CHARACTERIZING EXCAVATION DAMAGE IN HIGHLY-STRESSED GRANITE AT AECL'S UNDERGROUND RESEARCH LABORATORY

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ABSTRACT: Experience at AECL's Underground Research Laboratory (URL) has shown that sparsely fractured rock masses at depths of several hundred metres may be subjected to high *in situ* stresses and highly anisotropic stress ratios. Under such conditions, an excavation damaged zone (EDZ) may form around an underground opening. The nature and extent of the EDZ are of particular importance in terms of understanding the potential for increased permeability in the near-field. Results of *in situ* characterization and numerical modeling of a circular test tunnel excavated in highly stressed granite at the URL show that the EDZ is limited to a region within about 0.6 radii from the original perimeter of the tunnel. Within this region, however, the characteristics of the EDZ are highly variable around the tunnel. This paper describes the field characterization of the Mine-by test tunnel, and the interpreted characteristics of the EDZ based on numerical modeling. Results are compared to those from other excavations at the URL, illustrating that the nature of the EDZ can be controlled through tunnel design.

INTRODUCTION

Atomic Energy of Canada Limited (AECL) is conducting research at its Underground Research Laboratory (URL) related to the concept of deep underground disposal of nuclear fuel waste. The URL, located approximately 120 km northeast of Winnipeg, Manitoba in the Lac du Bonnet granite batholith, is a well-characterized site in a previously undisturbed rock mass. One of the main geomechanics issues under investigation is the development of excavation damage around underground openings, and its effect on the near-field permeability of the rock mass.

Introducing a tunnel into a stressed medium results in stress concentrations around the underground opening, and regions where there is an increase in compressive stress tangential to the opening. In an elastic medium, the shape and extent of these regions depends on the magnitude and orientation of the applied stresses relative to the tunnel orientation, and the shape of the opening. If the magnitude of the compressive stress is increased sufficiently, the near-field rock mass will experience stress-induced damage. In adverse stress conditions (i.e., where σ_1 and the σ_1/σ_3 ratio are high), the degree of damage will vary with respect to position around the tunnel, and may depend in part on the stress history associated with excavation [1].

Granitic plutons like the Lac du Bonnet batholith can comprise large volumes of sparsely fractured rock [2]. Experience at the URL has shown that this type of rock mass at depths of several hundred metres may be subjected to adverse stress conditions. Under such conditions, several zones of interest may form around an underground opening: 1) a disturbed zone in which the material behaviour is essentially unchanged, but the stress state is perturbed by the opening, 2) a smaller excavation damaged zone (EDZ) characterized by changes in both the pre-excavation stress

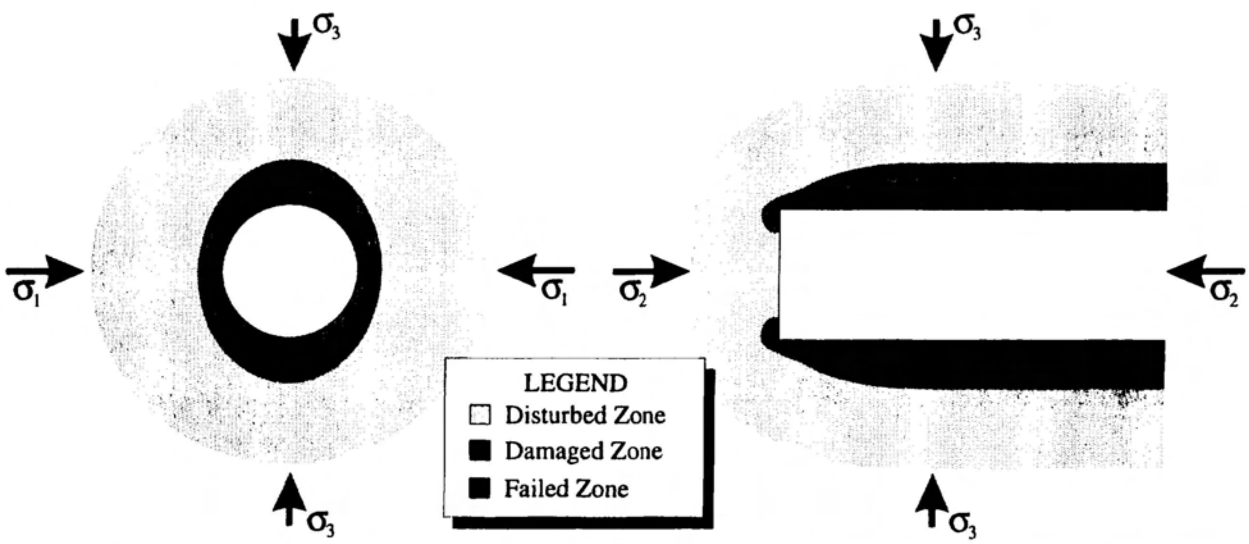


Figure 1: Schematic view of the disturbed, damaged and failed zones around a circular tunnel.

state and in the material behaviour of the rock mass, and 3) a failed zone in which rock slabs detach completely from the rock mass as a result of progressive failure. These zones are shown schematically in Figure 1.

While an understanding of the processes responsible for the failed zone is important in terms of excavation design and model development, the extent and characteristics of the EDZ beyond the margins of the failed zone are also of concern in assessing the potential for increased permeability around a disposal vault. This paper describes the *in situ* investigation and numerical modeling of the EDZ around a circular test tunnel, and compares the findings to observations from other underground openings at the 420 Level of the URL.

THE MINE-BY EXPERIMENT

The Mine-by Experiment [1] was conducted *in situ* at the 420 Level of the URL to study progressive failure and the development of excavation damage around a 3.5-m-diameter circular test tunnel under ambient temperature and humidity conditions. At this depth, the rock mass comprises sparsely fractured granite and is highly-stressed, i.e., $\sigma_1 = 60 \pm 3$, $\sigma_2 = 45 \pm 4$ and $\sigma_3 = 11 \pm 4$ MPa. The test tunnel for the Mine-by Experiment was designed parallel to the intermediate principal stress direction to maximize the potential for progressive failure and damage around the tunnel. In comparison to other stable openings at the 420 Level, the test tunnel represents a worst-case scenario, in terms of its shape and orientation, for damage development at this level [1].

Following excavation of access tunnels and installation of instrumentation for the experiment, the 46-m-long test tunnel (Room 415) was excavated. The non-explosive excavation method for the test tunnel [1] involved line-drilling and reaming a series of 1-m-deep perimeter holes around the design diameter of the tunnel, and then progressively breaking out the interior of the round using hydraulic rock splitters in a series of production holes. The first 34 m of Room 415 were excavated as full-face rounds, and a pilot-and-slash sequence was used for the final 12 m of the test tunnel. In total, 50 excavation rounds were required to complete the test tunnel.

Figure 2: The Mine-by test tunnel showing the well-developed v-shaped 'notches' associated with progressive failure of the rock mass.

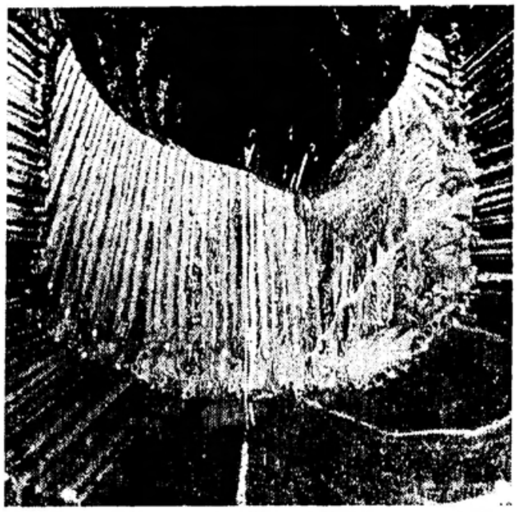
Rock Mass Monitoring

The Mine-by Experiment incorporated two tiers of instruments [1]. The first tier included extensometers and convergence arrays to measure displacements, triaxial strain cells to measure induced strains, and thermistors to measure temperature. The second tier, based on acoustic emission/microseismic (AE/MS) technology, was used to study the development of the damaged zone around the Mine-by Experiment test tunnel. In total, over 500 data channels were monitored during the main excavation stage of the Mine-by Experiment.

Geophysical studies were also conducted periodically during the experiment [1]. These studies included a series of crosshole seismic tomography surveys, an acoustic emission (AE) study in the sidewall region of the tunnel, and velocity imaging based on a study of wave propagation effects of an underground opening.

FIELD OBSERVATIONS OF THE EDZ

During excavation of the test tunnel, a multi-stage process of progressive brittle failure resulted in the development of v-shaped 'notches,' typical of borehole breakouts, in the regions of compressive stress concentration in the roof and floor (Figure 2). The steps associated with progressive failure in the test tunnel were: 1) crushing at a point on the tunnel periphery approximately 0.5 to 1 m back from the face; 2) dilation and small-scale flaking at a localized area resulting in the formation of thin slabs; 3) buckling of long thin slabs on the flanks of the developing 'notch,' becoming shorter and localized near the 'notch' tip as slabbing progressed; 4) further crushing at the 'notch' tip with dilation, resulting in reinitiation of the slabbing process. The process was driven by a localized process zone at the 'notch' tip, and continued until the geometry stabilized in a v-shape.



(a) Connected permeability trench.

(b) Close-up of 'notch' tip.

Figure 3: Exposure of the floor 'notch' in the connected permeability trench.

During the main monitoring phase of the experiment, induced microseismicity associated with the progressive failure process and damage development was evident around the test tunnel [1]. Following completion of the Mine-by test tunnel, a detailed field investigation was conducted using a series of trenches, slots and boreholes to determine the extent of observable damage beyond the stable tunnel profile [3].

Connected Permeability Trench

As part of a connected permeability experiment [4], a trench was excavated in the test tunnel using line-drilling and hydraulic rock splitting. The trench was 2.0-m deep and 3.75-m wide, extending over a 4.2-m-long section of the test tunnel. This excavation provided a sectional view of the EDZ and failed zone associated with the floor 'notch' in the plane orthogonal to the tunnel axis. Figure 3a shows the shape of the failed zone in the floor, illustrating the characteristic geometry observed in all breakouts at the 420 Level of the URL. The flanks of the 'notch' were sounded using a scaling bar, and were found to be 'drummy' (i.e., hollow-sounding) within about 300 mm of the 'notch' tip. A close-up view of the 'notch' tip, shown in Figure 3b, illustrates the localized dilation and observable damage associated with the active process zone, extending less than 100 mm beyond the 'notch' tip.

Roof and Floor Observation Slots

Two slots of connected 150-mm-diameter boreholes were drilled orthogonal to the tunnel axis in the test tunnel across the 'notch' tip in the roof and floor. The roof slot was 360 mm long and was located predominantly in granite. Remnants of slabs associated with the development of the roof 'notch' showed slickensides up to 380 mm from the 'notch' tip. The exposed walls of the slot showed a crushed, dilated zone at the 'notch' tip approximately 300 mm wide and 110 mm deep (Figure 4). Cracks oriented parallel to the 'notch' flanks extended to 180 mm depth, beyond which breakouts were evident in the slot. The start of breakouts at 180 mm coincides with the transition from highly damaged to intact rock, suggesting that the cracked material near the opening was destressed prior to drilling the slot.

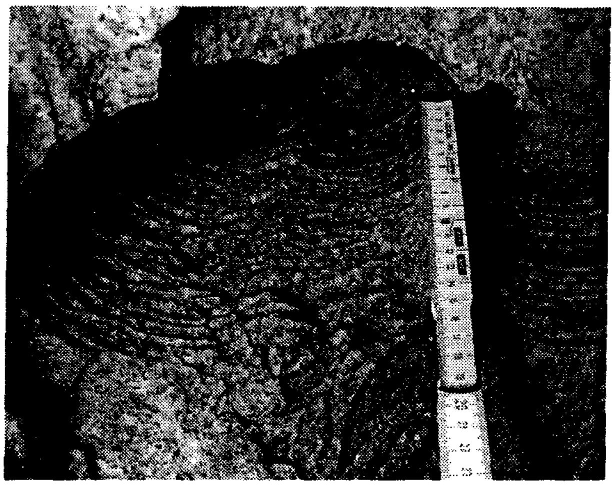


Figure 4: Details of damage in the roof slot drilled across the breakout 'notch'. Fracturing extends 180 mm beyond the 'notch' tip.

Figure 5: Damage in the floor slot drilled across the 'notch' tip. Fractures extend 200 mm into the rock mass, and show significant dilation.

The floor slot was 960 mm long and crosscut the 'notch' tip in the floor of the tunnel (Figure 5). As in the roof, the lithology was predominantly granite, and slickensides were noted on the flanks of the 'notch.' Material in the 'notch' tip area had been removed during earlier scaling activities, so much of the dilated material noticeable in the connected permeability slot was removed. However, fracturing was still visible in the slot, extending to 200-mm depth at the 'notch' tip, and diminishing with distance from the tip on the flanks of the 'notch.' At the extreme NW side of the slot, fracturing was limited to only two discrete fractures, both within 60 mm of the tunnel periphery. However, when sounded with a scaling bar, the walls were drummy over the entire 'notch' area, i.e., the region where 'half-barrels' had spalled off the wall.

Observation Boreholes

In order to assess the extent of the damage, and whether or not it was pervasive along the test tunnel, four 510-mm-deep observation boreholes were drilled between 16.5 and 22.1 m from the start of the tunnel along the apex of the floor 'notch.' Two of the extensometer boreholes drilled prior to the excavation of the test tunnel provided additional information. Fracturing was observed in the observation holes parallel to the 'notch' flanks to a maximum depth of 240 mm, and in all cases, borehole breakouts occurred at depths beyond the point where the fracturing ended. This finding again suggests that the observed fracturing is independent of the borehole drilling, and is related to *in situ* damage at the 'notch' tip. The start of the breakout zone is coincident with the transition from damaged to competent rock around the tunnel.

In the extensometer boreholes, breakouts were evident at the immediate tunnel periphery, suggesting that they formed prior to development of damage around the tunnel. A vertical extensometer borehole (Figure 6) showed two distinct fractures at 40 and 100 mm below, and parallel to, the floor. As shown in Figure 6, both fractures showed shear offsets of up to 1.5 mm, indicating movement of the upper slabs towards the 'notch' tip.

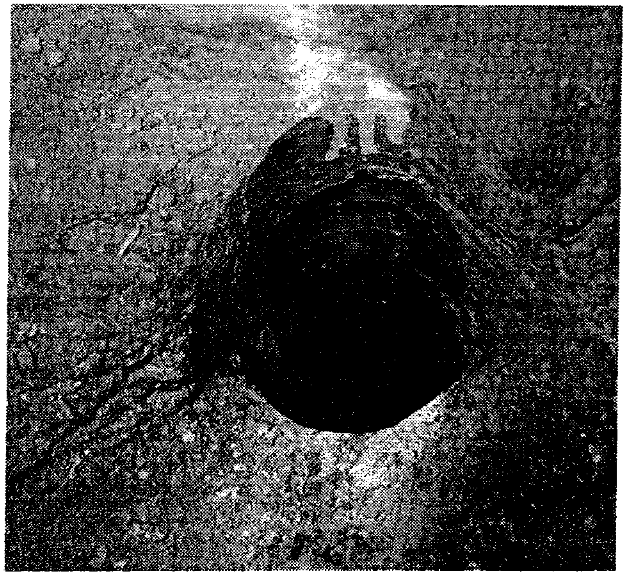


Figure 6: Shear offset in extensometer boreholes drilled prior to tunnel excavation. Movement in the upper slabs is towards the 'notch' tip.

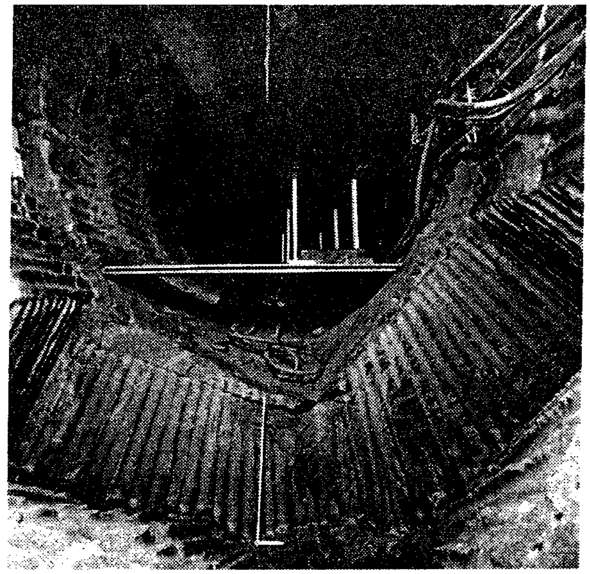


Figure 7: Wedge-shaped observation trench in the test tunnel.

Observation Trench

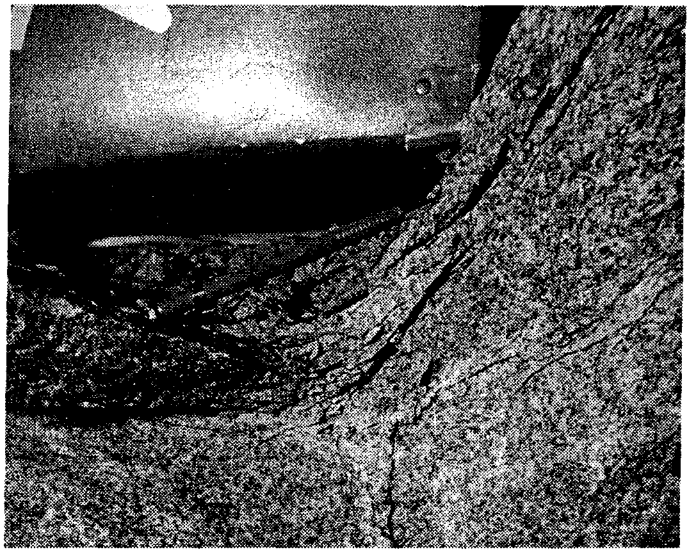
A wedge-shaped observation trench (Figure 7) was excavated in the test tunnel by first drilling two longitudinal cut-off slots to reduce the stresses in the area, then line-drilling a wedge from the destressed region. The lithology in this area was mixed granite and granodiorite. On the vertical face of the exposure, large-scale cracking, believed to be related to widening of the first 16 m of Room 415, was observed. Like the floor slot (Figure 5), the process zone at the 'notch' tip was disturbed prior to the trench excavation, and only a small remnant of the dilated material was left in place (Figure 8a).

However, the face of the trench that was inclined at 30° from horizontal provided a good inclined section through the damaged zone at the 'notch' tip (Figure 8b). Measurements of the damage showed that it extended to a maximum depth of 225 mm at the 'notch' tip, and was characterized by fracturing parallel to the free surface.

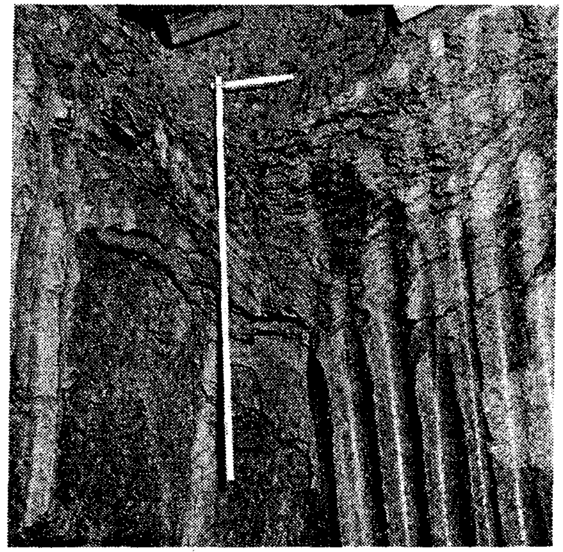
Summary of Damage Observed in Room 415

Characterization of the Mine-by test tunnel [3] identified highly-fractured zones near the tip of each breakout 'notch', extending approximately 180 mm into the rock mass in the roof, and up to 240 mm into the floor. Damage was evident a distance of about 500 mm laterally either side of the 'notch' tip in the roof. In the floor, there was no evidence of damage beyond lateral distances of 500 and 800 mm of the 'notch' tip on the NW and SE flanks, respectively.

Figure 9 shows the extent of observed excavation damage on a typical profile taken near the middle of the test tunnel. Aside from these zones, there was no other observable damage in the tunnel, e.g., no macroscopic tensile cracks in the sidewall.



(a) Dilation at the 'notch' tip in the vertical face.



(b) Damage in the upper 225 mm of the inclined face.

Figure 8: Extent of damage in the wedge-shaped observation trench.

Breakouts occurred in the investigation slots and boreholes, starting at the interface between the highly-fractured zone and the intact rock mass. This observation indicates that the rock beyond the observable EDZ is relatively intact and highly stressed, and that the material in the EDZ is destressed as a result of a reduction in modulus. The damaged zone beyond the 'notch' tip redistributes the point of maximum tangential stress further into the rock mass away from the tunnel boundary, thus allowing sufficient confining stress to develop so as to prevent further failure [3].

DAMAGE IN THE TENSILE REGION

According to elastic theory, tensile stresses are created around a circular opening when the stress ratio of $\sigma_1/\sigma_3 > 3$. In laboratory physical model studies on Lac du Bonnet granite [1], a single crack formed in the tensile region when the tensile stresses exceeded the tensile strength σ_t of about 8 MPa. Although the Mine-by test tunnel was excavated in a stress field where $\sigma_1/\sigma_3 > 5$, there were no discrete tensile fractures observed in the test tunnel sidewall.

An acoustic emission (AE) survey was conducted to investigate the damage in the tensile region around the Mine-by test tunnel. An array of four boreholes was drilled in the sidewall in a diamond pattern parallel to the far-field σ_1 direction, inclined up at about 11° from horizontal (Figure 10). The array enclosed a rectangular prism of rock approximately 0.7 x 0.7 m in cross-section and 1.1 m deep. In this region, σ_3 is tensile and approximately tangential to the tunnel wall, σ_2 is radial and tensile over a small distance from the tunnel wall, and σ_1 is axial and compressive. Acoustic emission monitoring and velocity surveys were conducted using five 1 MHz compressional transducers installed in each borehole and three additional transducers attached to the tunnel wall.

AE source locations from the surveys showed that most of the activity was concentrated near the sidewall surface. Most of the events occurred within 0.8 m of the tunnel wall; more than two-thirds of these within the first 0.4 m (Figure 10). The mean event-to-free-surface distance was 0.35 m, indicating that the development of microcracks is concentrated near the tunnel wall.

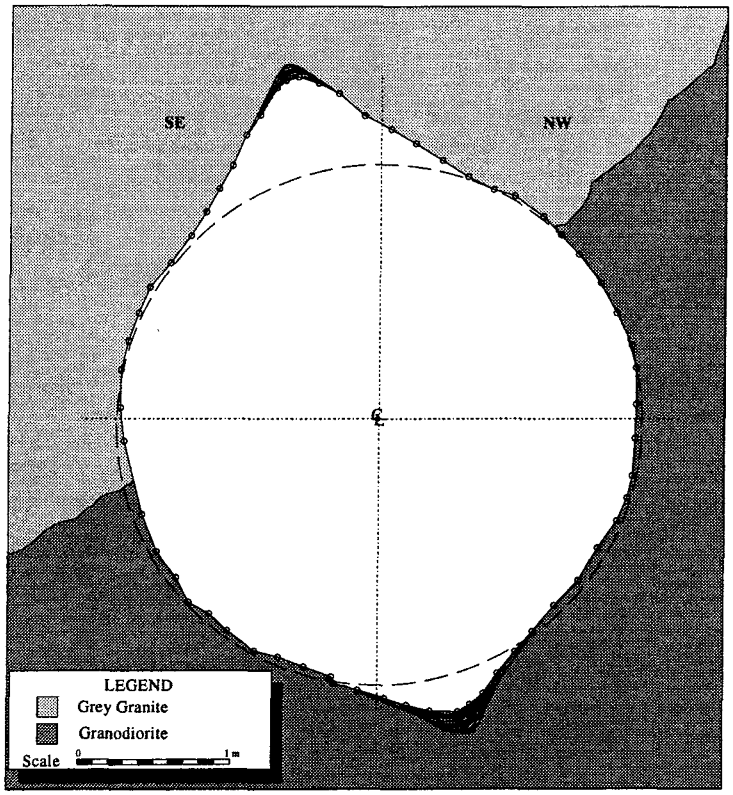


Figure 9: Typical profile showing the extent of observed excavation-induced damage around Room 415.

Reduced seismic velocities in this region provided further evidence that damage in the tensile zone is localized close to the tunnel wall [1].

The spatial distribution of AE events in Figure 10 shows that the tensile events align with the far-field σ_1 direction, and cluster in the region where macroscopic tensile cracking is expected. Thus, extensional damage does occur around the Mine-by test tunnel, albeit on the micro-scale and over a diffuse region rather than localized on a discrete fracture plane. Visible tension cracks were observed in access tunnels excavated at the 420 Level by drill-and-blast.

NUMERICAL MODELING OF THE EDZ

The observed tunnel profile and damage zones identified in the field characterization were incorporated into 3D boundary element and 2D finite difference models to characterize the material behaviour and the extent of the EDZ around the test tunnel [3].

Displacement patterns predicted from linear elastic models were compared to field results measured at different locations in the test tunnel. The measured and modeled results compared closely in the anterior domain (i.e., the region ahead of the tunnel face), with the model predictions falling within the 99% confidence (prediction) intervals for the measured data. However, in the posterior domain (i.e., the region behind the face surrounding the excavated tunnel), the radial displacements measured in the sidewalls exceeded those predicted by the numerical models, even when the observed damage beyond the 'notch' tip was taken into account as a zone of reduced modulus.

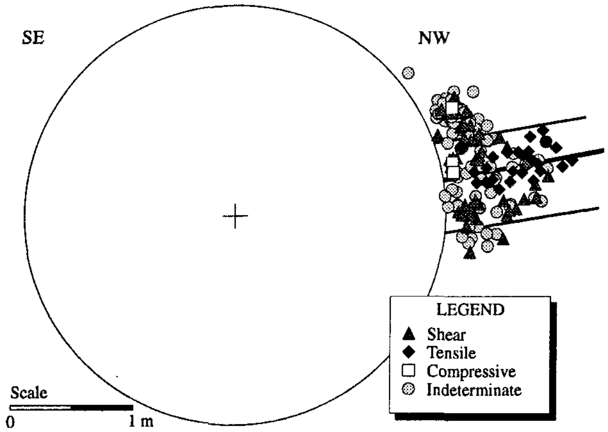


Figure 10: Acoustic emission locations sorted by event mechanism. Only the acoustic emissions within 0.75 m of the array centre are accurately located and plotted. Note how the tensile events align with the far-field σ_1 direction.

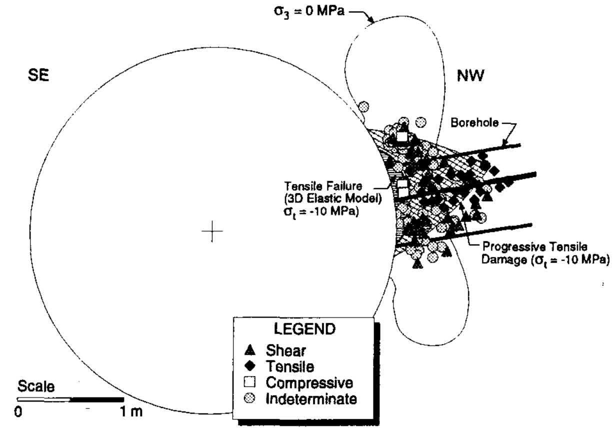


Figure 11: Comparison of extensional damage predicted by numerical model and acoustic emission events measured in the sidewall of the Mine-by test tunnel.

In areas of the posterior domain where one or more of the near-field principal stress components was tensile, the rock mass response was non-linear/non-elastic within about one radius of the tunnel wall. A series of 2D finite difference model simulations were conducted to investigate the material behaviour in the EDZ around the tunnel [3]. In comparing radial displacements predicted by the elastic case to measured results, the difference in responses is consistent with a reduction of about 60% in the shear modulus in the sidewall region within about one radius of the tunnel periphery.

Seismic velocity and acoustic emission studies [1] support the idea of damage development in the tensile regions around the test tunnel, resulting in induced anisotropy, i.e., directional cracking, and reduced shear modulus. A relatively simple model [3] was used to simulate this process, and the resulting radial displacement responses. The model incorporated a criterion to reduce the shear modulus in zones where $\sigma_3 < \sigma_t$. To account for the reduction in tensile load bearing capacity orthogonal to the induced cracking in the damaged material, ubiquitous joint elements were introduced into the zones where $\sigma_3 < \sigma_t$. Stress redistribution associated with the reduction in tensile stresses near the tunnel wall was captured by iteratively checking for new zones where $\sigma_3 < \sigma_t$, substituting ubiquitous joint elements for those elastic elements that violated the tensile cutoff criterion, then allowing the model to equilibrate. In this way, the zone of extensional damage propagated away from the tunnel wall until equilibrium was reached.

Depending on the value selected for σ_t, the final extent of the zone of extensional damage could be significantly larger than the region that initially exceeded the tension cutoff. The redistribution of stresses increased the radial displacement near the tunnel wall measured by the horizontal instruments. By incorporating a reduced shear modulus in the ubiquitous joint elements, and by taking variations in geology on opposite sides of the tunnel into account, the resulting displacement response from the model was very similar to the measured response. In addition, as shown in Figure 11, the predicted extensional damage zone in the sidewall compared closely to that measured in the acoustic emission study [1]. While this modeling approach has several limitations, it illustrates that stress redistribution and a reduction in shear modulus resulting from induced cracking in the tensile region can account for the difference between the measured and modeled radial displacement responses [3].

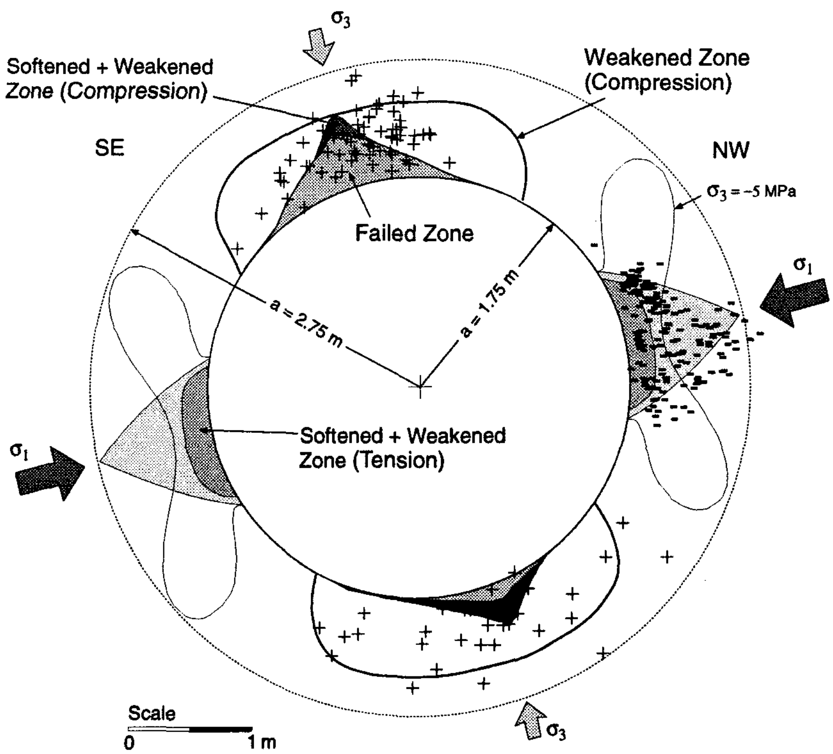


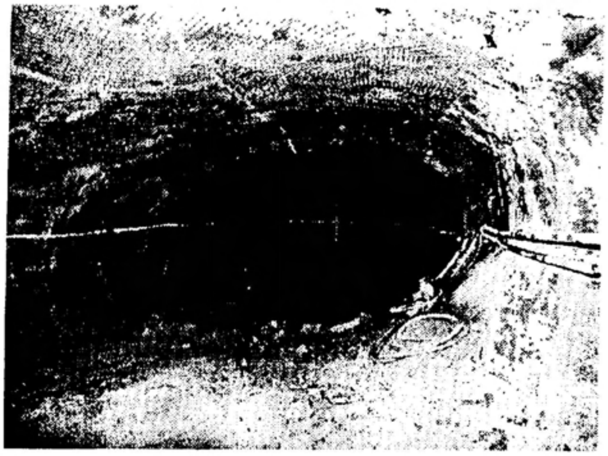
Figure 12: Schematic view of the extent and characteristics of excavation-induced damage around the Mine-by Experiment test tunnel.

COMPARISON WITH OTHER TUNNELS

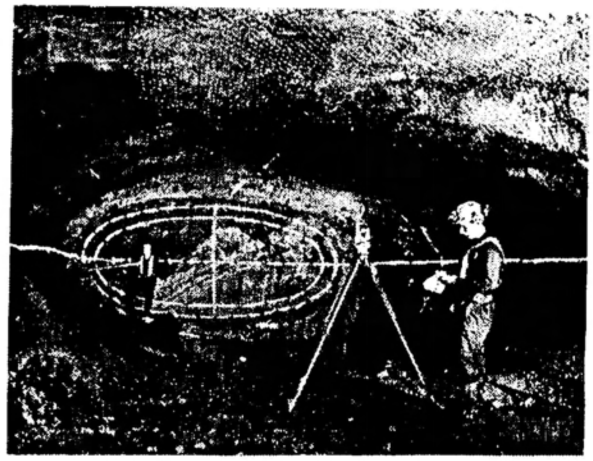
Results from underground characterization, geophysics studies and numerical modeling indicate that the excavation-induced damage around the Mine-by test tunnel is localized in the regions of compressive stress concentration in the roof and floor, and in the regions of tensile stress concentration in the sidewalls. The extent and characteristics of these damaged zones are shown schematically in Figure 12.

The damaged zone in the roof and floor comprises three distinct regions with different characteristics [1]. The outer limit of damage is defined by the $\sigma_1 - \sigma_3 \approx 70$ MPa contour, which extends approximately 0.7 m beyond the original tunnel perimeter. Within this region, the rock mass has been damaged (weakened) as a result of high deviatoric stresses and stress rotation associated with the advancing tunnel face. The failed zone within this damaged region is v-shaped and extends to about 0.6 m beyond the original perimeter in the roof, and about 0.4 m in the floor. At the tip of each v-shaped 'notch' is a localized process zone where the rock is crushed. Although the material in these zones is no longer part of the elastic continuum around the tunnel, it can be treated as a material that has been weakened and whose elastic modulus has been reduced. The extent of the various regions in the compressive damaged zone varies, depending on the local geology. Microseismic events recorded in these zones were typically in the 50 Hz to 10 kHz range.

In contrast, the damaged zone in the sidewall (tensile) regions of the tunnel is much more subtle than that in the roof and floor. The microseismic activity in this zone was typically in the 1 MHz range, indicating much smaller-scale cracking than in the compressive regions. Back-analysis using



(a) Inclined ovaloid segment of Room 418.



(b) Horizontal ovaloid segment of Room 417.

Figure 13: Typical ovaloid tunnel segments at the 420 Level. The openings are 6.6-m wide and 3.0-m high. In Room 418, the major axis is inclined 11° from horizontal to align with σ_1.

extensometer results [3] showed that the material behaviour in this zone can be characterized by a reduction of the shear modulus and anisotropic weakening (extensional cracking). Microseismic activity in the sidewall indicates that most damage occurs within 0.35 m of the tunnel wall and extends about 1 m from the tunnel, decreasing with radial distance. This damaged zone is more extensive in granite than in granodiorite, tending to expand into the tensile stress concentration lobes defined approximately by the $\sigma_3 \approx -5$ MPa contour shown in Figure 12. However, the radial extent of the zone in granite is similar to that in granodiorite. As with the compressive zones of damage, the extent of the damaged zone in the tensile region is partly a function of the local geology.

It is important to note that the Mine-by test tunnel represents an extreme case in terms of the near-field stress conditions and the potential for progressive failure and excavation damage development. This point is illustrated by the results from recent excavations at the 420 Level [5], constructed to evaluate tunnel stability and the extent of excavation damage as a function of tunnel geometry and orientation, geology, and excavation method. Scoping analyses illustrated that, for sub-optimum aspect ratios (i.e., the room aspect ratio is less than the maximum-to-minimum stress ratio), ovaloid tunnel geometries produced lower boundary stresses and stress gradients than elliptical openings of the same aspect ratio. A series of nine ovaloid and circular openings were excavated to achieve different boundary stress levels and near-field stress distributions to assess the effect of tunnel geometry on damage development. Several of these openings had sections in both granite and granodiorite lithology, providing a comparison of damage in rock types with different strength characteristics. Each tunnel segment was driven parallel to the azimuth of σ_2, approximately parallel to the Mine-by test tunnel.

The study showed that mechanically stable openings with minimal excavation damage can be excavated in the most adverse stress conditions at the URL. From borehole observations, the visible EDZ around the various openings was limited to a thin skin ranging from 0 to 80-mm thick in the roof and sidewalls, and to a maximum depth of 210 mm in the floor. Excavation damage was more apparent in more inequigranular, coarser-grained rock varieties (such as granite) than in more equigranular, finer-grained rock types (such as granodiorite). It was concluded that reduction of the peak stress and the stress gradient at the tunnel periphery reduces the potential for damage localization, a necessary precursor for large-scale 'notch' development.

CONCLUSIONS

Results of *in situ* characterization and numerical modeling of the circular test tunnel for the Mine-by Experiment showed that the EDZ is limited to a region within about 0.6 radii from the original perimeter of the test tunnel. Within this region, however, the characteristics of the EDZ vary with position around the tunnel, and are controlled or influenced by such things as the nature of the stress concentration (i.e., compressive versus tensile), and variations in geology. By engineering the tunnel geometry to accommodate the *in situ* stress conditions, stable openings with minimal excavation damage can be excavated parallel to σ_2 (approximately parallel to the Mine-by test tunnel) at the 420 Level.

From these findings, it can be concluded that: 1) the extent and nature of the EDZ in the compressive region around similarly-oriented underground openings can range from non-localized skin effects within a few millimetres of the opening, to localized 'notch' development extending up to 0.6 radii beyond the tunnel periphery; and 2) fracturing in the tensile regions of the tunnel sidewall can range from diffuse microcracks for mechanically-excavated openings to discrete tensile cracks for drill-and-blast excavations. Therefore, in conditions where an EDZ is likely to form, the first step in minimizing the potential for increased near-field permeability is to minimize the extent of the EDZ through optimization of the tunnel design relative to the *in situ* stresses.

The ovaloid openings excavated at the URL demonstrate that it is possible to create stable openings in adverse stress conditions. In combination with the Mine-by Experiment test tunnel, these excavations have advanced our fundamental understanding of the relationship between engineering design, rock mass behaviour and safety-related issues.

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