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Using seismic hazard to improve underground mine planning

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Abstract

This article presents a method to evaluate seismic hazard for different mine planning options, which enable mine operators to make informed decisions and develop robust mine plans that account for potential seismic hazards. By rigorously testing the mine plan against diverse scenarios, the design guidelines can be refined to enhance the overall efficiency, productivity, and resilience of the mining operation, ultimately contributing to the long-term sustainability and safety of the mining industry. The method is elaborated based on theoretical aspects and applied to a case study on Canadian sublevel stope mine. Since the results of this work are related to seismic hazard, it is encouraged to continue this research focused on rockburst hazard and in the impact of mitigation strategies in the reduction of the hazard and the improvement of work safety.

Keywords: *seismicity, mine planning, seismic hazard, rockburst*

1 Introduction

Rockbursts are a significant hazard in underground mining operations, particularly in deep, high-stress environments. Rockbursts are sudden, violent failures of the rock mass triggered by the redistribution of stresses due to mining activities. These events can cause severe damage to mine infrastructure, equipment, and (most importantly) pose a serious threat to the safety of mine workers (Małkowski & Niedbalski 2020; Sepehri et al. 2020; Kaiser & Malovichko 2022).

Rockbursts can occur in a variety of mining environments, from hard rock mines to coal mines (Jarufe & Vasquez 2014; Keneti & Sainsbury 2018). They are typically associated with the presence of geological structures, such as faults, joints, and bedding planes, which can act as planes of weakness within the rock mass (Sui-Mu et al. 2014; Reddy & Spottiswoode 2001). As mining progresses and the rock mass is excavated, the stresses within the rock can become increasingly concentrated, leading to the sudden and uncontrolled release of this stored energy in the form of a rockburst (Gong et al. 2020).

To effectively manage the rockburst hazard, it is crucial to develop a comprehensive mine planning strategy that considers the unique geological and geotechnical conditions of the mine site (Małkowski & Niedbalski 2020).

By carefully considering the geological and geotechnical conditions of the rock mass, engineers can develop mine layouts and excavation sequences that minimise the buildup of excessive stresses. Numerical modelling techniques, such as finite element analysis and discrete element modelling, can be used to simulate the complex stress distributions and rock mass behaviour under different mining scenarios; allowing for the identification of high-risk areas and the implementation of appropriate mitigation strategies (Potvin et al. 2010; Jarufe & Vasquez 2014).

The mine design-planning process starts with empirical design done by planning engineers, which is then analysed by rock mechanics experts looking for possible vulnerabilities in the design. Numerical methods, analytical and empirical tools are utilised by rock engineers to check the initial mine planning sequence and any possible unstable situation is discussed with the planning team to generate a new version of the mine plan that considers the geomechanics inputs. Since the geotechnical analysis can be quite long, a method

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where the initial mine planning sequence is built considering seismogenic conditions would improve the planning process, reducing the geotechnical review time and the discussions with planning.

Also, it is important to acknowledge that short-term variations and operational modifications to the planned mine sequence may be necessary, and these cannot always be adequately assessed through numerical modelling due to the short time response required. In such cases, the mine planning process must be aware of the restrictions that induced seismicity may pose to the proposed extraction sequence, but there are no tools to guide mine planning in the short-term decision that usually have to be made in mine operation.

2 Mine planning and induced seismicity

The mine planning process corresponds to the engineering stage where the appropriate mining units are defined (stope size, block caving undercut area, pillar size) and the rate at which the mine will be extracted. Both of these processes are closely related because the mining units size and infrastructure will define the rate the material can be drawn out of the mine. Also, the mine must produce a predefined amount of ore to fulfil mine plant capacity, keeping mine and plant at full production without bottlenecks in the process.

In the mine plan design process, an initial approach is generated by the planning department, where the design is ruled by mineral grades distributions, economical value of the mine sequence and empirical geotechnical design guidelines. Some of these guidelines correspond to stope dimensions according to Mathews or Potvin (Potvin 1988) empirical methods, pillar design following Lunder and Pakalnis methods (Lunder 1994) , Hoek–Brown among others or the minimum cave area based on the hydraulic radius defined by Laubscher (1990). While there may be other empirical methods used by mine engineers, most of them are related to geometrical aspects of the generated caves and through the control of the geometry, the rate of production is achieved. While these methods assess the excavations and pillars stability, none of these techniques considers the seismic and rockburst hazard. The evaluation of this hazard is done by rock mechanics engineers that receive the planning sequence and analyse it through several methods based on numerical modelling. The result from the rock mechanics team is discussed with the mine planning team, generating modifications to the initial planning sequence to reduce potential hazard associated with the original design that could not be evaluated with the current existing empirical tools that mine planning utilises.

While the resulting mine sequence has the geotechnical and economical backup to satisfy project's needs, it is common that during the operational stage of the mine, where the results from the planning-geotechnical design are being implemented into the mine, some changes to the accepted planning scheme have to be made. These are usually related to unforeseen conditions such as variations in ore grades, geotechnical conditions, or operational factors (such as low availability of mining equipment among other reasons). All these situations generate changes in the mine sequence that cannot always go through a detailed rock mechanics review due to the extensive response times that geotechnical analysis require.

Based on the previous discussion, it would be much more useful to the planning department to have design tools to allow the generation of planning decisions based on the expected seismic response of the rock mass.

There are numerous approaches to evaluating 'seismic potential,' yet the most reliable method involves calculating seismic hazard. This calculation determines the probability of experiencing a seismic event exceeding a specified magnitude. The determination of this probability hinges on the stochastic nature of seismicity, where the statistical distribution of seismic events is understood, although the actual values occurring in nature remain unknown. These statistical distributions have been elaborated upon by researchers such as Gibowicz & Kijko (1994) and Lasocki (2005), among others.

Wesseloo (2020) further elucidates the probability density function of the largest events, as illustrated in Figure 1 and Equation 1. This detailed description contributes to the understanding of seismic hazard by providing a mathematical framework for assessing the likelihood of significant seismic events.

$$f_{max}(M,n) = \begin{cases} 0, M < m_{min} \\ n \cdot f(M) \cdot F(M)^{n-1}, m_{min} \le M \le M_{UL} \\ 0, M \ge M_{UL} \end{cases} \quad (1)$$

where:

$f_{max}(M,n)$	=	probability density function of the largest events magnitude within n events.
n	=	number of events with magnitude greater than m_{min}.
$f(m)$	=	density function of the frequency–magnitude distribution of the seismic data.
$F(M)$	=	cumulative distribution of the frequency–magnitude distribution.

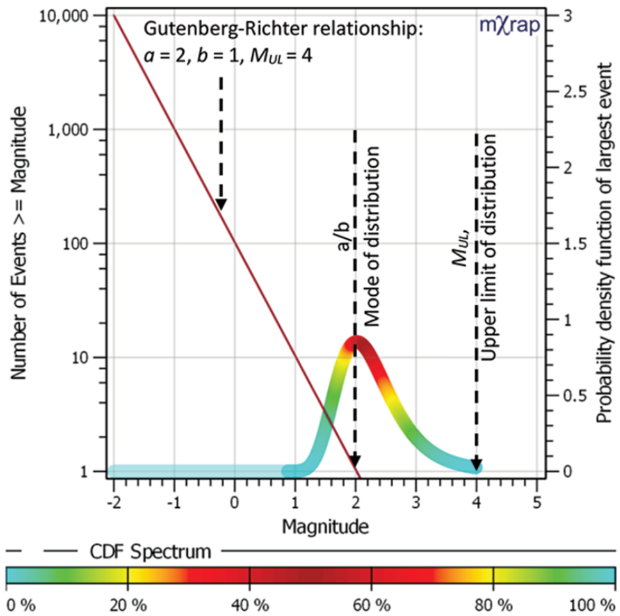

Figure 1 Wesseloo 2020 description of the density distribution function of the largest events calculated from the relations proposed by Gibowicz & Kikjo (1994)

3 Estimating seismic hazard for mine planning options

The present study proposes a methodology to estimate seismic hazard based on the mine production. The method is based on the empirical relationship between mined rock and released seismic moment, and in probabilistic models of the largest magnitude distribution (Lasocki 2005; Gibowicz & Kijko 1994; Wesseloo 2020).

The proposed method consists of the calculation of the total seismicity generated by the different production plans and evaluates the probability that this seismicity will exceed a certain value. While several manifestations of seismic activity can be used (seismic energy, apparent volume, seismic potency, etc.) this work will be focused on the use of moment magnitude (Hanks & Kanamori 1979) as a measure of seismic intensity, thus seismic moment (Mo) will be considered for the relations between seismicity and mined volumes. Finally, once the probability is calculated, it can be normalised to a yearly based time frame to evaluate the yearly hazard of experiencing a large seismic event.

The method can be broken down into the following steps:

1. Calculate the seismic moment generated by the planned monthly production activities.
   - Based on mine seismic history, a correlation between the monthly extracted tonnage (t) and the total released seismic moment (Nm) must be determined. This allows the estimation of seismic moment per tonne extracted and the generation of several scenarios of monthly

production e.g. 100, 500, 1,000, 2,000, 5,000 t per month and their respective total monthly released seismic moment (MRMo).

2. Estimate Gutenberg–Richter (GR) parameters for the MRMo.
   - The previously calculated MRMo corresponds to the total seismicity generated during one mining period (month in this case), however seismicity corresponds to several hundreds of exponentially distributed seismic events, where the inverse cumulative distribution of this events can be modelled through a Gutenberg–Richter model (Gutenberg & Richter 1956) defined by the a-value and b-value (considering a linear GR model). Since these a and b vales are needed to calculate the statistical distribution of the largest events (Equation 1 and Figure 1), the MRMo must be decomposed into synthetic seismic data that allows the calculation of the GR parameters. This procedure is described in Jarufe et al. 2022 and consist of a simplex optimisation exercise where synthetic seismic data is generated modifying the a-value (a measure of the number of events in the system) until the total generated seismicity (measured as seismic moment) equals the MRMo. The b-value remains fixed as it is related to the source mechanism (Wesseloo 2014; Ma et al. 2018; Bora et al. 2018) which is considered the same for all the analysed time.
3. Evaluate the probability of experiencing a seismic event larger than a specified magnitude.
   - Once the GR relationship is established, the distribution of the largest events can be calculated as described in Equation 1, which is based on the GR parameters (a and b values for the linear GR relationship). Equation 1 calculates the probability distribution of the largest possible event thus, an exceedance probability of experiencing a seismic event larger than a specific magnitude can be calculated for the analysed period (monthly in this case)
4. Normalise the calculated probability to a yearly time frame.
   - The probability calculated in the previous step corresponds to the probability of exceeding a specific magnitude over a month, however, for financial evaluations it could be important to consider the hazard as a yearly value. To do so the hazard normalisation equation (Equation 2) proposed by Wesseloo (2020) will be used:

$$P_{Tn} = 1 - (1 - P_{Te})^{\frac{T_n}{T_e}} \tag{2}$$

where:

T_n	=	normalised time frame.
T_e	=	original time frame.
P_{Tn}	=	probability normalised to the *Tn* time frame.
P_{Te}	=	probability normalised to the original *Te* time frame.

4 Case study: Canadian open stope mining

The previously described methodology will be implemented in a case study focused on mining-induced seismicity, which has been documented in prior publications. This case study's primary objective is to demonstrate the application of the methodology. It should be noted that the intention is not to conduct an analysis of the specific mining site itself, but rather to showcase the methodological approach. The study aims to highlight how the methodology can be effectively utilised to understand and address issues related to seismic activity triggered by mining operations, providing a clear example of its practical use in the field.

4.1 Location and general background

The case study mine, described in detail by Khalil et al. (2022), is located in Northen Ontario, at the Kirkland Larder Lake gold belt and intersected by a regional fault zone, known for its spatially associated gold camps.

The property is hosted in a felsic intrusive syenite unit of about 1,420 m east–west by 470 m north–south. Sedimentary rock is located at the footwall of the deposit and is also found to be interbedded layers throughout the syenite rock mass. The hanging wall of the deposit is predominantly mafic volcanic, consisting of interbedded mafic flows and ultramafic flows. The gold mineralisation is mostly related to quartz veins and disseminated pyrite mineralisation, hosted in a felsic intrusive syenite unit. Several mineralised gold zones are hosted in the syenite. All lithologies are cut by late, generally northeast-trending Proterozoic diabase dikes, as shown in Figure 2.

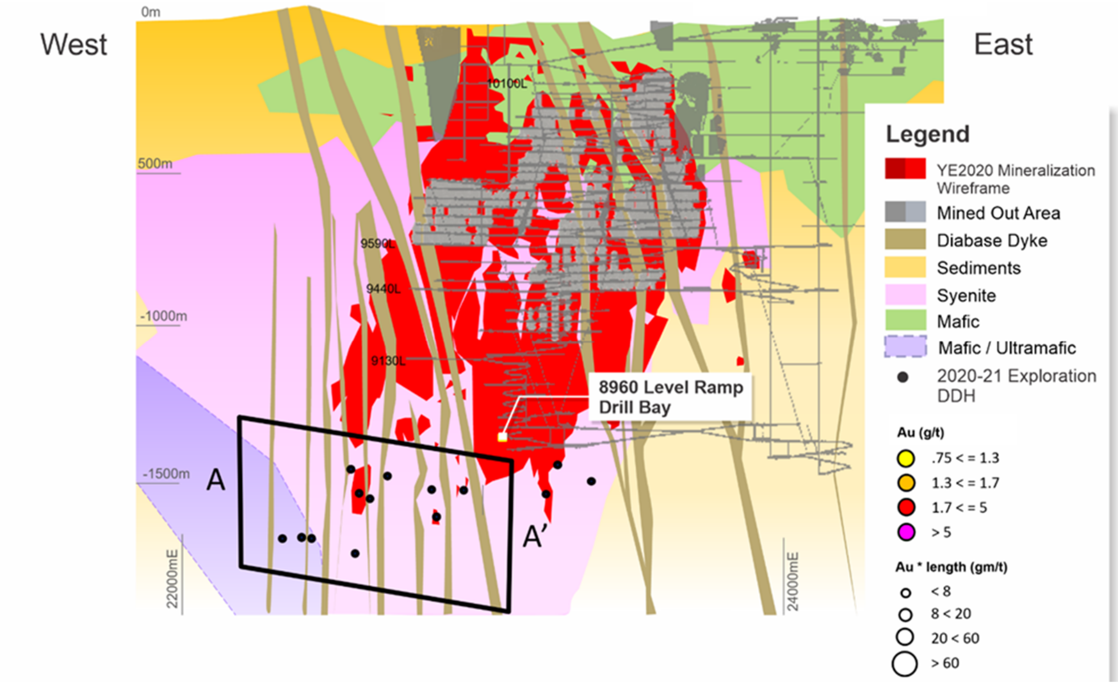

Figure 2 Main geological domains, host rock, diabase and syenite (ore) along with the mined-out area (www.juniorminingnetwork.com)

4.2 Mining–seismicity relationship

This case study is based on seismic data occurring during 2020 at depths of 600–800 m below the surface. To investigate the factors contributing to the large seismic events, Khalil et al (2022) analysed the relationship between production blasting and mine seismicity. As shown in Figure 3, the monthly blasting volume in 2020 and its comparison with seismic moment revealed that the relationship between blasting volume and mine seismicity is complex and not a simple, direct correlation.

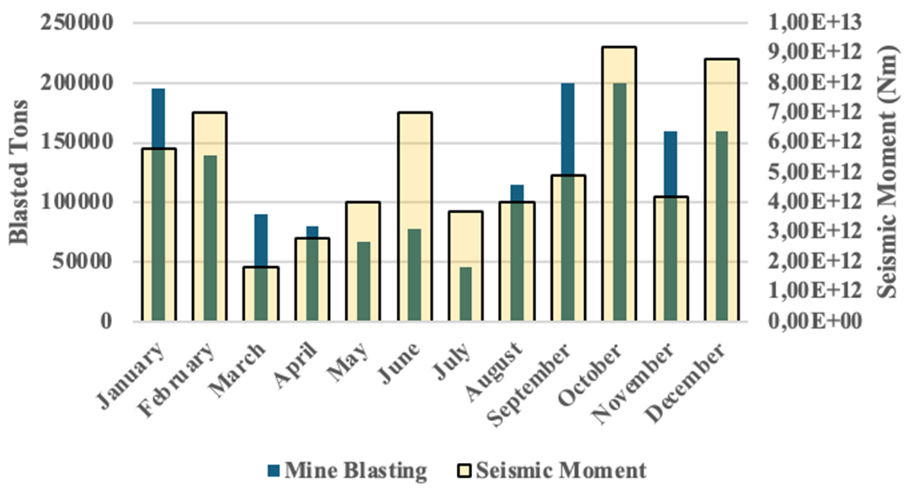

Figure 3 Production rate and seismicity for the case study mine (modified from Khalil et al. 2022)

While the results obtained do not show a direct relationship between mining and seismicity, it is important to note that there may be several reasons for this apparent discrepancy, as differences in the perturbed rock mass may be different from the blasted volume, or the intersection with some geological discontinuities such as faults or dikes. Since there is uncertainty in the perturbed rock mass volume that triggers seismicity, linear regression is not the best technique to correlate mining and seismicity. The quantile-quantile technique (Q-Q plot) will be used to compare both variables, which is more suitable to compare datasets with uncertainty (square series in Figure 4). Also, in the long-term history of the mine, the periods with low seismicity compensates with other periods with lower seismic productivity thus a cumulative relationship between mine extraction (expressed in tonnes) and seismic moment can be established (circles in Figure 4).

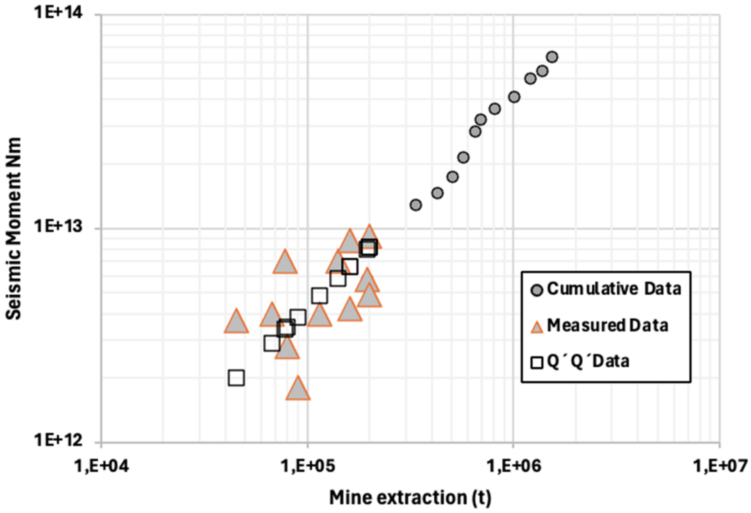

Figure 4 Relationships between mine production and seismic data considering published data, Q-Q plot and cumulative datasets

From the previous analysis it can be concluded that the monthly released seismic moment can be expressed as

$$MRMo = 8E{+}7 \cdot Tonnes^{0.9452} \quad (3)$$

where:

MRMo = the total seismic moment generated each month in Nm

Tonnes = weight of the extracted rock during the period, in tonnes.

The relationship between mined tonnes and seismic moment obtained from the present analysis, generated a good representation of the actual data and is also coherent with previously published relationships between mined volumes (t) and seismic moment (Vallejos & Mckinnon 2011). This is shown in Figure 5, where past published data is shown as circles and Equation 3 obtained from this study is shown as a dashed line.

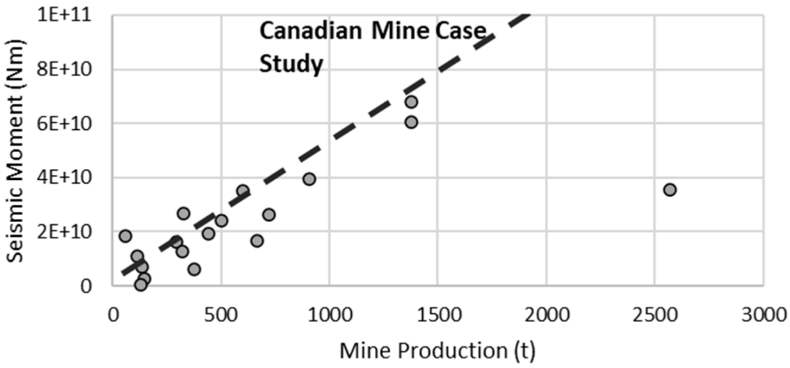

Figure 5 Relationship between mined volume and seismicity published by Vallejos & Mckinnon (2011) (circles) and the results from this case study (dashed line)

4.3 Seismic hazard for different mining scenarios

To generate design guidelines for effective mine planning, various monthly planning scenarios will be evaluated. The production scenarios outlined in Table 1 represent a range of planning scenarios that the mine may encounter. Also, utilising Equation 3, the total seismic moment released during the month for each mining plan alternative can be calculated.

Table 1 Planning scenarios and estimated seismic moment generated

Monthly mine production (Ktonnes)	5	10	15	20	40	80	100
Expected monthly released moment (Nm)	2.5E+11	4.8E+11	7.1E+11	9.3E+11	1.4E+12	1.8E+12	2.6E+12

The total estimated seismic moment for each production scenario can be represented by a series of synthetic seismic events following an exponential distribution and their total seismic moment is the same as the total moment for each planning scenario. By analysing the distribution of these synthetic seismic events, a frequency–magnitude chart and the corresponding Gutenberg–Richter model can be derived. The Gutenberg–Richter parameters obtained for each scenario (a-value, as discussed in the previous section) can then be used in Equation 1 to calculate the probability distribution of the largest expected event, providing valuable insights into the seismic risk associated with each mine plan.

Notwithstanding the probability distribution, described in Equation 1, defines the probabilities of experiencing any magnitude as the largest event. Operational rock mechanics and planning engineers only need to know the probability of a seismic event that has the potential to cause important damage to the mine infrastructure. In this case study, the magnitudes of interest corresponds to 0.5 (which is related to a medium risk level according to general mine experiences), 2.0 (corresponding to a high risk according to what has been observed in several underground mines) and an extreme magnitude of 2.5 is also included. The calculation of the exceedance probability for the magnitudes of 0.5, 2 and 2.5 is graphically shown in Figure 6.

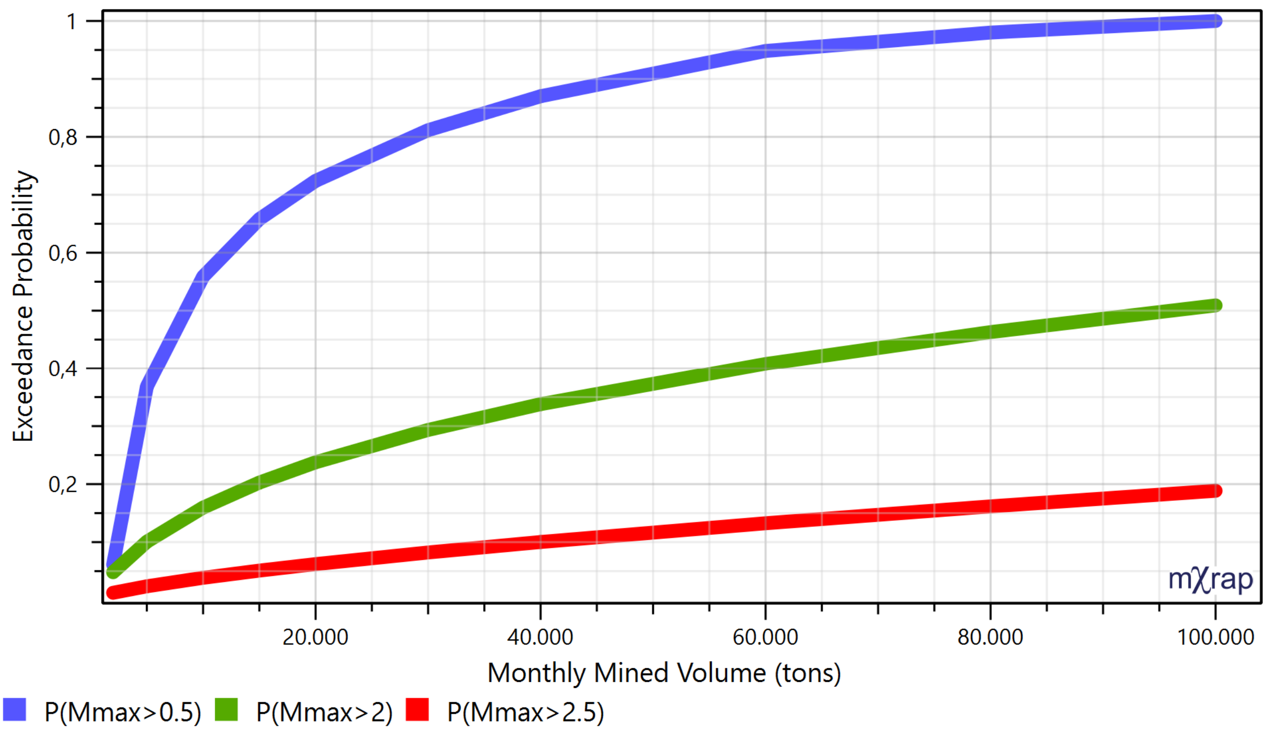

Figure 6 Monthly exceedance probabilities for different planning scenarios. This represents the probability of experiencing large seismic events for different mine planning scenarios

4.4 Temporal normalisation

The previous calculations refer to the probability over a one-month period. As discussed by Wesseloo (2020), the probability of experiencing a seismic event each month differs from the annual probability of experiencing that same seismic event magnitude. The probability of experiencing a large event during one month will be repeated each month thus the annual probability will be higher. In this case the annual probability of experiencing seismic events above magnitudes 0.5, 2 and 2.5 considering monthly productions rates continuous during an entire year are described in Figure 7.

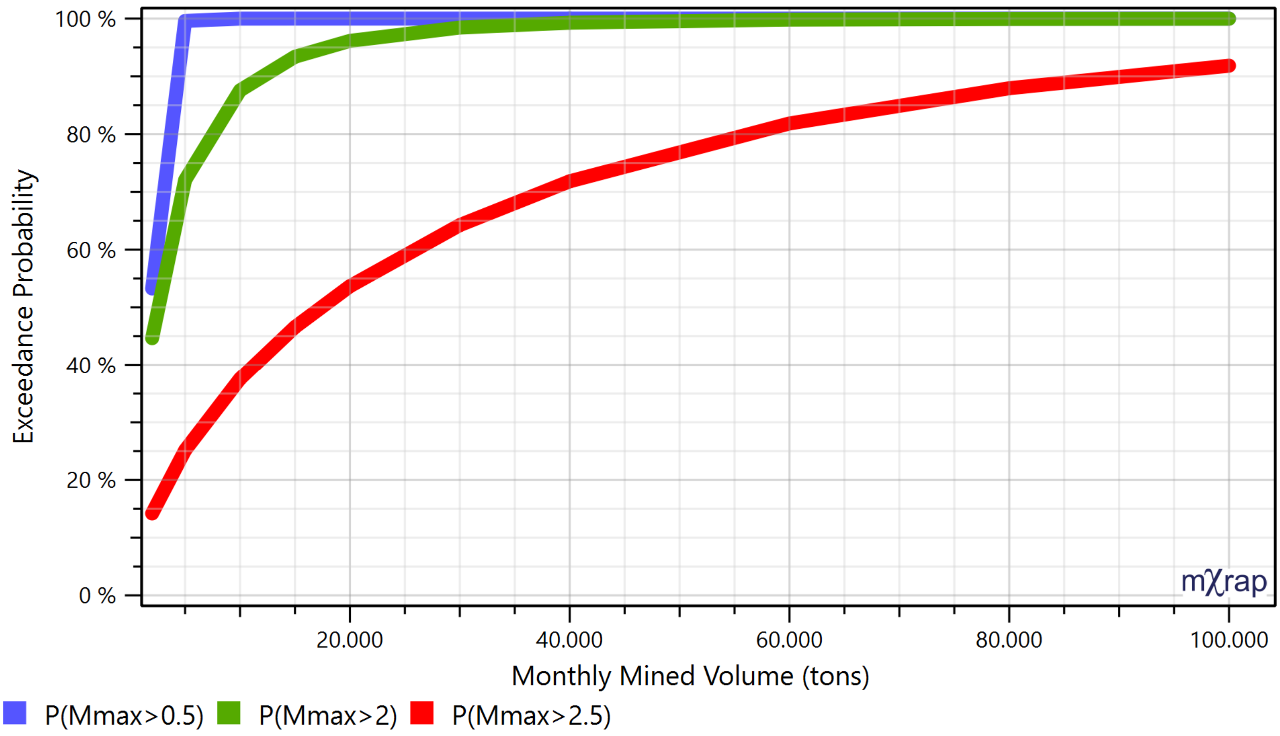

Figure 7 Annual exceedance probabilities for different planning scenarios

It is important to note that this chart corresponds to the probability of seismic events. The probabilities for a rockburst should be lower than these values and it is recommended to extend this work to evaluate rockburst probabilities. Also, these rockburst probabilities can be reduced using mitigation techniques as yielding support or exclusion hours. All of these mitigation strategies oriented to reduce personal exposure and business continuity.

5 Conclusions and further work

This work presents a method to evaluate seismic hazard for different mine planning options, which enable mine operators to make informed decisions and develop robust mine plans that account for potential seismic hazards. By rigorously testing the mine plan against diverse scenarios, the design guidelines can be refined to enhance the overall efficiency, productivity, and resilience of the mining operation, ultimately contributing to the long-term sustainability and safety of the mining industry.

As mentioned before, this investigation is focused on the seismic event occurrence thus, it is important to continue the hazard evaluation but focused on the rockburst itself and in the impact that mitigation techniques have into the occurrence probabilities. Numerical modelling is also an important area that may complement the results of this study.

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