Rock mass behaviour under seismic loading in a deep mine environment: implications for stope support

by A. Cichowicz*, A.M. Milev† and R.J. Durrheim†

Introduction

In this study we seek to apply techniques used by earthquake engineers to design earthquake-resistant structures to the rockburst problem. These techniques involve the prediction of ground motion at the site of the structure, and the design or reinforcement of the structure to reduce the amplification of motion at resonant frequencies.

One of the most important problems encountered in earthquake seismology is the prediction of ground motion parameters at the site of interest. The classical approach is to evaluate peak ground velocity as a function of distance between source and station ($R$) and magnitude of seismic event ($M$) (Kaiser1). In this type of relation, the stress drop of the seismic event ($\Delta\sigma$) may replace magnitude, as stress drop relates directly to peak ground velocity (McGarr et al.2). Analysis of seismically-induced falls of ground at East Rand Proprietary Mine show that damage occurred where predicted peak ground velocities were as little as 0.005 m/s, and that much damage occurred at predicted peak ground velocities smaller than 1 m/s (Cichowicz3). Similar low values of predicted peak ground velocity at sites of damage were noted by Butler and Van Aswegen4. These peak ground velocities were predicted by a $V_{\text{max}}(\Delta\sigma,R)$ relationship applicable for seismic stations located in solid rock. However, the presence of the free surface, fractured rock surrounding the excavations, and the geometry of the excavation influence the ground motion at the excavation wall. These phenomena can cause unusual amplification of ground motion parameters at the site (Durrheim et al.5).

Observation and analysis of seismic motion in the rock surrounding a stope

Field observations

A three-dimensional seismic array installed in the 93E4 panel, Tau Tona Mine (previously Western Deep Levels, East Mine) provided an opportunity to examine the change in the waveform close to an underground opening. A set of three-component geophones installed in a borehole above the panel revealed the development of surface waves as wave fronts reached the excavation, and an array of vertical component geophones fixed to the hangingwall provided a two-dimensional map of site effects. While the collected data do not include damaging seismic events, quantitative analysis enabled phenomena which could lead to damage, to be recognized.

In the vicinity of the excavation, the energy of the seismic signal is generally transformed from high frequency to low frequency. It was found that seismic events with relatively high corner frequency (150 Hz–200 Hz) usually excite several modes of vibration (30 Hz to 110 Hz), while events with low corner frequency (30 Hz–50 Hz) do not always excite higher modes of vibration in the structure. This implies that the rock mass around the excavation is a complex medium, and should be studied using the multi-degree-of-freedom model.

A strong structural effect (due to the excavation shape) was revealed as a low frequency coda wave (at 40 Hz and 60–70 Hz), well developed on the skin of the hangingwall. A strong site effect was revealed by changes in signal properties between hangingwall geophones, exhibiting strong resonances around 160 Hz and in the range 200 Hz to 300 Hz.
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sets of geophones were installed in a borehole (Figure 1). The signal of the top station ('A' in Figure 1) was dominated by a resonant frequency, probably due to inadequate grouting. The data from this site was excluded from further analysis. The deepest set used in the analysis (station B) was located at a depth of 6.5 m. The shallowest set (station E) was at a depth of 0.5 m. Stations C and D were located between station B and station E, 2 m apart. Five vertical-component geophones were fixed to the skin of the hangingwall in the vicinity of the borehole mouth, over an area of roughly 3 m x 3 m. Additionally, two vertical geophones were installed on the footwall. The geophones on the skin of the hangingwall and on the footwall were connected to the Ground Motion Monitor (GMM), while those geophones in the borehole were connected to a Portable Seismic System (PSS) (Hagan et al.7, Daehnke et al.8). Some 100 seismic events in the lower range of the magnitude scale were used in this study. After adjustment of time and amplitude scales of both systems, it was possible to compare the waveforms recorded in the vertical borehole array with the corresponding waveforms recorded on the skin of the excavation.

Identification of body and surface waves

Seismograms from the vertical borehole array (Figure 2)

Figure 2—Seismograms (for the same event) recorded by the borehole array (Portable Seismic System). Stations B, C, D and E are located from the top to the bottom of the borehole. The amplitudes are in mm/s
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show well-developed P- and S-waves groups, followed by low frequency surface waves. There are several points in time where the amplitude of the body wave groups show a sharp change in phase. These points are associated with new arrivals. This indicates that the structure of the medium is rather complex, and that the seismic events are located close to the three-dimensional array. The stations B and C have almost identical waveforms. A simple extrapolation from the waveform of station C to the waveform of station D or station E is difficult, because the last-mentioned stations have additional impulses associated with the latter part of the body wave groups. This complication could be associated with the presence of the Green Bar (Schweitzer et al.9).

The geophone array shows the development of surface waves as the wave front reaches the excavation. A well-developed low frequency coda is observed on and near the skin of the hangingwall (Figure 2, Station E). The absence of strong coda waves in seismograms recorded at the top of the borehole indicates that these waves propagate primarily close to the stope, and can be categorized as surface (probably Rayleigh) waves. High frequency body wave energy is partially converted to low frequency surface wave energy. The partition of energy depends on factors such as the frequency content and location of the seismic event. It is important to note that the surface wave amplitude can be greater than the body wave amplitude in the skin of the hangingwall.

Two-dimensional mapping of the site effect

The vertical ground motion recorded on the skin of the hangingwall is used to produce a two-dimensional map of the site effect (Figure 3). Geophone 2, which has been installed close to the borehole as an extension to the vertical array, shows a waveform very similar to that of station E. Geophones 2, 3 and 6 are similar in character, while geophones 4 and 5 show strong site effects. The ratio of the peak ground motion recorded on the skin of the hangingwall (geophones 2, 3 and 6) to the corresponding peak value in the solid rock, has been calculated for a number of seismic events. The peak particle velocity recorded on the skin was 0.7 to 4.5 times greater than the peak particle velocity recorded in the solid rock. The amplification factor depends on the dominant frequency of the seismic signal. The lower the corner frequency of a seismic event, the stronger the amplification on the hangingwall skin.

Decomposition of source, structural and site effects

Spectral analysis was carried out on all records to identify the influence of the excavation (the ‘structure’), and local effects such as variations in the intensity of fracturing or the influence of support elements (the ‘site’), on the seismic wavefield. The first task was to identify the corner frequency of the source using seismograms recorded by the borehole array. The horizontal components of body waves of station B were used to calculate the corner frequency of the seismic source. The spectrum of station D has several consistent peaks, which could be related to the interaction of the seismic wave with the Green Bar. Station E often showed amplification at 140 Hz. The surface wave spectrum, that carries information about structure, usually has two strong peaks at 40 Hz and 60–70 Hz.

In the time domain, the peak amplitude of the vertical component of the surface waves increases 3 to 4 fold from station B to station E. A significant difference between the spectral amplitude at station B and station E is to be expected. On average, the peaks in the spectrum at station E are about 3 to 4 times stronger than the peaks in the spectrum at station B. Figure 4 shows a systematic increase in the amplitude of the 70–80 Hz peak as the stations approach the skin of the excavation.

The geophones fixed to the hanging- and footwall were used to study structural and site effects. The spectrum of station B, situated 6.5 m into the hangingwall, was used as a reference. The spectral peaks observed at several points on the hangingwall, and not at station B, are considered to be due to the structural effect (Table II). The structure produces several spectral peaks, with resonance at 50 Hz and 60 Hz observed most frequently. All seismic events do not, however, excite all possible resonance frequencies. The location of seismic events with regard to the position of the recording site appears to affect the induced resonance.

The seismic array fixed to the hangingwall was used to study the site effect. Geophones 4 and 5 show strong site effects for all events. Geophone 5 has strong resonance at 160 Hz, while geophone 4 usually has several peaks around 160 Hz and 300 Hz. At geophone 3, a 160 Hz peak is observed, but it is very small. No site effects are observed at geophones 2 and 6. A band pass Butterworth filter (120 Hz–250 Hz) was applied to data from geophones 4 and 5 to study the character of the resonance signal in the time domain. At geophone 4, the resonance signal is strong at the arrival of the surface wave group, and then quickly decays. At geophone 5 the sequence of impulses is distributed across the entire seismogram (see Figure 3) although its amplitude is smaller than at geophone 4.

In some cases the records from the footwall site (geophones 7) display relatively strong surface waves not observed at the hangingwall sites. In one case, the footwall site had a very strong signal around 300 Hz, but no surface wave was observed.

Multi-degree-of-freedom analysis

A method for the time-domain identification of linear multi-degree-of-freedom structural dynamic systems was outlined by Cichowicz and Durrheim10 and Cichowicz et al.11. Seismic records of a single input and single output are sufficient to determine the transfer function between seismic sensors installed in the solid rock and at the skin of the hangingwall. The transfer function is parameterized as a series of damped oscillators, and is determined in a time domain inversion process. This approach has an additional benefit of being able to show how the structural and site effect develop during ground motion caused by a seismic event.

Data from the borehole array show at least three different phases. Two phases are observed in the shear wave group and a third phase is associated with surface waves. A model
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Figure 3—Seismograms (for the same event) recorded by the surface array (Ground Motion Monitor). Geophones 2, 3, 4, 5 and 6 are installed on the skin of the hangingwall and geophone 7 is installed on the footwall. The amplitudes are in mm/s.
of the transfer function obtained at the end of a seismogram matches the recorded seismogram reasonably well, but a better match is observed by using a separate transfer function for each of the three intervals of the seismogram.

Data from the hangingwall array are modelled reasonably well with a single transfer function. This indicates that the interaction between blocks in the hangingwall can be modelled using several damped oscillators. Figure 5 shows the sum of three modal responses calculated at the time 0.105 s, for the transfer function derived between geophones 6 and 5. The calculated and the real model of ground motion have a good correlation. The spectra of the real output, the calculated output, and the transfer function between geophone 6 and geophone 5 is shown in Figure 6. Resonance at 160 Hz is present, but is very weak.

**Interpretation of structural and site effects**

Wave groups were classified as surface (Rayleigh) waves when the following features were present: arrival after the S-wave; frequency content much lower than body waves; and a decrease in amplitude with the distance from the skin (free surface) of the underground excavation. Surface waves were identified on virtually all seismograms recorded at the hangingwall, footwall, and the borehole stations.

A number of different researchers have confirmed that the dominant frequency of the Rayleigh waves is strongly dependent on the variation of shear wave velocity with depth at the site (e.g. Murphy and Shah12). The characteristic dominant frequency $f_h$ in the layer can be approximated by the following Equation:

$$f_h = \frac{V_S}{2.3H}$$

where: $V_S$ is an average shear wave velocity in the layer and $H$ denotes the depth to the first significant discontinuity the coefficient of 2.3 was used for surface wave motion. In this

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Figure 4—Amplitude spectra of the surface waves for events recorded by the borehole array. The spectra from stations B and C are marked by a solid line; the spectrum from station D is marked by a dashed-dot line and spectrum from station E is marked by a dotted line

**Table II**

Spectral peaks observed at the skin of the hangingwall (geophones 2, 3 and 6), the peaks are marked with the symbol ‘*’

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Figure 5—The sum of three modal responses calculated from the transfer function at the time 0.105 s (solid line); and the real ground motion at geophone 5 (dashed line), for transfer function between geophones 6 and 5
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The site effect can be explained by a local contrast in medium properties, for example, the contrast in properties between the Green Bar and the quartzite, or differences in medium properties, for example, the contrast in properties where the interface between the softened and bulk material is bonded.

Surface waves were generated in all cases. The amount of energy converted to surface waves was increased by the presence of softened material, and increased further by the presence of a non-cohesive parting plane, as energy was ‘trapped’ within the hanging- and footwall beam in the form of reflected shear waves.

There are other explanations for the complex character of the surface waves. Lateral changes in the shear wave velocity could lead to the refraction of Rayleigh waves. Alternatively, vertical discontinuities could reflect the surface waves, causing them to propagate back and forth. The complicated structure of the recorded Rayleigh waves makes it impossible to identify vertical discontinuity using a small number of stations (Meier et al.17).

The site effect can be explained by a local contrast in medium properties, for example, the contrast in properties between the Green Bar and the quartzite, or differences in fracture intensity. The site effect is not observed at geophone 2 and geophone 6 indicating that the width of the inhomogeneity is less than two metres. The length of the inhomogeneity is not known, due to the limited span of the array.

**One-dimensional model**

A one-dimensional model is commonly applied to estimate the thickness of the layer causing resonance \(H = V_s / A f_h\), where the coefficient of 4 was used for body wave motion. Assuming one-dimensional resonance at 160 Hz and \(V_s = 1100\) m/s, a layer thickness of about 1.7 m is obtained. The one-dimensional interpretation must be rejected, in this case as geophone 2 and 6 do not show similar resonance frequencies, and lie within 2 m of the geophones exhibiting site effects.

**Sine-shaped inclusion model**

Using a numerical approach, Bard and Bouchon18 showed that the two-dimensional resonant frequency and the amplification factor for a two-dimensional inclusion differs substantially from the one-dimensional case. The transfer function for different sites on the surface above a sine-shaped structure exhibits specific resonance patterns, with the following characteristics:

- The two-dimensional resonance is controlled by the shape ratio of the inclusion (thickness to half-length ratio). The effect of the impedance contrast is insignificant.
- The amplification is the largest above the inclusion centre, and decays toward the edges.

Interpretation of the observed pattern of resonance peaks and the duration of the resonance in terms of the ‘sine-shaped inclusion’ model indicates that geophone 5 is in the centre of the inhomogeneity, geophone 4 is off centre, and geophone 3 is at the edge.

**Rectangular inclusion model**

The following approximate empirical Equation, Bard and Bouchon18 gives the resonant frequency of a soft rectangular inclusion (two-dimensional resonance):

\[
f_0 = f_h \sqrt{1 + (2.9H/L)^2},
\]

where: \(f_0\) is the SV fundamental resonance frequency and \(f_h\) is the one-dimensional resonant frequency. The estimation of the inclusion thickness, \(H\), using the two-dimensional resonance, requires knowledge of the length of the inclusion, \(2L\). Table III presents several options of a possible inclusion thickness, \(H\), and length, \(2L\). The geometry of surface seismic array and observation of the site effect (geophones, 4 and 5) indicates that the inclusion can not be wider than 2 m. As the model is only two-dimensional, the width does

<table>
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not come into the Equation. The calculated lengths (Table III) are strikingly large in comparison to the maximum inclusion width of 2 m.

Natural resonance model—structural effect

The resonance of the excavation itself (natural resonance) could be another possible explanation for the site effect pattern. The fact that stronger site effects (spectral peaks) are observed at the sites located in the central part of the excavation (geophones 5 and 4) supports this claim. Numerical modelling is needed to support or reject the concept of natural resonance of the excavation.

Conclusions

A comparison of the seismograms recorded in a borehole drilled into the stope hangingwall with seismograms recorded on the skin of the hangingwall quantifies the influence of an underground excavation on the ground motion parameters. The geophone array placed in the borehole provides information about the seismic source and structural effect, while the array fixed to the hangingwall provides information about the structural and the site effect.

Structural effect

- The peak ground motion is up to five-fold greater on the skin of the hangingwall than 6.5 m in the solid rock. The spectral peak associated with structural resonance can be up to ten times greater than the signal within solid rock.
- The amplitude of the low frequency signal of the surface wave can be greater than that of the body wave. This low frequency signal is created by the structural effect. A low velocity layer around the excavation with a non-cohesive material interface or vertical discontinuity around the excavation can be responsible for the creation of the strong low frequency signal.
- The broad spectrum of possible modal resonance (30 Hz, 50 Hz, 60 Hz, 80 Hz and 110 Hz) indicates that the structures surrounding the deep stope are complex.

Site effect

- The site effect appeared as a strong amplification of selected frequencies at two (of five) geophones fixed to the stope hangingwall.
- The observed pattern in time and frequency domain suggests that a two-dimensional inclusion is responsible for the site effect. Amplification associated with a two-dimensional inclusion may be extremely large. As a consequence, these phenomena should be taken into account during the assessment of the local seismic hazard.
- The resonance of the excavation itself (natural resonance) could be another possible explanation for the site effect pattern. The fact that stronger site effects (spectral peaks) are observed at the sites located in the central part of the excavation supports this interpretation.

Implications for stope support

This study is a first attempt to apply the techniques used by earthquake engineers to the design of rockburst-resistant excavations. We have shown that measurements of seismically-induced ground motion made in the rock surrounding an excavation and on the walls of the excavation are amenable to analysis using these techniques. The interpretation of the observations is still ambiguous due to the limited size of the seismic array, and lack of experience in applying these techniques to the underground environment.

In general terms, the ‘structural effect’ is controlled by features such as the excavation geometry, regional support systems such as pillars and backfill, bedding plane partings, and the extent of the fracture envelope. The ‘site effect’ is controlled by local features such as the intensity of fracturing, and the zone of influence of support elements such as props and packs.

Earthquake engineers seek to minimize risk by predicting expected ground motions, and designing structures to withstand the expected shaking. Structures are carefully analysed to ensure that dangerous resonance is not induced, and reinforcing or energy-absorbing elements are introduced. Similar concepts are already used in mine design and support, although the rock mass forming the underground structure is often an extremely variable medium. The effective transfer of earthquake engineering concepts to the field of rock engineering could lead to significant advances in design of rockburst-resistant excavations.

Acknowledgements

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**Professor wins research award**

Francis Petersen, MEng, PhD, graduated from the University of Stellenbosch, and joined the Cape Technikon in 1991. He was promoted to Associate Director and Head of Chemical Engineering in 1995. His unique research programme has produced 27 refereed articles in scientific journals, 43 published and 55 unpublished local and international conference paper presentations, and numerous research reports. Francis has successfully supervised 13 postgraduate students and a further 11 Master’s students are currently enjoying his research guidance.

This Y-rated NRF scientist has not only attracted substantial state funding for his registered Separations Technology Activity Area, but industry has also supported his problem-solving research surpassing the R3 million mark.

He is an active member of various professional committees and is a member of the board of Mintek.

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*Issued by Patricia Speedie, Specialist: Public Relations, Mintek, Private Bag X3015, Randburg, 2125. Tel: (011) 709-4111, Fax: (011) 709-4326.*

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At the recent graduation ceremony at the Cape Technikon, Professor Francis Petersen was honoured with the Researcher of the Year award.