



Strong ground motion and site response in deep South African mines

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Synopsis

A stand-alone instrument especially designed for recording strong ground motions was used in this study to create a large database of peak particle velocities measured on stope hangingwalls. A total number of 58 sites located in stopes mining the Carbon Leader Reef, Ventersdorp Contact Reef, Vaal Reef and Basal Reef were monitored. The peak particle velocities were measured at the surface of the excavations to identify the effect of the free surface and the fractures surrounding the underground mining. From the monitoring results obtained, the velocity criterion of 3 m/s will be an adequate value that support systems have to sustain during a rockburst in most cases. However, PPVs in excess of this criterion were recorded, and some PVDs were damaged or irretrievable, a consequence of which was that possible extreme events were not recorded.

The data recorded on the skin of the excavations were compared to the data recorded by the mine seismic networks to determine the site response, defined as the ratio of the measured peak ground velocity to the peak ground velocity inferred from the mine seismic data. The site response measured at all mines studied was found to be 9 ± 3 times on average. Values of the site response did not vary significantly with seismological parameters such as peak ground velocity, hypocentral distance and source radius.

Introduction

The most widely used support design criterion for rockburst-prone mines takes into account the kinetic and gravitational potential energy of the keyblocks^{1,2}. The criterion for effective rockburst-resistant support systems is to absorb the kinetic and potential energy² associated with the hangingwall moving with an initial velocity of 3 m/s and brought to rest within 0.2 m of downward movement³.

The kinetic energy is proportional to the square of the peak particle (or ground) Velocity (PPV). The dynamic resistance required is dominated by the kinetic energy component for a PPV greater than 1 m/s. Therefore, a comparatively small decrease in PPV results in a large decrease in the energy-absorption requirements of a rockburst-resistant support system. As a result, a decrease in PPV requirement would allow for

considerably lower energy-absorption demands on rockburst-resistant support systems. Conversely, an increase in PPV requirements would considerably increase the support requirements.

Considering that mine-wide seismic systems are installed at most rockburst-prone mines, it is expected that these systems would provide sufficient data for reliable PPV estimates in stopes. The use of such data for obtaining PPV estimates is suggested by Jager and Ryder (pp. 25, 26, 303 and 304)³. A number of previous studies on peak particle velocities and site response have shown that the PPV on the skin of the excavations may be larger by four to ten times the PPV at a point in solid rock^{4,5} at a similar distance from the source. In addition, points less than a metre apart show differences in amplitude and phase⁶, which can only be accounted for by large strain across fractures.

A simulated rockburst experiment was conducted on the wall of an underground tunnel. PPVs with maximum of 3.3 m/s and ejection velocities with maximum of 2.5 m/s were measured on the blasting wall⁷. The existing support comprised rockbolts. The mesh and lacing, comprising part of the original support of the tunnel wall, has been removed to allow ejection of the rocks during the experiment. The rockbolts were affected but not even a single rockbolt failed⁸ despite the severe dynamic loading. A similar effect was also observed in numerous rockburst investigations⁹. This can be explained by the rapid attenuation of the PPVs from the skin to the more competent rock mass in the solid. On the other hand, a severe failure of the rockbolts is also quite frequently observed¹⁰. Most probably, in these cases the stronger site effect, due to fractured ground, was contributing to the damage⁵.

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The relationship between the PPVs generated during the rockburst and the amount of damage were also studied by numerous authors¹⁻¹³, as was the attenuation of the PPVs with distance^{14,15}. However, the lack of sufficient data relating to PPVs on the skin of excavations resulted in limited success in quantifying the large PPVs generated by mining-induced seismic events, as well as the effect on the existing support system. The aim of this study is to systematically evaluate the level and variations of peak particle velocity and quantify the site effect on the skin of the excavations over a number of geotechnical areas.

Underground monitoring and analyses

The peak velocity detector

Early work on in-stope strong ground motion was done using general purpose mine-wide seismographs, e.g. Cichowicz and Durrheim⁴. Although such systems can be made mine-worthy, they still depend on cabling, mains power or large battery demands and are generally larger than is desirable in the stoping environment and therefore prone to being blasted out. It was found that the PPVs recorded on the skin of the excavations were many times larger than expected from the mine seismic data and that it was difficult to obtain data from close to the stope face⁵. More suitable in this sense are microseismic instruments such as a ground motion monitor (GMM) and impulse designed for in-stope monitoring. These systems, however, have limited dynamic range in their standard configuration and saturate the signal for ground velocities of more than a metre. It was decided to design a self-contained device that could record strong ground motion. The device could also be attached directly to the stope hangingwall as close as possible to the face.

A portable instrument especially designed for recording strong ground motion was therefore developed and manufactured: a peak velocity detector (PVD). The PVD is a battery-powered stand-alone device with backed-up memory capable of storing up to 512 PPVs for the largest velocity pulse exceeding some threshold during each time window of 25 seconds. The time window was decreased to 4 ms so that larger events could be identified by a number of swings: the largest in a short time period provides the PPV and the number of swings provides an indication of event magnitude. The instrument was fitted with a 14 Hz geophone severely overdamped to shift the dynamic range towards strong ground motion. The instrument is designed to record up to 4 m/s in the high-frequency range. However, for the low frequency signals, the mass of the geophone hits the limits, causing saturation of the peak.

Five parameters are stored for each pulse:

- (i) peak particle velocity
- (ii) time of the peak
- (iii) slope at the zero crossing immediately before the peak
- (iv) slope at the zero crossing immediately after the peak
- (v) peak width, measured between the nearest zero crossings-before and after.

These parameters enable the estimation of the following:

- frequency using (v)

- ground acceleration using (iii) and (iv)
- displacement using (i) and (v)
- velocity (i) using acceleration and frequency (iii), (iv) and (v), providing a redundancy check.

An overwriting procedure was implemented whereby, once the memory is full, the incoming pulses overwrite the existing pulses only if they are larger than the smaller amplitude stored in memory. Recording all the largest pulses has the potential advantage of enormously increasing the amount of data recorded from the largest events without severely reducing the number of events recorded. A picture of the instrument installed underground is shown in Figure 1.

A calculation procedure to verify the quality of recorded data was created. The procedure is based on a comparison of the measured velocities and velocities calculated from acceleration obtained in the beginning and at the end of the peak, and the frequency calculated from the half-period measured between two zero crossings.

The corresponding times were used to link the recorded PPVs by the PVD to data recorded by mine seismic networks.

Analysis

Extensive underground measurements of the PPVs were carried out for different remnants at Carbon Leader Reef, Ventersdorp Contact Reef, Vaal Reef and Basal Reef sites. A total number of 58 sites located at Tau Tona, Driefontein, Mponeng, Kloof, Harmony-Orkney, Harmony-Welkom and Bambanani gold mines were monitored. The sites were chosen together with the mine rock mechanics personnel to represent the areas that are most rockburst prone. A summary of these sites is given in Table I.

The PPVs recorded at each mine were plotted as a function of the number of events, normalized by the number of site days for the corresponding mine. A site day is defined as 24 hours of recording at a particular site. An annual rate was then estimated. The mine-wide data sets overlapping the total monitoring period were extracted from the seismic database for each mine.



Figure 1—Underground installation of peak velocity detector

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Table 1

Summary of the underground sites occupied during this study

Mine	Reef	No. of Sites	Monitoring period (site days)
Tau Tona	Carbon Leader Reef (CLR)	22	2437
Driefontein	Carbon Leader Reef (CLR)	6	284
Mponeng	Ventersdorp Contact Reef (VCR)	7	403
Kloof	Ventersdorp Contact Reef (VCR)	10	659
Harmony-Orkney	Vaal Reef (VR)	10	273
Harmony-Welkom	Basal Reef (BR)	2	53
Bambanani	Basal Reef (BR)	1	24
Total	CLR, VCR, VR, BR	58	4133

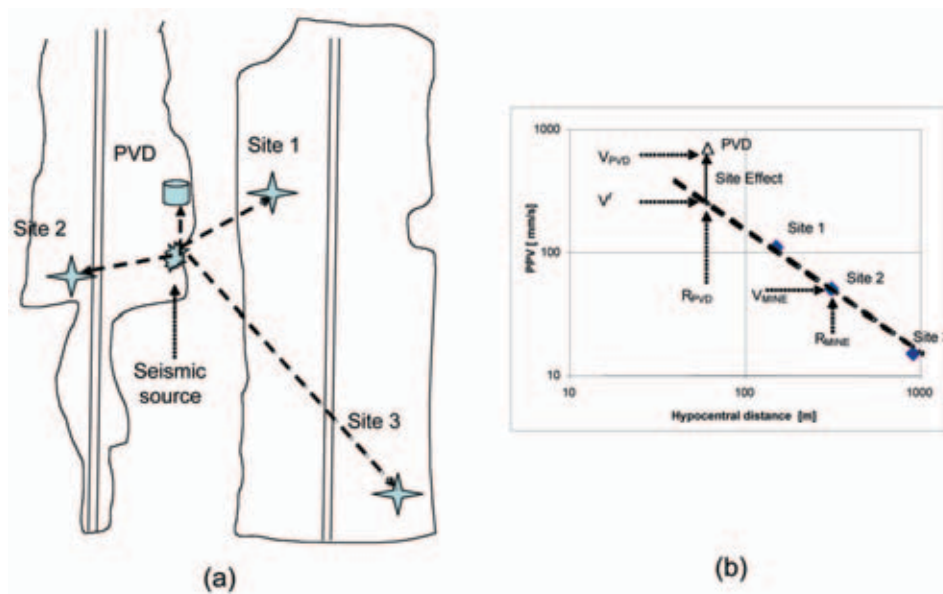


Figure 2—(a), (b) Schematic and graphical illustration of site effect

The seismic data recorded on the skin of the excavations was compared to the seismic data recorded by mine seismic networks. The transducers used by mine seismic networks are normally installed in boreholes drilled into solid rock. The PPVs recorded by mine seismic networks were extrapolated to the position of each PVD transducer located on the skin of the excavations. The measured PPVs instead of PPVs estimated from source parameters and distance were used. The reason for this approach was that the most direct comparisons between ground motions measured by the mine networks were required. The following Equation was used:

$$V' = V_{Mine} * (R_{Mine} / R_{PVD})^{-\alpha} \quad [1]$$

where V' is the PPV estimated at the point of each PVD
 V_{Mine} is the PPV recorded by the mine geophone
 R_{Mine} is the hypocentral distance to the mine geophone
 R_{PVD} is the hypocentral distance to the PVD
 α is the attenuation factor $\alpha = 1.0$ or 1.5 .

The relationship described by this Equation [1] is illustrated by the straight line fit shown in Figure 2. A value of $\alpha = 1.0$ was used in this study.

Then the average value of PPV for all sites that recorded the particular event was taken. The hypocentral distance was

calculated from a given event location to the PVD, and to each of the mine network geophones. All events recorded by the mine seismic network at more than four stations and with values of $V' \geq 10$ mm/s were compared to the seismic events recorded on the skin of the excavations. The site response is defined as the ratio of the observed PPVs recorded on the skin of the excavations and the PPV calculated from the mine seismic data using Equation [1]. The site response is expressed by the Equation [2].

$$\xi = V_{PVD} / V' \quad [2]$$

Figure 2 illustrates the application of Equation [2] to a hypothetical event recorded at three sites of the mine network (sites 1, 2 and 3) and at one PVD site in the stope. The expected peak particle velocity at the PVD site, given by Equation [1], is the average PPV estimated from each mine site and is 250 mm/s in this particular example. The observed PPV is 700 mm/s, giving a site effect of 2.8.

Additional analyses were conducted to gain more insights into the nature of the site response. The relationship between the site response and the following parameters, as reported by the mine, was analysed:

- site response vs. hypocentral distance
- site response vs. source radius
- site response vs. maximum velocity

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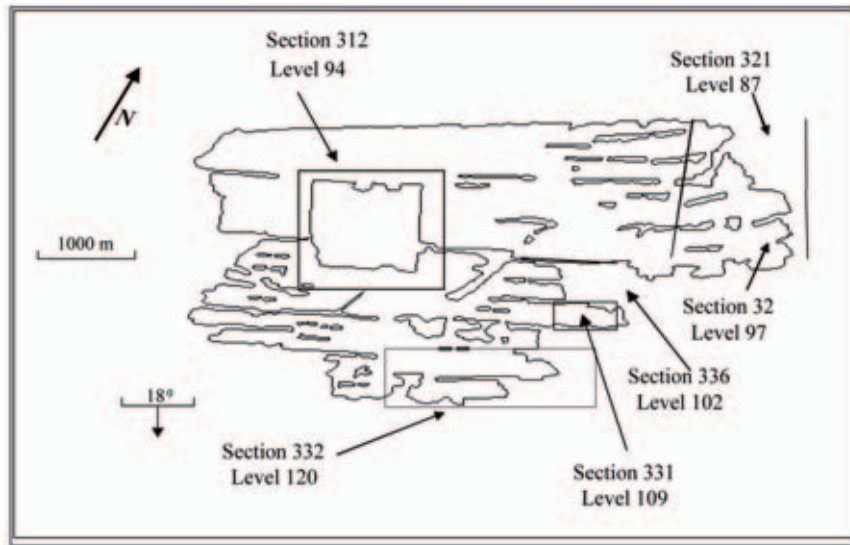


Figure 3—Monitoring areas at Tau Tona mine

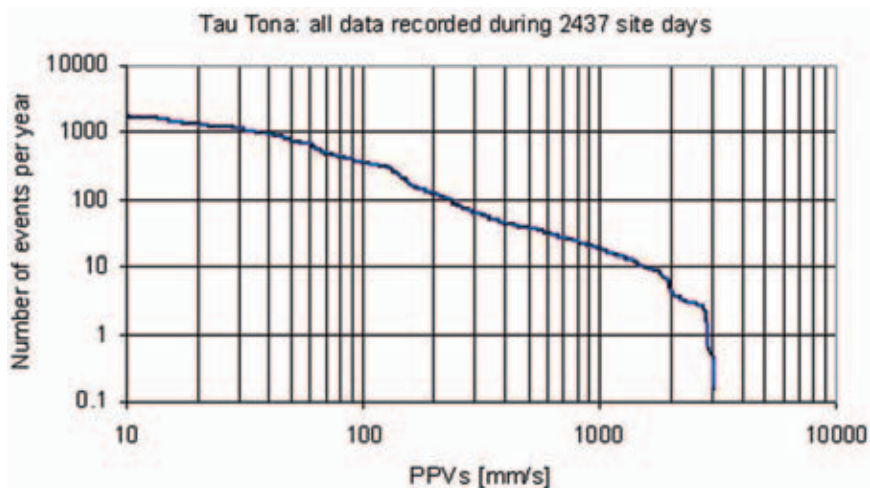


Figure 4—Peak particle velocities recorded at Tau Tona mine

- site response vs. wave length
- source radius vs. hypocentral distance
- source radius vs. magnitude.

In addition, the PPVs were measured at specific highly stressed mining structures. Different types of remnants, grouped in three categories, were studied.

Results and discussion

Tau Tona Gold Mine

Twenty-two seismically active sites in five sections were instrumented at Tau Tona mine. All stopes monitored were on the Carbon Leader Reef at depths ranging from 2 600 m to 3 600 m. Most of the sites were mined as longwalls protected by strike stabilizing pillars and well-placed backfill¹⁶. The positions of these sites are illustrated in Figure 3.

A total number of 15 139 seismic events were recorded during the monitoring period of 2 437 site days at 22 sites across the mine. The PPVs plotted as a function of the number of events is shown in Figure 4. This figure is

modelled after the standard Gutenberg-Richter Law (e.g. Jager and Ryder³) and describes the number of events exceeding PPV values. A straight line on such a plot shows power-law behaviour $N \approx V^{-1}$ where $b \approx 1.0$.

As is shown in Figure 4, a maximum value of 3 m/s is obtained, with a sharp cut-off above PPV = 2.8 m/s. The site response as a function of hypocentral distance is shown in Figure 5.

As is shown in Figure 5, most of the correlated seismic events are distributed in the range of 30 m to 320 m hypocentral distance. The paucity of events at hypocentral distance less than 30 m is an indication of the location error in three dimensions. The decreasing number of events at distances above 320 m indicates that few events at large distances generate significant ground motions. No obvious trend can be seen in this range. The average site response was calculated as 10.4 ± 7.1 .

Another important parameter is the relationship between the level of the site response and the source radius (as estimated by the mine). This relationship is shown in Figure 6.

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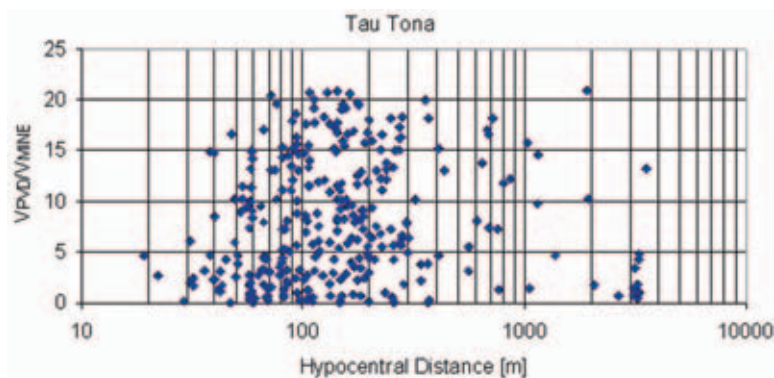


Figure 5—Site response obtained at Tau Tona mine as a function of hypocentral distance

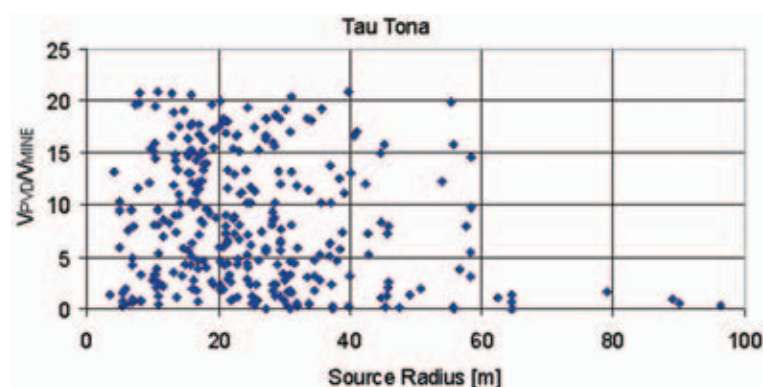


Figure 6—Site response obtained at Tau Tona mine as a function of source radius

As is indicated in Figure 6, the maximum site response is observed for source radii around 20 m, and decays for the radii bigger than 60 m. The maximum number of correlated seismic events is between 5 m and 30 m. The average source radius was calculated as $25 \text{ m} \pm 15 \text{ m}$.

To characterize the level of ground motion at the skin of the excavations and especially in the source region and the near field^{17,18}, it is also important to study the position of the source radius with respect to the face, as well as the rock type in the source region. It was shown¹⁹ that the strong ground motion in the source region is controlled by the strength of the rock mass that ruptures during the tectonic-type seismic event. The tectonic dislocations in a weak rock mass have low rupture velocity and are associated with a low stress drop that generates low levels of PPVs. In contrast, the strong quartzite rock mass surrounding the Carbon Leader Reef and the Ventersdorp Contact Reef ruptures with high velocity and is associated with a high stress drop that generates high levels of PPVs. It was also pointed by Cichowich²⁰ that, for the same magnitude seismic events high stress drop events are more damaging than low stress drop events. On the other hand, seismic events with high rupture velocities generate high frequency seismic signals, which can reach very high PPVs in the source region, but do not propagate very far due to the rapid attenuation of high frequency signals. Applied in practice, this means that the seismic events taking place in the face area will be responsible for the highest velocities recorded by the PVD on the skin of the excavations. In many cases, these events will

not have enough triggers to be recognized by the mine seismic network. Source radius as a function of the hypocentral distance is shown in Figure 7.

The data shown in Figure 7 indicate that 45% of the seismic events, with an average source radius of about 25 m, are taking place between 30 m and 300 m hypocentral distance. In these cases the face is outside the source region and is not subject to near-field loading.

Analysing the fatality database in the Carletonville mining area as a function of magnitude, Milev and Spottiswoode²¹ found that 50% of fatalities were associated with events smaller than $M \approx 2.0 \pm 0.2$ and that the other 50% of fatalities were associated with larger events. The value of $M \approx 2.0$ was then defined as a 'characteristic' damaging event and was related to the corresponding source radius. The source radii of 40 m to 60 m were found as a corresponding range. This range is slightly offset from the average source radius.

The wavelength (λ) was calculated from the shear-wave velocity and the time between two consecutive zero-crossings ($\lambda = TV_s$ where $V_s = 3\,400 \text{ m/s}$ and T is the period calculated from the zero-crossings). It was found that the site effect is less at lower frequency. Similar results were reported in a number of previous works²²⁻²⁴.

Analysis of the relationship between the site response and the maximum velocity shows a low site effect associated with the small maximum velocities. However, there was no trend obtained for the intermediate and large maximum velocities.

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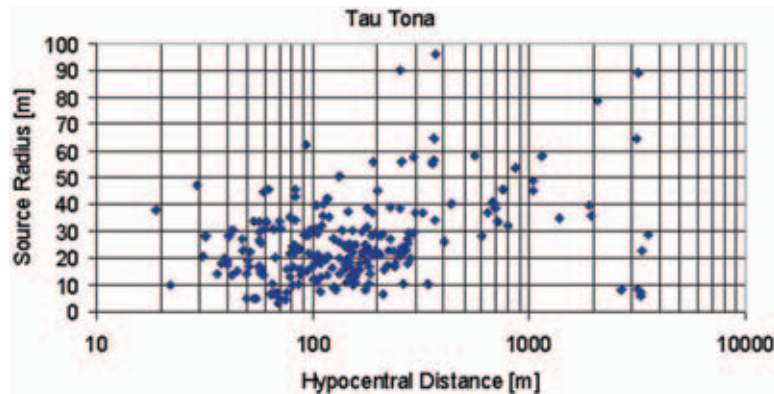


Figure 7—Source radius as a function of hypocentral distance

Driefontein gold mine

Six seismically active sites were instrumented at Driefontein gold mine. These sites were located within the shaft pillar. Most of the seismicity was associated with the extraction of the pillar. The sites were monitored for a period of 284 site days and during this period 3 818 events were recorded. The PPVs plotted as a function of the number of events are shown in Figure 8. The maximum value of 3.3 m/s was recorded during this period.

The average site response was calculated as 5.1 ± 4.4 . Most of the correlated events were in the range between 30 m and 110 m hypocentral distance. However, a significant number of events fall outside this range. The source radii were clustered in three ranges between 10 m and 40 m, with the maximum population between 42 m and 55 m, and 69 m and 85 m. The average source radius was calculated as 41 ± 29 m.

Mponeng gold mine

A total number of 1 183 seismic events was recorded at Mponeng gold mine during the monitoring period of 403 site days. The PPVs plotted as a function of the number of the events is shown in Figure 9.

As is shown in Figure 9, a maximum value of 2.3 m/s is obtained.

The average site response was calculated as 12.1 ± 6.7 . Most of the correlated events were in the range between 30 m and 300 m hypocentral distance. The source radii were regularly distributed between 10 m and 90 m. The average source radius was calculated as 38 ± 23 m. There was no trend or clustering found, neither in site effect vs. hypocentral distance nor in site effect vs. source radius. The size of the source radius was found to increase with respect to distance to the face.

Kloof gold mine

A total number of 6 060 seismic events was recorded at Kloof gold mine during the monitoring period of 659 site days. The PPVs plotted as a function of the number of events is shown in Figure 10. As is shown in Figure 10, a maximum value of 2.8 m/s is obtained.

The average site response was calculated as 8.6 ± 7.4 . Most of the correlated events were in the range between 60 m and 120 m hypocentral distance where the maximum site response was obtained. The maximum site response was also found for seismic events with a source radius of about 10 m, which then attenuated with distance. The size of the source radii was found to increase with distance from the face.

Remnants

One of the most important factors to characterize the strong ground motion on the surface of the excavations is adequate knowledge of the PPVs at different geotechnical or mining conditions. A number of studies^{25–27} conducted during the past few years have shown a significant variation in PPVs measured under different geotechnical conditions.

A large number of remnants, located in various geotechnical areas, were investigated in terms of PPVs²⁸. Three types of remnants were broadly categorized based on geology and mining conditions^{27,29}:

- 'geologically bounded' type of remnant
- 'reef sliver' type of remnant bounded by area mined
- 'shaft pillar' type of remnant.

The PPVs recorded on the Vaal Reef are shown for each remnant type in Figure 11. The results indicate that the 'shaft pillar' type of remnants indicated the highest PPVs followed by 'reef sliver' type remnant and the 'geologically bounded' type of remnant.

A similar comparison was performed for 'shaft pillar' and 'geologically bounded' types of remnant located on the Basal Reef, Figure 12. The results indicate higher PPVs for the 'shaft pillar' remnant when compared to the 'geologically bounded' type of remnant.

Although there are differences in the geotechnical and mining conditions such as rock type, geological structure, mining method, area mined, etc. among Vaal Reef, Basal Reef and Carbon Leader Reef, the mining of the 'shaft pillar' type of remnant is always associated with higher PPVs. A hypothesis of early slip on the geological structure defining 'geologically bounded' remnant type could explain the absence of extremely high PPVs in the presence of a large number of moderate events. Most probably this slip took place during the formation of the remnant.

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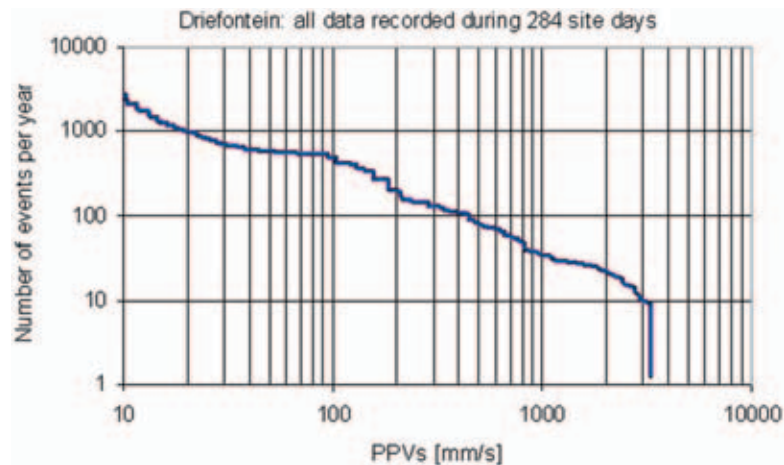


Figure 8—Peak particle velocities recorded at Driefontein mine

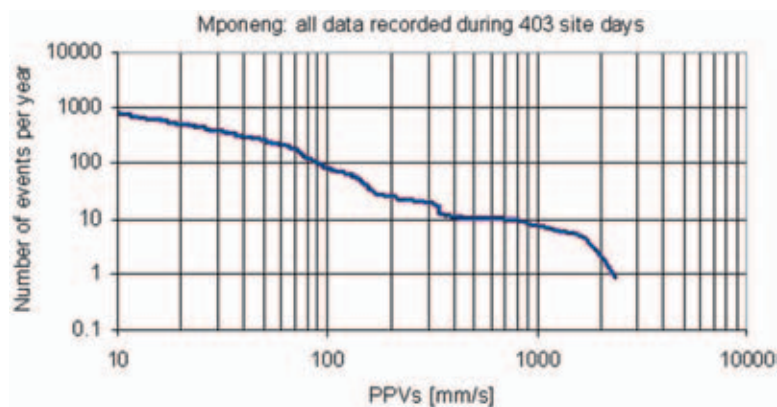


Figure 9 Peak particle velocities recorded at Mponeng mine

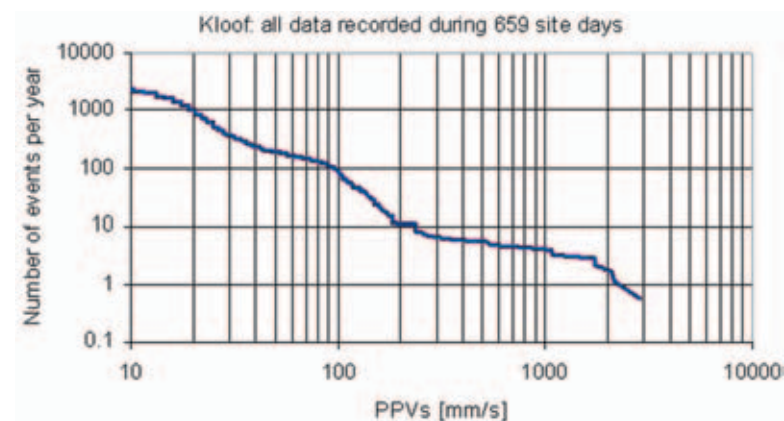


Figure 10—Peak particle velocities recorded at Kloof mine

All sites

A number of studies¹⁻³ carried out during the last few decades have suggested that the peak particle velocity of 3 m/s is an appropriate maximum value to which support systems in South African gold mines are subjected during rapid dynamic loading. This criterion is routinely used to estimate the energy-absorption requirements for support systems in rockburst-prone mines.

This is the first study that attempts to determine the validity of the velocity criterion across various reef types and different geotechnical areas. However, design of an adequate support is much more complex as many additional criteria are involved. The considered design criteria are: (i) height of a potential fall; (ii) quasi-static and dynamic deformations; (iii) compressive hangingwall stresses; (iv) fracture spacing and orientation; (v) consistency of support performance; (vi)

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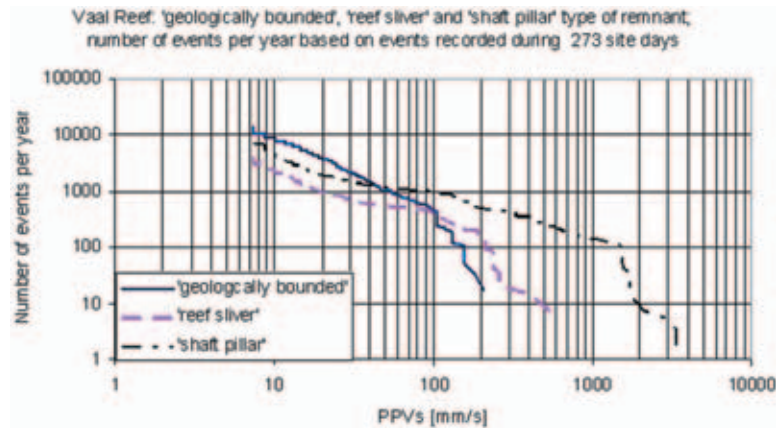


Figure 11—Peak particle velocities recorded at Vaal Reef: comparison of ‘shaft pillar’, ‘geologically bounded’ and ‘reef sliver’ type of remnant

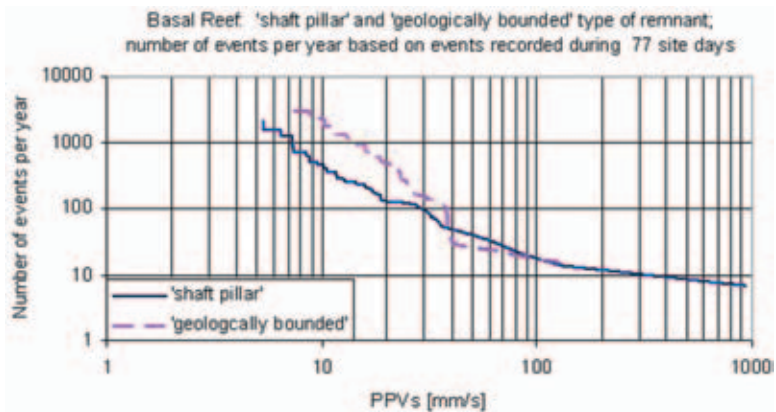


Figure 12—Peak particle velocities recorded at Basal Reef: comparison between ‘shaft pillar’ and ‘geology bounded’ type of remnant

Table II
Summary of the strong ground motion and average site response listed with the standard deviation

Reef/mine	CLRTauTona	CLR/Driefontein	VCR/Mponeng	VCR/Kloof	VR/Harmony-Orkney	BR/Bambanani Harmony Welkom
V_{max} [mm/s]	3054	3316	2338	2846	3342	943
Average site response	10.4 ± 7.1	5.1 ± 4.4	12.1 ± 6.7	8.6 ± 7.4	2.7 ± 4.9	N/C
Average stress drop [MPa]	1.4 ± 2.7	1.1 ± 1.3	0.5 ± 0.7	1.6 ± 2.2	2.5 ± 1.25	N/C
Average source radius [m]	26 ± 15	41 ± 29	38 ± 23	20 ± 19	51 ± 22	N/C

N/C – not calculated due to poor correlation between the seismic events recorded by mine seismic network and PVD

areal coverage and support spacing; (vii) zone of support influence³⁰. It is also worth pointing out that the areal coverage and spacing between the support units plays a very important role in the hangingwall stability during the seismic loading. Work done in this field³¹ indicated that the problem is site-specific and proposed a methodology to evaluate support systems catering for rockfall and rockburst conditions.

The results from the underground measurements at Carbon Leader Reef, Ventersdorp Contact Reef, Vaal Reef and Basal Reef sites were summarized and are shown in Table II. It is important to notice that in a few cases the recorded

instruments were damaged, buried under the rocks or irretrievable due to closing of an entire area. Therefore the direct measurements of such extremely damaging events were not possible.

In an attempt to relate the strong ground motion to the damage, PPVs measured at each mine were categorized in three statistical groups:

- PPVs less than 100 mm/s
- PPVs greater than 100 mm/s and
- PPVs greater than 800 mm/s.

The values of 100 mm/s and 800 mm/s used for definition of these groups were based on the observations

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obtained from the simulated rockburst experiment^{7,32} conducted adjacent to a tunnel. Figure 13 from Milev *et al.*⁷ shows the region of observed damage superimposed on the PPVs measured on the wall of the tunnel. Figure 13 indicates the areas of high and low intensity damage followed by an area where no visible damage was observed. A PPV of 800 mm/s was measured in the transition from low intensity to no rockburst damage. The value of 100 mm/s was subjectively chosen to separate the events with noticeable PPVs from the rest of the events that have an insignificant effect on the support system.

The total number of seismic events and the number of seismic events with $N_{100} \geq 100$ mm/s and $N_{800} \geq 800$ mm/s was calculated. The percentage of the strongest seismic events, $N_{800} \geq 800$ mm/s from all events with $N_{100} \geq 100$ mm/s was also calculated. A summary of the results is given in Table III.

On the other hand, there is no linear relationship between the size of the seismic event and size of rockburst damage. The severity of damage often varies significantly with the mining geometry, source mechanism and radiation pattern as well as the rock strength and the quality of the existing support systems. The rockburst investigations

undertaken by CSIR Miningtek were summarized²⁴ and highlighted the importance of deeper understanding of both the source and damage mechanisms, and the application of this knowledge to the design and support of excavations.

Conclusions

Extensive underground seismic measurements at Carbon Leader Reef, Ventersdorp Contact Reef, Vaal Reef and Basal Reef were carried out. The PPVs were measured at the surface of the excavations to account for the site effect due to the free surface and fractures surrounding the underground mining.

From the monitoring results obtained, the velocity criterion of 3 m/s will be an adequate value that support systems have to sustain during a rockburst in most cases. However, PPVs in excess of this criterion were recorded, and some PVDs were damaged or irretrievable, a consequence of which was that possible extreme events were not recorded.

The PPVs associated with remnant mining show differences with the different remnant type. The 'shaft pillar' type of remnant indicated the higher PPVs followed by 'reef sliver' type remnants and lastly 'geological bounded' type of

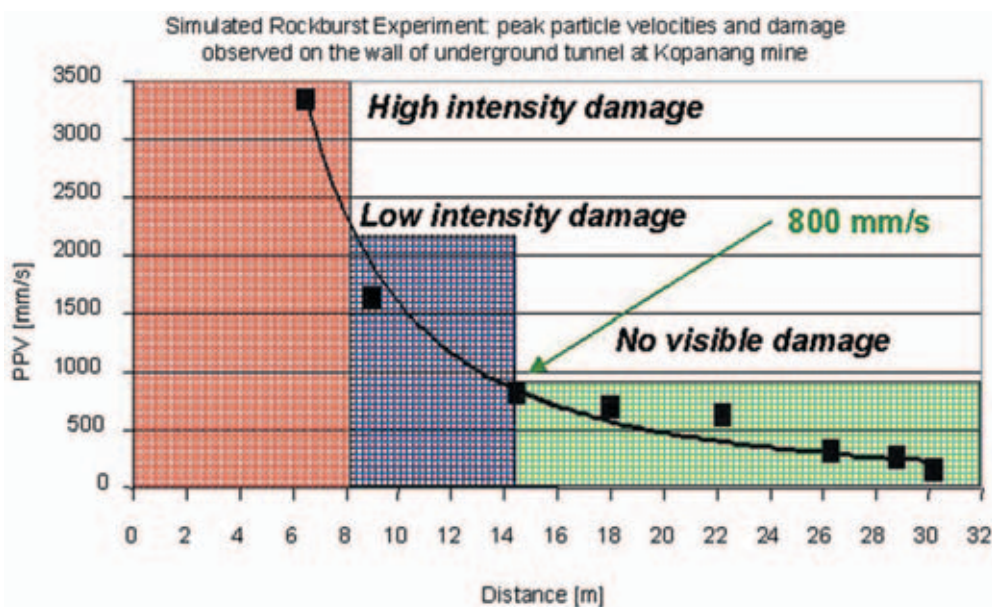


Figure 13—The attenuation of the PPVs on the wall of underground tunnel overlapped with the area of observed damage

Table III

Summary of recorded events: N_{100} is the number of events ≥ 100 mm/s; N_{800} is the number of events ≥ 800 mm/s

Mine	Total number of events	N_{100}	N_{800}	N_{800}/N_{100} %
Tau Tona	15139	2464	158	6
Driefontein	3818	380	37	10
Mponeng	1183	91	10	11
Kloof	6060	172	7	4
Harmony-Orkney	6833	623	100	16
Harmony-Welkom	307	2	1	50
Bambanani	264	1	0	0
All mines	33604	3733	313	8.4

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remnants.

Velocities inferred from the data for all mines studied, were found to be 9 ± 3 times on average lower than those measured by the PVDs on the skin of the excavations. The site effect did not vary with inferred ground motion, ground source size or hypocentral distance.

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