Investigating the stability of engineered structures using acoustic validation of numerical models.

R. Paul Young[1] and Will S. Pettitt[2]

Abstract.

Understanding the mechanical stability of rock and concrete structures is of utmost importance to the safe and efficient construction and operation of engineering projects. One of the most highlighted cases in recent years is the feasibility study for disposing of radioactive waste in deep underground repositories. Many international organisations are currently investigating this concept using underground laboratories as a tool to provide development and testing of engineering designs, storage methodologies and monitoring techniques.

Acoustic techniques allow fracture growth around underground excavations to be observed and allow a quantification of the extent of damage and how this affects the physical properties of the rock. Current work involves integrating physical measurements from these techniques with numerical models to further understand the mechanics of the damage processes. It is proposed to then use these models in the repository design process to predict instabilities in the engineered structures that may occur over the repository's operational lifetime. Acoustic techniques will then provide remote monitoring capabilities that give a feedback mechanism by which these models can be updated and validated. In this paper we demonstrate the integration of acoustic monitoring and numerical modelling and discuss its future applicability to engineered structures in both rock and concrete.

---

[1] Applied Seismology Laboratory, Department of Earth Sciences, Liverpool University, Liverpool, UK..Email: r.p.young@liverpool.ac.uk

[2] Applied Seismology Consultants, 10 Belmont, Shrewsbury, UK. Email: consulting@seismology.org.

Introduction

An important consideration for an engineered structure is its mechanical stability and how this is effected through its operational lifetime. This is particularly significant for large or critical structures such as dams, bridges or reactor vessels in concrete, and for slopes, mines or underground storage facilities in rock. For many such structures it is often not possible to physically observe damage processes occurring internally. The continued mechanical stability of the structure may also not be evident from external observations. Physical measurements of the properties of the structure can, in these cases, yield valuable information that engineers can use to ascertain how the structure is behaving. However, many techniques require cores to be taken out of the structure for testing, so damaging the structure to a greater extent. Instruments to measure displacements (or similar) can be embedded in the structure but these only acquire data at one point in space. A lot of instruments are then required to get an overall picture of what is occurring and can result in complex processing and interpretation. Acoustic monitoring provides a method of remotely monitoring the full three-dimensional volume of a structure so that information can be given on precise localisation, extent and mechanics of any damage processes. Furthermore, it provides a method of giving precise measurements of changes in material properties that are occurring within the structure.

Numerical models provide a method of identifying regions of a structure that are likely to be the most critically stressed and can thus provide predictions for its future stability. In many cases, however, the material properties used in the model are assumed to be uniform throughout the structure. Minor variations from these average values, resulting from small pre-existing flaws or cracks, or localisation of stresses and damage during loading, can change considerably the response of the overall structure, especially as failure conditions are approached. This can result in critical changes in the response of the overall structure from those predicted by the numerical model. When used in conjunction with acoustic monitoring of the actual response of the structure, effects from local features can be incorporated into the numerical model, which can then be re-run to examine the consequences. The updated predictions can then be checked against the acoustic observations and the model revised further, if necessary. Used iteratively in this way, combination of the two approaches provides a powerful tool for predicting the performance of engineered structures.

Damage and, in some cases, instability and collapse of rock around underground excavations is often controlled by pre-existing fractures or joints in the rock mass. The fracture system may be identified from geological exploration and included in the numerical model, but it is often assumed that all such fractures have the same properties (cohesion, limiting friction). In reality, slight variations in these properties will cause one fracture to slip first, changing dramatically the stress distribution and subsequent deformation response of the overall structure from that predicted by the model. Again, the use of acoustic techniques together with numerical modelling, in an iterative fashion can provide more accurate prediction of the actual behaviour of the structure.

This integration of acoustic monitoring and numerical models has been used in experiments at underground laboratories to provide information on the response of rock masses around excavations; similar to those that will be used to dispose of radioactive waste in deep repositories. In this case the process of excavation perturbs *in situ* stresses in the immediate vicinity of the excavations. Induced stresses may then be sufficient to cause permanent change or damage to the rock. It is important to be aware of these changes when planning tests in the excavations, or when planning further excavations during the final repository design process, especially when the rock properties and stress field will be further perturbed by applied mechanical and thermal loads. It is then important to predict and monitor the effect of these additional loads so that the final repository provides as stable an environment as possible during its operational lifetime.

In this paper, we demonstrate the use of acoustic monitoring techniques to appraise the stability of *in situ* engineered structures and to validate and up-date predictions made from numerical modelling. The models have been developed using Particle Flow Code (PFC) by Itasca Consulting Group Inc. Acoustic monitoring data from underground laboratories in Sweden (SKB's Äspö Hard Rock Laboratory, HRL) and Canada (AECL's Underground Research Laboratory, URL) are used as examples.

The integrated approach to acoustic monitoring and numerical modelling has applications in many other engineering scenarios in rock or concrete. There are numerous examples of critical concrete structures that are either under high applied loads (and may now be reaching the end of their lifetime), or concrete structures that are now being built in highly stressed, "difficult" environments. In either case the mechanical stability and integrity of such structures is an important consideration and, like the rock mass around radioactive waste repositories, has to be thoroughly understood. At the URL, concrete and clay engineered structures, that may be used to seal repositories from the environment outside, are being investigated as these provide a further critical barrier to radionuclide contamination. We demonstrate the use of acoustic monitoring in concrete using a pressurised retaining bulkhead at the URL as an example.

Acoustic Techniques

Acoustic methods are utilised to examine damage in rock masses [*Falls and Young*, 1998; *Pettitt et al.*, 2000; *Young and Collins*, 1999] using the same fundamental principals as those utilised in earthquake seismology. Passive acoustic techniques, e.g. at the acoustic emission (AE) frequency scale (35-350kHz) and at the microseismic (MS) frequency scale (0.5-10kHz), describe the localisation and extent of stress-induced micro-fracturing around underground excavations. These stresses may be induced by the perturbation of the *in situ* stress field or due to applied stresses from mechanical or thermal loads. Elastic waves emitted from a micro-fracture, as it is created or as it moves, are recorded across an array of sensitive transducers. Subsequent inversion of arrival time information provides a localisation of the source of the elastic waves.

Young and Collins[1999] gives example MS and AE data from the Tunnel Sealing eXperiment (TSX) at the URL. In this case (Figure 1a) an elliptical tunnel was excavated orthogonal to σ_2 (near horizontal) and σ_3 (near vertical) in Lac du Bonnet granite at the 440m depth level of the URL [*Martino and Chandler*, 1999]. The tunnel geometry was engineered to minimise the effect of perturbed *in situ* stresses around the void. Compressive stresses were modelled to be of the order of 105MPa in the roof and floor of the tunnel. This is compared to an estimated crack initiation stress of 70MPa for the rock mass. Two bulkhead keys were excavated into the rock around the tunnel, into which bulkheads (one concrete and one bentonite clay) were subsequently constructed. The intervening section was backfilled and then pressurised after bulkhead construction in order to examine the performance of the tunnel seals under simulated operating conditions (Figure 1b). Also shown in Figure 1a are two acoustic arrays installed around the tunnel volume. The first array (MS) monitors the entire tunnel volume and much of the rest of the 440m level of the URL (100x100x100m). The second array (AE and ultrasonic propagation experiments) monitors a small (10x10x10m) volume around the clay-bulkhead key.

Figure 2a gives example MS events recorded around the concrete-bulkhead key. Shown are the largest events (moment magnitude, M_W>-2.5) recorded in the array volume shortly after excavation. Each MS event is associated with failure over a fracture that has a dimension of 10s of centimetres. The key has a wedge shape with a vertical and a 45° interface, and a diameter of approximately 6m. A ring of these high-magnitude events occurred at the apex of the key where numerical models predict a high stress concentration. Figure 2b gives example AE data from around the clay-bulkhead key. These events are estimated to be three to four orders of

(a) (b)

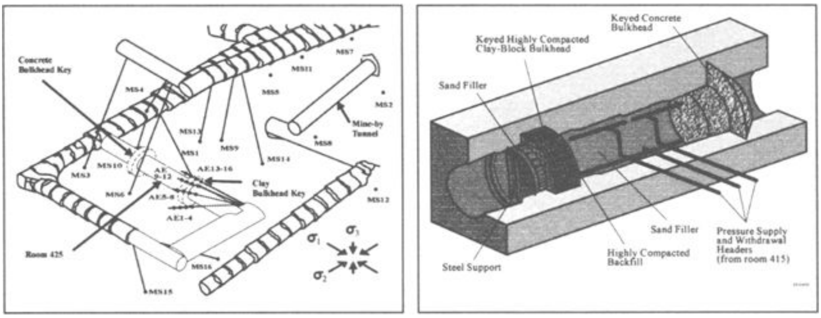

Figure 1: a) The tunnels associated with the TSX (room 425), relative to the principal stress field. The 16 AE and 16 MS receiver locations are shown. b) Schematic illustration of the TSX [*Martino and Chandler*, 1999].

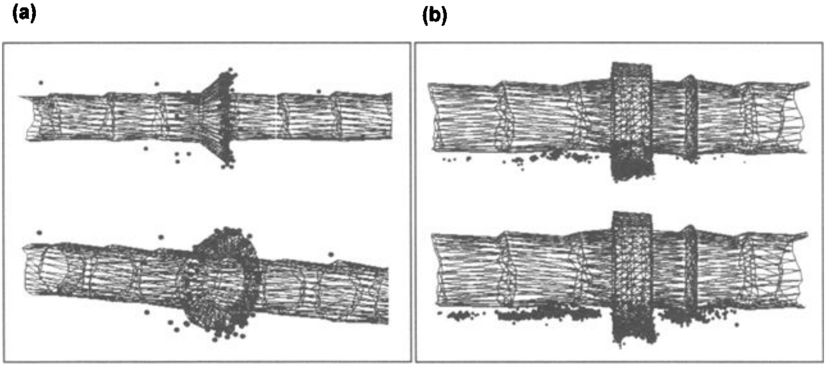

Figure 2: a) Two views of example MS locations (209 events with moment magnitude, M_W>-2.5) from the 440m level of the URL. The tunnel section shown is Room 425 (TSX tunnel) around the concrete-bulkhead key. b) Example AE locations around the clay-bulkhead key from two time periods: UPPER - 1686 AEs from 13th to 22nd August 1997 (during and immediately after excavation); LOWER - 22nd August to 9th December 1997 (post excavation).

magnitude smaller (M_W approximately -6) than the MS events and are associated with micro-fractures on the grain size scale (millimetres). The AEs describe clusters of activity in regions where models predict high compressive stresses. Furthermore, a time-dependent behaviour is observed with activity migrating away from the tunnel/key perimeter over time.

Further analyses of MS/AE activity can be obtained using amplitude information recorded on waveforms. This can provide information on the micromechanics involved in creating or moving the micro-fractures [*Baker and Young*, 1997; *Pettitt et al.*, 1998]. *Collins et al.*[2000] shows example moment tensor solutions for both MS and AEs that are closely associated in both time and space. Through this approach the AE activity can aid in interpreting the mechanics of the fracturing associated with the much more damaging MS activity.

Active acoustic techniques (e.g. velocity or attenuation measurements) quantitatively describe changes in rock mass properties [*Falls and Young*, 1998; *Pettitt et al.*, 2000; *Young and Collins*, 1999]. As ultrasonic sensors allow both passive and active operation the ultrasonic array can provide this information in conjunction with monitoring the AE activity. The observed measurements depend upon stress-disturbance, such as opening and closing pre-existing micro-fractures, or new stress-induced micro-fractures as indicated by the AEs. Figure 3a shows example P- and S-wave changes in velocity over a one year time period starting shortly after construction of the TSX tunnel. Utilising a waveform cross-correlation processing technique (velocity interferometry), very high-resolution changes in velocity can be obtained. Uncertainties in velocity differences between daily surveys are <3m.s^{-1} in this case. This is very important when rock mass changes are small and occur over a short length (5-25%) of the ray path.

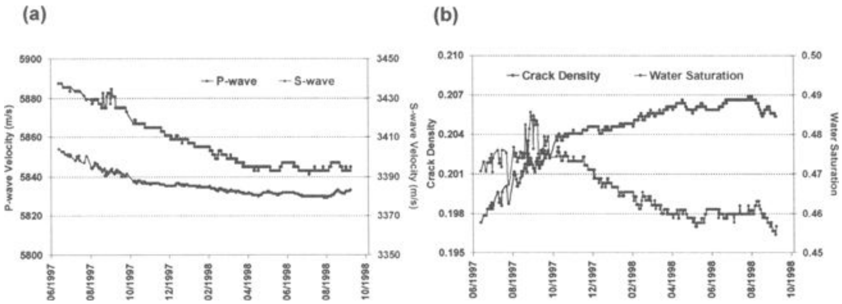

Figure 3: a) Example P and S-wave velocity changes measured through the near surface damaged rock of the TSX tunnel. b) Crack density and saturation changes inverted from the velocity measurements.

Developments in processing techniques, using ultrasonic velocity and amplitude information, are currently focussed on providing quantitative estimates of the effect of rock mass degradation on the physical properties of the rock. This is done by using the AE observations to provide an estimate of the volume in which the induced damage is occurring, and then high-resolution changes in velocity measurements made through this volume to quantify the effect of the damage on the rock [*Pettitt et al.*, 2000]. Understanding the magnitude of this effect is critical to understanding the stability of the engineered structure. Shown in Figure 3b is the crack density and saturation changes inverted from the measured velocity changes using the method of *Zimmerman and King*[1985] and using properties for Lac du Bonnet granite from *Maxwell et al.*[1998]. Crack density is observed to increase through time after excavation, although its rate of production decreases through time allowing the rock mass to equilibrate after approximately one year. This is also borne out in the AE activity with count rates reducing from greater than 400 events per day during excavation down to approximately 20 events per day a year later. In conjunction with the increasing crack density the water content in the rock mass is observed to decrease as micro-fractures open and allow desaturation. Utilising multiple transmitter-receiver ray paths across the ultrasonic array allows for three-dimension velocity and crack density investigations around the key.

It is hypothesised that the rock mass around the excavations at the URL reaches an unstable equilibrium. Any small perturbations in the stress field during subsequent operations can re-initiate micro-fracturing in highly stressed regions [*Hazzard et al.*, 1999]. In the case of the TSX the opposite occurred when the tunnel was back-filled with sand in July 1998. The sand exerted an estimated load of 15kPa on the floor of the tunnel. This confining pressure was sufficient to almost elliminate fracture growth in this region (AE counts dropped dramatically to 1 event per day).

Micromechanical models

Distinct-element micromechanical models such as PFC represent a rock mass as an assembly of thousands of particles bonded together at their points of contact. The particle assemblages are given elastic moduli and failure criteria to mimic a realistic rock mass. Each of the particles is free to move individually so that when a rock sample is stressed the particles can pull or slide apart inducing crack formation when the connecting bonds break. Using PFC to model laboratory experiments on realistic rock samples has resulted in remarkably similar results to that obtained in the laboratory. Figure 4 shows a granite sample in PFC during a compression test. The model provides a stress-strain curve similar to that seen in reality. Furthermore, micro-fractures created in the model coalesce into a macroscopic shear failure. This is observed to propagate across the sample.

PFC models can be run dynamically [*Hazzard et al.*, 1998] such that each crack causes a seismic wave to propagate through the model. Numerical damping is set to mimic realistic levels of seismic attenuation. Propagated waves can then be recorded and analysed using the same techniques used in laboratory or during *in situ* experiments. The added advantage of using numerical models is that the actual micromechanics of the events can be examined directly by observing the forces and motions of the particles at the sources that can then be related to observations performed during real experiments. Using this approach, PFC has been used to further understand the micromechanics behind microcrack initiation in the laboratory [*Young et al.*, 2000]. The question that arises is whether the same use of

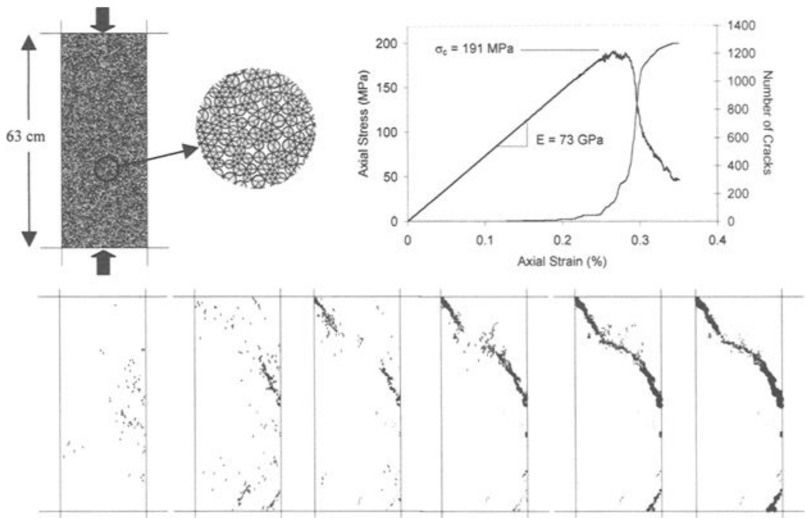

Figure 4: PFC model of a granite sample under compression showing the stress-strain behaviour and six snapshots of a macroscopic fracture development as the micro-fracture bonds break and rotate. From *Hazzard*[1998].

micromechanical models and physical observations, particularly using acoustic methods, can be utilised to examine the micromechanics of failure *in situ*. By developing the micromechanical models to realistically simulate physical observations then gives the models a predictive element for the design of future engineered structures. This approach is currently being explored for the Canadian radioactive waste program in a project funded by Ontario Power Generation (OPG) using data obtained at the URL [*Chandler et al.*, 2000].

Potyondy and Cundall[1998] show the application of PFC to modelling the notch formation in the roof and floor of the Mine-by test tunnel at the URL. The 3.5m diameter circular Mine-by tunnel was excavated in 1991 parallel to σ_2 using a ream and break method. This resulted in excavation damage being primarily due to perturbation of the *in situ* stress field. MS activity was recorded using a similar array to that now used in the TSX. Damage was shown to occur out to approximately 1m into the rock in the roof and floor of the tunnel [*Martin et al.*, 1995]. In these regions breakout notches were observed. Figure 5a shows MS activity associated with one round of excavation. The highly stressed (>150MPa) notch region is imaged in the data. In the subsequent few months after excavation MS activity slowly reduced and the notches self-stabilised as the rock mass reached an unstable equilibrium. In this case further perturbations of the stress field caused re-initiation of the fracturing. This was observed during excavation and heating of large-diameter boreholes in the floor of the tunnel [*Falls and Young*, 1998].

The PFC model developed by *Potyondy and Cundall*[1998] incorporates the time-dependent behaviour of Lac du Bonnet granite (stress corrosion mechanism). This allows the modelled *in situ* rock mass to undergo sub-critical crack growth in highly compressed regions, leading to the observed failure of the rock over large

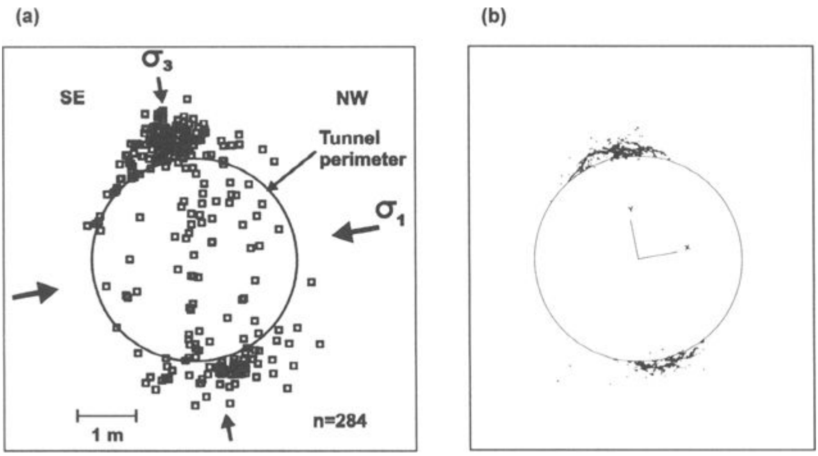

Figure 5: a) MS events associated with an excavation round of the Mine-by test tunnel. b) Fracturing located in modelled notch regions using PFC. After *Potyondy and Cundall*[1998].

time scales, even though modelled elastic stresses around the void are not greater than the classical uniaxial compressive strength (220MPa). Subsequent models have utilised new laboratory data from static-fatigue tests of Lac du Bonnet granite to calibrate the time-dependent effect [*Chandler et al.*, 2000]. Figure 5b shows the results from a model of the Mine-by tunnel. The micro-fracturing associated with breakout are evident in the model, mimicing that observed *in situ*. If the model is run without the stress-corrosion effect no such breakout is observed. The model also reproduces the observed time dependent behaviour in the notch regions. In the model notch growth stabilises due to contact forces across individual particles being focussed into a small high stress region at the apex of the notch [*Potyondy and Cundall*, 1998].

Simulated Canister Deposition Holes

Experiments are currently being conducted at the Äspö HRL, Sweden to investigate the feasibility of using vertical deposition holes to dispose of radioactive waste canisters. The deposition holes are 1.75m in diameter and 8m in length and are excavated vertically from the floor of a tunnel in 0.8m steps. Excavation of test deposition holes has been performed using a modified tunnel-boring machine. Future experiments at the HRL will utilise simulated waste canisters (1m in diameter and 5m in length) containing heater elements placed into these holes with hydrated bentonite clay acting as a buffer between the canister and the rock mass. The bentonite also acts as a very low-permeability barrier between the canister and the outside environment.

Acoustic monitoring has been conducted during the excavation phase of the deposition holes [*Pettitt et al.*, 2000]. AE locations have been used to delineate micro-fracturing around the perimeter of the deposition holes and ultrasonic measurements have been used to quantify the effect of induced damage on the rock

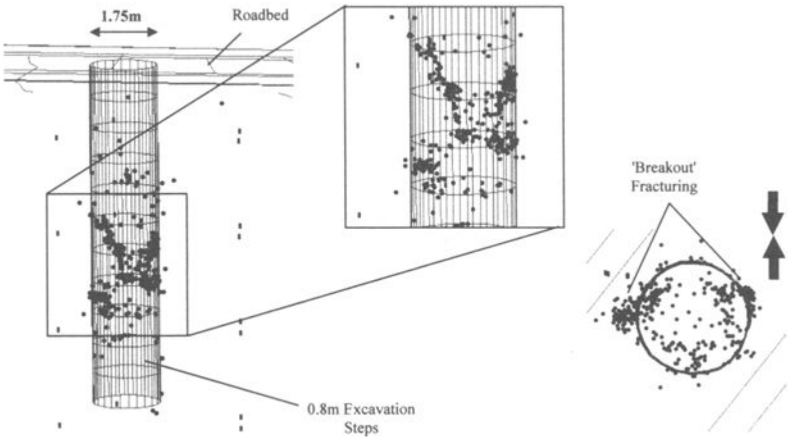

Figure 6: Example AE locations around a deposition hole at the Äspö HRL, Sweden.

mass properties. AEs were observed to occur in tight spatial clusters (Figure 6) and were primarily associated with weakened regions around pre-existing macroscopic fractures that the excavation has intersected and that are common in this rock mass. In plan, these clusters are orthogonal to the measured maximum principal stress (orientated close to the horizontal) and are hence associated with compressive stresses induced in the side-wall of the deposition hole. The majority of this stress-induced fracturing occurs within 20cm depth of the side-wall and over a very short time period after excavation. Within 12 hours the AE count rate dropped to less than 5 events per hour from peak count rates of >150 events per hour immediately after excavation. Although the induced stresses are found to be relatively low magnitude from modelling (approximately 100MPa), compared to the strength of Äspö diorite (220MPa), they are now shown to be sufficient to generate micro-fracturing, particularly in the weaker regions of the rock mass around pre-existing fractures.

Ultrasonic velocity surveys have provided three-dimensional measurements around the deposition hole volume. The velocity results indicate a relationship between observed velocity changes and both stress disturbance (causing pre-existing micro-fractures to open or close in loaded or unloaded volumes of the rock mass) and new fracture growth imaged by the AEs. Using the extent of the AEs as an estimate of the extent of the damaged zone allows for a calculation of the change in rock properties in this volume. This yields an estimated 15% decrease in Young's modulus for the damaged region.

A three-dimensional PFC model was performed for the upper 4m of the deposition hole excavation. This was undertaken as a preliminary indication of the rock response prior to acoustic monitoring. Figure 7a shows a slice through the centre of the model before and after excavation. The model consists of 60,000 spherical particles graded in size away from the deposition hole volume. The particles in the region of most interest, in and around the immediate deposition hole

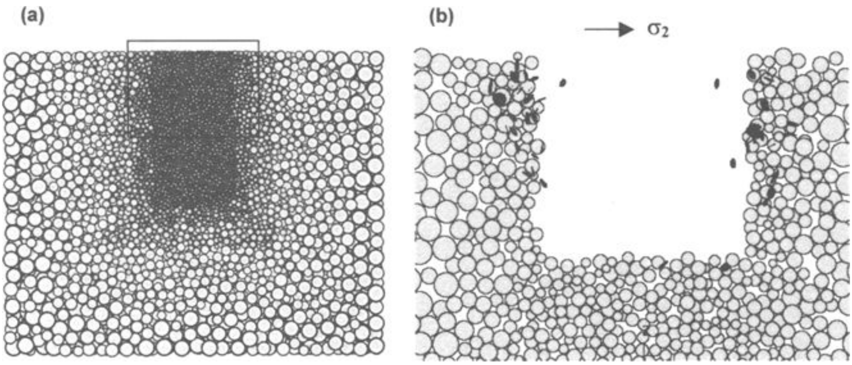

Figure 7: a) A cross-section of the entire three-dimensional PFC model for deposition hole excavation, prior to excavating the hole. b) Cross section of the deposition hole (1.75m diameter) after two excavation steps; enlarged area is shown as rectangle in (a). Cracks are shown as ellipses.