Advances in Mining Simulation

Stephan M. Arndt, Brent P. Fillery, David A. Beck

Beck Arndt Engineering Pty Ltd, Australia

Mine scale finite element simulations are now a key design and planning tool for some of the world's largest and most challenging open pit and deep underground mining projects. Models with more than ten million degrees of freedom are regularly used for forecasting and probabilistic analysis of Life-of-Mine scenarios. These simulations, sometimes analysing decades of the extraction and continuing deformation of complex infrastructure, are run in less than a day on the Abaqus/Explicit parallel solver using 32 CPUs. The speed and benefits of high-similitude analysis has allowed Abaqus simulation to become more commonplace, and in some cases to be considered a requirement for sufficient analysis of high-value mine developments.

The next phase of improved simulation for mines will involve the incorporation of more detail and a more accurate representation of the governing physics of continuum-discontinuum problems, to attain improved similitude at all length scales. Two areas where significant improvements are expected in the very short term are in the simulation of the loads in masses of granular materials and in the behavior of elementary volumes of fractured rock.

Keywords: Mining, Caving, Fragmentation, Discrete Fracture Networks, DFN, Seismicity, Rockburst, Rock Mass Properties, Homogenization, Cohesive Elements, Eulerian Analysis, SRM.

1. Introduction

The mining industry has only recently gained access to high similitude, three-dimensional Finite Element modeling. Initially, the new generation of FE models for mines were largely continuum models with few discontinuities. As recently as just a few years ago, this was sufficient to represent a genuine improvement over the status-quo, boundary element elastic and lower order Finite Difference approaches. The improvements over elastic modeling are obvious, but the main gains over the legacy non-linear approaches came from little more than better constitutive models (strain softening, dilation) appropriate boundary conditions, realistic 3D geometry, higher order elements and appropriately small excavation steps to capture the stress path. An example of such a mine scale model (8.5M degrees of freedom) is shown in Figure 1. Even these simple gains had not been realized using previous approaches, usually because of computational inefficiencies.

As the new FE approaches become the new status quo, mines will begin to demand the next incremental improvements, and these will likely come from more complex material behavior and phenomena at interacting length scales. The next step is in fact necessary because of the highly non-linear and complex behavior of rock. All length scales in rock are coupled, the material behavior in most mines spans a range from granular flow to solid continua and the excavations that are being analysed span length scales from metres to kilometers. It is essential to capture these inter-scale, coupled physics phenomena to achieve improved precision and reliability.

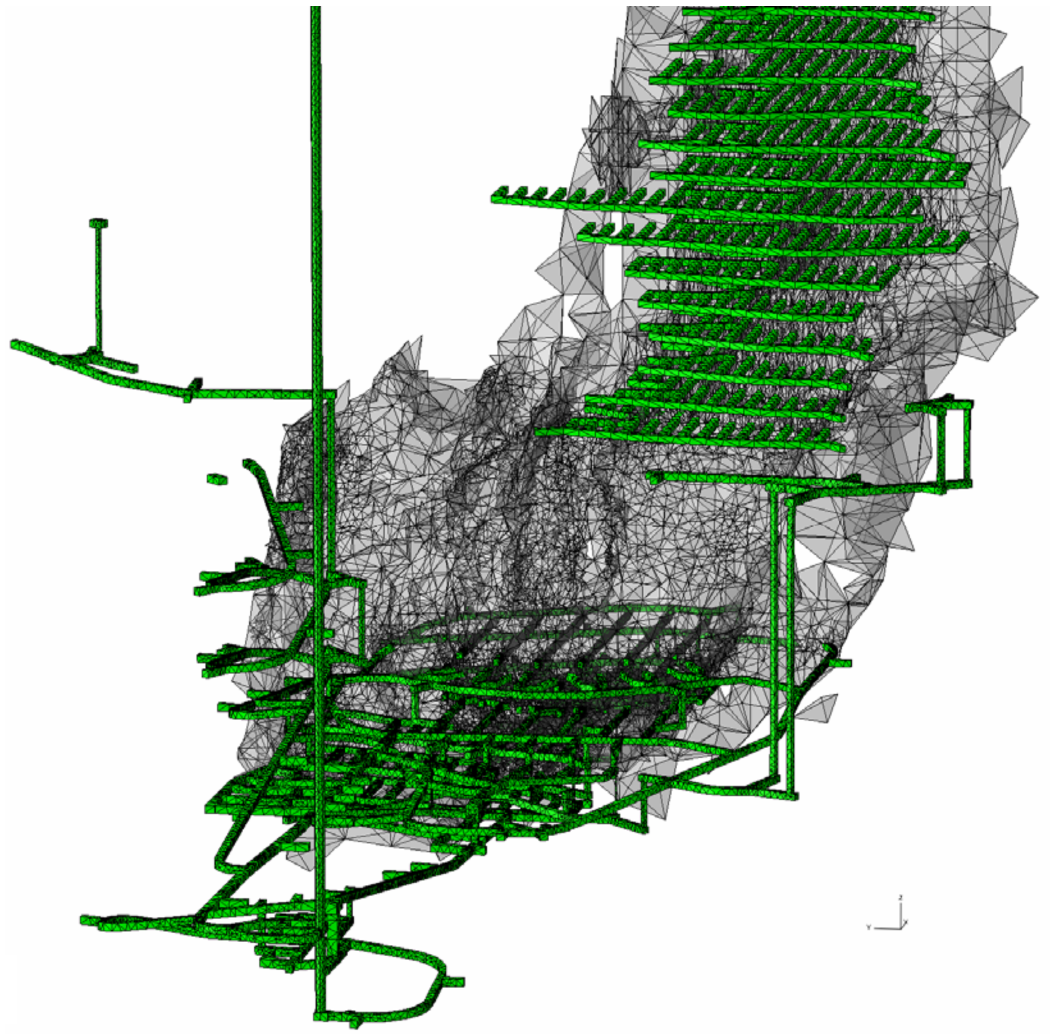


Figure 1. Mesh of a mine scale model geometry with a geological domain outlined.

Immediate gains are being realized by simulating the discontinuous rock behavior in elementary volumes using discrete fracture networks, modeled using cohesive elements and by simulating granular flow using an Eulerian representation. In individual mines, these disparate physical realms exist and interact in a complex way that cannot be simplified without introducing non-linear, and difficult to understand errors.

The methods and applications shown in this paper explain some recent developments and research activities related to these aspects of mining simulations, with a special focus on rock material behavior at different length scales and in changing states varying from the intact and stable rock mass to a distribution of broken particles in flowing cave material.

2. Modelling of Rock Materials

Rock exhibits a highly non-linear, inhomogeneous constitutive response. This arises because at every length scale, rock is observed to exhibit a jointed macrostructure that comprises intact segments of rock mass (bulk) separated by a network of faults or joints, referred to as discrete fracture networks (DFN). The inclusion of this structure in mine simulation is a most desirable outcome. However, it is almost impossible to do so at the present time. Instead, an effective or homogenised material response is usually required.

The preferred means of estimating homogenized material properties is by back analysis, where field measurements are compared with simulated values, with adjustments as required until a sufficient match is achieved. For quantitative calibration, measurements of 3D displacement or mining induced seismicity and micro-seismicity are most common though only the users of higher order, multi scale FE models aim for high levels of quantitative similitude.

For the quantitative approach, if the modeled values match the measured values with sufficient accuracy, a high confidence can be established in the calibration and forecasting performance. Examples of the successful application of FE models for quantitative calibration are shown in (Beck et al 2006, Reusch et al 2007 and Beck 2008). However, if measurements of rock deformation are unavailable or inadequate, another option for investigating material behavior is to construct detailed FE models of the Representative Volume Elements (RVE) of the rock mass. These RVE models are constructed using DFNs within Abaqus/CAE, to statistically match the distribution of the discontinuities in the rock mass.

These models can be used in a number of ways:

- Rock testing is usually limited to laboratory equipment used for small (<100mm diameter) specimens selected from intact rock, however at scales of just 1-4m, most rock masses can be up to an order of magnitude weaker than measured at this laboratory scale. By measuring the rock at laboratory scales, then by constructing DFNs composed of bulk material using these measured properties, the nature of rock at larger length scales can be estimated to a first pass level of reliability. 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 and joints that cannot otherwise be measured. Essentially, joint, fault and foliation properties are adjusted until the RVE being modelled reproduces the behaviour measured at a larger length scale. This in turn allows simulation of smaller scale phenomena using the DFN based RVE such as comminution, rock mass disassembly, fragmentation, tunnel stability and micro-seismicity with a very high precision.

The areas most at risk from seismic hazards are those which are most damaged. While a low probability source of seismicity, highly damaged areas are those most likely to be damaged by seismic waves. DFN based Abaqus models can be used to conduct dynamic tests of ground support. An example of a very heavy support system in an Abaqus model conditioned for this type of simulation is shown in Figure 2. Detailed explicit support simulation requires that the size and shapes of blocks and rock wedges in the walls is represented. Only a DFN approach allows this. Abaqus cohesive elements are well suited to this task.

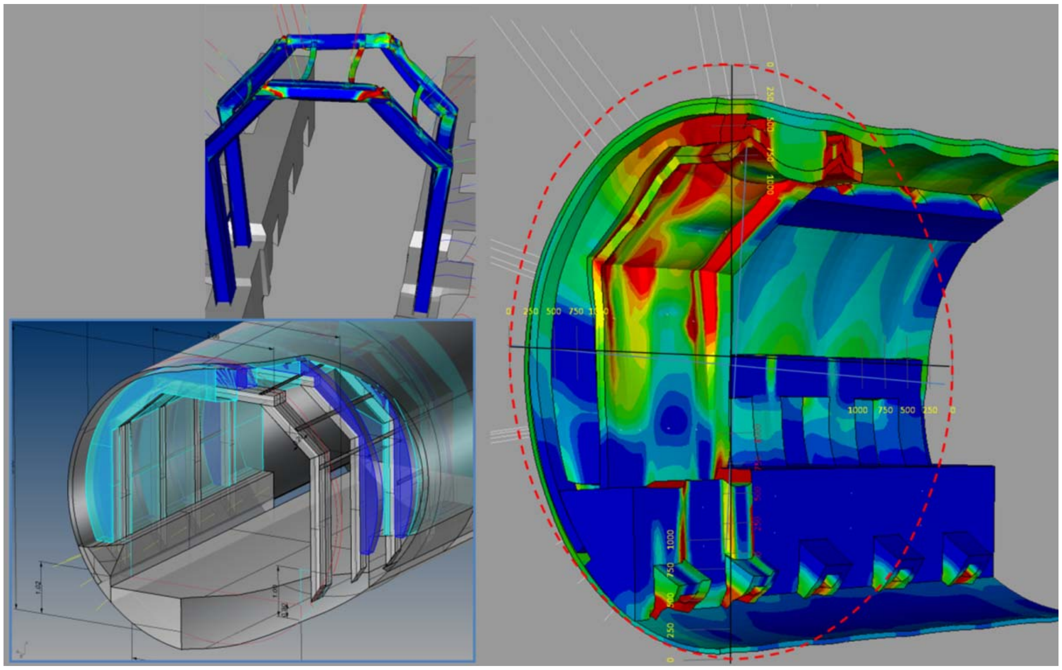


Figure 2. Example of detailed ground support model.

3. FE Modelling of complex discontinuous rock mass behaviour using Abaqus

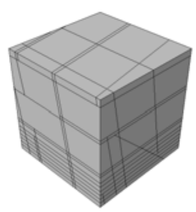
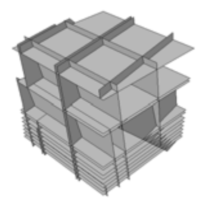
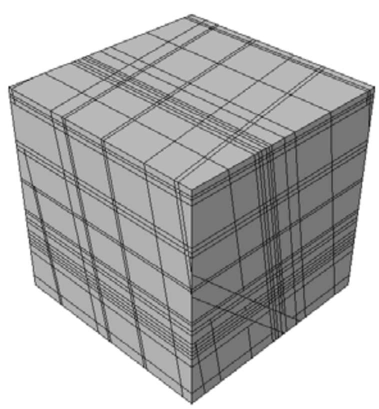
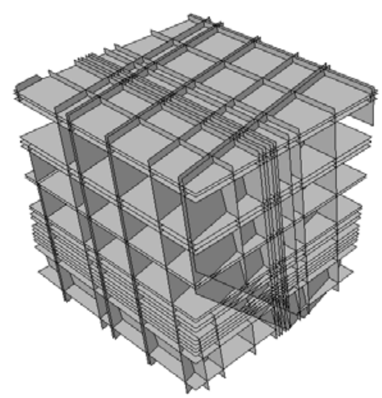
The feasibility of simulating complex DFNs using Abaqus has been tested by attempting to recreate well known, but difficult to capture interactions between stress, strain, structure, strength and energy.

First, Abaqus/CAE was used to construct DFNs of different sizes, 1m, 4m and 8m, of faulted rock mass specimens, as shown in Table 1, for materials for which a very reliable calibration of homogenised material properties was available, having been derived by using tens of thousands of field scale measurements. The joint spacing and orientation is taken from an extensive diamond core drill sample analysis performed by Western Australian School of Mines (WASM, Kalgoorlie) and applied to the DFN construction. Abaqus/Explicit was then used to test the response of these specimens to typical triaxial loading scenarios.

In this case, three levels of lateral confinement were used in successive runs, as the behavior of discontinuous rock masses is heavily dependent on confinement. Pressure scenarios were $\sigma_2=\sigma_3=5$MPa, $\sigma_2=\sigma_3=10$MPa and $\sigma_2=\sigma_3=30$MPa, which approximate the range of σ_2 and σ_3 conditions experienced in the shallow to moderately deep mines.

In this simple first test, the complex dependency of the known stress-strain response was captured, as can be seen partly in the summary shown Figure 3: strength and brittleness increased with confinement, strength decreased asymptotically with volume of the specimen, the violence of rupture depended heavily on confinement, scale and structural configuration. The degradation in friction angle, cohesion and stiffness over size of specimen was especially interesting, as there is no reliable empirical means for estimating this scale effect for geomaterials. The bulk response from intact rock not containing joints and therefore not size dependent shows a significant higher strength. It is possible that in the short term, parametric tests using DFNs in Abaqus may be used as the main standard for homogenization of studies of geomaterials.

Table 1. Discrete Fracture Network samples for different sizes.

 Characteristic Length = 1m	 Number of Joints / Cells = 2 / 3
 Characteristic Length = 4m	 Number of Joints / Cells = 31 /261
 Characteristic Length = 8m	 Number of Joints / Cells = 55 / 1388
Rock Mass Sample	**Joint Configuration**

For completeness the model specifics associated with these analyses are also summarised:

- The rock material was modeled using three dimensional 10 node tetrahedra (C3D10M) and a calibrated strain softening dilatant, user-defined Mohr-Coulomb based constitutive material (VUMAT).
- Fault / joint response of the DFN was approximated using a traction-separation based cohesive elements formulation (COH3D6) also on user-defined Mohr-Coulomb based constitutive material (VUMAT) setting the delete flag at a strain criteria.
- Fault / joint failure and subsequent remaining bulk material contact / sliding within the sample containing the DFN was modeled using cohesive element deletion in conjunction with Abaqus/Explicit`s General Contact capabilities.

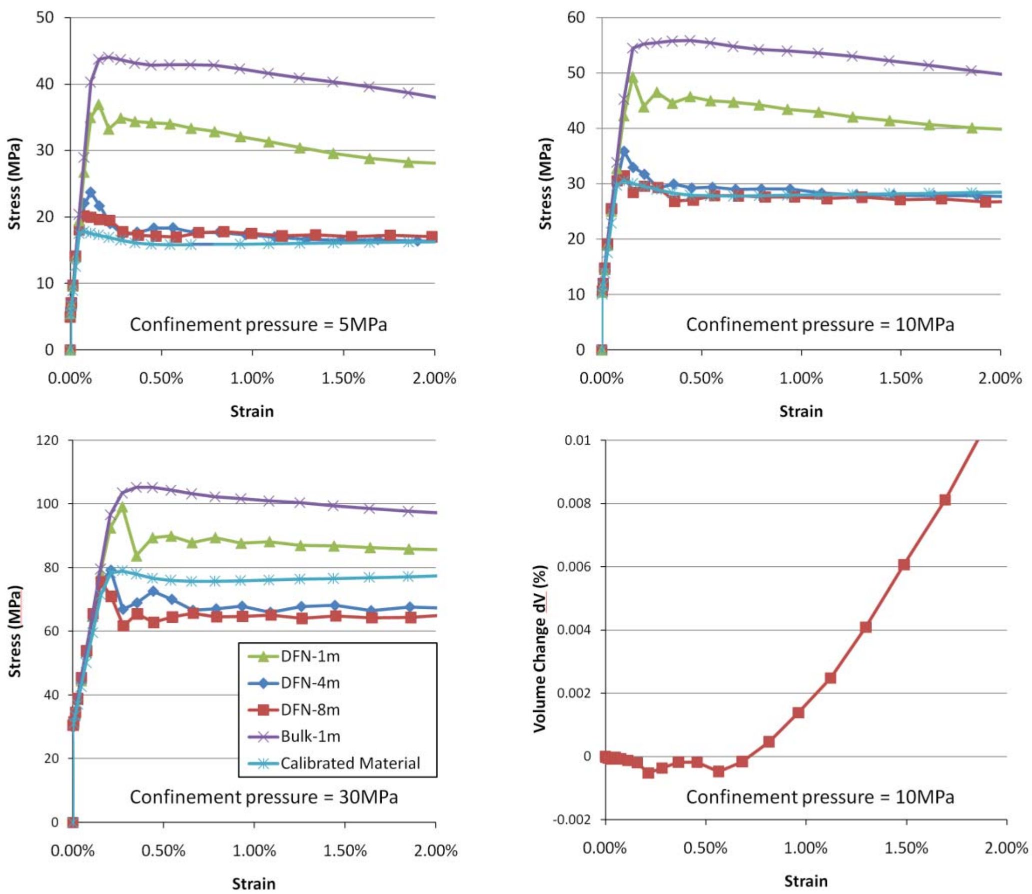


Figure 3. Size and confinement effects in uniaxial DFN tests.

There were two other especially 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 (CDS) and actual specimens of rock, recovered from locations within the mine where the corresponding level of damage was indicated by BAEs calibrated global model. There is an apparent complete compatibility between actual measured, DFN modeled and homogenized global model forecast rock condition.

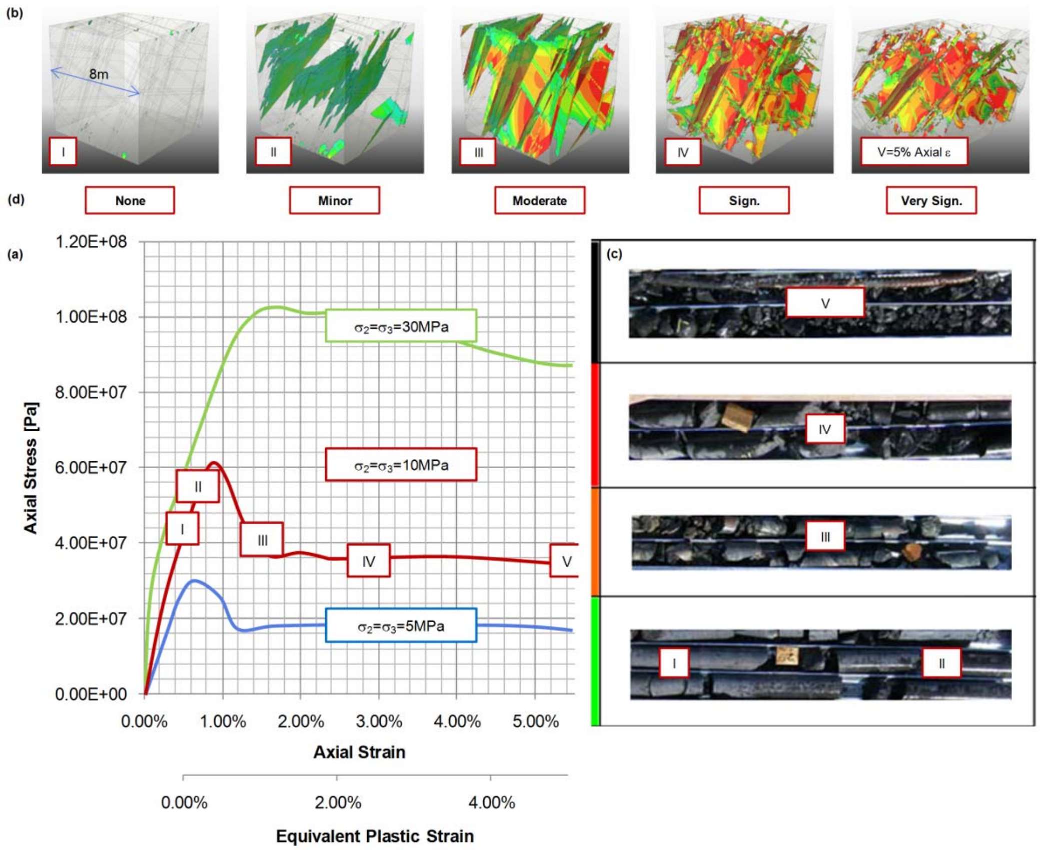


Figure 4. Comparison of (a) Stress-strain response of a simulated rock mass specimen (8m diameter) at varying levels of confinement. (b) The yield state of discontinuities and the deformation of the specimen at milestones of yield (c) photographs of diamond drill core specimens, simulated by the global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

Figure 5 shows the acoustic emissions indicated by high frequency transient stress waves at select locations within the DFN specimen during the tests. Acoustic emissions (AE) constitute a reliable and cost effective method of underground stress measurements at mine sites (Villaescusa et al, 2003). Shown as a cumulative plot on top of the modeled stress strain relation for one of the specimens, 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), followed by 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. This qualitative comparison provides an important confirmation of the nature of 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.

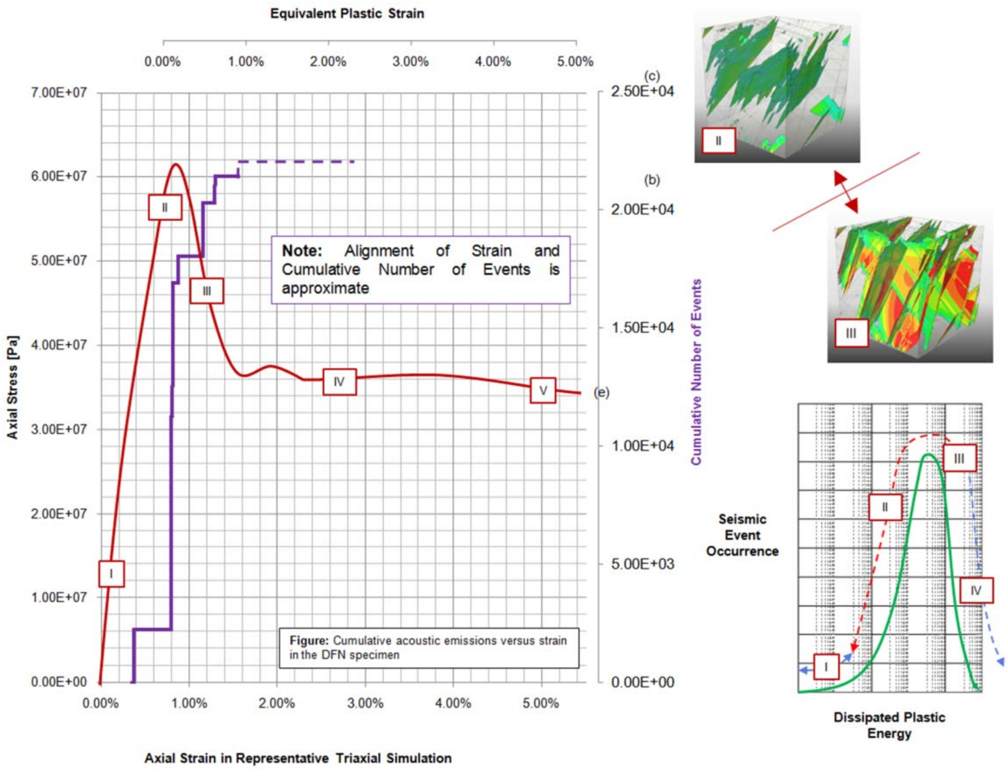


Figure 5. Correlation between stages of deformation and acoustic emissions for a DFN specimen.

4. Quantifying Rock Fragmentation and Disassembly

Caving methods are an important method for underground mining. In these methods rock is fragmented and mobilized by successively drawing material from the bottom of a column of 'caved' rock, at a level known as the extraction level. The initial cave is established by undercutting the cave column at a level just above the extraction level, known as the undercut. Provided conditions are sufficient, caves are propagated to the surface by the continuing draw from the extraction level.

From a mechanical standpoint there are several large interacting domains of differing material behavior: 1) the cave column comprising granular flow, 2) a loosened zone of rock material, heavily fragmented but not exhibiting granular flow where fractures are open and significant new fractures have been formed, and, 3) a seismogenic zone (Beck et al 2006) where fractures are nucleating and an elastic zone outside this. These zones closely match the five stages of rock behavior outlined in Figures 4 and 5.

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 financially ruin a caving operation. 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 Abaqus has been developed. Based on the DFN approaches outlined above, the main benefit is that the estimate is based on the complete stress path and can account for the complex three-dimensional interactions that occur at many different length scales.

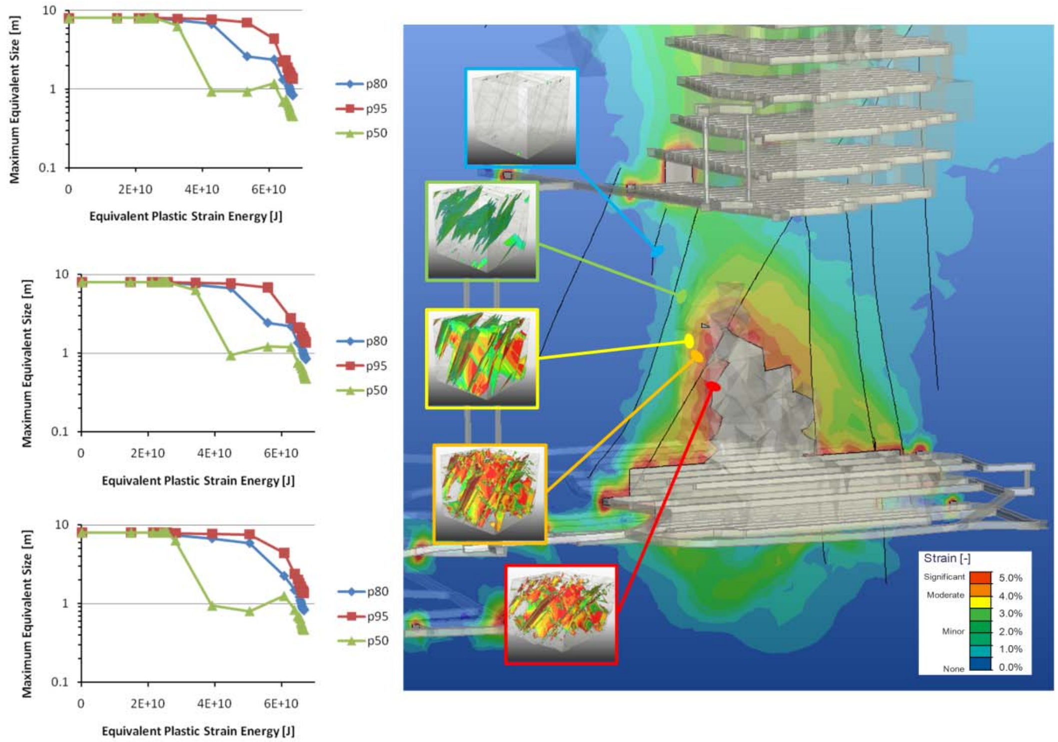
The procedure is as follows:

- The DFN procedure described above was used to calibrate the discontinuous behavior of a RVE 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.

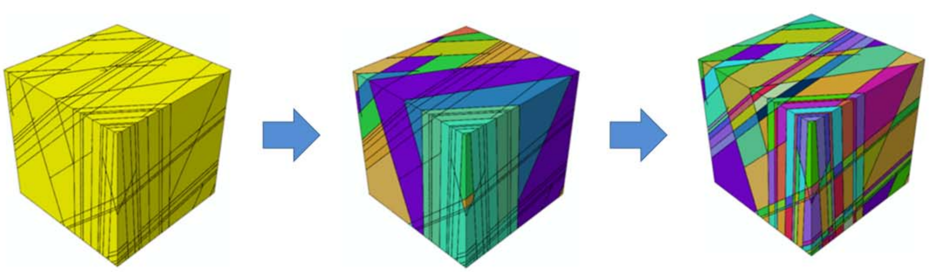
- A mine-global scale model including the entire mine and a large margin of the terrain surrounding the mine is then built to simulate the stress-strain path for the complete rock mass. The deformation in this model is used to drive the boundaries of RVE DFN models at selected locations within the rock mass. An example of this procedure, in this case showing the changes to a particular size fraction are shown in Figure 6.

- The relation between work done and changes in fragmentation are used to quantify a relation that can be used in the global models to provide a first pass estimate of primary fragmentation. The work done on the rock mass by the caving process is essentially equivalent to the equivalent plastic strain energy induced. An example of an 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 7. In this Figure, a poorly fragmented zone of material can be seen, and given the shape of this zone, it is probable that this would cause significant issues such as:
    - High cave loads on the extraction level,
    - More rapid drawdown from the exhausted overlying cave, and,
    - Poor caving in the unfragmented zone.

Particle size distributions are shown as the size for certain percentiles, i.e. P80 is the size of which 80% of the particles are smaller.



(a)



(b)

Figure 6. (a) Changes to the P80 size fraction at selected locations above the undercut, forecast using DFN Abaqus models. (b) Fragmented volumes formed by separation of joints.

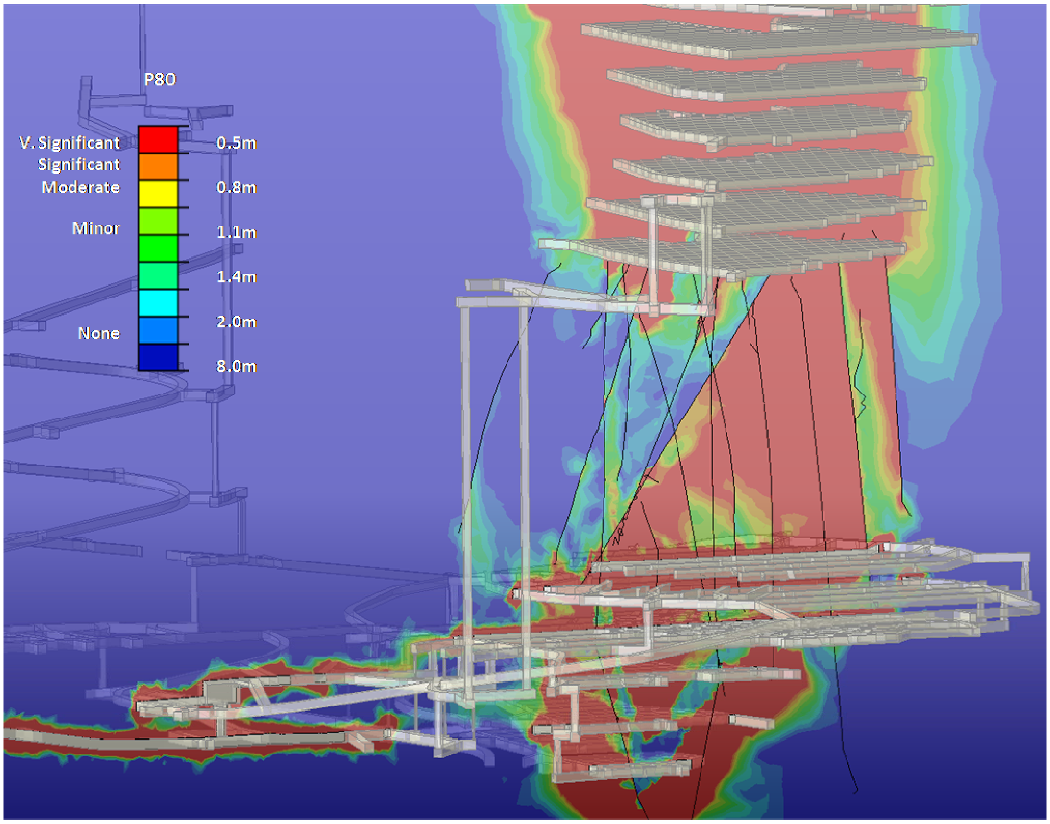


Figure 7. P80 (size of the 80th percentile fragment) on a section through an entire cave column.

5. Simulating cave loads and flow using Eulerian Capabilities of Abaqus

For caving mines the behavior of cave columns is a significant issue. The nature of flow of material within the column is a major factor in the underlying economic performance of a cave, while oversize material, or excessive cave loads can cause caving mines to fail. Globally, representing the behavior of the cave is also essential to simulate deformation, as the way that the rockmass and cave reach equilibrium is very complex. Capturing the nature of interaction is however essential if simulated deformation is to be correct.

There are few options for simulating the flow, mass scale properties and loads within cave masses:

- Typical size fractions for cave material mean that Discrete Element (DE) approaches are not yet applicable. Generally, 10^6-10^7 particles would be required, and such a simulation would currently take several months to complete on typical parallel compute clusters used for mine scale simulations.

- Lattice Grain Cellular Automata approaches are available, but only some aspects of the governing physics of material flow are captured. While in future this should change, it is not currently efficient to couple these codes to FE simulations as would be required.
- Stochastic approaches, currently most common, capture none of the physics of granular flow. There is no means for coupling such analysis, sensibly, to a physics based approach such as FE, or DE modeling, as is required if deformation and caving processes are to be simulated faithfully.

A new approach that is wholly contained within the Abaqus framework is to represent the granular flow using an Eulerian representation of the volume. The main benefits of this approach are:

- The boundaries between cave and rock mass can be efficiently coupled in the model using the general contact algorithm and cave loads on the extraction level and the confinement the caving mass provides are transmitted as contact pressure.
- The transition of material from the intact to the caved state is governed entirely by standard rock mechanics principles. There are no stochastic relations.
- The results of the DFN/RVE fragmentation analysis provide all necessary information that is required to conduct such analysis.

Some simple examples of this form of analysis in a mine setting are shown in Figure 8 and Figure 9. Figure 8 shows a comparison between a sand model after Kvapil (1965), where the use of colored layers allows tracking of the flow, and an Eulerian simulation in Abaqus. Simulated internal friction and subsidence are shown and compare well with the physical models. Differences in the extent of the ellipsoid of loosening (dashed line) are due to the material and geometry of the analysis not being intended to match this reference; the benchmark shows the ability to reproduce complex flow behaviour for granular materials.

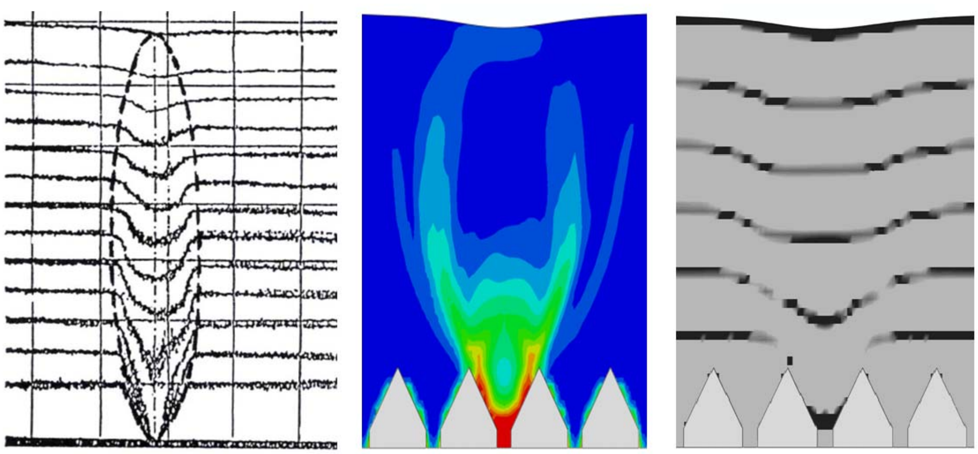


Figure 8. Zone of loosening in sand model (Kvapil, 1965, left) and eulerian analysis (middle, right)

Several applications of this type of analysis will become available as part of a mine scale model as performance tests on three-dimensional models show efficient run times and good scalability on parallel execution. The general draw performance of a cave is manipulated by adjusting the draw across different sections of the footprint to establish a favourable draw profile. At present these simulations are not based on physics, except for very limited sizes of problem. The general efficiency of the Eulerian approach in Abaqus will allow simulation of multiple caves.

An example of draw from multiple sources within the same cave is shown in Figure 9. The figure shows how draw contours can be influenced by changing between alternating draw, where draw occurs from only one source at a time, to interactive draw, where drawdown occurs from several sources at once.

In a mining context these techniques are proven, but when coupled with a mine scale FE analysis of deformation, especially within the framework of using DFN sourced relations between modeled work and fragmentation, there is potential to tailor draw strategies to achieve more significant outcomes. It is possible for example that coupled FE/Eulerian Abaqus models could be used to develop the best strategies to manage the kinds of problems shown in Figure 7.

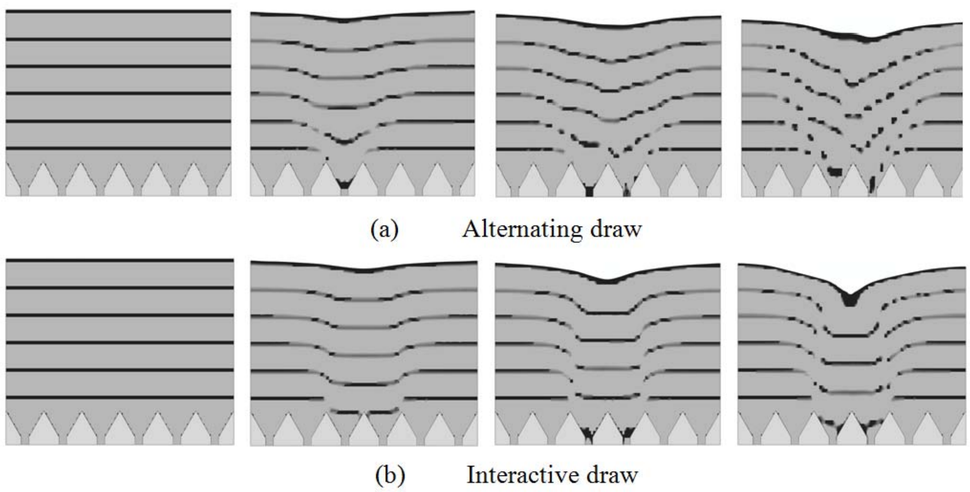


Figure 9. Flow comparison of example draw schedules

While caves generally propagate vertically, weak materials may preferentially cave. The simulation of this phenomenon requires that the complete process of rock mass degradation from intact material to cave material and then flow within the cave must be captured. A fully coupled simulation of continuum and flow domains is required to capture this. Abaqus with its eulerian capability is currently the only available code that can feasibly complete such a task in 3D for a mine scale problems.

A general fully coupled simulation capability for three-dimensional mine scale problems will require some further development. A user defined material interface such as VUMAT or access to volume variables is currently not available in Abaqus/Explicit.

6. Conclusions

Mines now have access to 3D FE simulation and it is already feasible to construct high similitude, multiscale models. The next phase of mine modeling will involve capturing more extreme rock behavior – large movements, granular flow and discontinuum behavior. Abaqus already provides many of the tools needed for this next step, off-the-shelf.

The main benefits of this will be significant freedom to analyse problems in a more direct manner. While these models will become increasingly sophisticated, the number of assumptions that are required will reduce, and the unknowns will become the subject of calibration.

Multi-scale, multi-physics models of higher complexity within the Abaqus framework will lead to improved standards for numerical modelling of mine deformation and better performing and safer mines.

7. References

1. D. Beck, F. Reusch, S. Arndt, I. Thin, C. Stone, M. Heap & D. Tyler. "Numerical Modelling of Seismogenic Development During Cave Initiation, Propagation and Breakthrough". Intl. Symposium Deep and High Stress Mining. Laval University, 2006
2. F. Reusch, D. Beck, S. Arndt. "Simulating Shaft and Crusher Damage in Deep Mines". Intl. Symposium Deep and High Stress Mining, Perth, 2007.
3. Beck, Pfitzner, Heap and Finn. "Interaction between block caves, large open pits and existing overlying caves". Proceedings of the 5th International Conference and Exhibition on Mass Mining, Luleå, Sweden, 2008.
4. Beck, D. A. "Multi-scale, non-linear numerical analysis of mining induced deformation". Proceedings of the 42nd US Rock Mechanics Symposium and 2nd U.S.-Canada Rock Mechanics Symposium, San Francisco , 2008
5. Kvapil, R. "Gravity Flow of Granular Material in Hoppers and Bins," Int. J. Rock Mech. Min. Sci., 8(3): 277-304, 1965
6. Villaescusa, E., C.R. Windsor, G. Baird and M. Seto. "Experimental verification of the Acoustic Emission technique of insitu rock stress tensor measurement, 3rd Int. Symp. on Rock Stress, Kumamoto University, Japan, 395402, Sugawara, Obra & Sato (Editors), Balkema, 2003.