

Seismic Magnitude and its Application in the Industry

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ABSTRACT:

Many deep South African gold mines currently use seismic networks to monitor and quantify the seismicity that is routinely experienced. The severity as well as the amount of seismicity experienced varies from mine to mine. This depends on the production rates and activity experienced along the different emission sources. What is surprising though is that the equations to calculate magnitudes in the mining areas of Welkom, Orkney, and Carletonville are not the same.

The severity of the damage for the same magnitude differs from area to area. This is due to a number of reasons including emission source, geology (mineralogy), ground conditions, mine design and magnitude equations that are not only different for the different regions but also dependent on the seismic instrumentation used. The latter being the only non-natural reason.

Each mining area has a local magnitude definition that incorporates the energy and moment, or just the moment, of the seismic event. The energy and moment are calculated directly from the waveforms received from the seismometers using a Brune model and has a standard deviation close to one. Add to this different equations and the difference in magnitude becomes potentially larger.

The magnitude definitions for the different areas have been assessed and compared in an attempt to determine a standard that can be used by all. This is then also compared to the magnitude used by the Council for Geosciences as well as the so-called Richter magnitude that is used internationally. This has become necessary due to (a) an international definition required by insurance companies and (b) a means of grading seismic hazard and possibly standardizing procedures across the different regions.

1) Introduction:

Many deep South African gold mines currently use seismic networks to monitor and quantify the seismicity that is experienced. Many factors influence the severity and amount of seismicity; these include production rates and emission sources which differ from mine to mine. Different variations of the Local Magnitude equation are used in each area. This results in different amounts of damage for seismic events of the same magnitude experienced in the various mining areas. There are many natural explanations for this, including emission source, geology (mineralogy), ground conditions, and mine design. It is the non-natural reasons such as magnitude definitions and differing seismic instruments that are of concern.

Besides the size of failure, the energy and moment of a seismic event are reflective of the physical properties of the rock mass in much the same way that mineralogy reflects density or magnetic susceptibility and consequently gravity or magnetism. Thus these properties would be different for different regions, and also different

within regions depending on the heterogeneity of the region. The magnitude of a seismic event, as measured on the Harmony mines, is a combination of the moment magnitude and the energy magnitude. However, the proportion of the local magnitude that is due to the Moment or Energy differs not only for the regions, but also for the different emission sources. Over the past 15 years the practice of varying the constants within the equation, in an attempt to normalize the magnitude for the regions, was standard and remains so. The question is has this been successful in providing a measure of a seismic event that is independent of region or emission source? More importantly is it equally reflective of the potential for damage, barring of course site effects like ground control or localized stress fields?

2) History of the Seismometer:

The earliest seismometer, believed to have originated in China, was invented by Chang Heng and called an Earthquake Weathercock. It was simple in design and incorporated a simple pendulum to amplify the earthquake signal. It

could also tell the direction that the earthquake came from.

There were many fallacies concerning the origin of earthquakes. In eighteenth century Europe it was believed that they were caused by exploding sulfurous matter and various salts in the interior of the earth. Only when the sources and mechanisms of earthquakes were identified could instruments to detect them be appropriately designed. Most of the earliest seismoscopes from the nineteenth century used simple pendulums (similar to the Earthquake Weathercock) to measure the amplitude of the seismic waves that were released from a major seismic event.

Since then there has been a lot of development of the seismometer, eventually resulting in the highly sensitive electronic instruments that are used today. Many parameters can now be calculated directly from the waveforms detected by the seismic instruments. Most important though are energy and moment.

3) Magnitude definitions:

The magnitude of a seismic event is a rating of an earthquake independent of the place of observation. But this is difficult to achieve as magnitude scales suffer intrinsic limitations such as saturation and discrepancies between various scales. For example, seismic energy describes the potential for damage to artificial structures better than the seismic moment, although seismic moment provides a better description of the overall size of the event (Gibowicz and Kijko, 1994). This is excluding the limitations of the instrumentation. The following are the best known and used magnitude definitions from the past century.

3.1) Mercalli Scale:

There are two main scales used when calculating seismic magnitudes, an intensity scale, and a scale based on scientific measurements such as energy and moment. The most commonly used intensity scale is called the Modified Mercalli scale. It measures the amount and type of damage to buildings and other man made structures. It is basically a damage scale which identifies the effect that the seismic event had on the population in the area. This is not an absolute way of measuring seismic magnitude. If the seismic event occurred in a densely populated area it will have a much larger magnitude compared to the same event occurring in a rural area. For the purposes of mine

seismology this method is not practical or very well suited.

3.2) Richter Magnitude (1935):

The Richter magnitude of an earthquake is defined as the logarithm of the maximum amplitude, traced on a seismogram from a standard Wood-Anderson seismograph at 100 Km from the epicenter. Amplitudes at other distances are corrected to the standard distance of 100 Km using empirical functions. The Richter magnitude is defined as follows:

$$M_L = \text{Log}(a) - \text{Log}(a_0) \quad (1)$$

Where (a) is the maximum amplitude and (a_0) is the amplitude for a magnitude zero event at the same distance.

A problem with the Richter magnitude is that it is specifically based on measurements taken on Wood-Anderson seismometers that are obsolete today and is reflective of the geology of Southern California. It is also based only on information from the time domain. Another problem lies in the correction of amplitudes, to the standard distance of 100 Km, using empirical functions. These functions assume that the ratio of maximum amplitudes at two given distances is independent of azimuth, and is the same for all earthquakes.

3.3) Moment Magnitude:

One of the more recently used magnitude definitions is called the moment magnitude. This essentially uses only the moment to calculate the seismic magnitude. The moment of a seismic event was first calculated in 1966 in Japan, and since then has been used increasingly in seismology. It is related to the fundamental parameters of the faulting process, such as the area of the faults rupture surface and the amount of slip experienced and is independent of the source model. The equation to calculate moment is as follows:

$$M_o = \mu S \langle d \rangle \quad (2)$$

Where (μ) is the rigidity of the rock mass involved, (S) is the area of the faults rupture surface, and ($\langle d \rangle$) is the average amount of movement on the fault (otherwise known as 'ride'). Moment is measured in Nm (Newton Metres).

For Moment magnitude the equation is as follows (Hanks and Kanamori, 1979):

$$M_w = \left(\frac{2}{3}\right) \log_{10}(M_o) - 6.0 \quad (3)$$

Moment magnitudes are valid for any size earthquake and generally show similar values to the Richter magnitude. Discrepancies start to develop when the magnitudes start approaching $M_L=7.5$ (Howell, 1990). Hutton and Boore (1987) suggest that the Local magnitude scale begins to saturate at about $M_L=6.0$, as it relies on measurements taken from a finite bandwidth seismograph. The Moment magnitude does not rely on the instrumental recordings, but rather on fundamental parameters of the faulting process.

Moment magnitudes are used extensively in the monitoring and reporting of large scale tectonic events that occur at seismically active plate margins. Since the Local magnitude scale and the Moment magnitude scale are so similar for seismic events below $M_L=6.0$ the application of this type of magnitude definition in mining seismology is relevant in terms of event size and source mechanisms only.

3.4) Energy Magnitude:

The equation used to determine the magnitude is as follows (United States Geological Survey):

$$M_E = \left(\frac{2}{3}\right) \log(E_s) - 2.9 \quad (4)$$

Where E_s is the radiated seismic energy in Joules. This definition is similar to the one used for the Moment magnitude, and is thought of as a measure of the seismic potential for damage. This magnitude definition is based on measurements taken in the frequency domain.

3.5) Duration Magnitude:

This magnitude scale used the duration time of the seismic event to calculate the magnitude. The duration scale was then calibrated against magnitudes reported by the Geological Survey. The generic form of the duration magnitude is as follows (Gibowicz and Kijko, 1994):

$$M_D = B \log(\tau) + CR + D \quad (5)$$

Where (τ) is the duration, in time, of the seismic event and all other variables are calibration and

site effect constants. This definition was used extensively in the past, but due to improvements in computers and digital electronics it has become redundant.

3.6) Surface-wave Magnitude:

This is a similar definition to Local magnitude, but is more useful over large distances as surface waves have a very long period (approximately 20 seconds). The equation is as follows:

$$M_s = \log\left(\frac{A}{T}\right) + S \quad (6)$$

Where (A) is the maximum displacement, (T) is the period of displacement, and (S) is a correction factor for the distance of the stations and depth of the seismic event.

This magnitude definition and variations of it are extensively used by earthquake (tectonic) seismologists as it is reflective of the damage potential of surface structures, particularly in high populated areas. However, within the mining environment the instrumentation and emission sources are within the solid rock mass and relatively very close. This magnitude scale would be relevant for potential damage to surface property but is less so for conditions underground.

3.7) Body-wave Magnitude:

The Body-wave definition was brought about to be used at teleseismic distances. It was used to infer information about the core of the earth by measuring P and S waves that travel through this region. It is these waves that affect the underground environment; however the magnitude definition was designed for research purposes (tectonic seismology) and not for the mining industry.

3.8) Local Magnitude:

The time domain Local Magnitude of a seismic event is an extension of Richter's ideas on measuring the amplitude of the seismic event. This magnitude definition has been modified to use modern seismometers by adding constants to the equation (see **equation 2**, Gibowicz and Kijko, 1994).

$$M_L = \log(A_{Max}) + B \log(R) - C \quad (7)$$

Where (A_{Max}) is the maximum amplitude, (B) accounts for the spreading and attenuation of S waves along the source receiver distance (R), and (C) is an amalgamation of calibration constants.

With the advent of digital electronics and computers, real time energy and moment calculations and conversion from the time domain to the frequency domain has been made quick and easy. This has resulted in the following magnitude definition being used within the South African mining industry:

$$M_L = A \log(E) + B \log(M_o) - C \quad (8)$$

4) Magnitude definitions used in Harmony mines:

Within the Harmony group of mines there are a number of magnitude definitions in use at the moment. These are all based on the Local magnitude definition, but with variations due to differences in the mining areas. All of the Harmony mines use the magnitude definitions inherent to the ISS International system.

The data presented comes from the three main mining areas of Carletonville (Elandskraal), Orkney (Harmony Orkney), and Welkom (Bambanani and Tshepong mines). The Magnitude definitions are as follows:

Carletonville:

$$M_L = 0.272 \log(E) + 0.393 \log(M) - 4.630$$

Orkney:

$$M_L = 0.263 \log(E) + 0.333 \log(M) - 3.612$$

Welkom:

$$M_L = 0.275 \log(E) + 0.433 \log(M) - 5.124$$

Two separate methods of comparing the magnitudes were performed. In the first method constant values of energy and moment were used to determine the magnitude (**Table 1**). In the second, the energy and moment for fixed magnitude from the three mining areas were compared. The average energy and average moment for events with a range of $M_L=0.5$ to 0.55 ; 1.0 to 1.05 ; 1.5 to 1.55 etc. were used. While a large database exists only 5000 events were used to ensure that software variation influences were not included.

	Log(M):Log(E)
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Area	9:4	10:5	11:6	12:7	13:8
Magnitude (M_L)					
Welkom	-0.13	0.58	1.29	2.00	2.71
Carleton.	-0.01	0.66	1.33	2.00	2.66
Orkney	0.44	1.03	1.63	2.23	2.82

Table 1: Magnitudes for specific Log (E) and Log (M).

As can be seen above, for the same moment and energy the different areas exhibit different magnitudes. The difference is not that drastic between the events in Welkom and Carletonville, but significantly different in Orkney ranging from 0.56 for smaller events, to 0.17 for larger ones. Essentially seismic events with the same fundamental parameters (energy and moment) have different magnitudes. The damage potential for the different regions is also significantly different.

Plots of E/M are shown on **Figures 1 & 2** for the purpose of visualization. The units are Joules/Mega Newton Metres. The resulting number is an estimate of the violence of the seismic event as it represents energy released per unit moment. The results are shown in **Table 2**.

Magnitude	Energy/Moment (J/MNm)			
	Tsh	Bam	Eland	Klerks
0.5	1.147	1.979	3.999	0.935
1.0	1.939	2.243	5.731	0.979
1.5	2.996	3.007	6.753	2.666
2.0	5.172	5.721	9.913	4.825
2.5	11.482	9.068	28.840	9.727
3.0	-	26.964	16.982	23.442

Table 2: Energy divided by magnitude for known seismic events

This highlights that the potential violence of events for a certain magnitude is not uniform across the various mining areas and increases exponentially with increasing magnitude i.e. per given moment an $M_L=2.5$ event is 10 times more violent than an $M_L=0.5$ event at Tshepong mine. It can be seen that the events at Elandskraal are a lot more violent than all the other areas. This might be expected as mining depths are greater creating a larger confining pressure on the rock mass, and the lithology is different as the Venterdorp Contact Reef (VCR) is being mined. This reef lies up against mafic lavas of the Ventersdorp Supergroup and exhibits much more brittle behaviour compared to the quartzite in Welkom and Orkney.

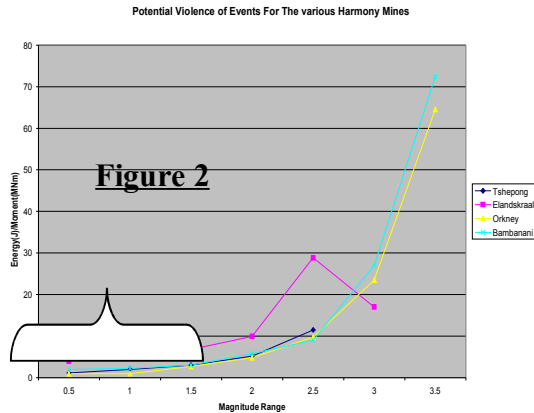


Figure 1: Potential violence of seismic events at the various mines

The large drop in the Elandsdraal curve at $M_L=3.0$ is surprising, but can possibly be explained by the fact that all of these large events have occurred along faults and that none have caused any damage in the last two years. The proportional potential for violence is less from this emission source (faults with a lower frictional surface) than from abutment failure and face bursts that occur within the more brittle and intact rock (primary shear rupture).

Figure 2 is a close up of the smaller events from **Figure 1**, which shows more clearly the contrast between the mines.

This again shows that the potential violence of all events in the Carletonville area is so much greater than all the other regions. This is due to both the different physical properties and different emission sources. In the Welkom and Orkney areas the major emission source of potentially hazardous events are geological structures (secondary shear rupture or reactivation of existing weak zones), whereas in Elandsdraal it is predominantly abutment failures and face bursts (primary shear rupture and/or explosive bursting).

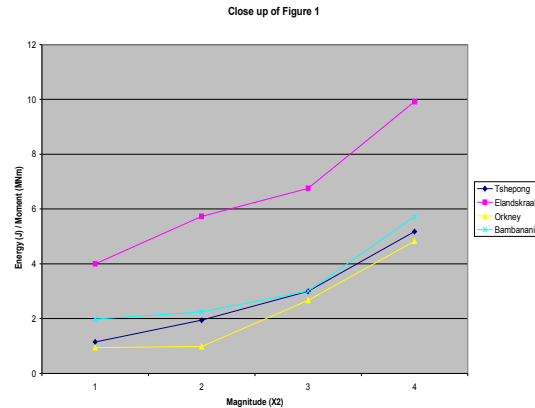


Figure 2: Close up of the potential violence curve.

5) Conclusions:

From the analysis undertaken on the magnitude definitions themselves, relatively large discrepancies in magnitude were found for the same energy and moment. Conversely seismic events with the same magnitude give different measures of potential violence for the different regions. Thus magnitudes are area specific, instead of being standard. Therefore seismic events with the same magnitude in the different mining areas will have very different damage effects underground.

This highlights the need to develop new or to modify the old magnitude definitions, most of which were developed for tectonic global seismicity. Mining seismology has very different needs to tectonic seismology, and thus should have definitions that are suited to our environment. Perhaps a measure of the potential violence should be incorporated into a definition. This would help production personnel to understand the damage potential of seismic events. Such a definition would need to incorporate the following term:

$$V_{EM} = \frac{E}{M_o} \quad (9)$$

Where (V_{EM}) is the potential violence of the event, (E) is the energy released in Joules, and (M_o) is the moment in Mega Newton Metres ($Nm \times 10^6$). This method or something similar will have to be developed further with extensive input from the seismic fraternity.

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