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Trigger action response development I: the use of event activity rates to assess re-entry times in caving

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Abstract

The seismic response following production blasts or large seismic events differs from location to location in a mine (intra-mine) and from mine to mine (inter-mine). When developing trigger action response plans (TARPs), a blanket approach, where the same settings are used for all locations, is inadvisable – areas should be assessed individually. Operators usually focus on a work domain, often an irregular two-dimensional shape defined in plan view. Care should also be taken in the determination of a monitoring domain which contains the work domain, and accounts for the impacts of seismic events at a distance.

One of the commonly used seismic parameter for TARP development is the seismic activity rate. We present a workflow to determine monitoring domains and use a seismic system-agnostic Python tool to rapidly assess decay rates for many areas in a mine over arbitrary periods.

Keywords: *seismic activity rate, TARP, monitoring domain, work domain, re-entry*

1 Introduction

Three time windows are usually considered when doing seismic hazard assessment on mines. Long-term hazard assessment typically spans a year or more and involves detailed seismic risk management plans (SRMPs) which are integrated into geotechnical risk management plans. These SRMPs include descriptions of medium and short-term hazard assessments. Medium term assessments are generally conducted on a monthly cadence and involve calibrations of peak particle velocity relations, exceedance probabilities, advanced analyses such as passive seismic tomography and seismic monitoring system assessment. Short-term, or tactical, hazard assessments focus on analyses and procedures relating to daily or even hourly decisions required when unexpected seismic activity occurs. These include managing exclusion of personnel from work areas after large events or blasts.

Short-term risk management procedures focus on exclusion times following significant seismic events and/or blasts. They are commonly based on the decay, to a defined or agreed background, of seismic release or activity rate from a peak at, or following, an event (the 'main shock') or blast sequence (see for example de Beer et al. 2018; Malek & Leslie 2006; Tierney & Morkel 2017; Tierney et al. 2019; Vallejos & McKinnon 2011; Figure 1). From experience, a commonly used measure for exclusion times is the rate of occurrence of seismic events. There is nothing wrong with this – it is quick, pragmatic, and useful as part of a larger process of evaluating an area.

It this paper, the assumption is that 'blanket' exclusion times (i.e. exclusion times that are applied across the board for fairly long periods before being re-assessed) are based on the most common time for an indicator of seismic response to decay to a background level (however defined). To develop defensible blanket exclusion rules, multiple responses to large events and blasts must be analysed quantitatively to generate a

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large enough sample from which to derive statistics. The analysis must test different post-event time windows and different time bins over which rates are calculated (e.g. number of events per hour, per 2 hours, etc.). This is time consuming and tedious. Time is always at a premium, and tedious work leads to errors. The analysis may have to be repeated several times as conditions change. Too often, recourse has to be taken to anecdotal evidence or judgement based on previous experience elsewhere. This is problematic because humans are notoriously bad at instinctively assessing statistics and our judgements are subject to a host of cognitive biases.

To address this, a Python-based prototype workflow which can evaluate the statistics and behaviour of post-event or blast rates in a few minutes is under development. Python is free and platform-independent, as are the huge number of numerical, statistical analysis, plotting, and report-generation modules coded in Python. This means that anyone can learn to develop tools using it. The purpose of this paper is to describe the workflow and to show some initial results.

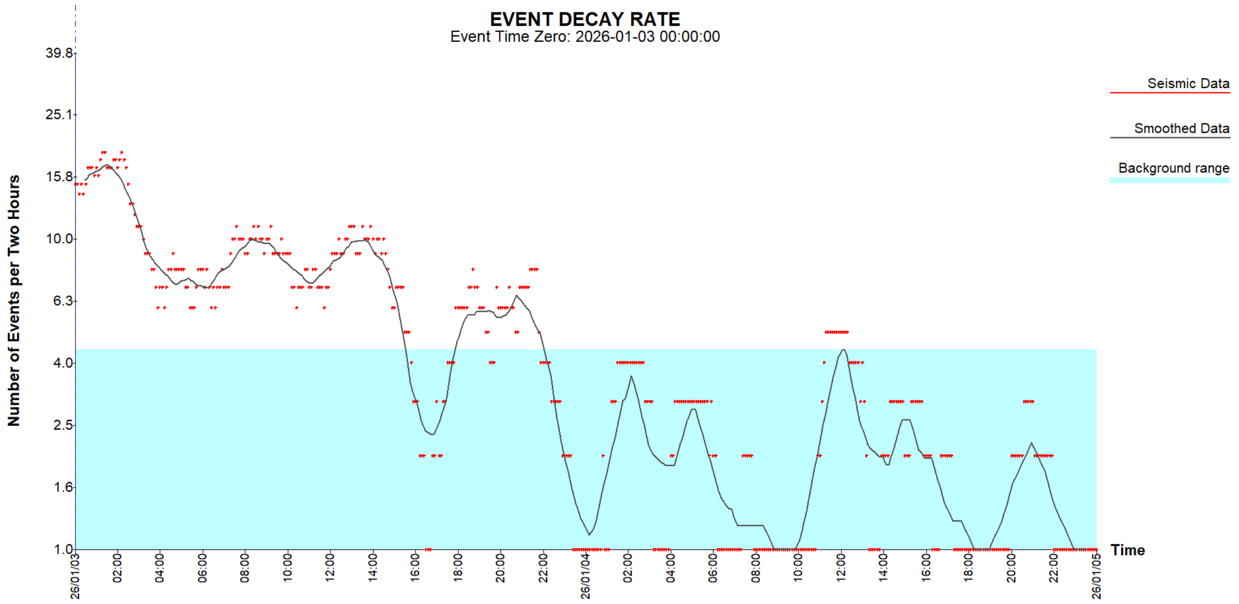


Figure 1 Example seismic activity rate decaying in an exponential fashion after a large seismic event

2 Methodology

2.1 Introduction

Analysis consists of data selection in space and time, considering the statistical properties of seismic event rates to determine likely background rates, and then separately calculating the event rates following undercut ring blasts and significant events. Passive seismic data is sometimes called four-dimensional, reflecting the fact that seismicity occurs in a three-dimensional spatial volume over a time period. To obtain as complete as possible a dataset for exclusion analysis, attention must be paid to all these dimensions. Spatial data selection can be done by eye or by sophisticated cluster analyses. In practice, there is rarely any significant differences between visual inspection and clustering routines when taking care of some basic heuristics. An example is that the rule of thumb support design criterion for shakedown damage due to a distant seismic event, is that an M_W 2.0 event will result in a peak particle velocity (PPV) in the order of $100\ mm \cdot s^{-1}$ at a distance of 100 m from its initiation point in competent homogeneous rock. This implies that the spatial data selection volume should be such that likely sources of M_W 2.0 events should be at most 100 mm away from the work area of interest. Note that ‘distant’ means the far field of the event, defined as a distance of more than several (usually 2 to 5) dominant wavelengths of the seismic waves generated by the event. This rule of thumb can be combined with the shape of the complementary cumulative size distribution to contextualise results in terms of the completeness of the dataset. A seismic dataset is considered complete above M_{min}, the magnitude at which the complementary cumulative size distribution, moving back from larger to smaller magnitudes, start rolling off from a linear region (Figure 2).

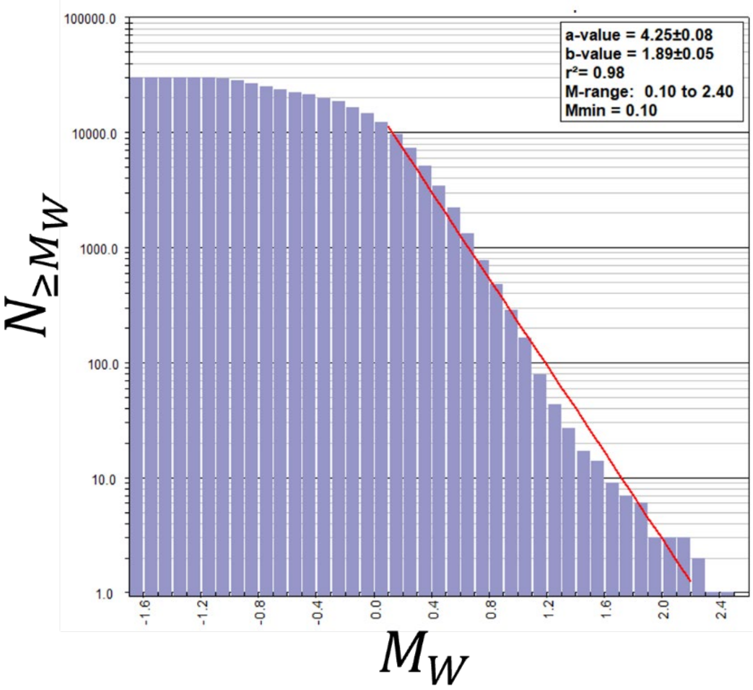


Figure 2 Complementary cumulative size distribution of events in the example monitoring domain

The time extent of a dataset is constrained by the duration of mining and the geology. A challenge in some types of mining is that the area being mined can change fairly rapidly (over months or weeks). Examples are undercutting in block caving and rapid development in reef mining. A useful metric for the completeness of the dataset in time is the distribution of event rates, which is widely expected to approximate a gamma distribution (see Corral 2003, 2004, 2006).

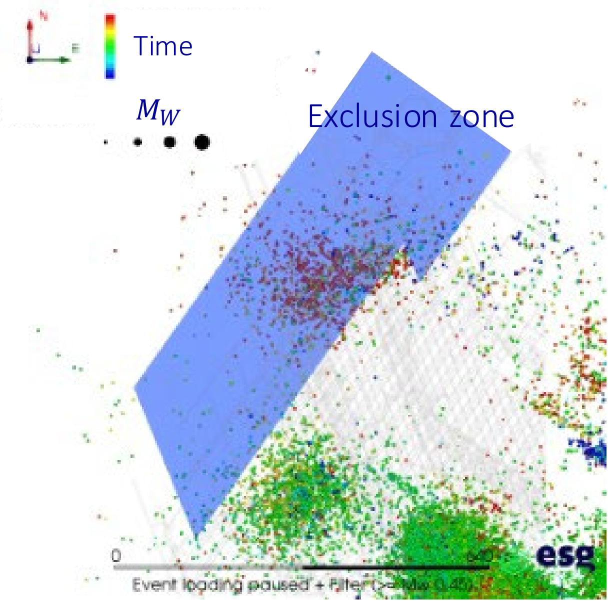
2.2 Spatial

It is important to distinguish between 2 different domains when designing exclusion criteria. An exclusion zone is an area where workers are exposed to seismic hazard, while a monitoring domain is a volume of space which contains the seismic events which impact an exclusion zone. Although it is customary for the exclusion zone to be encapsulated in a monitoring domain, as in Figures 3 and 4, there is no reason for a monitoring domain to not be distant from the corresponding exclusion zone. The data sets considered here are from 3 monitoring domains:

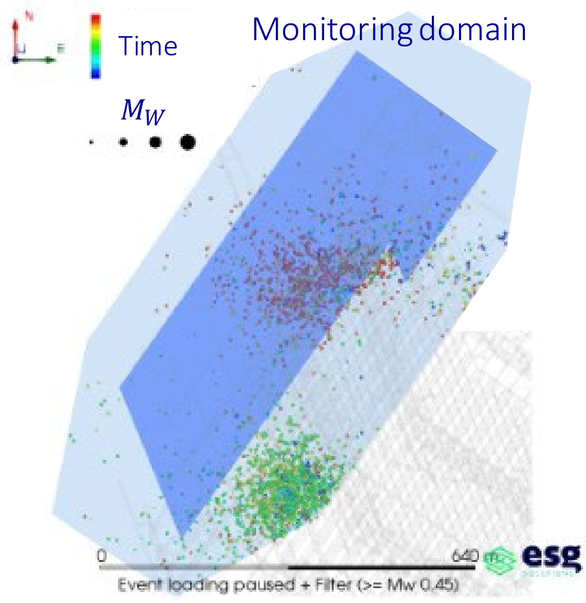
Domain 01 encompasses the abutment of a cave which is subject to considerable vertical stress due to depth. The geology is fairly uncomplicated and there are no significant structures or lithological contacts. The volume is characterised by high activity rates, although event sizes are predominantly small to mid-range ($M_W < 1.6$). Larger events do occur, but too few to be useful for statistical purposes. Therefore, the analysis of post-event activity is done for 32 events of $M_W \geq 1.3$. Analysis of post-blast activity used 189 production blasts.

Domain 02 likewise contains the abutment of a cave. However, in this case the abutment forms a diminishing pillar between the cave and a segmented sub-vertical regional fault zone. There is a contact between geological units of significantly different strengths, and an active subsidence zone above the area. The volume is characterised by very high activity rates. Larger events occur, but too few to be useful for statistical purposes. Therefore, the analysis of post-event activity is done for 177 events of $M_W \geq 1.5$. Analysis of post-blast activity used 211 production blasts.

Domain 03 is a growing cave. The volume is intersected by mine-scale faults which form blocks between them. The spatial distribution of the activity consists of clusters in the blocks or along the faults. The volume is characterised by high activity rates, but event sizes are predominantly small to mid-range ($M_W < 1.6$). Again, larger events do occur, but too few to be useful for statistical purposes. Therefore, the analysis of post-event activity is done for 30 events of $M_W \geq 1.3$. Analysis of post-blast activity used 550 production blasts.

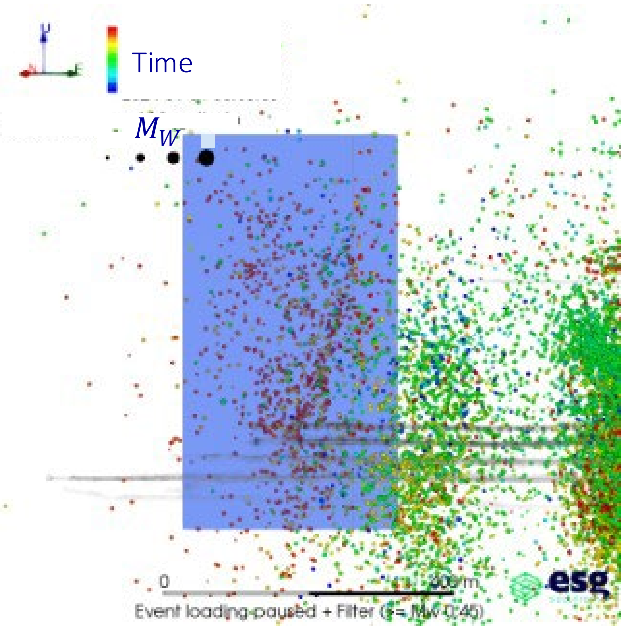


(a)



(b)

Figure 3 (a) A typical exclusion zone, defined in two dimensions, based on operational requirements; (b) A possible monitoring domain, defined to include clusters of seismicity possibly impacting on the exclusion zone



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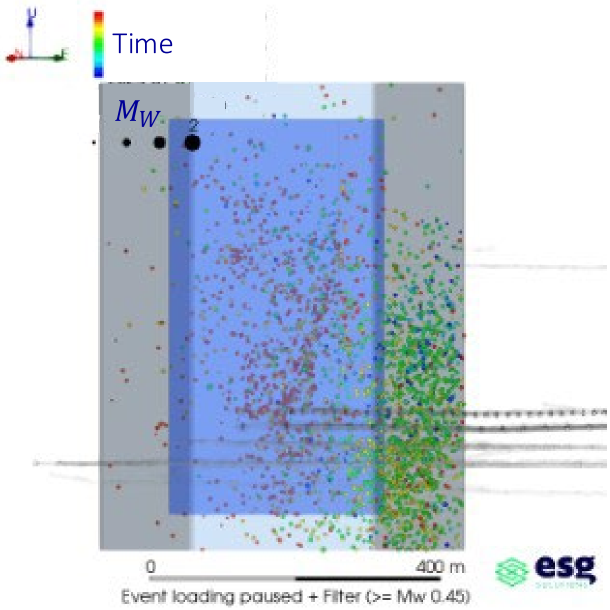


(b)

Figure 4 The same as in Figure 3, showing (a) the vertical extents of an exclusion zone and (b) possible monitoring domain

Figure 2 earlier shows the complementary cumulative size distribution of seismic events in the monitoring domain. It is mostly well-formed.

2.3 Event rate distribution

The expectation is that the typical rate follows a gamma distribution. This is founded in crustal seismology, and modifications and refinements have been proposed (see, for example, Godano 2015). However, the fundamental principle holds. Mining is not constant: mining rates fluctuate and geological conditions change as mining progresses. If nothing (i.e. mining and/or geology) changes in an area for a substantial period, the event rates in a given area approximate a dynamically stable process and the expectation of gamma statistics is reasonable.

It can be shown that subtracting 5% of the peak value of the distribution and taking all original values between the roots of the resulting downshifted distribution results in a subset consisting of 68% of the values (Figure 5).

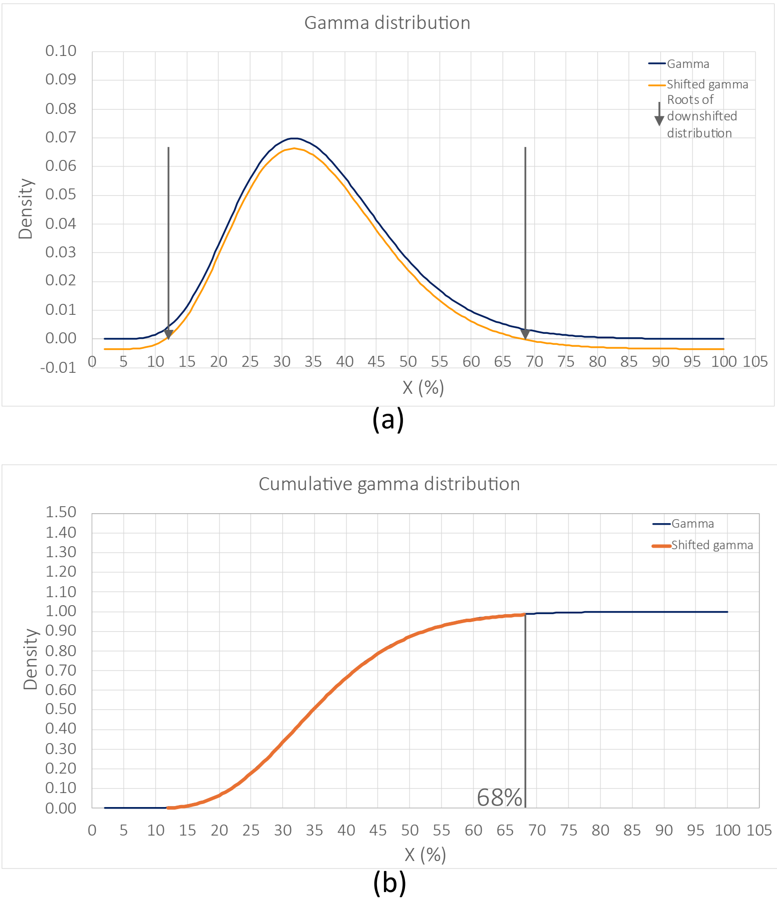


Figure 5 (a) Original and downshifted gamma distribution; (b) Cumulative original and downshifted gamma distribution

By analogy with the standard deviation of a normal distribution, the minimum and maximum of the background event rate is then taken to be the smaller and larger root of the downshifted distribution, respectively (see Figures 7–9). In these figures, possible alert levels (user specified) are defined in terms of the background band (Table 1). These levels are not hard-coded; a user is free to specify values derived in more sophisticated ways.

Table 1 Default alert level: background band mapping

Alert level	Percentage of background band
Idle	Value ≤ 0% (below background band)
Watch	0% < value ≤ 25%
Caution	25% < value ≤ 75%
Warn	75% < value ≤ 100%
Alert	100% < value (above background band)

Regaining a statistical distribution with discrete data is dependent on binning (Figure 6). Larger bins leads to over-smoothing (under sampling), while smaller bins produce noisier distributions and more empty bins (over sampling). For this paper, bins of one hour and half-hour were tested. Results are presented for the half-hour binning.

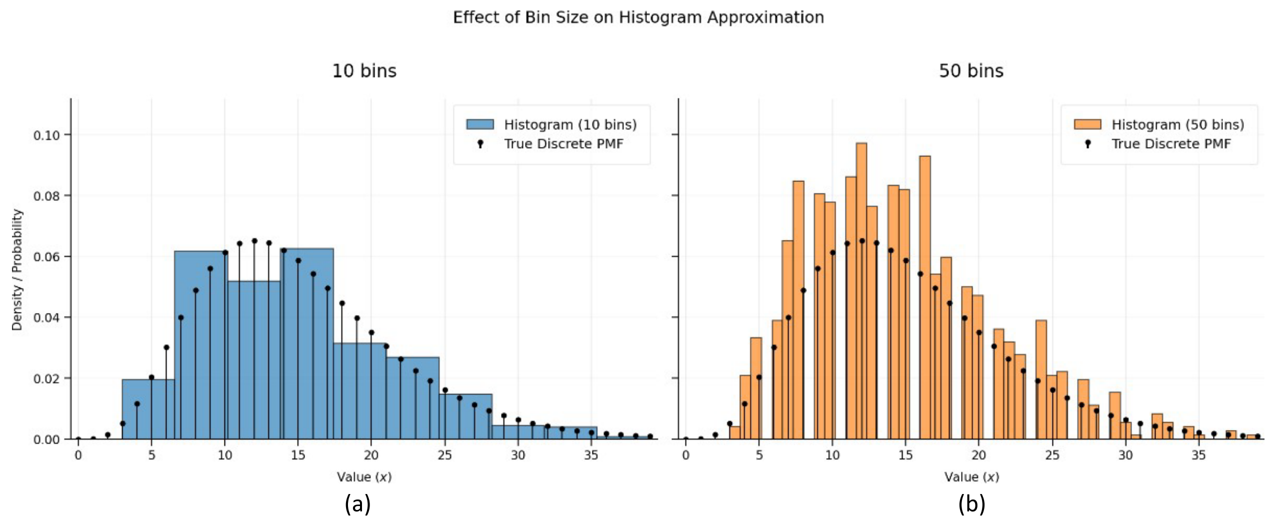


Figure 6 (a) Under-sampled and (b) over-sampled distributions

3 Results

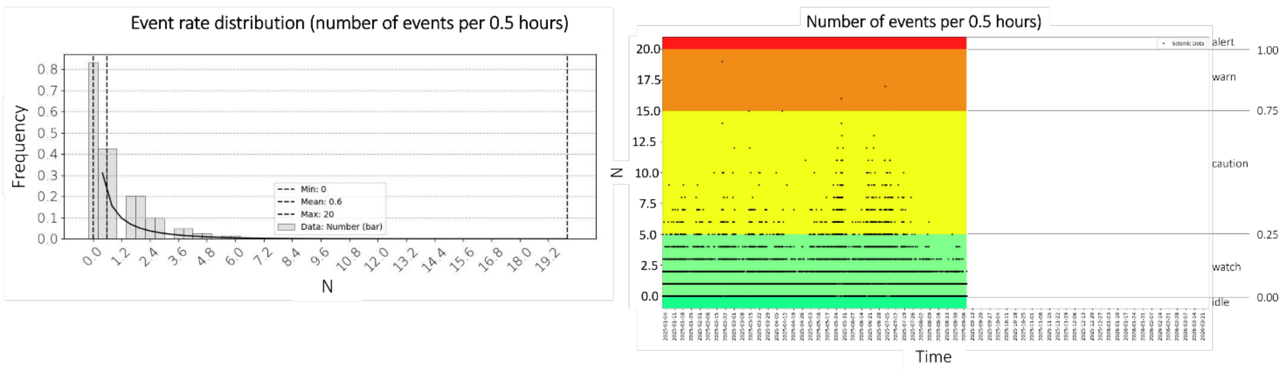
Results of applying the workflow are shown in Table 2. The seismic event rate background determination in the domains are shown in Figures 7–9. The minimum, mean, and maximum on the figure relate to background event rates (coloured bands) discussed above. Domain 02 (Figure 8) shows a well-developed gamma distribution of event rates. Domains 01 and 03 (Figures 7 and 9) apparently lacks the pre-peak rise. This difference may be due to the number of events, the resolution (in this case 30 minutes) or it may be intrinsic to the properties of the rock mass under consideration. Resolutions of 30 and 60 minutes were tested and there is no material difference between them. In Figures 10–12, event rates after an event or blast were plotted on the same axes together with an envelope tracing the maximum of all the rates at a particular time.

The results indicate that, even in the same mine, the response in different places not far from each other, can be very different and that therefore one should not apply the same assumptions to them. An area also changes over time; therefore, it needs to be recalibrated regularly. Bearing in mind that activity rate is only one of at least 4 indicators (de Beer et al. 2018) of post-event relaxation, it should be clear that it is a daunting task to manually analyse the statistics of many areas in a practical time frame.

It is noticeable that there are no strong indications of exponential decay.

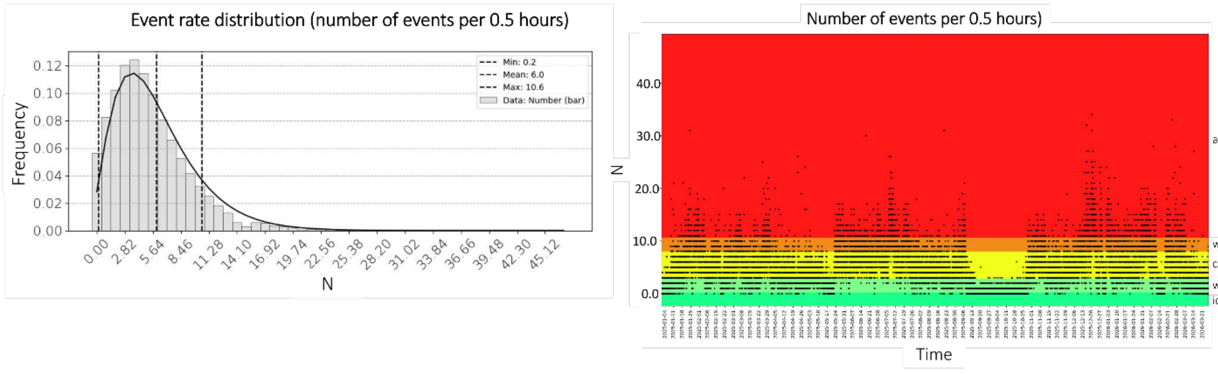
Table 2 Default alert level: background band mapping

Domain	Properties	Gamma distribution	Post-event 24 hours	Post-blast 24 hours
01	Cave abutment subject to considerable vertical stress due to depth. Geology fairly uncomplicated with no significant structures or lithological contacts	Pre-peak values missing at 30 minute resolution	Within background. Some peak activity in high background in first hour. Secondary peak after approximately 12 hours (may be related to secondary breaking), well within background	In general, well within background – one case of high background activity 12 and 23 hours after blasting, possibly related to secondary breaking or early blasting
02	Cave abutment forming a diminishing pillar between the cave and a segmented sub-vertical regional fault zone. There is a contact between geological units of significantly different strengths, and an active subsidence zone above the area	Well-formed distribution at 30 minute resolution	Activity well above background throughout 24 hours following event, with several large excursions	Activity well above background throughout 24 hours following event, with several large excursions. Suggestion of exponential decay
03	Growing cave. The volume is intersected by mine-scale faults which form blocks between them	Pre-peak values missing at 30 minute resolution	Activity fairly constant well within background	Activity within background range. Broad peak in first 3 hours



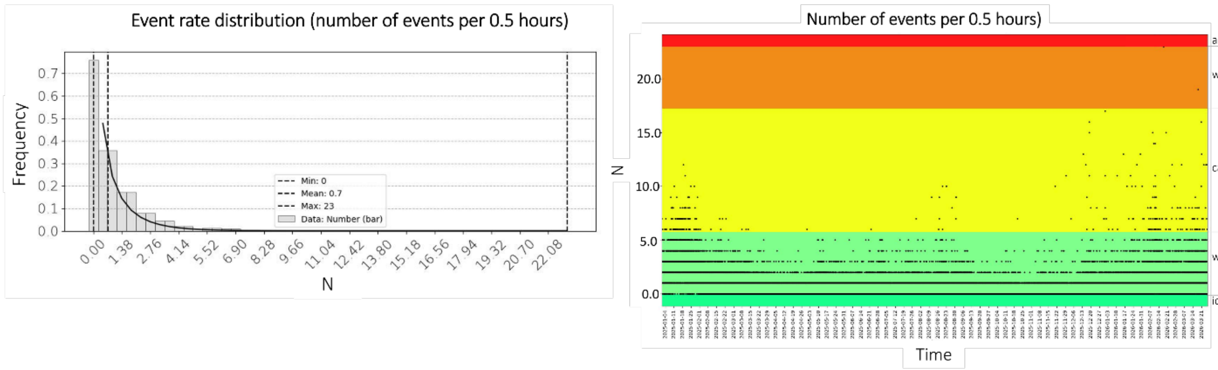
(a) (b)

Figure 7 Seismic event rate (number of events per hour) (a) over a period of approximately 18 months in monitoring domain 01, fitted to a gamma distribution and (b) displayed against the backdrop of the activity categories



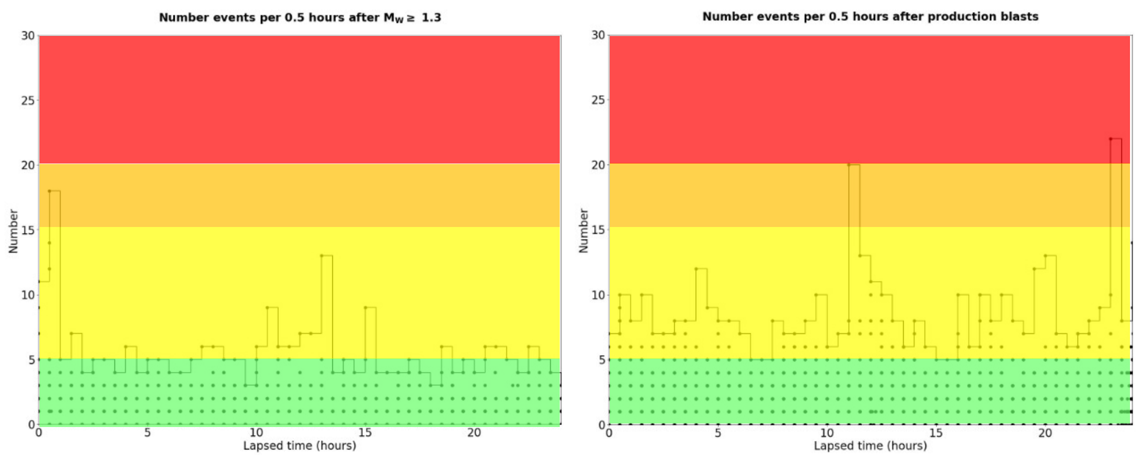
(a) (b)

Figure 8 Seismic event rate (number of events per hour) (a) over a period of approximately 18 months in monitoring domain 02, fitted to a gamma distribution and (b) displayed against the backdrop of the activity categories



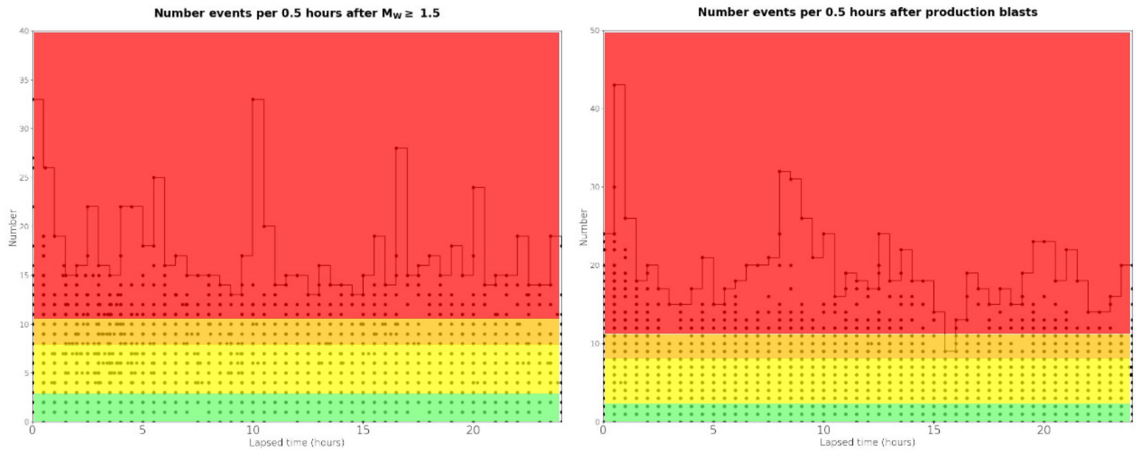
(a) (b)

Figure 9 Seismic event rate (number of events per hour) (a) over a period of approximately 18 months in monitoring domain 03, fitted to a gamma distribution and (b) displayed against the backdrop of the activity categories



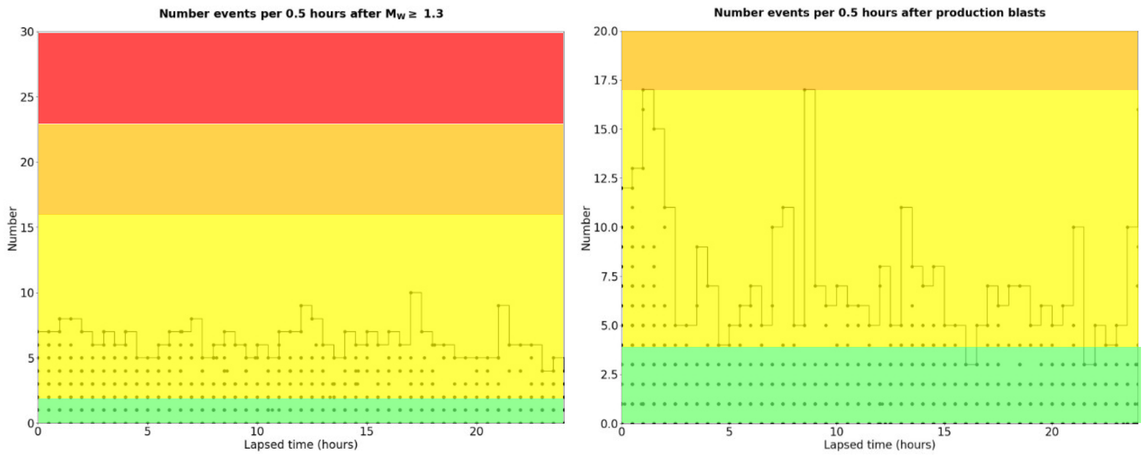
(a) (b)

Figure 10 Monitoring domain 01. (a) Event rate after significant events and (b) production (ring) blasts. Yellow band indicates background rate as determined event rate distribution fitting



(a) (b)

Figure 11 Monitoring domain 02. (a) Event rate after significant events and (b) production (ring) blasts. Yellow band indicates background rate as determined event rate distribution fitting



(a) (b)

Figure 12 Monitoring domain 03. (a) Event rate after significant events and (b) production (ring) blasts. Yellow band indicates background rate as determined event rate distribution fitting

4 Conclusion

A prototype Python-based rapid workflow was used to analyse post-significant-event or post-blast seismic event rates in 3 locations in 2 block caves. The results are ambiguous if strong exponential decay is expected. This indicates support for experiential and anecdotal suggestions that exponential decay may not be as universal as is generally accepted. Further rigorous study is required to confirm this. This is why the ability to perform these rapid evaluations is important. This workflow is in its infancy – refinements that are needed include objective spatial selection, possibly using concepts such as cumulative absolute displacement (Mendecki 2019), and extracting true background rates by removing large events, blasts and their aftershocks from the timeseries.

Acknowledgement

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Use of artificial intelligence disclosure statement

In the preparation of this work, the authors used Copilot to generate Python code to create Figure 6. The authors have reviewed the content and edited it where required and take full responsibility for said content.

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