Deep and High Stress Mining – Deformation and Seismicity

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Abstract: Recent advances in mine scale simulation allow direct calibration of modelled displacements using measurements of surface subsidence, tunnel wall closure, shaft deformation and observed damage. The ability to correctly simulate these phenomena on a mine scale, in a single model constitutes a significant step change. Legacy geotechnical modelling packages have been unable to simulate the whole of mine deformation.

The non-linear analysis, using the Mohr-Coulomb material model and user subroutines in ABAQUS/Standard, follows the stress path of the mining sequence in detail. Starting with the geostatic equilibrium, often itself the result of previous simulation of the geological history, the simulation includes methodical changes such as the transition from open pit to underground mining and often exceeds one hundred analysis steps in a 3D finite element model containing a mix of complicated underground geometry and geology. An excellent correlation of visible rock mass damage categories with plastic strain and the calibration of large numbers of seismic events with Dissipated Plastic Energy contribute to the relevance of forecasting capabilities. The implementation of performance indicators for underground support systems shows a typical application for using Finite Element simulations to improve the mine planning process.

Keywords: Mining induced Seismicity, Caving, Dissipated Plastic Energy, Mohr-Coulomb

1. Introduction

Recent step changes in non-linear modelling capabilities allow more detailed geometries and an ability to better simulate the complete stress-strain path in the rockmass surrounding underground mines. Compared to traditional non-linear modelling, the improvements allow significantly more realistic estimates of the nature and extent of yield, so deformation is forecast more accurately and with better reliability.

Consequently, simulated rock failure modes in such detailed models are more realistic. Also, the calculation of dissipated plastic energy is inherent to the inelastic material model and does not require further assumptions. This significantly simplifies model interpretation, as the quantities that are interpreted have simple to understand meanings.

The improved models have allowed detailed analyses of rock mass deformation processes.

1.1 Definitions

Back: Roof of an underground excavation, cave or tunnel.

Dissipated Plastic Energy (DPE, or DPE rate): The energy in joules dissipated as a result of yield in a mining step. The best parameter identified to date for correlation with seismic potential.

Draw: Material extracted from a cave. This results in the initiation and propagation of the cave.

Drive: Tunnel

Flow Cone (Caved Zone): The volume of mobile material inside a cave exhibiting discrete particle behaviour.

Fracture Cone: The volume containing macro-fractured material. Usually visible in aerial photograph of the area.

Fragmentation: Extend to which the intact rockmass is broken, resulting in smaller rock particle sizes. Low fragmentation can significantly increase production.

Seismogenic Zone: Refers to the volume where seismic events occur, usually large numbers of very small events induced by yield can be recorded on a monitoring system.

Subsidence: Surface movements, usually with a significant vertical component.

Subsidence Cone or Deformed Zone: The volume containing all material deformed by the cave, including elastic deformation.

Swell: increase in volume of extracted material / cave volume consisting of broken rock, compared to the initial rockmass volume.

2. Modelling

The key reason for selecting ABAQUS/Standard as the finite element solver are the robustness in highly non-linear applications and the performance for very large problem sizes. The capabilities significantly exceed those of the most frequently used geotechnical modelling packages.

2.1 Material Assumptions

The inelastic, dilatant material model using Mohr-coulomb plasticity is extended to strain softening, giving each different material peak and residual strengths. Once the peak strength is exceeded, cohesion and friction angle are reduced as a result of yield. Dilation angles for yielded materials are also calibrated. The implementation of this material extension in ABAQUS/Standard uses the User Defined Field (USDFLD) subroutine and solution-dependent state variables.

For material that has become part of the caved zone, either by blasting or caving processes, a field variable is used to change the properties to a low friction material that still accounts for the weight of the broken rockmass and provides the necessary confinement at the flow cone boundary. This is defined in the simulation history, derived from mine production schedules and swell calculations.

2.2 Mesh and Element Types

Due to the complexity of the geometries of mine scale models, only tetrahedral meshes, using quadratic elements (Type C3D10), are used. All models shown in this paper were built and meshed using ABAQUS/CAE.

3. Plastic Strain in an underground mining environment

Plastic strain is used to infer rockmass damage in the models of underground mines. Stress is not used as a higher order performance indicator as it is ambiguous – almost all deep mining is undertaken in an environment where the rock mass will yield as a result of the mining.

In this paper the description of damage is based on the Common Damage Scale or CDS (Beck and Duplancic, 2005). The CDS is presented in Table 1, with examples shown in Figure 1. The coloured contours for plastic strain are consistent throughout the paper.

	Class	**Description**
	Very Significant	Drive surface heavily deformed, drill holes crushed, support visibly loaded. → Substantial rehabilitation required to prevent frequent falls of ground
	Significant	Any or all of: Buckling, dilation of existing structure or induced fractures, failed corners and brows, hole problems. Bulking of the mesh is present in some areas. → "Spot" rehabilitation required to maintain access, more substantial rehabilitation required for drill and blast activity etc. Hole problems develop
	Moderate	Shearing on existing structure, visible yield. Frequent scats in the mesh, or material may be spalling under mesh. → Rehabilitation required only when intense activity will be undertaken in the area (ie drill and blast). Drive still safe for travel. Holes show more frequent signs of damage, sometimes requiring re-drilling.
	Minor	Minor signs of strain or displacement on persistent structures, some occasional scats in mesh. → No rehabilitation required.
	None	Blast damage/virgin stress damage only → Primary support controls drive surface

Table 1 Common Damage Scale (Beck and Duplancic, 2005)

Figure 1. Examples of Moderate to Significant Damage (Photograph by Capes, 1999, left) and Significant to Very Significant Damage (right)

4. Support Load

Ground support, typically consisting of steel bars, cables, concrete and steel mesh, is used to support the tunnels in an underground mine. Deformation induced by mining after installation of the support and to a lesser extent, rock mass creep, cause additional loads to develop.

This ‘support load’ is estimated following an approach incorporating ground characteristic curves (Brady and Brown, 2006). Ground characteristic curves compare the load-deformation response of an excavation boundary to the load-deformation response of a ground support system.

Historically, when this method has been applied for mining applications, a limited analysis of a handful of representative locations in a mine was undertaken as the analysis can be cumbersome and there is often difficulty calculating the ground characteristic curve. Advances in speed and model capacity using ABAQUS have allowed a step change and the analysis is undertaken for entire three-dimensional sections of very complicated mines, such as the example of a Sub-Level Cave (SLC) shown in Figure 2. This model consists of more than five thousand volume cells from partitions and boolean operations in the geometry part, meshed with about 240000 elements (1 million degrees of freedom).

To calculate support loads, the support load-deformation curves for each candidate support system are derived by numerically testing the stiffness of the complete support system in test sections of tunnels in a three-dimensional finite element model.

Next, the representation of support system is ‘installed’ in the mine-scale model to forecast the effects of induced deformation on the support. This is typically done within a model with monthly mining steps to ensure the stress path is simulated correctly. The excavation of the tunnel by blasting is represented by element removal and a substitute material stiffness representing the support system is introduced, following equilibrium, in a strain free configuration (**`*MODEL CHANGE, [REMOVE | ADD=STRAIN FREE]`**).

Subsequent mining induces the deformation and yield in the rockmass which load the support. In the example shown in Figure 3, the forecast and actual performance of support is compared for the SLC level highlighted dark grey in Figure 2. It was found that rehabilitation of ground support was required in 33% of areas where the modelled support load reached approximately 300kPa, and was required almost universally after 600kPa. In some areas 600kPa cumulative support load required multiple passes. The variation in the load required before rehabilitation is to be expected as there are a number of variables that aren't even recorded at the mines let alone simulated by the model.

To handle the variability, a qualitative probabilistic means was developed. By recording the total length of drive that requires rehabilitation in the mine, and comparing this to the result for the same period in each model step, a simple relation between support load and rehabilitation requirements is deduced.

The relation between support passes and support load is not direct-linear and this was expected; as deformation increases the likelihood of having to rehabilitate increases disproportionately as the annulus around the drive deteriorates more completely and the ground-characteristic softens. This means that in advanced stages of support load development it appears the rehabilitation demand grows very rapidly.

In this example, the match between the total measured rehabilitation and the forecast from support load for the relation is very good, better than +/- 10% for the first two passes of support repair. Figure 4 shows extensive forecasts of support performance and plastic strain throughout an entire mine section for one selected production sequence that was investigated.

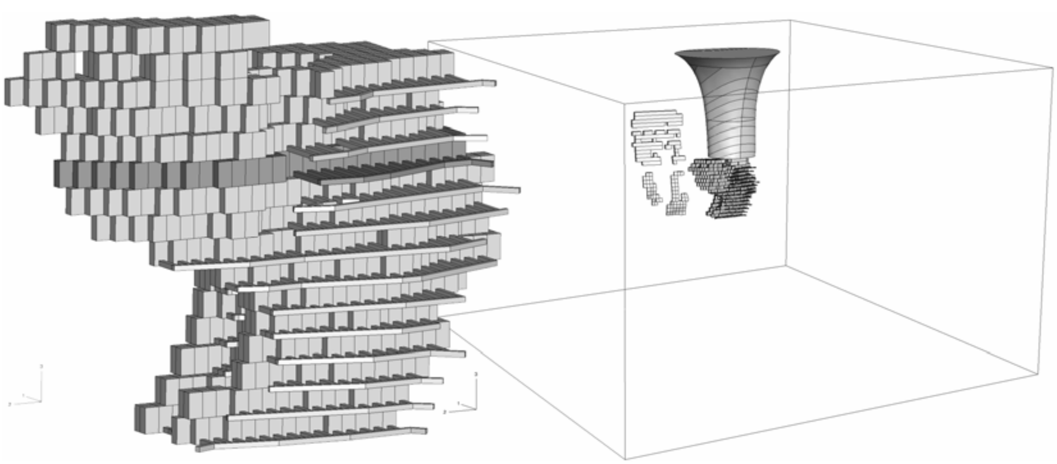

Figure 2. Geometry for the SLC (left) and volume containing selected adjacent mining regions in the ABAQUS/CAE model (right).

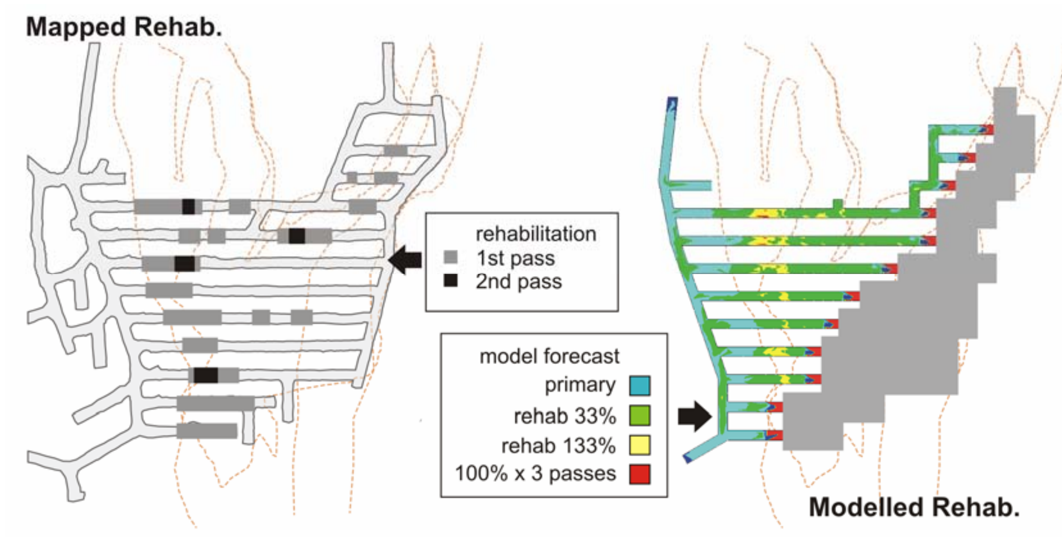

Figure 3. Interpretation of support load (right) and measured rehabilitation on a single level at an example mine (early production stage).

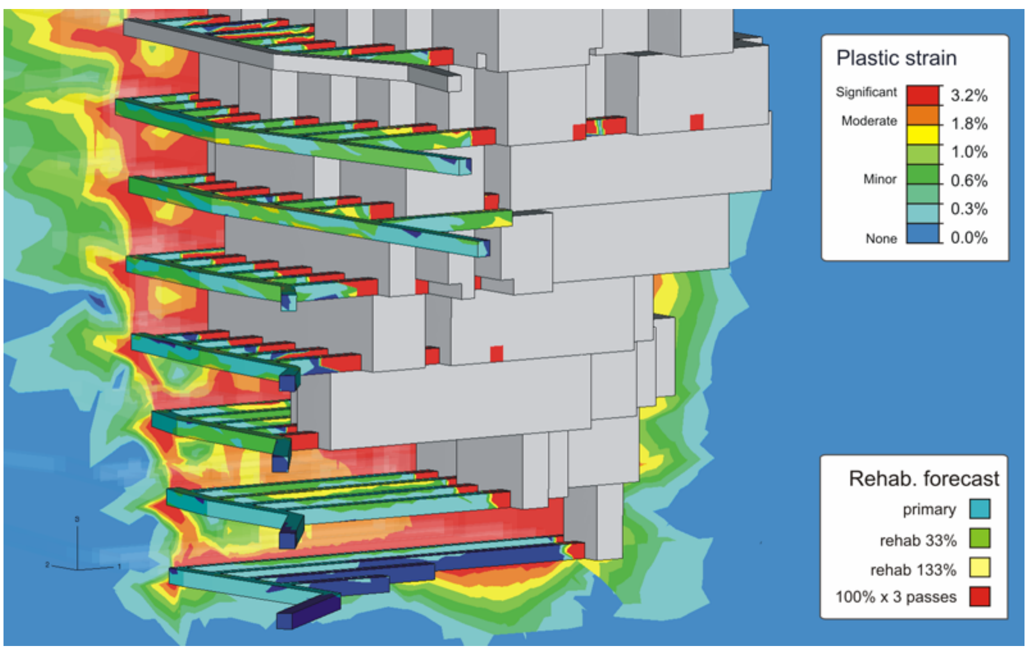

Figure 4. Modelled forecasts of support load (drive surface contours) and plastic strain (vertical cutting plane) through the lower section of a deep mine.

5. Interpretations of cave processes

Cave mining is an important mining method, as it allows extraction of ore from underground with low costs compared to other methods. It relies on the initiation and propagation of a continuously collapsing cave by extraction (or draw, as the broken material in the flow cone is drawn down) of ore from an underground horizon, generally consisting of an undercut level that establishes the cave and an extraction level for continuous production. The most fundamental engineering question arising from the method is the quantification of the cavability of the rock mass.

The finite element model is used to test the conditions for cave initiation and propagation by considering the size and nature of the zone of loosening and the seismogenic zone at each model step. To interpret cave processes, three main parameters are interpreted: plastic strain, modelled seismogenic potential and plastic strain decomposition. These are discussed below.

If at any stage the conditions for steady state caving are not satisfied after the planned caving Hydraulic Radius (HR) is reached (at which the draw percentage is planned to reach full production levels) the situation is flagged for further investigation.

5.1 Interpreting modelled rockmass damage using plastic strain

An example of modelled plastic strain at an early stage of cave draw is shown for an example mine in Figure 5. Areas of significant strain in proximity to the cave back and abutments are evident, and generally the damage diminishes with distance from the cave back, except in close proximity to the open pit which lies above the cave.

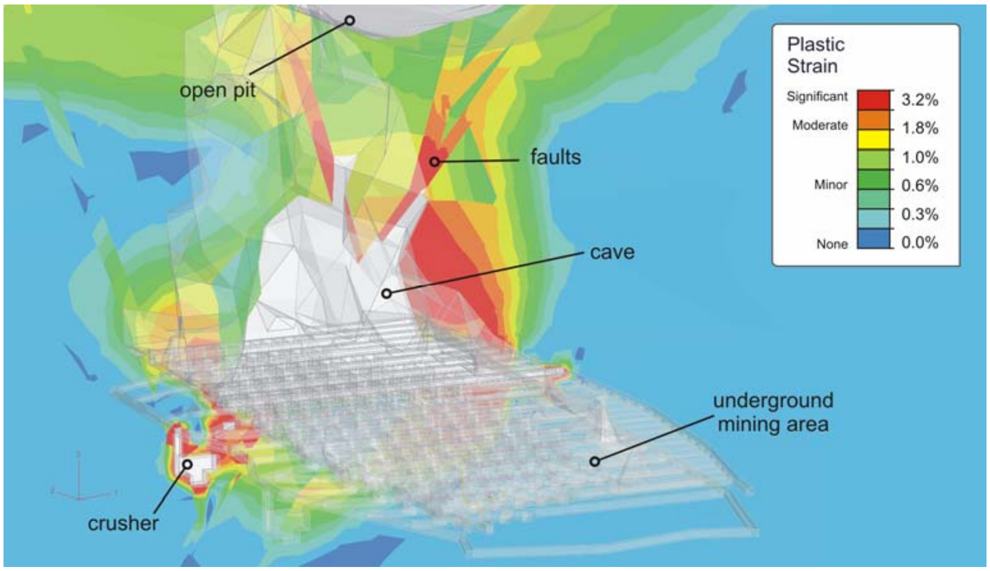

Figure 5. Example of modelled plastic strain at an early stage of extraction of a block cave.

In this calibrated example, high plastic strain in the cave back is a positive observation, as it suggests that there will be a good contribution to rock fragmentation by induced stress in advance of the cave.

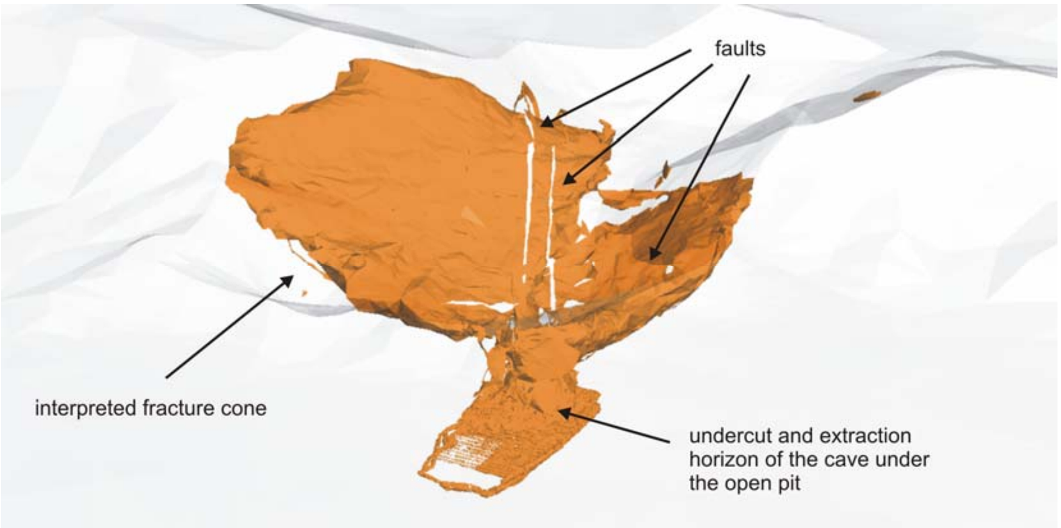

Figure 6. Volume containing 0.5% plastic strain, used to assist in interpreting the potential size of the fracture cone at an example mine.

In Figure 6, a view cut applied to the field output is used to visualize the volume containing more than 0.5% plastic strain. Experience at the example mines shows that this is a middle estimate for the extent of the visually discernible cave fracture cone. Naturally the plastic strain corresponding to observable, persistent fracturing varies with rock type, but generally plastic strain in the calibrated finite element model is the best single parameter for interpreting this important damage zone.

The figure demonstrates the characteristic fracture cone shape, the influence of the pre-existing pit on the growth of the fracture cone and the exaggeration of the damage zone due to significant faults which yield over a much larger extent than the rockmass.

The plastic strain interpretation is quantitative, but several key uses for the plastic strain plots are clear in the examples:

- A check for the contribution to fragmentation in the zone of loosening by cave induced stress redistribution (Figure 5).
- The effects of structure on cave induced fracturing (Figures 5 and 6).
- The potential for structure to prevent ‘desirable’ damage in areas of the cave (Figure 5).
- The size and extent of the fracture zone induced by the cave (Figures 5 and 6).

- The influence of the cave on the rockmass in the vicinity of important access-ways and infrastructure. The depth of the damage in the walls, as shown in the detailed example Figure 7 for a stage at the end of the mine life, and the magnitude of the strain can be directly related to support requirements and excavation stability.

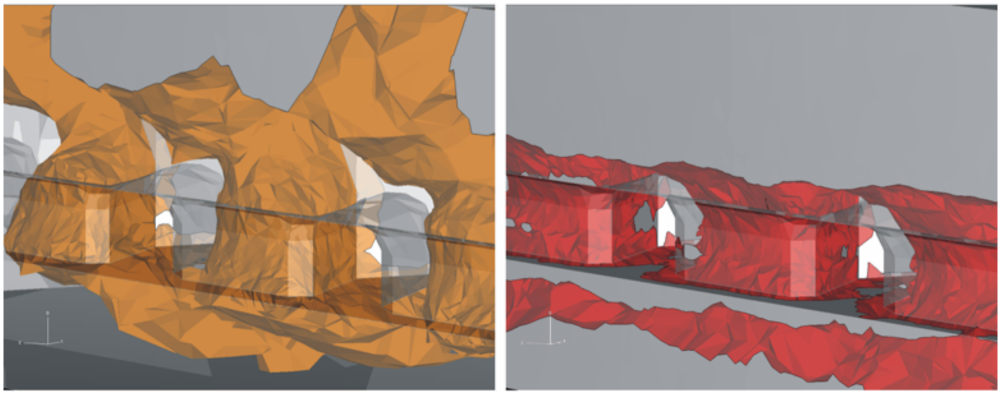

Figure 7. View cuts showing the intact pillars with less than moderate damage (left) and the extent of significant damage into the walls (right).

5.2 Plastic Strain Rate Decomposition

Any episode of yield can be decomposed into various components. Burridge and Knopoff (1964) explain the decomposition of strain due to yield, in order to interpret seismic source mechanisms using dipoles. Brady and Bray (1978) describe a solution for determining total stresses and mining induced displacements around dislocations in terms of dislocations or 'nuclei of strain' called quadrupoles, which were either volumetric (isotropic) or shear (distortional) strain. Brady (1978), extended the solution to a more arbitrary, three-dimensional case involving hexapoles. As a matter of interest, various types of strain singularities or dislocations, of which quadrupoles, hexapoles are a subset, were originally called 'nuclei of strain' by Love (1944).

The decomposition in these terms is useful, as the only remote quantification of yield that is possible – observation by measurement of seismic events – sometimes allows deconvolution of the measured ground motions to describe the seismic source in these same terms. Essentially, the modelled estimates of yield in a seismogenic zone can be directly compared to measurements from a 3D micro-seismic monitoring system. For this purpose, the plastic strain is split into its isotropic and deviatoric components:

Isotropic plastic strain is the component of plastic strain associated with dilation. For example, inside the zone of loosening the isotropic component is comparatively larger.

Deviatoric plastic strain is the component of plastic strain associated with shear dislocation or yield. For example, in the seismogenic zone the deviatoric component of plastic strain is comparatively larger.

An example showing the decomposition of the incremental strain components for a single mining step is presented in Figure 8. Decomposing the strain in this way allows detailed interpretation of the developing damage, and clear interpretation of a significant zone of loosening. It must be noted that these plots show the increment of plastic strain for a particular model-mining step.

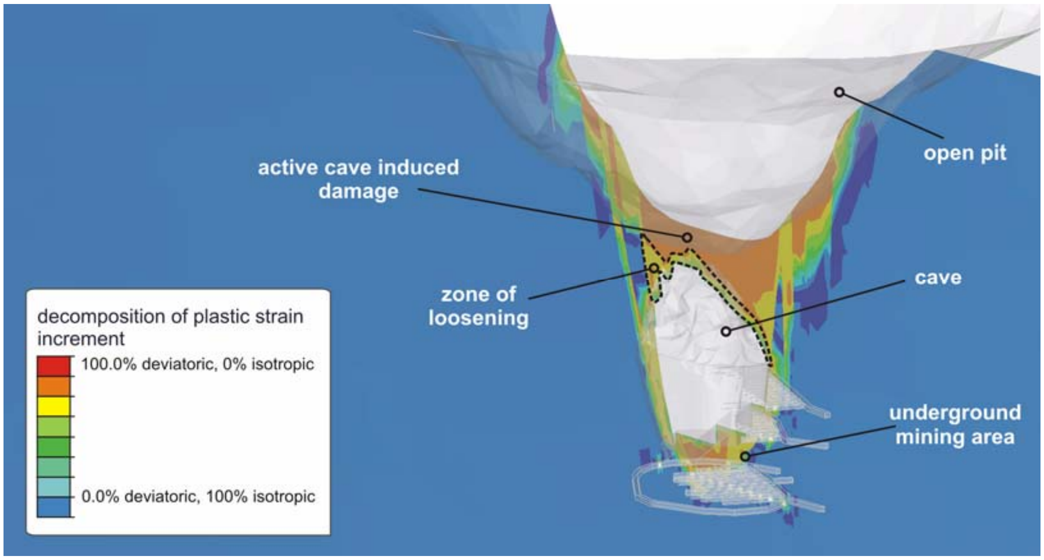

Figure 8. Split between isotropic and deviatoric plastic strain, showing mode of damage.

5.3 Seismogenic zone calculations

The Dissipated Plastic Energy (DPE) is the energy dissipated as a result of rockmass yield in a mining step. Generally DPE is all the energy released as a result of yield, and only a small fraction of this is released in the form of measurable seismicity. This ratio isn't constant, but is usually within a small range – typically 2-8% of total theoretical DPE is observed as seismic energy, (Gibowicz, 1993). The ratio is known as seismic efficiency.

To determine the regularity that certain levels of DPE release rate (DPE/ unit volume / time) will result in seismic events, a unique 'cell evaluation method' has been applied. The method is similar to the one described by Beck and Brady (2002) and involves discretising the entire model into regular, volumetric 'cells' or 'test blocks'.

To calibrate the relation between DPE rate and event seismogenic potential, DPE release rate is calculated in each of the test blocks for historic mining steps. Then, by comparing the proportion of blocks for each range of DPE release rate that contain and do not contain events, DPE release rate can be related to the probability of event occurrence.

The calibration procedure is performed at an example mine using 12 months of data and is presented in Figure 9. The figure shows that the boundary for event occurrence is continuous and bounded as required, evidenced by near-zero event probability at zero DPE release rate. Essentially, this means there are almost no unaccounted for seismic events (seismic events which occur where there is no DPE – this is an excellent and unmatched result).

The figure also shows that at approximately 2000 joules/m^3, the event probability decreases. This occurs because beyond this limit, the ground has been conditioned (softened by damage) and seismic activity must therefore decrease. For forecasting purposes, it is assumed that once a total DPE (cumulative for all steps) exceeds 5000J in previous mining steps, no more seismicity should be expected, and this is confirmed by analysis of the data at the benchmarked mine (less than 1-3% event probability where this limit has been reached in the model in previous steps). If greater than 2000J DPE is released in a test block in a single step, the probability decreases as shown in the graph. Smaller mining steps and smaller prediction periods would reduce the number of test cells affected by excessive deformation during an individual mining step.

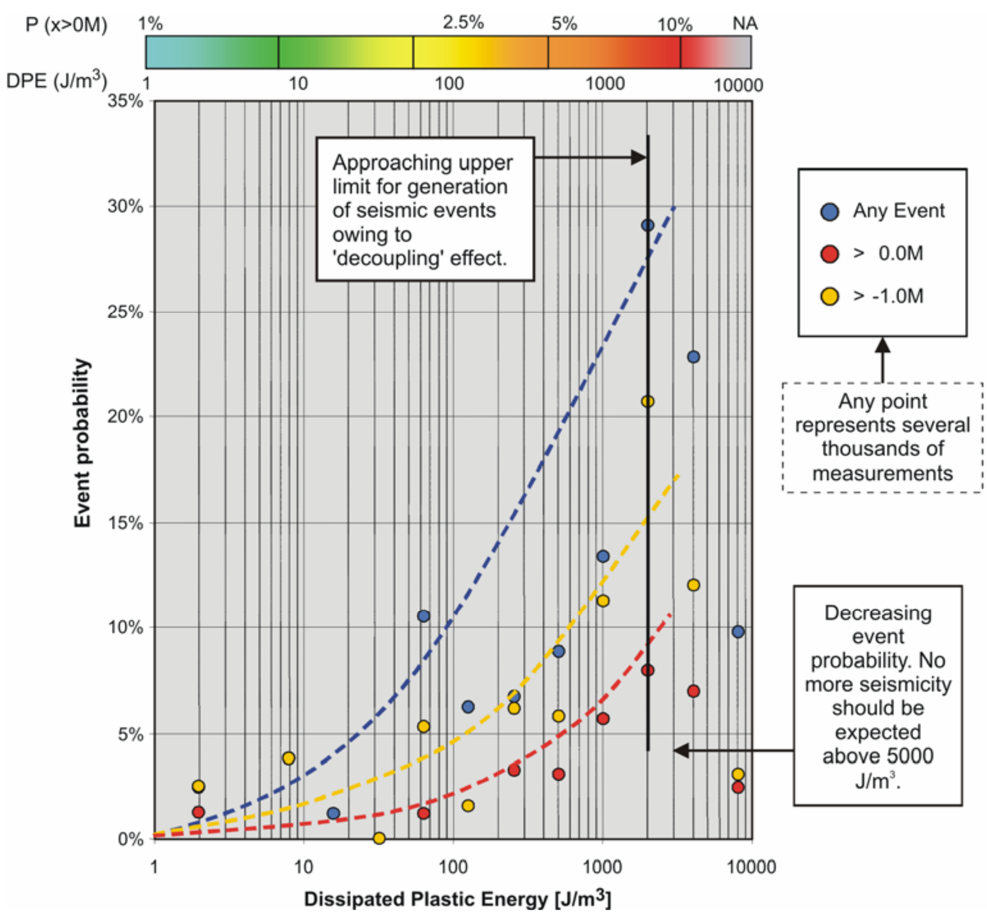

Figure 9. Correlation between event probability and Dissipated Plastic Energy [DPE] for a 1 month modelling step.

5.4 Seismogenic Zone Development

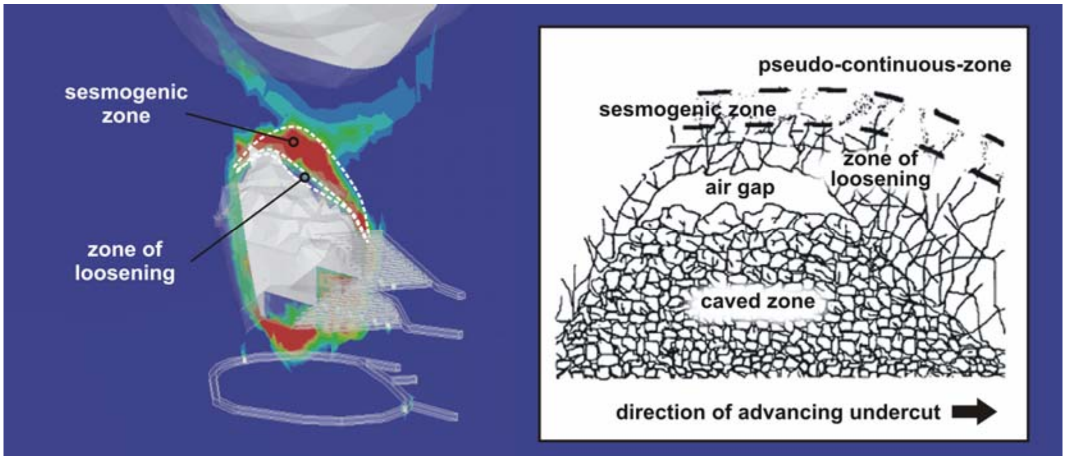

Figure 10. Caving process - Interpreted Seismogenic Zone and Loosening Zone using DPE (left) and Depiction of cave zones (Duplancic and Brady, 1999, right).

Figure 10 shows three basic zones in the steady-state cave. The seismogenic zone, named after the seismic events which are observed there, forms first. Here, new fractures are forming or damage is being done to existing discontinuities. Because rock will only be seismogenic until a certain level of damage has occurred, the seismogenic zone is transient; it is seen to migrate in advance of the cave.

Therefore, when assessing seismic risk, the complete history of model steps needs to be evaluated. Single pictures of DPE are simply 'snap-shots' and the sequence correctly never show areas of a mine to be permanently at a 'high' risk of significant seismogenic potential.

The zone of loosening forms next as the seismogenic zone moves away from the cave back. Less or no seismicity will be recorded in the zone of loosening, as too much damage has already occurred and ongoing damage in this zone does not satisfy the energy criterion (DPE) for seismic occurrence. The damage that occurs to a volume of rock after the onset of the seismic behaviour in it, right up to the material entering the cave zone is naturally cumulative, and this is measured using plastic strain as a direct measure of the accumulated damage.

Understanding the relationship between cave state and the nature of the seismogenic zone is important in order to appreciate the model results and to interpret seismogenic zone development during caving operations. The following is a brief list of some common seismogenic zone observations and possible explanations that will be used to assist in interpreting the seismogenic zone (DPE rate) model results, described by the current length of the undercut in relation to the Hydraulic Radius (HR) and illustrated by the sequence in Figure 11 for a deep mine:

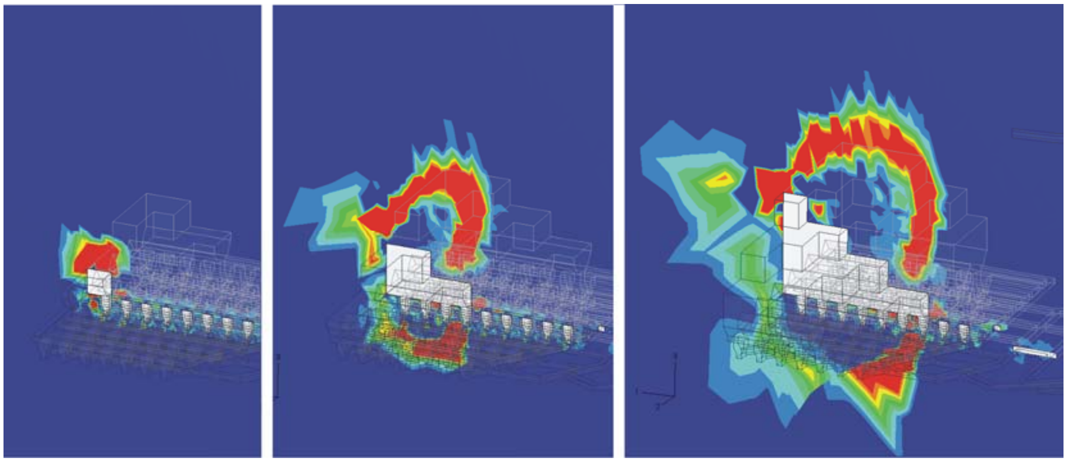

Figure 11. Seismogenic Zone and Hydraulic Radius (HR) - before HR (left), at (middle) and beyond HR (right) at an example mine.

- **Pre-Caving HR:** The seismogenic zone (if present) is constrained closely to the cave back. If local conditions allow the generation of an air gap or local caving, the seismogenic zone quickly dissipates as an arch is formed (Figure 11, left).

- **At Caving HR:** The seismogenic zone (if present) may be seen to move away from the cave back (and the zone between the seismogenic zone and the cave back becomes the zone of loosening). At some mines, caving appears to begin, but the seismogenic zone will then concentrate in the abutments while caving temporarily stalls. This can occur because some structure or other geological conditions were present that allowed cave initiation, but once caving begins the influence is reduced. The seismogenic zone moves to the abutments because an arch has formed, and stress is concentrating in the abutments of the arch. These observations sometimes mean that caving will occur in a stop-start fashion. It is important that this early instability isn't interpreted as steady state caving, as over-draw would result in an airgap. Usually, the cave is started again by continued advance of the undercut, by the conditions for caving being re-encountered or by assisting the cave by other means (Figure 11, middle).

- **Beyond Caving HR, Steady-State Cave growth:** If a steady state condition exists, the successive increments of draw-down of the muck pile will result in equal or greater advance of the seismogenic zone and a migration of the zone of loosening with the cave back. This is highly desirable, as if steady state caving is achieved no more unplanned rockmass conditioning is required and the air gap is minimised. It also means that risk control measures are more robust, as the mass balance to determine the air gap versus draw and cave height is simpler (Figure 11, right).

- **Cave Stalling due to inadequate HR or insufficient fracturing:** If the caving hydraulic radius is inadequate, the cave will stall. If the seismogenic zone never migrates away from the cave back, before seismic activity subsides, and then if draw does not propagate the cave, the HR is inadequate. If the seismogenic zone does migrate from the cave back, or becomes spread over a very tall column before the activity subsides, and then if drawdown does not propagate the cave, then fracturing is insufficient to propagate the cave. This may be evidenced by a low level of DPE in the seismogenic zone, but existing fractures can compensate for this so DPE shouldn't be relied upon alone to interpret caveability.

- **Beyond Caving HR, Run-away seismogenic zone:** This occurs when the conditions for stress induced damage are very favourable and the swell factor is low, but this is not always a good thing. Sometimes a runaway seismogenic zone could result from an unfavourable stress path, whereby the mining sequence causes only limited damage which is insufficient to generate good fragmentation, or else the loosening of the cave zone is inadequate for good flow. This is only relevant where the stress is being relied upon for good fragmentation. Other times, the runaway seismogenic zone may preferentially fracture a small part of the footprint, resulting in preferential draw from that zone. This is particularly important where waste ingress (material flow from outside the orebody) from above is a concern. Consideration of this vulnerability is particularly important when the developing fracture zone and cave may interact with other significant excavations or existing caves.

Using finite element simulation of the mining process in mine scale models at a number of mines, sequences with a pre-disposition to these problems have been identified. These mines have been able to adapt their designs in early planning stages. A detailed discussion of further aspects of caving for number of different mining sequences can be found in (Beck, 2006).

6. Conclusions

Recent advances in non-linear modelling allow realistic magnitudes and volumes of yield to be simulated during calibration at a number of mines, which in turn facilitates realistic forecast of deformation and support system performance.

Interpretation of the calibrated non-linear models assists in describing simple deformation processes using a number of variables. Some of these quantities may be unfamiliar to some rock mechanics engineers, but their interpretation is very simple as they are all theoretically measurable, and have meaningful physical definitions.

The quantities used to describe the caving process are:

- Plastic strain
- Displacement
- Dissipated plastic energy, which has been correlated with seismicity
- The split ratio of the isotropic and deviatoric components of incremental plastic strain.

The ratio of isotropic to deviatoric plastic strain is especially interesting, as the decomposition of plastic strain parallels the decomposition undertaken for measured seismic moment tensors. In the near future a detailed study of measured cave induced seismicity will be undertaken to compare the modelled damage mechanisms to the observed seismic events.

The understanding of cave mechanics will significantly improve as the new more-realistic modelling tools are used to interpret the interaction between stress, strength, strain and structure at a number of caving mines in near future.

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8. Acknowledgements

The work presented in this paper is a simple summary of some aspects of analysis and research undertaken at several mines over the last two years.

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