

Safety in Mines Research Advisory Committee

Final Project Report

Software tool for managing rock related hazards in South African mines

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Executive Summary

The objective of the project was to develop a software tool for the assessment of rock engineering (RE) risk based on the concept proposed in GAP 608 and to evaluate the software with real mine data from a deep level gold mine and a platinum mine.

Hazard is a physical situation, object or condition, which, under specific circumstances has the potential to cause harm, whereas risk is a measure of the likelihood that some specific harm, arising from an incident (a particular hazard), will occur.

The generic equation:

$$\text{Risk} = \text{Hazard} * \text{Vulnerability}$$

was, in this case, extended to:

$$\text{Risk} = \text{Seismic Hazard} * \text{Induced physical hazard} * \text{Systemic Vulnerability}$$

(Induced physical hazard = triggered by the ground motion; support failure; fall of ground.

Systemic Vulnerability = Exposure of people; economic vulnerability; quality of information.)

RE risk as defined in GAP 608 is a function of the potential ground motion; the vulnerability of the workplace; exposure of people; and a general term – quality of information.

The deliverable of this project is a prototype software package that is a combination between an expert system approach for determining overall risk assessment, a risk control recommendation and a basic GIS (Graphic Information System) approach for graphically overlying input parameters and the output risk. The expert system uses a Bayesian probabilistic approach to combine various workplace-related information, a quantified seismological environment and exposure of underground staff to provide an overall RE risk rating. The risk assessment is dynamic in that it is recalculated each time any input parameters change, for example each time a seismic event is recorded in the area of interest.

The code was tested on a data set from Savuka Gold Mine and Northam Platinum Mine. As risk assessment is not an absolute prediction it is therefore not possible to relate to individual case studies and the reliability of this method would only be determined after an extensive period of use.

Acknowledgements

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Malcolm Drummond from GeoVision is acknowledged for his contribution in developing the visualization platform for this project. There are components of the software that he retained all the rights thereof.

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1 Seismic and Rock Engineering Risk Assessment – An Overview

1.1 Introduction

A number of SIMRAC projects have addressed the issue of hazard/risk in gold and platinum mines and with the specific emphasis on the hazard/risk posed by rock-related incidents. Often the distinctions between hazard and risk were unclear. This project strived towards the development of a tool to assist in the assessment and management of seismic and rock engineering risk in general. All the earlier projects contributed towards the knowledge base used for the development of the risk assessment tool and will be referenced throughout the report. It is appropriate at this stage to list these projects and to give a short synopsis of their respective contributions.

SIMRAC GAP 112 – A. Cichowicz (1997), Abbreviated title – Develop a means of assessing safety risk due to rockbursts and rockfalls.

Applicable results extracted from the final report – GAP112.. "showed that damage is not only controlled by the magnitude and distance between a seismic source and panel but also other factors. Seismic events with large magnitudes (or seismic moments) and large source size can be less damaging than seismic sources with similar magnitudes but smaller source sizes. Damaging seismic events are characterised by very large stress drops. The average stress drop for all seismograms is 6.8 MPa, while the average stress drop of a damaging event is 17 MPa. The fact that peak ground velocities as small as 0.005 m/s can cause damage - is a striking feature.

Statistical analysis of falls of ground shows that panels with no geological features represent a more stable system than panels with geological features.

The seismic, geological and mining features are the prominent attributes of the risk forecasting in a stope face. For all those features the rating and the important factors are computed. To test the accuracy of the constructed hierarchy, priority values obtained from expert opinions have been compared with data from the mine.

Essential discrepancy occurs only in the interpretation of risk in geologically undisturbed panels along a pillar. "

Although GAP 112 was the first risk-related SIMRAC project it did look at a broader approach towards risk assessment and also initiated the use of artificial intelligence in risk management.

SIMRAC GAP 225 Tripartite Working Group on Risk Assessment

Applicable results extracted from the final report – This group provided a practical guide to the risk assessment process and listed the following steps for effective risk assessment:

- Make sure the risk assessment process is practical and realistic.
- Involve as many people as possible in the process, especially those at risk and their representatives.
- Use a systematic approach to ensure that all risks and hazards are adequately addressed.
- Aim to identify the major risks; don't waste time on the minor risks, don't obscure the process in too much detail.
- Gather all the information you can and analysis it as well as possible before starting the risk assessment.
- Start by identifying the hazards.
- Assess the risks arising from those hazards, taking into account the effectiveness of the existing controls
- Look at what actually occurs and exists in the workplace and, in particular, include non-routine operations.
- Always keep a written record of the assessment, including all assumptions you make, and the reasons for those assumptions.

SIMRAC GAP 303 G Van Aswegen & AJ Mendecki (1999) Title: Mine layout, geological features and seismic hazard

Applicable results extracted from the final report – “There are a number of factors that correlate positively with the potential for large(r) dynamic rock mass instability in response to deep level mining, e.g.:

- tectonic stresses, depth, mechanical strength of intact rock,
- the existence and the frequency of intermediate and larger geological features, specifically when parallel to the excavation faces and/or when their shear strength is comparable to shear stresses close to excavations,
- longwall type mine layout (as opposed to scattered mining layouts) without regional support (stabilising pillars, backfill) and with straight face shapes,
- concentrated mining, i.e. the proximity of a number of active faces excavating a large volume of rock,
- volume mined to date,
- mining remnants against seismically active structures,
- rate of face advance, etc.”

Stiffness and hazard: The following unique observations made during this project contributed towards the development of an improved mine layout

design methodology and the new interpretation of seismic data to confirm the design as mining progresses.

- The d-value, determining the slope of the log E vs. log M, called here E-M relation, tends to increase with the system stiffness. The E-M plot for the stiff system does not extend far into the large(r) events range until the stiffness is degraded and the d-value drops. For a given slope an increase in c-value of the E-M relation reflects an increase in stress.
- The power exponent of the size distribution of seismic events, called also the b-value of the Gutenberg-Richter relation, positively correlates with the stiffness of the system, i.e. the stiffer the system the higher the b-value and the lower the size distribution hazard -
- In general stiffer systems/layouts are characterised by lower M_{max} but by a time-of-day distribution with larger statistical dispersion in relation to the time of blasting, thus they are less time-predictable, while softer systems have larger M_{max} but they trigger or induce most events during the few hours after blasting.”

SIMRAC GAP 339, W.A Naismith, 1998, Risk assessment for Rock Engineering

This report suggested methods of hazard identification and risk assessment and presented guidelines for a practical and structured hazard identification methodology. The researcher identified the interaction between two or more hazards along with their causes and consequences. He also recognised ‘passive and ‘active’ hazards, where ‘passive’ hazards exist as a result of nature or previous activities. ‘Active’ hazards exist as a consequence of any current or proposed mining activity.

SIMRAC GAP 409, W. de Beer, 2000, Seismology for rockburst prediction

De Beer concentrated on the predictability of rockbursts. He presented a method for predicting larger mining induced seismic events in gold mines. This predictor, based on accelerating seismic release, depends on the existence of sufficient data, a past history in an area, and power law accelerating behaviour of a seismic time series. He concluded that:

- Simple, quantitative examples serve to illustrate that seismicity is not a random phenomenon and therefore not somehow inherently unpredictable.
- Temporal patterns in seismicity can be quantified.
- Abundant, quantitative evidence for criticality and deterministic, reasonable limits of predictability exists.
- The prediction algorithm can achieve uncertainties in the predicted time of occurrence of a large instability of less than a week.
- The prediction strategies followed are very far from random, and present a significant improvement, by a factor of about 4 over a pessimistic random forecasting strategy.

It is in particular the accelerating behaviour of a seismic time series that is used in this report as an indicator of seismic risk.

SIMRAC GAP 610, G. Van Aswegen, 2001 Evaluation of the risk to underground mine personnel due to the rockmass response to continuous mining operations.

Van Aswegen introduced a simplistic concept of Seismic Exposure (SE). He defines the hourly hazard as the average number of events greater than magnitude 1. The liability is the average number of workers during that hour. The average daily risk is the product of the hazard and the liability. The full risk for the period under consideration would be the daily SE multiplied by the number of working days. This may be normalised with production.

A similar concept for handling the exposure of the underground worker is adopted in this project.

1.2 Suggested procedure for evaluating seismic risk

The authors of this report had the opportunity to evaluate the various risk assessment methodologies and tools during their consultation with the industry. It was clear that the RE risk, and even seismic risk does not correspond exclusively to the few very large seismic events. Figure 1.1 shows the distribution of production shifts lost relative to the size of the damaging seismic events. It cannot, of course, be concluded that Mag 1,5 to 2,0 events are a greater hazard than a Mag 3,5 event, but that with their shorter re-occurrence time, the former, in fact, poses a greater risk.

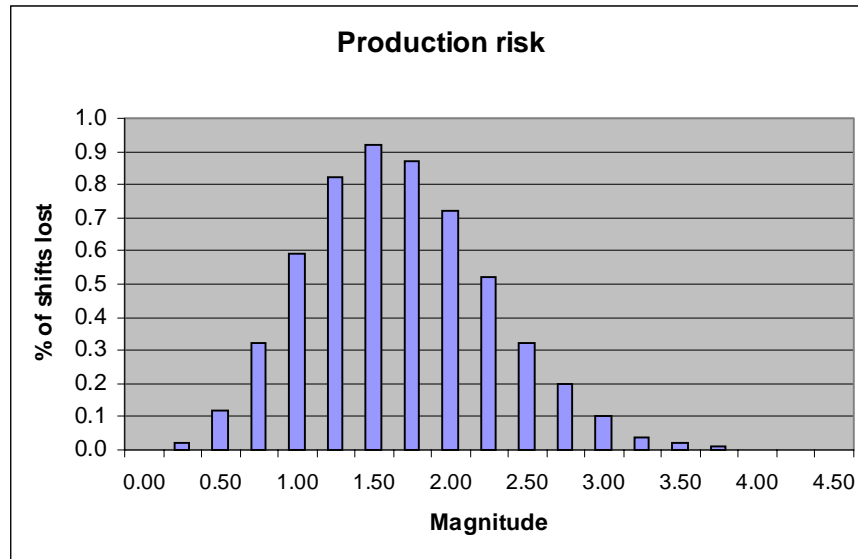


Figure 1.1 Production losses as result of seismicity as a function of the magnitude of the damaging seismic events. (from Lenhardt, 1998)

A fundamental problem with many risk assessment procedures is the degree of subjectivity involved. However, the researchers are confident that the holistic approach adopted in compiling the rating system proposed by Brink et al (2000), will provide a better assessment of seismic risk. It should be noted that this is presented as a conceptual approach and it would trigger significant debate on some detail. It is not implied that this approach is ready for implementation by the industry.

Brink et al (2000) summarise the proposed procedure for evaluation of seismic risk. The assessment is made in four categories, namely

- Level of Ground Motion
- Vulnerability of the Excavation to ground motion
- Exposure of people
- Quality of information

Each category has effectively the same relative importance or weighting.

An overall seismic risk assessment is achieved by combining individual category ratings. The process of achieving a single rating is discussed later.

Each category is subdivided in various parameters contributing to that category. The parameters are rated individually and averaged to provide a category rating. A risk rating ranges from 1 to 5, where 1 implies a very low risk and 5 an always-unacceptably high risk.

Table 1.2.1 The proposed risk assessment methodology as set out in GAP 608

Rating	Risk Assessment Category	Parameter	Parameter rating
P ₁	Level of Ground Motion	M _{max}	p ₁
		Distance from source	p ₂
		Mean Return Time (Frequency) Seismic/Time Distribution	p ₃
P ₂	Vulnerability of Excavation to Ground Motion (or Falls of Ground)	ERR	p ₁
		Geology	p ₂
		Support	p ₃
		Ground condition	p ₄
		Escape ways	p ₅
		(Site Effect Amplification)	(p ₆)
P ₃	Exposure of people	People/Time distribution	p ₁
P ₄	Quality of Information	Mine plans/Structure/layout	p ₁
		Seismic Monitoring	p ₂
		Early Warning	p ₃
		Assessment interval and volume	p ₄
		Experience reference	p ₅
		Communication	p ₆

$$P_{\text{risk}} = f(P_1, P_2, P_3, P_4)$$

Possible 'real time' inputs to the risk assessment process are:

- Quantitative seismic information
- Mine's panel/stope ratings

- Mine geometry (face position)
- Numerical analyses output
- GMSI's risk database (IRMS2000)

2 An expert system approach as used in a coal mining application

2.1 Introduction

Brink and Newland, (2001) conducted a research project for the Australian Coal Association Research Program (ACARP) to automatically assess the risk of experiencing a windblast in a longwall-operated colliery. (For the purpose of this report the mine is called AusMine) The logical extension of the risk assessment was the automatic generation of an alarm should the risk exceed pre-determined risk levels.

The research done in the above project forms the basis of the expert system approach adopted in developing a software tool for managing the seismic risk in South African seismically active mines. The expert system determines the probability of a certain outcome, in the case of the ACARP research, a windblast within the next two hours.

2.2 Automatic assessment of the risk of a large instability in a coal mine

Well-understood conditions need to be present to experience windblasts of an intensity that can threaten the safety of the underground worker. These conditions include the geological configuration and the dimensions of the mining excavation (mine layout). Mine planning and operation constraints provide limited flexibility in preventing or controlling the occurrence of large goafs and subsequent windblasts. (Hatherly et al, 1997)

The ACARP project endeavoured to provide the methodology to automatically generate windblast early warning alarms. The concept was first coded into a threshold-based decision tree in an attempt to duplicate the decisions made by the on-site operator. Individual early warning parameters were tested. These parameters were: the precursive event rate; changes in the volume of coseismic inelastic strain (Apparent Volume); and the comparison of radiated energies of seismic events of similar moments. It was found that the precursive event rate was the most reliable parameter.

In order to show clearly that the seismic response to mining, as reflected by these seismic parameters, exhibits an early warning to a pending large instability in the roof, a probabilistic risk-assessment approach was developed and tested. An expert system philosophy was used as the basis for applying a probabilistic approach in risk assessment. The result was an early warning system more effective than the threshold-based decision tree concept and as effective as the full-time operator.

2.2.1 Description of a Suggested Stability Concept

In the handbook *Seismic Monitoring in Mines*, Mendecki (1997) summarizes a concept for stability in Figure 2.1.

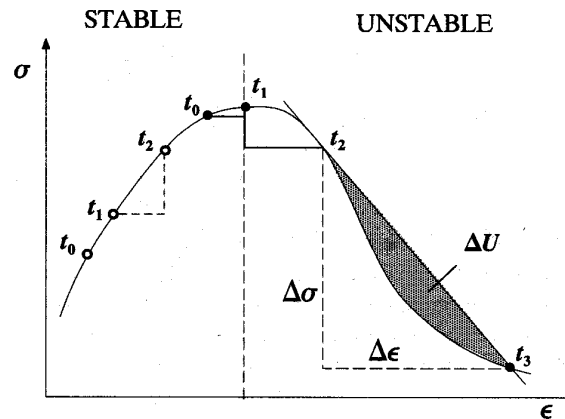


Figure 2.1 Typical stress-strain diagram of a rock sample (from Mendecki 1997)

For finite stress and strain departures from the current state at $t_1[*](t_1, \epsilon(t_1))$ to the next stage $t_2[*](t_2, \epsilon(t_2))$, the definition of instability of the volume element V is given in equation (2.2.1).

$$\int_{\Delta V}^{\epsilon(t_2)} [\sigma(t_2) - \sigma(t_1)] d\epsilon(t) dV < 0 \quad (2.2.1)$$

Mendecki implemented this stability concept in some South African gold mines by equating a softening process with the drop in Φ as observed in the Energy Index. Instability is inferred when an increase in coseismic deformation is associated with the decrease in Energy Index. The coseismic deformation is measured by the cumulative Apparent Volume $E)V_A$.

Mendecki (1997) also employs other parameters to observe the softening and coseismic deformation, such as seismic viscosity and seismic diffusion. These parameters could not be meaningfully employed at AusMine.

A number of researchers recorded a decrease in seismic activity at the beginning of the strain softening stage, followed by an increase in the rate of seismicity immediately prior to a large instability. (Brady, 1977, and Main et al., 1992.)

2.2.2 Application of Instability Parameters for the Early Warning of Large Goafing

The seismological parameters used at AusMine were Event Rate, Apparent Volume and Energy Index. Some procedures were developed to quantify changes in these

parameters and to relate their respective temporal behaviour to the recognition of an early alarm.

2.2.2.1 Event Rate

Event rate was defined as the number of events per 5-minute period. The effectiveness of this single parameter was tested against the total data set of seismic events and goaf falls for the period February 1998 to December 1999 at AusMine.

Figure 2.2 shows the number of events per time unit (or bin). In this case the bin size was 5-minutes and each bin had at least 1 event during that period. Should the warning threshold be 5 events or more per 5-minute period, 40 of the goaf falls would have been preceded by valid warnings, 12 would have been missed and 561 false alarms would have been issued. With an increased threshold of 7 events per 5 minutes or 10 events per 5 minutes the respective results in terms of valid, missed and false alarms are apparent from Figure 2.2. A valid warning is when a large goaf occurs within two hours after the warning.

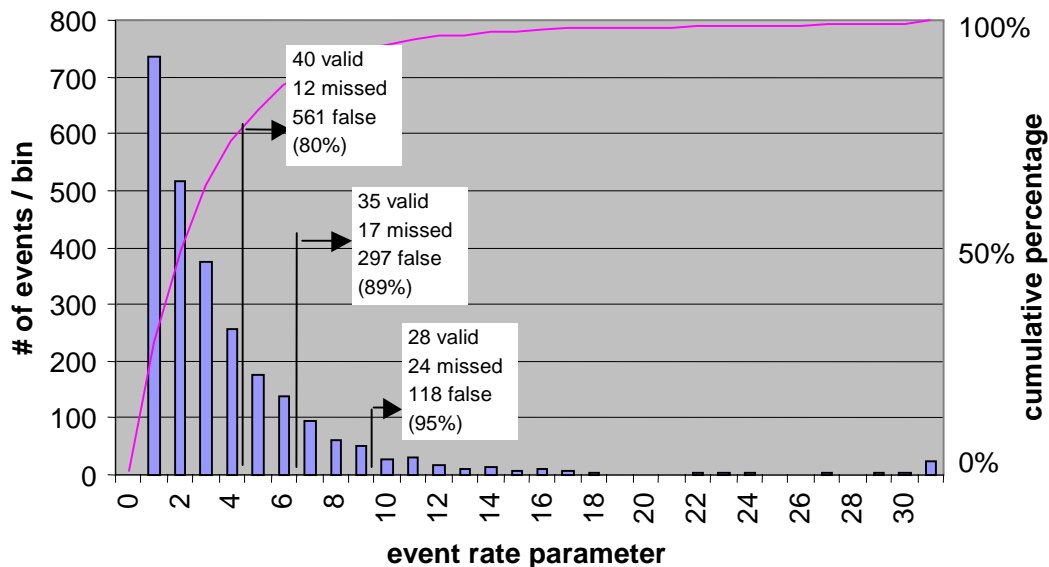


Figure 2.2 An indication of the effectiveness of Event Rate as an early warning parameter.

To test the above observation, a random time (drawn from a uniform random distribution with a range -6 to $+6$ hours) was added to each event time. A similar test of the effectiveness of Event Rate as an early warning indicator yielded 7 valid, 45 missed and 21 false alarms for a warning parameter of 5 events per 5-minute period.

2.2.2.2 Apparent Volume

Apparent Volume (Units m^3) is calculated as $V_A = M/(c_3\Phi_A) = M^2/(c_3 GE)$ where $c_3 = 2$ (a scaling factor), M is the seismic moment, Φ_A is the stress drop, G is the shear modulus and E is the released energy. The Apparent Volume relates to the volume of rock with coseismic inelastic strain.

Mendecki (1997) quantifies accelerated deformation through *accumulated* Apparent Volume, EV_A .

Figure 2.3 shows a histogram of 'short term / long term' Apparent Volume ratio. The ratio is calculated at each event occurrence and is the median of the Apparent Volume for the last 10 events divided by the median for the last 50 events. For a ratio of two, 30 valid warnings would have been issued with 23 falls missed and 645 false alarms.

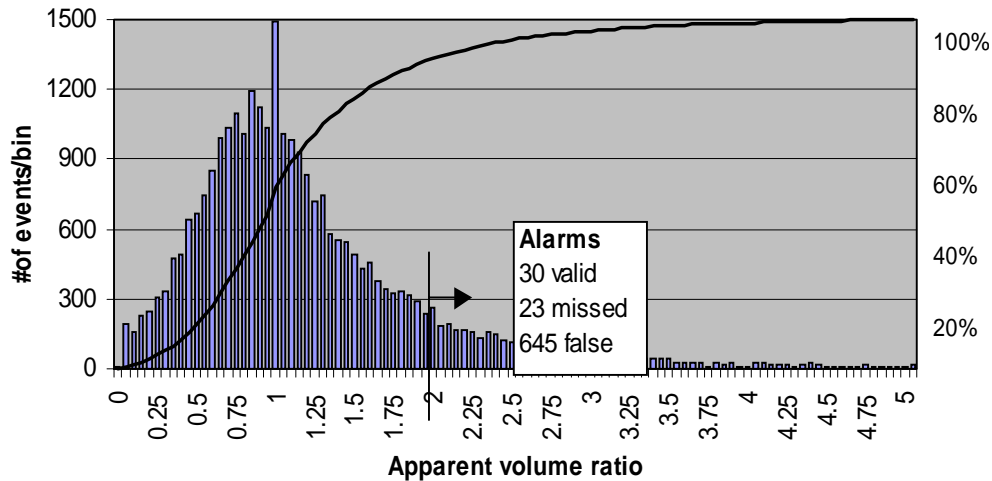


Figure 2.3 An indication of the effectiveness of Apparent Volume as an early warning parameter

2.2.2.3 Energy Index

The parameter Energy Index was also initiated by Mendecki, (1997) as a way of comparing radiated seismic energy from events of similar seismic moments. An event with Energy Index >1 would suggest a higher than average shear stress at its location. The opposite applies when Energy Index is < 1 .

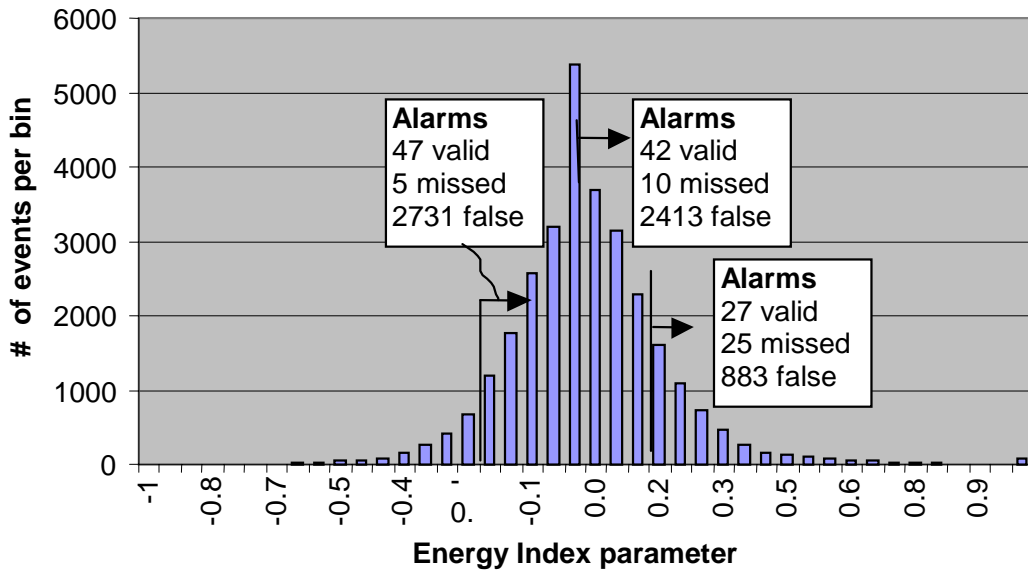


Figure 2.4 An indication of the effectiveness of Energy Index as an early warning parameter

From the stability concept, an increase in the Apparent Volume and an associated decrease in Energy Index were expected before instability. In Figure 2.4 the effectiveness of Energy Index alone in providing early warning is shown.

The methodology employed to quantify the temporal changes in Energy Index is similar to Apparent Volume, and a 'short term / long term' approach is used in comparing the respective median value from 10 and 50 preceding events. In terms of Energy Index the difference between the long-term median and the short-term median is calculated. (A positive difference will be observed with a short-term decrease in Energy Index.)

2.2.3 Development of a Threshold-Based Decision Tree

The initial approach for providing early warning of large goafing at AusMine was the implementation of a threshold-based decision tree. A basic schematic presentation of such a process is given in Figure 2.5.

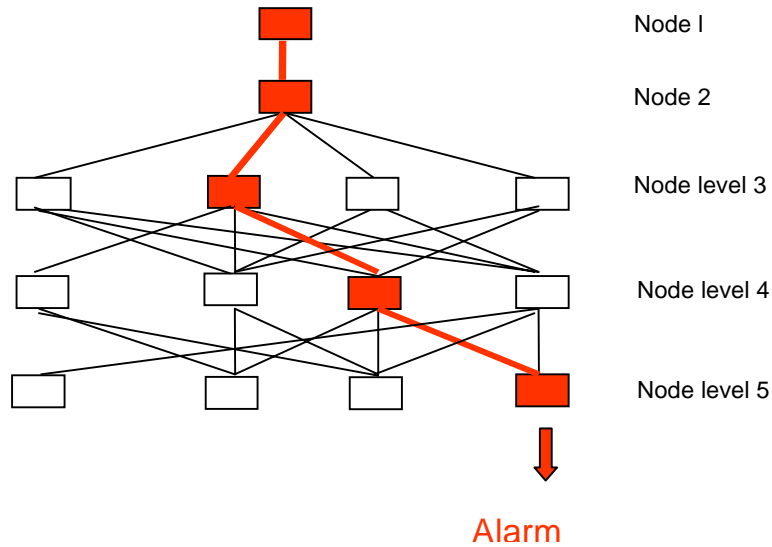


Figure 2.5 A basic alarm decision tree where certain predetermined conditions should be met before an alarm is generated

The decision-making process for early warning at AusMine can be described as a decision tree. Each node is effectively a test whether a threshold was exceeded or whether a specific condition existed.

To illustrate the process, the 1st node could be whether anyone at that time is exposed to the risk of windblast. The 2nd node will be whether more than 20 m of roof are standing, and if more than 20 m, how much roof is hanging? Depending on this answer the next layer of nodes will be selected where questions such as the seismological parameters would be asked. The level of risk already contributed by earlier nodes will determine the way that the system would respond to these questions. 20-metre roof hanging may be perceived as lower risk than 50-metre of roof hanging and, therefore, allow for a less conservative requirement at the next level. Only certain combinations of conditions or responses can lead to an alarm.

At AusMine each node can change independently and the alarm is issued when the preset conditions are met. The process described above is a sequential decision-making process. AusMine required a dynamic and parallel decision-making process.

Early warning parameters

The parameters and threshold used in the decision tree, and to a large degree by the AusMine operations, are as follows:

'Trend-based alarms'

- Event Rate
- Apparent Volume
- Energy Index
- Log₁₀ Schmidt number

'Trip switch alarms'

- More than 6 triggers in 10 sec
- More than 5 events (multi-triggered) in 60 sec
- More than 2 events larger than Magnitude –1 in 120 sec

In terms of the trend-based alarms, the operator's decision is subjective. It is also influenced by the perceived windblast risk in that he would more readily issue an alarm should a large amount of roof be standing.

'Trip switch alarms' is in most cases used as an imminent alarm with a typical warning time of seconds to about 2 minutes. This type of alarm was the basis for 32 out of the 49 valid alarms issued at AusMine between February 1998 and December 1999. The early recognition of precursive trends in the seismological behaviour of the rock mass was the basis of 15 out of the 49 valid warnings. The recognition of trends was never the exclusive basis for an alarm.

With only the trend analysis as basis for the decision-tree automatic alarm, 17 valid alarms out of the total of 52 falls would be achieved.

It was not possible to evaluate the effectiveness of the 'trip switch alarms', because the seismic-data base only includes accepted event triggers. A single site trigger would have been rejected.

2.2.3.1 Comments

A threshold-based decision tree for generating automatic windblast alarms was developed and tested. A similar performance to the performance an operator could achieve, would have been achieved with the threshold-based decision tree.

The fundamental problem with this approach is the rigid outcome that associates safe conditions with a threshold that is not exceeded and, similarly, a warning (an unsafe condition) should the threshold be exceeded. An associated problem is the possible arbitrary setting of thresholds. Such arbitrary setting of thresholds will tend to be conservative, resulting in an uneconomical number of false alarms.

A probabilistic assessment of the windblast risks promises to provide a more sound and quantifiable early-warning methodology.

2.2.4 Development of Probabilistic Risk Assessment Using an Expert System Philosophy

The expert system philosophy adopted for the ACARP project was based on Bayes' Theorem. The basic concept is that a hypothesis be developed that is tested against pieces of evidence. In this case a hypothesis was made that a large goaf would occur within the next 2 hours. A prior probability, $P(H)$, is set. This is the probability that a large goaf may occur within the next 2 hours (the probability of the hypothesis being true) without any knowledge of associated evidence.

The evidence associated with the hypothesis of a large goaf fall is that a high event rate will be observed. In this example the probability of observing the evidence, that is a high event rate, with the hypothesis being true, $p(E|H)$ is set at 75%. Similarly the

probability of observing the evidence, but with a hypothesis that is not true, $p(E|\sim H)$, is set at 2.88%.

Based on Bayes' Theorem, the probability of observing the hypothesis H if the evidence E has been observed is the probability $p(H|E)$:

$$p(H | E) = \frac{p(E | H)p(H)}{p(E | H)p(H) + p(E | \sim H)p(\sim H)} \quad (2.2.2)$$

($p(H)$ is the prior probability of the hypothesis being true and $p(\sim H)$ the prior probability of the hypothesis not being true).

Similarly, the probability of observing the hypothesis H if the evidence E has *not* been observed $p(H|\sim E)$:

$$p(H | \sim E) = \frac{p(\sim E | H)p(H)}{p(\sim E | H)p(H) + p(\sim E | \sim H)p(\sim H)} \quad (2.2.3)$$

The initial importance (or Rule Value) of each item of evidence is given as:

$$RV = | p(H | E) - p(H | \sim E) | \quad (2.2.4)$$

A typical expert system will have a number of possible hypotheses and more items of evidence that can be associated with these hypotheses. For the purpose of testing the hypothesis of a large goaf within the two hours that follow, the expert system only considers this single hypothesis, tested against the available items of evidence.

The main advantage of employing an expert-system philosophy is that it can cater for uncertainties. The earlier automatic alarm software was based on a decision-tree mechanism and only if predetermined thresholds were exceeded was an alarm possible.

The expert-system philosophy, from XMaster®, (Chris Naylor Research Limited, Naylor, 1998 and Naylor, 2000) allows for an actual response that is between a 'yes' and a 'no'.

It is possible to calculate a new posterior probability for each hypothesis, conditional upon the response.

$$p(H | R) = p(H | E)p(E | R) + P(H | \sim E)p(\sim E | R) \quad (2.2.5)$$

With a user response of 'yes' then $p(E|R)$ would be 1 because there would be certainty that the evidence had been identified. Similarly with a user response of 'no' then $p(E|R) = 0$ if there is certainty that the evidence had *not* been identified.

A 'do not know' will result in $p(E|R) = 0.5$ with all other situations resolved by interpolation.

The next step is to be able to calculate the final posterior probability of the hypothesis being true if various bits of evidence of various degrees of confidence are observed. The simplest approach is to calculate the final posterior probability by the successive application of the appropriate formulae for a single item of evidence to each of the items of evidence in turn.

Initially the hypothesis starts off with the given prior probability. This prior probability is updated by the application of one item of evidence, which may or may not be observed with a given degree of uncertainty, to produce a new posterior probability. This new posterior probability is then used as the new prior probability into a re-application of the same equation to the next item of evidence. The process continues in this way until all of the items of evidence have been accounted for.

2.2.4.1 The AusMine Expert System

An expert system is the ideal approach for a probabilistic approach towards windblast early warning. The data that is recorded is primarily the seismic waveforms. The seismic system provides the tools for converting this data to knowledge by extracting parameters that can provide precursory information on a pending large instability in the roof of the mined-out area.

Windblast risk, however, requires more than only the seismic knowledge. Knowledge of the amount of goaf hanging, the exposure of underground personnel, the vulnerability of underground staff in terms of their physical position within the mining geometry, and the nature of their protection gear can all assist in quantifying the risk of a windblast.

The approach taken is to assess the probability of a windblast occurring within a predetermined time. This is achieved by stating as a hypothesis that windblasts will occur within the two hours that follow. The parameters that the operator currently has at his disposal, namely goaf hanging and the precursive seismic parameters, are used as associated evidence.

The Hypothesis

A single hypothesis is used and it is stated that a windblast will occur within the next two hours. A period of two hours was chosen because of the initial operational decision at AusMine to stop production and to evacuate for a period of two hours after each alarm. A false alarm was recognised as such if the goafing did not occur within a period of two hours after the alarm. A similar criterion was used in the evaluation of the expert system approach.

Prior Probability

The prior probability, $p(H)$, is the probability of the hypothesis being true before anything is known about the evidence with which it might be associated. A total of 4752 periods of two hours each were recorded. During 32 of these two-hour periods, a significant fall occurred. Thus

$$\begin{aligned} p(H) &= \frac{32}{4752} \\ &= .0067 \end{aligned}$$

There is a probability of .0067 that a significant fall can happen during any two-hour period.

The Evidence

A number of items of evidence were used as being associated with the hypothesis that a windblast will happen within the next two hours. For every item of evidence the following two parameters should be estimated, namely: $p(E|H)$, the probability of observing the evidence E if the hypothesis is true, and $p(E|\sim H)$, the probability of observing the evidence E if the hypothesis is false.

A known $p(H)$, $p(E|H)$ and $p(E|\sim H)$ in equation (2.2.2), will yield $p(H|E)$, the probability of observing hypothesis H if the evidence E has been observed.

Amount of Goaf Hanging

The amount of goaf hanging over the period February 1998 to February 1999 is shown in Figure 2.6. This figure shows the effect of the roof hanging until a significant fall can be seen.



Figure 2.6 An indication of the amount of goaf hanging for the period Feb 1998 to Feb 1999

The total period of time monitored was 396 days, equating to 4752 two-hour periods. The accumulated period during which there was more than 30 m of goaf hanging is 210 days (2520 two-hour periods).

In the data set covering the period Feb 1998 to Feb 1999, a total of 32 significant falls occurred. (A significant fall is a fall that could have resulted in a windblast.) In the data set 25 falls occurred when more that 30 m of goaf were standing.

The probability of observing the evidence E if the hypothesis is true,

$$p(E|H) = \frac{25}{32}$$

$$= 0.781$$

Similarly, the number of two-hour periods during which more than 30 m of goaf was hanging, without a significant fall can be extracted from the data. Therefore, the probability of observing the evidence E if the hypothesis is false:

$$p(E|\sim H) = \frac{2520 - 32}{4752 - 32}$$

$$= 0.526$$

Values for a 100% confident 'yes' answer is set at 30 m of goaf hanging, and for a 100% confident 'no' answer a value of 10 m of goaf hanging is set. This will imply that a significant fall, in terms of its potential to result in a windblast, cannot occur with less than 10m of goaf hanging.

To summarise, the input parameters contributed by the amount of goaf hanging towards the overall probability of the hypothesis of a significant fall within two hours being true, are: -

$$p(E|H) = 0.781$$

$$p(E|\sim H) = 0.523$$

$$R_{yes} = 30$$

$$R_{no} = 10$$

From equations (2.2.2), (2.2.3) and (2.2.4) the importance of this evidence with respect to the hypothesis can be calculated as:

$$RV = 0.0061$$

This item of evidence that, should it be observed, would have an importance of the above RV (Rule Value). The Rule Value is very low, therefore, the *amount of roof hanging* is of little importance as an early warning parameter. At best it would reduce false alarms when an alarm condition should be recognised with a small amount of roof hanging. The reason for a low level of importance is that a large number of two-hour periods were observed when no falls occurred. ($p(E|\sim H)$ is high.)

Event Rate

A similar process to that explained above is followed to quantify Event Rate as an item of evidence.

In the data set (February 1998 to February 1999) 24 out of the total of 32 significant events were preceded by an event rate of at least five events in five minutes. The probability of observing the evidence (high event rate) if the hypothesis of a significant fall in two hours, is true,

$$p(E|H) = \frac{24}{32}$$

$$= 0.75$$

The number of two-hour periods during which more than five events per five minutes were observed, without a significant fall, is 70. Therefore, the probability of observing the evidence (high event rate) with no significant falls is:

$$p(E|\sim H) = \frac{70}{4752 - 32}$$

$$= 0.015$$

The values for a 100% confident 'yes' answer is set at five events per five minutes and a 'no' answer is set at 1. The minimum activity rate observed before a significant fall was two events per five-minute period.

A summary of the input values relating to Event Rate is:

$$\begin{aligned}p(E|H) &= 0.75 \\p(E|\sim H) &= 0.015 \\R_{yes} &= 5 \\R_{no} &= 1\end{aligned}$$

Again from equations (2.2.2), (2.2.3) and (2.2.4) the importance of this evidence with respect to the hypothesis can be calculated as:

$$RV = 0.22$$

This will prove to be the most reliable parameter and this relatively high level of importance shows it.

Apparent Volume

The methodology for observing changes in the Apparent Volume was an observation of the changes in the median value of Apparent Volume in the short term (10 events) over the median value of Apparent Volume over a longer term (50 events). The effectiveness of Apparent Volume as an early warning parameter was shown in Figure 2.3.

By following a similar procedure to that described above, the following summary of the input values relating to Apparent Volume is obtained:

$$\begin{aligned}p(E|H) &= 0.55 \\p(E|\sim H) &= 0.138 \\R_{yes} &= 2 \\R_{no} &= 0.8\end{aligned}$$

The importance of this evidence with respect to the hypothesis is calculated as:

$$RV = 0.02,$$

which is again a low value and what could have been expected from the high level of false alarms as shown in Figure 2.3.

Energy Index

The methodology for observing changes in the Energy Index was the observation of the changes in the median value of the Energy Index in the short term (10 events) over the median value of the Energy Index over a longer term (50 events). The effectiveness of Energy Index as early warning parameter was shown in Figure 2.4.

By following a similar procedure to that described above, the following summary of the input values relating to Energy Index is obtained:

$$\begin{aligned}p(E|H) &= 0.535 \\p(E|\sim H) &= 0.147 \\R_{yes} &= 0.15 \\R_{no} &= 0\end{aligned}$$

The importance of this evidence with respect to the hypothesis is calculated as:

$$RV = 0.018,$$

which is also a low value and relates well to the high level of false alarms.

2.2.5 Evaluation Of An Expert-System Approach Towards Assessing The Probability Of A Windblast

The input parameters used for the AusMine expert system were the amount of goaf standing; the Event Rate; Apparent Volume and Energy Index. The input parameters were coded using Bayes' Theorem and allows for uncertainty as described by Naylor (1998, 2000).

2.2.5.1 Evaluation methodology

A comprehensive evaluation process was developed. The 'database' comprised the following:

- all the processed seismic events;
- the amount of roof standing at any time;
- all incidents of goafing;
- and all the alarms issued by the operators.

An operational decision at AusMine to evacuate the face for two hours subsequent to an alarm been issued, formed the basis for the evaluation of the expert system. A warning was deemed to be valid, should a significant fall occur in the next two hours. It must be appreciated that the data includes periods where the operator did evacuate the mine and that the evaluation technique did not treat these periods any differently from normal stoppages. Similarly an alarm condition recognised by the evaluation methodology did not necessarily result in the mining process stopping. Such a problem is fundamental in any 'hindsight' early warning.

The evaluation process will determine the risk level each time that an event happens. The process has no knowledge of future events. Should an alarm be issued, the process will continue for two hours or the 1st significant fall, whichever comes first. Depending on which is first, the warning will be flagged as a valid warning or a false warning. Should a significant fall occur without a warning in the preceding 2 hours, the fall will be flagged as missed.

2.2.5.2 Evaluation of results

Routines were developed to continuously display any number of early-warning parameters. (Brink and Newland, 2001) The idea was to allow the operator, in a 'VCR-mode', to fast forward from some historic starting point and review the response of early-warning parameters to the mining process. A 'snap shot' is shown in Figure 2.7. The input parameters are displayed on the left as the previous 50 values plotted on a time axis, the centre display is the overall probability shown over the last 50 incidents. On the right is an indicator bar with the different alarm levels shown. This was the display 4 minutes prior to a large goaf.

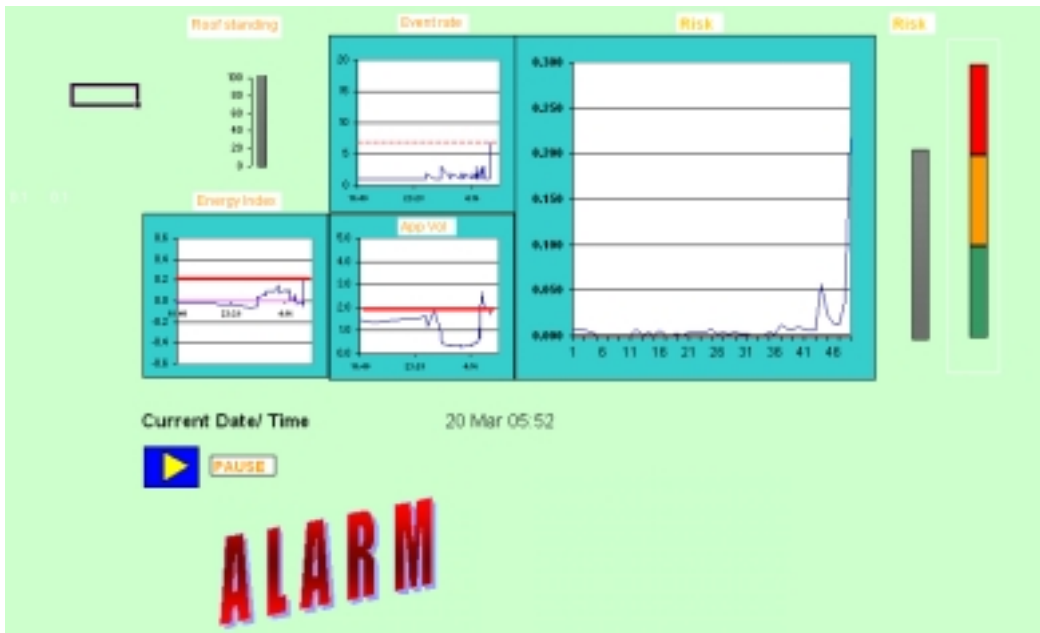


Figure 2.7 A continuous display of the probability of large goaf. Display as at 4 minutes prior to a large goaf

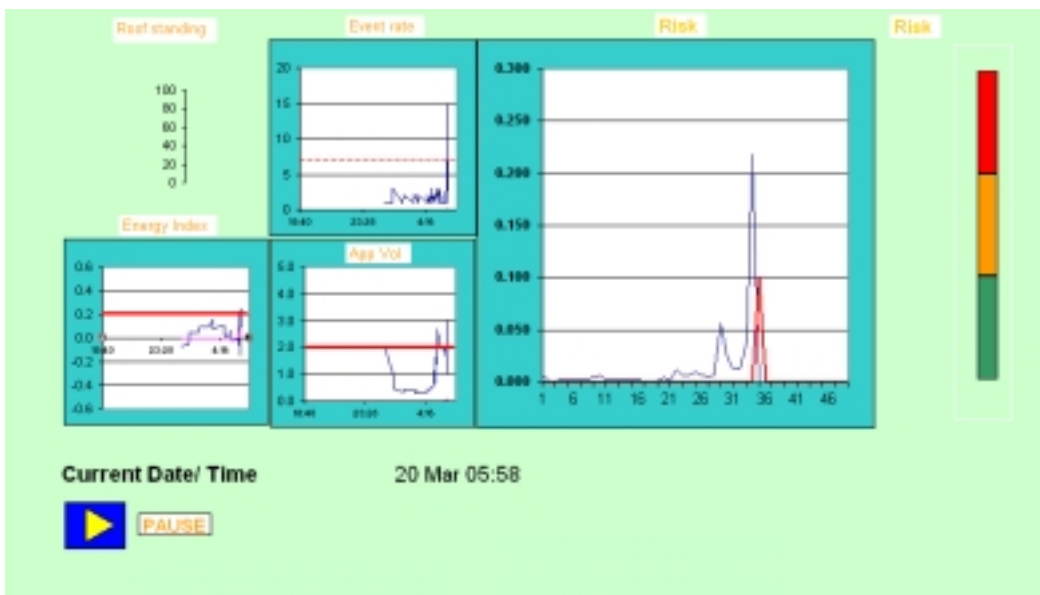


Figure 2.8 Same in Figure 2.7 but about 2 minute after the goaf. Note that the roof standing is now zero and therefore that there is also no probability of another goaf at this time

For the period February 1998 to November 1999, the operator issued 49 valid alarms out of 58 large goaf falls. This is an 84% success rate. During the same time 406 false alarms were given, potentially resulting in approximately 800 hours of production lost.

The probabilistic risk assessment through an expert system achieved 34 alarms out of the 58 falls. (a success rate of 58%). Only 104 false alarms would have been issued. It must be noted that the expert system made its assessment exclusively on

processed seismic data. The data set did not allow the testing of the methodology within the 60 seconds preceding a large goaf. The reasons were that a common time base was not used to log the time of the fall. A more important factor was that the operator used the 'trip switch alarm' for 32 of the warnings. These were short-term alarms and 12 of the alarms were based on triggers of individual sites (not seismically processed and therefore not in the seismic database).

2.3 Conclusions

An expert system approach is proven to be effective for the assessment of rock related risk in a coal environment. A possible reason for the success achieved in coal could be the simple and repetitive failure process associated with goafing. A typical deep hard rock mine experiences diverse modes of failure in the rock mass and these failures are most often not recursively recognised.

3 Implementation of an expert system approach of the risk assessment concept as suggested in GAP608

3.1 Introduction

This chapter describes the implementation of an expert system approach as demonstrated in Chapter 2. The parameters describing the potential and level of ground motion that an excavation can be subjected to and the vulnerability of the excavation, are combined through a probabilistic approach. The exposure and quality of data are used as weighting factors.

The earlier SIMRAC work as summarised in Chapter 1, described numerous RE hazard/risk parameters. The seismic research specifically resulted in parameters that were developed in the quest for rock burst prediction. This project did not intend to provide a new prediction methodology, but a concept and prototype tool for assessing the overall RE risk.

To achieve this objective any parameter that can be shown to be relevant evidence that a specific hypothesis be true, should be considered. The hypothesis in this case is that a rock related incident with the potential to cause injuries/fatalities might occur within the next shift.

With parameters already described in the referred SIMRAC research, the following input parameters should also be introduced.

3.1.1 Peak ground motion as an risk indicator of possible rockburst damage

The design criterion for support is currently based on its ability to absorb the kinetic energy associated with a certain thickness (H) of hangingwall and density ρ , that is moving downwards at a take-off velocity, v . The hanging wall must then be stopped within a distance h . The energy required to absorb the potential and kinetic energy, in Joules / m^2 , is then:

$$E = \rho.H.(g.h + \frac{1}{2}.v^2) \quad (3.1.1)$$

“h” is generally taken as 0.2 m.

When $v^2 > 2.g.h$, more kinetic than potential energy must be absorbed. This occurs when $v > 2 \text{ m/s}$. As the kinetic energy is proportional to v^2 and its effect on support

design against rockbursts increases strongly for $v > 2$ m/s, it is critical to be able to estimate the probability of encountering peak ground velocities in excess of 2 m/s. As we have very few actual measurements in this range, we need to consider models that extrapolate observations made using mine-wide seismic systems.

In this section, we present a model of peak ground velocities in the near to far field and apply it to data from a deep level mine. A picture of the historical occurrence of ground motions is currently the end result of this analysis. Some suggestions are made for providing a comprehensive picture of likely risk.

3.1.1.1 Assumptions

We assume that:

- all seismic events occur on Brune-type circular slip zones in plan around each event location.
- the ground motions are well described by McGarr (1991), but with one alteration motivated here.
- the rock mass is elastic and homogeneous. Site effects and amplification at the skin of the stope are neglected.

Future seismicity is likely to be similar to historical seismicity. This can obviously be qualified by considering likely changes as new mining layouts encounter new geological features.

Models of seismic sources generally consider strong ground motion either in the near field or in the far field. In the near field, the peak velocity is

$$v_N = V_S \Delta\sigma / G \quad (3.1.2)$$

where v_N = near-field ground motion,

V_S = shear-wave velocity,

$\Delta\sigma$ = static stress drop,

and G = modulus of rigidity

Similarly, in the far field, (McGarr, 1991, equation 38), we have the following:

$$Rv_F = f_{\theta\phi} V_S \Delta\sigma r_0 / G \quad (3.1.3)$$

where $f_{\theta\phi}$ = radiation pattern for S waves

and r_0 = source radius

McGarr used the median value of $f_{\theta\phi} = 0.57$. Using the most conservative value, namely $f_{\theta\phi} = 1.0$, we have $v_N = v_F$ at $R = r_0$. Equations (3.1.2) and (3.1.3) collapse into a single equation:

$$v = (V_s \Delta \sigma / G) \quad \text{for } R \leq r_0 \quad (3.1.4)$$

$$= (V_s \Delta \sigma / G) * (r_0 / R) \quad \text{for } R > r_0$$

By considering the circular source in the X-Y plane, $r_0 = \sqrt{(x_0^2 + y_0^2)}$, we can define the hypocentral distance "R" in terms of elliptical functions around this source as:

$$R' = (\sqrt{((r-r_0)^2 + z^2)} + \sqrt{((r+r_0)^2 + z^2)}) / 2 \quad (3.1.5)$$

and the peak velocity can then be expressed as a single equation:

$$v = (V_s \Delta \sigma / G) * (r_0 / R') \quad (3.1.6)$$

3.1.1.2 Implementation

Figure 3.1 shows an example of the implementation of peak ground motion as a risk parameter. A grid with a resolution of 25 m was placed over the selected area. (Figure 3.1 specifically shows an area on the VCR).

At each grid element all the seismicity in the area is evaluated for its respective peak ground motion at that point. An arbitrary threshold (say .1m/s) is set. The number of times that a grid element experiences a ground motion of more than the threshold, is logged. It is clear that the highest values are experienced at the current face position. It is assumed that each grid element is in fact in an excavation and a multiplication factor of 3 is used to allow for site amplification.

Peak ground motion and the number of times that an excavation experience significant ground motion can be linked to physical damage in the excavation (Andersen et al, (1999)).

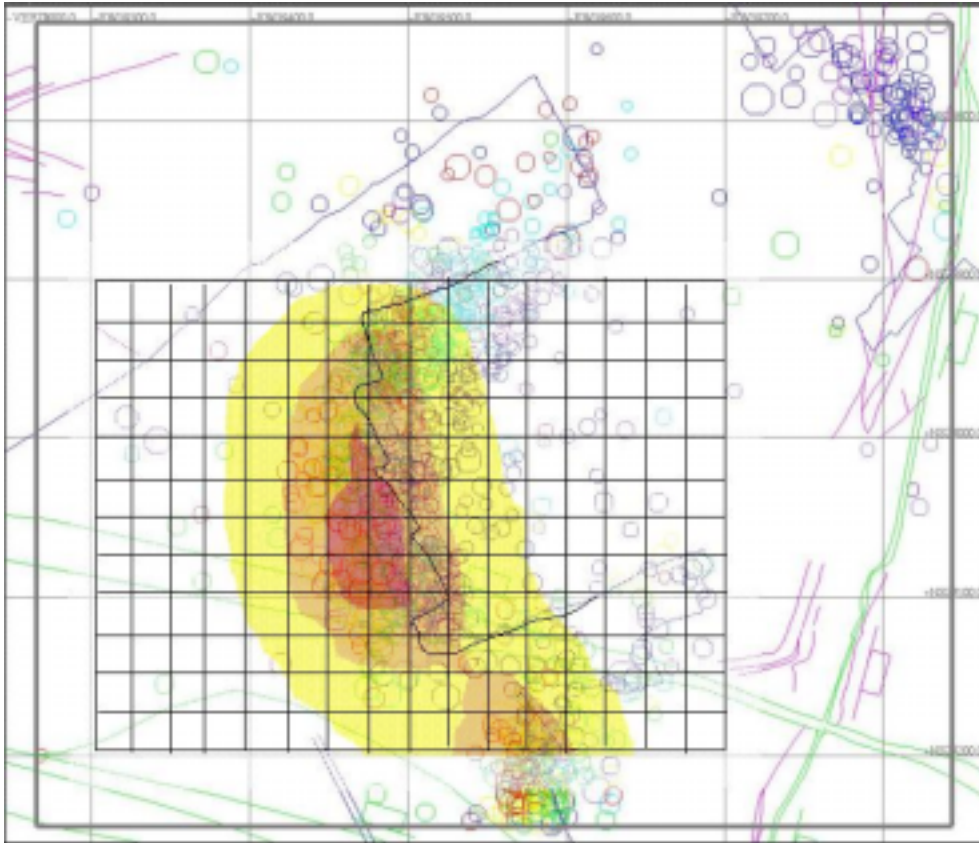


Figure 3.1 An area on the VCR used to demonstrate the application of a grid system to determine the number of times that the peak ground motion exceeds a preset threshold value.

The comparisons between the normalised data sets from the three respective mining areas are shown in Figure 3.2.

The implication is that, with broad assumptions, the risk posed by ground motion resulting from seismicity at Northam, is approx. 6 times less than comparable mining on the VCR and more that 12 times less that mining at depth on the Carbon Leader Reef in the Far West Rand.

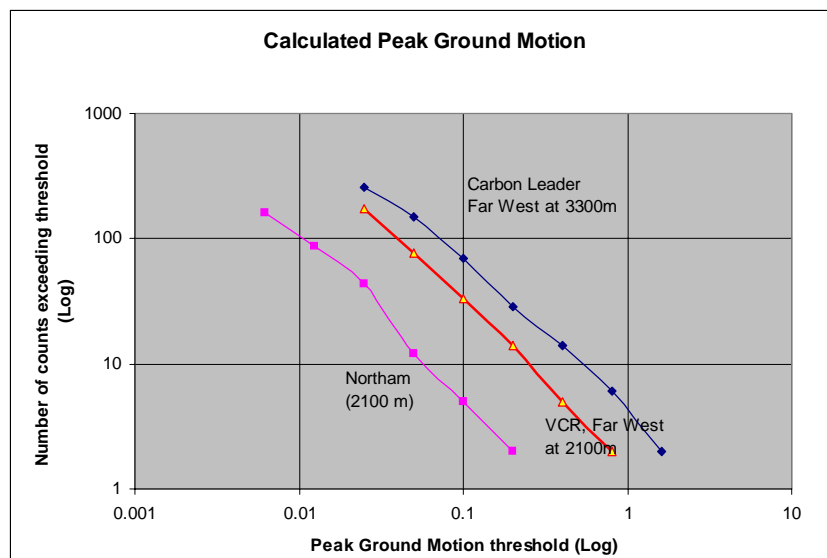


Figure 3.2 A comparison of the observed number of times that a peak ground motion threshold is exceeded.

4 Development of a software tool for risk assessment

4.1 Introduction

The objective was to develop computer code that would integrate various seismic and non-seismic hazard/risk parameters in a single risk assessment. A further objective was to facilitate this integration through an expert system approach.

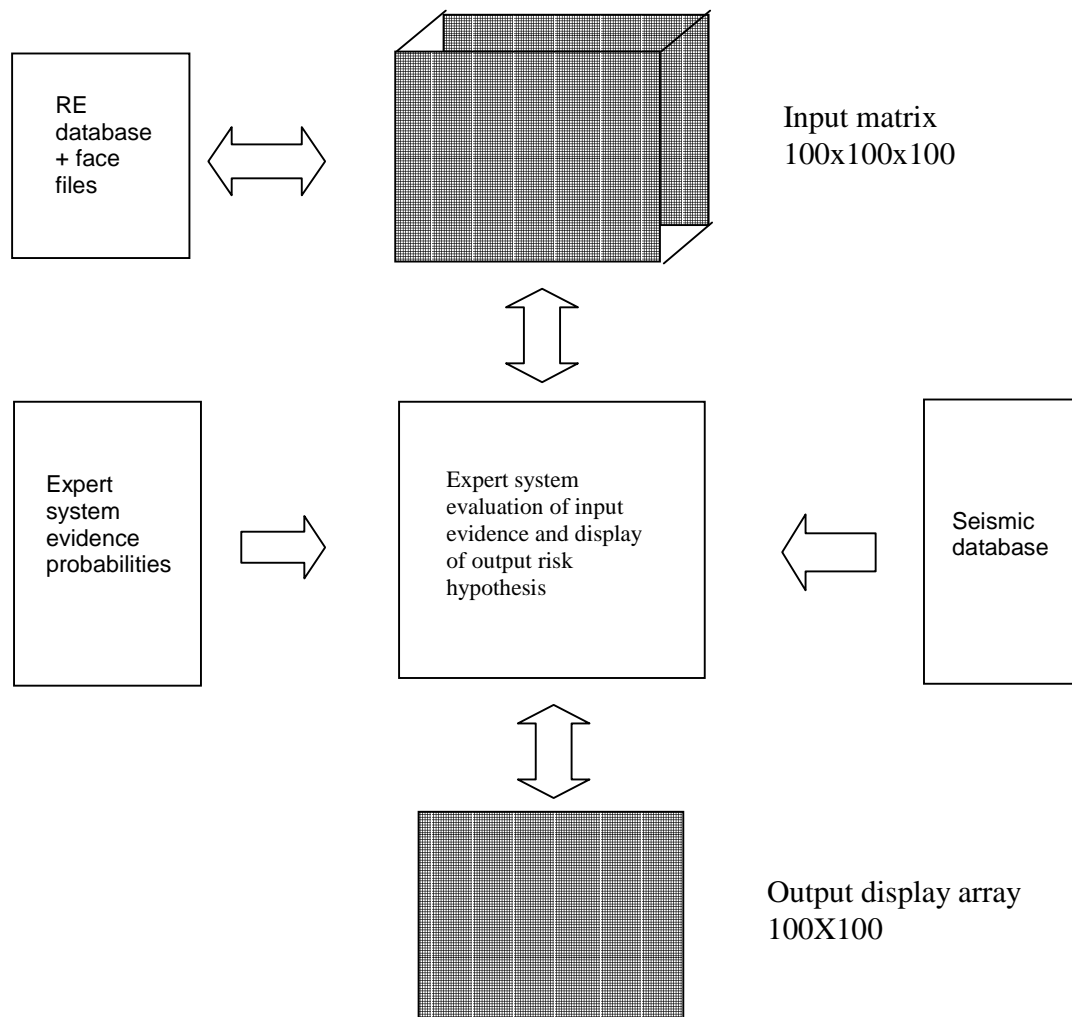


Figure 4.1 A schematic of the integrated approach towards risk assessment.

Figure 4.1 demonstrates the approach used in the development of the code for RE risk assessment. The non-seismic, or general rock mechanics, data tends to be linked to face names rather than geographic positions. Similarly, the seismic data is

purely geographical, with no links to the actual face name. It was necessary to adopt a GIS (Graphic Information System) methodology to easily link different inputs.

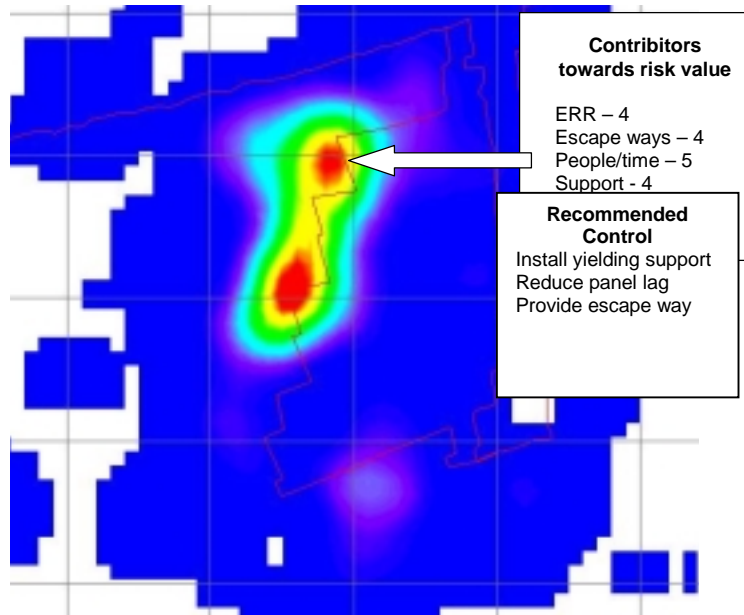


Figure 4.2 The planned output visualisation of the overall RE risk with the ability to report on the parameters contributing to the particular risk level and the recommended control measures.

Basically, the mining configuration is overlain with a 1 km x 1 km grid with a grid resolution of 10m x 10m. Each grid element has its own attributes describing the various static risk conditions (typically the conditions describing the vulnerability of the excavation) and the dynamic conditions (parameters describing the seismicity as experienced at that specific grid element).

Each grid element allows for 100 attributes per grid element. The software therefore has to manage an overall risk matrix with dimensions of 100x100x100.

Figure 4.2 shows the planned user interface. The calculation and display of RE risk are limited to a relatively small area, typically a mine overseer's section.

4.2 Description of various software components

The different components of the risk assessment tool are shown in Figure 4.1. Each component is described briefly.

4.2.1 RE database

The RE database included information quantifying the vulnerability of the work place to potentially large ground motions. The input data is typically derived from panel

audits and is seen as 'static' inputs (as opposed to the seismic input as being 'dynamic')

Figure 4.3 shows a possible input sheet for the parameters describing the static environment and vulnerability of the excavation to large ground motion. It also includes the exposure of people.

Working place setup parameters			Range	Default	Value	
Name	Code #	Risk parameter				
104W1	1	<i>Vulnerability of excavation</i>				
		ERR			30	
		Support	1 to 5		3	
		Ground Conditions	1 to 5		3	
		Escape ways	1 to 5		3	
		Site Amplification	1 to 5		3	
		<i>Exposure</i>				
		# of people (day)			30	
		# of people (night)			10	
		Start Day shift			8:00	
		Blasting time			14:00	
		Start Night shift			20:00	
		<i>Quality of information</i>				
		Mine plans/Structure/layout	1 to 5		3	
		Seismic monitoring	1 to 5		3	
		Early warning	1 to 5		3	
		Assesment interval and volume	1 to 5		3	
		Experience reference	1 to 5		3	
Communication	1 to 5		3			

Figure 4.3 Suggested input sheet for working place parameters.

The choice of parameters is not prescribed and a mine may wish to include or exclude any parameters as may be applicable.

The exposure of people is described with a simple time distribution as follows: (Figure 4.4)

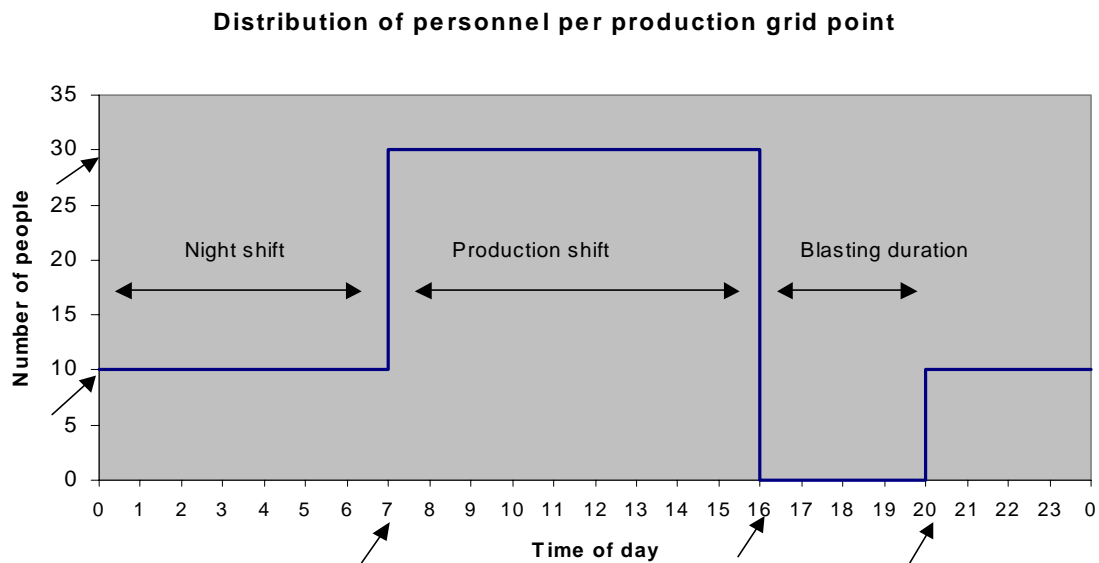


Figure 4.4 A simplified distribution of underground personnel per grid element. The arrows indicate the data values to be included in the workplace attributes

The individual parameters are linked to a working place name, e.g. panel/face name. The RE database also includes the geographical position and extent of the underground workplace (e.g. face files). The panel name/number is linked to the face files that comprise a coordinate-based description of the mining geometry

4.2.2 Seismic database

The seismic data comprises quantified seismological parameters. The seismic parameters include time location, moment, and energy. Where the system provides extracted information such as Apparent Volume, Energy Index, parameters pertaining to the flow of the rock mass, etc., these parameters may be included.

The seismic data is geographically based and is changing dynamically. Close to real-time access to the mine's seismic system output is required.

4.2.3 Probability data

Each input parameter (or evidence) confirming or rejecting the hypothesis that a certain outcome will occur, has to be quantified in terms of $P(H)$, $P(H|E)$ and $P(H|\sim E)$. The thresholds defining the certainty levels for observing the evidence are also included. (see description of Bayes' Theorem, Chapter 2.2.4 page 21). Typical input data is shown in Table 4.2.1.

Table 4.2.1 Typical input data quantifying the evidence as used in the expert system based on Bayes' Theorem

prior probability	p(H)	0.0067
ppv	p(E1 H)	0.781
	p(E1 ~H)	0.523
	Ryes	3
	Rno	0
event rate	p(E1 H)	0.67
	p(E1 ~H)	0.016
	Ryes	2
	Rno	0.5
app volume	p(E1 H)	0.5
	p(E1 ~H)	0.136
	Ryes	2
	Rno	0.5
energy index	p(E1 H)	0.53
	p(E1 ~H)	0.147
	Ryes	0.15
	Rno	-1

4.2.4 Input matrix

The input matrix is an implementation of, effectively, a GIS process. The input to the matrix is from the respective databases.

The input matrix is defined as a 100 x 100 x100 matrix. The basic 2D array of 100 X 100 relates to a grid with a resolution of 10m, thus allowing an overall array of 1 km by 1 km, projected on to the reef plane.

The 3rd array index accommodates the different attributes describing each grid element. These attributes are allocated as follows:

1 to 9	Rock Engineering related parameters
10 to 19	Seismic parameters
20 to 35	Short & long term event rate
40 to 45	short & long term App Volume
60 to 75	Short & long term Energy Index

4.2.5 Links or linking processes

A number of linking processes are defined and developed to link the databases with the expert system process, as shown in Figure 4.1. The linking process between the seismic database and the expert system has to be 'real-time'. The different seismic systems employed on the mines will require different interfacing to their database. Earlier versions of the ISS system allowed for a user programmable link with ISS provided libraries. Later versions since 8.2 will require special licensing from ISS International.

4.3 Visualization

Visualization of input and output parameters is accomplished through extensions to a basic 2D data- integration environment developed by GeoVision. The environment offers the ability to dynamically view several spatially related datasets together in a single window.

Internally, the VTK library (Visualization ToolKit) is employed to filter, transform and render datasets. VTK employs a data flow model that allows the connection of filters into 'pipelines'. The output of each pipeline is rendered as a separate layer within a single 2D projection. Though ostensibly a 3D library, VTK can be used for 2D projections through the application of appropriate transformations to dataset geometries and view systems.

Externally, the scripting language Tcl (Tool Control Language) is used to assemble pipelines and to create the user interface that facilitates both dynamic control of parameters and interaction with the rendering process. Many scripting languages provide the ability to interface with additional libraries through extension architectures - a process known as 'wrapping'. The VTK library has been 'wrapped' with Tcl, allowing the creation and adjustment of pipelines from the scripting level.

Special pipelines were developed for the import of mine plans, creation/editing of static input datasets (input rasters), and dynamic import of spreadsheet data (output raster). Connection to the spreadsheet is via COM - Microsoft's Common Object Model. The COM interface allows the environment to monitor updates to the spreadsheet-data at runtime and can request the execution of VBA scripts (macros) stored within the spreadsheet

5 Evaluation of the risk assessment software.

5.1 Introduction

In this chapter the implementation of the coding described in Chapter 4 is demonstrated. Data from Savuka mine was used. The actual seismic data was processed as the dynamic risk component, however, artificial data was used for the 'static' component.

5.2 Seismic risk assessment

The code was developed to allow for ten seismic parameters to constitute the seismic risk. These parameters will be used as evidence to quantify the probability for a large ground motion at a particular point on or close to the reef plane. The respective position of the seismic events is given in 3-D but the risk evaluation is done on a 2-D plane, with due consideration for location accuracy and source extent.

The seismic input parameters used are the respective short term / long term changes recorded in event rate, apparent volume and energy index. In adopting the Bayes' Theorem expert system approach, the outcome that is hypothesised, is that a rock related incident might occur during the current or next shift within the boundaries of the grid resolution, i.e. 10m. Smoothing is applied to include the input parameters of adjacent grid elements, which results in an effective resolution of about the dimensions of a typical panel length. The first input is the prior probability, $p(H)$ that the hypothesis outcome will occur without any evidence either supporting or rejecting the hypothesis.

$p(H)$ is estimated by looking at all the related incidents over a period and over the area of interest. The prior probability is then:

$$p(H) = \frac{\# \text{ of incidents}}{(\# \text{ of grid pnts}) \times (\# \text{ of shifts})}$$

where *# of incidents* is the number of rock incidents that caused physical harm;

of grid pnts is the number of grid elements included in the working areas; and

of shifts is the number of shifts in review period

Each input parameter or item of evidence is quantified in terms of the probability of observing the evidence, with the hypothesis being true, $p(E|H)$, and similarly the probability of observing the evidence, but with a hypothesis that is not true, $p(E|\sim H)$.

For the purpose of demonstrating the code, a seismic sequence leading up to an event of a Mag 2 during the morning production shift is used. All the plots shown relates to the knowledge available to an operator 8 hours prior to this event. Figure 5.1 shows a contour plot of the rate of change in the number of events per time unit. A Mag 2 event occurred at 10 am during the morning shift at the position indicated by the star.

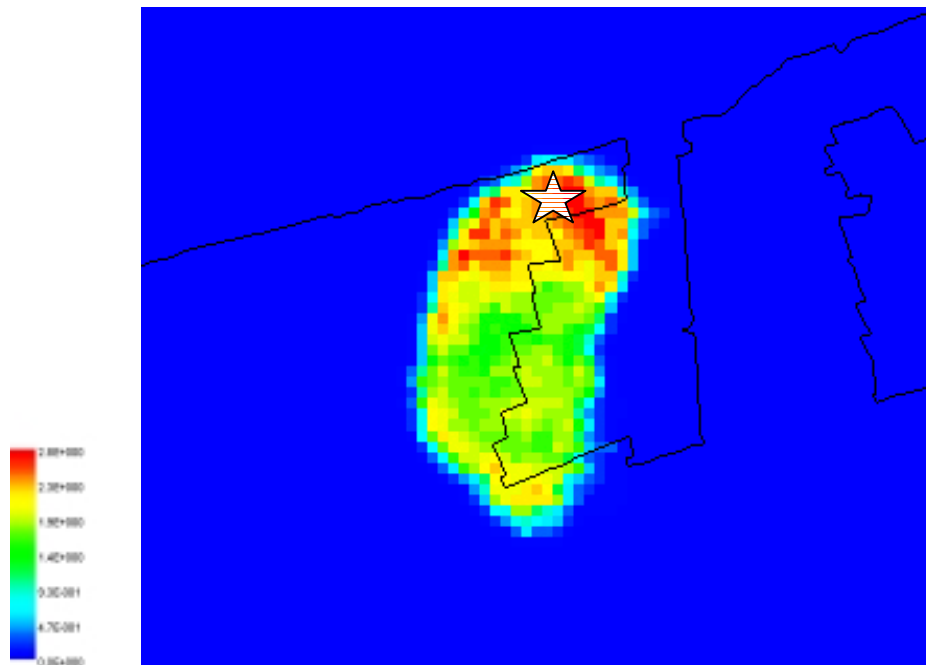


Figure 5.1 Rate of change in the number of events per time unit is shown. The red contour relates to a doubling in the event rate. The position of a Mag 2 event 8 hours later is indicated.

In this example the area that observed an increase in event rate is the same area that suffered a relatively large event (Mag 2) in the next shift.

Although a grid resolution of 10mx10m is used, event source size and location accuracy does not allow the process to link an event to a single grid position. A zone of influence around the event location is used. This zone of influence may be determined, for example, using source dimension, apparent volume or just a $1/(\text{distance to location})$ relation. For the purpose of this proof of concept a fixed zone of influence of 50 m is used.

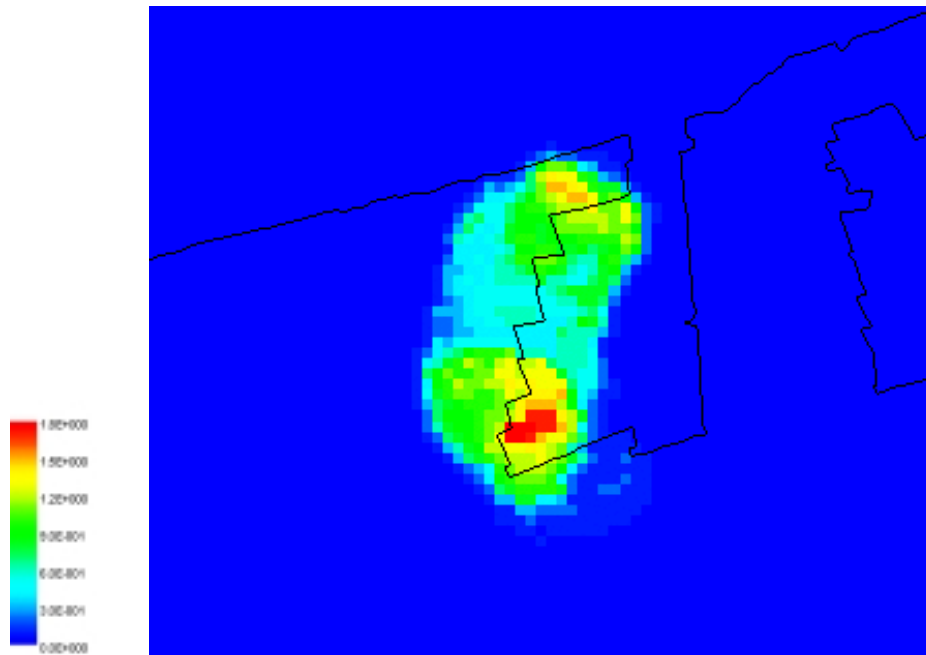


Figure 5.2 Rate of change in the Apparent Volume as observed in a short-term long-term ratio.

The distribution of the rate of change in the Apparent Volume parameter is shown in Figure 5.2. The same short term and long-term periods were used. This approach differs from the more standard (ISS) approach of looking at the rate of change in accumulated Apparent Volume. The latter approach combines Apparent Volume and number of events whereas the expert system process treats them separately.

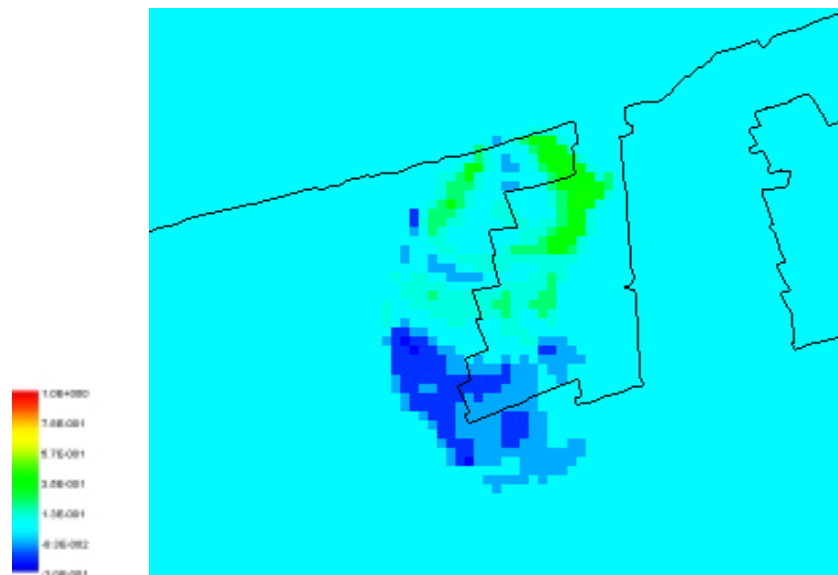


Figure 5.3 As in Figure 5.1 and Figure 5.2 but this time the rate of change in Energy Index is overlain on the mining operation. A positive value means that the expected energy for a certain moment is larger than the observed energy.

Energy Index changes per grid element is also calculated and shown in Figure 5.3. With the inferred relation between Energy Index and stress, a positive value implies lower stress levels.

The following parameter, a peak particle velocity (ppv) count, does not necessarily relate to the potential for experiencing a high ppv at a specific grid position, other than that the return time between incidents of high ground motion is shorter. The ppv count is used in this evaluation as an indicator of the vulnerability of the excavation to ground motion. A larger number of large ground motions should relate to the extent of seismic related damage in an area. A higher degree of earlier damage makes an area more vulnerable to the next higher level of ground motion. In Figure 5.4 the centre of the mini-longwall experienced the largest number of ground motions larger than .2 m/s. The power law distribution of ppv counts as shown in Figure 3.2 (page 33) justifies the expectation that this area also would have experienced more large ground motions.

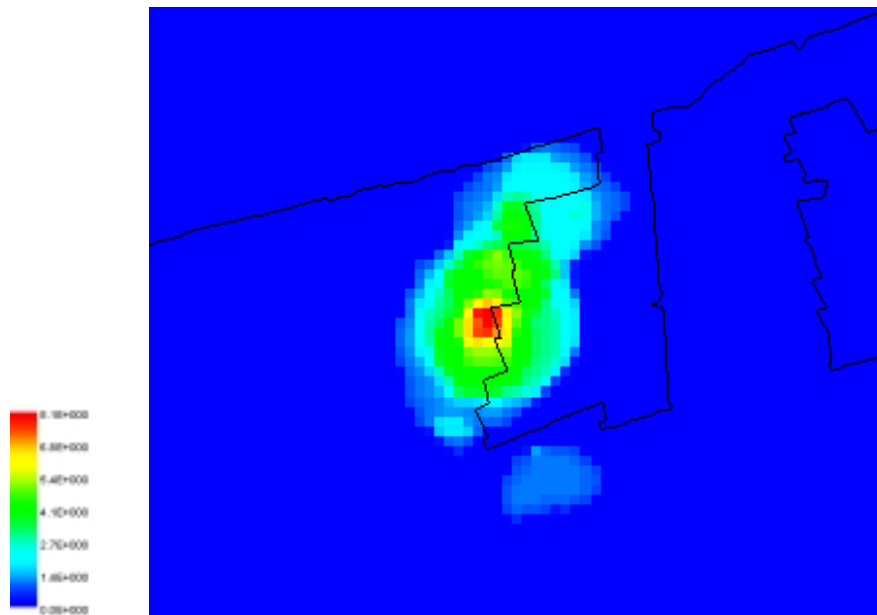


Figure 5.4 A plot of the number of times during the previous 30 days that an estimated peak particle velocity of .2 m/s was exceeded.

All the earlier mentioned evidence, namely event rate, Apparent Volume, Energy Index and ground motion is combined in estimating the probability for experiencing a rock related incident at a specific grid element during the next shift.

The following input parameters were used to quantify the evidence in terms of Bayes' Theorem (Equation(2.2.2)).

Table 5.2.1 Summary of input values for the application of Baye's Theorem for estimating the probability for a rock related incident

$p(H) = 007$	$p(E H)$	$p(E \sim H)$	Ryes	Rno
Event Rate	.67	.016	2.0	.5
Apparent Volume	.5	.14	2.0	.5
Energy Index	.53	.15	.15	-1.0
PPV count	.8	.5	3	0

The application of the input values as given in Table 5.2.1 yielded a risk probability as given in Figure 5.5. The higher risk area (in red) yielded a probability of .5 that a rock related incident with the potential to causing an injury would happen within the next shift.

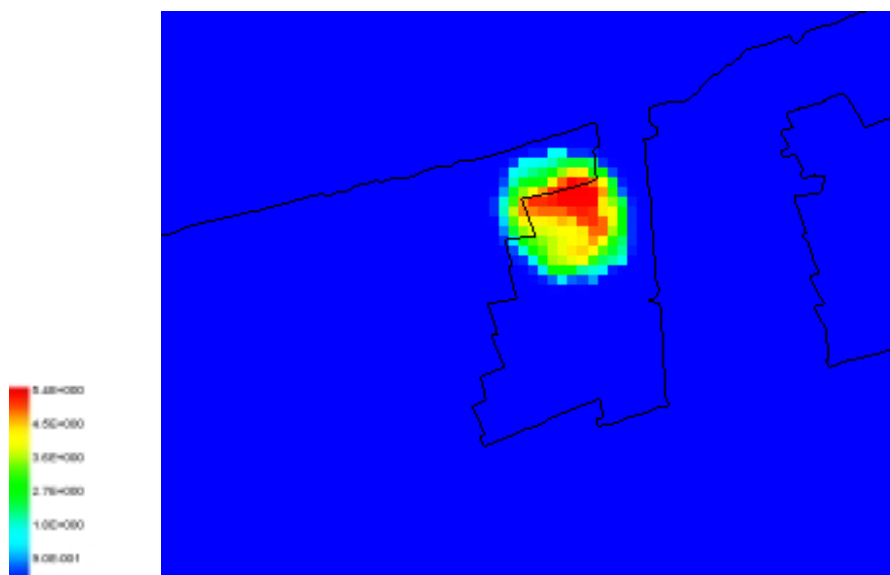


Figure 5.5 Overall seismic risk as estimated through a combination of the evidence, namely Event Rate, Apparent Volume, Energy index and ppv count).

5.3 Incorporating rock mechanics parameters

The above mentioned is still purely based on the 'dynamic' information and does not take into account the vulnerability of the excavation as described by parameters such as ERR, support quality and local ground condition. It also does not take into account the exposure of the underground workers as described in section 4.2.1.

To incorporate the 'static' risk information, it is necessary to define the total working area, i.e. the active panels and the back areas. The total working area is defined in

Figure 5.6. In this example the back areas are only considered in terms of the exposure of people. No specific risk attributes were allocated to any grid position, but there is no limitation to identify specific access ways, for example, as being of higher risk.

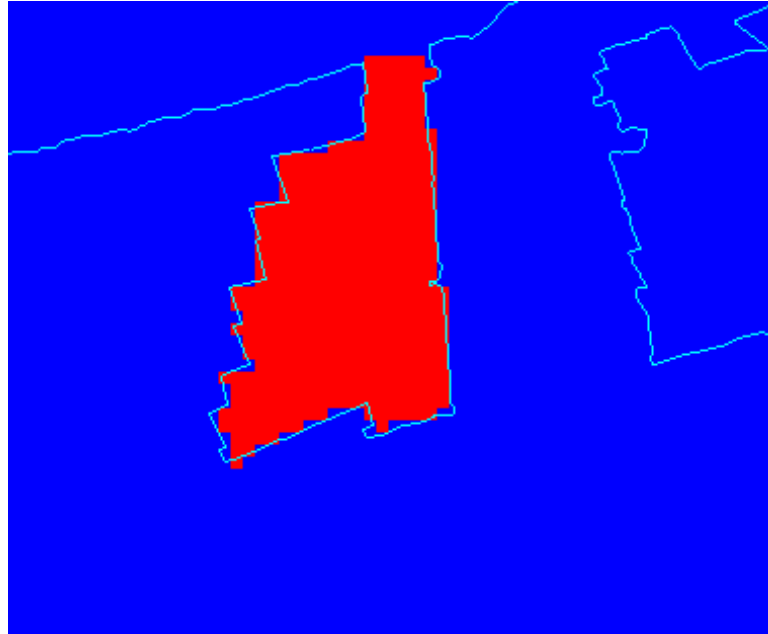


Figure 5.6 Total working area to be considered in terms of risk to the underground personnel. The area includes the active panels and the back areas.

The next step is to use a GIS approach to specify the input parameters to specific active panels. Panels are typically known by name rather than geographic position. The suggested working place data set is described in section 4.2.1 and Figure 4.3. A panel name and its associated attributes have to be linked to a specific geographical area. The output of this process is shown in Figure 5.7. Every panel, in terms of its geographical position, is now linked to the RE database as shown in Figure 4.3. The attributes describe the vulnerability of the excavation to large ground motion and also include the exposure at a particular time of day as well as the more general 'Quality of information'.

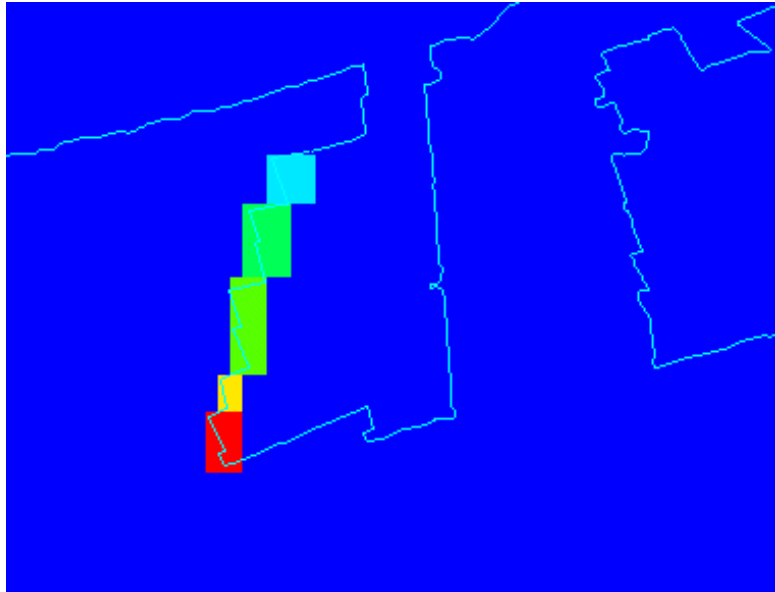


Figure 5.7 This figure demonstrates the process of linking a geographical area of an active panel to a set of attributes as described in section 4.2.1.

Combining the overall seismic risk as shown in Figure 5.5 with the static information yielded an output as shown in Figure 5.8. This output is now the total RE risk as defined in Table 1.2.1.

5.4 Integrated RE risk

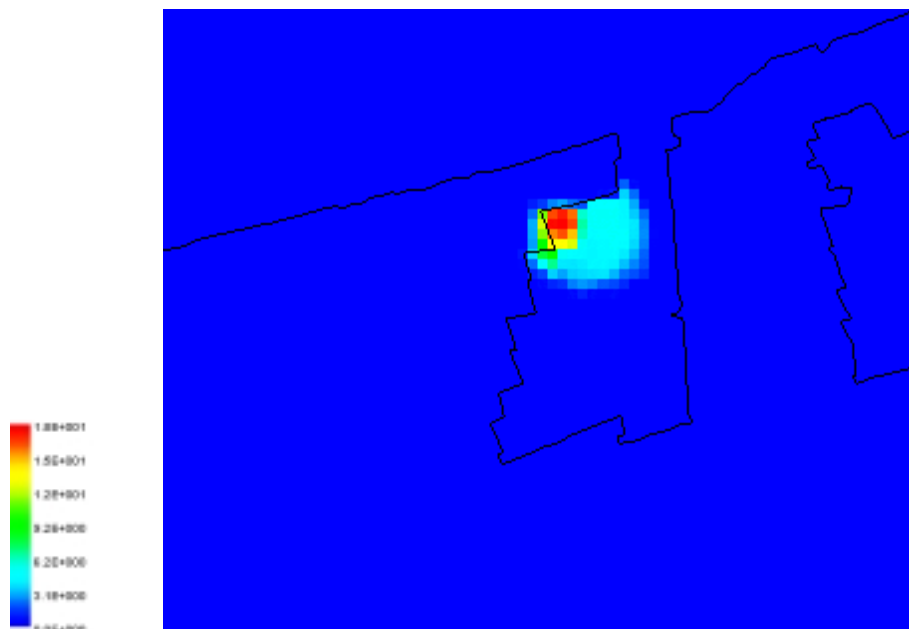


Figure 5.8 Overall RE risk plotted on a linear scale.

The probability approach leads to a large dynamic range in output levels and the linear display may give the impression of a zero risk in some areas. Figure 5.9 shows the same probability plot but using a logarithmic scale.

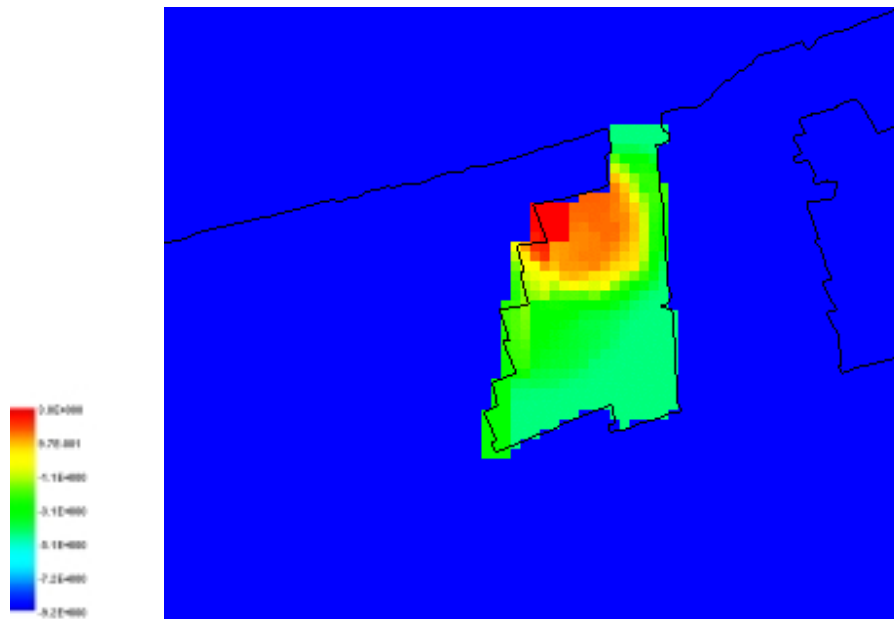


Figure 5.9 Similar to Figure 5.8 but now the overall RE risk is plotted on a logarithmic scale

5.5 Conclusions

The above figures were used to demonstrate the concept and methodology of an integrated RE risk assessment. The software is in an early (alpha-) stage of development. All the individual components were debugged and tested, but the total integration of all its components in a single product is outstanding,

Better 'units' to quantifying the overall risk have to be developed. The dynamic inputs resulted in a probability of a specific hypothesis being true. Most of the static parameters, however, do not affect the probability of the hypothesis being true, but rather act as a weighting factor. For example, it may be argued that the lack of escape ways cannot increase the probability of a rock-related incident, but does increase to risk to the underground worker. Similarly, 'Quality of information' does not affect the direct probability of having a rock-related incident, but provides a weighting of the assessed risk levels, because of the implied uncertainty in the original input data.

6 Conclusions and recommendations

The deliverable of this project was a prototype software package that is a combination of an expert system approach for determining overall risk assessment, a risk control recommendation and a basic GIS (Graphic Information System) approach for graphically overlying input parameters and the output risk. The expert system uses a Bayesian probabilistic approach to combine various workplace-related information, a quantified seismological environment and exposure of underground staff to provide an overall RE risk rating. This objective/ deliverable was met.

It has to be stressed that the objective of the project was not to provide a tool for the *prediction* of large seismic events, but to provide an integrated approach towards the dynamic assessment of the overall *RE risk* at a particular place in the mine, and with cognisance of the exposure of the underground worker to the inferred RE risk.

Evaluation of the methodology proved to be difficult. It can only be properly evaluated through extended use in an operational environment. The code was tested on data from a Far West Rand mine and on data from a relatively deep platinum mine. It is not possible, and rather ambiguous, to define specific case studies and to claim a percentage success rate as in the case of prediction.

The concept of integrated RE risk assessment was described and an initial version of the software was developed. This report could not fully describe or demonstrate the application of this code, in particular the dynamic display of information, and it is recommended that a SIMRAC workshop be arranged to present the concept, methodology and some evaluation to the industry.

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