Forecasting mine seismicity – towards a more established methodology

A Vakili[1], F Harvey[2] and H Greaves[3]

1. Abouzar Vakili MAusIMM(CP), Principal Geotechnical Engineer, Mining One Consultants, Australia
2. Fred Harvey MAusIMM, Senior Geotechnical Engineer, St Barbara Limited, Australia
3. Harley Greaves MAusIMM, Senior Geotechnical Engineer, Mining One Consultants, Australia

ABSTRACT

Mine seismicity is one of the most difficult geotechnical risks to manage in seismically active mines. There are currently some established empirical and statistical methods that provide quantitative measures for seismic hazard assessment in operating mines. However, these methods are mostly suitable for quantifying the current or historical seismic hazard and often cannot be directly used to forecast the future hazards.

Numerical modelling is the only analytical tool that can capture the level of complexities required for a meaningful analysis of mine seismicity and therefore to facilitate a reliable forecast of future hazards. However, there is currently no widely accepted and established guideline and methodology for analysing and forecasting mine seismicity using numerical modelling.

This paper first provides a background on previous published studies on this subject and then outlines the key aspects that can affect the reliability of the forecasting for mine seismicity. These aspects include a) processing of historical seismic data, b) selection of suitable numerical modelling approach, c) Post-processing and interpretation of the model outputs. A case study is then presented for the Gwalia Deeps Mine where a new framework was developed to forecast future mine seismicity. High-quality seismic data for a period of five years was used for back-analysis and comparisons with the numerical modelling outputs. After development of the method, the future seismicity was forecast for the next 12 months and the actual seismicity was monitored against the forecast during this period.

Results of this study shows promising potential for the proposed framework to be applied more routinely and at other mine sites. However, more validations are required at Gwalia Deeps mine as the mine proceeds to deeper levels. In addition, the method needs more improvements and should be tested and validated at other mining operations before it can be established as a proven method.

INTRODUCTION AND BACKGROUND

Mine seismicity is a major issue in many underground mines and it is expected that this hazard will become more common as mines continue to expand deeper. Numerical modelling has the potential to reduce the uncertainties surrounding mining induced seismicity and using numerical models for forecasting has the potential to both improve mine safety and optimise mining practices in seismically active environments.

Currently, mine scale numerical modelling cannot predict specific seismic events at a given time and location, but rather is used to correlate various modelling outputs (e.g. released energy, seismic moment, differential stress or strain) to historic event data and to estimate the expected seismic hazard. Several modelling methodologies have been proposed with levels of complexity ranging from simple two- and three-dimensional (2D and 3D) elastic models to more advanced 3D continuum and discontinuum mine-scale simulations.

Beck, Reusch and Arndt (2007) published the results of using a 3D, mine-scale, non-linear numerical model to correlate Dissipated Plastic Energy (DPE) with recorded seismic event data. The results showed that a useable correlation between DPE and seismic event probability was found for two underground mines using the finite element modelling package ABAQUS and strain softening, dilatant constitutive material models.

Iterations of this method have appeared in several subsequent publications with methodology changes including:

- The adoption of the strain-softening, continuum/discontinuum Levkovitch Reusch (LR2) constitutive model for the rock mass and faults (Beck, Levkovitch and Simser, 2012).

- The incorporation of total strain energy with DPE to produce a modelled energy release output to correlate with seismic event data (Arndt et al, 2013).
- The calculation of Rate of Energy Release (RER) to be used as the modelling output to correlate with recorded seismic event data (Levkovitch, Beck and Reusch, 2013).

This method appears to hold potential, however there are several difficulties in adopting it routinely at different mine sites and validating its effectiveness. Essentially, the process described in the above papers requires the use of proprietary elements (the LR2 constitutive model) and a software package not widely used or available in the Australian mining industry (ABAQUS). In addition, no clear guideline was provided for others to implement the method. The published validations for this method have been generally qualitative and not detailed. With the exception of the Arndt et al (2013) work which provides a more transparent and detailed guideline and validation work.

Simpler methods have also been developed using 3D elastic numerical models by correlating differential stress or strain to seismic event data, though these have shown variable success (Turner and Player, 2000; Spottiswoode, Linzer and Majiet, 2008; Morissette et al, 2014; Morissette, Hadjigeorgiou and Punkkinen, 2017). An alternative elastic modelling approach has also been proposed using the Salamon-Linkov method (Malovichko and Basson, 2014; Malovichko, 2017). Of the elastic modelling approaches, the main limitations include the failure to account for post-peak material behaviour, the failure to incorporate cumulative rock mass damage and difficulty in modelling the changing stress state as mining progresses. In fact, Malovichko and Basson (2014) state that their modified Salamon-Linkov method may not be accurate for individual mining scenarios but instead is suitable when assessing the differences between multiple mining scenarios is required.

With the various modelling strategies available to estimate the seismic hazard in underground mines, the issue of what level of modelling complexity is required to achieve a useful seismic correlation, and for which seismic mechanisms they can be applied to, remains unsettled. This paper outlines a modelling framework that has shown potential at forecasting the seismic hazard at an Australian, seismically active, underground mine. The framework is considered a step toward establishing a more standard methodology for seismicity forecasting. When compared with the previous methods discussed above, the aim for the proposed framework has been to:

- Provide a clear, simple and transparent guideline on how to implement the method.
- Apply numerical modelling software and material models that are readily available and accepted in the mining industry and are easy enough to learn, for most geotechnical practitioners, but at the same time are reliable enough to use in various rock mass conditions.
- Conduct detailed and transparent validations of known historical mining cases.
- Be able to forecast the potential for seismicity in terms of expected severity and expected locations for an individual mining scenario.

PROCESSING OF HISTORICAL SEISMIC DATA

The first step before completing any numerical modelling exercise is to process the existing seismic data so it can be utilised effectively for model calibration and validation. Without any processing or filtering, the existing seismic data can often be excessively detailed, making it very difficult or sometimes impossible to interpret. This is particularly the case when the seismic data over several years is under study.

Frequency, magnitude and location of the seismic events are usually the most common parameters that are used for post-processing and filtering of the seismic data. Frequency is the number of events occurring within a certain period and around a particular spatial location.

There have been several works completed to quantify the seismic hazard in mines using the above parameters. The quantified seismic hazard is a good measure to use for calibration/validation of the numerical models and to compare with the modelling outputs.

One of the more recent and accepted methods for quantifying the seismic hazard in mines was proposed by Hudyma and Potvin (2004). The method was developed using the Gutenberg-Richter Frequency-magnitude relationship and the seismic data gathered from 21 mines in Western Australia. The Seismic Hazard Scale (SHS) is derived from the Gutenberg-Richter relation and is expressed as:

$$SHS \approx \log_{10} {}^{N}\!/_{b} + M_L$$

where ML is any given event magnitude, N is the number of events with Richter magnitude of at least ML, and b is the slope of the frequency-magnitude relationship. The descriptive relative seismic hazards associated with various SHS values is listed in Table 1.

TABLE 1 SHS compared with relative seismic hazard and the magnitude of the largest event that may have occurred (after Hudyma and Potvin, 2004).

SHS	Relative Seismic Hazard	Approximate Magnitude of Largest Event
-2	Nil	-2
-1	Very Low	-1
0	Low	0
1	Moderate	+1
2	High	+2
3	Very High	+3

In the proposed framework detailed in this paper, the Hudyma and Potvin method has been adopted due to its ease of application and its ability to provide a local comparison with other mines in Western Australia.

However, there has been more recent research and development in this area and the current framework will need to be updated to ensure the best methods are being adopted to process and quantify the current seismic hazard at the mine. An example of the most recent state-of-art developments in processing the seismic data is provided by Wesseloo (2018) and through application of software tools such as mXrap (Wesseloo and Harris, 2015).

In addition to quantifying the current seismic hazard, other forms of data post-processing are often required to improve the data clarity for spatial comparison with the numerical modelling outputs. In the current framework, a simple cell-based clustering technique is used to filter the seismic data. As shown in Figure 1, the first block model (or grid) is constructed around the available seismic data points. The block model contains cubic cells with constant dimensions (often between 5 m and 8 m side lengths) throughout the volume. An algorithm was developed which outputs the number of seismic events, the centroid coordinates and the maximum event magnitude of the events located in each cell. This output can then be used for better visualisation of the seismic data in a 3D space. Examples of these outputs are presented in Figure 2.

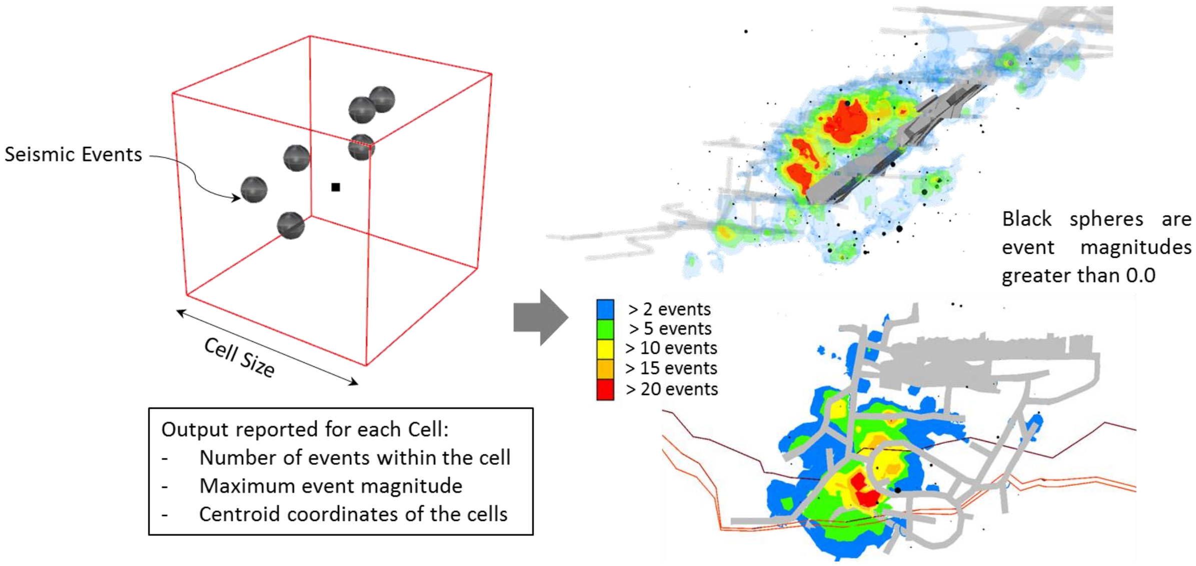


FIG 1 - The cell-based clustering of the seismic data.

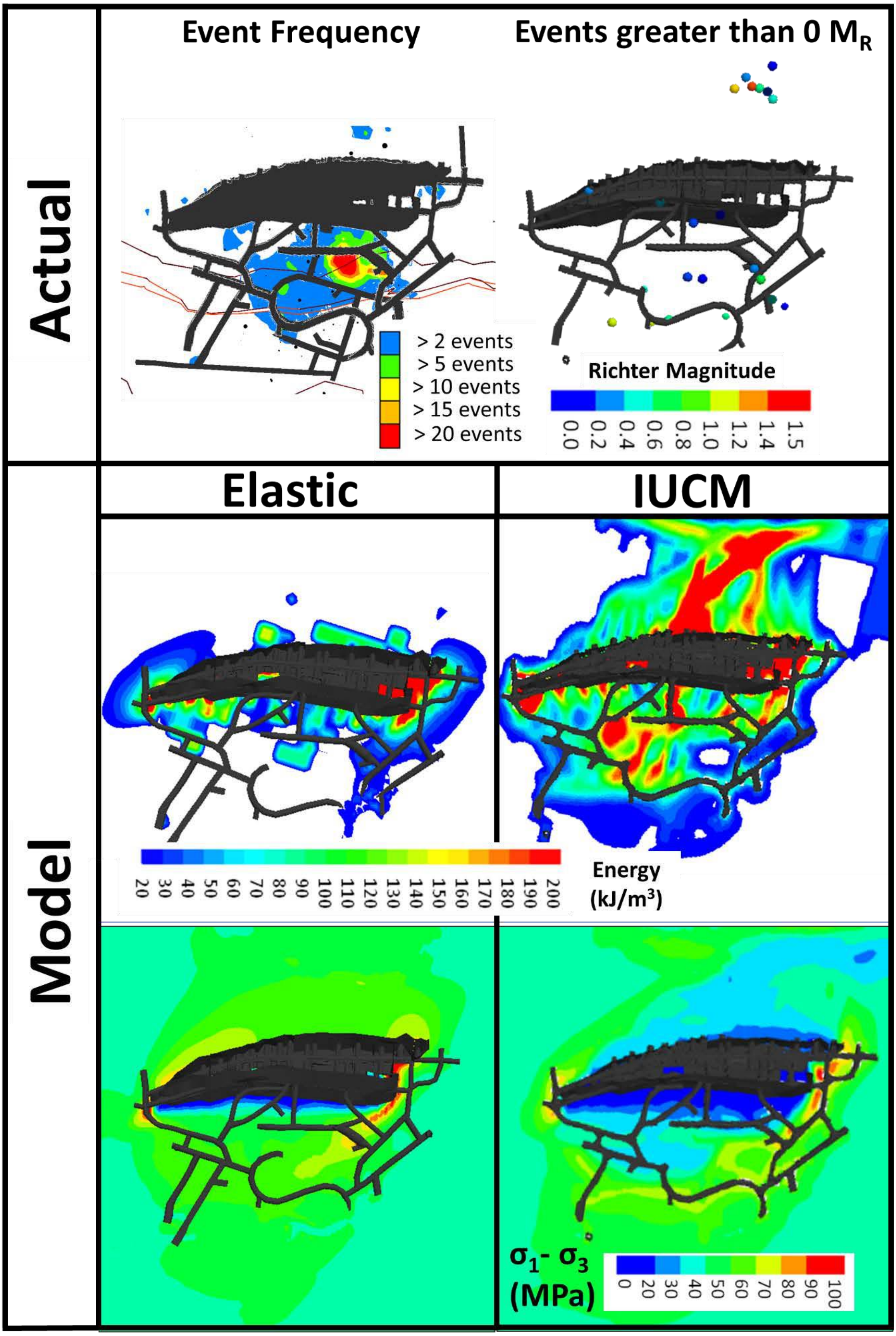


FIG 2 - Comparison between model results generated using the FLAC/StopeExamine/IUCM approach and the conventional elastic model for a case study at Gwalia Deeps Mine.

SELECTION OF A SUITABLE NUMERICAL MODELLING APPROACH

The numerical modelling code and the applied constitutive models can significantly affect the reliability of seismicity forecasting. However, these points are still the subject of much debate by rock mechanics professionals and many practitioners hold that a numerical model using elastic or conventional Mohr-Coulomb material models is sufficient, and even preferred, in most practical mining applications. There are several notable studies, focusing on mine seismicity and using simplistic boundary element elastic modelling methods (e.g. Malovichko and Basson, 2014; Linkov, 2013; Beck and Brady, 2002).

This debate persists despite several studies to the contrary, including Andrieux et al (2007) who could demonstrate and prove, through worked examples, that in many cases it can be very difficult to correctly interpret the results computed by a simple elastic approach, particularly when highly stressed mining fronts are involved, and extensive failure occurs. Beck, Reusch and Arndt (2007) and Levkovitch, Beck and Reusch (2013) also support this assumption and each showed the importance of the modelling method and the adopted constitutive models on mine seismicity forecasting.

Nevertheless, the authors' experience has shown that in complex rock mass conditions, the modelling method and the applied constitutive model can have a substantial impact on the reliability of modelling predictions. High stress environments and strength anisotropy are two of the most important factors which can add substantial complexity to rock mass behaviour. Vakili and Sandy (2014) provided a comparison between various numerical modelling methods and proposed a conceptual complexity matrix which relates multiple factors such as rock mass anisotropy, stress, etc. to the level of expected rock mass complexity. Application of simplistic numerical modelling methods in rock masses dealing with "significant complexity" can lead to considerable errors. Vakili, Albrecht and Sandy (2014) and Hadjigeorgiou and Karampinos (2017) detailed the complexities that need to be accounted for when modelling rock masses in high stress and highly anisotropic rock mass conditions.

In the proposed framework, FLAC3D (Itasca, 2012) software is used together with StopeExamine (Cavroc, 2017). StopeExamine is a plug-in to FLAC3D which significantly simplifies the application of advance inelastic numerical modelling. This makes it possible for all geotechnical practitioners to learn and apply a more rigorous analysis than the current elastic boundary element tools. In addition, StopeExamine has the Improved Unified Constitutive Model (IUCM) as its built-in material model. This material model is the only commercially available model that can account for mechanisms involved in more complex rock mass conditions. For example, IUCM can account for important and fundamental mechanisms, such as the transition from brittle to ductile response, confinement-dependent strain-softening, dilatational response, strength anisotropy, and stiffness softening. All these mechanisms can significantly affect the seismicity in the rock mass and are generally ignored by most commercially available material models. A detailed and transparent description of the IUCM components are presented by Vakili (2016). This includes step by step instructions on the procedures that were implemented in each of the model's algorithms. Vakili (2017) showed comparisons between the IUCM model results and other conventional models (i.e. Elastic and Mohr-Coulomb) for several well documented case histories.

The main advantage of applying the FLAC3D/StopeExamine approach are:

- Models can be constructed faster and easier and they require minimum computer software skills, so most geotechnical engineers can use this approach.
- The built-in material model (IUCM) has been extensively validated on several well-documented mining case histories.
- The method only requires four compulsory input parameters for isotropic rocks and three additional inputs for anisotropic rocks. All the inputs can be obtained from conventional laboratory testing and rock mass characterisation, which are often available in most mining projects.
- A detailed guideline for selection of input parameters is provided by Vakili (2016).
- The entire package is commercially available for public use through software leasing.

Figure 2 shows an example at Gwalia Deeps mine, where results of a conventional elastic model is compared against the FLAC/StopeExamine/IUCM modelling approach. In this example the combination of high stress and strength anisotropy (due to existence of well-defined anisotropic fabric) led to progressive yield and damage in the hanging wall and foot wall which cannot be captured in an elastic model. In addition, the extent of the yield in the foot wall and hanging wall considerably affected the stress re-distribution around the stoping area which could not be represented in the elastic model.

The energy and stress outputs in the elastic model suggested that most of the seismicity should be expected in the stoping abutments. However, in reality, the largest and most frequent events occurred in the foot wall and hanging wall of the stopes. The FLAC/StopeExamine/IUCM modelling approach was able to capture this behaviour well. It should be noted that the input parameters used for this model are well within the ranges obtained from laboratory testing and rock mass characterisation and no extreme adjustments were made during model calibration. In fact, the initial model used inputs which were directly derived from laboratory testing and rock mass characterisation data. This initial model was able to provide an acceptable match with the seismic data, and particularly in terms of the event frequencies. With some minor adjustments to the inputs (still within the variability range of the testing data), a closer match was achieved to both the event frequency and the larger events.

Although the proposed modelling approach is considered one of the most reliable commercially available methods, there are still various aspects and limitations of the IUCM that can be improved in the future, as summarised in Vakili (2016). Also, the current definition, process and requirements of model validation has been poorly defined in existing publications and frequently subjective in nature. The most rigorous way to evaluate the suitability of a numerical method in forecasting seismicity is perhaps through validation against carefully controlled and monitored laboratory or physical testing. This is another area where improvements are needed in the proposed framework.

POST-PROCESSING AND INTERPRETATION OF THE MODEL OUTPUTS

Following the post-processing of historical seismic data, selection of a suitable numerical modelling method and completion of the analysis, the next step is to post-process and interpret the modelling results. This is particularly important since standard model outputs, like stress and strain, can generally not be directly correlated with mine seismicity.

Several methodologies are available for the post-processing of model results and several modelling outputs can potentially be used. One of the most widely applied methods is the so-called “explicit modelling of seismicity”, as described by Malovichko (2017). This method provides a way to forecast the expected seismic response for a planned mining sequence and therefore evaluate the seismic hazard. The most well-known studies which used this method were presented in Board (1994), Salamon (1993) and Linkov (2005). Board (1994) used the Excess Shear Stress (ESS) method which is defined as the magnitude of shearing stress in excess of the shear dynamic frictional strength. The method proposed by Salamon (1993) and Linkov (2005), also called the Salamon-Linkov method, is based on finding the possible flaws (i.e. cracks) in an elastic rock mass model and then to transfer the parameters of modelled flaws into a seismological domain (Malovichko and Basson, 2014). Both of these methods are implemented within an elastic model framework and use the stresses obtained from an elastic stress analysis.

An alternative method assumes that a seismic event is generated when the stored energy in the rock mass is not dissipated in a gradual manner. Therefore, energy outputs might be the better indicator for the seismic event potential. Some notable studies, which used or discussed these stored or released energy methods include Beck, Reusch and Arndt (2007), Levkovitch, Beck and Reusch (2013), Wiles (1998) and Kaiser, McCreath and Tannant (1996).

There are also other methods that apply indirect approaches to quantify the potential for seismicity. Board et al (2001) demonstrated a simple approach based on the stress path that a point in the model follows from pre-mining state through to completion of mining. This method provides a way to measure the potential for a violent energy release in the rock mass. As shown in Figure 3, a rock mass under loaded conditions, can either store strain energy due to a state of high confinement (“Bursting”) or rapidly lose confinement which leads to nonviolent yielding (“Low”). If a “Bursting” stress path occurs in a brittle, high-strength rock, such a loading system is more prone to violent energy release. This method has been used by others such as Andrieux et al (2008).

It is important to understand how various model interpretation methods compare and which approach is most suitable for future application. To evaluate this, perhaps the best approach is through laboratory and physical testing, coupled with numerical simulations. In absence of such studies, the only other possible approach is through a qualitative comparison between modelled and actual measured seismicity at a mine site with a good seismic database, as well as a good understanding of the rock mass properties and stress state.

Gwalia Deeps mine is a good candidate for such evaluations. The seismic data over a period of five years was used together with the mined sequence to perform a numerical back-analysis. Good information was available for this site in terms of mine geometries, adopted mining sequence, stress state and rock mass properties. The resulting model was post-processed using various interpretation methods and compared.

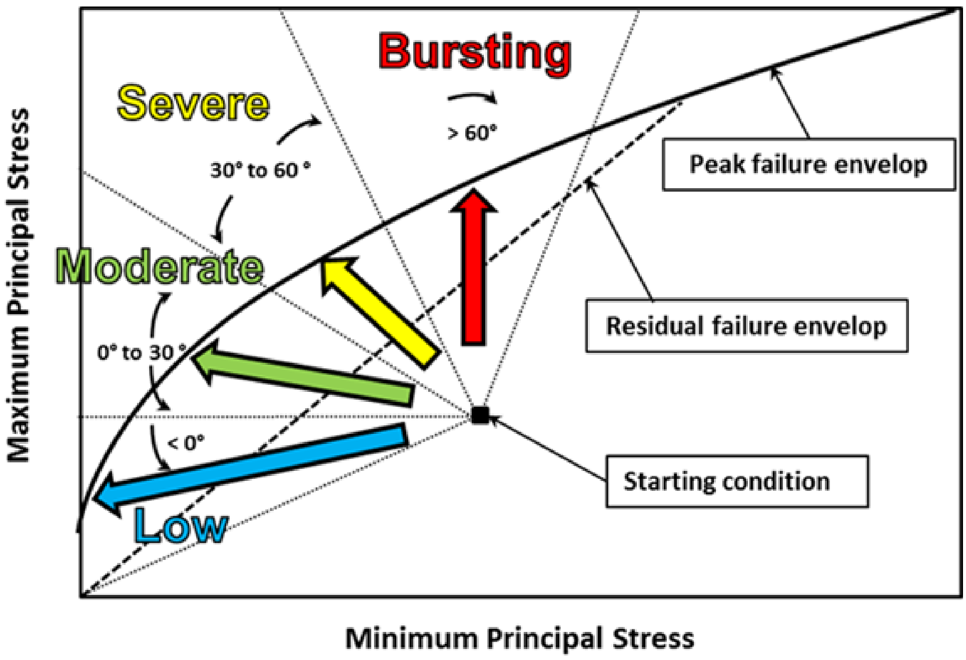


FIG 3 - The stress path method for quantifying the potential for seismicity (modified from Board et al. 2001).

Only the model energy methods and the stress path method (shown in Figure 3) could be applied with an inelastic model (other methods and frameworks are only suited for elastic models). FLAC3D (Itasca, 2012) currently provides the option to output the model energy and this includes automatic energy output for Elastic Stored Energy and Dissipated Plastic Energy (DPE). With an elastoplastic rock mass behaviour, the total energy balance can be expressed in terms of the release energy (Wr). In the numerical model this can be calculated as the difference between the work done at the boundary of the model and the total stored and dissipated strain energies (Itasca, 2004 and Kaiser et al, 1996):

$$W_r = W - (U_c + U_b + W_j + W_p)$$

Where Wr is release energy; W is total boundary loading strain energy; Uc is total stored strain energy; Ub is total change in potential energy of the system; Wj is total dissipated energy in joint shear; and Wp is total dissipated work in plastic deformation. Note that the Wj component can only be evaluated if the joints, faults and geological structures are explicitly included in the models. The calculation of the release energy was calculated in FLAC3D based on equations provided in Itasca (2004).

For post-processing of the model results using the stress-path method and to quantitatively measure the potential for the "Bursting" case, the slope angle (ψ) of the stress path line in the principal stress space can be classified as shown in Figure 3, and be assigned to various levels of bursting risks proposed in Board et al (2001). In the numerical models, a routine is implemented which records the starting stress conditions ($\sigma 1$ and $\sigma 3$) for each zone right through to its failure state. Once the zone has failed, the ψ is calculated by finding the gradient of the line connecting the starting condition to the failure state. This angle is then compared against the criterion described above, and a relative index is assigned to the zone.

The model outputs using the energy variables (Release Energy, DPE and Elastic Stored Energy) and the stress-path method were compared against the actual seismicity at Gwalia Deeps mine. The comparison was made visually (comparing event locations with the model outputs like what is shown in Figure 2) and by comparing the total sum of energy at each mining step versus the number of recorded events (see Figure 4). The comparisons were mostly qualitative, and it was concluded that Energy Release showed the best correlation with the actual seismicity.

Several publications have claimed to have a calibrated numerical model, validated by the available seismic data, though this often appears to be a subjective process and conducted visually. More quantitative criteria need to be developed to better define what exactly a validated numerical model is, and until then it remains difficult to compare modelling results within or between studies.

In the current framework, several improvements can be made to increase the confidence of how the model results are interpreted and post-processed. These include:

- Studying the seismicity at a more fundamental level, including results from laboratory and physical tests.
- Conduct a more quantitative comparison between the modelled and actual seismicity. For example, the cell evaluation method proposed by Beck and Brady (2002) or the grid-based analysis method by Wesseloo et al. (2014) can be used to post-process the model outputs in a spatial manner and then compare it with the actual seismic data.
- A quantitative validation process should be developed to determine the success of the modelling approach.
- Comparisons should be completed at various mine sites to ensure that similar correlations can be achieved.

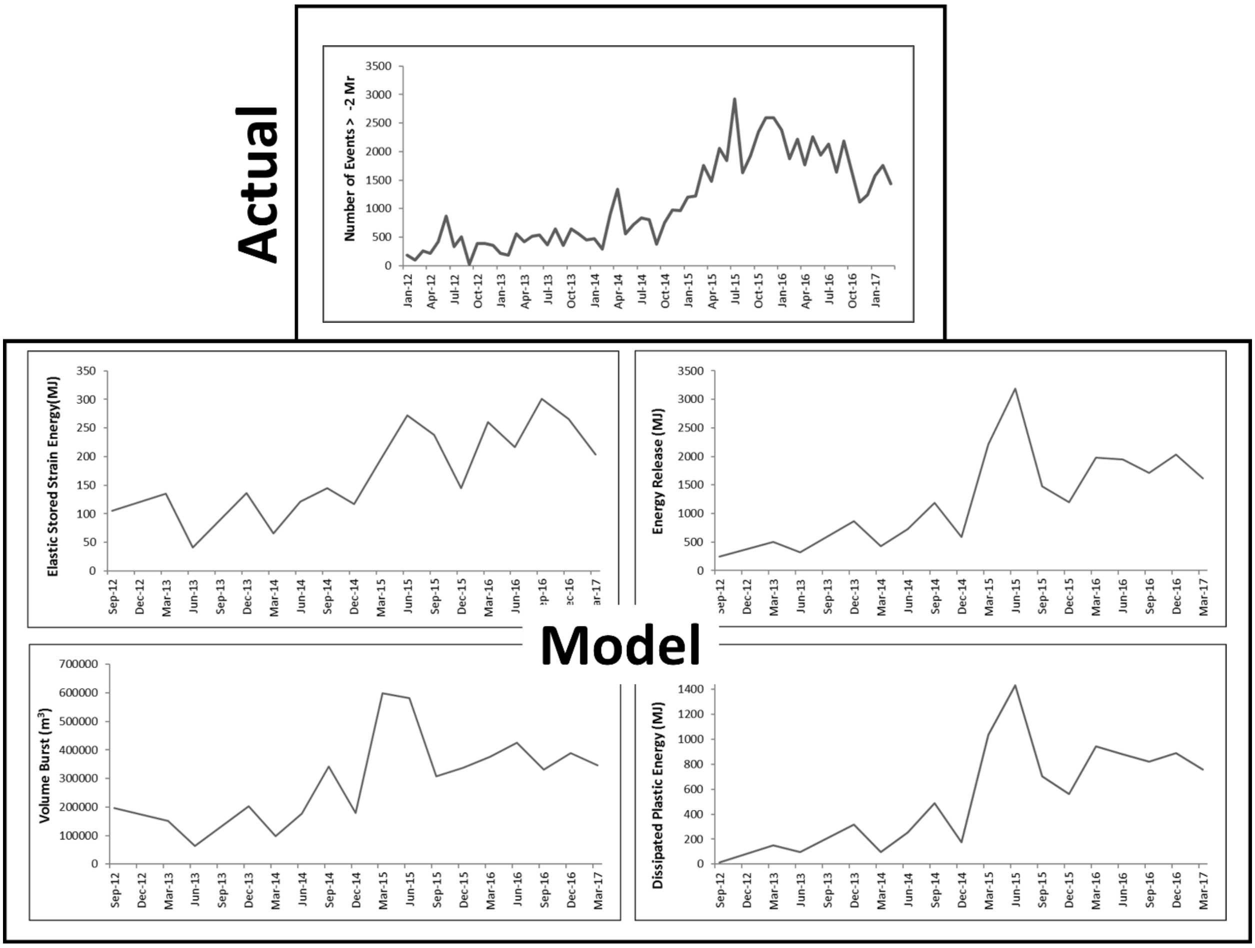


FIG 4 - Comparison between different actual historical seismicity and model forecast using the energy outputs and the stress-path method.

A CASE STUDY AT GWALIA DEEPS MINE

The Gwalia Deeps Mine is located three kilometres south of the town of Lenora, Western Australia. The mine is currently operated by St Barbara Limited and has 2.1 million ounces of gold reserves (June, 2017). The mine uses a Longhole Open Stoping (LHOS) mining method and the main decline, called the Hoover Decline, was extended to 1620 m below surface in 2017 to allow for production from a range of ore sources. Despite the mine being the deepest trucking mine in the world, it plans to deliver more consistent production and lower operating costs over its life of mine outlook, even when compared to most mid-tier gold mines in Australia.

Effective geotechnical management has had a significant impact on achieving these targets. The geotechnical team at Gwalia Deeps has been pro-active in data collection, mapping, monitoring and sensible numerical modelling. The team has put together comprehensive geotechnical databases of underground damage mapping, laboratory testing, stress measurements, seismic hazard and stope geotechnical reconciliation. These databases have enabled the calibration of advanced numerical models, to high level of detail and accuracy. These holistic geotechnical practices have provided several benefits to the operation including:

- Reduced hanging wall dilution of up to 50 per cent, through optimising stope strike spans.
- Applying mining strategies to achieve sustainable high production rates.
- Managing the seismic hazard through improved forecasting of seismic hazard scale and locations most prone to dynamic loading.
- Proactively locating long term infrastructure outside future potential seismic influence associated with stoping operations.

The ore body and the immediate foot wall of stoping at Gwalia Deeps is comprised of a high strength, massive schist and the hanging wall and far foot wall is within a massive basalt unit. A lower strength unit exists between the boundary of the schist and basalt units in the far foot wall side of stoping. Jointing within the schist and basalt units is sparse with Rock quality designation (RQD) generally over 80 per cent. Both the schist and most of the basalt units are medium to highly anisotropic due to the existence of a well-defined foliation fabric. At depths below 1300 m, high stress and strength anisotropy largely control the geotechnical performance of the mine's development and stope stability.

The Gwalia Deeps mine was used as a case study to validate the suitability of the proposed framework and its ability to forecast the future seismic hazard. For this purpose, the stoping sequence from late 2012 until early 2017 was used for numerical back-analysis. The validated numerical model was then used to forecast the expected seismicity for the next 12 months of stoping. For the reasons listed below, Gwalia Deeps is considered an ideal mine for investigating the suitability of the proposed framework:

1. There's a comprehensive database of uniaxial compressive strength (UCS), Triaxial and Brazilian tests. This includes 288 UCS tests, 178 Triaxial tests and 182 Brazilian tests. The angle between the foliation and the loading axis (β) for all tests was recorded so that the anisotropic properties of each sample could be estimated.
2. More than 10 insitu stress measurement (eight of them were by the HI cell overcoring method) have been carried out so far. Most valid measurements provided a consistent magnitude and orientation and the adopted field was further validated through numerical back-analysis with a seismic source analysis completed by Institute of Mine Seismology (IMS).
3. The rock mass characterisation for estimation of the GSI was carried out based on underground mapping and core logging data.
4. The historical mining sequence, for the time interval under study, was reasonably well known and the stope design geometries were available for all the mined stopes.
5. There is a comprehensive database of development damage mapping, monitoring data, geotechnical stope reconciliation and a high-quality seismic database. Therefore, detailed model validation and calibration is possible.
6. There are no known major structures below 1300mbs that need to be included in the analysis.
7. The mine has a good track record of adhering to the planned mining sequence which facilitates the most appropriate method of validation by comparing the forecast with the actual mine seismicity.

Figure 5 shows a visual summary of the assessments carried out to derive the input parameters for the numerical model.

Table 2 and Table 3 shows the rock mass parameters and stress state used in the model. Note that the input parameters in Table 2 are summarised according to the required inputs for the Improved Unified Constitutive Model (IUCM) model, as outlined in Vakili (2016).

The calibration and validation of the numerical model using the IUCM framework, was completed over a period of four years (since 2014) and with continuous fine-tuning and improvements. The damage mapping, hanging wall Stretch Measurement to Assess Reinforcement Tension (SMART-cable) monitoring, hanging wall over-break and seismic data has been used to validate and calibrate the model. This model has become a valuable tool for the mine to assist with short to long term mine planning and identifying potential geotechnical hazards.

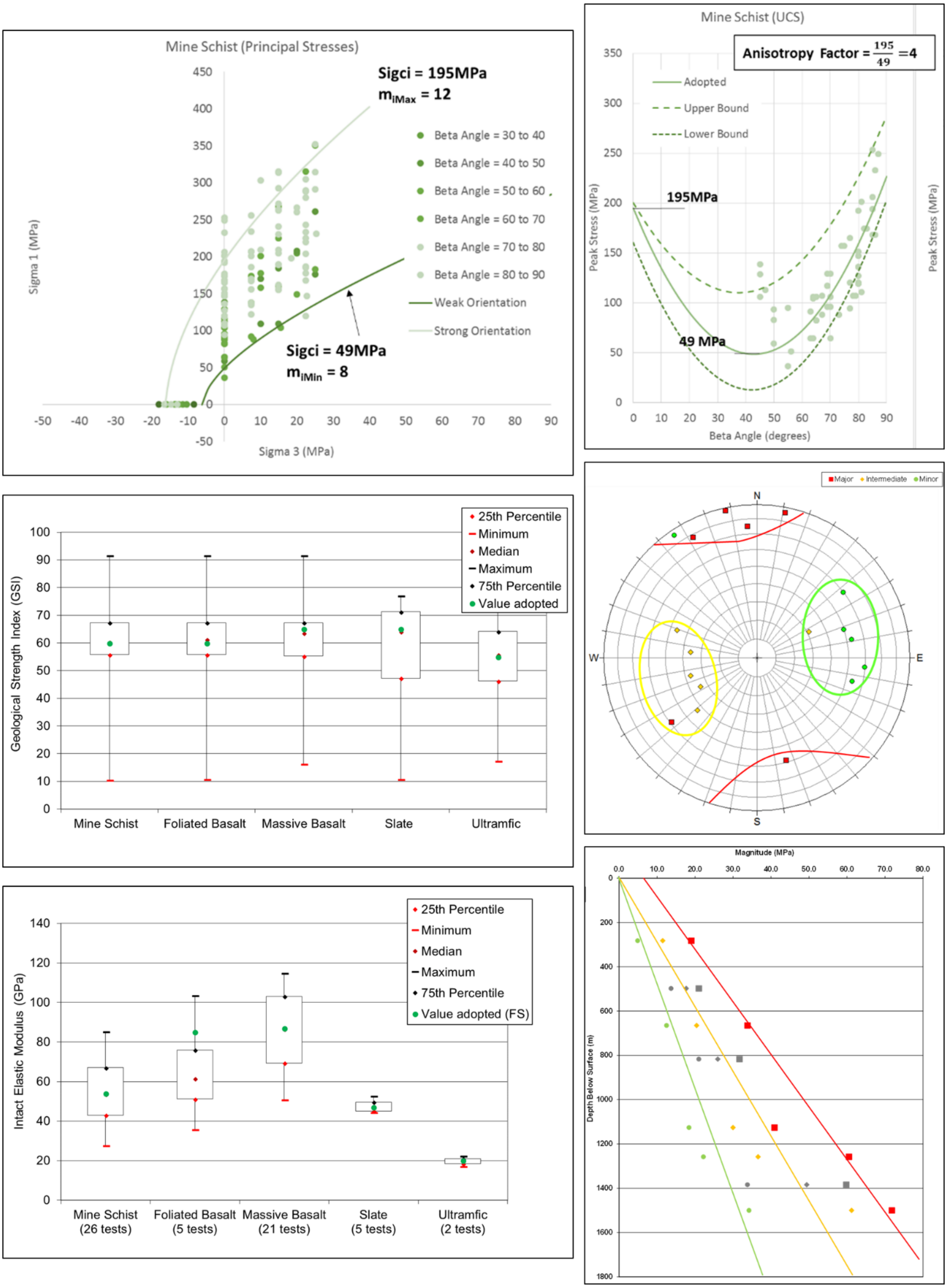


FIG 5 - Examples of assessments to derive the rock mass properties and the Insitu Stress state.

TABLE 2: Model input parameters used in numerical models for Gwalia Deeps Mine.

Rock Unit	IUCM[1] Input Parameters												
	Density (t/m3)	E_i[2] (GPa)	Sig_{ci}[3] (MPa)	mi_{Max}[4]	mi_{Min}[5]	Anisotropy Factor[6]	Dip[7] (°)	Dip Direction[8] (°)	GSI[9]	C_{Res}[10] (MPa)	Fri_{Res}[11] (°)	Ten_{Res}[12] (MPa)	$Crit_{Red}$[13]
Mine Schist	2.8	54	195	12	8	4	45	75	60	0.0	45	0.0	1.0
Foliated Basalt	2.8	70	195	12	8	3	45	75	60	0.0	45	0.0	1.0
Massive Basalt	2.8	87	120	8	N/A	N/A	N/A	N/A	65	0.0	45	0.0	1.0
Slate	2.8	49	150	7	5	2	45	75	65	0.0	45	0.0	1.0
Ultramafic	2.8	20	60	8	4	10	45	75	55	0.0	45	0.0	1.0

[1] Improved Unified Constitutive Model

[2] Elastic modulus of intact rock (obtained from laboratory test results)

[3] UCS of intact rock (obtained from laboratory test results)

[4] Hoek-Brown constant mi for the intact rock matrix (obtained from laboratory test results)

[5] Hoek-Brown constant mi for the plane of anisotropy of the intact rock (obtained from laboratory test results)

[6] Anisotropy factor (obtained from laboratory test results)

[7] Dip angle of bedding plane (obtained from structural sets reported in the most recent GCMP)

[8] Dip direction of bedding plane (obtained from structural sets reported in the most recent GCMP)

[9] Geological Strength Index (obtained from rock mass characterisation data)

[10] Residual cohesion (Typical value used as default for the IUCM model as described by Vakili, 2016)

[11] Residual friction angle (Typical value used as default for the IUCM model as described by Vakili, 2016)

[12] Residual tensile strength (Typical value used as default for the IUCM model as described by Vakili, 2016)

[13] Reduction factor for critical strain ((Typical value used as default for the IUCM model as described by Vakili, 2016)

TABLE 3: Adopted Stress State in numerical models for Gwalia Deeps Mine.

Stress Components	Gradient (MPa)	Plunge (°)	Trend (°)
σ_1	0.042 x Depth + 6	00	345
σ_2	0.035 x Depth	50	255
σ_3	0.021 x Depth	40	80

For model back-analysis, the historical seismic data for the time period between 2012 and 2017 was first processed according to the Hudyma and Potvin (2004) method. Considering the importance of larger events, the SHS values were calculated for events with magnitude greater than 0MR (Richter Magnitude). The SHS values were then compared against the modelled energy release output. The Energy Release was divided by the mined volume and its common logarithm calculated for each mining step. It was determined that using the logarithmic value for the energy output provided a much better correlation with the actual SHS values.

This is reasonable considering the fact that the SHS value is also expressed logarithmically.

The comparison between the model output and the actual SHS values are shown in Figure 6. Given the variabilities in the rock mass and all other geotechnical uncertainties associated with every mining problem, the obtained correlation (with a correlation coefficient (R2) of 58 per cent) is considered very satisfactory.

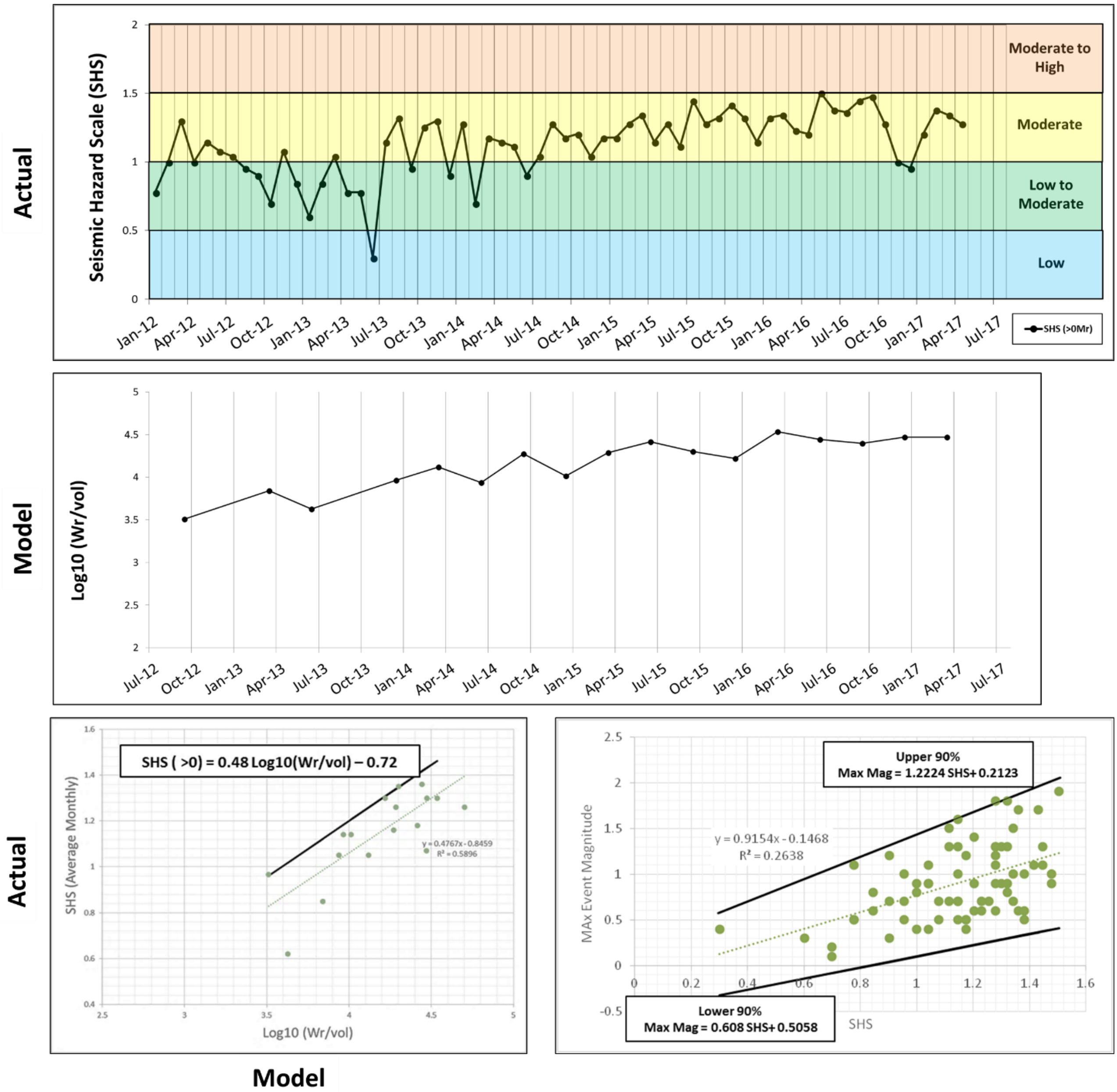


FIG 6 - Validation of numerical model energy release output against the calculated SHS values obtained from the seismic database.

The comparison between the model and the actual seismicity was also conducted visually and based on the location of the events and the location of high energy release in the model. Examples of these comparisons are shown in Figure 7. Note that the plot of the modelled release energy and the plot of events greater than 0MR shows the cumulative events and energy between late 2012 and early 2017 (the back-analysis model), however the event frequency plots show the events between 2012 and late 2016. It is evident from the spatial comparison that although the overall correlation was satisfactory, there are locations where the model forecast was not satisfactory.

Following the initial back-analysis and establishing the criterion for seismicity forecasting, the validated numerical model was used to forecast the expected seismicity for the next 12 months of planned stoping. This forecasting was completed prior to September 2017 and subsequently, the actual seismicity has been monitored continuously to cross-check with the model forecast and confirm the suitability of the proposed framework. Results are shown in Figure 8. Note that the forecasted maximum event magnitude from the model results was obtained by correlating the energy output to SHS and subsequently correlating SHS to the maximum expected event magnitude.

The results so far have been well within the model forecast and suggest that the proposed framework can be used routinely to forecast and better understand the future expected seismic hazard. However, the validation process needs to continue, and the proposed framework needs to be tested at other mine sites before it can be established as a proven method. Also, the spatial comparison between the model and the actual seismicity for the forecast period (from August 2017 through to January 2019) is currently underway and will be included in future publications.

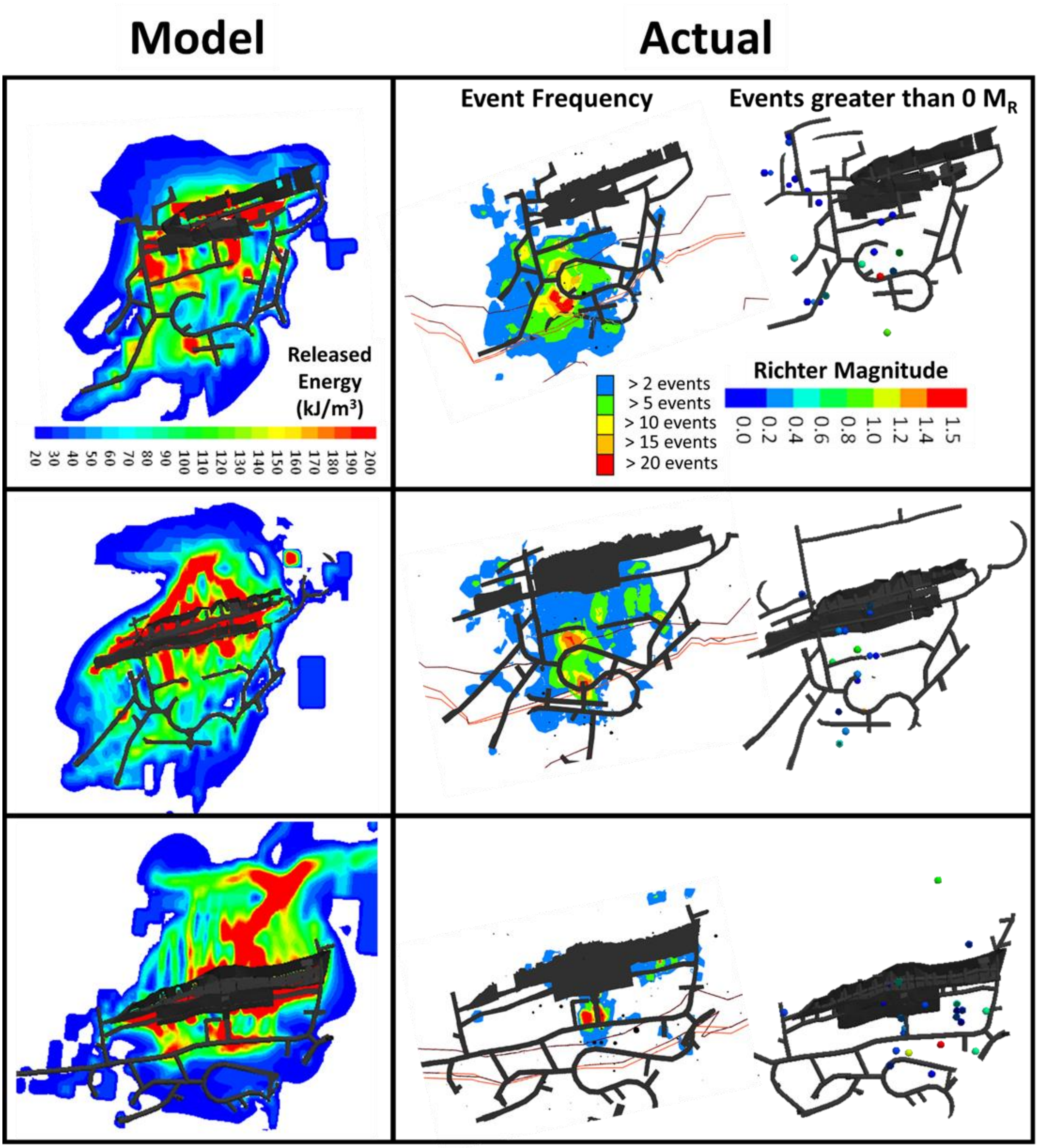
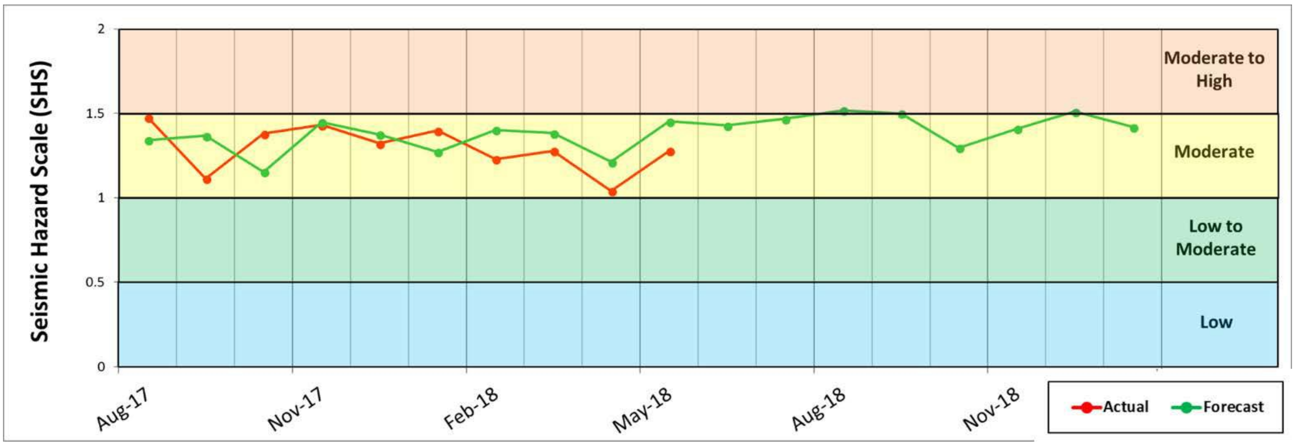


FIG 7 - Spatial comparison between actual seismicity and model forecast.



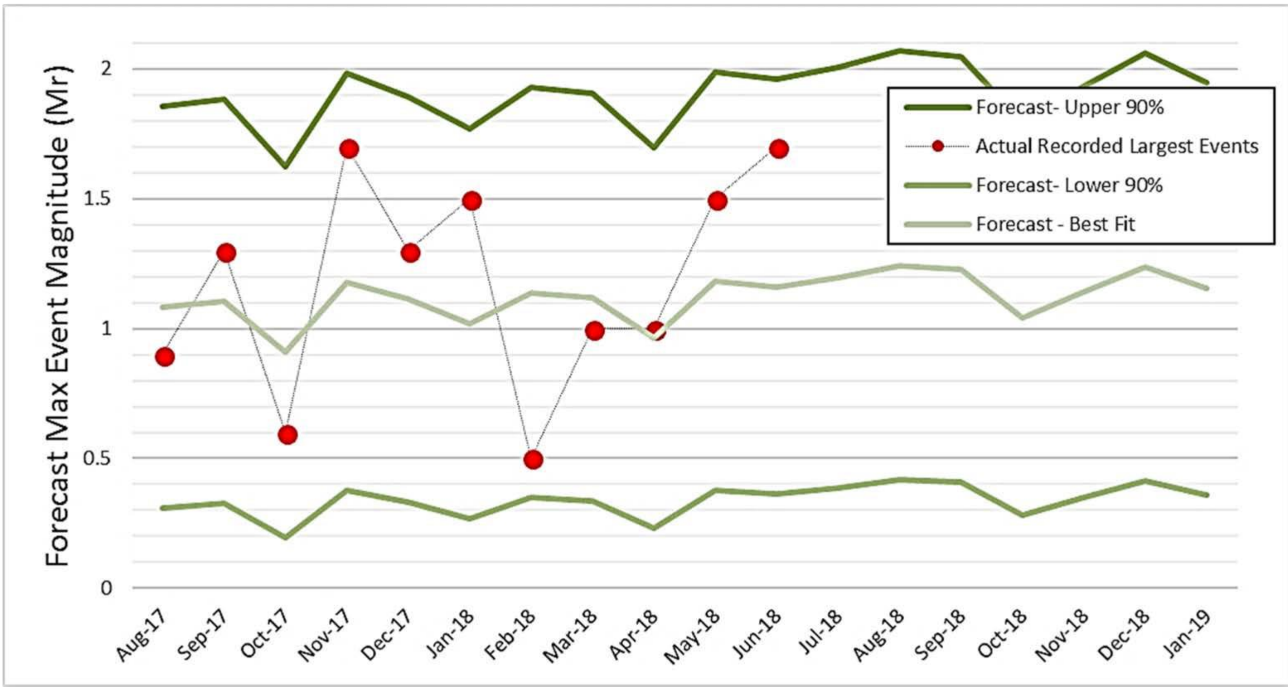


FIG 8 - Comparison between model forecast and actual recoded seismicity for the period between late 2017 until early 2019. Note: Actual seismicity (shown in red) was unknown at the time when model forecasting was complete.

CONCLUSIONS

This paper has outlined the key aspects and challenges of using numerical modelling to forecast mining induced seismicity. A methodology has been proposed, which can be used by geotechnical practitioners at other mine sites in the hope that it can be further validated and eventually established as a transparent, proven method. The paper has also highlighted several limitations and potential improvement which should be explored, including:

- Evaluating, and potentially adopting, more recent advances in the processing of seismic data and how the 'current' seismicity hazard is assessed.
- Exploring the applicability of the forecasting methodology in different mining environments, subject to different seismic mechanisms.
- Creating a thorough modelling validation criteria and definition, so different modelling methods and complexities can be compared quantitively.
- Expanding the scope of forecast models to assist geotechnical practitioners evaluate the key parameters needed in dynamic ground support design.

Finally, the methodology has been implemented at a seismically active Australian mine and the presented results have been promising. To date, the numerical model has been able to forecast the seismic hazard for the given mining sequence and provide a quantitative estimate on the maximum expected event magnitude and location. The model has proven a useful tool for mine planners, and it is expected that the model will continue to develop as methodology improvements are continually implemented.

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