Integration of seismicity and modelling made simple

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Mine layout designs under rockburst conditions aim to control the incidence of seismicity and rockbursts. Design decisions are based on previous experience, numerical simulations of proposed mining and assessment of the seismic history in the area, and on grade. The numerical simulations and seismic analysis are generally undertaken separately and some formal or informal weighting system is used when decisions are made.
This paper introduces a methodology in which the spatial distribution of future seismicity is estimated based on past seismicity and past and future elastic energy release. It is shown that this combined approach may more accurately estimate the impending seismicity than using either modelling or previous seismicity on their own.
This work was done using the MINF and MinSInt programs that have been developed for SIMRAC for integrated analysis of modelling and seismicity.

Introduction

Rockbursts from mining-induced seismicity pose the most severe hazard in deep-level mining. While use of appropriate support will contain rockburst damage, proper layout design and sequencing is also necessary to reduce seismicity and the resulting strong ground motion in the workings. In the case of deep-level tabular mining, such as in the South African deep-level gold mines, mine layout design is aimed at reducing the overall seismicity using the now well-known criteria of Energy Release Rate (ERR), Excess Shear Stress and Average Pillar Stress (Ryder and Jager, 2002).

ERR is the criterion most widely used to control span in the relatively unfaulted Carletonville mining region. From about 1970 onwards, strike-parallel pillars were most commonly used to satisfy the ERR criteria set by several mines (e.g. van Antwerpen and Spengler, 1982). In recent years, mines are usually achieving this by leaving regional support pillars aligned on dip (e.g. Handley et al, 2000 and Klokow, 2003). Dip pillars offer the advantage that geological features are more easily left behind within a skin of bracket pillars, thereby increasing the extraction ratio and reducing the need to mine within dykes or close to faults.

The level of anticipated seismicity may be estimated in a number of ways. In the ideal case, long-term stability of mines would be assured if enough were known about the rock mass before mining took place. For many reasons, this ideal is never realised and an on-going stability assessment is necessary, based on improved knowledge of the geological structures and the actual response of the rock mass. Furthermore, there are still no simulation programs that can solve the "full" problem of brittle failure resulting from mining of rock around even the most ideal hypothetical mine.

These design criteria are all based on numerical modelling and are sensitive to small changes in rock mass properties and stresses. Seismic data are used on a less detailed basis, but do provide a more direct measure of the response of the rock to mining. Consideration of modelling and seismic data in mine design is generally considered as two entirely different approaches. Only recently have ways been proposed to combine these approaches into a single analysis and design methodology. Hoffmann et al (2001) and Spottiswoode (2001 and 2004a) have proposed ways to integrate the two approaches to mine layout design, namely modelling and seismicity, into a coherent whole.

The work of Spottiswoode (2001 and 2004a) consisted of back-analyses aimed at understanding the relationships between modelled and observed deformations. This paper will take a more direct and challenging approach to the integration problem and will use both data sets to estimate the future seismicity in time and space.

The ultimate objective of this approach is to develop a computer program that will use mine seismic data and modelling to allow a mine to quickly estimate the amount of seismicity that will be likely to follow different mining options. This will assist in deciding between different mining options.

This paper describes recently developed procedures to predict impending seismicity on a scale of months and ~100m. Although the results are not sufficiently convincing to be implemented, they are encouraging. Certain conclusions are drawn that will hopefully lead to better results and perhaps procedures that can be implemented.

A more complete mathematical description of the methodology will be presented in Spottiswoode (2004b).

Approaches to Designing Mine Layouts

Three approaches to designing macro mine layouts may be used:

Numerical Modelling Only

This is the normal procedure for macro layout design. A generic approach is initially used to ensure that the layout satisfies the set criteria. In the dip pillar situation, raise spacing, spans and pillar sizes are set. The pillar positions are then adjusted to avoid mining the larger geological discontinuities, but usually without reducing pillar widths. More ground is commonly left behind than was originally planned (e.g. Klokow et al, 2003).

Past Seismicity Only

The hazard posed by tectonic earthquakes may be judged in terms of the likely incidence of strong ground motion. A definition of seismic hazard in mines has been proposed by Kijko et al (1998) and is based on the probability of events above certain magnitudes occurring within a certain time period.

This hazard definition assumes that the future seismicity will be the same as the past rate of seismicity. This might be true for a large production area, but will, in general, not be true locally as the mining and geological conditions continually change. An immediate improvement in accuracy will be expected if corrections are made for the area to be mined, as is done in this paper.

Integration of Modelling with Seismicity

The "ultimate" integration model will consist of an advanced numerical model that will continually adapt according to the actual response of the rock mass to mining.

This paper takes a simple approach to the numerical modelling and will be considering only the Energy Release associated with the change in elastic strain energy with mining.

These three approaches are briefly explained in the next section and then tested in the case study analysed in the following section.

A Methodology for Estimating Future Seismicity

Future seismicity is estimated using the MinSInt program that is being developed for SIMRAC. Figure 1 shows the relationship between MinSInt and other programs. MINF was described by Spottiswoode (2004a) and in previous papers.

As discussed by Spottiswoode (2004a), seismic data needs special processing before it can be compared in spatial detail with modelled results. In particular, the "strength" of each seismic event is distributed into the same square grids that are used for the numerical simulations and are mined at the time of each event. This comparison methodology has been considerably extended in this study to include spatial comparisons between past and future modelling and seismicity on an on-reef square grid. This method has two steps (see Figure 2):

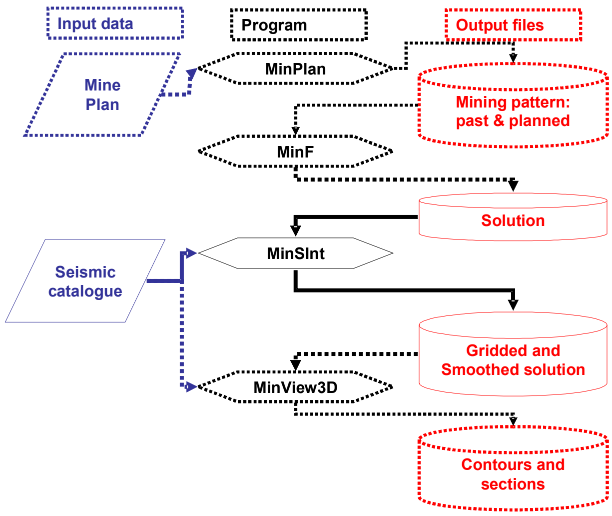


Figure 1. Block diagram summarising operation of program MinSInt within the full analysis path

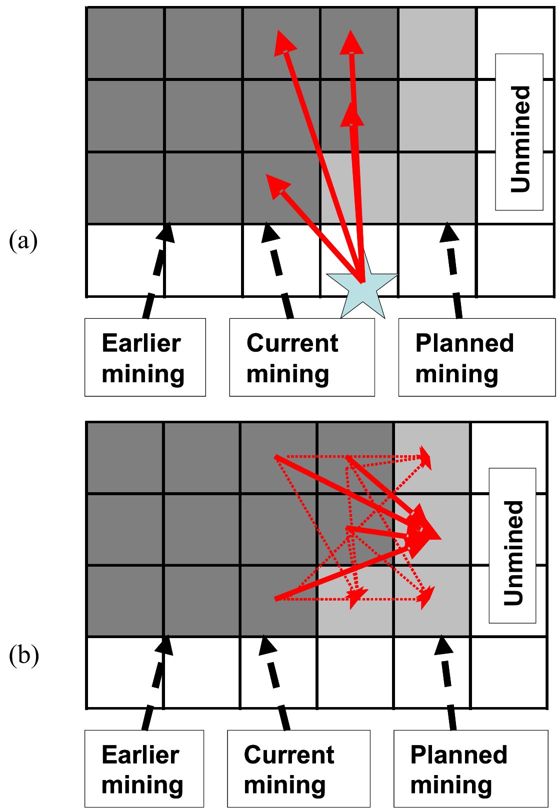


Figure 2. A sketch illustrating (a) distribution of a seismic event onto the grid squares that are currently being mined, followed by (b) distribution of values in currently mined areas onto planned mining areas

1. The location accuracy of mine seismic events is typically tens of metres, whereas the stress peak on faces and abutments is only several metres wide. We postulate that it is necessary to shift the seismic event onto the face. This is achieved here by distributing the seismic event onto areas of mining with a smoothing function, where the function is set to zero where no energy release is expected. A further smoothing function is applied to emulate the source dimension of

each event. This has the effect of spreading the seismic deformation of bigger events over a bigger area than smaller events. The smoothing function is flat, tapering to zero with a Gaussian function.

2. To ensure one-to-one comparisons between past and future data, past modelling and seismicity is shifted on to areas of planned mining, using the same Gaussian function. The values at each element for which mining is planned are based on a minimum number of mined elements and seismic events, 20 elements in the simulations that follow.

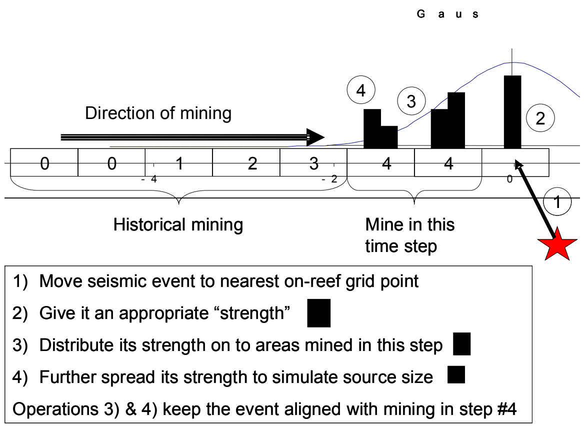


Figure 3. A sketch illustrating the process of attributing a seismic event to the area currently being mined. The process is described in the text.

One of the challenges in any comparison between modelled and observed deformations is to set up a way of comparing the different types of data. A widely recognised way of presenting and analysing spatial data is through a Geographical Information System (GIS). Two relevant definitions, extracted from (http://www.geo.ed.ac.uk/agidexe/search) are:

GIS: "…Typically, a Geographical Information System … is used for handling maps of one kind or another. These might be represented as several different layers where each layer holds data about a particular kind of feature. … …

Layers of data are organised to be studied and to perform statistical analysis. …"

Grid Squares: "A regular array of square cells referenced to a grid, used as a basis for holding spatially referenced information."

Square grids have been used for many years for modelling the elastic deformations around tabular excavations (Ryder and Jager, 2002).

In this methodology, one set of layers is defined for each time step, with each set consisting of combinations of mining and seismicity data. Each array is used to describe some property in three dimensions, two in space and one in time.

Seismicity can be quantification in various ways. The measure that relates best to the total amount of deformation is seismic moment, expressed as ΣM_0, the summed seismic moment. However, as a few large events account for most of the total, a simple count of the number of recorded events in any area and time will provide a more even statistical base.

Numerical Modelling Only

The ideal numerical modelling will directly predict the amount of seismicity. However, if we allow our model to be incorrect by some factor that can be estimated from previous seismicity and modelling in the general area, then we can estimate future seismicity. Future seismicity is estimated by multiplying the expected elastic strain energy release by the ratio of past seismicity to past elastic energy release.

Previous Seismicity Only

Here we assume that the current rate of nearby seismicity per area mined will persist into the future.

Integration of seismicity and modelling.

Here we assume that the seismicity rate per area mined changes by the expected change in the rate of elastic strain energy release.

Case Study

Our study area on No 5E shaft, Driefontein Gold Mine covers an area of about 1000 m by 1400 m in extent in which 7 raises were wholly or partially mined. The mine plan was digitised from 1999 to 2002 using the program MinPlan from the MinSim2000 suite of programs (Figure 1). The mine plan was drawn at quarterly face positions from 1999 to August 2002 and then every month until December 2002. The MinPlan program creates files that contain the pattern of mining over a range of time steps as digitized off the mine plan. The "size" of the simulations was 128 by 128 square elements, each 11m on a side. These files were then used as input for program MINF (Spottiswoode, 2001) which then solves for the elastic convergence, stress and elastic energy release.

Selection of seismic events.

The mine catalogue included numerous small events that were associated with off-reef development (footwall haulages and cross cuts to reef). Richardson and Jordan (2002) showed that events associated with advancing development had Moment-Magnitude M(Mo) < 0.5 in a study of nearby mines. They labelled these events type "A" events and interpreted them as "fracture-dominated" rupture events, as against the normal type "B" "friction-dominated" slip events. We presented several lines of evidence in Cichowicz et al (2004) that these events were the actual development blasts. They will be called "blasts" in this study.

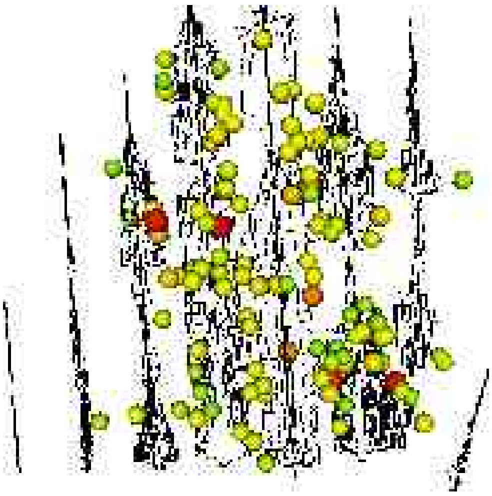


Fig. 4. Mining & seismicity, with larger recorded seismic events (M>≈2).

As this present study relates to seismicity induced by stoping and not by tunnel development, we need to exclude these blast events from the analysis. The simplest was to exclude development events would be to exclude all events with M(Mo) < 0.5. This would unfortunately involve excluding in excess of 80% of the recorded events.

Richardson and Jordan (2002) also noted that the development events located closely in space and time to one another. Figure 5 shows a very clear increase in clustering in time and in space for M(Mo) < 0.5.

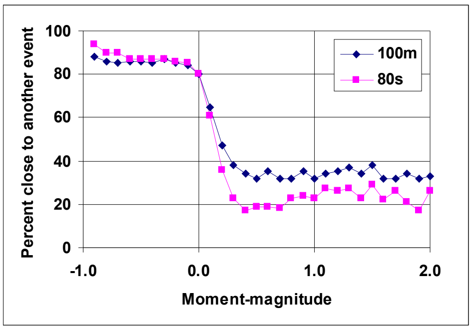


Figure 5. The proportion of events that are within 100m or within 80s of the previous or following event

Following the suggestion of Richardson and Jordan (2002), the development blast events were identified as those with M(Mo)<0.5 **and** that located within 100m of another events **and** within 80s of another event.

Table 2. Number of blast and induced events greater than three values of Moment-Magnitudes

N	M>-0.5	M>0.0	M>0.5
Blast	26425	5652	49
Induced	17082	12198	7284
Total	43507	17850	7333

This division of events into "blast" and "induced" events is shown in Table 2 and Figure 6. An increasing proportion of all events are likely to have been blast events as the threshold magnitude drops below 0.5. In the process, the "hump" in the frequency-magnitude distribution in the range 0.0<M<0.5 that is visible in the graph for the entire data set disappears.

The 12198 events with M>0.0 that were most likely to be induced events are used in this study.

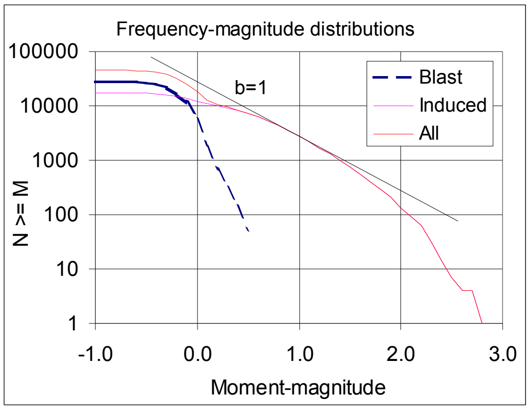


Figure 6. Size distribution of events identified as blast events, mining-induced events and all events

Identification of "Working Areas"

The methodology outlined above was applied to the Driefontein data set. An example of mining and seismicity within part of the area during a single time step is shown in Figure 7. Three distinct regions of active mining can be identified. These will be termed "working areas". In the normal mining operation these working areas would probably be lumped together into a single "polygon" for seismic analysis to avoid misallocating events into the wrong polygon. In this analysis, the influence of events that locate between the working areas, such as A, B and C in Figure 7, are split between these areas according to their proximity to current mining.

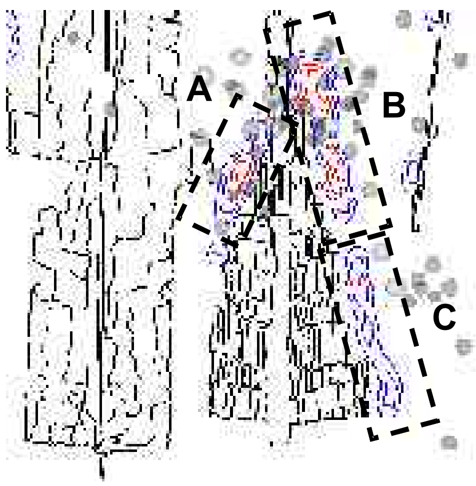


Figure 7. An example of extraction in the three months from November 2001 shown as contours, the larger seismic events as opaque balls and mining steps up to August 2001 as outlines

An algorithm was written to identify such regions for each mining step. This algorithm was based on their being separated by at least three elements that were not being mined at that time.

Analysis of Predictions using the Three Methods

Observed seismicity is compared to seismicity predicted using the three methods described above. Data for the 99 working areas that included at least 10 mined elements are now shown in Figures 8, 9 and 10.

In Figure 8, the total observed in each region is compared to the seismic moment predicted using the integration model. Note the dominant contribution of the few largest events, which appear as unpredicted (labelled "under-predicted": Y>X) or as over-predicted (Y<X) depending whether the large events are to be predicted or are "current" events.

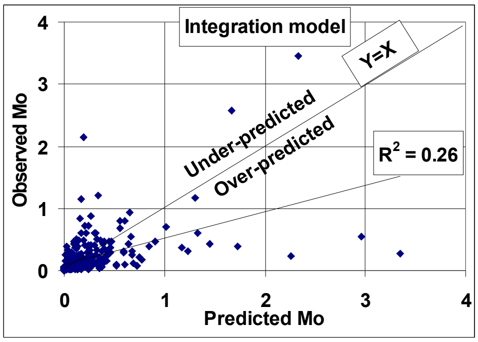


Figure 8. Predicted and observed seismic moment.

Using the number of events eliminates any dominance of the effect of any event on any other. Figure 9 shows the comparison between predicted and observed number of seismicity per area mined. An inspection of this Figure shows, *inter alia*, that:

a) Although the correlation factor (R^2 value) is well below 0.5, this is a reflection of the detail of the data as most of the more active working areas, in which more than two events per element occurred, were predicted as being more likely to be seismically active.

b) The most noticeable feature in this figure is fact that almost all predictions were under-estimates, in other words the seismic event rate almost always increased with time in any working area. This occurred because the span and therefore the face stresses and values of ERR increased.

c) This figure is similar in shape to Figure 9(b). The data are about evenly spread across the "perfect" line, labelled "Y=X". This means that the ERR correction provided, on average, an appropriate correction for the deficit apparent in Figure 9 (b).

   If these values were to be used for deciding whether to continue mining in an area or not, the bounding line labelled Y=X+1 provides a conservative upper limit to the impending seismicity. Working places that were predicted to result in less than one event per element did indeed generate this small seismicity rate.

The data points within the dashed ellipse in Figure 9c were the most severe examples of over-prediction. This will be contrasted later with a similar region in Figure 10c.

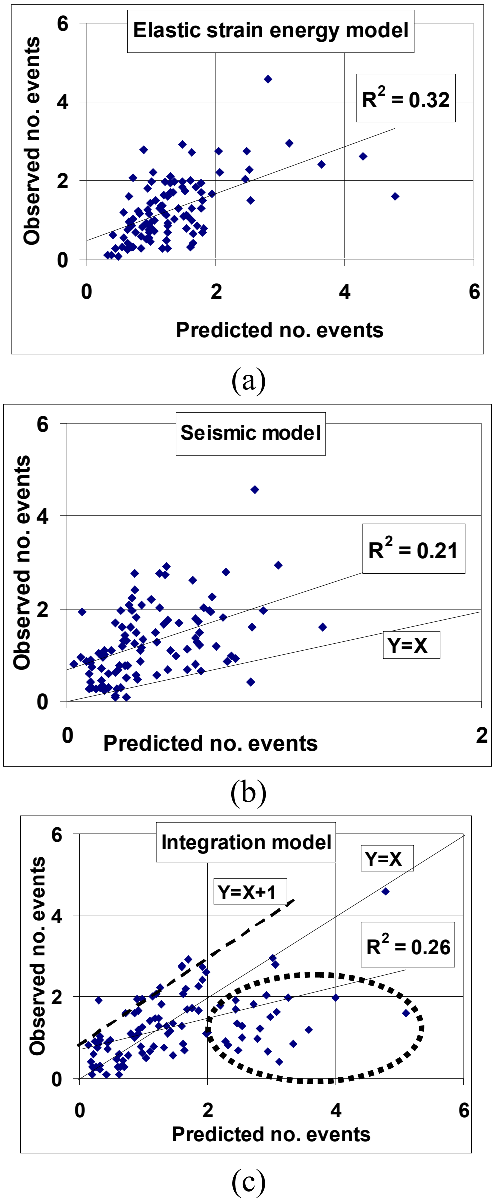
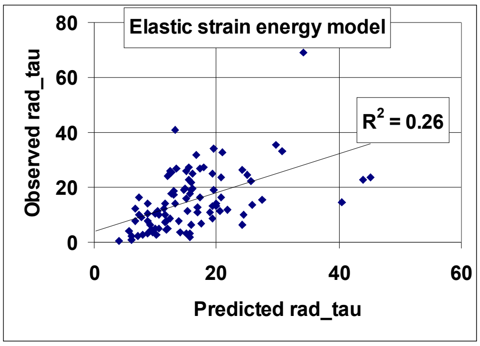
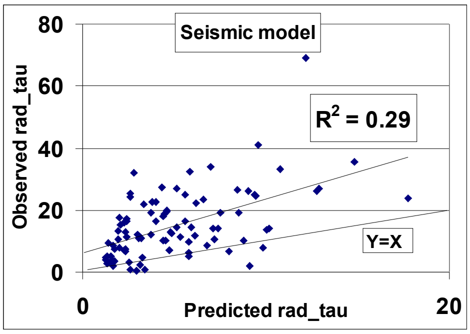


Figure 9. Comparison of the observed number of events per mined element with the predicted number of elements by each of three model approaches. The ellipse in (c) is drawn around some of the data that were over-predicted

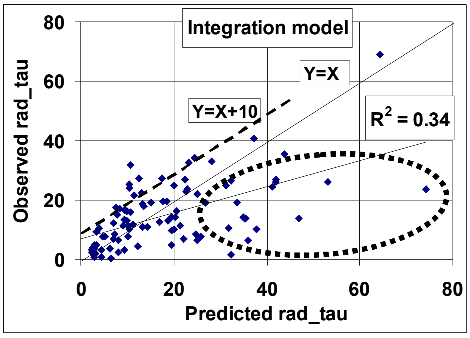
Predicting the number of events is of limited value because most of these events are of negative magnitude and do not cause any damage. As shown in Figure 8, the opposite extreme of using seismic moment to predict the amount of seismic moment is ineffective. We now compromise by measuring each seismic event as source radius multiplied by apparent stress ($r_0 \times \tau$), labelled "rad_tau" in Figure 10. This parameter was chosen in an attempt to represent both the extent (r_0) and the intensity (τ) of strong ground motion.



(a)



(b)



(c)

Figure 10. Comparison between the observed number of events per mined element and source radius time apparent stress.

The small weighting given to larger events by applying a "strength" of $r_0 \times \tau$ gives better results for the seismicity-related predictors (10 (b) and 10 (c)). In particular, the number of working places that had their seismicity severely over-predicted decreased, as can been by fewer events falling in the ellipse region of 10 (c) compared to the similar region in 9 (c).

Conclusions and Discussion

This paper introduces a methodology and computer program for an integrated analysis of both rock mass modelling and observed seismicity to predict, or forecast, the amount of seismicity that will be likely to occur over the next month or quarter in any working area.

These results show the potential benefits of this type of integration work for mine layout planning. The techniques presented here for associating observed seismicity with modelled seismicity are still quite new and more detailed analysis will undoubtedly lead to better interpretation of the response, in time and space, of seismicity to mining.

As this is the first analysis using this methodology, there will obviously be much scope for improvement, even in the short term. A partial list would include:

- **Modelling**. There are a number of ways of introducing easy approximations to simulate actual rock failure (e.g. Spottiswoode, 2001). These should provide better insights into the rock mass response at high levels of ERR and over time.
- **Seismic data**. Seismic locations can be improved using methods described in Cichowicz (2004)
- **Statistical processing.** Very simple methods have been used in this study. For example, all working areas have been given equal weight and equal symbol sizes in Figures 8 to 10, even though the larger areas behaved better. Improved methods will be essential before this work can be used for quantitative hazard analysis.

Acknowledgments

This work was supported by SIMRAC under projects SIM 02-03-04 and SIM 04-03-01. Thanks to Driefontein Consolidated for permission to use their data. Members of the SIMRAC Rock Engineering expert committee encouraged me to move forward with this predictive model. Discussions with and reviews by Ray Durrheim and Mark Hildyard were essential in keeping this work reasonably comprehensible.

References

HANDLEY, M.F., DE LANGE, J.A.J., ESSRICH, F. and BANNING, J.A. (2000) A review of the sequential grid mining method employed at Elandsrand Gold Mine. J. S. Afr. Inst. Min. Metall., pp. 1183-1194.

CICHOWICZ, A., SPOTTISWOODE, S.M., LINZER, L.M., HEYNS, S.P., DRENT, D. and HANDLEY, M.F. (2004) Improved seismic locations and location techniques. SIMRAC final report in preparation for SIM020304.

HOFFMANN, G., SEWJEE, R. and VAN ASWEGEN, G. (2001). First steps in the integration of numerical modelling and seismic monitoring. In 5th Intl Symposium on Rockbursts and Seismicity in Mines, S. A. Inst. Min. Metall., pp. 389-395.

KIJKO, A., LASOCKI, A. and GRAHAM, G. (1998) Quantification of Seismic Hazard from Seismic Events in Mines. SIMRAC GAP517.

KLOKOW, J.W., RIEMER, K.L. and FERREIRA, R.I. (2003) An initial assessment of the closely spaced dip – pillar mining layout as practiced at Driefontein Gold Mine. In ISRM 2003- Technology roadmap for rock mechanics, S. A. Inst. Min. Metall..

RICHARDSON, E. and JORDAN, T.J. (2002). Seismicity in deep gold mines of South Africa: Implications for tectonic earthquakes, Bull. Seism. Soc. Amer., 92: pp. 1766-1782.

RYDER J. A and JAGER A. J. editors (2002): A textbook on Rock Mechanics for tabular hard rock mines. 1st Edition, SIMRAC: Johannesburg.

SPOTTISWOODE, S.M. and DE BEER, W. (1999) A review of current seismic prediction and hazard assessment practice and capability, Final Report for Deepmine Project No 5.4.1.

SPOTTISWOODE, S.M. (2001) Keynote address: Synthetic seismicity mimics observed seismicity in deep tabular mines. In *5th Intl Symposium on Rockbursts and Seismicity in Mines*, S. A. Inst. Min. Metall., pp. 371-378.

SPOTTISWOODE, S.M. (2004) A seismic and modelling analysis of dip-pillar mining. 2nd International Seminar on Deep and High Stress Mining, S. Afr. Inst. of Min. Metall., pp. 67-78

SPOTTISWOODE, S.M. (2004) Mine layout design and medium-term prediction of seismicity, submitted to *6th Intl Symposium on Rockbursts and Seismicity in Mines*.

SPOTTISWOODE, S.M. (2004) A seismic and modelling analysis of dip-pillar mining. 2nd International Seminar on

VAN ANTWERPEN, H.E.F. and SPENGLER, M.G. (1982) The effect of mining-related seismicity on excavations at East Rand Propriety Mines, Limited. In 1st Intl. Symposium on Rockbursts and Seismicity in Mines, Johannesburg, S. Afr. Inst. of Min. Metall : pp. 29-37.