



Seismic hazard in Western Australian mines

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Synopsis

A Seismic Hazard Scale (SHS) has been developed to provide a practical seismic hazard assessment tool applicable to mine site personnel. It has been applied to seismic data sets from numerous Western Australian mines. The SHS is applicable when quantifying seismic hazard on a minewide scale, on a mining block scale, and on a local cluster-by-cluster scale. Spatial mapping of variations in seismic hazard is a particularly powerful application of the scale.

The SHS is sensitive to temporal increases in seismic hazard. It has also been shown that the SHS can be applied to estimate seismic hazard when seismic monitoring data are not available.

The SHS is a simple derivation of the Gutenberg-Richter relation. There are assumptions and limitations to the SHS that need to be considered when applying it to mine seismicity data.

Introduction

Although there has been considerable work done on the topic of seismic hazard in mines, there is currently no widely accepted definition or universal measure for seismic hazard in mines. In this paper, seismic hazard is defined as the likelihood of occurrence of a seismic event of a certain magnitude. One of the key issues in evaluating seismic hazard is determination of the maximum potential seismic event size, M_{\max} .

There is a wide range of empirical, statistical, parametric and non-parametric approaches for estimating seismic hazard or calculating the maximum potential event size. Detailed discussions of these techniques can be found in Brink *et al.*¹, Kijko², Mendecki³, and Kijko *et al.*⁴. However, owing to the complex nature of most of these techniques, they are rarely utilized by mine site personnel on an operational basis to evaluate seismic hazard. Seismic hazard quantification should consider the seismic response of the geological features, mine stopes and pillars, and other local mine conditions. Paradoxically, the people best equipped with the necessary knowledge of these local mine conditions are mine site personnel familiar with the geology and mine design. A seismic hazard technique

that will be accepted and used by mine site personnel is required.

Seismic hazard scale

In 2002, a survey was conducted to investigate the occurrence and severity of mine seismicity in underground, mechanized, hardrock mines⁵. One of the requirements for the analysis of the mine seismicity survey data was to compare the level of seismicity reported at different mines. To compare those data effectively, a seismic hazard scale was needed that could reliably quantify levels of mine seismicity ranging from negligible to severe. This requirement was complicated by the fact that half of the 72 mines that responded to the survey did not have local seismic monitoring systems to provide quantitative data related to mine seismicity. The Seismic Hazard Scale (SHS) introduced below was developed for use in comparing and interpreting data from the mine seismicity survey.

Defining the Seismic Hazard Scale (SHS)

Kijko and Funk⁶ discuss some of the most commonly used parameters to describe seismic hazard. The Seismic Hazard Scale proposed uses two of these parameters:

- the rate of events of a given magnitude
- the b-value parameter from the Gutenberg-Richter relation⁷.

The Gutenberg-Richter relation asserts that the frequency of occurrence of events increases according to a power law as the magnitude of events decreases (Figure 1). This can be expressed as:

$$\log_{10} (\text{Number of Events}) = a - b * m$$

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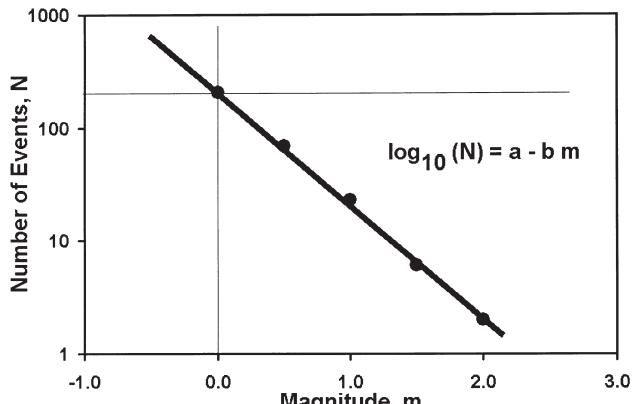


Figure 1—Gutenberg-Richter relation for mine seismicity

Where

m is event magnitude,

Number of events is the number of events in the population equal or greater than magnitude, m, a is a constant related to the amount of seismicity, and

b is the slope of the relation.

Definition: Let a relatively high daily rate of microseismicity, in a typical hard rock, mechanized mine, be defined as 1 event with Richter magnitude ($M_L \geq -1$) per day

This is purely a starting point for relative comparison. Also, assume the b-value of the mine seismicity is approximately 1. Then using the Gutenberg-Richter relation, the average daily rate of seismic events with $M_L \geq 0$ is 0.1, the average daily rate of $M_L \geq +1$ is 0.01, and the average rate of microseismic events $M_L \geq -2$ is 10 per day. This can be simplified to:

$$\text{Daily rate of events} = 10^{(-M_L - 1)} \quad [1]$$

Where

M_L is the Richter magnitude of the events, and

Daily rate of events is the frequency of occurrence of events equal or greater than magnitude M_L .

A qualitative description of how an event feels in a mine was proposed by Potvin and Hudyma⁸, and is reproduced in Table I. Using the qualitative descriptions between how events feel in a mine and Richter magnitude, the daily rate of events from the above definition can be compared with magnitude and event description (Table II).

If significant rates of seismicity are then defined to be power law increases and decreases compared with this original definition, a relative 'Seismic Hazard Scale' can be defined (Table III). The scale is designed to include rates of seismicity from very low to extreme.

The rate of seismic events in the table can be simplified to the following equation:

$$\text{Daily rate of events} \geq 10^{(SHS - M_L - 3)} \quad [2]$$

Where

M_L is Richter magnitude,

Daily rate of events is the frequency of occurrence of events equal or greater than magnitude M_L , and SHS is the seismic hazard scale.

Considering the typical short mine life for most western Australian mines, it is reasonable to assume that the maximum event size occurs at a rate of about 0.001 (an event of this size 'occurs every few years'). Seismic Hazard Scale (SHS) for a rate of 0.001 events per day is compared with maximum event size in Table IV.

This can be simplified to:

$$X_{MAX} \approx SHS \approx \log_{10}(\text{event rate}) + M_L + 3 \quad [3]$$

Where

X_{MAX} is the largest event observed,
SHS is the seismic hazard scale,

M_L is the Richter magnitude of a seismic event, and Event rate is the daily rate of events with a magnitude equal to or greater than M_L .

Table I
Richter magnitude of events compared with how these events would be felt at a mine

Approximate Richter Magnitude	Description
-2.0	<ul style="list-style-type: none"> Felt locally as thumps or bangs at a short distance from the event. May be felt more remote from the source of the event (i.e. more than 100 metres away). May be detectable by a microseismic monitoring system.
-1.0	<ul style="list-style-type: none"> Often felt by many workers throughout the mine (i.e. hundreds of metres away). Similar vibration to a distant underground secondary blast. Will be detected by a microseismic monitoring system.
0.0	<ul style="list-style-type: none"> Vibration felt and heard throughout the mine. Bump commonly felt on surface (hundreds of metres away), but may not be audible. Vibration felt on surface similar to those generated by a development round.
1.0	<ul style="list-style-type: none"> Typically felt and heard very clearly on surface. Vibrations felt on surface similar to a major production blast.
2.0	<ul style="list-style-type: none"> Vibration felt on surface is greater than large production blasts. Vibration detectable with regional earthquake monitoring systems.

Table II
Relative rates of seismic events assuming a power law rate of occurrence and compared with qualitative event descriptions

Quality description	Mine seismicity frequency per day	
	Approx. Richter magnitude	High rate of events
Felt locally	$M_L > -2$	>10
Felt in a few parts of a mine, like a secondary blast	$M_L > -1$	>1
Often felt on surface, or like a development blast	$M_L > 0$	>0.1
Felt like a production mass blast	$M_L > +1$	>0.01
Detected by regional earthquake network	$M_L > +2$	>0.001

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Table III

Seismic Hazard Scale (SHS) defined from daily rates of seismic events and qualitative event descriptions

Mine seismicity frequency per day					
Qualitative description	Felt locally	Felt in a few parts of a mine, like a secondary blast	Often felt on surface, or like a development blast	Felt like a production mass blast	Detected by regional earthquake network
Approx. Richter magnitude	$M_L > -2$	$M_L > -1$	$M_L > 0$	$M_L > +1$	$M_L > +2$
Seismic hazard scale and qualitative description					
-2	Nil >0.001 (once every few years)	0 (has never occurred)	0 (has never occurred)	0 (has never occurred)	0 (has never occurred)
-1	Very low > 0.01 (a few times per year)	>0.001 (once every few years)	0 (has never occurred)	0 (has never occurred)	0 (has never occurred)
0	Low >0.1 (at least weekly)	>0.01 (a few times per year)	>0.001 (once every few years)	0 (has never occurred)	0 (has never occurred)
0.5	Low to moderate >0.3 (a few times per week)	>0.03 (monthly)	>0.003 (yearly)	<0.001 (may have happened once)	0 (has never occurred)
1	Moderate >1 (at least daily)	>0.1 (at least weekly)	>0.01 (a few times a year)	>0.001 (once every few years)	0 (has never occurred)
1.5	Moderate to high >3 (a few a day)	>0.3 (a few times a week)	>0.03 (monthly)	>0.003 (yearly)	<0.001 (may have happened once)
2	High >10 (more than 10 a day)	>1 (at least daily)	>0.1 (at least weekly)	>0.01 (a few times a year)	>0.001 (once every few years)
2.5	High to very high >30 (more than 30 a day)	>3 (a few a day)	>0.3 (a few times a week)	>0.03 (monthly)	>0.003 (yearly)
3	Very high >100 (more than 100 a day)	>10 (more than 10 a day)	>1 (at least daily)	>0.1 (at least weekly)	>0.01 (a few times a year)
3.5	Very high to extreme >300 (more than 300 a day)	>30 (more than 30 a day)	>3 (a few a day)	>0.3 (a few times a week)	>0.03 (monthly)
4	Extreme >1000 (more than 1000 a day)	>100 (more than 100 a day)	>10 (more than 10 per day)	>1 (at least daily)	>0.1 (at least weekly)

Table IV

SHS compared with relative seismic hazard and the magnitude of the largest event that may have occurred

SHS	Relative Seismic Hazard	Approximate Magnitude of Largest Event
-2	Nil	-2
-1	Very Low	-1
0	Low	0
1	Moderate	+1
2	High	+2
3	Very High	+3

Mathematical basis of the seismic hazard scale

The Seismic Hazard Scale is a simple derivation of the Gutenberg-Richter relation (Figure 1). For any given magnitude, m, the SHS scale is the x-axis intercept of the Gutenberg-Richter relation, or

$$SHS \approx \log_{10}(N) / b + M_L \quad [4]$$

Where

SHS is the seismic hazard scale,
 M_L is the Richter magnitude,
 N is the number of events with a Richter magnitude of at least M_L , and
 b is the slope of the frequency magnitude relation.

Features of the seismic hazard scale

The SHS is conceptually simple. It employs one definition and

relies on the power law relation for defining levels of mine seismicity.

When the power law relation holds true, the SHS will give the same rating regardless of the magnitude being used to evaluate the scale. This also gives the flexibility to calculate the SHS using multiple magnitudes, adding confidence to the SHS rating.

There are also some advantages in the SHS when dealing with data loss or seismic system limitations. The loss of a few large events due to seismic system malfunction is unlikely to affect the SHS scale dramatically, as the number of smaller events also gives an equivalent indication of seismic hazard.

For seismic monitoring systems with a limited dynamic range, it is possible that the magnitude of large events is not properly calculated by the system owing to waveform clipping. The SHS scale is not dependent upon accurate magnitude calculation for a small number of large events. The seismic hazard will be reflected in the frequency of occurrence of smaller events. For example, in Figure 2, the seismic data from a Western Australian mine are shown in a Gutenberg-Richter plot. The seismic system saturates with an upper magnitude bound of about Richter 1.0. However, the smaller events suggest that the SHS should be close to 2.0.

Assumptions and limitations of the seismic hazard scale

There are important assumptions and related limitations to the Seismic Hazard Scale:

- It is assumed that mine seismicity reflects local rock mass failure mechanisms within the mine. If the

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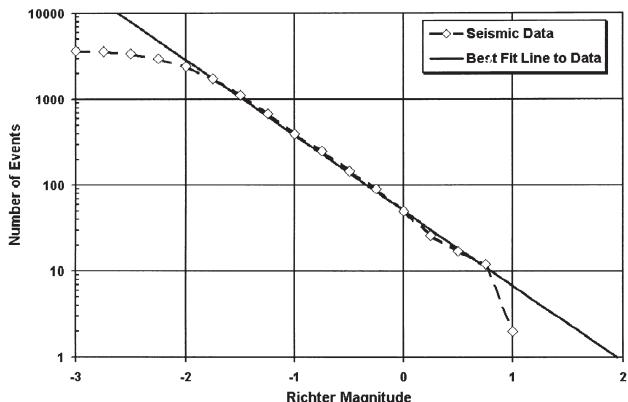


Figure 2—Seismic data from a Western Australian mine in which the seismic system has a limited dynamic range and saturates at about Richter magnitude 1.0. The SHS for this data set is calculated to be about 2.0

seismicity is being driven or caused by regional influences, the local seismic data and the SHS may not reflect the regional influences.

- The SHS scale has been used extensively to investigate and describe seismic hazard for data sets with events of up to about Richter magnitude +3. The scale is largely untested for extreme levels of seismic hazard and seismic events greater than Richter magnitude +3. It is quite possible that rates of occurrence for seismic events greater than Richter magnitude +3 may not conform to the SHS scale. Events of this magnitude are commonly related to regional seismic source mechanisms rather than local seismic source mechanisms. Many authors have reported non-self-similar behaviour of large seismic events, suggesting that the mechanisms of large events may be fundamentally different from smaller events, i.e. for Richter magnitude $\geq +3^{9-11}$. Under these circumstances, the SHS methodology could lead to erroneous estimates of seismic hazard.
- The basic premise of the SHS scale is that the occurrence of seismicity closely follows a power law with an exponent (*b*-value) of 1.0. In most cases, this is a reasonable assumption. Multimodal data sets containing very large seismic events and bi-linear Gutenberg-Richter relations have been observed particularly in South African mines⁹⁻¹¹. The SHS scale is dependent on a well-behaved Gutenberg-Richter relation. To date, there is little evidence of multimodal behaviour of large seismic events recorded in western Australian mines.
- In this paper, SHS is a measure of the past seismicity that has occurred in the mine. Past seismic response to mining is often used to estimate future seismic response. However, future seismic hazard is not guaranteed to be related to past seismic hazard. This is particularly true if the mechanisms or driving forces of future seismicity are different from those of past seismicity. Extrapolation and forecasting using the SHS scale may be unwarranted if the rock mass conditions, or mining influences of future seismicity are significantly different from past seismicity. This may occur

for a number of reasons, including changing geological environment, changes in mining method or mining sequence, or owing to the maturing of a mining operation potentially changing the regional loading/unloading system stiffness.

- An adequate seismic record is necessary. If there are few seismic events, or the monitoring period is brief, or there are extended periods of seismic system downtime, the seismic record may be inadequate to apply the SHS to evaluate seismic hazard.

Applying the seismic hazard scale

Mine seismicity survey

In 2002, a survey was created to investigate the occurrence and severity of mine seismicity⁵. The 148-question survey was circulated to 135 underground, mechanized, hardrock mines in 18 countries. The intent of the survey was to identify and better understand the geotechnical, geological and mining factors conducive to mine seismicity specifically in underground, mechanized, hardrock mines.

Using the mine seismicity survey to evaluate seismic hazard

There are six questions in the mine seismicity survey that can be used to evaluate the seismic hazard (SHS):

- Question 105 – Do underground workers report rock noise?
- Question 106 – Does the ground work (pop, crackle, snap, bang) for more than a few hours after development blasting, or after stope blasting?
- Question 107 – Are seismic events felt throughout the mine, with a vibration similar to a secondary blast?
- Question 108 – Are large seismic events felt throughout the mine and on surface similar to a development blast?
- Question 109 – Are large seismic events felt throughout the mine and on surface, with similar vibrations to a large stope blast?
- Question 110 – Are large events in the mine detected by the Geological Survey (generally > Richter magnitude +2)?

Each of the survey questions relating to seismic hazard is given a response from 1 to 9, where: 1 = Has never occurred, 2 = Every few years, 3 = Yearly, 4 = A few times per year, 5 = Monthly, 6 = Weekly, 7 = A few times per week, 8 = Daily, 9 = I don't know.

Table V combines the survey responses, and utilizes the SHS definition in Table III, to estimate SHS for each mine site.

Effectively, the survey respondent was asked 6 times for data that can be used to evaluate SHS. If the power law frequency-magnitude relation holds true, the response of the six questions should give the same SHS. So, although there may be a level of inaccuracy in the response of any one question (also given the assumptions stated above), the responses for the six questions give an overall estimate of seismic hazard.

For the data collected in the mine seismicity survey, it was found that the responses for the six questions gave a reasonably consistent SHS, with the typical SHS range for each mine rarely varying more than 1.

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Table V

Mine seismicity survey questions used to estimate seismic hazard

Evaluating SHS							
Survey question	Q105, Q106	Q107	Q108	Q109	Q110		
Qualitative description	Felt locally	Felt in a few parts of a mine, like a secondary blast	Felt weakly on surface, like a development blast	Felt strongly on surface, like a large stope blast	Detected by regional earthquake network		
Approx. Richter magnitude	$M_L \geq -2$	$M_L \geq -1$	$M_L \geq 0$	$M_L \geq +1$	$M_L \geq +2$	SHS scale	Qualitative seismic hazard description
	2 (every few years)	1 (has never occurred)	1 (has never occurred)	1 (has never occurred)	1 (has never occurred)	-2	Nil
	4 (a few times a year)	2 (every few years)	1 (has never occurred)	1 (has never occurred)	1 (has never occurred)	-1	Very low
	6 (weekly)	4 (a few times a year)	2 (every few years)	1 (has never occurred)	1 (has never occurred)	0	Low
	7 (a few per week)	5 (monthly)	3 (yearly)	1 (has never occurred)	1 (has never occurred)	0.5	Low to moderate
	8 (daily)	6 (weekly)	4 (a few times a year)	2 (every few years)	1 (has never occurred)	1	Moderate
		7 (a few a week)	5 (monthly)	3 (yearly)	1 (has never occurred)	1.5	Moderate to high
		8 (daily)	6 (weekly)	4 (a few times a year)	2 (every few years)	2	High
			7 (a few a year)	5 (monthly)	3 (yearly)	2.5	High to very high
			8 (daily)	6 (weekly)	4 (a few times a year)	3	Very high
				7 (a few a week)	5 (monthly)	3.5	Very high to extreme
				8 (daily)	6 (weekly)	4	Extreme

Comparing the mine seismicity survey results with seismic monitoring data

Seismic monitoring data were available for a number of the case histories in the mine seismicity survey. Figure 3 compares SHS evaluated from the mine seismicity survey with the largest Richter magnitude event recorded in the seismic data.

The dashed line represents the ideal situation, in which SHS is equal to the largest event recorded. Figure 3 shows that SHS is usually within an order of magnitude of the maximum event recorded (grey zone in Figure 3). This is a good result considering the SHS is evaluated using the semi-quantitative survey questions, and without the use of the seismic monitoring data. It adds further confidence that the SHS scale and its method of calculation in the mine seismicity survey is a good estimate of the maximum event size expected from a mining block.

Seismic hazard in 72 underground, mechanized, hardrock mines

The Seismic Hazard Scale rating for the 72 mines in the survey is summarized in Figure 4. It was found that mines with seismicity and rockbursting problems were more interested in the survey, and more likely to complete it. Consequently, the relative proportion of seismically active case histories in Figure 4 is an over estimation of the frequency of occurrence of seismicity in underground, mechanized, hardrock mines.

A total of 135 operating mines were approached to complete the mine seismicity survey. The mines that were

approached for the survey were chosen with no regard to the level of seismicity in the mine. There were 30 mines that reported having at least one mining block with a high level of seismicity ($SHS \geq 2$). If we assume that most of the mines with high levels of seismicity and rockbursting completed the survey, this would suggest that the frequency of occurrence of high seismic hazard ($SHS \geq 2$) in underground, mechanized, hardrock mines is about 30/135, or about 22%.

A total of 27 operating mines in Western Australia were approached to complete the survey. Nine of the 21 mines that responded had a high seismic hazard ($SHS \geq 2$). If we assume that most of the mines with high levels of seismicity and rockbursting completed the survey, this would suggest that the frequency of occurrence of high seismic hazard ($SHS \geq 2$) in underground, mechanized, hardrock mines is about 9/27, or about 33%. The incidence of high seismic hazard appears to be somewhat greater in western Australia compared with underground, mechanized, hardrock mines elsewhere in the world.

Minewide seismic hazard

The SHS scale can be used in conjunction with data from seismic monitoring systems to estimate seismic hazard and maximum event size.

The Seismic Hazard Scale (SHS) was compared with data from 11 mines with seismic monitoring systems in Australia. Table VI compares:

- the monitoring period of the seismic system
- the number of seismic events recorded
- the Gutenberg-Richter b-value of the seismicity in the mine

Seismic hazard in Western Australian mines

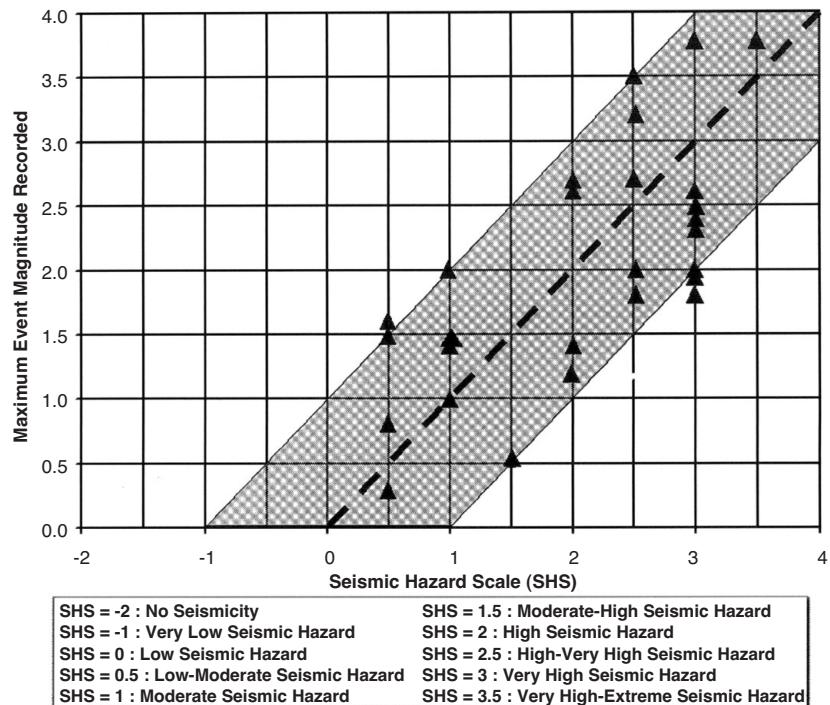


Figure 3—SHS (determined using the mine seismicity survey questions) compared with the largest event recorded in the mining block. The dashed line represents the SHS equal to the largest event recorded. The grey zone represents a maximum event size within 1 magnitude unit of the SHS

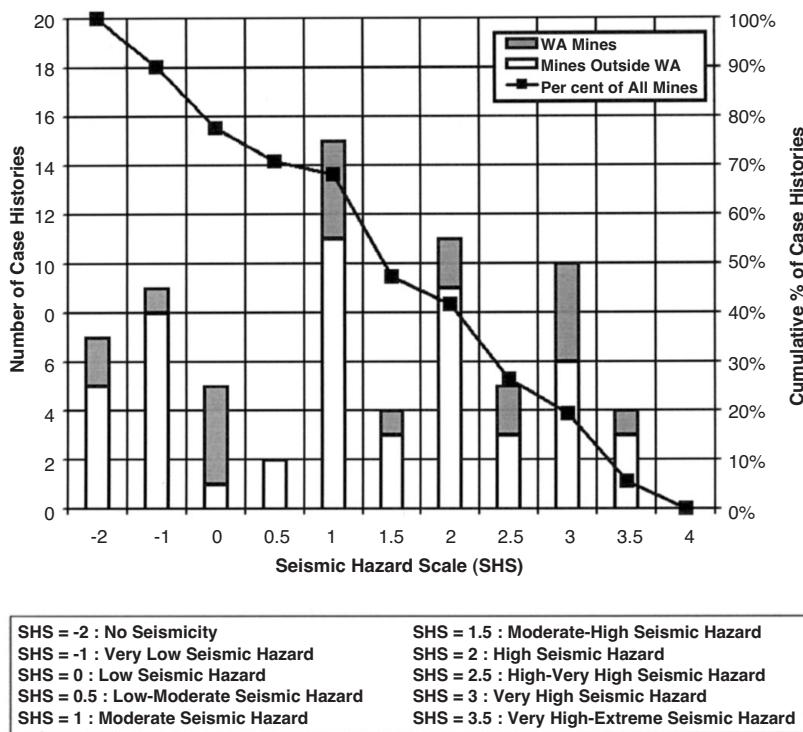


Figure 4—The range of Seismic Hazard Scale (SHS) for the 72 mines in the mine seismicity survey. There were 21 Western Australian mines that responded to the survey

- the largest Richter magnitude event recorded in the mine during the monitoring period
- the average and maximum SHS calculated from Equation [4] and calculated for seismic events with 0.5 magnitude increment equal or greater than 0, and

assuming $b=1.0$.

The largest Richter magnitude event recorded for each mine in Table VI is compared with the maximum SHS (Figure 5). There is a good agreement between the maximum SHS and the maximum event size, with the maximum SHS

Seismic hazard in Western Australian mines

Table VI

Seismic data from 11 Australian mines compared with the Seismic Hazard Scale

Mine	Monitoring period (years)	Number of events recorded	b-value	Magnitude of largest event recorded	Seismic hazard scale (SHS) for magnitude equal or greater than								Ave. SHS	Max SHS
					0	0.5	1	1.5	2	2.5	3	3.5		
1	2.3	3,000	0.9	2.4	2.1	2.1	2.3	2.2	2.1	-	-	-	2.1	2.3
2	2.8	7,000	1.1	2.0	2.2	2.2	2.2	2.0	-	-	-	-	2.2	2.2
3	4.9	11,000	1.2	2.6	2.6	2.6	2.5	2.5	2.5	2.2	-	-	2.5	2.6
4	1.9	8,000	1.2	2.4	2.8	2.7	2.5	2.5	2.2	-	-	-	2.5	2.8
5	0.9	15,000	1.3	2.8	3.3	3.3	3.1	2.8	-	-	-	-	3.2	3.3
6	1.8	4,000	0.9	1.7	1.9	1.9	1.5	1.7	-	-	-	-	1.8	1.9
7	4.0	31,000	1.3	2.4	2.8	2.8	2.6	2.4	2.1	-	-	-	2.5	2.8
8	4.4	2,000	0.8	3.5	2.4	2.5	2.7	2.9	3.1	3.1	2.8	3.3	2.9	3.3
9	4.3	400	0.8	2.3	2.0	2.3	2.3	2.4	-	-	-	-	2.3	2.4
10	1.8	6,200	0.9	1.2	1.6	1.5	1.2	-	-	-	-	-	1.4	1.6
11	2.4	17,000	1.1	2.4	2.9	2.9	2.8	2.7	2.4	-	-	-	2.7	2.9

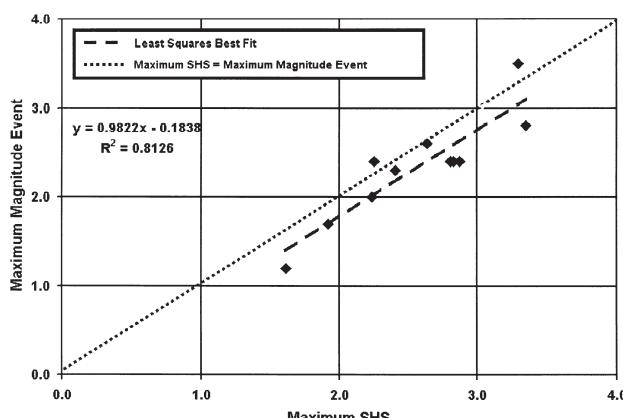


Figure 5—Comparison of maximum SHS to the maximum magnitude event recorded in minewide data sets from 11 Australian mines

averaging 0.2 magnitude units greater than the largest event recorded in the mine. The maximum SHS appears to be a reasonable upper bound to the maximum event size recorded in each mine. The data in Table VI also suggests that the SHS for each of the magnitude ranges gives a reasonable estimate of the maximum event size, with the exception of Mine 8.

The slope of the Gutenberg-Richter frequency-magnitude relation (b-value) is often considered a good estimator of seismic hazard. The data in Table VI suggest that b-value is insensitive to seismic hazard and does not correlate well with the maximum event size recorded in the mine (Figure 6).

Some mines use the total number of events in a time period (such as number of events ar day, or events a month) as an indicator of seismic hazard. The yearly number of events recorded by seismic systems in 11 Australian mines is compared with the maximum event size in Figure 7. The total number of events recorded is a poor indicator of maximum event size and a poor measure of seismic hazard.

Seismic hazard in a mining block

Seismic hazard varies spatially in a mine. It is strongly influenced by geological, stress and mining factors, all of which vary considerably throughout the mine. It is a conservative assumption to presume that the maximum seismic hazard in a mine is an adequate measure of seismic hazard

for all of the regions of a mine. Even in very seismically active mines, there will be many regions with relatively low seismic hazard. From a seismic risk management perspective, knowing the spatial distribution of seismic hazard allows seismic risk management control measures to focus on the areas of highest risk.

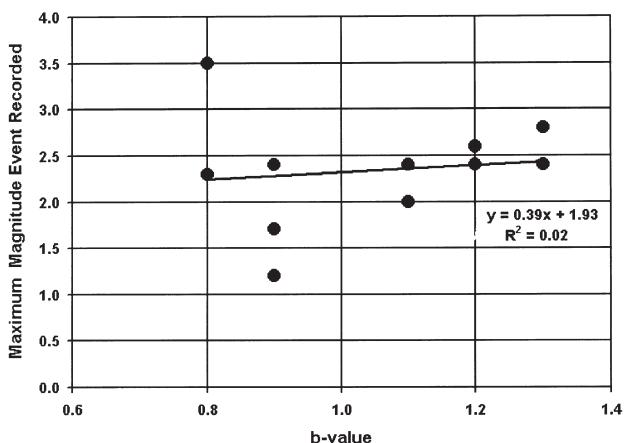


Figure 6—Comparison of b-value with the maximum event size recorded in 11 Australian mines

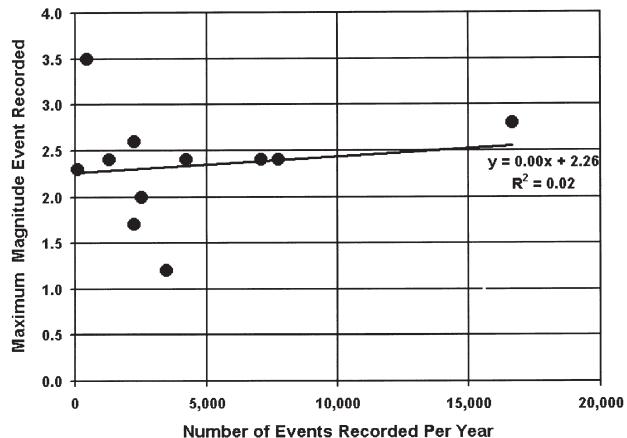


Figure 7—Comparison of the yearly number of events recorded in a mine with the maximum event size recorded in the mine

Seismic hazard in Western Australian mines

The Seismic Hazard Scale can be used to evaluate seismic hazard associated with various regions in a mine, such as a mining block, by evaluating the seismicity that has occurred in the region. This allows seismic hazard assessment to better reflect the local failure mechanisms causing the seismicity in the region.

Table VII compares the mine seismicity that has occurred in 16 mining blocks in several mines in Western Australia. In Figure 8, SHS is compared with the magnitude of the largest event recorded in the mining block. The average and maximum SHS are calculated using Equation [4], over several different magnitude ranges and assuming $b = 1.0$.

Figure 8 shows the maximum SHS overestimates the maximum event size by an average of about 0.4. The maximum SHS appears to be a reasonable upper bound for the maximum event size in a mining block. The same basic conclusions can be drawn for mining blocks as were made

above for minewide data sets:

- each magnitude range often gives a good estimate of seismic hazard
- the maximum event size is not particularly sensitive to b-value
- the maximum event size is poorly related to the number of events recorded.

Assessing the SHS on a mining block scale allows for the factors causing seismicity in the mining block to be reflected in the hazard assessment. This allows higher hazard mining blocks to be identified, which potentially aids in identifying the root causes for the higher seismic hazard. From a practical mine site perspective, assessing seismic hazard on a mining block scale provides quantitative evidence to support what mine site personnel have probably already recognized – some parts of a mine are much more prone to large seismic events than other parts.

Table VII

Comparison of mine seismicity in mining blocks in several Western Australian mines

Mine block	Monitoring period (years)	Number of events recorded	b-value	Magnitude of largest event	Max SHS	Seismic hazard scale (SHS) for magnitude equal or greater than								Max SHS	Ave. SHS
						0	0.5	1	1.5	2	2.5	3	3.5		
1	1.7	315	0.9	1.0	1.3	1.2	1.3	1.2	-	-	-	-	-	1.3	1.3
2	1.8	3,600	1.0	1.2	1.2	1.0	0.7	1.2	-	-	-	-	-	1.2	1.0
3	1.7	1,300	0.8	1.2	1.7	1.5	1.7	1.5	-	-	-	-	-	1.7	1.6
4	1.7	800	1.1	0.3	0.8	0.8	-	-	-	-	-	-	-	0.8	0.8
5	0.9	2,100	0.8	1.8	2.5	2.5	2.5	2.3	-	-	-	-	-	2.5	2.5
6	0.9	5,100	0.9	2.8	2.8	2.8	2.8	2.6	2.7	-	-	-	-	2.8	2.7
7	1.8	900	0.9	1.5	2.0	1.8	2.0	1.9	1.7	-	-	-	-	2.0	1.8
8	1.8	1,300	0.8	2.0	2.2	1.8	2.0	2.1	2.0	2.2	-	-	-	2.2	2.0
9	1.5	600	0.9	2.4	2.3	2.1	2.0	2.0	2.2	2.3	-	-	-	2.3	2.1
10	2.8	1,500	1.0	1.5	1.9	1.9	1.7	1.7	1.5	-	-	-	-	1.9	1.7
11	2.8	6,400	1.0	2.0	2.7	2.6	2.6	2.7	2.4	2.0	-	-	-	2.7	2.5
12	0.8	11,800	1.2	2.4	3.0	3.0	3.0	2.9	2.6	2.5	-	-	-	3.0	2.8
13	1.5	220	0.8	1.6	2.1	1.8	2.0	1.9	2.1	-	-	-	-	2.1	1.9
14	4.5	900	0.7	3.5	3.3	2.3	2.3	2.5	2.7	2.8	3.1	2.8	3.3	3.3	2.7
15	2.5	5,400	1.0	2.4	2.3	2.2	2.3	2.2	2.2	2.3	-	-	-	2.3	2.3
16	2.5	4,400	1.0	1.8	2.2	2.2	2.2	2.2	2.2	-	-	-	-	2.2	2.2

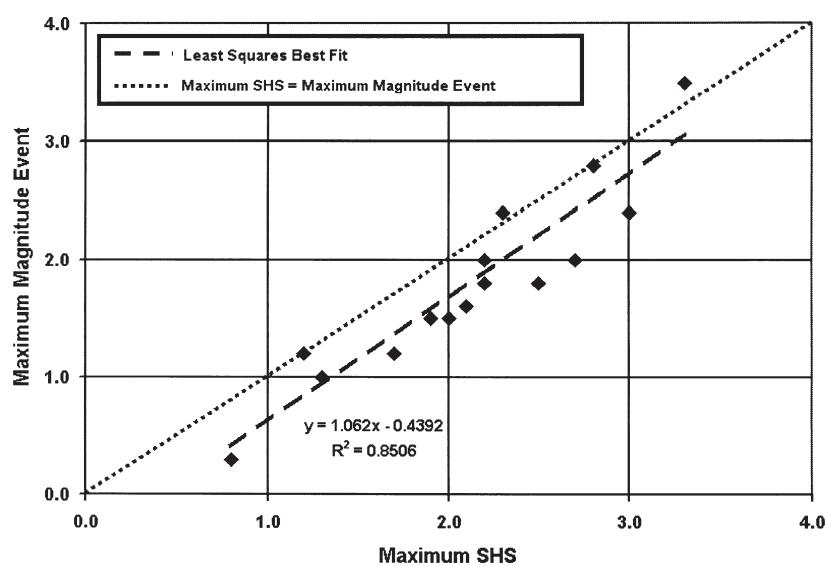


Figure 8—Maximum SHS is compared with the maximum magnitude event recorded in mining blocks in several Western Australian mines

Seismic hazard in Western Australian mines

Seismic hazard in a cluster of seismic events

Well-located seismic events often exhibit strong spatial clustering¹²⁻¹⁴. It is proposed that each cluster of seismic events potentially represents a separate seismic source mechanism, as determined by a unique local combination of stress, structure and mining influences. The magnitude distribution of seismic events that occur at each seismic source is dominated by the local failure mechanism.

The SHS can be extrapolated to individual clusters of seismic events in a mine. Conceptually, each cluster of seismic events represents a local rock mass failure process occurring in the mine. Typical failure processes include pillars deforming or failing owing to increased average load or due to loss of confinement, faults displacing, abutments of stopes responding to stress increase in nearby stoping, etc.

Seismic events from a Western Australian mine are shown on a mine plan in Figure 9. The SHS is applied to clusters of events on a mine plan to create a seismic hazard map (Figure 10). The data in Figure 10 suggest a higher

seismic hazard near two of the geological features (A and B).

Several unpublished case studies of seismic data from Western Australian mines have found that this seismic hazard mapping technique is very effective in understanding spatial variations in seismicity¹⁵. It identifies areas of high seismic hazard, as well as areas of low seismic hazard. It facilitates interpreting the sources of high hazard by spatial comparison to geological features, mining structures and high stress zones. It is much easier to identify control measures to manage seismic risk when the high-risk areas and the root causes of the high hazard have been identified.

Some of the assumptions associated with seismic hazard mapping by cluster include:

- seismic data must be sufficiently well located to identify clusters of events reliably
- seismic hazard is considered to be constant at all points within a cluster of seismic events
- there must be an adequate seismic record, so that the seismic data adequately reflects the seismic response at each source of seismic activity.

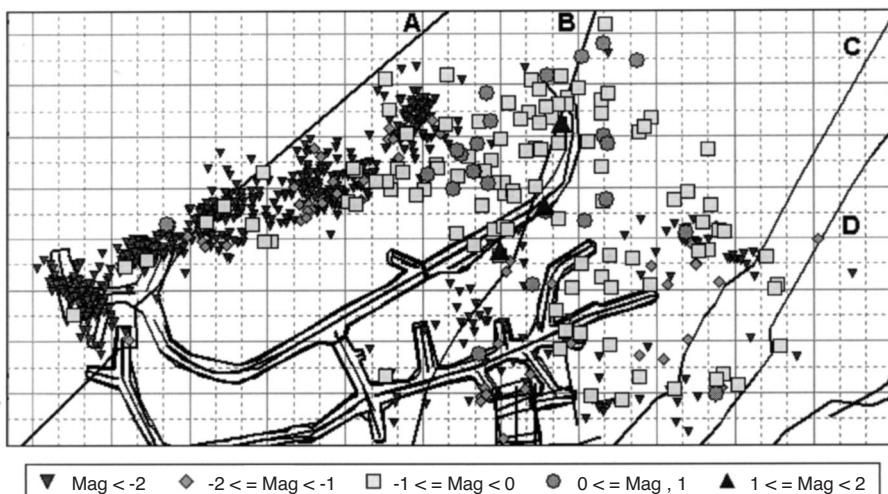


Figure 9—Events near a level in a Western Australian mine. The four thin lines (A B C D) represent the location of geological features in the mine

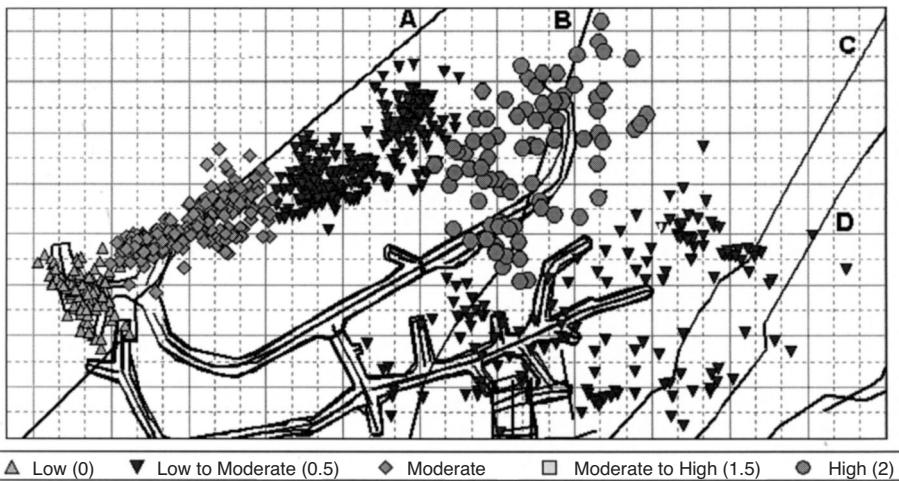


Figure 10—Clusters of events near a level in a mine related to the events in Figure 9. The events are displayed according to the seismic hazard assessed to the cluster using the Seismic Hazard Scale. The number following the name represents the largest event expected in the cluster

Seismic hazard in Western Australian mines

Temporal variations in seismic hazard

In the detailed analysis of data on Western Australian mines, it has been found that mines prone to large seismic events almost always have a significant history of smaller and moderate sized events prior to the large events. This observation is based on detailed analysis of seismicity at several mines in Western Australia¹⁵. If the power law with respect to mine seismicity holds true, the frequency of occurrence of smaller events could be used as an indicator of the maximum event that could occur.

Examples of seismicity in a mining block and a stoping block in two Australian mines are shown with magnitude time history charts in Figure 11 and Figure 12. In Figure 11, an incomplete seismic event record is shown for a several million ton mining block (significant seismicity pre-dated the installation of the seismic system in May 1994). Figure 12 shows the complete seismic record for a several hundred thousand ton stoping block. The occurrence of seismic events in both charts is shown as diamond shaped symbols. The

average and maximum SHS (calculated from Equation [4] and using several magnitude ranges) is shown as lines in Figures 11 and 12. In the cases of both the mining block and stoping block, the rate of occurrence of smaller events often suggests the occurrence of larger events, before the larger events occur.

Table VIII shows the occurrence of increasing event size in the two examples in Figures 11 and 12. At the time of occurrence of an event larger than has been previously recorded in the mining and stoping block, the maximum SHS often gave a good indication of the future event magnitude. For example, in the first row in Table VIII, on 5 July 1994, a Richter magnitude +0.3 event occurred. Prior to this event, the largest event that had occurred in the mining block was Richter magnitude 0.0. Based on the seismic history prior to 5 July 1994, the average SHS was 0.5 and the maximum SHS was 0.7. In 10 of the 13 cases in Table VIII, the maximum SHS is an indicator of the maximum magnitude of the next large event.

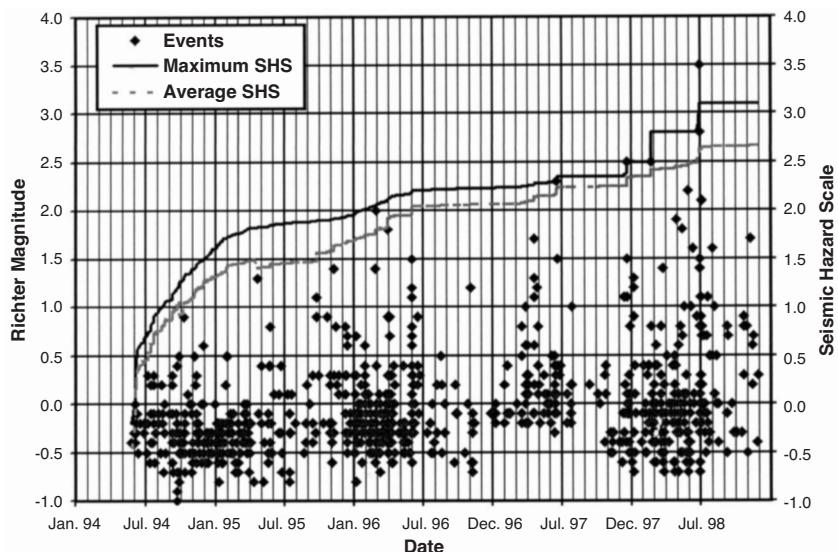


Figure 11—Magnitude time history chart for seismicity in a several million ton mining block in an Australian mine. The time of occurrence of seismic events is shown with diamond symbols, while the average and maximum SHS are shown with lines

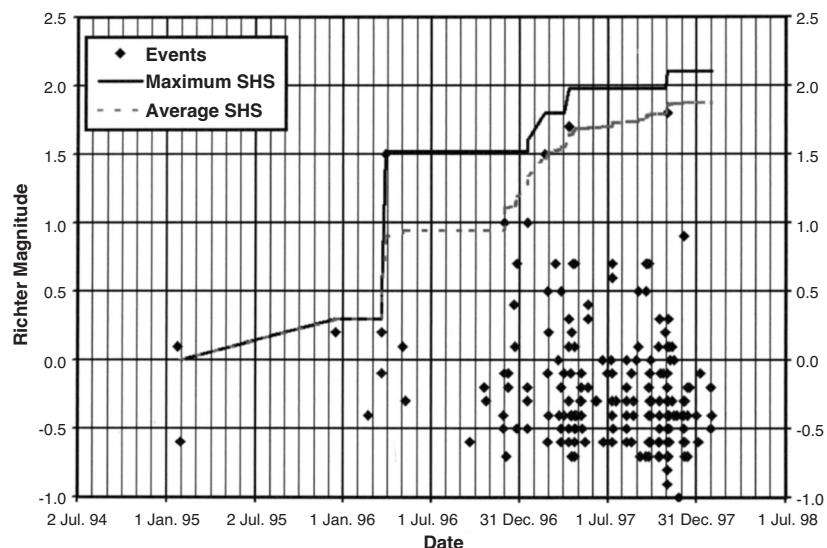


Figure 12—Magnitude time history chart for seismicity in a several hundred thousand ton stoping block in an Australian mine

Seismic hazard in Western Australian mines

Table VIII

Data is presented for increasing event sizes for a several million ton mining block (top) and a several hundred thousand ton stoping block (bottom)

Date	Event magnitude	Largest event prior to that date	Average SHS	Maximum SHS
05 Jul. 1994	0.3	0.0	0.5	0.7
19 Sep. 1994	0.4	0.3	1.0	1.2
27 Sep 1994	0.5	0.4	1.1	1.2
06 Oct 1994	0.9	0.5	1.0	1.3
11 Apr. 1995	1.3	0.9	1.5	1.8
09 Nov. 1995	1.4	1.3	1.6	1.9
27 Feb. 1996	2.0	1.4	1.8	2.1
18 Jun. 1997	2.3	2.0	2.2	2.3
20 Dec. 1997	2.5	2.3	2.3	2.4
19 Jun. 1998	3.5	2.5	2.5	2.8
27 Mar. 1996	1.5	0.2	0.2	0.5
11 Apr. 1997	1.7	1.5	1.3	1.8
26 Oct. 1997	1.8	1.7	1.7	2.0

The data in Figure 11 and Table VIII also suggest that a complete seismic history may not be necessary to obtain a reasonable estimate of seismic hazard. This implies that if there is an adequate monitoring period for the smaller seismic events to reflect the seismic hazard, the frequency of occurrence of the smaller events may give a good indication of long-term seismic hazard potential.

The SHS scale can also be used to investigate temporal changes for individual clusters of seismic events. Results from analysis of numerous clusters of seismic events give comparable results to those found in Figure 11, Figure 12, and Table VIII.

Summary

The Seismic Hazard Scale (SHS) is a measure built around the Gutenberg-Richter frequency-magnitude relation of mine seismicity. Essentially, SHS is the x-axis intercept of the relation. SHS is strongly related to the frequency of occurrence of events of a given magnitude. It is also highly dependent upon a well-behaved frequency-magnitude relation. The data analysed show relative insensitivity to b-value. This suggests that calculating b-value is often unnecessary and that it may be reasonable to set $b = 1.0$.

The SHS is meaningful and useful on three scales of seismicity: minewide, for a mining block, and on a seismic event cluster basis. It can potentially be used for seismic hazard estimation for data sets of less than 1000 events, and for time periods as short as several months.

The SHS can be used to estimate seismic hazard without the availability of seismic data, as demonstrated through the mine seismicity survey.

There is value in using the SHS to investigate temporal changes in seismicity. It has been demonstrated that the rate of occurrence of small- and medium-size seismic events often gives a good indication of long-term seismic hazard potential.

This work shows that, in Western Australian mines, the application of the Gutenberg-Richter relation can be very useful to understand general seismic hazard as well as spatial variations and temporal increases in seismic hazard.

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