COMPARISON OF EXCAVATION DISTURBANCE AROUND DEEP TUNNELS IN HARD ROCK USING ACOUSTIC EMISSION AND ULTRASONIC VELOCITY METHODS

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ABSTRACT

Acoustic emission (AE) and ultrasonic velocity monitoring studies have been undertaken at both the Atomic Energy of Canada Limited (AECL) Underground Research Laboratory (URL) and at the Swedish Nuclear Fuel Waste Management Company (SKB) Äspö Hard Rock Laboratory (HRL). At both locations the excavations were tunnels in granitic material at approximately 420 m depth. However, the stress regime was more severe at the URL Mine-by tunnel site than the HRL ZEDEX tunnel. Different parts of the ZEDEX tunnel were created using different excavation techniques.

AE and microseismic monitoring at the URL showed that events were most concentrated in the floor and roof of the tunnel, with less activity in the side walls. The side-wall activity was clustered primarily within 0.5 m of the tunnel wall. AE monitoring in the floor of the tunnel showed that small numbers of AE continued to occur in the notch region in the floor of the tunnel over two years after excavation was completed. This activity became more acute as the rock was heated, imposing thermally-induced stresses on the volume. Ultrasonic-velocity studies both in the floor and the wall of the tunnel showed that the velocity is strongly anisotropic with the slow direction perpendicular to the tunnel surface consistent with cracks parallel to the surface. The velocity increased with distance into the rock from the tunnel surface. In the floor, this effect was seen up to two metres from the tunnel surface. Most of the change occurred within the first 0.5 m from the tunnel perimeter.

At the lower-stress HRL, most of the AE again occurred close to the tunnel surface. The occurrence of AE under relatively low stress conditions suggests that the regions experiencing AE activity were damaged during the excavation process, thereby reducing their strength. The section of tunnel excavated by tunnel boring machine had fewer events, clustered much closer to the tunnel surface, than the sections excavated using drill and blast extraction techniques. P-wave velocity changes of only about 0.1% were experienced due to the tunnel excavation for ray paths within zero to two metres from the tunnel surface indicating that crack damage was relatively low.

INTRODUCTION

As various organisations examine the feasibility of deep geological disposal of radioactive waste, there has been increased interest in the excavation-induced disturbance to the rock mass around tunnels. For nuclear-waste repositories situated below the water table, there is a need to minimise potential pathways for ground-water flow and potentially radionuclide transport around tunnels that would be created to store such waste materials. Methods need to be developed and evaluated to determine the nature of development of the excavation-disturbed zone (EDZ). In terms of mechanical properties, the character, magnitude and extent of the EDZ depend upon the void represented by the tunnel, the method of excavation, and the value of certain *in situ* parameters such as frequency and orientation of discontinuities, rock mass strength properties, and stress. The near-field EDZ, less than one tunnel radius from the tunnel perimeter, may be expected to be include a significant component of brittle deformation. This damage may be either a direct result of the excavation process, or caused by stress redistribution and concentration or relaxation around the tunnel. In the far-field EDZ, the disturbance would be expected to be dominated by the elastic effects caused by redistribution of the stress field. The disturbance may also include preferential opening, closing or shearing on pre-existing fractures.

AE activity in rocks results primarily from the formation of cracks and sudden movements on pre-existing crack faces. As such, source locations and any other source characterisation gives information on brittle damage as it occurs. In crystalline rocks the existence, orientation and the population density of microcracks and saturation of those cracks are among the major factors affecting P-wave velocity.

This paper reports the results of case studies using these techniques around three tunnels created at similar depths in granitic rocks. The first site was the Atomic Energy of Canada Limited (AECL) Underground Research Laboratory (URL), near Pinawa, Manitoba, Canada. Results of AE and ultrasonic studies associated with the Mine-by Test and the Mine-by Heated-Failure Test will be discussed. The other tunnels studied were at the Swedish Nuclear Fuel Waste Management Company (SKB) Äspö Hard Rock Laboratory (HRL) on Äspö Island in south-eastern Sweden as part of the Zone of Excavation Disturbance Experiment (ZEDEX).

Along with extensive larger-scale microseismic monitoring at the Mine-by tunnel [1], two acoustic emission experiments have been undertaken there. During excavation of the tunnel AE activity was monitored and P-wave velocity was measured in the side wall of the tunnel. The Mine-by tunnel was initially excavated as a cylindrical tunnel 3.5 m in diameter. The tunnel was excavated using a mechanical drilling and rock-breaking method (i.e. no blasting) to minimise any damage caused directly by the excavation method [2]. The AE and ultrasonic velocity studies conducted concurrently with excavation were described by Carlson and Young [3]. Between December 1993 and December 1995, well after completion of the excavation, AE and ultrasonic studies were undertaken as part of the Mine-by Heated-Failure tests. This involved monitoring the disturbance caused as a 600-mm-diameter borehole was drilled into the floor of the tunnel and the surrounding rock mass was heated. Although the authors do not intend to discuss the thermally-induced disturbance in detail in this paper, some of the results are pertinent to discussion of excavation-induced disturbance.

The ZEDEX experiment was devoted to the EDZ phenomenon. Two near-by sections of tunnel in similar orientations and experiencing similar initial conditions were excavated using different excavation techniques. One section of tunnel was excavated using a tunnel boring machine (TBM), while the other section was created using "smooth blasting" drill-and-blast techniques (D&B). The D&B tunnel was excavated using low-shock explosives and a blast design intended to minimise excavation disturbance. Both tunnels were cylindrical five-meter-diameter tunnels, although the D&B tunnel had a flattened floor.

INITIAL CONDITIONS

Both sites are hosted by medium-grained granite to granodiorite rock masses. Furthermore, both experiments took place at 420 metres depth below the surface. The Mine-by tunnel at the URL is in unfractured rock, whereas the rocks around the ZEDEX tunnel at the HRL are cut by several joint sets at that depth, some of which are water bearing.

Another major difference between the sites is in the *in situ* stress fields. Although the σ_3 stress values were of similar magnitude (~10 MPa), the ratio of σ_1:σ_3 at the Mine-by tunnel is approximately 6:1 versus 3:1 at the ZEDEX tunnel [2]. Furthermore, the Mine-by tunnel is oriented approximately parallel to the σ_2 stress direction, such that the stress concentration around the tunnel was maximised. The ZEDEX tunnel is at an oblique angle to the σ_1 stress direction.

Falls [4] developed a technique to fit 3-D travel-time data to an ellipsoidal velocity model. For both sites velocity models were created using data extending well away from the tunnels. Both sites were found to be weakly anisotropic. The background velocity anisotropy at the Mine-by site was only about 1% of the fast direction velocity. The velocity anisotropy was slightly higher (2-3%) in the Äspödiorite of the ZEDEX test. In that case the velocity slow direction was perpendicular to a prominent joint set.

EXPERIMENTAL SET-UP

In each experiment there were arrays of 16 ultrasonic transducers used for AE monitoring. These were deployed in four boreholes surrounding each volume of rock being studied and were approximately evenly spaced in each borehole.

For the Mine-by excavation monitoring, the four boreholes were arranged in a square pattern extending radially into the side-wall of the tunnel. The edges of the square were 0.6 metres in length. The boreholes extended about one metre into the side wall perpendicular to the tunnel surface. For the heated failure tests, the instrumentation boreholes were drilled vertically in the floor of the tunnel. They were arranged in a nearly square pattern, 1.8 meters on edge. The holes extended about four metres into the tunnel floor. All of the 16 transducers could be used as ultrasonic sources as well as receivers. Periodically during the tests velocity surveys were conducted by pulsing each transducer and receiving on the remaining transducers. This was done to examine the 3-D velocity structure around the tunnel.

For the ZEDEX experiment, the instrumentation boreholes were approximately parallel to the tunnel sections being studied. Sensors with integral 40 dB preamplifiers were deployed up to 35 m down these holes, evenly spaced 1.2 m apart as part of a four-sensor borehole probe. A fifth transducer was deployed 1.2 m beyond the final receiving transducer in each borehole probe unit to be used to transmit signals to the other sensors for velocity determinations. At the sensor array, the boreholes were arranged in a rectangular pattern with one hole at either side of the tunnel, one above and one below the tunnel position. The boreholes were about 6.5 m apart. The transducers were spread along a length of tunnel extending approximately 5-6 metres in total length. The sensors were in place before the tunnel was excavated, and AE and velocity changes were monitored as the tunnel progressed through the study volume. See Falls and Young [5] for more details.

VELOCITY RESULTS

Mine-by Excavation Monitoring

In the wall of the Mine-by tunnel, shortly after excavation, it was found that the velocity was strongly anisotropic [3]. Figure 1a shows a lower hemisphere stereonet projection of P-wave velocity versus angle. Fitting the data to an ellipsoidal velocity model, the P-wave slow-velocity direction was found to be approximately horizontal, perpendicular to the tunnel wall. The difference in velocity between waves propagating in the fast direction versus the slow direction was about 11% of the maximum velocity, much higher than the background anisotropy. This velocity-field orientation is consistent with the presence of an aligned set of microcracks parallel to the tunnel surface. This result indicates that a spalling type mechanism dominated brittle deformation in the side wall region.

Researchers working with physical scale models have often identified breakout or spalling occurring in the a region equivalent to the roof and floor of the Mine-by tunnel, with tensile or "primary" cracks extending radially outward from the circular opening occurring in the sidewall regions [6]. The orientation of these modelled primary cracks is not consistent with the P-wave velocity anisotropy *in situ*.

Carlson and Young [3] showed that there was a drop in P-wave velocity as a function of distance

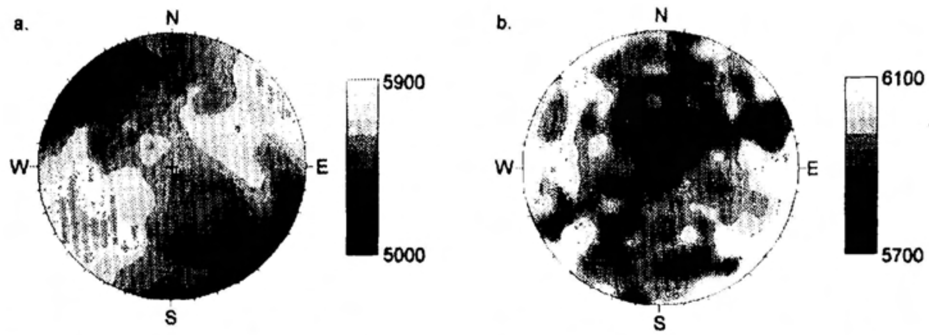

Figure 1. Lower hemisphere stereonet projections of P-wave velocity around the Mine-by tunnel in (a) the side wall of the tunnel and (b) the floor of the tunnel. The tunnel runs NE so the P-wave slow-velocity direction was perpendicular to the tunnel surface in both the side wall and floor of the tunnel.

from the tunnel surface. The velocity rose by between 200 m/s and 300 m/s over the one metre interval into the tunnel wall. Most of the change occurred within 0.5 metres of the tunnel wall.

<u>Mine-by Heated-Failure Test</u>

The velocity measurements in the floor of the Mine-by tunnel showed a similar trend to that in the wall. Plotting velocity as a function of direction on a stereonet (Figure 1b), the P-wave slow direction is again approximately perpendicular to the tunnel perimeter, although in this case vertical. The P-wave fast direction is again approximately parallel to the tunnel axis. This is again consistent with a set of microcracks aligned parallel to the tunnel surface, as would be expected for spalling deformation. A velocity fit showed that the anisotropy was about 6% of the fast direction velocity. This anisotropy is slightly lower than the sidewall values, possibly reflecting the fact that the raypaths examined were further from the tunnel perimeter on average. Furthermore, the velocities were somewhat higher in the floor than the wall, which may result from higher stress concentrations in the floor, along with the effect of greater distance from the tunnel perimeter.

Figure 2 shows the change in velocity with depth below the floor. The velocity increased as a function of depth below the tunnel floor. This increase occurred within the first two metres of the floor and then levelled off to a constant velocity. The decrease in velocity between 2.0 m and 0.5 m from the tunnel floor was about 350 m/s. Based on the results from the Mine-by excavation monitoring experiments, we would expect further velocity decrease closer to the tunnel wall.

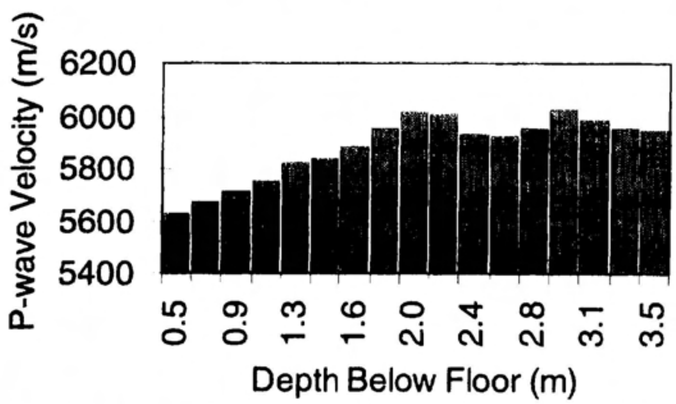

Figure 2. Variation in P-wave velocity with depth below the floor of the Mine-by tunnel.

ZEDEX Tunnel

The velocity around the perimeter of the ZEDEX tunnel was monitored as the tunnel was excavated through the volume. Only raypaths that were not interrupted by the presence of the tunnel were examined. Many of the raypaths were between transducers that were all about 2 metres from the tunnel surface. However, the path between many sensors passed within a few centimetres of the tunnel perimeter along parts of their raypaths. The average change in velocity for the TBM tunnel is shown in Figure 3. On average there was only a slight decrease in velocity of about 5 m/s. Similar magnitude of change was seen in the D&B tunnel sections. The raypaths that did not pass close to the tunnel generally showed no change in velocity. If we assume that all the change occurred within a given radius of the tunnel perimeter, it is possible to estimate the extent of velocity change in that region. For example, one might assume that the velocity change occurred in the first 0.5 m from the tunnel perimeter. This accounts for 20 percent of the raypath length. Thus, there would have been a drop in velocity of 20 m/s if all the change occurred within 0.5 m of the tunnel. Clearly, the velocity change is of lower magnitude, and lesser extent than at the Mine-by tunnel. Detailed velocity anisotropy studies have not been completed around the ZEDEX tunnel.

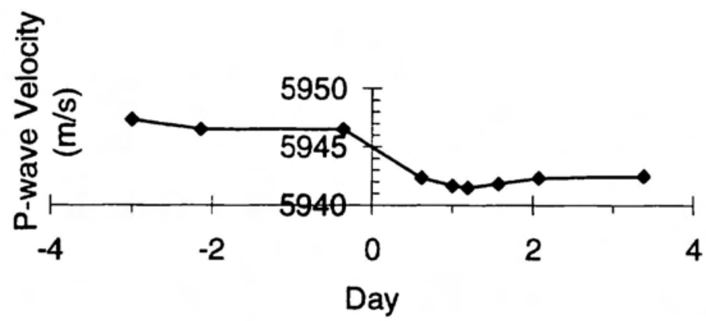

Figure 3. Variation in P-wave velocity with time as the TBM tunnel was excavated through the study volume. Time zero is the time when the TBM tunnel face passed through the centre of the sensor array. During the period shown about 25 m were excavated, approximately centred at the centre of the sensor array.

AE MONITORING

Mine-by tunnel excavation

Collins [7] analysed several thousand microseismic events recorded around the Mine-by tunnel during excavation. He found that microseismic events were primarily occurring in the floor and roof of the tunnel where differential stresses were most highly concentrated. The result of this activity was that major breakout notches formed in the roof and floor of the tunnel. A spatial-density plot of these microseismic events is shown in Figure 4.

AE monitoring in the side wall of the tunnel during excavation [3] showed that most of the recorded activity originated outside of the sensor array, predominantly coming from the regions closer to the roof and floor breakout notches. Only 12 % of the events analysed originated within 0.75 m of the centre of the array on the wall of the tunnel. Examining these events, approximately two thirds occurred within 0.4 metres of the tunnel surface, with the remaining events mostly occurring within the next 0.4 metres. Only one event was detected beyond 1.3 metres from the tunnel surface.

Mine-by heated failure tests

The Mine-by heated failure tests took place in the floor of the tunnel, immediately adjacent to the

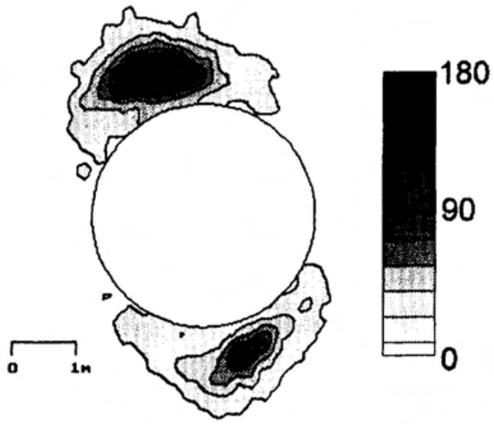

Figure 4. Spatial density of microseismic events recorded around the Mine-by tunnel during excavation [7].

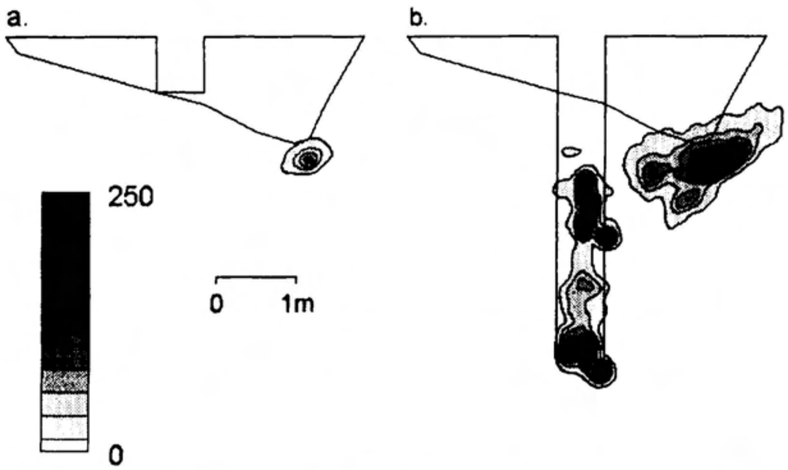

Figure 5. AE event density in the floor of the Mine-by tunnel during the heated failure tests. (a) Events occurring in the floor of the tunnel before the tests. (b) Events induced by heating the rock mass and drilling a 600-mm-diameter borehole into the floor of the tunnel.

breakout notch that had developed there. AE monitoring began over a year after the completion of all excavation in the Mine-by tunnel. Examining the results from phase 2 of this test, in which the initial stages involved AE monitoring before the test and during heating of the rock volume, we saw that a low yet significant level of AE activity was still occurring in the notch in the floor of the tunnel over a year after the excavation was complete. Figure 5a shows an event density plot compiled from 307 source-located AE events recorded over an interval of one month. The activity was tightly clustered in the region that Martin [8] referred to as the "process zone" in the apex of the notch. It was conjectured that activity in the process zone drove spalling and slabbing on the flanks of the notch. Our results indicate that although the notch had stabilised at a macroscopic scale, sporadic AE activity was still occurring in this process zone.

As the rock mass was heated toward a temperature of 85° C, there was a dramatic increase in AE activity in this region. Thermally-induced stress perturbations resulted in both increased activity in the apex of the notch, and along the flanks of the notch (Figure 5b). The notch region appears to have been in a state of critical equilibrium, such that any change in the stress field can cause a substantial increase in AE activity. The activity on the flanks of the notch seems to result from slip between the surfaces of slabs that existed before this stage of the test. Observations within boreholes in the test region showed that large cracks existed about 15-20 centimetres below the granite floor of the tunnel, parallel to the tunnel floor. These cracks experienced 1-2 mm of reverse dip-slip displacement during the test [9]. Figure 5b also includes AE activity that occurred in a large-diameter borehole drilled in the centre of the AE array as part of the heated failure tests. After about two weeks of heating the increased AE activity rate levelled off and eventually began to decrease as the system again came into a state of critical equilibrium.

ZEDEX tunnel

Figure 6 shows the cumulative AE event density during three periods of AE monitoring for both the TBM and the D&B ZEDEX tunnels. Each period represented about eight hours of monitoring immediately following either a TBM excavation stop, or a blast round detonation.

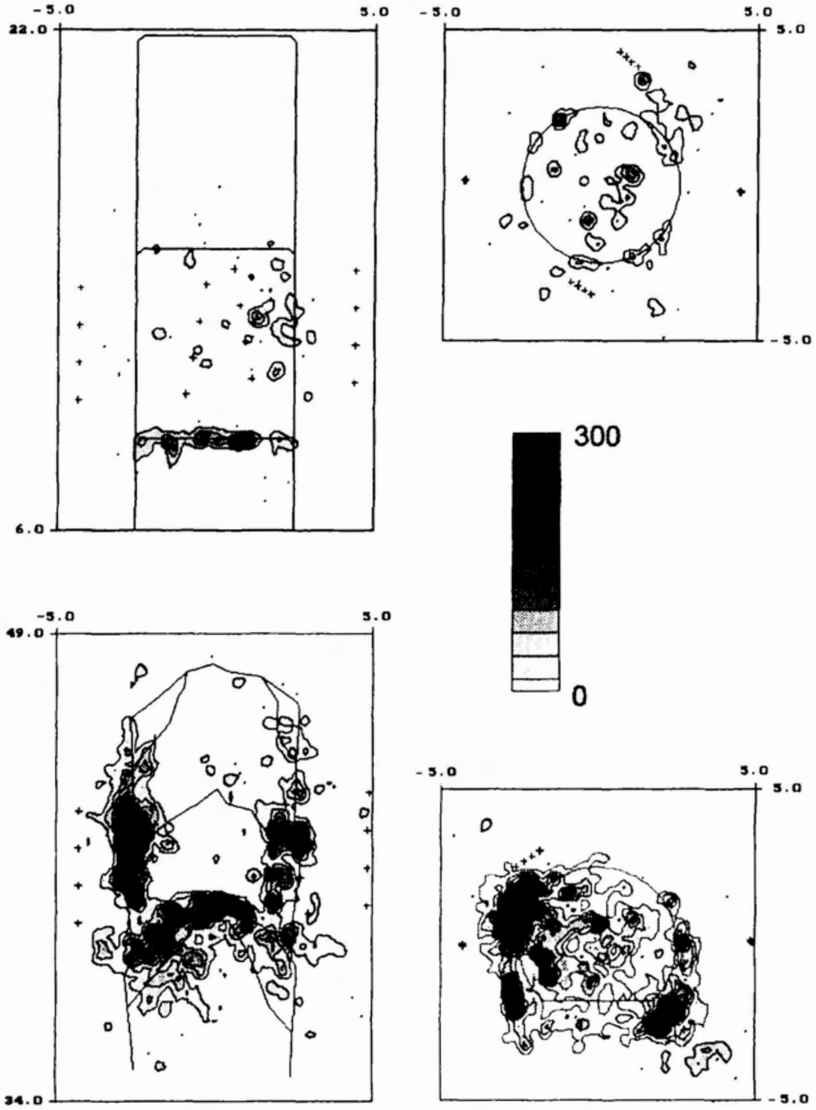

Figure 6. Spatial density plot of AE activity around the ZEDEX tunnels. The TBM tunnel is shown above and the D&B tunnel below with views are from above and looking along each tunnel.

For the TBM tunnel, which is the most analogous case to the Mine-by tunnel in terms of excavation method, there was no sign of clustering of activity in the region of highest differential stress. The greatest concentration of recorded events was on the tunnel face after the first TBM stop. At that time there was an unobstructed path between the face and all the sensors. The tunnel obscures these events for later stops. The stress was not highly concentrated across the tunnel face. This activity may represent AE in rock damaged directly by the crushing and plucking action of the TBM.

On the perimeter of the cylindrical tunnel, the greatest concentration of AE activity is within 0.1 m of the wall of the tunnel, with most of the activity less than 1.0 metre from the tunnel perimeter. There were some scattered events up to several metres from the tunnel. These were interpreted as being due to slip on pre-existing joints and natural fractures.

The D&B tunnel experienced a much greater amount of AE activity despite being excavated in a similar geometry and under very similar stress conditions. The rate of AE occurrance was generally about ten times higher during monitoring of the D&B tunnel than the TBM tunnel. Again the spatial density of the AE activity about the perimeter of the tunnel showed little apparent relationship to the concentrations of differential stress about the tunnel. There was no anomalous clustering of AE activity in the roof of the tunnel. While there appears to have been some clustering of events near the edges of the floor of the tunnel, it is unclear whether this effect was a stress related result, or if it was related to the blast design with higher explosives used in the floor. The events around the D&B drift were concentrated in a broader zone around the perimeter than for the TBM tunnel. The zone of maximum event density extended out to about 0.7 m from the tunnel wall. In the far-field EDZ, beyond about 2 m from the tunnel perimeter, there were similar event densities for both tunnels.

CRACK INITIATION

Martin *et al.* [10] used numerical modelling to estimate the stress acting at microseismic event locations around the Mine-by tunnel. They defined the *in situ* crack-initiation stress (σ_{ci}) as the differential stress ($\sigma_1 - \sigma_3$) the rock was under at the event locations assuming that the microseismicity represented the initiation of the failure process. For the microseismic events in the regions experiencing breakout, they found that cracking occurred at $\sigma_{ci} \approx 70$ MPa (Figure 7). This is about 0.3 σ_c (σ_c = uniaxial compressive strength). Typical laboratory values for σ_{ci} are between 0.3 and 0.6 σ_c [10]. A Hoek-Brown failure envelope for Lac du Bonnet Granite is also shown in Figure 7.

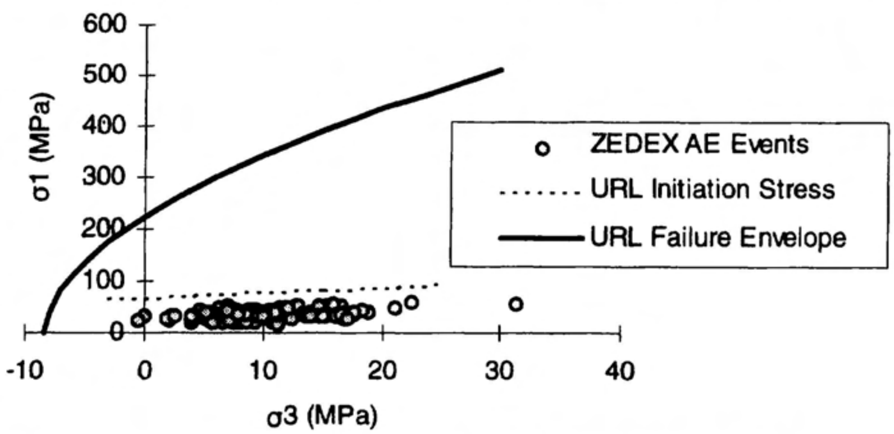

Figure 7. Crack initiation stress for ZEDEX AE events and fit to Mine-by microseismic events.

Plotting the stress estimated using the Examine^{3D} modelling program [11] at AE event locations around the ZEDEX tunnels (Figure 7), we see that the AE activity was occurring at lower stress levels than at the URL. The average *in situ* crack-initiation stress was $\sigma_{ci} \approx 25$ MPa. This is about 0.12 σ_c, which is well below the typical range of crack initiation stress. Similar values were estimated for the events around both the TBM and D&B tunnels. This is further evidence that the AE activity at these tunnels occurred in rock that was damaged directly by the excavation process, rather than solely by the stress-induced initiation of new cracks.

CONCLUSIONS

The case studies presented in this paper show how the disturbed zones surrounding deep underground excavations are affected by both the stress regime in the rock mass, and the excavation method.

Under the exceptional stress regime at the Mine-by tunnel, where the ratio of maximum to minimum principal stresses approaches 6:1, the redistribution of stress around the tunnel has a profound effect on the EDZ. AE and microseismic events show a strong clustering of events in the roof and floor of the tunnel where the maximum tangential stresses are concentrated. Low-level AE activity continues to occur in these regions months or even years after the completion of the excavation. The system is in a state of critical equilibrium, such that any disturbance to the stress regime, such as that caused by thermal loading of the area can cause great increases in AE activity. The initial larger-scale microseismic activity was located over a broad zone, whereas the later more detailed AE studies showed that the continuing activity was located in a tight cluster around the process zone in the apex of the breakout notches. As the stress regime was disturbed, activity began to occur in the flanks of the notch, possibly driven by the more intense deformation occurring in the process zone along with thermal expansion of the slab.

Detailed ultrasonic P-wave velocity anisotropy studies both on the flank of the lower notch, and in the side wall of the tunnel showed two main features. There was a distinct velocity decrease below background levels approaching the tunnel wall. The effect was greatest within the first 0.5 m of the tunnel side wall. The low velocity zone was more extensive in the tunnel floor, extended to about 2 metres into the floor of the tunnel. Secondly, there was a clear velocity slow direction perpendicular to the tunnel perimeter. The anisotropy was much greater than the background anisotropy. This indicated the presence of an extensive aligned set of microcracks parallel to the tunnel perimeter. This suggested that a spalling type of deformation was dominant. While this was anticipated in the flanks of the breakout notch, it was unexpected in the sidewall regions. Laboratory physical models of breakout show that the radial tensile failure would be expected in the sidewall of the tunnel.

The ZEDEX TBM tunnel, which, like the Mine-by tunnel, was mechanically excavated with no explosives, showed much less extensive damage. While excavated at a similar depth and in similar rocks to the Mine-by tunnel, the $\sigma 1:\sigma 3$ stress ratio was just over 3:1. Furthermore, the tunnel was not oriented to maximise the stress concentrations. The AE activity was not obviously clustered in the regions of highest tangential stress concentration. AE activity was most concentrated in a narrow zone immediately about the tunnel perimeter and at the tunnel face.

The D&B tunnel was excavated under very similar to the TBM tunnel, except that a smooth-blasting technique was used rather than tunnel boring machine. The damage around the D&B tunnel was more extensive than the TBM tunnel. The AE event rate was about ten times higher for the D&B tunnel. The zone of maximum AE event density extended further into the rock. However, velocity studies around both tunnels showed that the excavation caused only minimal changes in P-wave velocity around both tunnels. The average velocity change was for ray paths in a region between zero and two metres from the tunnel perimeter was under 10 m/s compared to hundreds of metres per second drop around the Canadian Mine-by tunnel.

Stress analyses showed that the events at the ZEDEX tunnels occurred under lower stresses than would generally be expected for crack initiation. This indicates that the AE were occurring in rock that had been previously damaged by the excavation process.

The results indicate that the stress conditions can play a greater role in determining the extent of excavation disturbance than the excavation method. While the smooth blasting excavation technique resulted in more AE activity than the tunnel boring machine, the velocity results indicate that in both cases the disturbance was minimal compared to the damage at the high-stress Mine-by tunnel.

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