Numerically simulated Rate of Energy Release and its correlation with measured seismic potency

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ABSTRACT: As mines are getting deeper, mining induced seismicity becomes a major hazard threatening the health, safety, and security of operations. In today's mines, seismicity is well measured and documented. However, the ability to foresee events lags behind. This paper will discuss the correlation between numerically simulated Rate of Energy Release (RER) and measured seismic potency in the real rock mass. RER is defined as the rate of elastic strain energy emitted into the surrounding rock as a result of abrupt fracture or deformation. RER has proven to be a good candidate for probabilistic forecasting of seismic potential (the capacity to develop seismogenic activity) in the rock mass. In the following sections, we will describe a computational framework for simulating RER and subsequent analyses for evaluating the likelihood of mining induced seismic events. We will present example results from mines where model predictions matched measured seismicity.

Keywords: Mining induced seismicity, rate of energy release, RER, hazard management, seismicity forecast.

1 INTRODUCTION

As underground hard rock mines are getting deeper, they are experiencing more seismicity and ground control challenges. Seismicity poses the highest risk to the frontline crew at the mining or excavation face. Whilst improvements in seismic monitoring systems have enabled operations to monitor mining induced seismicity and identify areas with high seismogenic activity, these systems do not have the predictive power to forecast if and when the risk of a high magnitude event is elevated. Therefore, seismicity remains one of the major hazards in mining.

The source of seismicity in mines is very similar to acoustic emissions captured at various stages of the stress-driven failure process during a simple compression test. A seismic event is the sudden release of potential or stored energy in the rock as a result of abrupt deformation or failure. The released energy is then radiated through the rock mass as seismic waves that are captured by seismic monitoring sensors (seismic event). The nature of seismic events depends on physical and mechanical properties of the rock mass and discrete structures.

Mining gives rise to seismic activity ranging from micro-seismic events radiating 10^{-5}J (-6M) to rockbursts or tremors radiating 10^{9}J (5M) (Cook, 1976).

Mines have been recording their seismicity for several years now. Amongst the captured data is the strain energy magnitudes, which are proportional to the intensity of the source events. These historic records therefore can be used for statistical prediction of incidence of seismic events and their magnitudes. The Gutenberg-Richter plot (Gutenberg and Richter, 1949) is one the common methods used to estimate the likelihood of seismic events of a certain magnitude occurring in a given region. Statistical analyses, whilst useful, are not sufficient for predictive evaluation of seismic hazard in mining. This is because mining induced seismic events are also a function of operational factors, such as mining rate and sequence.

This paper discusses the use of numerically calculated rate of energy release (RER) for forecasting seismic potential in mining operations. RER is the instantaneous rate of surplus elastic strain energy (Levkovitch et al, 2008) emitted to the surrounding rock mass as a result of fracture or deformation. Therefore, it is directly correlated to the released strain energy that travels into the rock mass and is recorded by seismic sensors. RER is determined using finite element numerical modelling methods in mine scale simulations. The following sections describe the methodology for calculating RER and subsequent analyses to forecast mining induced seismic potential.

2 MODELLING METHODOLOGY

The simulation uses explicit finite element modelling techniques with a three-dimensional (3D) mine scale geometry. The 3D dimensions of the model geometry span the global mine scale to consider the regional aspects of stress distribution and lithology, and to capture true confinement conditions within the mine. The area of interest is constructed with a higher resolution of elements, in order to be fit for purpose.

The mine's past and future excavations are explicitly built and sequenced in a sufficient number of separate steps (called frames) to establish a realistic stress path in the areas of interest and to obtain the necessary temporal resolution for the project scope.

The mechanical behaviour of the rockmass and structures are prescribed using the Levkovitch-Reusch (LR4) constitutive framework (Levkovitch et.al. 2010). LR4 is 3-dimensional yield criterion based on a generalised Hoek-Brown failure envelop with strain softening dilatant (SSD) capacity. It accounts for all components of stress and can simulate the softening and loss of strength in the rock when it is over-stressed. These features enable assessment of the impact and effect of yield or failure in one area on the rest of the system.

Discrete structures are defined as cohesive finite elements. These elements are free to dislocate, dilate and degrade and can realistically capture the behaviour of thin structures, which tetrahedral finite elements cannot achieve as effectively. The model is also large strain. This is an essential feature for any mine where significant plasticity has occurred or where failure needs to be disconfirmed.

3 RER COMPUTATIONAL FRAMEWORK

The model tracks and computes the stored, dissipated and released energy at every frame, for every tetrahedral and cohesive element in the FE simulation, accounting for the stress path induced by excavation and void filling, confinement loss, dilation, and large strains. RER is then calculated as the surplus of elastic strain energy and plastic free energy for the homogenized rockmass (represented with tetrahedral elements), and for the explicit structures (represented with zero-volume cohesive elements). Both rock mass and fault slip RERs are important. Whilst the largest events are expected on structures, many lower magnitude events are anticipated in the intermediate rockmass.

As the magnitude of the released energy during seismic events can be measured in a mine using a seismic monitoring system, the computed instantaneous rate of energy release is directly comparable to the measured data.

From a modelling point of view, softening, dilatancy and discontinuities are critical model elements needed for calculation of realistic RER. For this reason, a main effort of model calibration is to refine the softening and dilatancy response of the rock and discontinuities to match observations. Calibration for seismicity involves analysing recorded event clusters, which represent measured seismic potential, and adjusting material properties to achieve as close a match as possible between RER isosurfaces and event clusters. Close seismic calibration also depends on:

1. A reliable structural model. Structures must be included at the necessary resolution and the relative strengths of the structures need to be captured.
2. Accurate records of mining history at regular intervals.
3. Good quality seismic data, which comprises accurately located events with few temporal or spatial gaps and a complete population of events down to small magnitudes (i.e. not missing events due to the sensor distribution, system sensitivity or shadowing effects of mined voids for example).

3.1 Seismic Potential

Seismic potential in the model is represented by the calculated rate of energy release (RER). For this purpose, the forecast RER is directly compared to the measured seismicity—event occurrence and magnitude—to establish a quantitative relation between modelled RER and expected or measured seismic potential. Overall, the higher the RER, the greater the probability of seismic events of a high magnitude. Seismic potential is presented in three levels:

- High Seismic Potential
- Medium Seismic Potential
- Low Seismic Potential

RER thresholds for these levels are determined based on probability of seismic events at a particular RER. It should be noted that the threshold levels are material dependent and vary for every rockmass and fault slip.

4 CASE STUDY

The selected mine for the case study is the hard rock Goldex mine located in northwest Quebec, Canada. The mine has been seismically active since 2009, with overview of the seismicity records shown in Figure 1a. The probability relation, Pr(m ≥ M), for the recorded data are shown in Figure 1b using a normalized Gutenberg-Richter (G-R) relation of seismicity frequency versus magnitude. The graph demonstrates the probability of the observed events having magnitude greater or equal to M, assuming that all seismic events in the dataset are independent, and that each single event has equal probability of occurring.

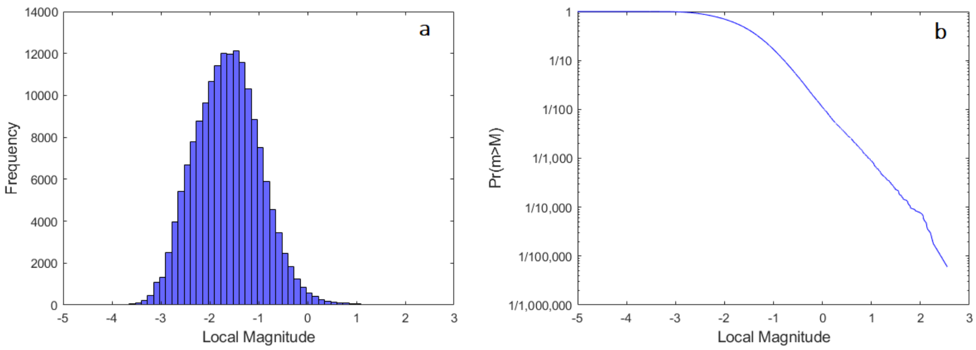

Figure 1. Overview of seismicity records at the mine. (left) distribution of the magnitude of the recorded events over the life of the mine; (right) Gutenberg plot or the seismic data.

Figure 2 shows the seismic probability profile of RER for various rock masses (denoted as RM) and fault slips (denoted as FS) at the selected mine site for years 2017 to 2021. These plots are produced by comparing modelled RER to measured seismic occurrences in every single cell within the modelled geometry of the mine. A Cell Evaluation Method or CEM (Beck & Brady, 2001) was used to establish a quantitative relation between modelled RER and measured seismic potential. Note whilst overall probability of events at significantly high RER (>10^6) is low, the probability is not zero. Events that occur at high RER are also high magnitude, therefore, these are treated as high risk. The Gutenburg-Richter plot indicates that the probability of an event larger than 2M is 1 in ~14,000 events (Figure 1).

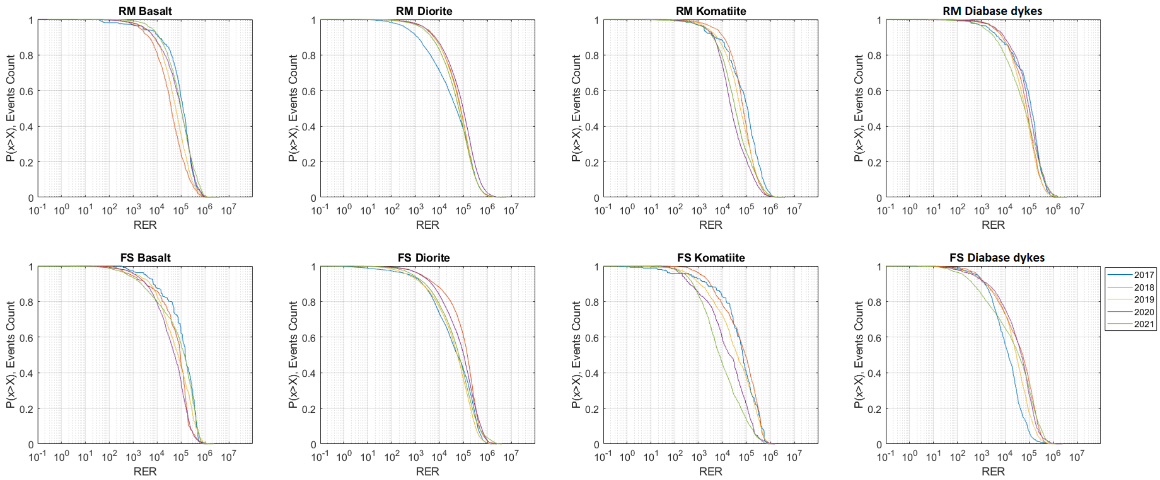

Figure 2: Probability of events occurring at a particular RER for every rock mass and structure (data are cell based).

Seismic potential, however, does not directly specify the event magnitude. The association of RER to event magnitude can be established through its relationship to seismic moment in a calibrated model. Moment magnitude, $M,$ is a function of seismic moment, M_0, (Hanks & Kanamori,1979):

$$M = (\log_{10} M_0 - 9.05)/1.5 \tag{1}$$

Figure 3 compares the distributions of the normalized number of events within cells corresponding to a particular RER to their subsequent normalized seismic moments. As can be seen, the two plots follow a similar distribution, indicating a possible relationship between RER and seismic moment.

To assess the relationship between RER and seismic moment, seismic moments of biggest events for specific RER bins are sampled and plotted with respect to mean RER of the selected bin. These results are shown in Figure 4 for different rock types. Colour in these plots indicates the year of the recorded data. The analyses indicate a power law relationship between measured seismic moment and modelled RER: $M_0 \propto aRER^k$, 0<k<1. The constant a and exponent k are expected to be material dependent.

The three levels of seismic potential scales can then be interpreted based on likelihood and severity of the expected events as below:

- High Seismic Potential ($RER \geq 10^6$) have potency for high magnitude events; these are low likelihood (~1/100000), but severe consequence events: M≥ 2.
- Medium Seismic Potential ($10^5 \leq RER < 10^6$) have potency for moderate magnitude events; these are medium likelihood (1/1000), moderate consequence events: $+1 \leq M < +2$.
- Low Seismic Potential ($RER \leq 10^4$) have potency for low magnitude events. These are high probability (1/100) with low consequence events ~M≤ 0.

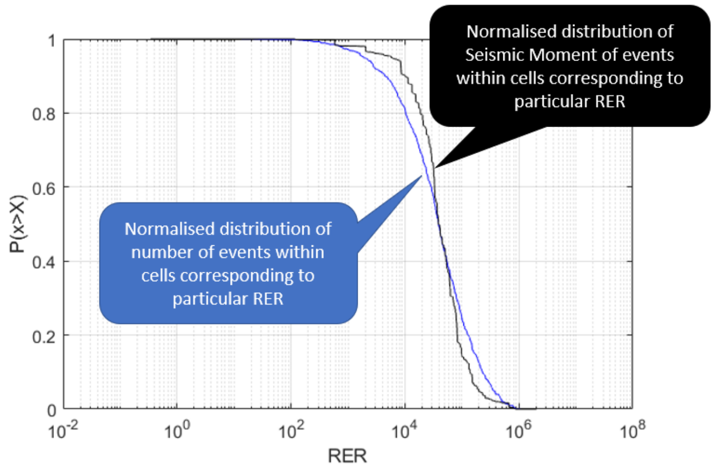

Figure 3. Comparison of measured seismic event and their corresponding seismic moment with RER.

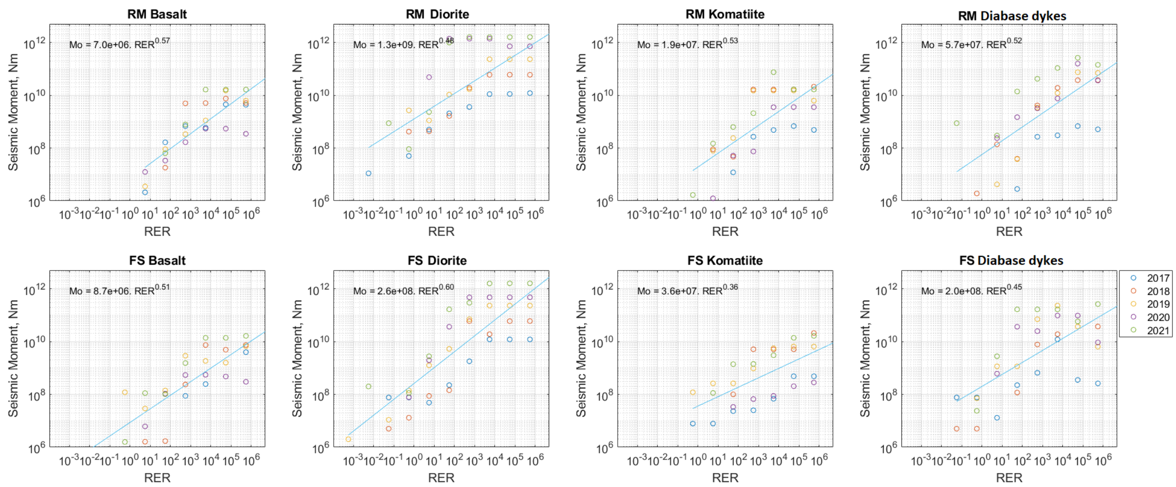

Figure 4. Seismic moment versus RER in each rock type.

Figure 5 shows an example of validation data. In this figure the blue, yellow, and red isosurfaces represent the model forecast for seismic potential and measured data (i.e. seismic events) are shown with sphere markers. The model forecast for high seismic potential shows a good match the measured seismic clusters. The close match is representative of the model's performance during each period of the study. The match between the forecasts and measured data ultimately validates the tool for its intended use, which is assisting the mine to plan extraction strategies. Note that the tool does not replace any other component of sound mine design, day-to-day geotechnical practice or seismic risk management. Rather, it is an adjunct to existing mine design procedures to minimise seismic hazards.

5 CONCLUSION

Data shows that RER correlates with event rate and event probability. At zero RER, event probability is near zero. The correlation between event rate and material stability is intuitive (event rate related to stages of fracture).

Comparison of modelled RER and measured seismic moment indicates a power law correlation between the two. The correlation between RER and seismic moment, and therefore moment magnitude, allows the probability of a certain moment magnitude event to be determined for a given location and time, based on the modelled RER forecasts within particular rock mass or geological structure. Further work is in progress to better understand what controls the power law constants.

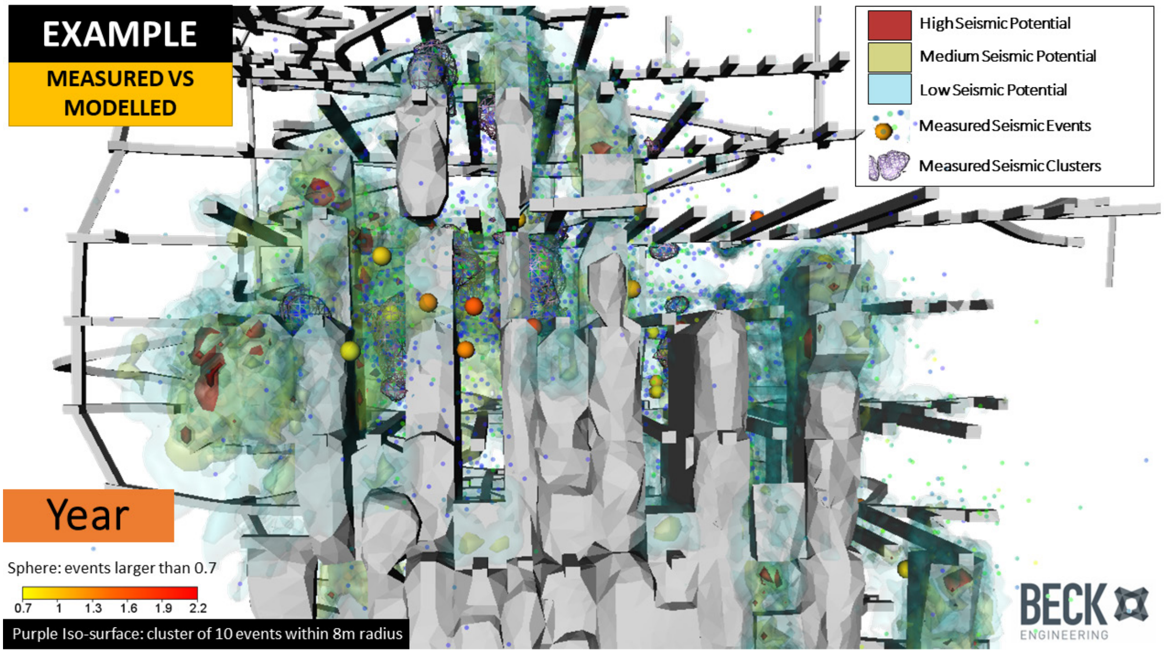

Figure 5. Comparison between forecast seismic potential and measured seismicity.

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