Estimating rock mass properties and seismic response using higher order, discontinuous, Finite Element models

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ABSTRACT: The load-deformation response of discontinuous rock under static and dynamic loading conditions has been simulated using Explicit Finite Element models. The intent of the analysis was to investigate the effects of specimen size and confining stress on strength, dilation and comminution.
The simulations allow the development of homogenised constitutive material properties for discontinuous rock masses using laboratory scale measurements and representative Discrete Fracture Networks (DFNs). A procedure for this is presented which includes a comparison of measured seismic response in a mine to the Dissipated Plastic Energy (DPE) that is released in the simulated rock masses. The models also show how confinement and scale affect the stress-strain and DPE response of the simulated rock specimens, reproducing a number of known rock phenomena that are often poorly captured in geotechnical modelling.
A case study is presented showing a satisfactory match between the model-derived, homogenised material properties and values achieved by calibration of a mine-scale model where many thousands of seismic, displacement and damage measurements were available.

1 INTRODUCTION

In the absence of data for quantitative calibration of numerical models, there are not many options. Rock testing is usually limited to small specimens (<100mm diameter) by the scale of laboratory equipment, however, at the larger scales most relevant to the typical simulation of mining problems, some rock masses can be almost an order of magnitude weaker. This limits the usefulness of laboratory testing for larger scale material property estimation, especially as empirical schemes that can be used to scale laboratory measurements to rock mass scale estimates are problematic.

The main issue is confidence; even experienced practitioners can produce a spread of estimates of material properties using empirical scaling schemes and generally only some of the properties necessary for high similitude analysis are estimated (peak strength and elastic stiffness are usually estimated, but post-peak, strain softening and other parameters are usually not available). Empirical rock mass classification schemes such as GSI (Hoek, 1994), which are also used in some scaling procedures, have similar issues.

Calibration is always the preferred method of rock mass material property estimation because it is possible to test the reliability of the model at the same time. Calibration involves demonstrating similitude by comparing measured and modelled quantities. The intent must be for modelled estimates of deformation and other phenomena to match both the extent and magnitude of the same quantity measured in the field while covering a sufficient range of conditions and time.

Examples of quantitative calibration would be the direct ability of a subsidence model to match measured surface movement in three dimensions over time with a known and reliable estimate of precision. Alternatively, the probability of seismicity measured in space and time can be correlated with the plastic energy release in a model of an underground mine (Beck et al, 2006). The models can be said to be calibrated because such matches are only possible if the underlying mechanisms and governing physics of the problem are captured.

2 NUMERICAL HOMOGENISATION OF ROCK MASS PROPERTIES

An emerging technique for rock mass scale property estimation is numerical homogenisation, sometimes referred to as synthetic rock mass analysis (SRM), though the rock mass is simulated rather than synthetic. In this family of approaches several, differently sized, discontinuum models of a rock mass domain, or rock type are constructed. The models are constructed using Discrete Fracture Networks (DFNs) that statistically match the distribution and replicate the physical properties of the discontinuities in the rock mass. The statistical and physical descriptions of the discontinuity distribution can come from core or from mapped exposures of rock. A simple example of a DFN of a skarn built from underground mapping data is shown in Figure 1.

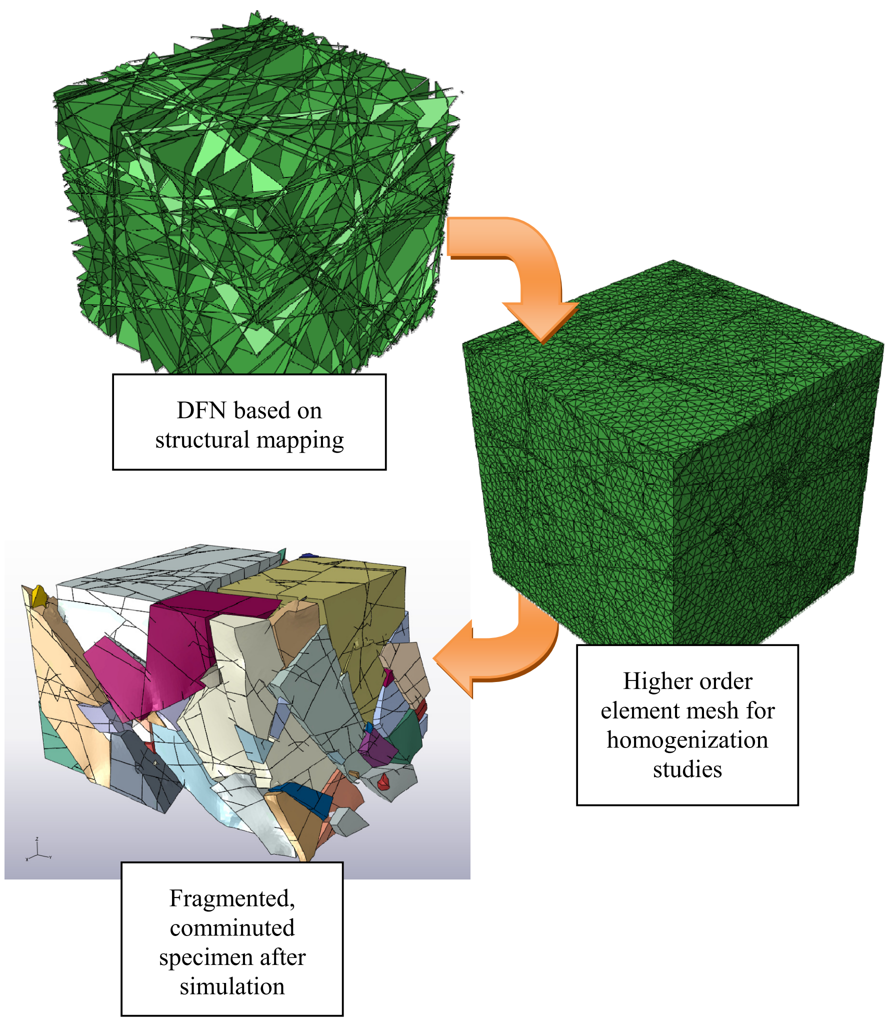

Figure 1. An example of a DFN model of skarn

The DFN specimens are then subjected to stress paths representative of the mining environment and the properties of the mass are inferred from the movements at the specimen boundaries, much as they would be in a laboratory tests. Generally, strengths and properties degrade asymptotically with length scale and the dimension beyond which an increase in specimen size does not result in further strength and property reduction is known as the Representative Elementary Volume, or REV.

The REV is a very important concept. In larger models such as mine scale models, the properties of the REV for a particular geological domain or rock type can be used as the homogenised properties of that rock mass. For investigations at smaller length scales than the REV, such as ground support investigations, homogenised rock mass properties may not be appropriate, and a model with the mass represented as a discontinuum is more likely to be appropriate. In a multi-scale model, the REV and the length scale of interest will define the smallest scale of structure that must be included in the model.

2.1 *Usage*

These models can be used in a number of ways;

- The nature of rock masses at larger length scales can be estimated to a first pass level of reliability initially by measuring the rock properties in a laboratory and then assigning these properties to a DFN. It must be noted that calibration using field measurements of rock movement and damage are preferred over this approach.
- Where measurements of induced deformation are available, the DFNs can be used to infer the properties of discontinuities such as joints, faults and foliation that cannot otherwise be calibrated using data from field scale measurements.

  In this procedure, joint, fault and foliation properties may be adjusted until the DFN simulation reproduces the three dimensional, stress-strain behaviour measured at a larger length scale. This in turn allows simulation of smaller scale phenomena using the DFN based REV such as comminution, rock mass disassembly, fragmentation, tunnel stability and effects of seismicity with enhanced precision.

  An example of when this approach is useful is when a model is sufficiently well calibrated to reproduce general deformation on a large scale, but subsequent studies of rock mass disassembly are needed and data for calibration at the smaller scale is insufficient. In such analyses the properties of blocks and wedges in the tunnel walls is critical but would not have been calibrated using field measurements of excavation convergence.

3 TEST APPLICATION

The feasibility of simulating complex 3D DFNs using a common, non-linear finite element modeling package with discontinuum abilities has been tested. The aim was to recreate well known, but difficult to simulate, interactions between stress, strain, structure, strength and energy for the sample rock masses.

For the test application, Abaqus was chosen for the following reasons;

- Abaqus allows "off-the-shelf" multiple-parallel simulation. This means that many millions of higher order elements can be used. With 32 processors (now considered accessible computing power), a complete DFN simulation takes less than 12 hours.
- Suitable Abaqus constitutive models are available for both the rock and the discontinuities. The contact mechanics for discontinuum applications in Abaqus is well tested and robust.
- Tetrahedral or brick (hex) elements can be used so there are no voids within the model unless they are intentionally constructed.
- At this time there are few packages with the requisite computational efficiency to run problems of this size using accessible computing hardware in a practical time.

For completeness the model specification associated with these analyses is summarized:

- The rock material was modeled using three dimensional 10 node tetrahedra and a calibrated strain softening, dilatant, user-defined Mohr-Coulomb based, constitutive material.
- Fault/joint response of the DFN was approximated using a traction-separation based cohesive element formulation (COH3D6).

3.1 *Laboratory simulation*

The DFNs of three rock masses were constructed using Abaqus/CAE. The particular DFN specimens were for rock masses at a Western Australian mine with a very reliable calibration of homogenised material properties based on tens of thousands of field scale measurements. Abaqus/Explicit was then used to test the response of these specimens to typical triaxial loading scenarios and the discontinuity properties were iteratively adjusted until the DFN specimens matched the basic, homogenised, mine-scale behavior arrived at via calibration. Laboratory scale values were used for the solid rock fragments between discontinuities.

The benefit of this procedure in this example test was that the global behavior was entirely realistic; however, the effect of the joints on other rock mass properties, not usually able to be calibrated in mine-scale studies, could be interrogated. In future studies, laboratory scale properties could be used to derive all properties, but the objective here was to only calibrate the joint properties and to rely on testing for rock properties.

The first phase of analysis was simulation of typical laboratory tests using 1, 4 and 8m DFN specimens, at 3 levels of lateral confinement (Figure 2). The lateral confinement scenarios for each test were $\sigma_2=\sigma_3$=5MPa, $\sigma_2=\sigma_3$=10MPa and $\sigma_2=\sigma_3$=30MPa, which approximate the range of σ_2 and σ_3 conditions experienced in the shallow to moderately deep mines relevant to the study. In this simple test, all 3 stress components were increased at a constant rate from zero until the confinement ($\sigma_2=\sigma_3$) reached the target, and then the axial load (σ_1) was increased slowly to approximate a pseudo-static problem. A summary of the stress-strain results for these tests is presented in Figure 2, where the nature of the dependency of the known stress-strain response on confinement and specimen size is captured. Figure 3 shows the relationships between strain and various material properties by specimen size for a single confinement case.

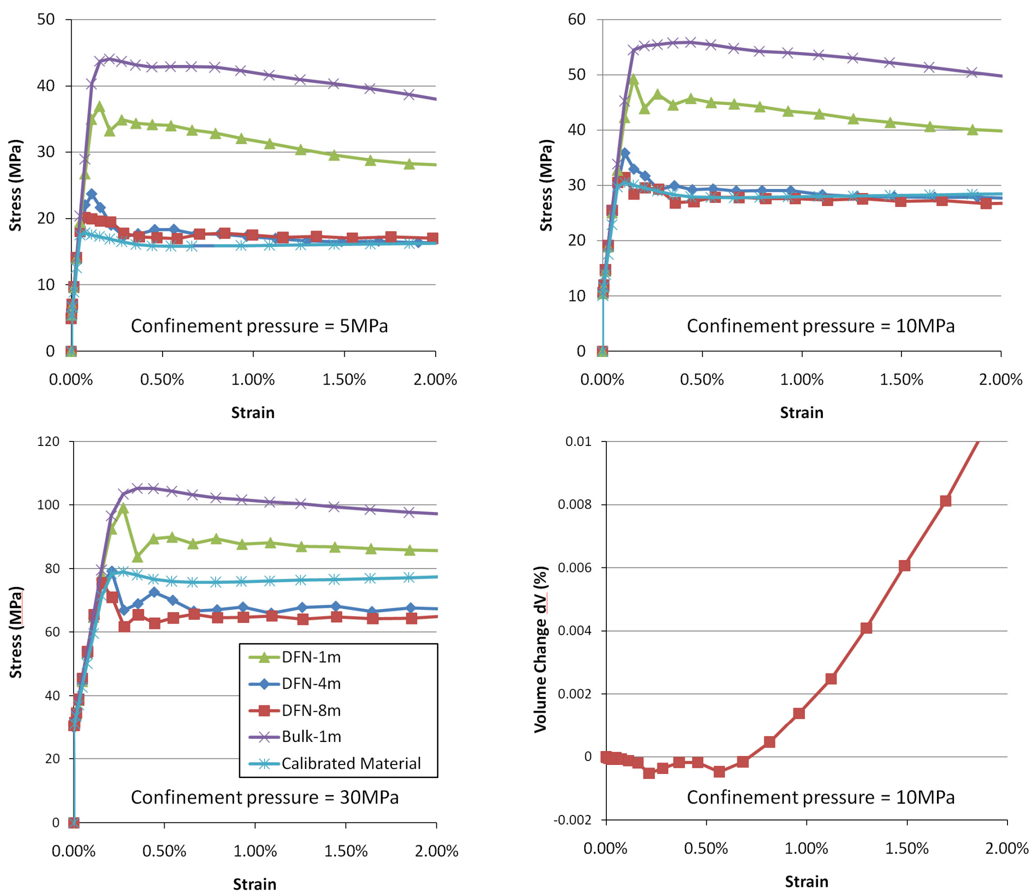

Figure 2. Stress-strain response of DFN representations of differing volumes of a rock mass subjected to three different states of lateral confinement

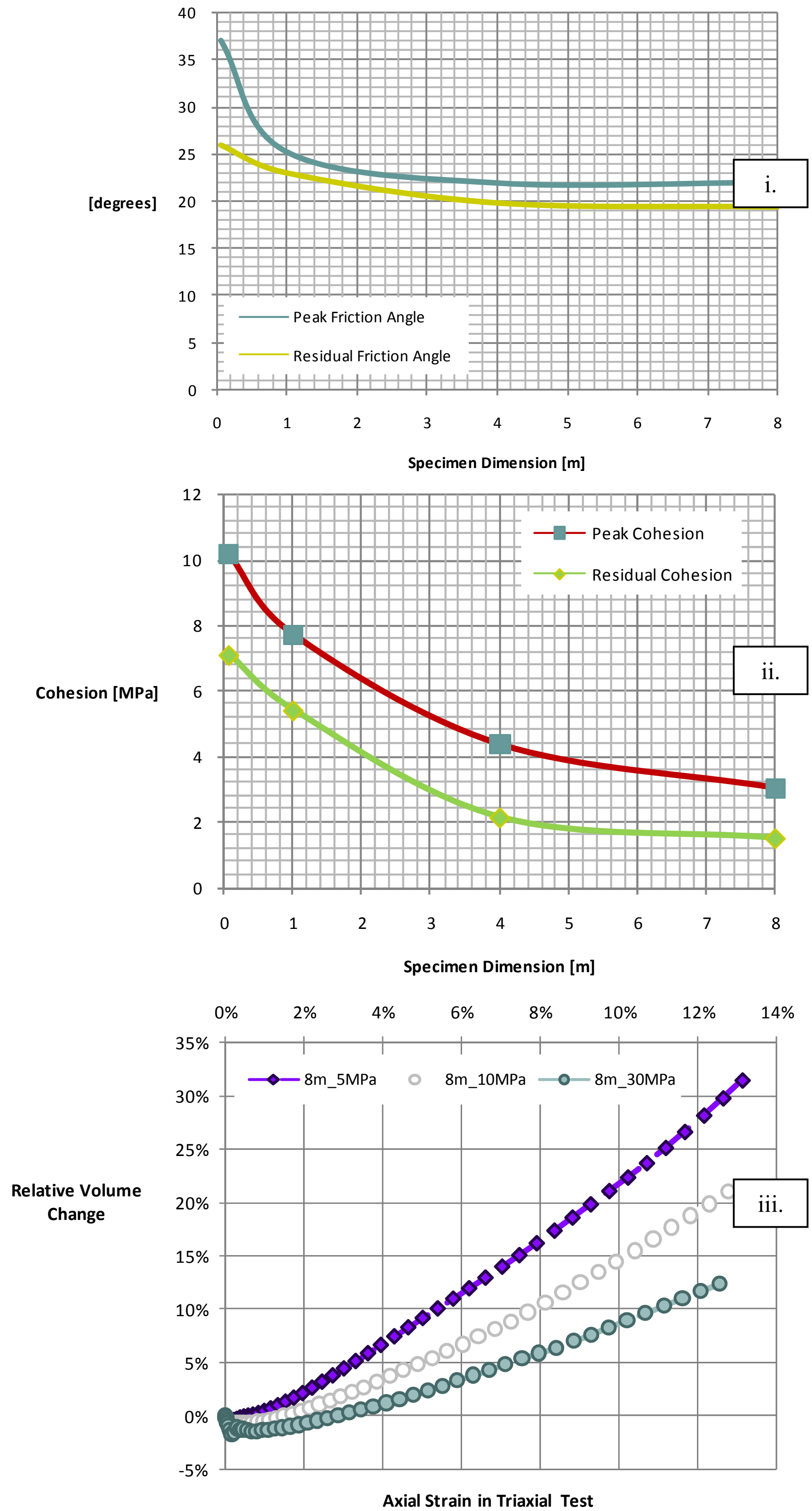

Figure 3. Relation between (i. and ii.) specimen dimension and selected material properties and (iii.) volume change, axial strain and confining pressure for a selected specimen

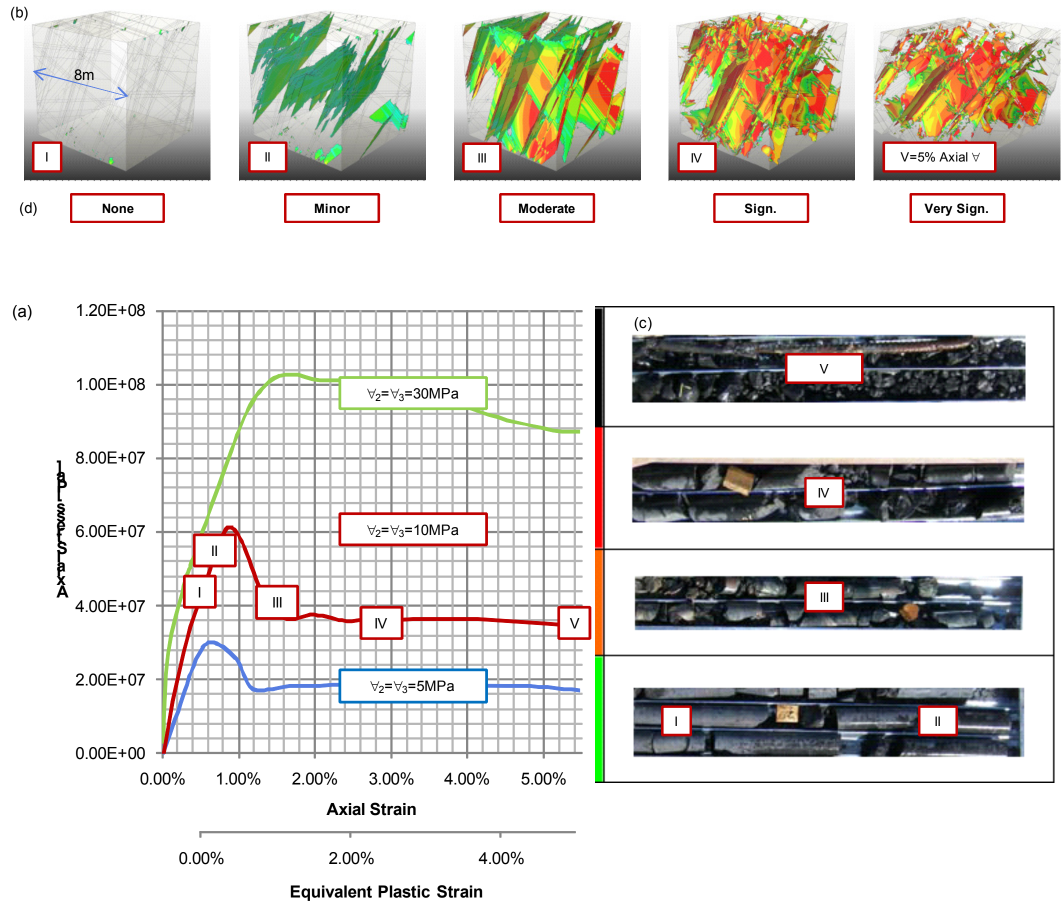

Figure 4. Comparison of (a) Stress-strain response of a simulated rock mass specimen (8m diameter) at varying levels of confinement. (b) The yield state of discontinuities and the deformation of the specimen at milestones of yield (c) photographs of diamond drill core specimens, simulated by the global model to be at these respective states of strain d) the Common Damage Scale.

Generally, strength and brittleness increases with confinement and strength decreases asymptotically with volume of the specimen. The degradation in friction angle, cohesion and stiffness with the size of the specimen was especially interesting, as there is no reliable empirical means for estimating this known scale effect for geomaterials. With some additional verification, it is possible that in the short term parametric tests using DFNs in suitable FE or similar packages may become a useful tool for homogenization of studies of geomaterials.

There were two other interesting aspects to the results that suggest that the DFNs offer a significant tool for simulation of geomaterials;

- Figure 4 shows a comparison between stages of deformation for a DFN specimen, the Common Damage Scale (Beck and Duplancic, 2005) and actual specimens of rock, recovered from locations within the mine where the corresponding level of damage was indicated by the calibrated global models. There is an apparent compatibility between actual measured, DFN modeled and homogenized global model forecast rock condition.
- Figure 5 shows the acoustic emissions indicated by high frequency transient stress waves measured at select locations within the DFN specimen during the tests. Shown as a cumulative plot of the number of events on top of the modeled stress-strain relation for one specimen, the stages of synthetic seismic response approximate what would be expected:
  - Initial spikes in seismic activity are measured during Stage 2 deformation (initial stable plastic degradation)
  - A second stage of intense activity during the transition from Stage 2 to Stage 3 when specimen stability is lost.

– After Stage 3 there is a rapid decrease in seismic emissions. Importantly, the specific mechanism of initial seismicity prior to specimen instability (yield on a single joint set), followed by specimen instability and the associated seismic response (yield on multiple joints) is clearly visible in the DFN.

The close correlation between acoustic emissions and the stages of instability is important. Beck et al (2006, 2007) showed that in well conditioned, mine scale, strain softening dilatant models, there is a good correlation between Dissipated Plastic Energy (DPE) and seismic event occurrence (measured as the probability of experiencing a seismic event within a defined distance and time period).

An example of a DPE/seismic event correlation from a Western Australian mine is shown in Figure 6. Each visible data point represents a calculation involving many hundreds of seismic events within a certain magnitude and DPE range. The data points are the average probability (not single events) for a discrete DPE range. In this case, the probability equates to the chance of having an event at the indicated magnitude within a 25m radius of the test location during the time period of the model step. A probability of >100% means that more than one event should be expected.

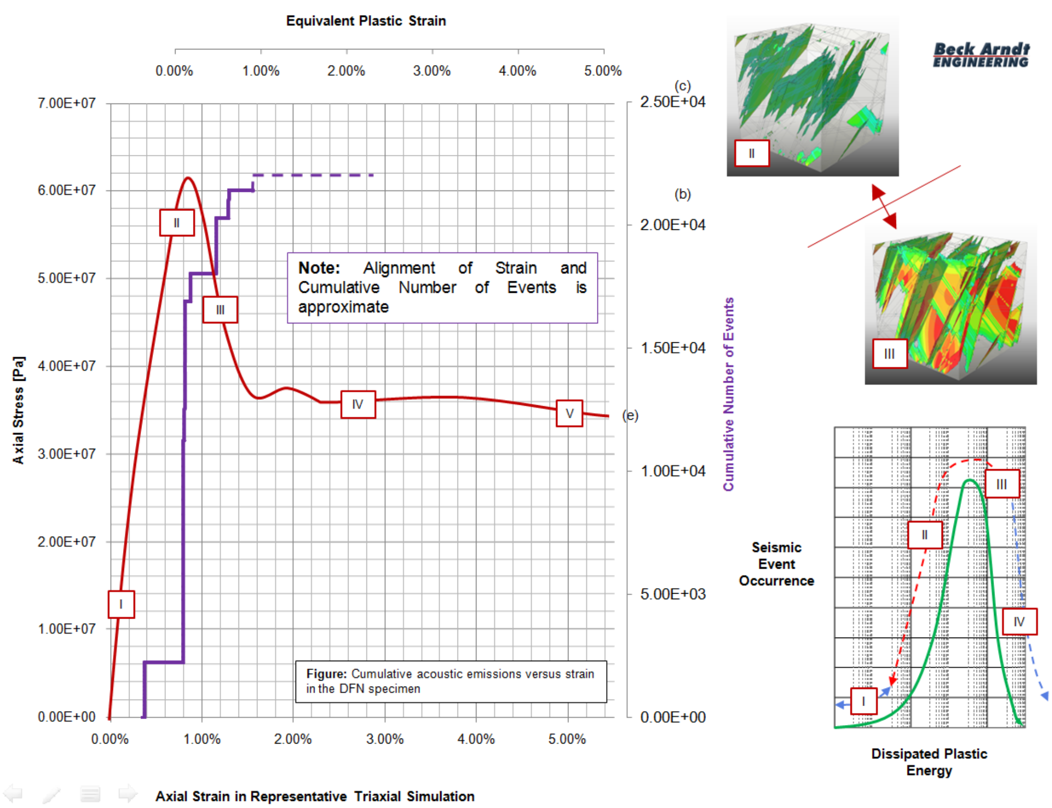

Figure 5 Correlation between stages of deformation and acoustic emissions for a DFN specimen

In summary, it has been shown at several mines:

– The boundary for event occurrence is continuous and bounded with a near-zero event probability at zero DPE release rate. This corresponds to the observation in the DFN models of near zero event rate prior to stage 2 of Figure 5.
– There is a peak DPE beyond which the event probability decreases. This occurs because beyond this limit, the ground has been conditioned (softened by damage) and seismic activ-

ity must therefore decrease. This same observation is evident in the DFN, and corresponds to strains beyond stage 3 of Figure 5.

– There is a linear, log-normal relationship between event probability and DPE. A similar relationship can be inferred from Figure 5.

The results at the mine scale and at the DFN specimen scale are thus in good qualitative agreement and aspects of the results, such as the peak seismic probability relative to the state of strain, and the material stability are in quantitative agreement. In future research, it will be determined if some aspects of the mine scale DPE/seismic event probability correlation, such as the conformance with measured Gutenberg Richter relations for event populations, can be scaled from the DFN tests directly.

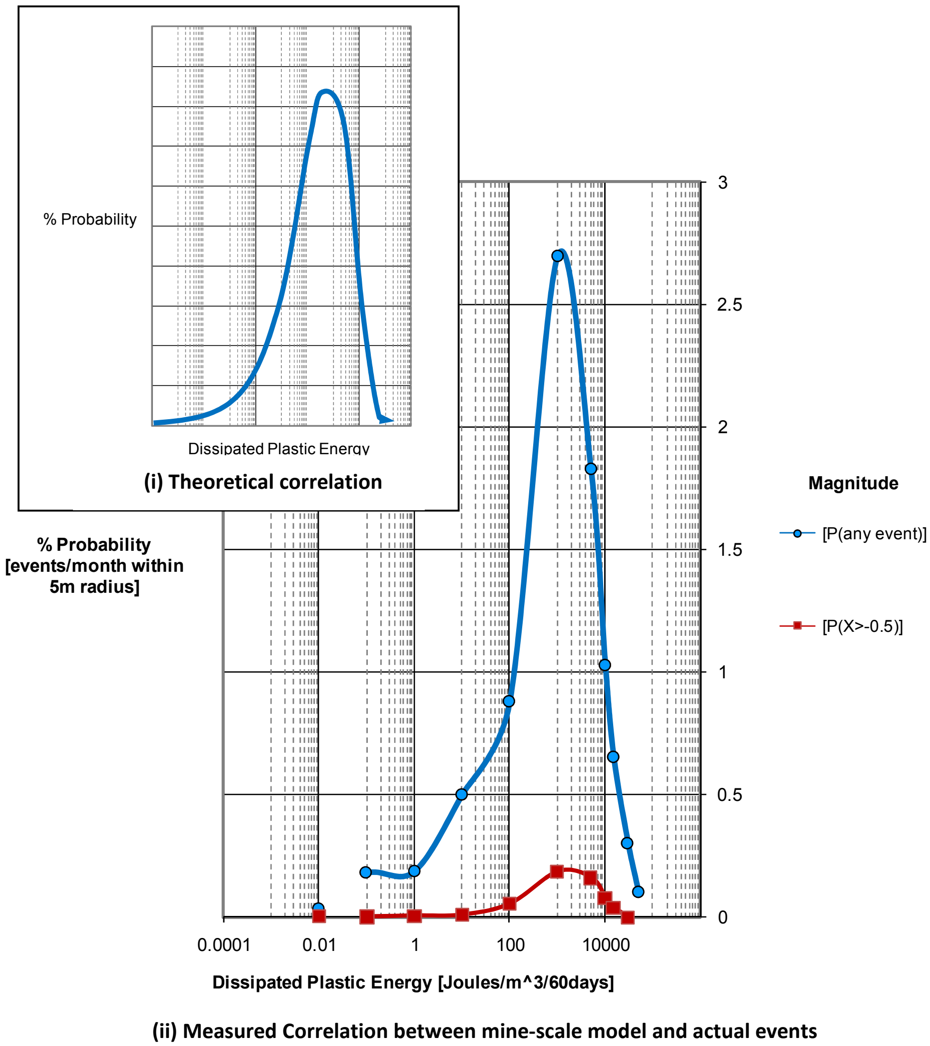

Figure 6 Correlation between DPE and event probability from a mine-scale analysis at an example mine

3.2 *Dynamic simulation*

A further comparison of the DFN with seismic behavior was undertaken as a demonstration of the dynamic simulation potential of DFN based models. A DFN for a brittle rock known to be prone to large seismic events in certain situations was subjected to the complete strain-deformation path forecast at a location in a mine-scale, strain softening, dilatant model that was indicated by DPE to be a high risk area for large events. In Abaqus, DFN sub models can be loaded using displacements at each node on the boundary, mapped directly at each model step.

The particular scenario simulated was the interaction between a deep block cave and an overlying cave, at a time when the lower undercut is just staring to interact with the overlying operation.

The DFN specimen at the high risk location was observed to undergo a violent and rapid transition from stable plastic deformation (stage 2) to unstable deformation (stage 3). The resulting 'synthetic' seismogram is shown in Figure 7. The Figure also shows a diagram of the state of yield on joints for a typical DFN before and after such a transition as well as the location of the DFN simulation within the global model.

The stable deformation during stage 2 is clearly seen to be associated with yield mostly on a single discontinuity set, and the transition to material instability occurred when another joint set yielded very rapidly. A close-up view of the seismogram during the early stages of the event, seen to the right of the Figure indicates a large P wave arrival for a single velocity component, and this corresponds very well to source mechanism, which resulted in an impulsive change in deformation in that axis at the point of rupture.

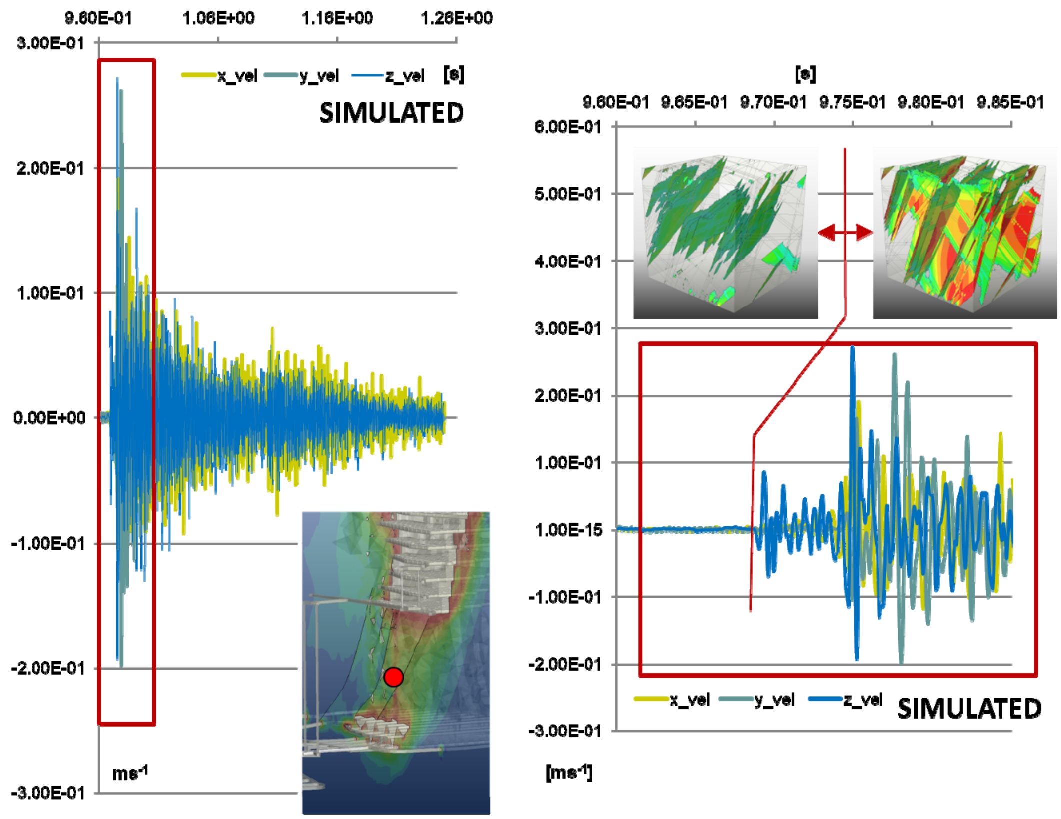

Figure 7 Simulated Seismogram of event occurring at transition from Phase 2 to 3. “Measured” at a corner node of the DFN sub model, loaded using stress path at the point shown in the block cave global model.

4 QUANTIFYING ROCK FRAGMENTATION AND DISASSEMBLY

Caving methods are an important method for underground mining. From a mechanical standpoint there are several large interacting domains of material behavior: the cave column comprising granular flow, a loosened zone of rock material, heavily fragmented but not exhibiting granular flow where fractures are open and significant new fractures have been formed, a seismogenic zone (Beck et al 2006) where fractures are nucleating and an elastic zone outside this. These zones closely match the 5 stages of rock behavior outlined in Figures 3 and 4.

The equilibrium that is reached between these zones is complex and a function of the physical coupling between them. Simulating deformation in any single one of these zones, as may be essential to ensure safe mining, requires that the deformation and load within all of the other zones is replicated as well: no zone of material behavior is decoupled completely from any of the others.

From an economic standpoint, the feasibility of a particular cave is affected by the particle size distribution within the cave. If fragmentation is insufficient, the cave may not propagate, or else the caved material may be too large to be handled efficiently by equipment. Fine material generated in one zone will also be significantly more mobile than coarse material, and as the fine material may not contain valuable material, an early ingress of excessive fine material can ruin a cave. Traditionally, empirical techniques for estimating the induced particle size distribution have been used, but these methods do not account for the complexity of the stress path in the cave back that is induced as the cave is propagated.

A new approach for assessing rock fragmentation and comminution using FE based DFN specimens has been developed. Based on the DFN approaches outlined above, the main benefit is that the estimate is based on the complete stress-strain path and can account for the complex 3 Dimensional interactions that occur at many different length scales.

The procedure is as follows:

– The DFN procedure described above was used to calibrate the discontinuous behavior of a REV for each geological domain of interest at the mine. As discussed, the intent was to make the DFN model reproduce as best as possible the stress-strain-strength-energy-structural interactions which have been measured at the mine.
– A global mine-scale model including the entire mine and a large margin of the terrain surrounding the mine is then built to simulate the stress-strain path for the complete rock mass.
– The deformation in this global model is used to drive the boundaries of REV DFN models at selected locations within the rock mass. An example of results from this procedure, in this case showing the changes to a particular size fraction at a specific location are shown in Figure 7.
– Each DFN produces an estimate of primary fragmentation at the location where it is simulated, as shown in Figure 7, or else the relation between plastic work and changes in fragmentation can be used in the global models to provide a first pass estimate in the 3D mass.

The work done on the rock mass by the caving process is essentially equivalent to the equivalent plastic strain energy induced. An example of application of the work-fragmentation relation derived using the DFNs, to interpret fragmentation in 3D using results of a global scale model is shown in Figure 8. In this Figure, a poorly fragmented zone of material can be seen, on this section of the cave. The rest of this particular cave footprint was not badly affected, but if a cave were to exhibit behavior like this over a significant portion of the footprint, significant issues including areas of high cave loads, more rapid drawdown from the exhausted overlying cave and poor caving in the unfragmented zone would be very likely.

At present, using existing empirical and stochastic techniques, estimates of fragmentation are provided at very few locations in the cave. The 3D nature of this estimation method is may offer a significant improvement, especially given the potential for it to be calibrated using measured data where it exists, or in new mines to provide a first-pass estimate based on laboratory scale measurements and field mapping alone.

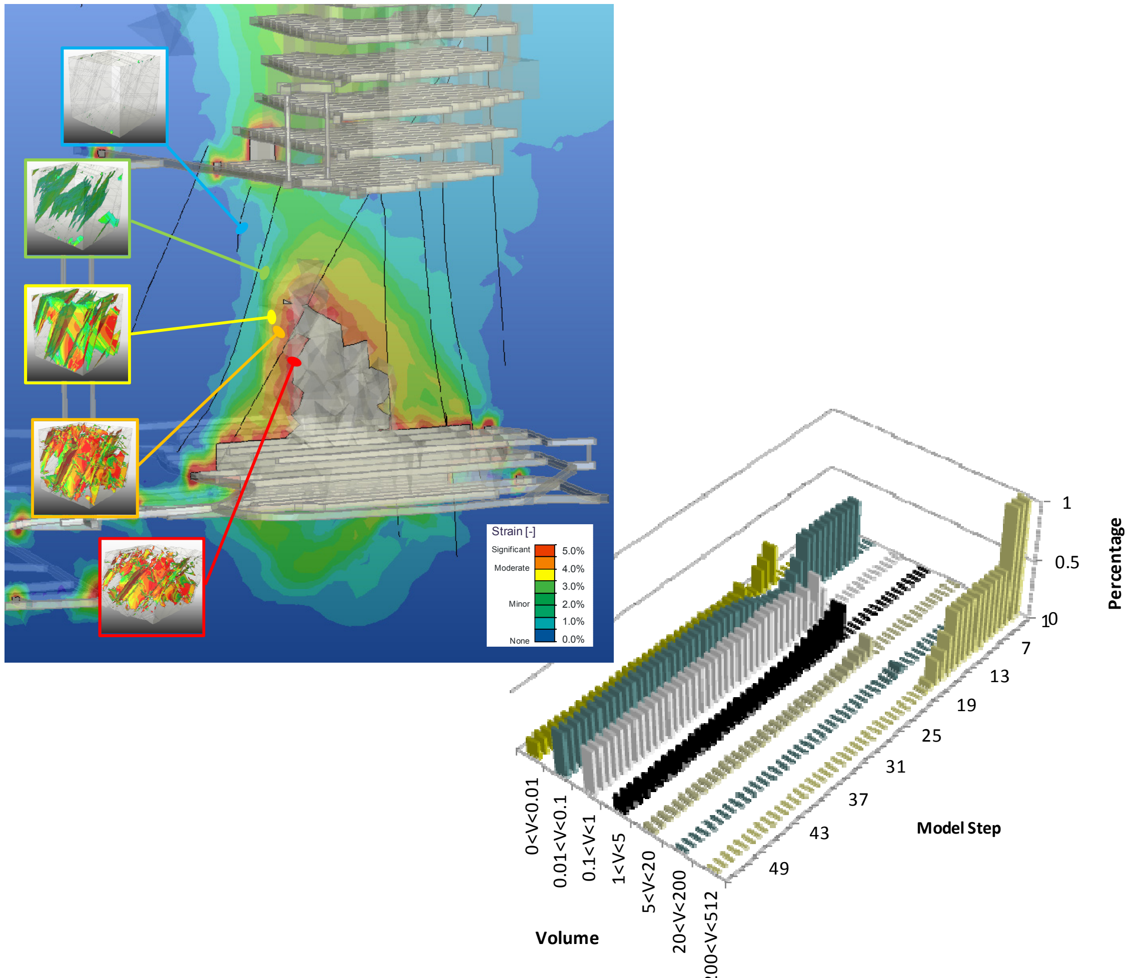

Figure 8. Changes to the P80 size fraction at selected locations above the undercut, forecast using DFN Abaqus models

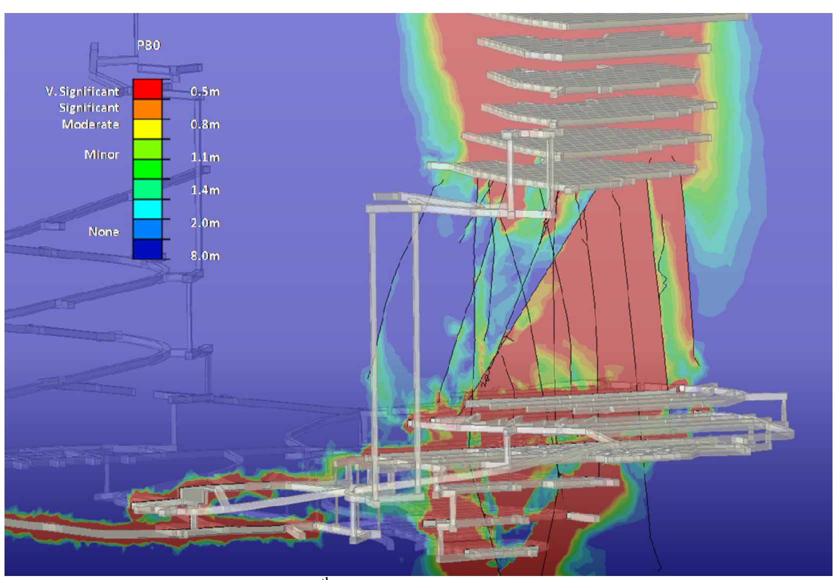

Figure 9. P80 (size of the 80th percentile fragment) on a section through an entire cave column. Any size fraction can be plotted

5 CONCLUSIONS

Some procedures for rock mass scale property estimation using 3D, discontinuous FE models and some potential applications have been tested. The results show that it is feasible to re-create realistic rock mass phenomena, including confinement dependence of the residual response, seismic behavior and comminution.

More work is required to better understand some of the applications of this technology, but it is probable that the techniques could eventually offer an analytical option for estimating rock mass scale material properties that improves on current empirical tools and serves as an adjunct to quantitative calibration.

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