CONNECTED PATHWAYS IN THE EDZ AND THE POTENTIAL FOR FLOW ALONG TUNNELS

Neil A. CHANDLER, Edward T. KOZAK
AECL, Whiteshell Laboratories, Pinawa, Manitoba, Canada

C. Derek MARTIN
Geotechnical Research Centre, Laurentian Univ., Sudbury, Ontario, Canada

ABSTRACT: Two connected permeability experiments have been conducted at the Underground Research Laboratory. The tests allowed the examination of the hydraulic properties of the excavation damaged zone (EDZ). One test was conducted in a drill-and-blast excavation in a low stress environment, the second in a mechanically excavated tunnel in highly stressed rock. These two experiments allowed the comparison of flows through a blast-induced EDZ to flows through a stress-induced EDZ. In the drill-and-blast excavated tunnel, 98% of the flow was eliminated by forcing the fluid pathway to span adjacent blast rounds, suggesting a predominantly discontinuous EDZ. In the mechanically excavated tunnel, high stress concentrations created a very small continuous zone (0.05 m^2) of highly fractured rock through which most of the flow occurred. Numerical modeling of a tunnel seal suggests that the construction of a well-designed EDZ cut-off will serve to minimize flows that would otherwise by-pass the tunnel seals.

1 INTRODUCTION

Construction of an underground nuclear fuel waste repository will require the excavation of several kilometres of tunnels and shafts. In the Canadian disposal concept, a vault would be located at a depth of between 500 and 1000 m in the granitic rock of the Canadian Shield. In this environment, it is expected that a zone of rock adjacent to each excavation, referred to as the excavation damaged zone (EDZ), will have properties which are considerably different from those of the undisturbed rock mass.

A measure of performance of a nuclear fuel waste repository is the ability of the engineered and natural barriers to inhibit the transport of radionuclides from the waste form to the earth's surface. The primary transport mechanisms include diffusion and advective transport within the pore water of the rock or backfill. The ability of the rock mass to act as an effective barrier will depend largely upon the degree of fracturing in the rock, the distance between tunnels and major conductive pathways, and the extent of excavation induced damage adjacent to the tunnels. For nuclear waste repositories, an important measure of damage is the increase in the hydraulic conductivity of the EDZ over and above that of the undamaged rock. The extent of damage around an excavation is dependent upon the strength and deformation modulus of the rock mass, the *in situ* rock stress, the room geometry and orientation, and the excavation method. An important element of the design of seals in a repository will be their ability to cut off potential advective pathways along the EDZ.

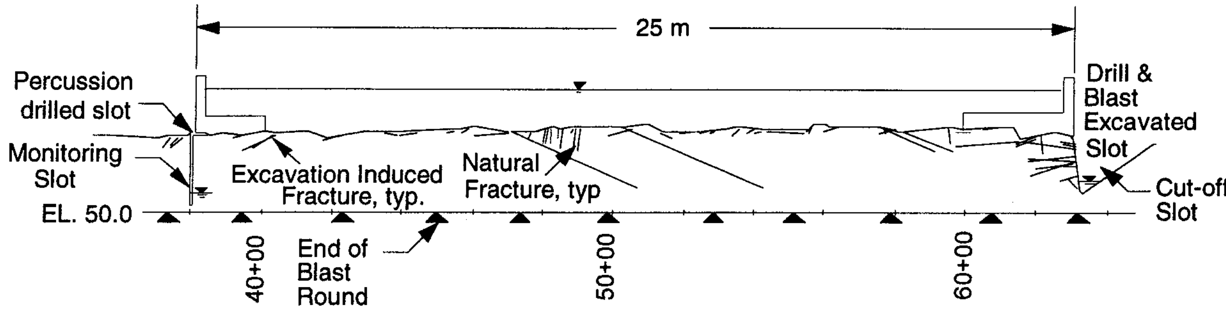

Figure 1: Arrangement of the Room 209 Connected permeability Test

There is a concern that an EDZ might provide a pathway by which contaminants could bypass one of the engineered barriers or the natural barrier of lower permeability rock. Although the EDZ will not extend significantly beyond the surface of the excavation, a small zone of enhanced hydraulic conductivity will likely exist along the length of each individual room. Unless the damaged zone intersects a high permeability pathway, or fracture, the contaminant transport mechanism from the EDZ to the rock mass will be by diffusion in the absence of large hydraulic gradients. To minimize the potential for bypassing the engineered barriers, room bulkheads would be required to cut-off the EDZ either by excavating through it (i.e. by keying a bulkhead into undamaged rock) or by injecting the EDZ with low permeability grout.

2 THE CONNECTED PERMEABILITY EXPERIMENTS

Two connected permeability experiments were carried out to evaluate the hydraulic properties of the EDZ in the floor of excavations at the URL. The Room 209 Connected Permeability Experiment [1] was carried out in a drill-and-blast excavated tunnel on the 240 Level, while the Mine-by Connected Permeability Experiment was conducted in a mechanically excavated tunnel on the 420 Level. In each experiment, a concrete dam was constructed to create a reservoir from which water flowed into the EDZ, under the dam, and into a collection system on the downstream side (Figure 1). Incrementally increasing the length of the dam and repeating the test allowed the evaluation of the connectivity of the hydraulically conductive flow path.

2.1 Room 209

The Room 209 experiment was conducted on the 240 Level of the URL. At this depth, the rock mass around the excavations responds essentially as an elastic material to variations in rock stress, hence on this level, the EDZ is a result of drill-and-blast excavation and not stress redistribution. Room 209 was excavated using the drill-and-blast technique employing a pilot-and-slash method (Figure 2). The primary purpose of the pilot-and-slash design was primarily to reduce the blast induced damage in the roof and walls of the room, but as in normal excavation methods, no special precautions were taken to control the damage in the floor. One method used at the URL to quantify the blast induced damage is the measurement of the length of the visible perimeter blast hole traces observed on the excavation profile. This blast hole trace index typically ranges from 60 to 70% on the walls and crown of the excavation but is 0% for the floor of excavations on the 240 Level, indicating more extensive damage in the floor due to blast design. The greater potential for blast induced damage in the floor of Room 209 is evident from the comparison of the powder factors for

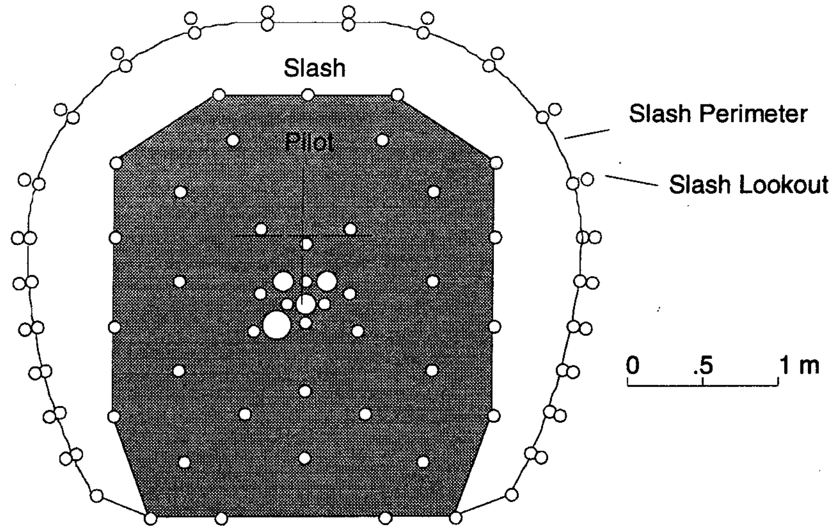

Figure 2: Typical blast pattern used for the Room 209 pilot-and-slash excavation.

the pilot (3.15 kg/m^3), which included the floor of the room, with the powder factor for the slash (1.55 kg/m^3).

Mapping of the excavations on the 240 Level indicates the presence of both natural and excavation-induced fractures. The excavation induced fractures are distinguished from the natural fractures by their lack of mineralization, and are predominantly skin-like features which form sub-parallel to the tunnel axis regardless of tunnel direction. It is these fractures which are thought to enhance the axial permeability around excavations.

The objective of the connected permeability experiment was to quantify the connectivity of the excavation-induced fractures in the axial direction of the tunnel. The arrangement of the test is shown in Figures 1 and 3. The test set-up consisted of a reservoir between a pair of concrete dams and a monitoring slot formed by line-drilling overlapping boreholes. The resulting slot was 2-m deep and 130 mm in width.

The concrete dam adjacent to the monitoring slot was initially 2 m long and confined within the boundaries of a single blast round. The rock beneath the concrete was scaled to remove "loose and drummy" pieces, and 25-mm-diameter bentonite strips were placed across the floor of the room to provide a seal against seepage directly along the concrete-rock interface. The same procedure of scaling and applying bentonite strips at the interface was used for construction of a second 2-m-long concrete slab. The second concrete slab spanned portions of two adjacent blast rounds. Considerably more "loose" material was removed from the 2 m of rock below the second dam, however it is likely that this increased loosening of the damaged zone is related to the extended presence of water during the first test.

Initially the water level between the two dams was raised to the level of the overflow pipe. It was obvious from the preliminary results that water was finding short-cuts through the excavation walls above the 0.5-m thick concrete pad down into the EDZ in the floor of the room. An appropriate comparison of the flow was only obtained from tests conducted with the water level at the elevation of the top of the concrete pad, approximately 0.5 m of head.

A plot of the measured flow versus time is shown in Figure 3 for the tests in which the pad lengths were 2.0 (Test 2) and 4.0 m (Test 4). The flow decayed slightly with time in the first test, presumably

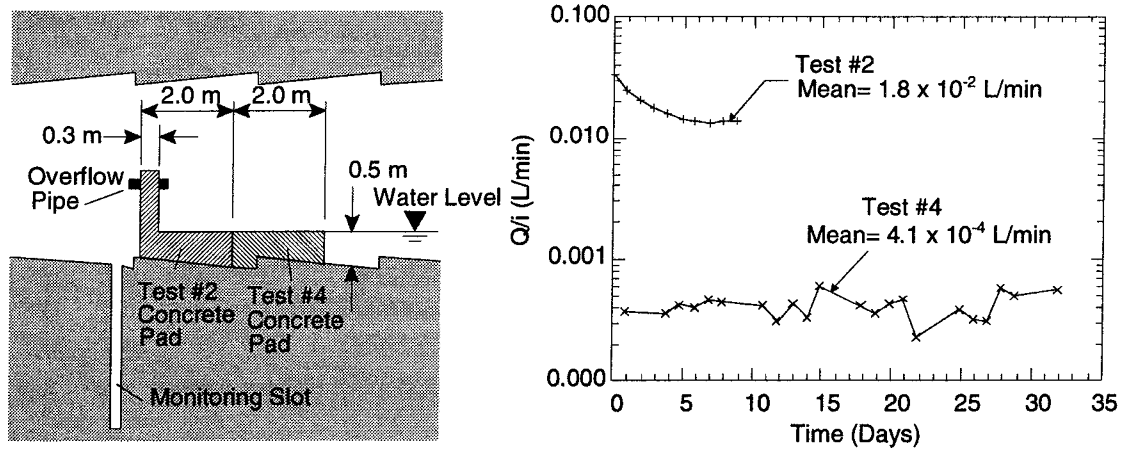

Figure 3: Arrangement of the Room 209 experiment and summary of the test results. The flow has been divided by the gradient assuming all flow is along the room axis.

as the bentonite strips took on water and created an effective interface seal. Comparison of the results from the two tests shows that simply increasing the seepage path length to span the end of a blast round decreased the flow by 98%. This suggests that there is very little hydraulic connectivity along the excavation-induced fractures in adjacent blast rounds.

After completion of the flow tests, boreholes were drilled into the rock floor and hydraulic pressure pulse tests were conducted in 100-mm-long packer isolated intervals, to determine the depth of the EDZ. Below approximately 0.3 m, the hydraulic conductivity of the rock was in the range of 10^{-13} to 10^{-14} m/s which is consistent with the hydraulic conductivity of intact rock measured elsewhere on the 240 Level. At depths less than 0.3 m the hydraulic conductivity increased by 1 or 2 orders of magnitude. A depth of 0.3 to 0.4 m of blast-induced damage in the floor of excavations on the 240 Level is consistent with measurements and observations in experiments in other locations [2]. An estimate of the apparent connected hydraulic conductivity of the rock in the floor of Room 209 can be estimated by dividing the measured flow from the 4.0 m test by the gradient and the cross-sectional area of the damaged zone. Assuming approximately a 2 m width and a 0.3 m depth of the EDZ (a 0.6 m^2 area) the apparent hydraulic conductivity of the EDZ is 10^{-8} m/s. Although this calculation is based on flows which are just barely measurable and is sensitive to assumptions of background or interface flow, it does imply that blasting can create a limited EDZ with a hydraulic conductivity orders of magnitude greater than that of the undamaged rock.

2.2 The Mine-by Experiment

On the 240 Level, stress-induced damage is almost non-existent. Hence, connected pathways resulting from blast-induced damage can be evaluated. On the 420 Level, where horizontal *in situ* stresses are much higher, the Mine-by tunnel was excavated without explosives, thus eliminating blast-induced damage. However, the geometry and orientation of the excavation (circular and perpendicular to the maximum principal *in situ* stress) was chosen to produce a measurable amount of stress-induced EDZ.

The Mine-by connected permeability test was carried out in the last 12 m of the test tunnel for the Mine-by Experiment [3]. The test tunnel was constructed using a mechanical excavation technique. In the technique used, pilot holes were drilled around the tunnel perimeter at a set spacing, then

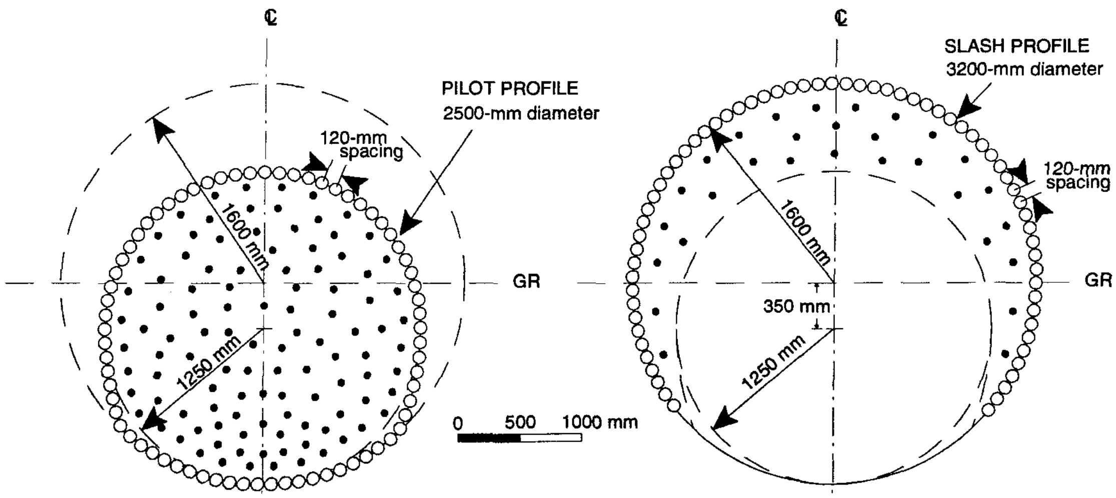

Figure 4: Design of the perimeter and hydraulic splitter boreholes for pilot and slash rounds of the Mine-by Tunnel

the boreholes were reamed with a larger diameter drill, effectively connecting adjacent boreholes. The interior rock stub was broken apart using hydraulic rock splitters inserted into pre-drilled boreholes. The Connected Permeability Test occupies the portion of the Mine-by tunnel which was excavated using a pilot-and-slash design. The pilot tunnel was 2.5 m in diameter with the rounds being 1.0 m in length (Figure 4, [4]). The slash rounds were 3.5 m in diameter and 1.5 m in length. The design elevation of the floor of both the pilot and slash rounds was the same. Instead of a monitoring slot, as constructed in the Room 209 test, an observation trench was excavated using the same line-drilling and hydraulic rock splitting technique employed in tunnel construction. The observation trench was sufficiently large to allow visual observation and photography of the EDZ below the floor of the Mine-by test tunnel, and to facilitate the use of a number of flow collection troughs on the face of the observation trench.

The face of the observation trench and the floor of the reservoir was predominantly in granodior-

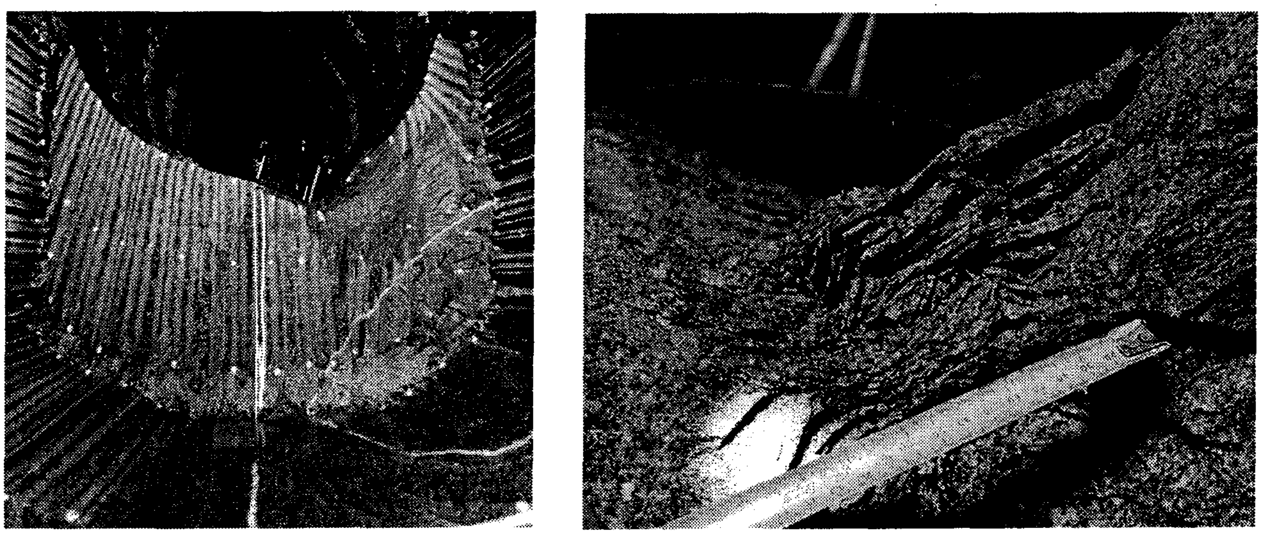

Figure 5: The face of the Mine-by Connected Permeability Experiment observation slot (left) and a close-up view of the "process" zone at the notch tip (right)

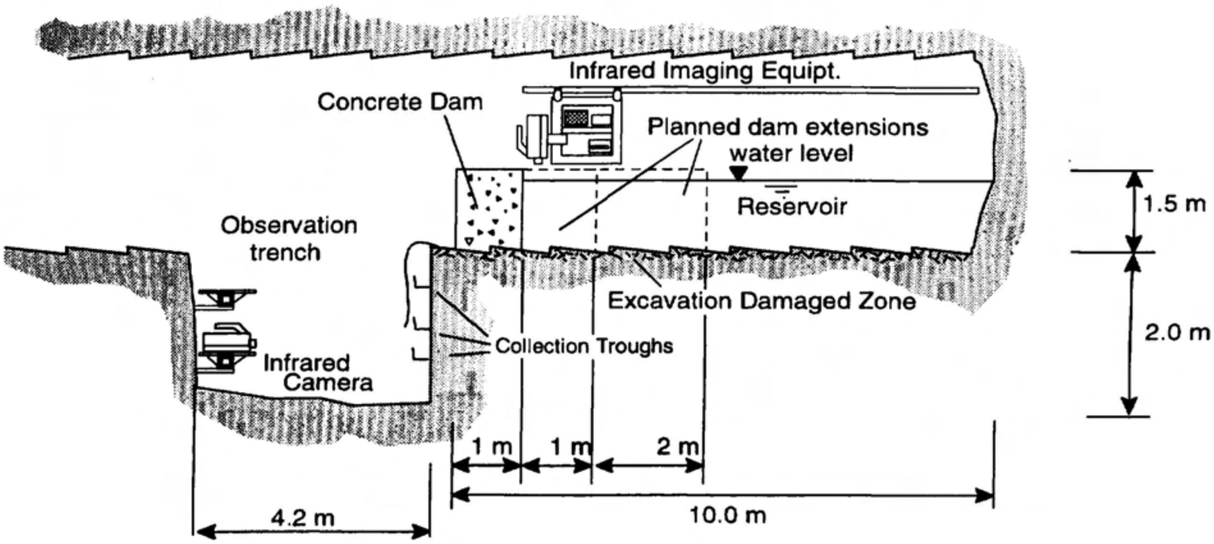

Figure 6: Configuration of the Mine-by Connected Permeability Experiment

ite [5]. Although the extent of breakout in the granodiorite is visibly less than that in grey granite, the breakout still existed, and a "process" zone of intense cracking was evident to a depth of 20 cm below the stable tip of the notch that formed (Figure 5). The tip of the breakout notch was roughly 30 cm below the design elevation of the floor of the tunnel.

A survey carried out using infrared photography revealed fractures in the floor that formed slabs of rock of varying thicknesses up to about 2 cm. These slabs were generally connected to the rock floor but when tapped with a hammer produced "drummy" or hollow sounds. During construction of the concrete dams, the "process" zone and rock slabs were not disturbed. Only pieces of "loose" (rock pieces no longer attached to the rock mass) were removed prior to the concrete pour.

Three concrete dams were poured (Figure 6). The first dam was 1.0 m in length and approximately 1.5 m in height at its deepest point. As with the Room 209 tests, bentonite strips were placed across the floor to prevent flow of water along the interface between the concrete and the rock. The concrete dam was subsequently extended to create total path lengths of 2.0 and 4.0 m. A path length of 3.0 m was obtained after removal of the first 1.0-m-long dam. The geometry of the concrete dams allowed the reservoir to be filled up to the elevation of the overflow pipe without creating potential short-cuts for water flow.

Plots of measured flow as a function of time divided by the hydraulic gradient for path lengths of 1 to 4 m is shown in Figure 7. For the 1- and 2-m-long path lengths, the plots show a gradual decrease in flow as the bentonite strips take on water and form an effective interface seal. Presumably in the 3 and 4 m tests, the interface flow has been cut off by the strips. Almost all the flow through the EDZ was collected in the trough just below the process zone at the notch tip. The spike in the data from the 1 m test at approximately 50 days was the result of emptying and refilling the reservoir. The location of flow was also apparent from visible evidence of precipitation of dissolved materials on the face of the observation trench. When the path length was only 1.0 m long a small component of the flow occurred underneath the thin slabs in the notch area. The greatest component of the flow in the 1 m test, and all the flow in the remaining tests, occurred through the process zone below the notch tip. Increasing the length of the dam to 4 m did not appreciably affect the flow suggesting that the process zone forms a connected pathway of high permeability along the length

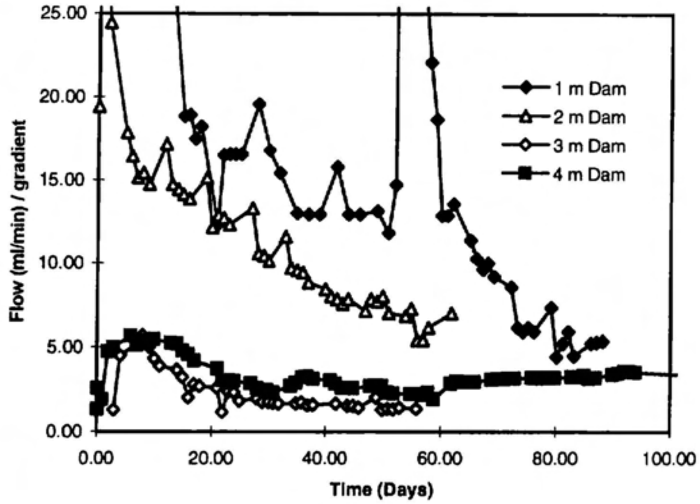

Figure 7: Flow divided by gradient versus time for the 4 stages of the Mine-by Connected Permeability Experiment

of the Mine-by test tunnel. The data from all four tests appear to converge on the same value for flow divided by the hydraulic gradient (approximately 5 ml/min). This value divided by the cross-sectional area of the process zone (approximately 0.05 m^2) provides a hydraulic conductivity of the process zone of about 10^{-6} m/s.

2.3 Summary of Experiments

The two connected permeability experiments provide information on the depths of stress-induced and blast-induced damage adjacent to excavations in intact rock. They also provide an apparent hydraulic conductivity for both types of damage.

Blast-induced damage beneath the floor of excavations on the 240 Level is less than 0.4 m in depth, which represents about 30% of an average tunnel radius (approximately 15% of the volume of excavated material). Damage in the walls has been observed to be even less as a result of controlled blasting methods. The apparent hydraulic conductivity of blast damage is discontinuous and decreases if the flow of water is required to cross from one blast round to the next. The Room 209 connected permeability test results suggest that the connected hydraulic conductivity is still orders of magnitude greater than that for intact rock. Pulse tests in the floor of the room also suggest that the hydraulic conductivity of the blast-induced damaged zone may be increased by two to three orders of magnitude.

In the Mine-by test, the volume of rock having stress-induced damage in which hydraulic conductivity was greatly enhanced is only about 1% of the volume of excavated material. However this zone, referred to here as the process zone, is very highly fractured material having a hydraulic conductivity which is 6 or 7 orders of magnitude greater than that of the intact rock. Although small in area, this zone is continuous and traverses the length of the Mine-by test tunnel.

There are a number of implications from the results of these experiments with respect to sealing of the EDZ. Blast-induced damage can be greatly reduced by controlled-blasting methods. Blast damage somewhat enhances the hydraulic conductivity of rock around a tunnel, but only to depths

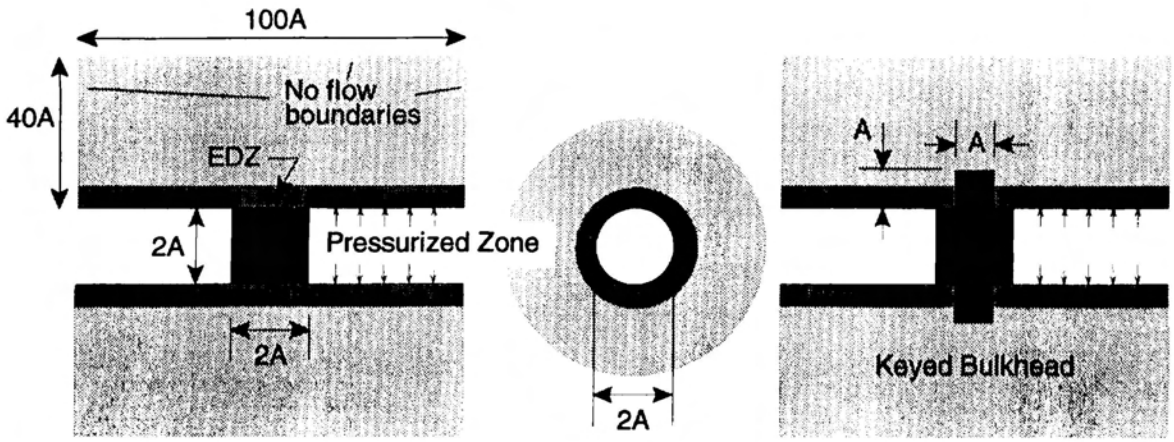

Figure 8: Configuration of the FLAC model used for flow calculations around bulkheads with (left) and without (right) an EDZ cut-off.

of about 0.4 m. Seals in drill-and-blast tunnels should span at least one adjacent blast round. If a process zone is formed as a result of stress-induced damage then this zone must either be cut-off or grouted as part of the construction of an excavation bulkhead.

3 A SIMPLE NUMERICAL MODEL

A numerical model of a single seal in a cylindrical tunnel was constructed to assess the relative effects of the size and hydraulic conductivity of the damaged zone (Figure 8). A single bulkhead which created an impermeable boundary between pressurized and unpressurized regions of the tunnel was modeled. The bulkhead width was equal to the tunnel diameter. The depth of the EDZ ranged from 0 to 100% of the radius of the tunnel, with the volume of the damaged rock, therefore, varying between 0 and 3 times the volume of the excavation. The hydraulic conductivity of the EDZ is normalized with respect to the hydraulic conductivity of the undamaged rock, and this ratio spans five orders of magnitude from 10 to 100,000.

FLAC[1] was used to perform the modeling, however, the results should be similar regardless of the software used. Flow into the tunnel from the "upstream" segment of the tunnel was calculated and compared to the flow out of the rock into the unpressurized "downstream" segment (Figure 8). The flow into the model was required to be approximately equal to the flow out to meet the requirements for steady flow. No flow through the bulkhead or along the bulkhead/rock interface was allowed. In presenting the results of the model, flow through the combination of damaged and undamaged rock was normalized with respect to flow through the model which had no damage. This means that normalized flows near 1.0 suggested very little increased flow due to the existence of the EDZ whereas flows of 10 or 100 represent flow increased by one or two orders of magnitude respectively.

A second set of models evaluated the effectiveness of an impermeable EDZ cut-off. A radial slot was excavated into the rock a distance equal to one tunnel radius, sufficient to cut off the EDZ in all simulations, and therefore a portion of the flow path would always include undamaged rock. Another set of tests examined the effect of doubling the length of a bulkhead with no EDZ cut-off.

The results are shown in Figure 9. The normalized damaged zone volume plotted on the horizontal

[1] Fast Lagrangian Analysis of Continua, Itasca Consulting Inc., Minneapolis

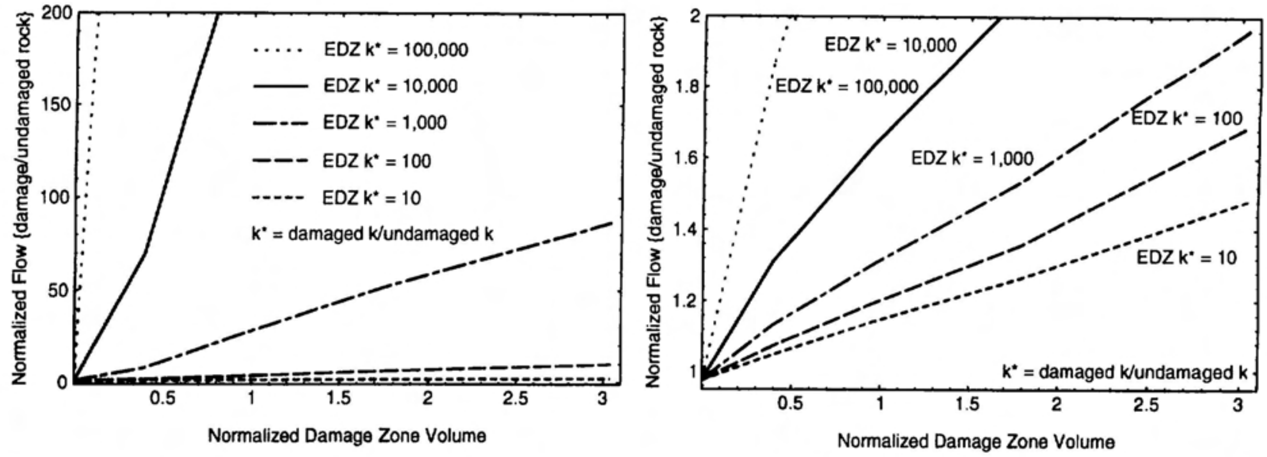

Figure 9: Plots of calculated flow around a tunnel seal from a numerical simulation plotted against EDZ volume divided by the excavation volume. The figure on the right shows the same model with an impermeable EDZ cut-off.

axis is the volume of the damaged zone divided by the volume of the excavated tunnel. Note that for a tunnel where the damaged volume extends to a depth equal to 30% of the tunnel radius, as observed at the URL, the normalized volume is 0.7. Since the calculated flow is normalized with respect to the flow through undamaged rock under the same pressure, the effect of pressure on flow disappears from the FLAC calculation. An interesting observation is that if no action is taken to reduce flow along the EDZ, there is still relatively little additional flow if the hydraulic conductivity is within two orders of magnitude of that of the intact rock. The EDZ must be at least three orders of magnitude greater in hydraulic conductivity before the flow is increased by at least one order of magnitude. Four order magnitude increases in the hydraulic conductivity of the EDZ represent cases in which the effect of the damaged zone would have to be minimized, either by excavating a cut-off or by injecting low permeability grout or both.

It should be noted that very high EDZ hydraulic conductivities, such as those measured in the Mine-by test tunnel process zone, would generally occur over very small volumes (in the Mine-by test tunnel the normalized volume is 0.01). Smaller increases in hydraulic conductivity are produced by blasting. The normalized volume from the uncontrolled blasting in the floor of Room 209 would be 0.7. In a moderately fractured rock mass, slippage along existing fractures may increase the axial hydraulic conductivity of the rock mass over even larger volumes (this effect has been predicted by some to extend to one tunnel radius, which represents a normalized volume of 3). However, the increase in hydraulic conductivity over this rock volume will probably be less than the two-orders of magnitude increase measured by pulse tests in blast-damaged rock.

The model was also run with a doubled bulkhead length and no cut-off. The result was to reduce the flow by 57% when the ratio of damaged to undamaged hydraulic conductivity was 10, and by 50% for all higher values of EDZ hydraulic conductivity. This simulation suggests that the only effect of doubling the bulkhead length is to cut the hydraulic gradient, and hence the flow, by one-half.

The effect of an impermeable cut-off is the most dramatic. In most simulations flow through the combined damaged and undamaged rock was not greater than twice the flow through undamaged rock with no cut-off. A five order-of magnitude increase in hydraulic conductivity in a volume of rock equal to the volume of the excavation, still only resulted in a three-fold increase in flow. It is recognized that the ability of the cut-off to minimize flow is greatly dependent upon the cut-off design and the conductivity of the cut-off fill material. However, this modeling still suggests that an excavated cut-off will be an effective means of sealing an excavation.

4 SUMMARY

Two connected permeability experiments have been conducted at the URL. The Room 209 test examined the flow through an excavation damaged zone created in the floor by the effects of drilling and blasting. A second test was conducted in the more highly stressed region of the Mine-by Experiment test tunnel which was excavated without blasting. These two experiments allowed the comparison of flows through a blast-induced EDZ to flows through a stress-induced EDZ. In the Room 209 test, 98% of the flow was eliminated by forcing the fluid pathway to span adjacent blast rounds. However, it was still evident that an EDZ existed to depths as great as 30 to 40 cm in the floor and that the EDZ may have a hydraulic conductivity at least two orders of magnitude greater than that of the intact rock.

In tunnels in the URL, the EDZ induced by stress will not significantly affect the potential for flow along the axis of a sealed tunnel unless the stresses are sufficient to cause the formation of a process zone. In the Mine-by tunnel, this process zone covers an area of only 1% of the total excavated volume, however it is composed of very highly fractured rock. The hydraulic conductivity of this zone is 6 or 7 orders of magnitude greater than that of the intact rock.

Numerical modeling of a bulkhead seal in a cylindrical tunnel, suggests the EDZ must be at least three orders of magnitude more conductive than the undamaged rock before it presents a potential for greatly enhancing the flow around seals. It also suggests that construction of a well-designed EDZ cut-off will serve to prevent excessive flows from by-passing the tunnel seals.

Acknowledgement: The experimental program at the Underground Research Laboratory is jointly funded by AECL and Ontario Hydro under the auspices of the CANDU Owners Group. The Mine-by Connected Permeability Experiment was partially funded by the Agence nationale pour la gestion des déchets radioactifs (ANDRA, France). Thanks are extended to Patrick Lebon of ANDRA for his contributions to this experiment.

REFERENCES

[1] C. D. Martin and E. T. Kozak. Flow measurements in the excavation-disturbed zone of room 209. In J. A. Hudson, editor, *Proc. of Int. ISRM Symp. on Rock Characterization*, pages 402–407, Chester, 1992. London: Thomas Telford Services Ltd.

[2] C. D. Martin, E. T. Kozak, and N. A. Chandler. Hydraulic properties of the excavation-disturbed zone around underground openings. In *Proc. 45th Can. Geotech. Conf.*, pages 89:1–10, Toronto, 1992.

[3] R. S. Read and C. D. Martin. Technical summary of AECL's Mine-by Experiment, Phase 1: Excavation response. AECL Report AECL-11311, Atomic Energy of Canada Limited†, 1996.

[4] S. G. Keith and D. P. Onagi. Mine-by Experiment data summary: Part 8 - Construction summary. Protected-Proprietary Report COG-93-252, Atomic Energy of Canada Limited, 1994.

[5] P. Gann and R. A. Everitt. Geology of the Mine-by Experiment connected permeability phase floor slot. Protected-Proprietary RC-1080-2, Atomic Energy of Canada Limited, 1994.

† Available from SDDO, AECL, Chalk River, Ontario, K0J 1J0