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Numerical Modelling of Seismogenic Development During Cave Initiation, Propagation and Breakthrough

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ABSTRACT

Large numbers of seismic events and displacement measurements were used to calibrate regional scale non-linear numerical models at a number of mines. Using these models, caving scenarios were investigated as part of initial design studies. A number of important caving phenomena were able to be directly simulated in the models.

Some of the mining variables and environmental controls that affect critical caving phenomena such as stalling, rapid propagation and a number of outcomes for initiation have been investigated and some new interpretive concepts for interpreting measured seismicity and strain during caving operations have been developed.

These concepts are based on common rock mechanics principles, but include consideration of techniques very similar to considerations for moment tensors at selected milestones during cave development.

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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. 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.

As deformation is forecast more accurately, energy terms and simulated rock failure modes are also more realistic. This significantly simplifies model interpretation, as the quantities that are interpreted have simple to understand meanings.

The improved models have allowed detailed analyses of caving processes, from initiation to propagation, to breakthrough and growth of the fracture zone.

1.1 Definitions

Swell: un-swelled volume of extracted material / cave volume. In most modelling swell inside the cave is assumed.

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.

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

Plastic Strain: dilation (swell) due to yield

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

Deviatoric plastic strain: 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.

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.

2 MODELLING

The modelling package used was Abaqus Standard. Abaqus is a general purpose, 3-D, non-linear, production oriented finite element analysis product designed specifically for advanced, significant plastic deformation applications.

The key reason for selection of Abaqus as the simulation package for cave simulation, is its speed, very large problem sizes and the ability to simulate very large strains. The capabilities significantly exceed those of the most frequently used geotechnical modelling packages. These have more significant effects than just short run-times and model complexity:

- Rapid run times allow economic simulation of large numbers of model cases.
- Small time steps allow proper simulation of the stress path. Most legacy modelling packages are too inefficient to allow small model steps, resulting in excavation steps that ‘jump past’ areas of interest in the model. If the stress path is not correctly simulated, the extent and magnitude of yield will not be properly simulated and displacements and strains will be meaningless.
- Small time steps give more opportunities to match model data to field measurements.
- Comparatively large problem sizes almost eliminate the need for sub-modelling techniques for most mining problems. When sub-modelling techniques are used in Abaqus, the donor model is completely non-linear, the excavations and geology inside the sub-modelling area are still represented in some detail in the donor model, and the complete load deformation path is matched perfectly to the sub model boundary at each model step. The boundary material conditions, stress and displacement are perfectly transferred to the sub model for each model step.
- The high model efficiency allows the use of quadratic elements throughout the problem. Quadratic elements provide improved precision because derived quantities, such as strain vary throughout the element, whereas for linear elements these values are constant throughout the element.

Combined, these advantages facilitate the necessary simulation capabilities to replicate realistic caving phenomena.

2.1 Material Assumptions

Mohr-coulomb strain softening, dilatant material models for material behaviour are usually used.

The inelastic material model assumes that each material has peak and residual strengths and elastic properties. Once the peak strength is exceeded, residual strength and elastic properties are introduced. Cohesion, friction angle and compressive strength are all reduced as a result of yield, and a dilation angle for yielded materials is calibrated at the benchmarked mines.

2.2 Cave growth Assumptions

The cave is represented as a low friction material, introduced manually following the planned draw strategy and assuming a swell factor based on experience. The cave geometry is based on a simplistic assumption of cave growth in order to reflect the draw strategy. As the swell factor is not known, a range of swell factors are tested.

Cave growth is simulated in the NL-FE models by converting rock elements into cave elements, subject to a model for cave growth that is based on the expected geometry, prescribed draw strategy and swell factor.

The contact between the cave material and the rock interface is assumed to be active. It is also assumed that cave growth is initially vertical, as at depth this is almost always the case. During cave propagation a significant fracture zone develops around the growing cave, and this is often skewed from vertical. At depth the growth of the fracture zone is calculated by the calibrated NL-FE model and is often very large, accounting for the occasional mis-interpretation that non-vertical cave-growth is occurring. To simulate the effects of draw from yielded zones outside vertical, a coupled DE-NL FE or FE-stochastic flow model would be required.

The assumed swell factor is a significant factor in many of the geotechnical conclusions. To limit the effects of the swell factor on conclusions, results are referenced against the geometry of the cave at the time, rather than the scheduled time that geometry would be achieved at the assumed swell factor. This is useful, because the required controls to manage deformation are often geometric, such as the height the cave must be allowed to develop to before outer drawbells in a block cave are developed.

3 INTERPRETATIONS OF CAVE PROCESSES

The 3-D NL FE model tests the conditions for cave initiation and propagation considering the size and nature of the zone of loosening and the seismogenic zone at each model step. To interpret cave processes, 3 main parameters are interpreted: plastic strain, modelled seismogenic potential, 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 is reached (the HR at which the draw % is planned to reach full production levels) the situation is flagged for further investigation.

BAE chose this method because realistic cave geometries are interpreted, the effect of different draw strategies on cave back stability can be tested, a large number of parameters are evaluated to interpret ongoing cave propagation and the interpretation is transparent.

The method relies on simple and accepted rock mechanics, based solely on the well known mechanics of rockmass yield and strain softening.

3.1 Interpreting modelled rockmass damage using plastic strain

Plastic strain is the strain due to yield in the model. It has a positive correlation with damage, unlike ‘stress’, which has a non-linear correlation with damage. This means that when forecasting rockmass damage, plastic strain is easier to interpret.

Factor of safety is often used to interpret rockmass damage in the model, but it doesn't correlate with observed damage in a directly calibrated non-linear model. This is because in the well conditioned model, all areas that should have yielded have softened and degraded, and the stress condition has compensated. Material is either yielded or unyielded, and the extent and magnitude of the yield should closely match field observations.

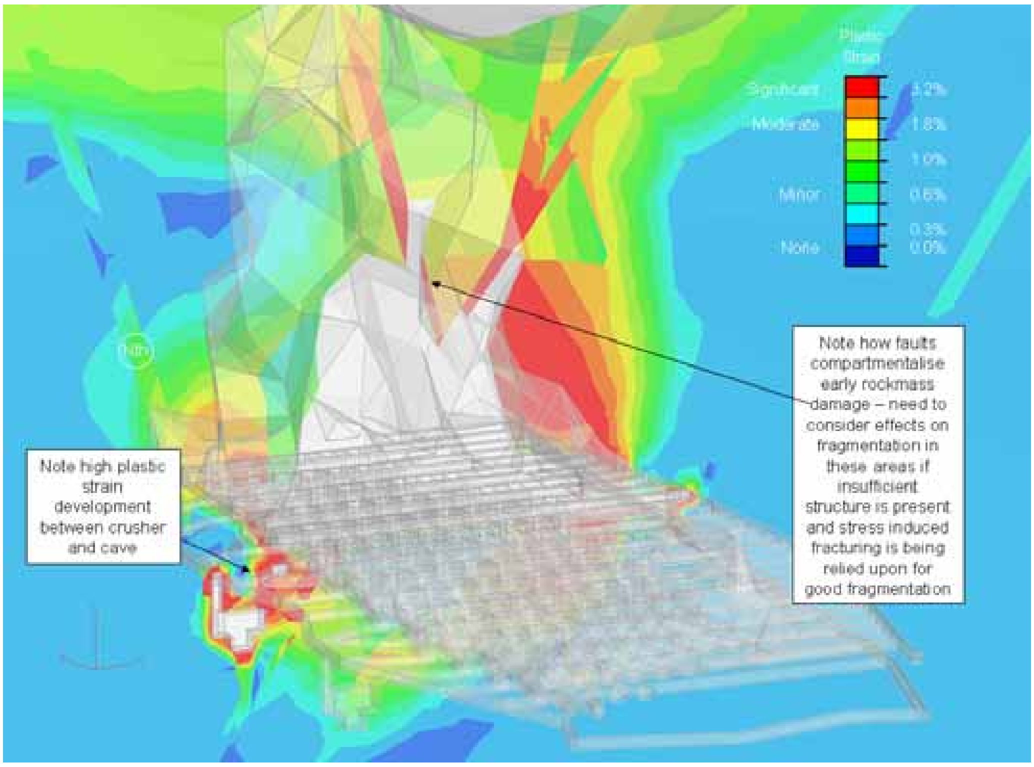
To assist in interpretation of the meaning of plastic strain, the Common Damage Scale, or CDS (Beck and Duplancic, 2005) can be used to interpret the meaning of Plastic Strain. The CDS is presented in Table 1.

Table1 BAE Common Damage Scale

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

An example of modelled plastic strain at an early stage of cave draw is shown for an example mine in Figure 1. Areas of high 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.

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.



Note high plastic strain development between crusher and cave

Note how faults compartmentalise early rockmass damage – need to consider effects on fragmentation in these areas if insufficient structure is present and stress induced fracturing is being relied upon for good fragmentation

Figure 1 Example of modelled plastic strain at an early stage of extraction of a block cave. Differential growth in the damage zone around the cave and the effects of regional structure are clearly evident. The mine was able to adjust the cave layout to optimise the effects of plastic strain.

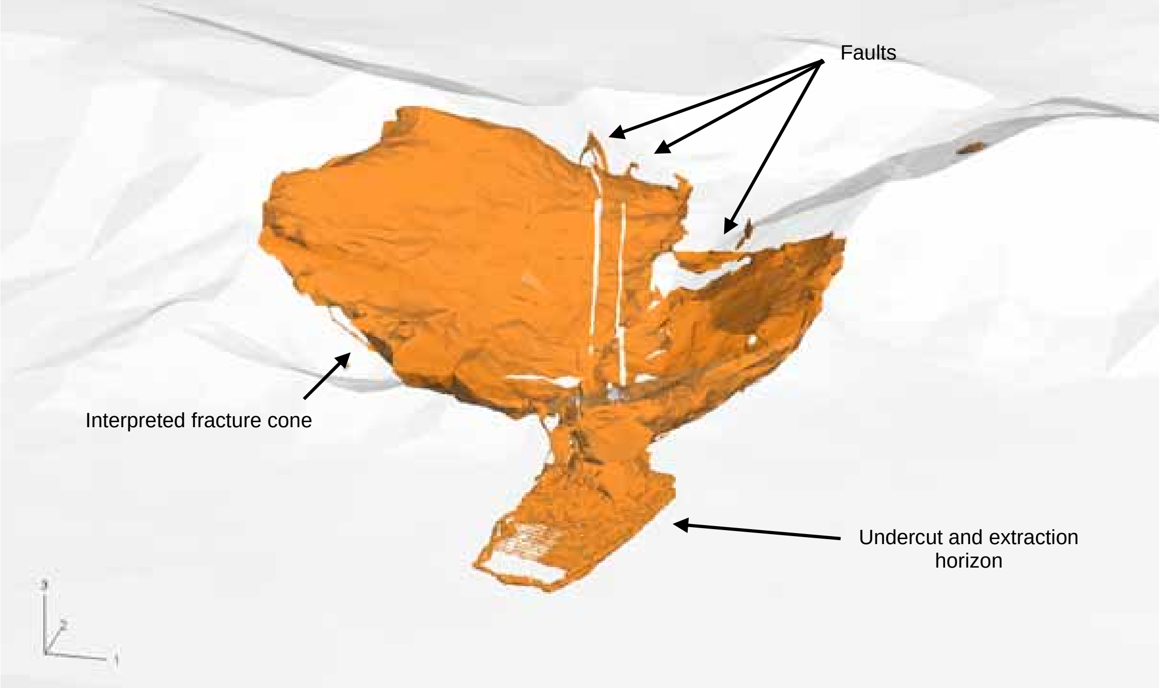


Figure 2 Volume containing 0.5% plastic strain, used to assist in interpreting the potential size of the fracture cone at an example mine.

In Figure 2, a surface has been fitted around 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 3D-FE model is the best single parameter for interpreting this important damage zone.

The figure shows 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 (Figure 1).
- The effects of structure on cave induced fracturing (Figures 1 and 2).
- The potential for structure to prevent good damage in areas of the cave (Figure 1).
- The size and extent of the fracture zone induced by the cave (Figures 1 and 2).
- 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 and the magnitude of the strain can be directly related to support requirements and excavation stability.

3.2 Plastic Strain 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 quadrupoles. Brady (1978), extended the solution to a more arbitrary, three-dimensional case involving hexapoles.

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.

Generally, any episode of yield is most simply described by decomposition into two major invariants. These invariants are the isotropic and major deviatoric components. In terms of energy dissipated plastically, these two major components account for the majority of total plastic strain.

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 of modelling showing the decomposition of the incremental strain components for a single mining step is presented in Figure 3. 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.

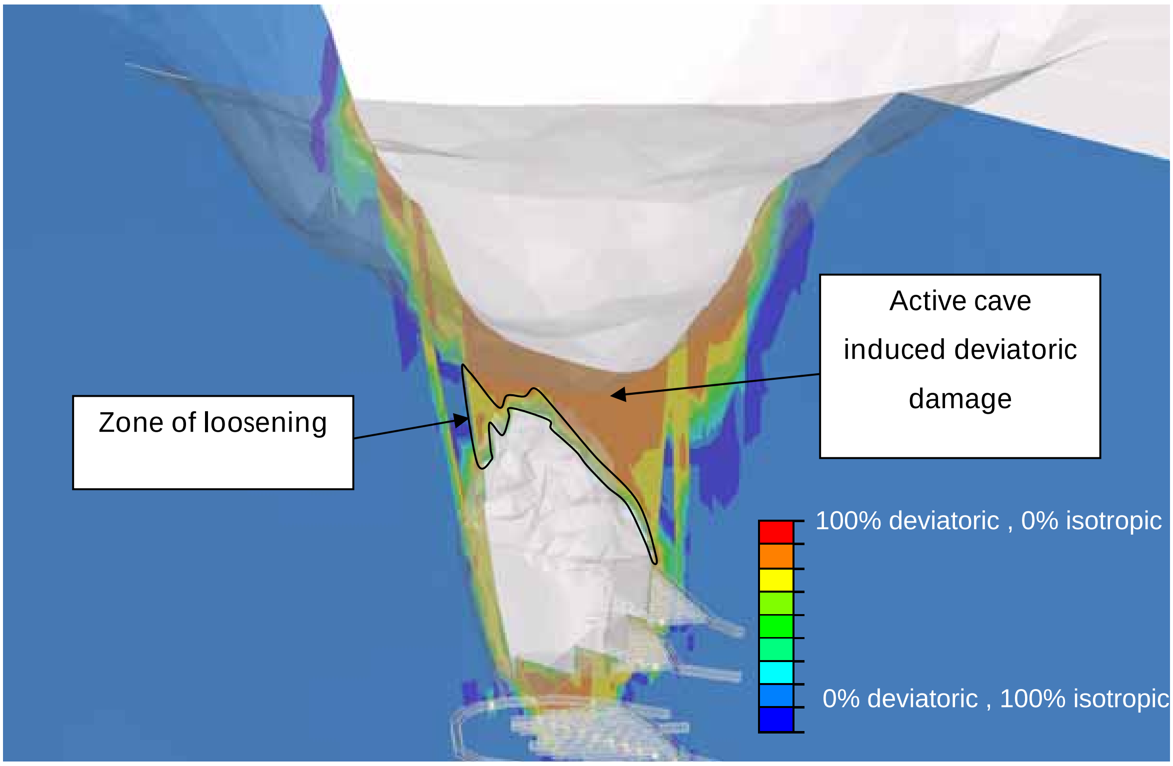


Figure 3 Split between isotropic and deviatoric plastic strain, showing mode of damage

3.3 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'. In Beck and Brady (1999), a number of factors affecting seismic potential were used as correlates to probability, but in the present case, only DPE needs to be used. This is possible owing to refinements in the modelling technique (In the original work, only Map3d elastic models were available, and elastic modelling has significant flaws for this type of analysis that require extra considerations).

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 relation between DPE release rate and the event probability, (x) of a mine tremor of a certain magnitude, X, occurring in a test block, may be denoted:

$$p(X_{DPE}) = x_{DPE} \qquad [1]$$

The total number of test blocks having values within any range of DPE release rate can be denoted e_{DPE_i} where i is the fixed interval of DPE being evaluated (eg 1000J to 2000J). If the total number of test blocks containing events of a test magnitude within a certain range for each e_{DPE_i} range is counted, we can denote the sum of blocks containing events within that magnitude range as n_{DPEj}, where j is the event magnitude range (eg $0M_L$ to $1M_L$) being considered.

If the volume containing the test blocks completely encompasses the seismogenic zone of influence of mining and exceeds the volume containing any level of DPE for that step, then an observation of event versus non-event occurrence for each DPE release rate range can be made. If the relation is a satisfactory predictor, then

$$p(X) = x \approx \frac{n_{DPEi}}{e_{DPEi_j}} \qquad [2]$$

This means that based on DPE, an estimate can be made of the likelihood of an event of a certain magnitude occurring in future modelled blocks. This is however only true if the yield zone is correctly calculated in the model.

The calibration procedure performed at a similar benchmarked mine used 12 months of data and is presented in Figure 4. 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).

In Figure 4, 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 that the probability calculation has been undertaken for.

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 1-2% 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.

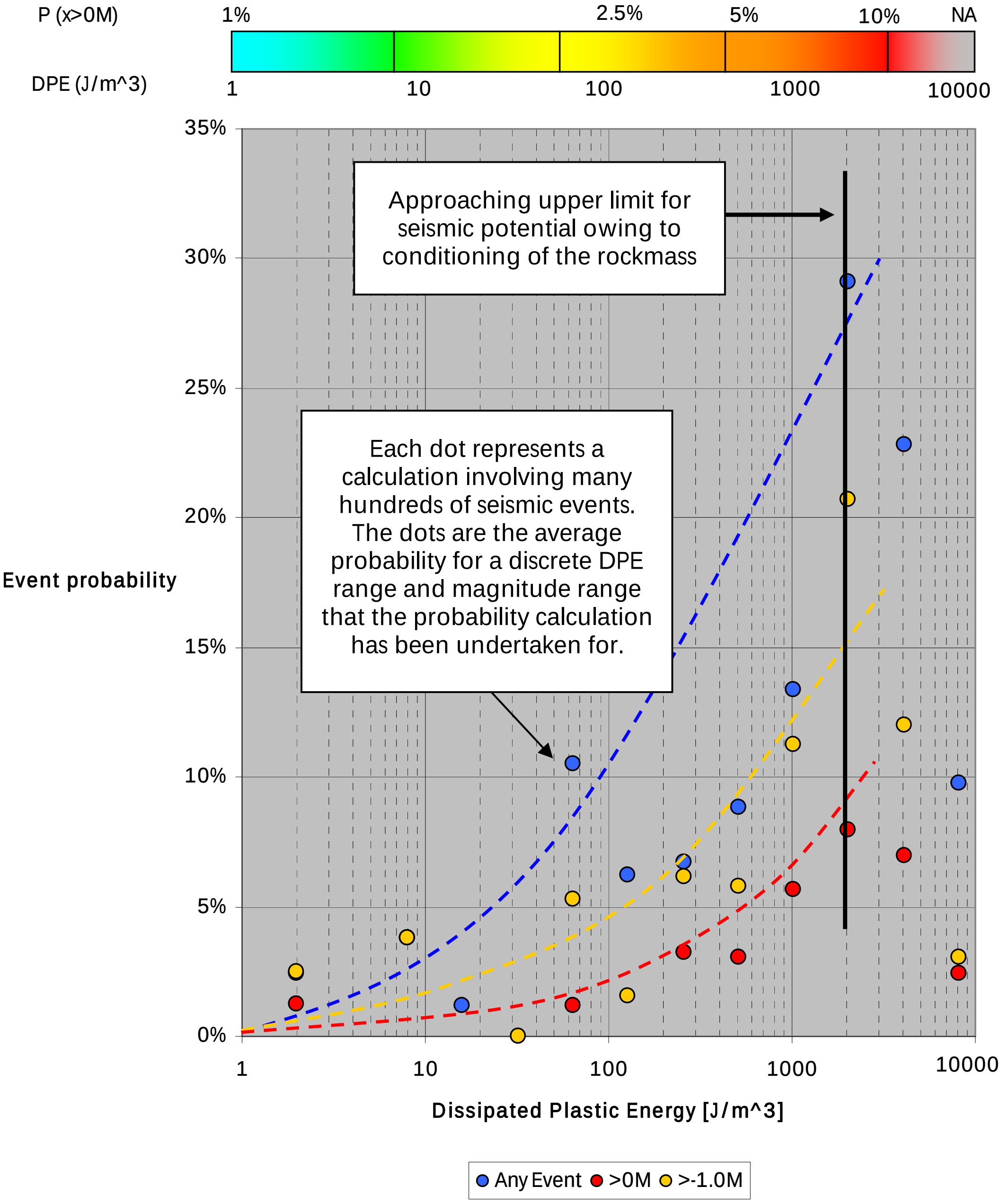
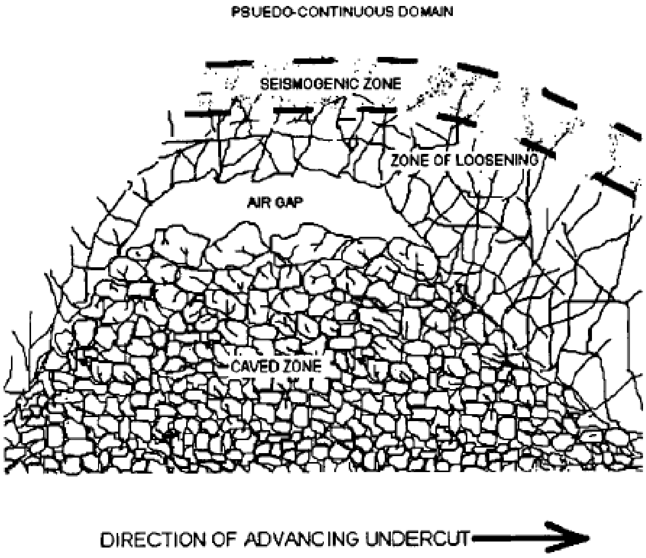
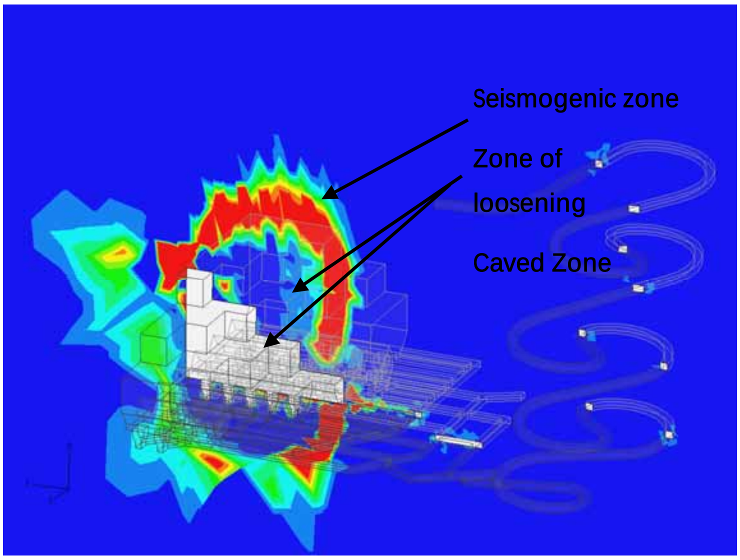


Figure 4 Correlation between event probability and Dissipated Plastic Energy [DPE] for a 1 month modelling step

4 SEISMOGENIC ZONE DEVELOPMENT



(i) Theoretical Model by Duplancic and Brady (1999)



(ii) Numerical model of the seismogenic zone (Beck, 2005)

Figure 5 Depiction of the caving process

Figure 5 shows three basic zones in the steady-state cave. The seismogenic zone forms first. It is literally the zone where new fractures are forming or damage is being done to existing discontinuities. The seismogenic zone is named after the seismic events which are observed there. The seismicity is associated with the damage – it is not the cause of it.

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. Generally, where data exists the Dissipated Plastic Energy (DPE) is able to be correlated with seismic potential as discussed in the previous section, in such a way that there is a cut-off for DPE beyond which no more seismicity is expected. Correlations are achieved with the 3-D NL-FE models only because the model is well conditioned in terms of the simulation of the stress path and the modelled time-steps are very small.

Because DPE is transient, when assessing seismic risk, the complete sequence of model steps needs to be evaluated. Single pictures of DPE are simply ‘snap-shots’ and correctly never shows 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 seismicity, 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 Plastic Strain is a direct measure of the accumulated damage.

An example of the zone of loosening and the seismogenic zone at an example mine in one model stage is shown in Figure 6. The quiescence in the zone of loosening is very clear.

In some of the caves back analysed as part of the study, Plastic Strain of up to 10% (i.e. 10% dilation or swell) has been successfully modelled using the NL-FE code, at which point the dilation is such that the material absolutely must be considered to be part of the “Caved Zone”, even though the model is a continuum code.

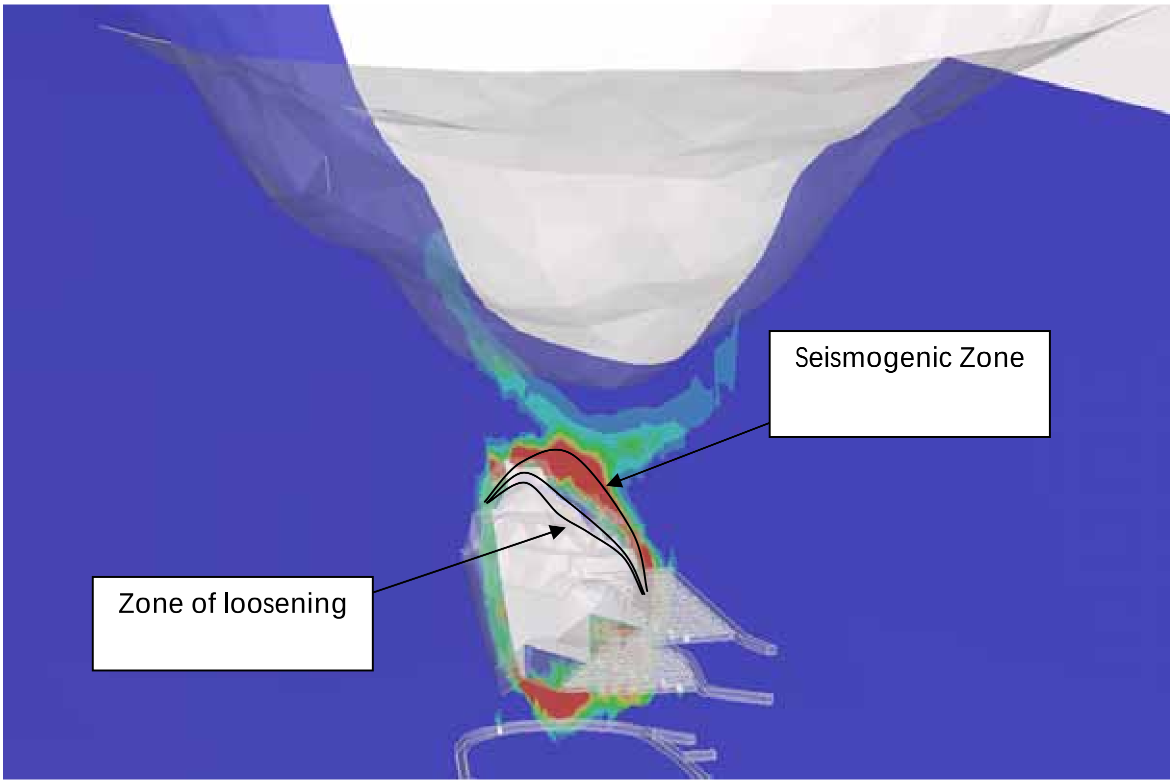


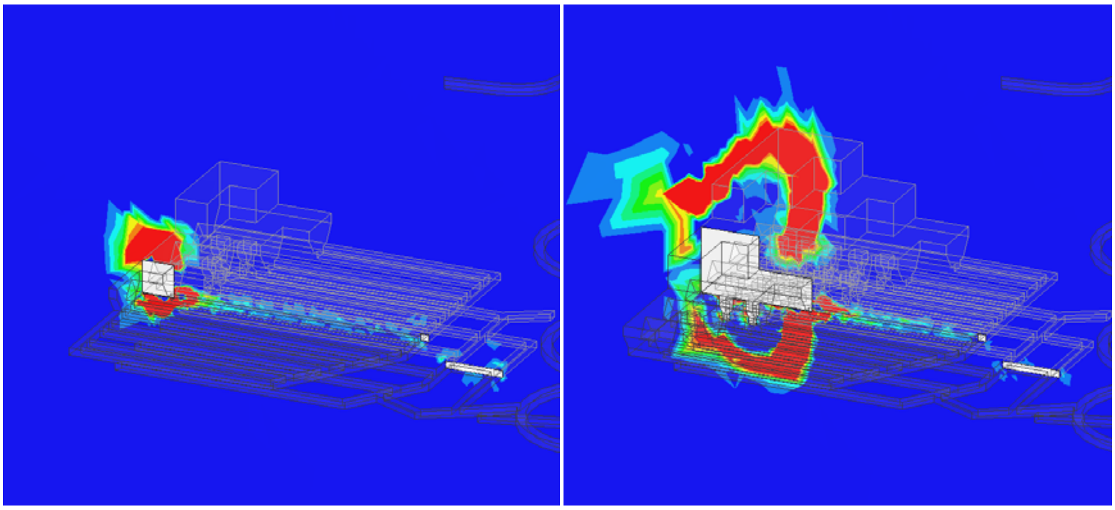
Figure 6 Interpreted Seismogenic Zone and Loosening Zone using DPE

Understanding the relationship between cave state and the nature of the seismogenic zone is important in order to appreciate the NL 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:

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. This condition is shown for modelling of an example in Figure 7 (i).

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). This condition is shown for modelling of an example in Figure 7 (ii).

In Figure 8, the modelled seismogenic zone is shown for an inclined cave sequence, with and without a de-stress slot. The intention of the de-stress slot was to reduce stress in working areas. In this case the model clearly shows that the zone of loosening is significantly influenced by the slot, but there is no significant reduction in seismogenic potential in the working areas.



(i) (ii)

Figure 7 Seismogenic Zone Before Caving HR (i) and at Caving HR (ii) at an Example Mine

Without the de-stress slot, the classic Duplancic and Brady (1999) zone of loosening develops, with more predictable results for draw and an unambiguous interpretation of likely steady state caving. With the de-stress slot, the seismogenic zone is discontinuous, much closer to the cave back and not distributed across the entire cave back.

At some mines, caving appears to begin, but the seismogenic zone will then concentrate in the abutments while caving temporarily stalls. This occurs 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.

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.

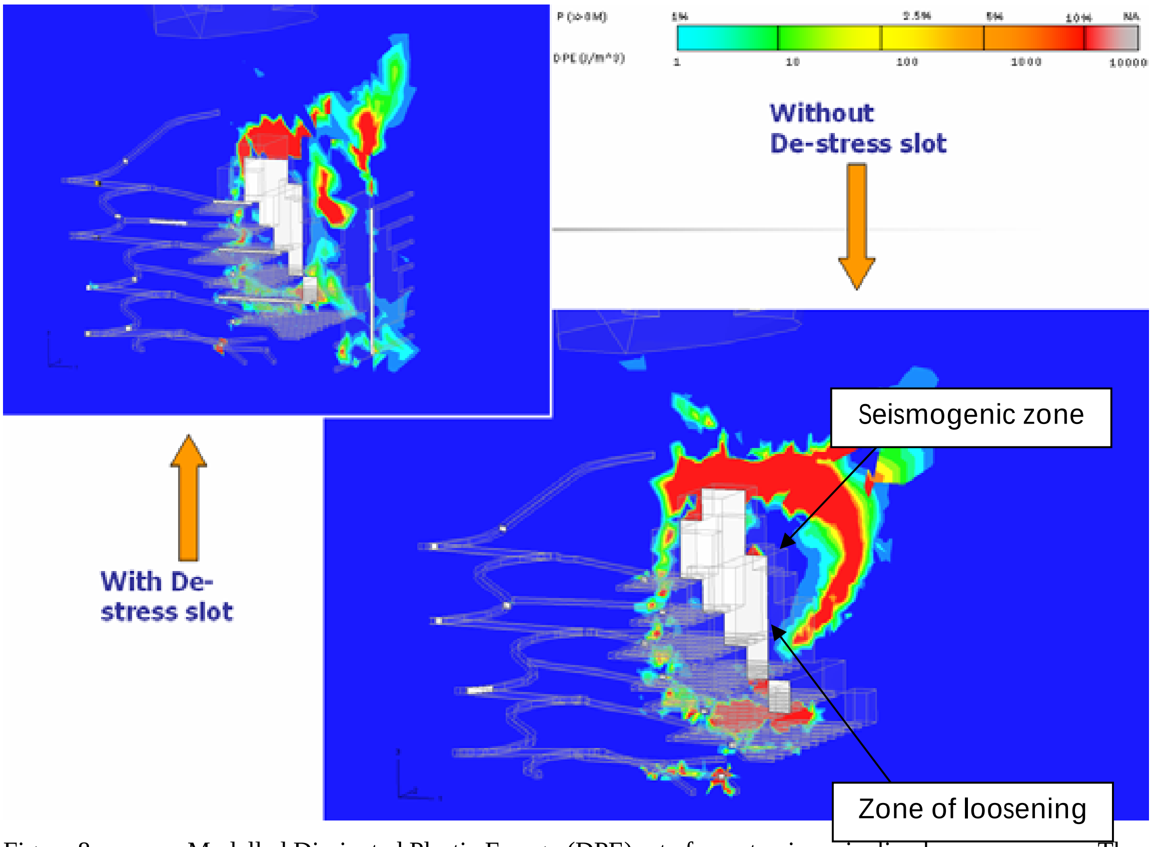


Figure 8 Modelled Dissipated Plastic Energy (DPE) rate for a step in an inclined cave sequence. The DPE rate is shown for the same sequence with and without an adjacent de-stressing slot. In this case, the de-stress slot results in a less developed zone of loosening, which may have had complications for draw.

Beyond Caving HR, Steady-State Cave growth: If a steady state condition exists, the successive increments of draw-down of the muckpile will result in equal or greater advance of the seismogenic zone. 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 more simple.

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 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.

5 CONCLUSIONS

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

The calibrated non-linear models were interpreted to assist in describing simple cave process using a number of parameters that describe deformation. 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.

6 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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