ACOUSTIC REMOTE MONITORING OF ROCK AND CONCRETE STRUCTURES FOR NUCLEAR WASTE REPOSITORIES

R.P. Young
Applied Seismology Laboratory,
Department of Earth Sciences,
University of Liverpool, United Kingdom

Abstract

Excavation and thermally induced damage is of significance for many types of engineering structures but no more so than in the case of nuclear waste repository design. My research and that of my group, formally at Queen's University Canada and Keele University UK and now at the University of Liverpool UK, has focused on the development of acoustic techniques for the *in situ* detection and quantification of induced damage and fracturing. The application of earthquake seismology to this problem has provided the opportunity to study the micro mechanics of damage mechanisms in situ and provide validation data for predictive geomechanical models used for engineering design. Since 1987 I have been a principal investigator at Atomic Energy of Canada's Underground Research Laboratory (URL), responsible for the development of acoustic emission techniques (AE). In the last twelve years, the application of acoustic techniques to rock damage assessment has been pioneered by my group at the URL and successfully applied in several other major international projects including the ZEDEX, Retrieval and Prototype repository experiments at the Aspo Hard Rock Laboratory (HRL) of SKB Sweden. In this paper I describe what information is available by remote acoustic monitoring of rock and concrete structures and demonstrate this with reference to two international scientific experiments carried out at the URL Canada and the HRL Sweden.

1. INTRODUCTION

The principles employed in the acoustic detection of damage in rock and concrete are closely related to those employed by seismologists to study earthquake mechanics and the internal structure of the Earth. At the scales generally associated with civil engineering projects, acoustic methods can be broadly split into two categories, depending on the frequencies of the sound waves considered. Microseismic (MS) systems monitor energy in the 0.1–10 kHz band and are suitable for monitoring large volumes of rock ($\leq 1 \times 10^7$ m^3), around a mine or tunnel complex. Acoustic emission (AE) systems record higher frequencies (30–250 kHz or greater) and are used for high resolution monitoring of smaller volumes of rock or specific concrete structures (volumes between 1m^3 and 1×10^4 m^3).

Acoustic methods are particularly suited to the monitoring of rock and concrete associated with civil engineering structures, as they are relatively non-invasive and, once installed, can monitor for extended time periods with little or no user intervention. In most cases a volume can be monitored by an array of sensors inserted in a few narrow boreholes, attached to the surface of the structure, or, in the case of concrete, embedded in the structure when it is cast. Once installed the same instrumentation can be used for both passive monitoring (listening for acoustic emissions) and active monitoring (measuring the rock properties using ultrasonic pulses or artificial shots). Data from these sensor systems are recorded as waveforms from which a wealth of information can be derived. Ultrasonic monitoring has been shown to be an effective tool for observing induced fracturing and the response of a medium to applied stresses. Falls and Young (1998) give a review of acoustic emission and ultrasonic velocity results from a number of excavation experiments conducted in different underground environments.

2. WHAT INFORMATION CAN AE STUDIES PROVIDE?

Acoustic monitoring can tell us much about the behaviour of a volume of rock or concrete over time. In particular, these methods are ideal for the delineation and characterisation of damage. Such damage may occur as the result of, for example, stress field changes or material degradation. In many early investigations, AE studies were used in laboratory rock mechanical experiments, and the number of AE 'events' was used as a simple measure of damage within the sample. More recently these techniques have become more sophisticated and considerable information can now be obtained in both laboratory and in situ studies. Acoustic methods can be used to:

- ***Say where damage is taking place.*** Using the arrival times of the seismic phases, the AE/MS events can be located within the rock with great accuracy.
- ***Assess the extent of the damage.*** The location of events and the event rate can be used to assess the areas within a material where the most damage is occurring. The velocity of seismic waves within the material (derived from passive seismic tomography) can also be used to assess areas of damage as, in general, regions of high damage will show lower velocities when compared to those from intact material.
- ***Determine information on the damage mechanism.*** The shape of the waveforms recorded at each sensor is a function of the source mechanism and the path effects experienced by the acoustic energy as it travels from the source to the receiver. From these data it is therefore possible to derive information about the orientation and mechanism (e.g. shear, isotropic) of the failure.
- *Derive information relating to the stress field.* Studies have indicated a relationship between zones with high velocity anomalies and regions of higher stress and, therefore, increased damage potential. These may be identified by passive tomographic imaging and used in conjunction with stress models derived from numerical modelling and/or in situ measurements. In addition, the orientation of the principal stresses acting at the source of the acoustic activity can be interpreted from waveform processing of the AE/MS activity.
- ***Determine material properties of the volume.*** As energy travels through rock, concrete or other materials the frequency and amplitude are affected by the material properties. Measurements of seismic velocity, anisotropy and attenuation are therefore sensitive to changes in these material properties.
- ***Assess the time-dependent behaviour of the material in response to engineering activities.*** The response of the material may vary with time in response to excavation or other engineering activities. The ability of acoustic methods to monitor in a continuous and passive manner is one of their greatest assets.

3. APPLICATION OF ACOUSTIC TECHNIQUES FOR MONITORING ENGINEERING STRUCTURES

The techniques described above offer a powerful tool for non-destructive evaluation in an engineering environment. The methodology for these techniques has been verified in a number of important experiments. Several of these are associated with developing technology suitable for the long term storage of nuclear waste in sub-surface repositories. As part of such studies a number of underground research facilities have been built, in which experiments to study their behaviour are on going. At these facilities delineating zones of damage associated with tunnel excavation (i.e. the Excavation Disturbed Zone) is very important for determining the hydrogeological properties of the rock. This technology has been very important in developing an understanding of the relationship between the in situ stresses, the excavation method and the long term behaviour of the rock mass. AE technology has also been used to investigate the long term behaviour of a rock mass undergoing loading due to thermal stresses.

Case study 1: The Tunnel Sealing Experiment at the Underground Research Laboratory (URL) of Atomic Energy of Canada: The URL is situated within essentially homogeneous Lac du Bonnet granite, which is initially unfractured (below 240 m depth) before the excavation of tunnels. The results described here are taken from the Tunnel Sealing Experiment (TSX) located at a depth of 420 m in the URL. The objective of the TSX is to study the problems associated with the construction, sealing and pressurisation of a tunnel to pore pressure (see Young and Collins, 1999). The TSX tunnel is elliptical in shape (4.4 m × 3.5 m) and is oriented in the direction of the principal stress. The maximum stress concentrations from elastic modelling are 105 MPa in the roof and floor, with –0.5 MPa in the sidewalls. Induced seismicity and AE associated with excavation damage has been used to investigate the mechanics of microcracking around the TSX. Fig. 1 shows a 3D view of the TSX tunnel, seals and AE monitoring boreholes. 10 triaxial accelerometers, operating in the 10 Hz to 10 kHz range, are used to monitor the largest induced seismicity at the URL (–1 moment magnitude). 24 ultrasonic transducers were positioned in boreholes around the clay seal volume and monitor very small-induced AE activity in the 50–250 kHz band. AE transducers were also placed within the concrete bulkhead.

The events are overlaid on the tunnel geometry and keys and the mean location error is 0.54 m, calculated by a calibration survey. Fig. 2a shows the events clustering around the new excavation rounds which occurred in Period 1 and also activity in the roof and floor of the region excavated. The events clearly cluster within an approximate 0–2 m shell around each new excavation round, including the region ahead of each blast round. The concentration of activity in the roof and floor are the regions where stress modelling shows the greatest predicted stress concentration and delineates the areas of breakout potential.

During Period 2, approximately 500 events are recorded over the length of the tunnel mainly in the roof and floor regions (Fig. 2b). This seismic response indicates that slight stress changes are occurring along the tunnel over this approximately 2.5–month period, even though excavation is not taking place in the immediate vicinity. These stress changes and the resulting microseismicity may be resulting from activities such as time-dependant deformation and/or triggered seismicity from adjacent experimental excavations. Fig. 2c shows a significant MS response during the excavation of the rectangular clay key slot. Part of the concrete key slot in the floor is also excavated during this Period and a number of events are recorded in this region. During Period 4, MS events mainly cluster around the newly excavated concrete key, but also a significant response occurs around the clay key and a couple of meters to the SE of the clay key where the steel restraint slot is being cut (Fig. 1 and 2d).

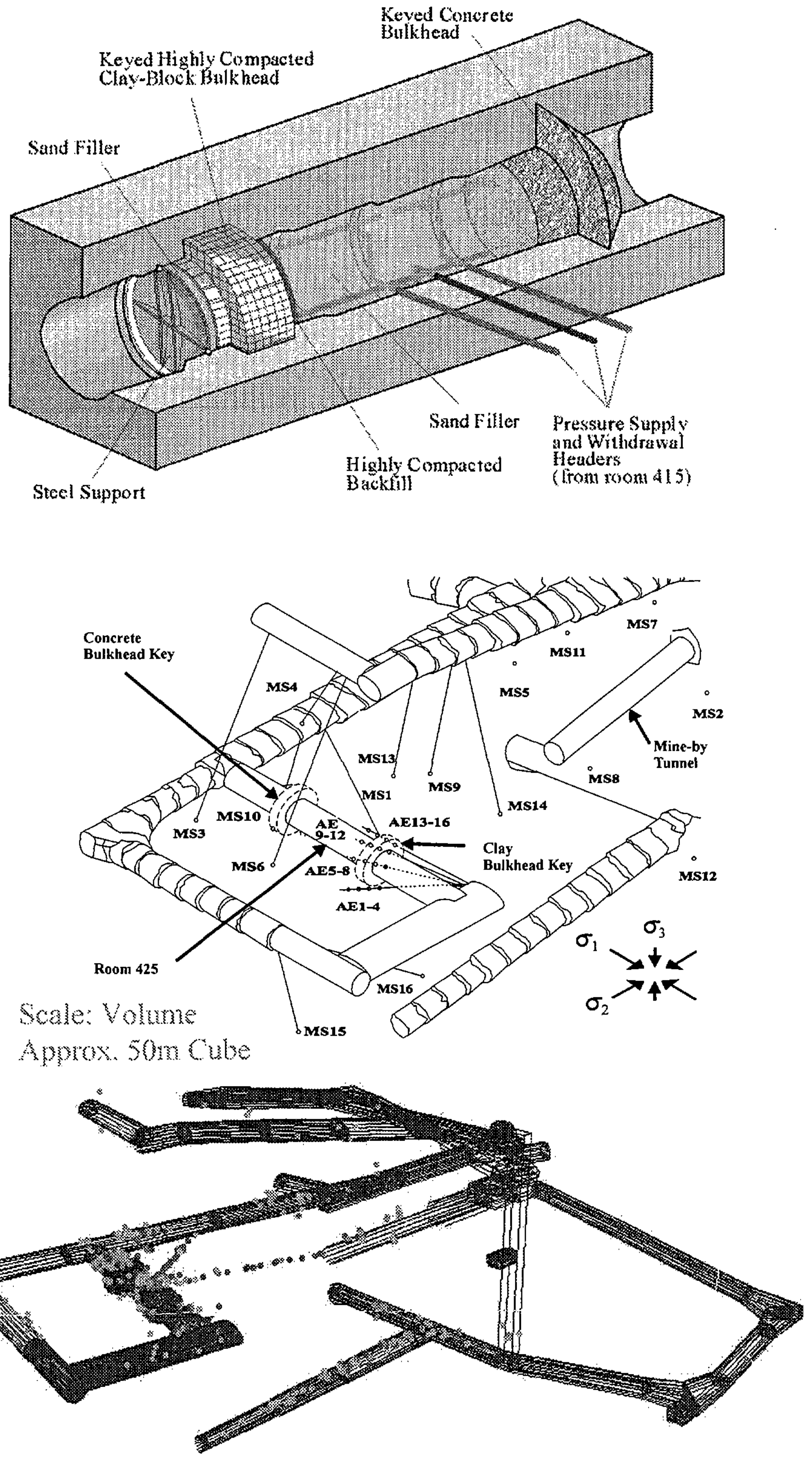
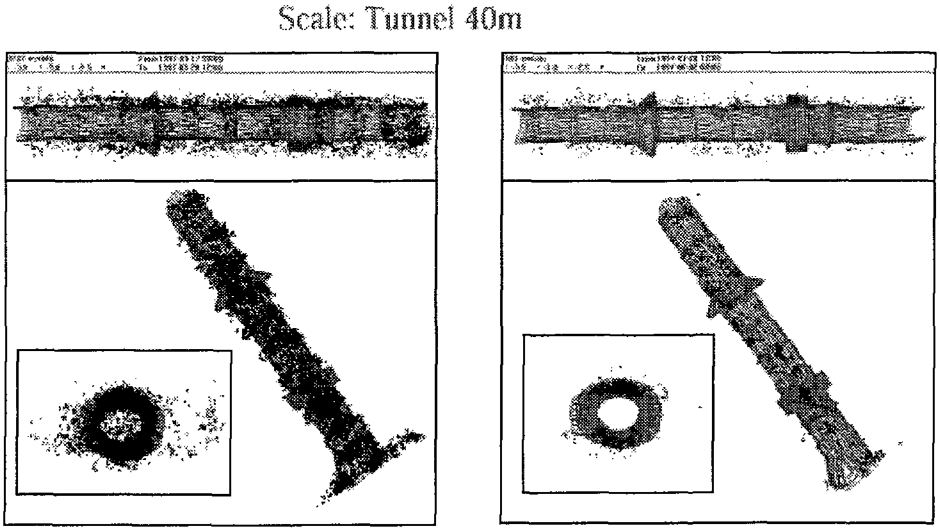


FIG. 1. The upper diagrams show the TSX tunnel, the two seal technologies, filler material and pressurisation boreholes. Also shown are the location of triaxial accelerometer boreholes around the TSX volume and the AE sensors in four boreholes surrounding the clay key. AE sensors were also placed within the concrete bulkhead to monitor long term curing of the concrete and rock/concrete seal integrity. The lower diagram shows some microseismicity aligned along pressurisation boreholes which highlights the resolution and sensitivity of the technique.

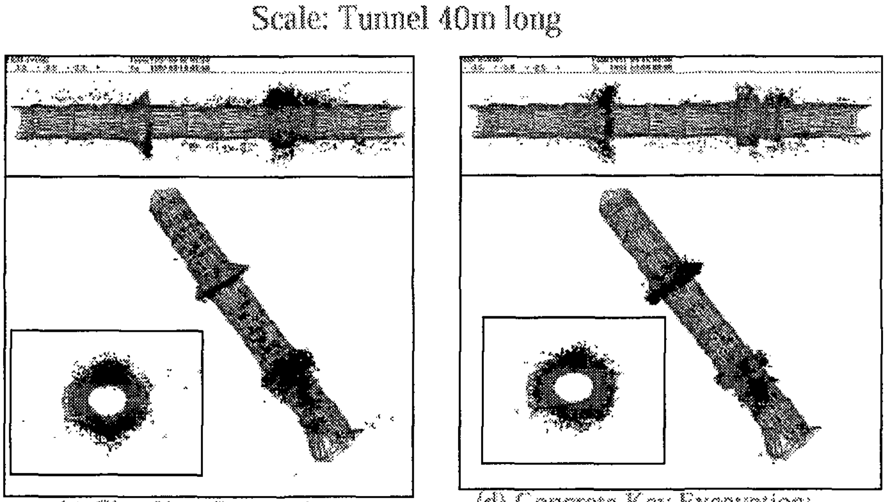
Figures 2a–d display the 6775 microseismicity (MS) events that occur in the vicinity of the TSX during the 4 periods of excavation activity (Table I).



(a) Tunnel Excavation: January-March, 1997

(b) Time-dependant response: April-June, 1997

FIGs 2a and 2b. Excavation induced microseismicity mapping the excavation-damaged zone around the TSX tunnel.



(c) Clay Key Excavation: June-September, 1997

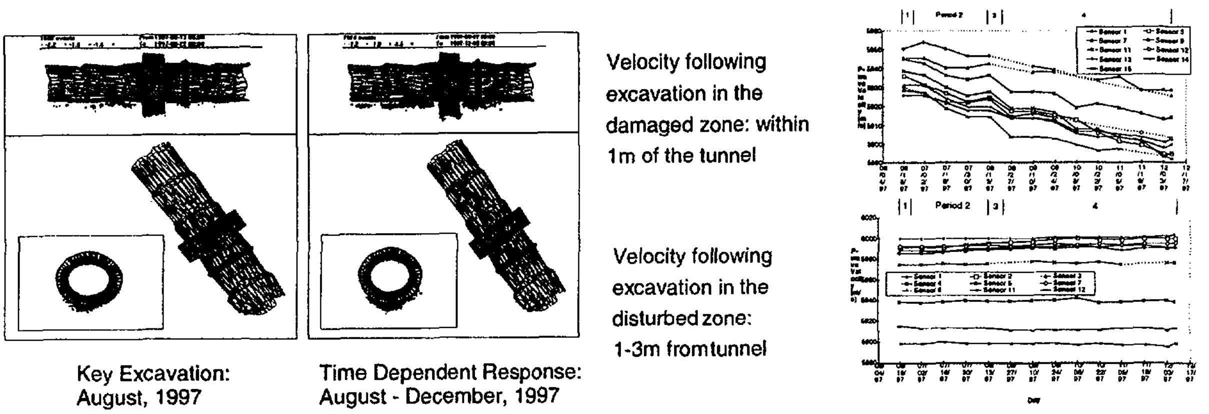
(d) Concrete Key Excavation: September-December, 1997

FIGs 2c and 2d. Excavation induced microseismicity mapping the excavation-damaged zone around the TSX tunnel.

TABLE I. ACTIVITIES DURING 4 PERIODS OF MS MONITORING

Date	Activity
Period 1: Jan 17 - Mar 20	Blast excavation of TSX tunnel (rounds 1-13)
Period 2: Mar 20 - Jun 2	No excavation in TSX tunnel
Period 3: Jun 2 - Sep 16	Part of concrete key excavated in floor. Complete clay key excavation.
Period 4: Sep 16 - Dec 9	Concrete key excavation. Excavate steel restraint slot.

Figure 3 shows the AE activity in the floor and walls of the TSX clay key, which was excavated for a bentonite bulkhead in August, 1997. The AE is only shown for the lower half of the tunnel where detailed monitoring was carried out. The calibrated mean location error of the AE events is 3.3 cm. The activity is concentrated in the modelled high stress regions in the floor of the tunnel and around the newly excavated key and along the boundary between the tunnel damaged zone and intact rock. The gap between the AE activity and the tunnel perimeter is because the induced AE from the key excavation is now activating the boundary between previously damaged rock from the tunnel excavation and intact rock. The time dependant response to the key excavation can be seen between August to December, 1997. In order to monitor the changes in elastic properties of the rock, the same AE sensors were used to pulse ultrasonic waves through the damaged zone, delineated by the excavation-induced AE.



Key Excavation: August, 1997

Time Dependent Response: August - December, 1997

Velocity following excavation in the damaged zone: within 1m of the tunnel

Velocity following excavation in the disturbed zone: 1-3m from tunnel

FIG. 3. AE activity and velocity change in the vicinity of the TSX clay seal.

Figure 3 also shows the change in P–wave velocity from June to December, 1997 in the seismically active zone within 1m of the tunnel perimeter and through the stress disturbed zone 1–3 m from the tunnel. By using cross-correlation/interferometry techniques, velocity change can be determined to an accuracy of between 1-3 m/s depending upon ray-path length. These data can therefore be used to monitor small excavation and stress induced changes in the rock volume. The graphs show ray paths, which pass in different orientations through the rock mass but each show consistent trends following excavation. In the damaged zone for the 5 months after excavation of the key the velocity reduces by 19–44 m/s dependant on ray path as the induced seismicity and damage continued. In the disturbed zone slight increases in P–

wave velocity are thought to be associated with preferential closure of microcracks in response to stress redistribution from the excavation. S–wave velocity measurements have been performed, with the results showing similar changes to P–wave data. This confirms that the velocity changes associated with the AE activity are primarily the result of microcracking rather than desaturation. The in situ AE and velocity data shows evidence for some time-dependant deformation in granite. This is consistent with a stress corrosion model proposed by Potyondy and Cundall (1998) using PFC for the modelling of notch development in the Mineby tunnel at the URL.

This technology has recently been applied to the study of the operational behaviour of the TSX concrete bulkhead. The methods have been successfully used to study:

- The curing process and its relationship to the material parameters of the concrete.
- The development of damage and the growth of macroscopic fractures. Using ultrasonic and AE methods the amount, location and orientation of fractures within a concrete bulkhead have been resolved.

Figure 4 shows an example of using ultrasonic methods to delineate and map the growth of a fracture in a concrete bulkhead. The acoustic emissions detected by an array of sensors embedded within the concrete are shown in 3 time intervals on 24 September, 1998. This allows us to identify the point of origin of the fracture and observe its development with time. The formation of this crack corresponded with a significant drop in pressure behind the bulkhead AE locations delineate a growing macroscopic fracture within the TSX concrete bulkhead. The P–wave velocity and amplitude variation for the ray path between pulser 4 and receiver 9 show initial increases during curing followed by rapid loss as the fracture grows. This ray path passes through the region of AE that occurred on 24 September, 1998, resulting in the large drop in AP, and no subsequent VP measurements. Subsequently the fracture was grouted and the AE and interferometer data used to determine if the fracture had been sealed. The data shows continuous VP measurements following grouting, and the AP value to have significantly increased, suggesting that the injected concrete grout has successfully filled in the connected microcracks along the ray path.

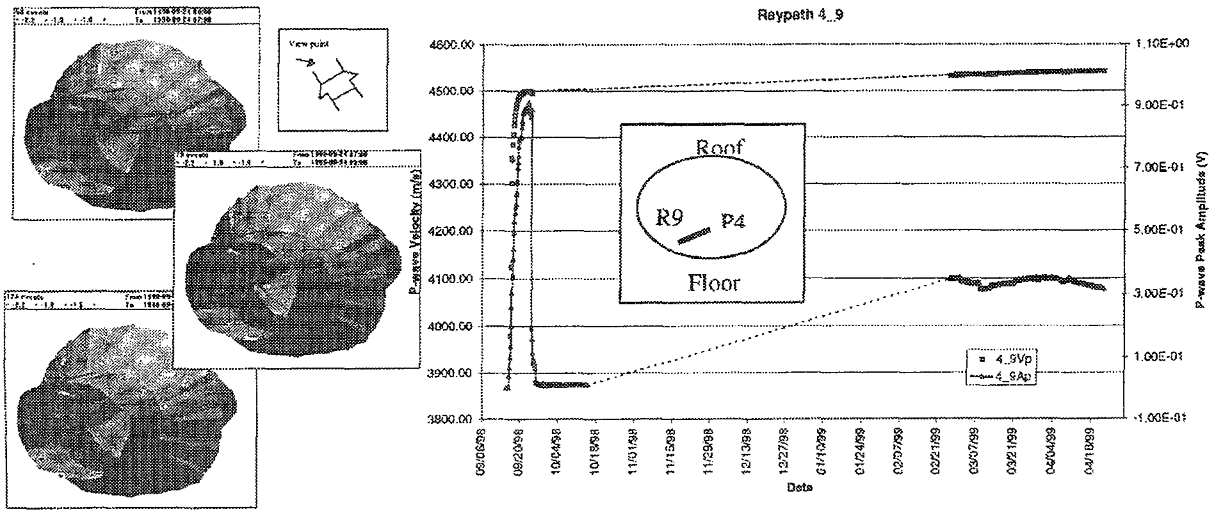


FIG. 4. AE data showing the delineation of a fracture during the curing of the concrete bulkhead. The velocity and amplitude interferometry data shows significant increases during curing. This is followed by signal loss during fracturing and the later data shows that the subsequent remedial grouting had filled the fracture and velocity and amplitude values recovered.

Case Study 2: Canister Retrieval Test (CRT) at the Aspo Laboratory, Sweden: The aim of the CRT is to illustrate that waste canisters can be safely retrieved from a repository underground environment. It is located at the 420 m level in SKB's Hard Rock Laboratory (HRL), Sweden (Fig. 5).

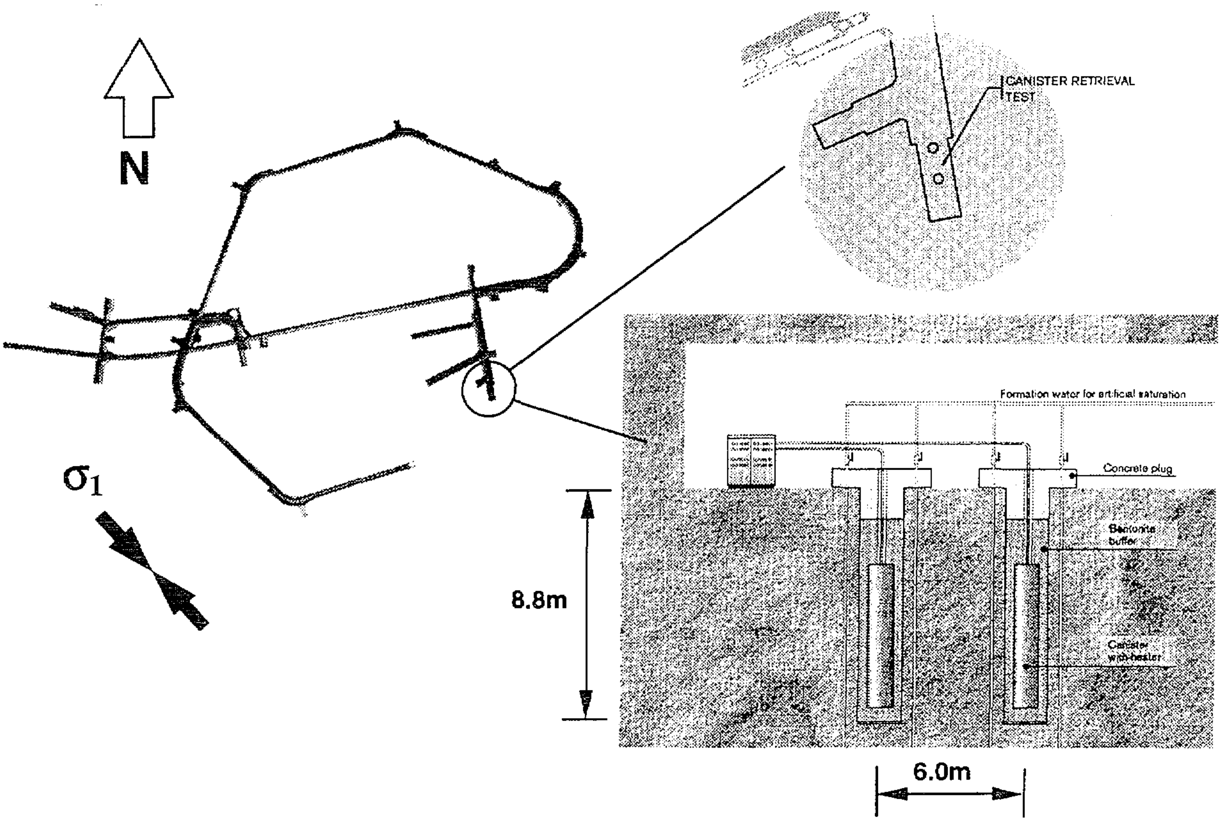


FIG. 5. Plan view of the experimental tunnels at the Äspö HRL and the location of the CRT. A schematic illustration of the final CRT experimental set up is shown with canisters and bentonite clay installed in the two 1.75 m diameter deposition holes (courtesy of SKB).

Two experimental deposition holes have been excavated in the Äspö granite as part of the CRT at the HRL, Sweden using a large diameter boring machine. The holes are 1.75 m in diameter and 8.8 m in length and were excavated in eleven 0.8 m rounds. An ultrasonic array was installed around each deposition hole to investigate the response of the rock mass to the excavation. Acoustic emission (AE) monitoring has been used to delineate zones of stress-related fracturing around the deposition hole perimeter. Changes in ultrasonic velocities, measured every hour, have been used to investigate the response of the rock mass over a broader time and volume than the AE scale, and to quantitatively measure the accumulation of fracturing in the damaged zone.

The AE results show regions of microfracturing located in clusters down the deposition hole wall (Fig. 6). These regions are orientated orthogonal to the maximum principal stress at the 420 m level. The damaged zone is restricted to approximately 20 cm from the deposition hole wall and activity decays rapidly within the first few hours after excavation. The clusters are probably a result of the interaction of induced stresses with excavation through pre-existing features. A linear macroscopic fracture is also imaged. AEs are strongly time-dependent with fracturing being reinitiated around previous rounds when excavation of the deposition hole continues. AEs occur at a much-reduced rate after completion of excavation. These effects are believed to be associated with stress redistribution in the pre-weakened regions.

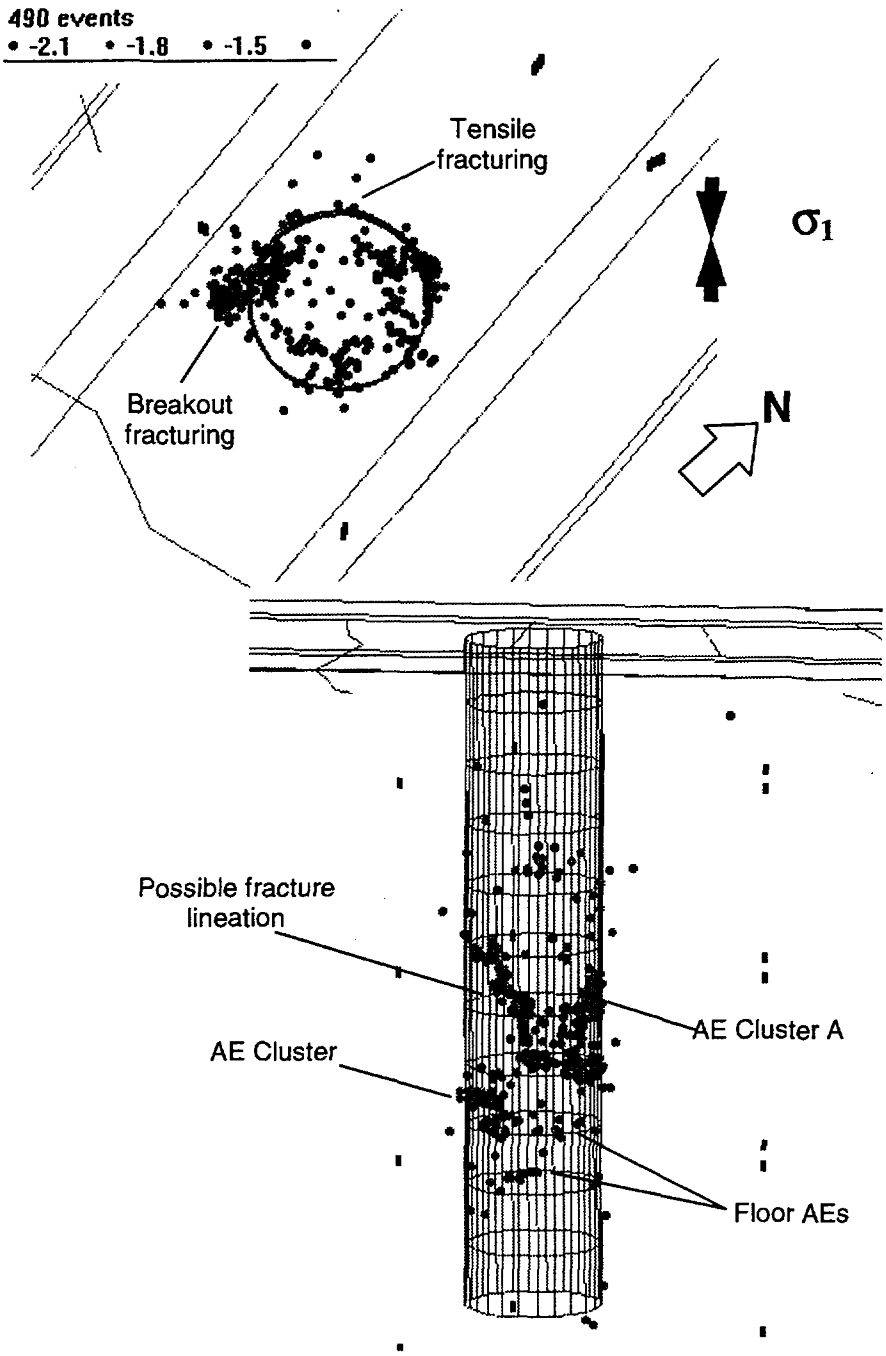


FIG. 6. AE locations from monitoring an experimental deposition hole. Events shown within the hole volume are those AE recorded ahead of the bottom of the hole at the time of excavation. The marker colour indicates the relative ultrasonic magnitude and black markers show transducer locations.

Ultrasonic surveys give velocities for the pre-disturbed rock mass as approximately 5900 $m{\cdot}s^{-1}$ for P–waves and 3350 $m{\cdot}s^{-1}$ for S–waves. A 3% anisotropy has been imaged. Surveys generally describe a drop in velocity during excavation. Observed changes vary from 4 $m{\cdot}s^{-1}$ for ray paths at distance from the deposition hole to sharp drops of 20–30 $m{\cdot}s^{-1}$ for ray paths skimming the deposition hole wall. These variations can be explained using a disturbed and a damaged zone model. As ray paths travel through the disturbed zone, in which induced stresses have preferentially opened or closed pre-existing microcracks, then the ray experiences small increases or decreases in velocity. This results in, for example, a 4 m•s^{-1} change observed at distance from the deposition hole. However, ray paths skimming the deposition hole perimeter at 2–3 cm distance pass through a region of accumulated damage close to the wall. These then experience a much sharper change in velocity of the order — 15 m•s^{-1} measured over the entire ray path. This corresponds to a 15% decrease in Young's modulus for the damaged zone. Fig. 7 shows the effect of excavation on velocity change in the EDZ.

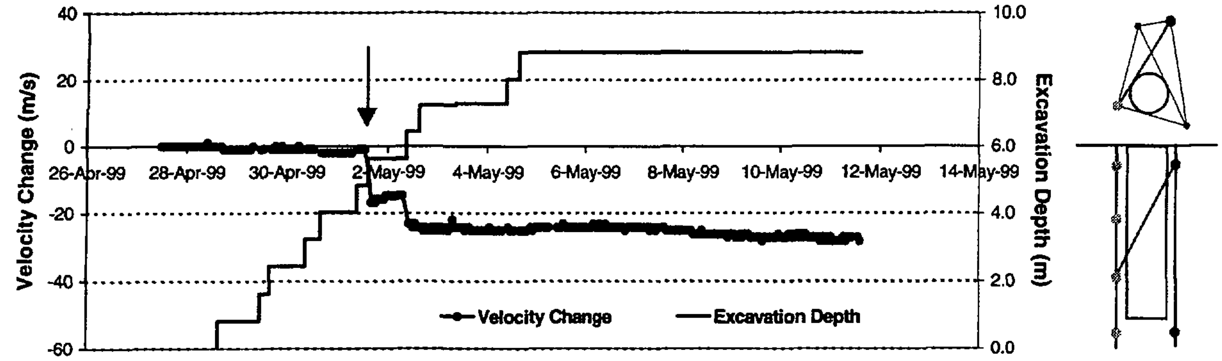


FIG. 7. Velocity change measured on the ray path illustrated in the right-hand margin. The red arrow shows the time at which excavation passed the ray path.

4. CONCLUSIONS

Acoustic Emission and ultrasonic techniques provide a remote, non-destructive method of monitoring the response of rock mass or concrete structure over a wide range of volumes. The relatively non-invasive nature of the technique, coupled with its ability to monitor both passively and actively over a long time period makes it ideal for civil engineering scenarios, particularly where the early identification of damage or damage potential is critical to the safe operation of the facility.

ACKNOWLEDGEMENTS

I thank the TSX international project team, AECL, ANDRA/EDF, PNC and WIPP for their scientific and financial support and permission to use some of the URL data. I also thank the Aspo Hard Rock Laboratory (HRL) team and SKB for their permission to use some of the HRL data. I also thank the staff of the URL and HRL for their continued support and enthusiasm for my work, especially Neil Chandler and Jason Martino of AECL and Dr Olle Olsson of SKB. I am especially grateful to members of my research group past and present especially Drs Calum Baker, Dave Collins, Jim Hazzard, Will Pettitt and Roger Bowes (ESG) who have contributed to different aspects of this work. I am also grateful to the staff of Applied Seismology Consultants (ASC) who were involved in the HRL case study.

SELECTED REFERENCES

AECL, ASC, SKB, Keel University, Queen's University and Liverpool University, Internal Research Reports.

COLLINS, D.S., YOUNG, R.P., Acoustic Emission/Microseismicity Research at the Underground Research Laboratory, Canada (1987–1997), Ontario Hydro Report 06819–REP–01200–0045–R00, Toronto, Canada (1997).

COLLINS, D., YOUNG, R.P., Monitoring an Experimental Tunnel Seal in Granite using Acoustic Emission and Ultrasonic Velocity. Proceedings of the 37 th US Rock Mechanics Symposium, Rock Mechanics in Industry. Colorado, USA, Balkema, (Rotterdam) (1999) 869–876.

FALLS, S.D., YOUNG, R.P. Acoustic emission and ultrasonic-velocity methods used to characterise the excavation disturbance associated with deep tunnels in hard rock, Tectonophysics, 289 (1998) 1–15.

FALLS, S.D., YOUNG, R.P., Examination of the Excavation Disturbed Zone in the Swedish ZEDEX Tunnel Using Acoustic Emission and Ultrasonic Velocity Measurements in Prediction and Performance, EUROCK Symposium (1996) 1337–1344.

MARTIN, C.D., COLLINS, D.S., YOUNG, R.P., Monitoring progressive failure around a tunnel in massive granite, in Proceedings of the 8th International Conference of the International Society for Rock Mechanics (FUJII, T. (Ed.), Tokyo, Japan, Balkema (Rotterdam), September (1995) 627–634.

MAXWELL, S., YOUNG, R.P., Seismic characterization of a highly stressed rock mass using tomographic imaging and induced seismicity, J. Geophys. Res., 97 (1992) 12361–12373.

YOUNG, R.P., Seismic methods applied to rock mechanics, Int. Soc. for Rock Mechanics News Journal, 1, 3 (1993) 4–18.

QUESTIONS (Q), COMMENTS (C) & ANSWERS (A) AFTER THE PRESENTATION

Q: What is the design life of the sensors? Would you need to be routinely replacing them if you wanted to save fifty years of retrievability?

A: Probably most of these sensors would last at least twenty years; probably they may even last fifty years. Some sensors that we use at the underground lab were installed in 1987 and they are still working today. This gives an idea.

Q: I think that if you conceive using them, for example, for safeguards application, it might be open-ended, because as long as there is a safeguard requirement you will have to listen to what happens and to any activity in the repository. But then, changing the sensors is not a problem because you are remotely located from the facility. Do you have any experience about efficiency of the method in different kind of rocks, for example, in clays?

A: I did not talk about this, because I kept it specifically to these two laboratories, but we have done work in Mon Terri and in Tournemire, both in Opalinus clay and also in the claystone materials that ANDRA is interested in. The softer rocks, of course, do not behave anywhere near as nice in terms of creating acoustic noise as granite will. They do create acoustic noise, but it depends on the speed at which the rock is deformed. If you, for example, deform rock salt very slowly, you might not get very much acoustic activity, but if you create a hole in it, the immediate response can create acoustic activity and it is the same in the claystone. So it is not as widely applicable for softer rocks. It depends on how fast the process takes place.

Q: Therefore safeguards application would work also in soft rocks I think.

A: Yes certainly if somebody would be drilling.

Q: Over what distances would you be able to use this? Would you be able to use it from the surface in a post-closure phase?

A: Well, that sort of question is like: how long is a piece of string? It depends to a certain extent on what level of threshold you want to go down to. If you want to detect a pencil lead break then you are not going to be able to do that from the surface. You need to be close. If you want to detect the equivalent energy releases of hammer blows, then you can do that from quite a considerable distance away from the repository. Likewise, you could detect really major activity from a long distance away from the repository. But to improve this whole monitoring process, the best way is not to do it from the surface, but to do it from just the sub-surface, because the first few metres of the upper surface of the rock are very weathered and they attenuate and dampen the sound waves. So if you get below that zone, you can improve the efficiency significantly without actually going into what might be considered the repository volume.

Q: What would be the resolution? You mentioned a couple of centimetres if you were close to the object. But say from 200–300 metres distance, what kind of precision in your geometric determination would you get?

A: Well, in the equivalent of the hammer blows, this was being done in a 50 × 50 × 50 metre volume. Hundreds of metres away you might get to accuracies of a metre resolution, which would tell you whether you were near to the repository or not, whether this activity was lining up in terms of some drilling or whatever.

Q: Do you think these techniques are really going to be of use in safeguards areas? We heard several people say: what are you going to be able to monitor in the short term to know whether you have to retrieve or not? Do you think these measurements are only going to be concentrated on safeguards?

A: I believe that they will be used probably predominantly for model validation, because, at the final repository stage, there is going to be some concern about drilling lots of boreholes in the actual volume itself, because of all the sealing problems that would follow. So I think the whole idea of developing this technology is that because it is remote and we will always have models to try and determine the processes that are going on. In order to make sure that these models are doing what we believe they should be doing, you have to have some way, some measurement, to actually validate them. I think these processes, these techniques are very valuable for that, and I think that probably will be a prime use of these techniques in the future.

Q: You mentioned, I think it was in the framework of the Canadian programme, the detection of micro-cracks or micro-whatever, in the concrete sealings. Do you know if — within the frame of that programme — anyone looked at what to do with the results of those measurements, like when is your sealing not good enough?

A: To be fair here I am giving you some results from an ongoing programme, so you can see that, at the moment, they are just starting to pressurise this particular tunnel, so the experiment is only half-way through. But some of these issues are going to be studied during the course of this experiment. I am giving you results from the early phases, if you like, the excavation phase and also the start of the pressurisation phase. The important thing here was that these instruments were in place before anybody went into this volume of rock, so you had the instruments sitting by and you could study as the first excavation took place and monitor any micro-cracks, and then see how those micro-cracks respond to any subsequent loading that might take place. And the loading can be when they simulate heat, which they hope to do in this experiment. This particular volume of water in that test tunnel will be heated to 80^{o}C, so you can, if you like, map out damage and disturbance that is happening around this tunnel and then see what aggravation the increased thermal load would have. And in fact they have developed models to try and predict the amount of extra stress that will occur on these micro-cracks. But what you do not have is an easy way of validating that, so this is where those techniques come in.

Q: I just wonder about the significance and definition of one metre damage zone and that one to three metre disturbed zone, respectively, in Canada in the URL. Can you say something about these zones at the conditions we have in crystalline rock here in Sweden? Also, do you plan to use this AE technique to study the concrete plugs in the tests at Äspö?

A: With regards to the first question, part of the problem is to try and relate this micro-cracking to permeability change. At the URL, this particular seal geometry was designed to try and cut off the excavation disturbed zone. So modelling had shown, that by creating a sealed plug of a certain shape and size, it was possible to cut off that tunnel excavation damage, and therefore reduce the axial permeability down the borehole. Studies are continuing to relate the mapped out zone to physical changes in permeability, and this work is ongoing. With regards to sealing experiments at SKB, at the present time, we are working on the retrievability test and I am not certain as to what other tests we may be involved in at Äspö at this point. But we are going to be monitoring in the prototype repository as well.