1 Introduction

A medium-size deep level gold mine in South Africa may experience losses in the region of several million rands per year due to mining induced seismicity. These losses can include direct and indirect costs related to injuries, loss of production, damage to equipment and the costs of re-supporting excavations after rockburst incidents. A single fatality, followed by the suspension of mine-wide operations by the mine safety inspectorate may result in revenue losses of tens of millions of rands.

Mine seismology as a discipline, largely through cooperation with rock engineering, geology, and mine planning, has a significant contribution to make to reduce these losses. Over the past decades, interdisciplinary cooperation resulted in the identification of mining practices and layout details that increase the chances of seismic failure while others were shown to reduce seismic hazard. A good example is the development of the sequential grid mining method (SGM) to the extent that it increasingly replaces longwall methods as the preferred mining strategy for deep and ultra-deep mines.

The advances made in mine seismology allowing the detailed description of seismic sources and the rock mass in which they occur would not be possible without large amounts of seismic raw data collected in a range of different rock types and from various depth ranges. Digital mine-wide seismic networks have been in operation since the late 1980s and research driven by the industry and the state over the past twenty years have resulted in the development of seismic parameters that feed into analysis methods suitable to assess and quantify seismic hazard levels in tens of different working areas on a single mine in a matter of minutes. Both, the analysis methods and the resulting reports are in electronic format and are conveniently distributed by means of SMS or e-mail.

It is estimated that between the three largest South African gold producers AngloGold Ashanti, Goldfields and Harmony in excess of 200 working areas (polygons) are assessed in terms of their seismic hazard level every day. In some cases, hazard ratings are issued twice a day to allow for the evaluation of short-term trends in the hope that unfavourable trends in seismic parameters can be detected prior to a large seismic event.

Thus, it would be fair to say that seismic data analysis is an integral part of risk management on deep level gold mines and increasingly also on platinum mines. At the same time, the industry has to admit that rockbursts still occur and, although rarely of
the severity experienced by DRDGold in the so-called Stilfontein tremor in March 2005 (Figure 1), that injuries and fatalities still result from these tremors.

![Figure 1: Damage as a result of the 9/3/2005 tremor to outer wall, roof and staircase observed on a building of flats in Stilfontein (left). An identical building 17m away appeared to be unaffected.](Photo: author)

The detailed investigation into the Stilfontein event concluded that it was caused by long-term mining activity (Durrheim et al, 2006a). Its magnitude was estimated to be 5.3, which appears to define the upper limit for South African mining induced earthquakes. Historic data suggests that this type of major regional failure may occur roughly every ten years in either the Free State or the Klerksdorp mining region while active mining continues.

Mines experiencing dynamic rock mass failure on any significant scale are taking steps to manage this hazard: In survey results published in 2006, eight out of ten mining operations in the gold and platinum sector stated that they routinely integrate seismic information with rock mechanics information, for instance for the treatment of unstable geological structures, for pillar design and during the planning stage of future reef block extractions (Durrheim et al, 2006b). Most of these operations, however had never established the success rate of seismic hazard assessments and only one of ten mines had conducted a cost-benefit analysis on the operation of the seismic system, an issue discussed in more detail below.

The survey results point to the possibility that seismic data may often be collected and analysed without a clear view on the value this adds to the operation. The following chapters take a brief look at the capabilities of today’s mine seismic networks, the information they provide and the benefit that can be derived. During the course of the discussion it will become apparent that seismic data interpretation faces certain threats which will be outlined together with barriers which need to be overcome in order to derive maximum benefit from a mine seismic network.
2. Data collection

In nearly all cases, mine networks consist of ground-motion sensors that produce an output in [V/m/s], i.e. voltage proportional to ground velocity. The signal is weak; therefore each sensor is connected to a seismometer in close proximity that amplifies, filters, digitises and stores the electric signal. There can be several seismometers on a shaft level, usually installed in haulages or crosscuts, but usually not in stopes unless for research applications. Up to thirty seismometers make up a network by being linked to a central system computer on surface. All communications within the network are digital to accommodate higher data speed and greater bandwidth.

A seismic system consists of a combination of hardware and software that allows the collection of seismic data, data processing for basic event parameters, and the creation of data bases from these data. The design of a suitable system is directly linked to the aims of monitoring: Sensitivity and location accuracy are common performance criteria of seismic systems. Networks should be designed to satisfy the requirements in terms of these two parameters, which may vary across the depth range of the mine and from one mining area to another. The required location accuracy is usually determined by the source size of relevant events: A few metres in case of face monitoring, a few hundred metres for large regional type events.

![Figure 2: Compact 3D ground-motion sensor set (left, courtesy of ISSI); seismogram recorded by a tri-axial sensor set includes 3 components of ground motion.](image)

Since seismic event locations are most useful when expressed in the mine co-ordinate system, sensors are aligned with the mine’s co-ordinate axes when installed. When using a tri-axial set the recordings are a direct reflection of the physical rock mass movement: In a sensor set, usually an orthogonal assembly, each sensor records one of three components of the ground motion (see Figure 2).

Generally, a seismic system produces two types of information. While the focus is mostly on the first type when it comes to data analysis and interpretation, the importance of the second type should not be underestimated:

1) Seismic raw data in form of seismograms to calculate source parameters (time, location, seismic energy, seismic moment etc.);

2) Information relating to the operation of the system such as quality of data communication, station up/down time and sensor health.
The former is input into data analysis and interpretation to quantify seismic events and changes in event clusters. The latter is crucial to maintaining a healthy network and to ensure that seismic raw data is of sufficient quality to allow further analysis. As audits of mine seismic systems have shown the accuracy and reliability of final outputs of data interpretation is at times impaired by poor quality of the underlying raw data.

3. Data analysis

Methods of seismic data analysis are based on a set of specialised tools used exclusively in seismology and others such as descriptive statistical methods universally applied in various scientific fields. Among the former are those borrowed from global earthquake seismology to characterise single seismic failures or groups of events:

- Location in space and time
- Slip-Burst type distinction
- Stress-drop estimate
- Source dimension estimate
- Peak Particle Velocity estimates (PPV)
- Moment Tensor inversion
- Gutenberg-Richter graph
- Seismic hazard/risk quantification

In addition, the field of mine seismology has added its own set of tools many of which originate from ISS International’s research efforts over the past decades:

- Energy Index (stress indicator)
- Apparent Volume (source size)
- Potency (strength)
- Seismic Schmidt number (predictability)
- Polygon ratings

Figure 3 below summarises the two main streams found in routine seismic data analysis as they are implemented on most South African mines that follow seismic risk management procedures. The analysis outputs relate to either a single, usually large event that may have resulted in damage or was otherwise significant; or they relate to a group of seismic events analysing either trends over time or patterns in space.

A typical output of a single event analysis is the failure mechanism at the source and the relative importance of explosive over shear component in the source mechanism, estimates of stress drop and source dimension. For event groups contour plots reflecting seismic deformation in space are common, and ‘time-history plots’, a label applied to trend analysis over time.

In the subsequent chapter we show by way of select examples how seismic data from modern seismic networks may lead to the identification of unfavourable mine layouts and assist in the planning of intervention strategies for high stress mining environments.
4. Data interpretation

Seismic data interpretation delivers inputs into the risk quantification, evaluation and control process. These are mandatory tasks for every mine with a significant risk of rock fall or rockburst. The correlation of seismicity with mine design parameters, geological data, rock mechanics and support design, mine production and loss control information offers numerous ways to quantify and intervene in processes that are inherently unsafe or at least carry an appreciable level of risk.

The ability to quantify hazard levels offers the opportunity to use seismic information to optimise operations. Some examples are given here:

- Critical dimensions of stabilising pillars to prevent foundation failure;
- Maximum panel leads to prevent abutment failure;
- Maximum face length to limit failure size, i.e. maximum magnitude $M_{\text{max}}$;
- Critical remnant size to avoid core failure;
- Stable design of bracket pillars and regional stabilising pillars;
- Correlation of medium-term trends in seismic activity with production rate to detect increased hazard levels;
- Recurrence time and $M_{\text{max}}$ estimates for large events;
- Estimates of peak ground motion in excavation surfaces near large events;
- Classification of working places and geo-technical areas as low or high seismic hazard areas;
- Quantification of rockburst risk for working areas;
- Detection of short-term rock mass instabilities;
- Design of safe re-entry criteria after large events.

This list is not exhaustive as it does not even consider any specialised monitoring application in massive mines and open pit operations. It is evident that in order to ask pertinent questions, rock engineering personnel and mine management need to be aware of the methods and the types of information mine seismology as a discipline is able to deliver. Likely the most discussed topic in this context is the short-term prediction of rockmass instability from workplace ratings.
There are at least two opposing views: Some perceive the limitations of successful event prediction to be a matter of research and, to some extent, of technology. This position would promote the continued use of the methodology and the deployment of more monitoring equipment to detect ever finer changes in rockmass conditions at ever higher data speeds.

Others question whether it is physically possible to decide based on measurements whether a small fracture will grow into a large one while the process of failure is on-going. The latter group which includes many earthquake seismologists doubt that the rock has ‘made a decision’ whether to fail on a small or on a large scale at the time of failure initiation. It is possible that such a ‘decision’ is taken while the process is ongoing, not beforehand.

To settle on one position over the other the industry should make available large numbers of seismic instability assessments, the conditions under which they were produced and the quality indicators of the data that the assessments were based on, together with their success or failure to predict large events. To the author’s knowledge, only two mines have made data samples of this nature available for broader discussion. Even in combination the two samples are small and would not allow a judgement on the merits of the method. It would be beneficial if more mines released their data sets (polygon ratings) for scrutiny in order for a meaningful discussion of this methodology to take place.

An in-depth analysis of seismic events recorded prior to large events was conducted recently searching for marked changes in seismic parameters prior to large events within a certain radius and time window of large events (Spottiswoode, 2010). The study found no significant difference in the occurrence of markers before large events compared to markers before small events.

Instability assessments are only one of many assessment types carried out by mine seismologists. The following case studies illustrate the potential benefit derived from detailed seismic data interpretation, each undertaken to answer a single pertinent question.
4.1 Case 1: What is the critical distance to holing in a scattered layout?

In a scattered mining layout, panels mine towards each other from neighbouring raises creating a remnant that decreases in width as the faces advance (Figure 4). As pillar width decreases, the width:height ratio decreases leading to potential instability when the load exceeds the pillar strength and failure occurs. This can take place slowly over days or weeks, or suddenly in the form of a seismic event, depending on the loading stiffness of the system.

Six such pillar extractions were evaluated in terms of monthly mining rate, remaining pillar width, and seismic deformation (Essrich, 2002). The results can be used to raise awareness amongst production personnel when nearing the critical phase when large seismic events are likely to occur, to adjust support requirements and to prepare the crews for increased rockburst hazard. The evaluation of seismic records thus helps to focus on critical items and to be prepared for possible rockburst damage.

4.2 Case 2: What is the rockburst risk associated with service excavations?

One significant shortcoming of routinely applied seismic hazard assessments is that they do not consider the potential losses that can result from exposure to the hazard. A situation in which two reef blocks are exposed to the same seismic hazard, but one block has significantly higher grades than the other, calls more urgently for protective measures than the other. The logical step beyond hazard assessments is towards seismic risk assessments. These are particularly relevant where people are exposed to hazards since injuries must be considered amongst the most severe losses to a mining operation.

The following example describes the quantification of rockburst risk to service excavations in a shaft pillar. Damage to shaft barrels and winder chambers are potentially life-threatening incidents to a mining operation as they have the capacity to fatally injure workers and severely interrupt operations for extended periods. To have knowledge of risk levels and the type of damage that may be incurred by seismic events enables an engineering manager to provide for extra protection or to treat the risk by lowering the exposure.

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<th>Lift Shaft</th>
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Table 1: Results of a seismic risk assessment for service excavations in a shaft pillar.

To quantify the seismic risk for service excavations in a shaft barrel the seismic hazard needs to be calculated separately for each major service excavation in the shaft pillar. Since the potential for damage increases with event magnitude and the likelihood for occurrence decreases as fewer large events occur than small events the hazard calculation is to be performed for a number of magnitude ranges. Following a methodology outlined by Handley (1999), each excavation is being assigned a
probability of rockburst damage based on its volume and the probability of damaging events occurring close enough to result in damage\(^1\). Subsequently, the damage likelihood is combined with the likelihood of people present in the excavation resulting in a risk rating for each excavation (Table 1).

The results indicate that the two shaft barrels are exposed to the highest risk level and that this risk does not necessarily emanate from the largest magnitude event (Essrich, 2002). The risk for all other excavations is lower by approximately three orders of magnitude which emphasises the importance of all actions aimed at preserving the integrity of the shaft barrels. With above information relevant actions to reduce the probability of damage could be initiated. Among these could be a thorough investigation into all possible sources of seismic events in the magnitude range M=2…3 in the vicinity of the shaft pillar in an attempt to reduce their frequency.

4.3 Case 3: What is the seismic hazard level associated with geological structures?

The key factors determining seismic response to mining are the geo-technical setting (including the stress field), the rate at which production volumes force stress changes onto the rock mass, excavation skins and geological discontinuities and the overall mining strategy applied in the area. Together they determine the interaction between stress levels and the rock mass hosting the ore body and mining excavations.

For the quantification of the geo-seismic hazard associated with major structures in the case of a planned shaft in the Western Bushveld region, three major dolerite intrusions extending from historic operations into the planned shaft area were assessed. Relevant data to estimate the seismic hazard associated with geological structures originated from the mine planning the new shaft and from neighbouring mines (Figure 5).

\(^1\) The ground motion intensity required to damage intact rock or, in the case of shaft barrels, concrete linings, generally depends on the strength of the seismic source, hypo-central distance, and local rock conditions. Data from the West Rand suggest that a peak ground velocity (PGV) of 0.7m/s is a reasonable approximation.
The common approach to geo-seismic hazard classification is to express discontinuity based seismicity in terms of severity and frequency of large events. Frequency is a function of magnitude and time; severity can be expressed as the maximum expected magnitude $M_{\text{max}}$.

A prerequisite to such an assessment is the existence of seismic records that are sufficiently detailed and extend over a minimum of several years to allow an estimate of the long-term seismic behaviour of the structure. The assessment resulted in the following: Where the structures had been mined in the past their long-term seismic hazard remained within a manageable range. Expected maximum magnitude $M_{\text{max}}$ did not exceed 1.6 on the local magnitude scale. The frequency of events with $M_L > 1.5$ was low, approximately 0.5 over a 12-months period. Structures without historic seismic record cannot be assessed in this way.

4.4 Case 4: Which panel configuration generates higher seismic energy release?

In conventional longwall mining as well as in sequential grid mining, the panel configuration is frequently a matter of choice. In practice, an overhand configuration is more common and the reasons are associated with a number of factors such as the ease of cleaning the panels, ventilation, blasting of gullies etc. The question arises which configuration is more favourable in terms of seismic emissions, or more generally, is there an appreciable difference at all in seismic response between over- and underhand configuration (Figure 6).

In an example from a VCR mine in the West Rand Region, four panel sets mining underhand and five mining overhand were compared in terms of event frequency in different magnitude ranges, $M_{\text{max}}$, cumulative seismic source sizes and seismic energy emission normalised by production. As far as possible, other factors contributing to seismic response were eliminated during the work place selection: Mining depth, major geological structures, backfill and mining rate.

The data suggests that in the mining environment investigated here no significant difference exists between the number of events generated by either layout. The maximum magnitude is also comparable between the two layouts. But when seismic energy release per area mined and seismic source volume per area mined are compared the panel sets mining in overhand configuration appear to generate events.
with higher seismic energy release and smaller source dimension, which indicates that they occur in a high-stress environment. The relevance of high-energy release events lies in the fact that radiated seismic waves result in higher ground particle velocity with an associated higher rockburst risk.

In conclusion, based on seismic data in this particular case, underhand mining should be the preferred choice when aiming at lower seismic risk. In practice, seismicity levels are not the only issue to consider when deciding on a panel set configuration.

5. Challenges and barriers to effective seismic monitoring

Seismic system operators on deep level gold and intermediate level platinum mines face a number of challenges ranging from technical skills shortages to budget constraints and to limitations imposed by the instrumentation and the software that together make up a system. Which of these are systemic and which can be remedied with relatively small effort depends on the individual mine.

The author has audited in excess of fifteen seismic systems in the South African mining sector. The factors shown to have the highest impact on successful seismic data interpretation are the following:

- objectives of monitoring not well defined;
- networks not designed according to objectives;
- necessary network upgrades delayed;
- poor sensor health and long replacement time in case of faulty sensors;
- lack of seismic technician skills on mines;
- sub-optimal setting of system parameters and software bugs;
- inadequate reporting on system status;
- inconsistent / incomplete data bases;
- inaccurate source parameters;
- spurious and irrelevant data collected;
- objectives of data analysis poorly defined;
- data analysis methods not performance assessed;
- lack of ‘plan-operate-review-improve’ approach;
- supplier / service agreements not independently reviewed;
- no independent system audits conducted;
- recommendations following audits not implemented.

Although the list contains a number of specific issues some of which are of technical nature the overarching criticism that has to be aimed at mines operating seismic systems (there are notable exceptions!) is the lack of a coherent, integrated quality management approach to seismic services. On many such mines mine management’s involvement is limited to receiving routine seismic reports and allocating at budget time the financial resources required for the network operation.
It is suggested that the purpose of collecting seismic data be clearly defined in terms of value-add deliverables; that the ability of the seismic service to deliver these outputs be assessed annually; and that necessary modifications are implemented to continually improve on the service. This will ensure maximum benefit to the mining operation, improved management of seismic risk and as a by-product compliance with legal obligations.

6. Conclusions

The potential benefits of rock mass instability monitoring are substantial: They range from short-term hazard assessments to work place ratings, identification of unfavourable seismicity trends and seismicity patterns to the detailed analysis of large seismic failures, why they occurred and under which circumstances.

Seismic data analysis is able to support rock engineering functions, among other stabilising and bracket pillar design, comparison of different mining configurations in terms of their hazard level, calibration of rock mass modelling, evaluation of mining rate and overall mining strategy to reduce rock related risk. In the Western Bushveld, shallow and intermediate depth operations currently have an opportunity to study seismic response and devise ameliorating strategies while hazard levels are still comparatively low. When mining depth increases over the coming years this is likely to change.

But seismicity related information can only be relevant if it is accurate and reliable and oriented on the needs and expectations of stakeholders. These expectations and the obligation of mines exposed to seismic risk to manage such risk can largely be fulfilled with the technology and methodologies currently available in the mine seismology discipline. The industry could make a greater effort to draw maximum benefit from this discipline.

References


F Essrich (2002): *Bringing seismological information to Rock Engineers and Production Personnel*, Colloquium on Knowledge and Technology Transfer, Randburg, S. Africa
