# The implementation of ‘automatic’ polygons for relevant data selection in short-term seismic analysis

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ABSTRACT: Mining at depth and high rock-stress environments can induce unanticipated dynamic rockmass deformation, posing a serious risk to the workforce. Time-trend analysis of certain seismological parameters has been used for many years to produce daily workplace seismic risk ratings which are meant to characterise rockmass behaviour and enable the identification of developing or imminent rock instability, allowing timeous ameliorating action to be taken – pro-actively and successfully. The impracticality of the daily reviewing of dozens of prior user-defined data selection polygons has meant that often an inappropriate assessment of the seismic hazard is done. Depending on the methodology or application of data analysis and interpretation, some of the information may not be relevant and even detract from the objective. By using the spatial event clusters associated with active workplaces to define the shape and size of the polygons for data selection for subsequent analysis, a problematic subjective component can be eliminated.

*Keywords: seismicity, risk, warning, short-term, ratings.*

## 1 PREAMBLE

Dynamic rockmass deformation induced by mining in deep and high-stress environments can rapidly augment an already voluminous recorded seismic database with hundreds, if not thousands, of newly acquired, processed and stored seismic occurrences at mines employing sensitive ground motion networks. The aims of longer-term regional analysis are different from those of short-term workplace seismic risk ratings. The selection of recorded seismicity in space and time must follow those aims. In particular, the selected data should be relevant, accurate and as objective as possible. User-defined polygons (i.e., delimited three-dimensional volumes in space) for the selection of a statistically significant number of seismic events associated with individual workplaces have sometimes included irrelevant seismicity that obfuscated the desired interpretation results or failed to include some that was relevant. Very often, a lack of regular verification of polygon geometries causes a mixture of these two problems. Other efforts to automatically generate seismicity polygons have endeavored to minimize user influence. Wesseloo *et al.* (2014), for example, describe the selection and analysis of data sub-filtered on clusters using a grid-based approach. This allows for anomalies to be identified without prior binning by polygons, thereby reducing interpretation bias, but they recognize that grid-based interpretation, although partially automated, is still affected by the chosen analysis parameters and not free of user subjectivity.

Short-term seismic risk ratings are a controversial topic, especially when the expectation of an advance warning of imminent seismicity often far exceeds the actual deliverables of seismic analysis. Despite wide use in South Africa, routine success has not been demonstrated in the estimation of seismic hazard in seismicity-prone mines (Tierney *et al.,* 2019). Nonetheless, unanticipated on-shift seismicity can lead to injuries or fatalities, and some sort of daily seismic risk assessment remains necessary before the workforce proceeds underground. The question invariably arises as to whether the seismic occurrence(s) could have been foreseen and, therefore, prevented. As a useful predictive tool, such methods of analysis and interpretation have failed. We aim to improve on the low success rates of the advance warning of instability at the rockface by eliminating a very subjective component and allowing the spatial event clusters associated with active workplaces to define the shape and size of the polygons used for data selection for subsequent analysis and interpretation. Distant but also possibly relevant large seismic events are included in these 'automatic' polygons.

What initially began as a very onerous manual selection of pertinent subsets of the seismic record, with visual inspection of temporal trends of some seismic parameters, soon evolved, with software development and upgrades automating the process to the point of merely running a computer programme at a scripted time, with relative ease. The ratings reports are routinely emailed to a large number of recipients, usually just before the workforce descends underground for the start of the shift.

## 2 SEISMOLOGICAL SETTING

Sibanye Stillwater's deep gold mines operate in a high-stress environment. The occurrence of dynamic ground motions is frequent, as demonstrated by Figure 1, which indicates the mining plan of the Kloof operations, bound by the mine lease area (202 km$^2$, oriented to local mine coordinates), and locations of seismic events $M_L$0.0 and larger over the 24-month period from January 2021 to December 2022. Kloof Mine experienced five occurrences with local magnitudes $M_L \geq 3.0$ (largest recorded: $M_L$3.7).

The seismic coverage and sensitivity to ground motions are, according to the density of the geophone array, generally good. The Kloof mine has 40 4.5 Hz tri-axial geophones strategically located for optimum seismic coverage of workplaces. New sensors are installed with the progression of mining or when conditions necessitate it. The seismic system is given high importance and is efficiently maintained. The location accuracy (usually better than 50m) is sufficient for detailed study.

## 3 SEISMIC PARAMETERS AND RATINGS OF WORKING PLACES

In the interests of brevity, we will not delve into the rigorous mathematical definitions of those seismic parameters we think are more relevant for short-term analysis because of their sensitivity to rapidly changing rockmass characteristics (these are covered extensively elsewhere, e.g., Mendecki *et al.*, 2013), but will list them with an abbreviated physical meaning.

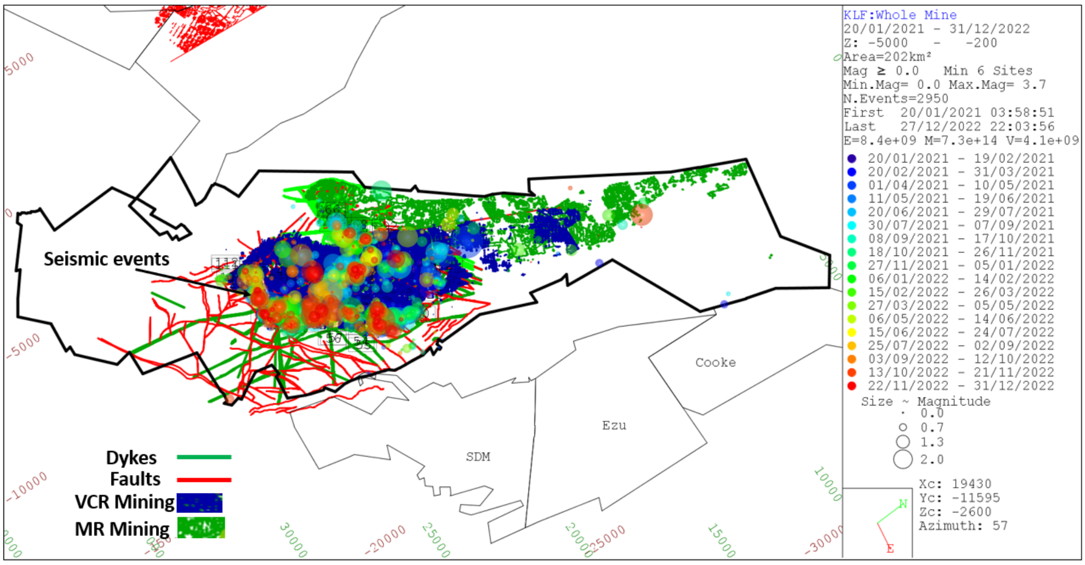


Figure 1. Mining plan of the two tabular reefs extracted at Kloof Gold Mine. Major geological features are delineated (faults in red; dykes in green). The location and magnitude of events $M_L$0.0 and greater (2950 in total), in the period January 2021 to December 2022, are shown by discs, warmer colours indicating the latest. Frequency-magnitude distributions reveals the sensitivity of the seismic network to events as small as $M_{min}$-2.0 (or better). Maximum magnitudes ($M_{max}$) of 3.9 can be expected.

### *3.1 Seismic parameters*

The short-term time changes in the trends of four seismic parameters, compared to the longer-term average trends, are used to rate the individual working areas (i.e., polygons): seismic apparent volume, seismic activity, energy index and seismic Schmidt number. A fifth 'parameter', the time between occurrences (or frequency) of large events (user-defined, but usually $M_L$>1.0), has also been used in recognition of the often-encountered periodicity of seismic behaviour. Although many seismic parameters describe seismic stress and strain rates in one form or another, these four parameters were found to be more sensitive to changes in rockmass characteristics with mining (Ferreira, 1999), and have been in use for over two decades in similar forms in many seismically active mines across the industry.

Parameters used in some other schemes (e.g., seismic energy and moment, seismic potency, viscosity and diffusivity) are incorporated in the four parameters.

- Apparent volume: calculated cumulatively, scales the differential deformation, or strain rate, of the rockmass around the workplaces. The increase is rated.
- Seismic activity: measures the increase in the number of events (activity) per specified unit of time. The increase is rated, based on the mean return period (recurrence time) of a larger event. If an event has a certain occurrence time in some particular working place, this parameter is rated according to the time period of expected recurrence being exceeded as mining continues.
- Energy index (EI): measures the increase or decrease in seismic stress. Either an increase or decrease in EI are rated. The relationship between seismic energy and seismic moment in some geotechnical environments is established. This delineates the average seismic energy for a corresponding seismic moment. When the seismic energy of a subsequent seismic event is higher than the average (i.e., EI > 1) the event exhibits higher seismic stress drop than the norm; and vice versa.
- Seismic Schmidt number: measures the spatio-temporal degree of complexity (i.e., the extent of turbulence) of the seismic flow of rock. It is the ratio of kinematic viscosity to diffusivity and incorporates all four independent parameters describing seismicity (time, location, seismic energy and seismic potency). A decrease in seismic viscosity and

increase in diffusivity translates into more complex and less stable deformation and should result in a sharp drop in the seismic Schmidt number before instability. This change is rated.

## *3.2 Polygon size and geometry*

Instead of having a user-delineated polygon for the selection of relevant seismicity for each working area, a polygon is automatically constructed as an envelope, starting with a specified radius, around panels. The radius is user-specified, usually starting from 50 m (according to location accuracy) and automatically increasing in increments until a statistically significant number of seismic events are included in the search, or until a maximum radius (also pre-defined) is attained. The polygons around panels merge until the entire workplace is incorporated into a single polygon. A 'cluster' is defined as several events occurring in some finite space and time. Cluster recognition involves a user-defined near-history of events (usually hours), a size of search (a radius of 50 m) and a minimum number of events in the cluster (usually at least ten). If a cluster of events occurs and part of it lies in a working area polygon, then all events from this cluster will be included, and the polygon volume or shape self-adjusts accordingly. Figure 2 illustrates the concept.

## *3.3 Possible influence of nearby large events*

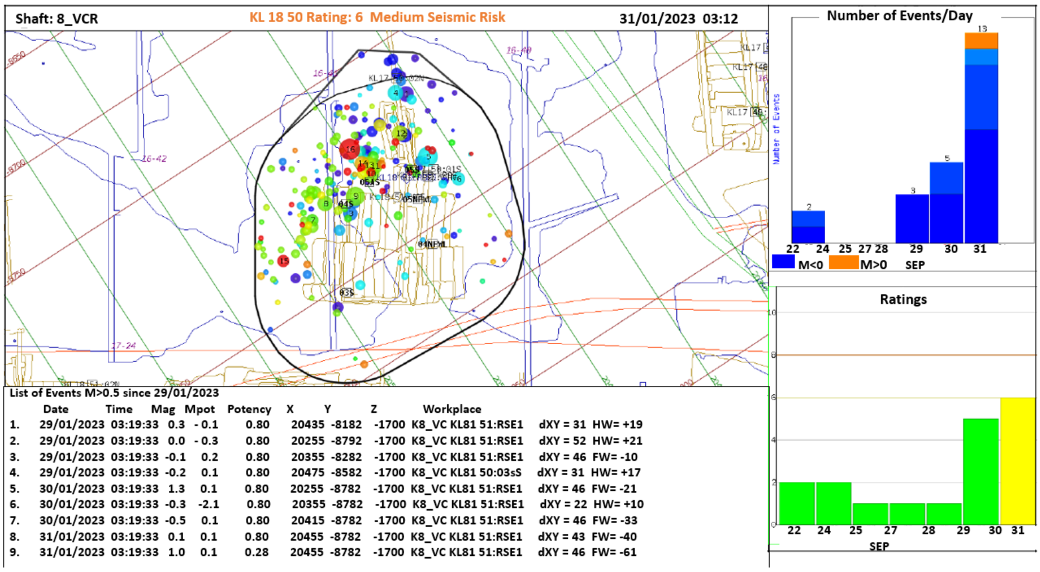
If an event (or more) of sufficiently large magnitude occurred nearby, it can be included into the events contained by the geometry of the polygon. These events are classified as 'damaging' events, usually $M_L1.0$ or greater. When such events occur, a radius of possibly damaging ground motions is calculated, centered on the focus of the event, and used to assist with the notification of the workforce and workplace evacuation efforts when the seismic risk is elevated. Such an event will be included if the distance from the working area is contained within the volume affected by damage-causing ground motions, previously established as at least 0.08 m/s through *in-situ* inspection.

## *3.4 Rating methodology*

The ratio between the short-term trend and the long-term average is equated to an integer (either 0, 1 or 2) according to the size of the variance in each of the four seismic parameters (seismic apparent volume, seismic activity, EI and seismic Schmidt number). Ideally, there would be a regular interval between the occurrence of larger events ($M_L1.0$ and above), but the rockmass is far too inhomogeneous for this to happen. An integer (again, 0, 1 or 2) is assigned when a large event occurs, becomes due, or very overdue according to past behaviour. These are added together to produce a maximum sum of ten, then categorized into ranges for remedial action according to severity. Figure 3 exemplifies the rating methodology for the five parameters. In the report that is distributed, a plot showing a list of event occurrences and locations augments each rating and, in addition, allows a visual assessment of the seismic clusters, along with bar charts depicting the frequency of events in magnitude ranges and the history of the ratings over the past week.

## *3.5 Ratings and response actions*

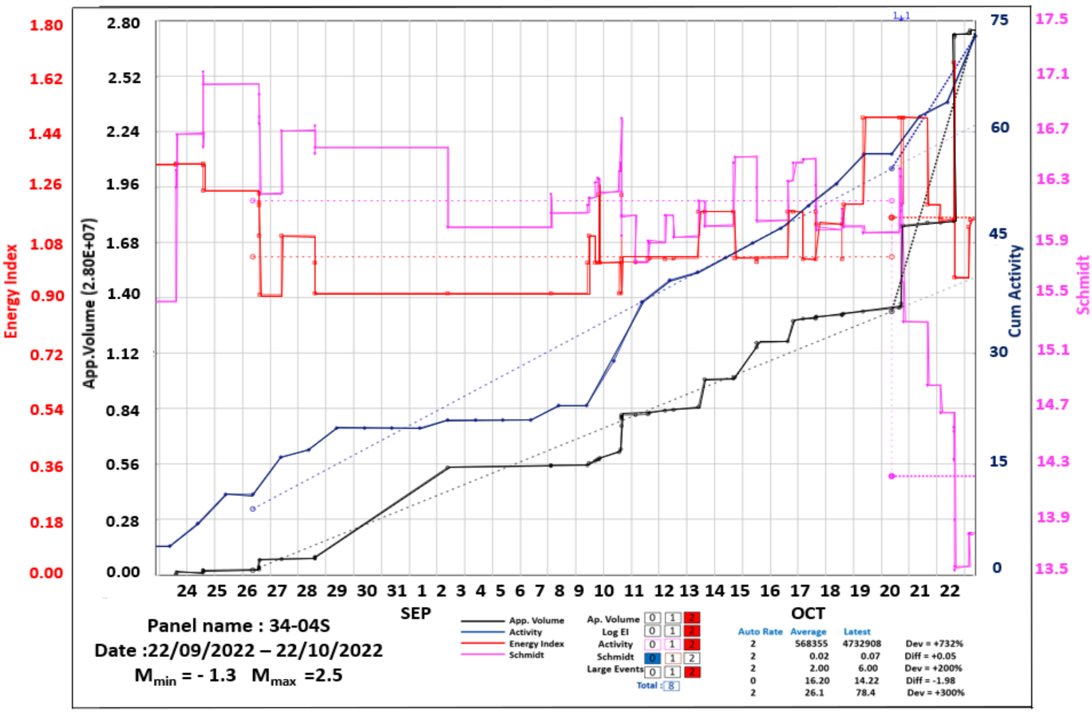
Individual ratings are classified into three ranges (or colours) for improved understanding and acceptance by the workforce: ratings 0 – 5 (green) are classified as 'low', ratings 6 – 7 (yellow or amber) are classified as 'medium', and 8 – 10 (red) as 'high'.



List of Events M>0.5 since 29/01/2023

|  | Date | Time | Mag | Mpot | Potency | X | Y | Z | Workplace |  |  |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1. | 29/01/2023 | 03:19:33 | 0.3 | - 0.1 | 0.80 | 20435 | -8182 | -1700 | K8_VC KL81 51:RSE1 | dXY = 31 | HW= +19 |
| 2. | 29/01/2023 | 03:19:33 | 0.0 | - 0.3 | 0.80 | 20255 | -8792 | -1700 | K8_VC KL81 51:RSE1 | dXY = 52 | HW= +21 |
| 3. | 29/01/2023 | 03:19:33 | -0.1 | 0.2 | 0.80 | 20355 | -8282 | -1700 | K8_VC KL81 51:RSE1 | dXY = 46 | FW= -10 |
| 4. | 29/01/2023 | 03:19:33 | -0.2 | 0.1 | 0.80 | 20475 | -8582 | -1700 | K8_VC KL81 50:03sS | dXY = 31 | HW= +17 |
| 5. | 30/01/2023 | 03:19:33 | 1.3 | 0.1 | 0.80 | 20255 | -8782 | -1700 | K8_VC KL81 51:RSE1 | dXY = 46 | FW= -21 |
| 6. | 30/01/2023 | 03:19:33 | -0.3 | -2.1 | 0.80 | 20355 | -8782 | -1700 | K8_VC KL81 51:RSE1 | dXY = 22 | HW= +10 |
| 7. | 30/01/2023 | 03:19:33 | -0.5 | 0.1 | 0.80 | 20415 | -8782 | -1700 | K8_VC KL81 51:RSE1 | dXY = 46 | FW= -33 |
| 8. | 31/01/2023 | 03:19:33 | 0.1 | 0.1 | 0.80 | 20455 | -8782 | -1700 | K8_VC KL81 51:RSE1 | dXY = 43 | FW= -40 |
| 9. | 31/01/2023 | 03:19:33 | 1.0 | 0.1 | 0.28 | 20455 | -8782 | -1700 | K8_VC KL81 51:RSE1 | dXY = 46 | FW= -61 |

Figure 2. The delineation of a 'polygon' for the exclusive selection of events in the direct vicinity of nearby working places is exemplified in this diagram. The polygons are determined automatically to include clusters of seismic events and incorporate sufficiently close large events which may not necessarily form part of the clusters. The report format includes a plan diagram of the working place, spatial cluster and listing of selected seismicity, and graphical time-histories of seismicity and ratings for the past week.



|  |  |  |  | Auto Rate | Average | Latest |  |
|---|---|---|---|---|---|---|---|
| Ap. Volume | 0 | 1 | 2 | 2 | 568355 | 4732908 | Dev = +732% |
| Log EI | 0 | 1 | 2 | 2 | 0.02 | 0.07 | Diff = +0.05 |
| Activity | 0 | 1 | 2 | 2 | 2.00 | 6.00 | Dev = +200% |
| Schmidt | 0 | 1 | 2 | 0 | 16.20 | 14.22 | Diff = -1.98 |
| Large Events | 0 | 1 | 2 | 2 | 26.1 | 78.4 | Dev = +300% |
| Total : | 8 |  |  |  |  |  |  |

Figure 3. Time history plot showing the five seismic parameters used in the calculation of the daily workplace ratings. The rated parameters relate the change in the short-term to the longer-term trends. As seismicity is recorded and added to the database, a moving window considers the trends (slope of the graph) of these seismic parameters over the last few days and compares these to the trends over a previous longer time period (user-defined). In this way, a rating which ranges between a value of zero (virtually no change between the short- and longer-term trends), a value of one (some change), and a value of two (marked change). Together, these ratings may add up to a maximum value of 10. The parameter ratings for three successive days are shown.

Reaction procedures and actions vary according to the level of a rating. Anomalous or high ratings may occasionally precede anomalous (larger) seismic events, but they normally only follow the occurrence of adverse seismicity. The severity of the ratings – and, by implication, the response thereto by the management team to the mining activities in the relevant working area(s) – triggers pre-established actions and procedures. Low ratings don't warrant further action. Medium ratings require signed acknowledgement by production personnel, including discussion with the relevant working crew. Checklists are performed and sub-standard conditions (or non-compliance with standards and norms) are targeted for correction, with geotechnical input. High ratings will prevent the workforce from proceeding underground and entering the affected workplace(s) (or immediate withdrawal if the perceived seismic risk increases), along with planning audits and more stringent geotechnical review.

## 4 IN CLOSING

The hitherto subjective and problematic selection of seismicity for short-term analysis can now be automated for objective, less error-prone assessments. A better approach has produced a very autonomous workplace seismic risk rating procedure, defined according to clusters of seismic events in space-time, where the polygons are created with each run of a software programme at pre-determined times of the day. The possible effects of larger events further afield, likely to cause damage, are incorporated in the seismic trend analysis. Higher ratings draw the attention of geotechnical engineers and mine seismologists for verification. The workforce is assured of a fresh overview of seismic behaviour just before entering the workplace and on-shift if seismicity occurs.

The next evolution of the rating methodology, now as work-in-progress and under investigation, involves both seismic and non-seismic monitoring, with cheap, next generation in-stope instrumentation (accelerometers, strain and closure meters) integrated through underground and surface communications networks, to provide real-time, continuous measurement of rockmass deformation at the workplace.

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