of Mode I cracks in a compressive stress field. Three of the crack growth models investigated by Kemeny and Cook were: cracks around a cylindrical pore (or soft inclusion); cracks resulting from sliding along existing discontinuities; and cracks caused by differential strain at the interface of mismatched elastic materials (Figure 10*a*). Using linear elastic fracture mechanics, the fracture will propagate when the stress intensity factor (K_I) exceeds the Fracture Toughness (K_{I_c}). For example the stress intensity factor for the sliding crack model when $c \gg c_o$ is given by Kemeny and Cook [11] as:

$$K_I = \frac{2c_o\tau\cos\beta}{\sqrt{\pi c}} - \sigma_3\sqrt{\pi c} \tag{4}$$

where

$$\tau = \frac{1}{2}[(\sigma_1 - \sigma_3)\sin 2\beta - \mu(\sigma_1 + \sigma_3 + (\sigma_1 - \sigma_3)\cos 2\beta]$$

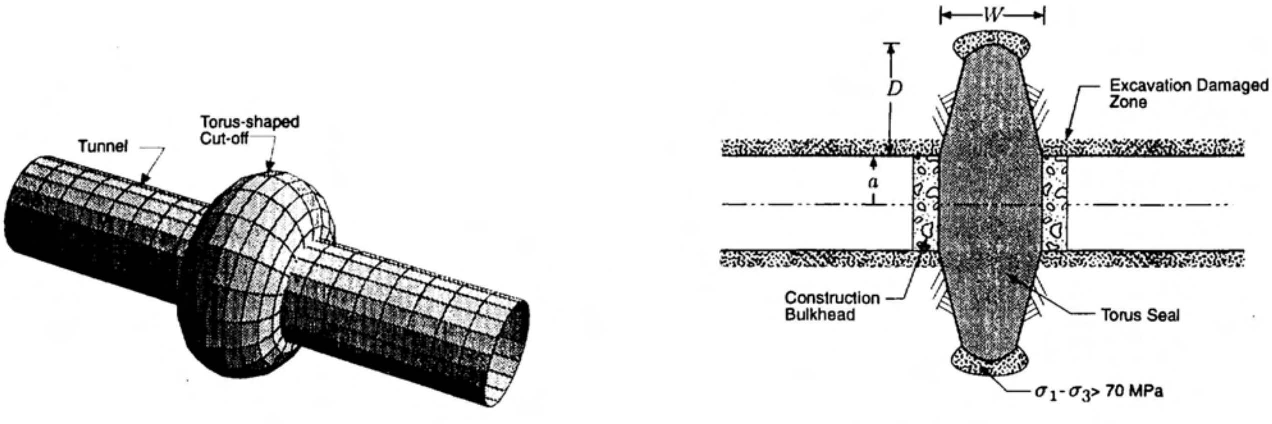
Equation 4 can be used to determine the length the crack will propagate as a function of σ_3/σ_1. Figure 10*b* shows the results for all three models using $K_{I_c} = 1.5$ MPa$\sqrt{\text{m}}$ for Lac du Bonnet granite [12] and keeping $\sigma_1 = 50$ MPa. The sliding crack model and the elastic mismatch models



(*a*) Crack models

(*b*) Crack length

Figure 10: Crack models and crack extension as a function of σ_3/σ_1.



(a) Isometric View (b) Section View

Figure 11: Illustration of a tunnel plug for a high stress environment using a torus concept as a cut-off.

show a relationship between crack extension and the σ_3/σ_1 ratio similar to what Hoek [8] measured in the laboratory. The sliding crack model provides the best agreement with Hoek's data. However, unlike Hoek's data, the sliding crack model indicates that the crack length is finite when $\sigma_3/\sigma_1 \to 0$. The pore model, while exhibiting the largest crack is an unlikely model for Lac du Bonnet granite because of the low *in situ* porosity, which is less than 0.1%.

Both the experimental work by Hoek [8] and the theoretical work by Kemeny and Cook [11] indicate that crack-induced damage is very sensitive to confining stress. Hence, a sealing system for a repository should be designed such that a radial pressure is applied to tunnel wall rock. This radial pressure would effectively provide a confining stress to the excavation disturbed zone and hence minimize the potential for crack-induced damage from transient loads, e.g., thermal loads and glacial loads.

6 CUT-OFF DESIGN FOR HIGH STRESS ENVIRONMENT

The demands on a tunnel plug or seal to control the flow of groundwater increase as the permeability of the excavation damaged zone increases relative to the background permeability of the rock mass. For example, a tunnel plug constructed in sand would do little to control the ground water flow whereas a tunnel plug constructed in massive intact rock would effectively control the ground water flow in the tunnel. Hökmark [10] conducted a series of numerical studies that examined the efficiency of tunnel plugs in controlling the groundwater flow in the EDZ. Hökmark concluded that a tunnel plug keyed into the rock mass provided the most effective cut-off. However, in an environment where the *in situ* stress magnitudes are sufficient to induce damage around a tunnel, such as the Mine-by test tunnel, it is not obvious what benefit would be gained by keying the tunnel plug into the rock mass as it is generally assumed that the stress-induced damage would also form around the excavation that is required to create the key.

Martin [13] showed that a constant deviatoric stress criterion, Equation 3 for the Mine-by experiment, can be used to define the damage limit around circular openings in massive rock. Martin and Read [14] concluded that there was no evidence from the Mine-by experiment which suggests that the spalling and slabbing failure process extends beyond the limits defined by Equation 3. More recently, Castro [3] has shown that this damage criterion can also be applied to moderately jointed rock masses at depth. Martin [13] noted however, that damage is controlled by the loading path and hence will vary with the *in situ* stress state and rock type. A series of analyses were carried

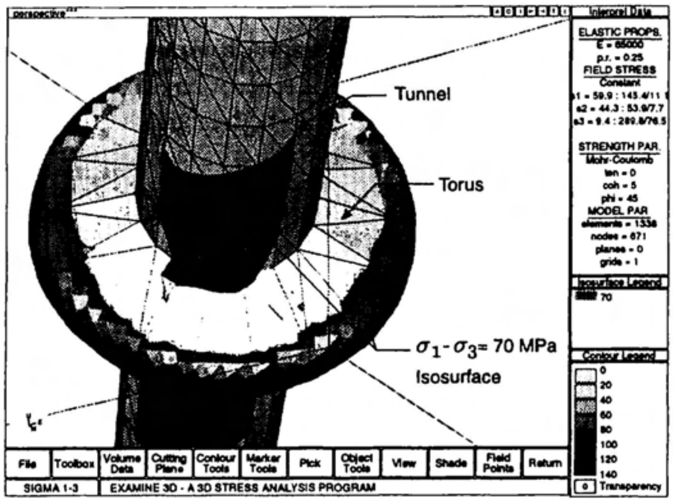


Figure 12: Numerical results from EXAMINE^{3D} showing the effect of a torus-shaped seal as a cut-off to damage-initiation around the Mine-by test tunnel. The $\sigma_1 - \sigma_3 = 70$ MPa isosurface is only calculated over the portion of the test tunnel close to the torus, and hence does not extend the full length of the tunnel in the figure.

out to explore the effect of a torus-shaped cut-off and the extent of damage around the Mine-by test tunnel (Figure 11)

Three dimensional elastic numerical analyses were carried out using the boundary element program EXAMINE^{3D} [5]. The *in situ* stress state and the dimensions for the tunnel were the same as those in the Mine-by Experiment. The extent of damage was determined by Equation 3. The torus shape used in the analysis is similar to that shown in Figure 11*b*. The results from the analysis are given in Figure 12 and show that damage that forms around both the test tunnel and the tip of the torus is not continuous, i.e., the torus provides an effective cut-off to the damage process. These numerical results were supported by the findings from the Mine-by experiment. After the test tunnel was excavated, a partial torus-like slot, approximately 2 m deep, was excavated in the floor of the test tunnel. While slabbing had formed a continuous damaged zone in the floor of the test tunnel it did not form a continuous damaged zone on the wall of the torus-like slot (see Figure 8*a*).

The actual shape and depth of the torus required to form an effective cut-off is site specific and will depend on the *in situ* stress state, tunnel geometry and rock mass strength. For the Mine-by test tunnel, it appears that D would have to be approximately equal to a to provide for an effective cut-off. In addition the backfilling of the torus-shaped cut-off with materials that swell would promote the development of a confining stress on the excavated wall. As shown in Figure 10, crack extension is quite sensitive to confining stress. Thus backfilling the torus would minimize the potential for crack growth under the loading conditions created by thermal and glacial loads.

7 CONCLUSIONS

Practical experience indicates that the initiation of stress-induced damage occurs when the damage index (D_i) expressed as ratio of the maximum tangential boundary stress to the unconfined compressive strength of the rock mass exceeds 0.4. It is suggested that D_i will not exceed 1 for a repository located between a depth of 300 and 1000 m, and with an extraction ratio of less than 0.4. Evidence from the Mine-by Experiment indicates that for $D_i = 0.7$ the region of stress-induced damage does not exceed $1.6a$ from the tunnel centre, where a is the radius of the tunnel.

When the damage index exceeds 0.4, a continuous zone of damage will form along the tunnel. For the Mine-by test tunnel, the extent of this damaged zone could be approximated by a constant deviatoric stress criterion ($\sigma_1 - \sigma_3 = 70$ MPa). This criterion was used in numerical analyses to evaluate the effect of tunnel geometry on the continuity of the damaged zone.

Numerical analyses indicate that a torus-shaped seal is effective in providing a cut-off to the continuous zone of stress-induced damage that formed around the Mine-by test tunnel. These findings were supported by the excavation of a partial-torus in the floor of the test tunnel. A sealing system that promotes the development of a confining stress will minimize the potential for crack-induced damage under transient loading conditions, e.g., thermal loads and glacial loads.

Acknowledgment — This work was supported by the Canadian Nuclear Fuel Waste Management Program which is jointly funded by AECL and Ontario Hydro under the auspices of the CANDU Owners Group, and by the Natural Sciences and Engineering Research Council of Canada through a grant to the first author.

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