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A Numerical Method for Engineering Management of Induced Seismic Risk in Hard Rock Mining

By D A Beck [1] and B H G Brady [2]

Abstract

A quantitative method is proposed in this work for managing seismic risk. This assessment is produced using three-dimensional, elastic, boundary element modeling of a continuum or jointed continuum, to compare proposed excavation options in terms of seismic event likelihood and event strength. Parameters from the modeling can be compared to historical observations of seismicity to generate probabilistic relations between seismic event occurrence and event strength.

The parameters used in the event spatial occurrence relations and event strength estimates are the Factor of Safety against seismic failure for seismic types inferred from back analysis and the Modeled Ground Work (MGW). The calculation of MGW is related to the Local Energy Release Density (LERD).

The modeled estimates of these parameters, are analogous to the controlling quantities for a seismic event. Namely, an unstable accumulation of energy - energy in excess of that which can be released non-violently - and a sufficient stress condition to allow failure of rock.

At Brunswick Mining and Smelting, Number 12 Mine and at Kalgoorlie Consolidated Gold Mines, Mount Charlotte Mine, the method produced useable relations in case studies of damaging seismic events.

Introduction

In order to best manage seismic risk, the likelihood of induced seismicity must be influenced by appropriate mine design. However, at present there is no definitive means for quantitatively assessing the seismic risk of alternate designs and mine sequences at any stage of planning.

Ideally, the means used to compare mining alternatives for seismic risk should be related to the way mining influences the controlling quantities of seismic events. This would allow the influence of alternative sequences and excavation geometries to be measured in terms of effects at potential seismic sources.

The Controlling Quantities of Seismicity

The controlling quantities of seismic events have been extensively discussed in the literature[1,2]. There is general agreement that the occurrence and strength of an event is dependent on:

- A state of stress in excess of the strength of the existing or newly formed discontinuities in the rock – a condition for fracture propagation is required.
- The energy state of the source volume and surrounding rock and the relative stiffnesses of the failing volume and the loading system.

The first controlling quantity for seismicity listed above describes whether yield is possible in rock. Namely whether a sufficient stress condition exists for rock to be damaged or for discontinuities to slip or dilate. It is well known that in the stress regimes normally encountered in mines, the same strength criteria control failure at all seismic magnitudes[3,4,5].

The second controlling quantity for seismicity listed above, defines how rapidly and how vigorously an event of yielding in rock might occur. Wawersik and Fairhurst (1969)[1] studied brittle rock fracture to determine how the violence of failure is affected by the confinement and energy state of the source volume and loading system by crushing specimens of rock in uniaxial and triaxial compression, using a loading frame with variable stiffness. They demonstrated clearly how the confinement of the specimen at yield, and the relative stiffnesses of the loading system and source, control nucleation and generation of fractures as the strength of specimens was reduced during yield.

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Combined, the two controlling quantities describe the potential for failure by defining where in space yield may occur and in variable terms how violent the induced motions from the source might be based on a description of the local controls on energy release.
The result of this formulation of the problem is that, if the controlling quantities for seismicity can be correlated with model behavior in an idealised representation of the host rock, it may be possible to define event likelihood using numerical modeling. The following section describes the numerical quantification of the controlling quantities for seismicity. Subsequent sections detail how they can be compared to historical seismicity to better describe the requirements for seismic events.

Defining the Required Stress Conditions for Seismic Yielding of Rock

Potential for yield in a rock mass is often qualitatively equated with seismic potential, by comparing modeled estimates of stress with laboratory scale estimates of rock strength. This attempts to define the first controlling quantity for seismicity. The use of laboratory scale strength measurements is not always satisfactory and the assessments may be refined by back analysing seismic events which have been located using a micro-seismic monitoring system.

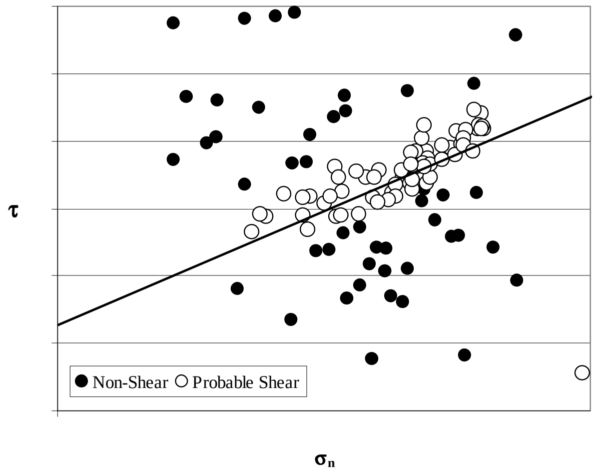
The generic algorithm that was used in this work to characterise events using numerical modeling, is described by Beck (1995)[6]. The scheme aims to provide criteria for seismic yield using accepted models of rock mass degradation and is described below:

- The micro-seismic system locates the seismic events. Modeling using a suitable boundary element code determines an estimate of the state of stress at the estimated source hypocentres. The solution is elastic and is thus best interpreted as representing the state of stress prior to the seismic event.
- Once the pre-event state of stress is indicated by the numerical analyses, the entire population of data, which contains a significant number of seismic events, is tested for fit against a number of standard models of rock failure - or failure criteria.
- Using observations at Mt Charlotte, Enterprise and BMS#12 mines, it has been shown that the simplest populations to identify are those probably described by Coulomb slip. To initiate the tests for this type of event, no initial assumptions are made about likely orientations of slip surfaces. Therefore, all possible seismic plane orientations are tested if required. The match between known orientations of structural features and interpreted orientations for shear events serves as a test for validity of the process.
- The populations, or seismic types, are deduced by identification of linearities in the data set, which form when certain parameters are compared. For example, where the expected response of rock subject to a model of rock failure is linear as for shear events in the τ/σ_n space, the events that occur because that criterion is satisfied, will align in that parameter space. An example of the formation of such linearity in the parameter space, for a particular test plane orientation, is shown diagrammatically in Figure 1. This shows that as test plane orientations are gradually changed and the event stress tensors are transformed to the new orientations, the linearity becomes apparent.
- When likely event types related to a mechanism or a unique discontinuity set are identified, the events that appear to be due to that type are removed from the test. The test is then repeated for different plane orientations, with successive populations removed from the data set as other event types are identified.
- Events due to highly deviatoric stresses, but which can be characterised without a specific joint orientation should be identified after all orientations for shear events are exhausted. Other criteria suspected to be useful should be trialled last.

In the case studies undertaken for this work, at least 80% of the seismic events were found to be associated with shear failures and the seismic failure orientations identified correlated well with the known structural orientations in the mine. Remaining events could be characterised using a simple Hoek-Brown relation, very similar to laboratory strength measurements[7].

The modeling of event hypocenters using boundary element elastic modeling does not seek to absolutely define the stress state for every event. Rather, the efficient computation of an estimate for a large number of events is sought, to allow 'average' criteria to be determined.

Figure 1 - ***Depiction of a linearity in τ/σ_n space and identification of events relevant to the type being tested.***



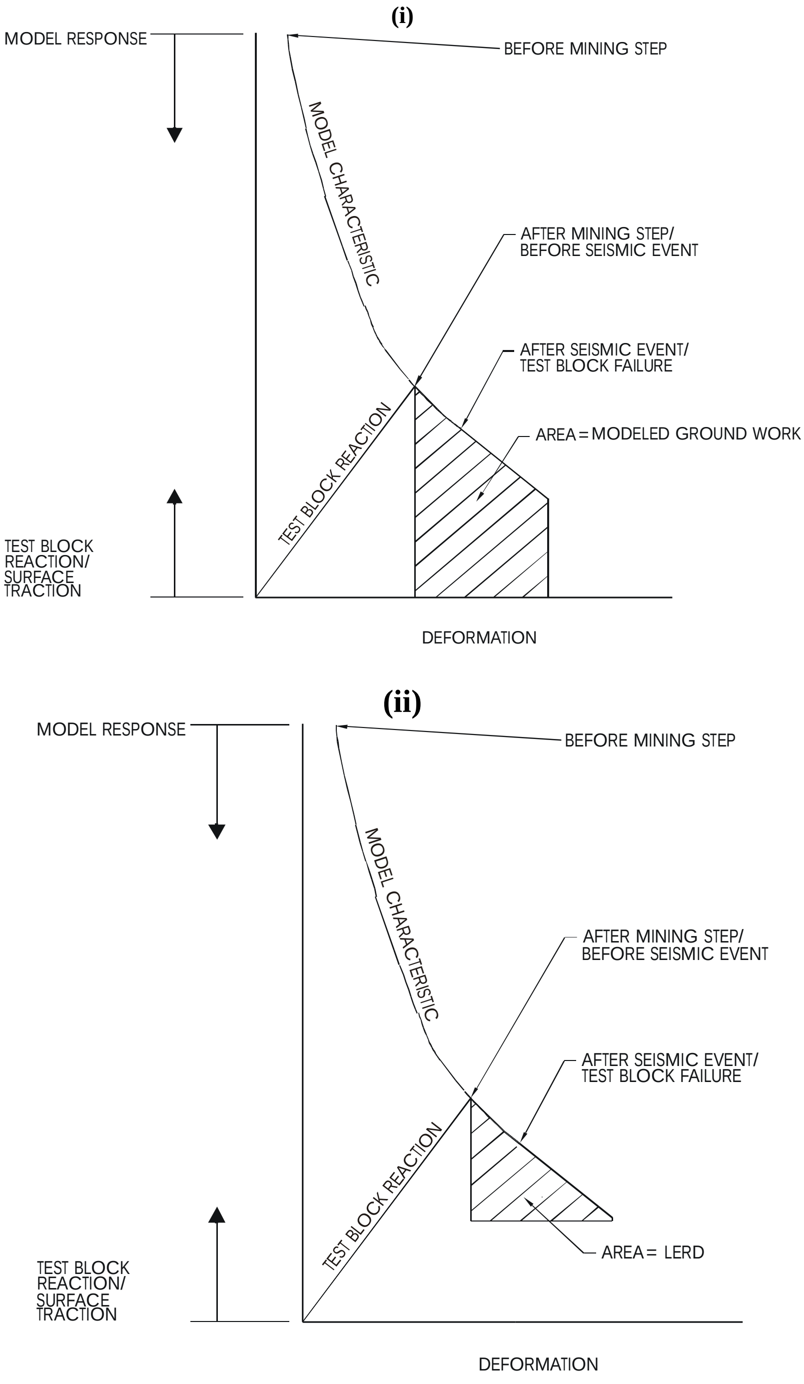
Defining the required energy conditions for seismic yielding of rock

To quantify the second controlling quantity for seismic occurrence, the energy state, simple descriptions were sought. The Local Energy Release Density[8] (LERD) and Modeled Ground Work (MGW) were tested as they are similar numerical constructs related to the energy state of localised test volumes, that have been related to bursting or seismic conditions in mines. Both of these quantities are also simply computed using numerical modeling.

Both LERD and MGW compare the load-deformation state of a volume of rock, or the loading system, before and after an event, by simulating the event as a change of material property within a volume. The reason MGW and LERD have been given considerable attention, is that both values have the potential to be related to the energy parameter of the controlling quantities of seismicity.

LERD is interpreted as the available kinetic energy, equal to the energy arising from differences in stiffness between the loading system and the failed volume. MGW is the complete, modeled energy change about the surface of a volume that experiences degradation in properties. The difference between the quantities is shown in Figure 2.

Figure 2 - ***Calculation of MGW (i) and LERD (ii).***



The nature of the solution for MGW or LERD is presented in Figure 3 for a generalised test block shape. The test shape is subject to a disturbed stress field due to the presence of mine excavations. The volume within the surface, *S* is subjected to a degradation in rock mass properties.

The initial work on the test block is given by:

$$\sum_{i=1}^{n} t_{xi} u_{xi} + \sum_{i=1}^{n} t_{yi} u_{yi} + \sum_{i=1}^{n} t_{zi} u_{zi} \qquad [1]$$

where n is the number of elements on the surface of the test shape. Similarly, the work being done after the episode of rock mass degradation is:

$$\sum_{i=1}^{n} t_{xi}' u_{xi}' + \sum_{i=1}^{n} t_{yi}' u_{yi}' + \sum_{i=1}^{n} t_{zi}' u_{zi}' \qquad [2]$$

Based on the differentiation between LERD and MGW of Figure 2:

$$\mathrm{MGW} = \sum_{\mathrm{i}=1}^{3} \left[\sum_{\mathrm{j}=1}^{\mathrm{n}} \frac{1}{2} \left(t_{ij} + t_{ij}' \right) \left(u_{ij}' - u_{ij} \right) \right] \qquad [3]$$

$$\mathrm{LERD} = \sum_{\mathrm{i}=1}^{3} \left[\sum_{\mathrm{j}=1}^{\mathrm{n}} \frac{1}{2} \left(t_{ij} - t_{ij}' \right) \left(u_{ij}' - u_{ij} \right) \right] \qquad [4]$$

The solution procedure used to calculate stresses and displacements induced by excavations and the introduction of test blocks was the indirect boundary element method. This procedure is used by Map3D[9] and the code Seismap[10] and was first applied in a mining problem by Deist and Georgiadis (1973)[11]. The indirect boundary element method was chosen because it is computationally efficient for very large problems of this kind.

In an investigation of the utility of the MGW concept, at Mount Charlotte Mine and Brunswick Mining and Smelting Number 12 Mine, observation of MGW for equally sized test blocks placed at observed event centres demonstrated a correlation between MGW and event strength, in terms of energy, seismic moment and magnitude. In this case, the failed seismic volume was taken to retain no stiffness, with the source volume providing no reaction against the loading system.

With test blocks constructed in this way, any relation between observed event strength and the MGW is a correlation between the modeled pre-event deformation and the final displacement of the simplified test block and event strength.

The MGW model studies for the small test blocks revealed that the event strength at observed seismic sources increased with decreasing MGW, when careful consideration of likely mechanisms for individual events was used to first segregate event types. A typical example of the relation between MGW and the logarithm10 of measured seismic moment is shown in Figure 4, for an event type observed at BMS#12 Mine. The figure clearly demonstrates that the observed seismic moment decreases with increased MGW in test blocks, but there is some recent evidence[8,12] that suggests at larger values for MGW or LERD and for larger events, event strength may increase monotonically with MGW. This reflects the correlative nature of the observations, with significant interpretation of model behavior required to identify the mechanical relation between event strength and the modeled values. It is also apparent that the negative correlation between MGW and event strength is counter-intuitive and probably demonstrates the dependence of the results in an elastic model on the relative sizes of the test blocks, the excavation and the event.

Figure 3 - ***Problem geometry for determination of MGW or LERD, for an element on a generalised test block.***

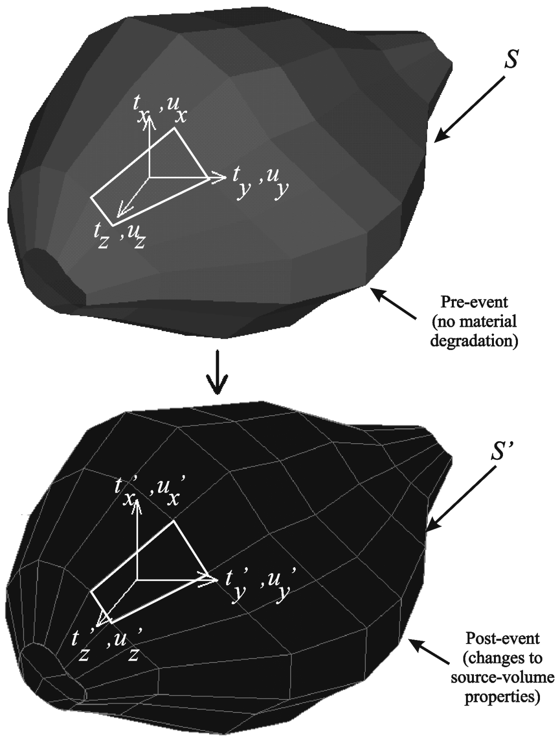
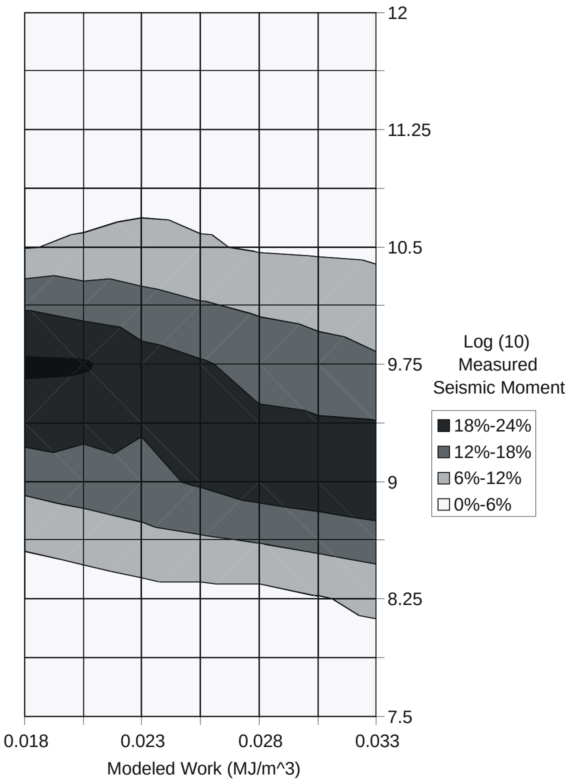


Figure 4 - ***Observed seismic moment probability distributions, compared to MGW for BMS#12 Type [C] seismic events.***



Defining event likelihood

A 'Factor of Safety', S_T, against a certain type of known mechanism (where the subscript T denotes the event type) can be determined using criteria determined from back analysis of seismicity as described above. The Factor of Safety is typically the quotient of the stress components thought to restrain failure and the stress component thought to drive failure. For example, for Coulomb slip where there is no cohesive strength, the Factor of Safety is the ratio of $\sigma_n \tan\phi$ to the shear stress acting on the discontinuity.

The results of modeling with these criteria describe whether yielding by the relevant mechanism can possibly occur. It can be assumed that event occurrence is in some way dependent on the indication of yield potential given by S_T, though not necessarily correlated in any useful manner when considered in isolation of other factors. Further, MGW can also be determined by modeling, providing an estimate of the second controlling quantity for seismicity. If it is true, as suggested by Figure 4, that certain conditions of MGW will result in aseismic yield while others will result in violent rupture, event likelihood, given satisfactory conditions for yield, will also depend on MGW. This is because if MGW or LERD can describe the conditions for successively more energetic events, they must be correlated with the conditions that describe the nucleation and extension of damage in the source.

To determine the regularity with which combinations of the MGW and S_T result in seismic failures, a unique 'block testing method' was developed to calculate event probability by using MGW and S_T. The block testing method involved discretising the entire the zone of influence of a historic mining step into regular, volumetric 'test blocks', such that the complete volume of influence is filled. A demonstration of the discretisation process for an example back analysis at BMS#12 mine, is shown in Figure 5.

In each of the test blocks, S_T and MGW are calculated. Then, by comparing the proportion of blocks that contain and do not contain conditions satisfying the occurrence of events, particular pairings of MGW and S_T can be related to the probability of event occurrence.

The relation between S_T and MGW parameters and the event probability, (x) of a mine tremor, X, occurring in a test block, may be denoted:

$$p(X_{S_T,\mathrm{MGW}}) = x_{S_T,\mathrm{MGW}} \qquad [5]$$

Next, the continuous distributions of S_T and MGW are divided into discrete intervals. The intervals can be defined using subscripts i and j, such that:

$$f[S_T] = \begin{bmatrix} S_{Ti} \\ S_{Ti+1} \\ \vdots \\ \vdots \\ S_{T\max} \end{bmatrix} \quad \& \quad f[MGW] = \begin{bmatrix} MGW_j \\ MGW_{j+1} \\ \vdots \\ \vdots \\ MGW_{\max} \end{bmatrix} \qquad [6]$$

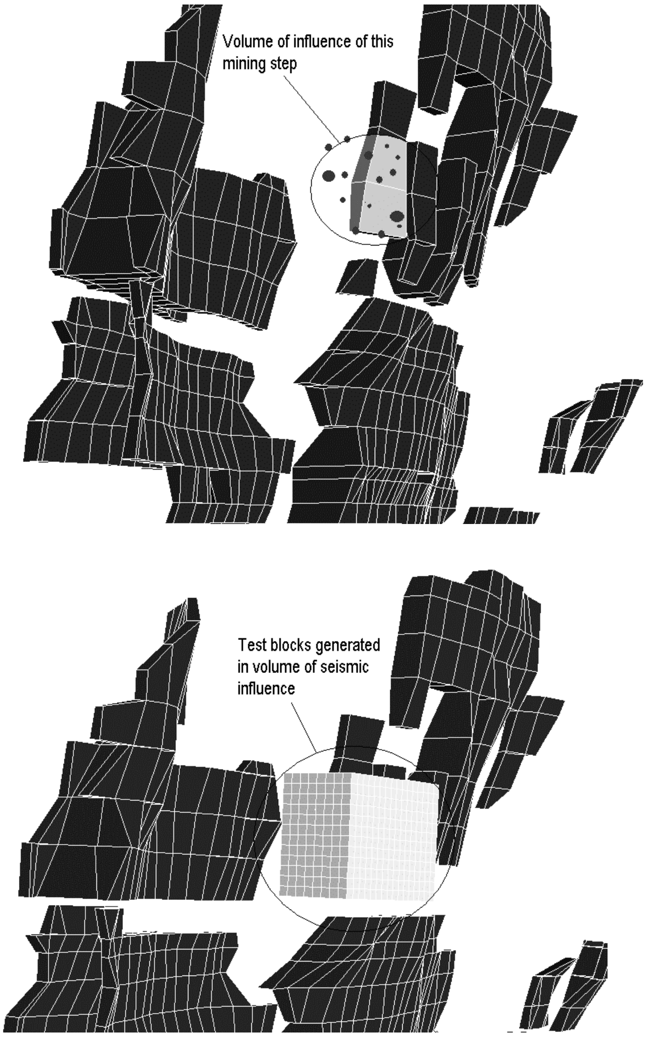
The total number of test blocks having values within any combination of MGW and S_T intervals can be denoted $n_{S_{Ti},MGW_{ji}}$. If the total number of events that occur within blocks of that description are counted, we can denote the sum of events in each combination of intervals as $e_{S_{Ti},MGW_{Wj}}$.

If the volume containing the test blocks completely encompasses the zone of influence of seismicity, then an observation of event versus non-event occurrence for pairings of the controlling quantities can be made. If the relation is a satisfactory predictor, then

$$p(X) = x \approx \frac{n_{S_{Ti},MGW_j}}{e_{S_{Ti},MGW_j}} \qquad [7]$$

This means that based on the two parameters proposed, an estimate can be made of the likelihood of an event occurring in future modeled blocks having similar seismic potential characteristics. This is however only true if the boundary of the zone of influence, as defined for the limit of generation of test blocks, is shown to have zero probability of event occurrence.

Figure 5 - ***Demonstration of the generation of test blocks for interrogation of the zone of influence around an excavation representing a historic mining step***



This procedure was performed for all event types at Mt Charlotte Mine and at BMS#12 Mine. Figure 6 presents the results for an event type at BMS#12, while a similar result is shown for a representative event type at Mt Charlotte in Figure 7. In both Figures and for other event types not shown from both mines, the boundaries for event occurrence were continuous and bounded.

Figure 6 - ***Probability of a BMS#12 Type [C] seismic event for pairings of modeled Factor of Safety and MGW using 10 metre cubic test blocks***

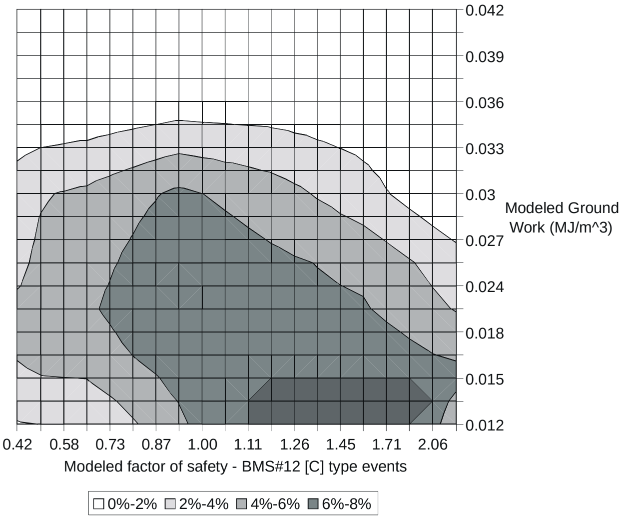
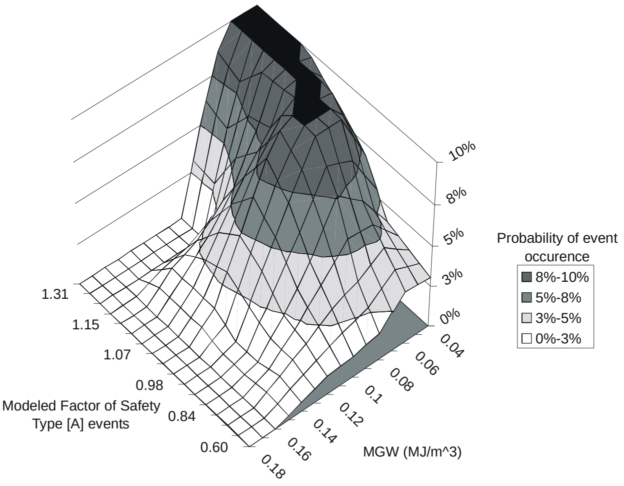


Figure 7 - ***Probability of a Mount Charlotte Type [A] seismic event for pairings of modeled Factor of Safety and MGW using 10 metre cubic test blocks.***



Application for prediction

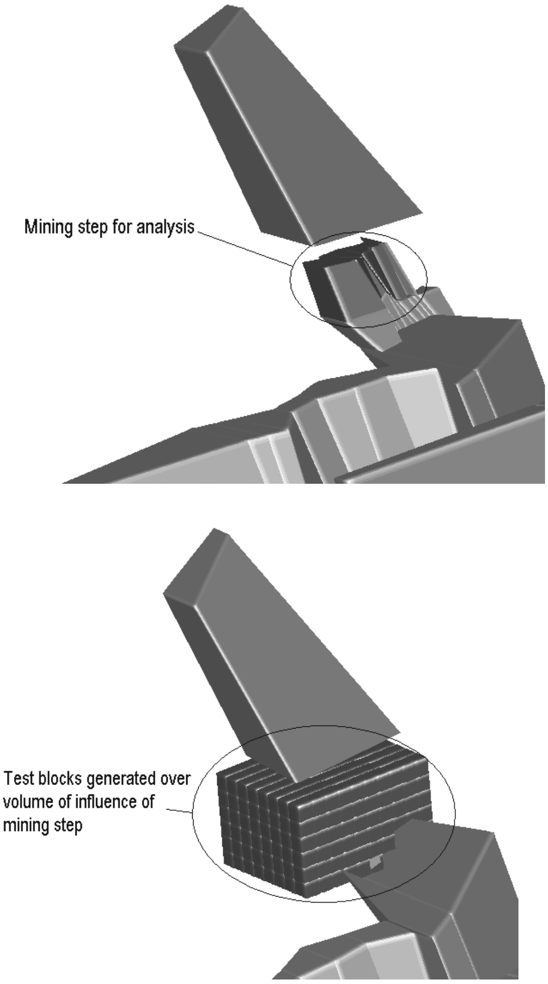
Having established relations for event strength and probability from the back analysis of historic seismicity, it remains to apply the relations to achieve quantification of seismic risk. This proceeds by:

- Establishing a regular volumetric test grid about the likely volume of influence of proposed mining geometries as shown in Figure 8.
- Modeling S_T at test block centres, recording the potential event types in each test block and determining the MGW related to the specific event type identified by S_T.
- Determining the expected probability of event occurrence within the blocks, using plots such as Figures 6 and 7.
- After susceptible test blocks are identified, MGW is compared to the derived seismological relations (as in Figure 3) to estimate event strength.

The discretisation of the test blocks for the extraction of 19E stope at BMS#12 is shown in Figure 8. The test blocks are oriented perpendicular to the horizontal plane, to correspond with the known orientation of events in the area.

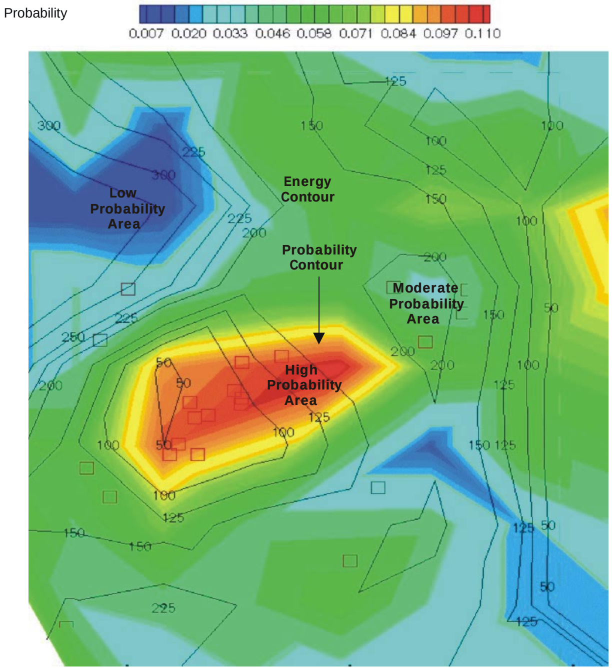
An evaluation of this procedure has been conducted by calculating the Factor of Safety against an event type and the associated MGW and by generating contours of event probability, for comparison with actual event occurrence. The probabilistic relation between event occurrence, the MGW and Factor of Safety of Figure 6 was used in this case. Figure 9 is a picture of the predicted contours of Type [C] event probability, with the actual seismicity overlayed. In the Figure, the indicated probability at any point, is the likelihood of an event occurring within a 10 metre square of the point, corresponding to the test block size and the radius of the smallest event used in the study. To assess and compare the predicted event strengths, event strength potential from the MGW-event strength relations, has been overlaid as contour lines on the plot.

Figure 8 - ***Demonstration of the generation of test blocks about the zone of seismic influence, for the purpose of quantifying the seismic risk of a planned mining step.***



Some interesting results are observed in Figure 9. The events that occur in the regions of low predicted probability, are also predicted - and were observed to be – the most energetic. The cluster of events in the area of high probability was predicted to be less energetic and were similarly observed to be so. This is important because the confidence in a method to estimate of the probability of a seismic event should be measured not only by the ability of the method to predict seismicity, but also in the ability of the method to predict seismic quiescence or minor activity.

Figure 9 - ***Plot of predicted event probability (flooded contour), observed event location (squares) and contoured energy potential (lines) of test blocks. The energy potential is the predicted event energy if the event were the same size as the test blocks.***



Prediction of the continuous probability distribution of seismic event strength

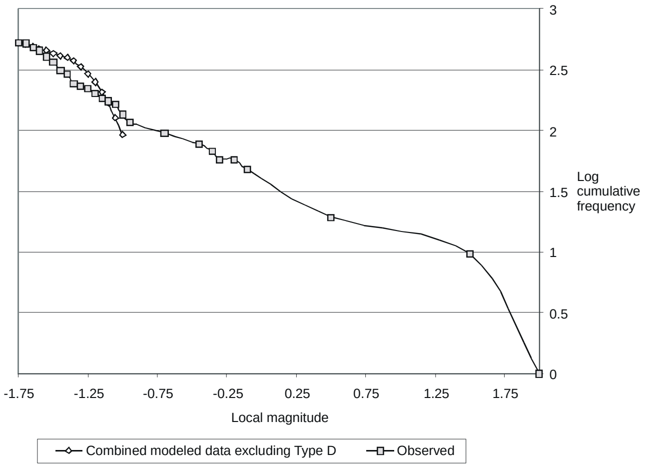
A population of test blocks, with strength value estimates and likelihood of association with real events, can be constructed in terms of traditional plots such as the Gutenberg-Richter plots, or can be plotted spatially for visualisation. This would proceed by using the predicted event probability and the predicted event strengths to produce a cumulative probability distribution.

For the Brunswick case study, the method of magnitude calculation over time was not consistent and therefore a magnitude probability distribution has not been prepared. Instead, predicted and observed cumulative probability distributions of Log_{10} Seismic moment were calculated to estimate event strength.

The distributions of event strength versus MGW were only prepared for the intervals of potential seismic moments, for which an observed population of 30 or more was available from back analysis. As the prediction of seismic moment relies on the relation in Figure 4, it is clear that there are some problems that will correspond to the limited precision of the data, arising from the sparsity of events of extreme magnitudes.

The observed seismicity was significant, even if the number of events was small. In this case, the smallest events were removed from the observed event distribution and the predicted population was standardised using the Gutenberg-Richter population for historical seismicity to predict the proportion of events above Log10 Seismic Moment 9.9, so that the predicted and observed populations could be compared. This is necessary when the predicted population is truncated for the statistical reasons stated above. The results of this work are shown in Figure 10.

Figure 10 - ***Gutenberg-Richter distribution of modeled and observed magnitudes associated with extraction of S2 stope. The distributions have been standardised against the number of events observed historically for the purpose of comparison of seismic a and b values at the mine.***



A similar analysis was performed for a period of mining at Mount Charlotte Mine, corresponding to the occurrence of a 2.5 ML seismic event. In Figure 11, magnitude contours forecast using a relation between MGW and observed event magnitude have been laid over observed magnitude contours in the region of the 2.5ML event. Although it is not entirely satisfactory to contour between discrete events in this way, the plot demonstrates a good visual correlation. Figure 12 is the Gutenberg-Richter distribution of modeled and observed magnitudes associated with extraction of S2 stope. The distributions have been standardised against the number of events observed historically for the purpose of comparison of seismic a and b values at the mine[13] (Mikula and Poplawski, 1995).

The event strength probability distributions for both case studies from different mines are similar and despite the limitations posed by the limited data set of very large events, interpretation of the contouring related to both cases suggests that areas of high event likelihood will be indicated where energetic events are to be expected. The application of such methods is thus still not completely quantitative, but it is for most purposes quite soundly based and reproducible. The correlation between modeled and observed event occurrence distributions is also sufficiently close to make the calculations useful for decision making regarding seismic risk.

Conclusions

A method for quantifying seismic risk using numerical modeling and case studies of historic seismic events has been presented. The method produced useable relations that would have assisted in management of seismic risk in the case studies undertaken.

Although the correlations demonstrated in this work were good and were proven to be useful, the method remains to be demonstrated at geometric scales different to those observed at Mount Charlotte and Brunswick. Although the operations are quite different, the scales of the interaction between mining, the geological environment and the dimensions of the test blocks are similar. However, it is possible that the relations observed in these cases between MGW or LERD and event strength will not hold true for mine domains characterised by other internal geometric scales.

Figure 11 – *Flooded contours of Type [C] seismic event modeled magnitude, under contour lines of observed event magnitudes for S2 stope. Events are shown as squares.*

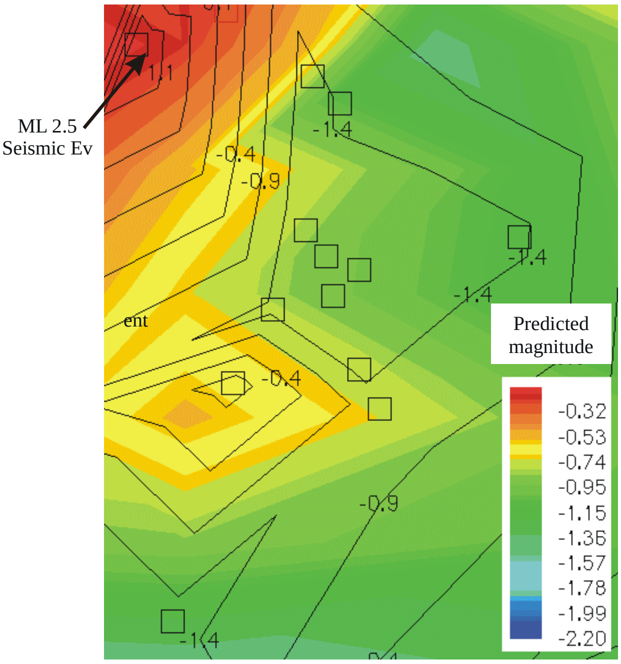
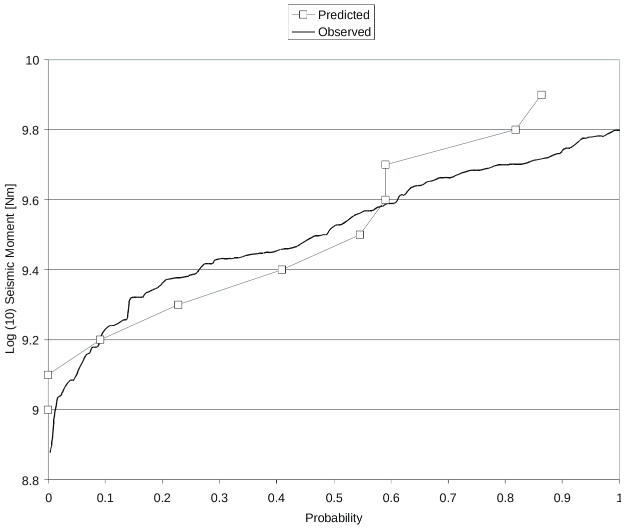


Figure 12 - *Cumulative probability distribution function of predicted magnitude, associated with extraction of 19E stope for event Type [C].*



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