Rationale for the quick withdrawal of the underground workforce following (large) dynamic ground motions – how extensive should the exclusion zone be?

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ABSTRACT: The mining of the tabular auriferous reefs on the rim of the Witwatersrand Basin in South Africa is very extensive, and even within individual mines, underground workplaces are often widespread. There is just cause not to evacuate an entire operation's workforce following the unanticipated occurrence of a large mining-induced seismic event. We present the rationale for the quick withdrawal of the possibly affected underground workforce following such seismic events and the calculation methodology based on the damaging peak particle velocities (PPV) of the past seismicity. A minimum PPV from the source at which observable damage to the underground excavations is no longer apparent was inferred. The radii from the source within which ground velocities exceed this amount are then calculated for all recorded events with local magnitudes $M_L1.0$ and greater. Those workplaces located within these negatively affected volumes are deemed at risk and the workforce is withdrawn.

Keywords: seismicity, risk, workforce, evacuation, safety.

1 INTRODUCTION

The old gold mines that have been extracting the rich tabular reefs on the Witwatersrand Basin have reached or are approaching the end of their lives after many decades of production. Those still in operation are mostly mature, with widespread active stopes. A non-mechanized method of reef extraction necessitates a large workforce. Such is the case with Sibanye Stillwater's Kloof and Driefontein gold mines. The distances between underground workplaces can be of the order of kilometres. The question arises about the size of the zone of negative influence following the occurrence of mining-induced seismicity and, specifically, what portion of the workforce should be evacuated when the elevated seismic risk demands it.

When and where possible, a record of damage due to seismicity is usually kept for rockmass re-support or rehabilitation efforts. This information is regularly updated in the mines' Codes of Practice. The records are expected to be incomplete since access to older accessways and workings is restricted, and often impossible due to personnel barricades and ventilation seals. Given a significant number of large-event occurrences, the threshold distance of observable damage can nonetheless be ascertained. Having the magnitudes of causative events coupled to the calculated ground motions experienced at these distances, the baseline peak particle velocity (PPV) associated with damage can be determined. A further step sees the application of this knowledge, calculating the radius around the focus of all future events of M_L1.0 and greater, where the baseline PPV is reached. Personnel whose workplaces are located within the volume defined by this radius will receive notification to move to a safe place and then return to the surface in an orderly fashion, or until such time as safe re-entry, post-inspection, is declared.

2 SEISMIC HAZARD AND COVERAGE

Driefontein mine operates in a deep and high-stress environment, and the occurrence of large dynamic ground motions is frequent. It also performs mining at shallow-to-intermediate depth but, by virtue of the multi-reef environment, the presence of geological discontinuities and the legacy of long spans of mining, it suffers a concomitant seismic hazard.

Figure 1 indicates the mining plan of Driefontein operations, bound by the mine lease area (each square represents 25 km^2, oriented to local mine coordinates), and locations of seismic events M_L3.0 and larger over the 24-month period from November 2020 to October 2022. This period includes an incident of protracted industrial action, workplace lockdown and production disruptions, between April and June 2022. The Driefontein operation experienced 13 such occurrences (largest recorded: M_L3.8).

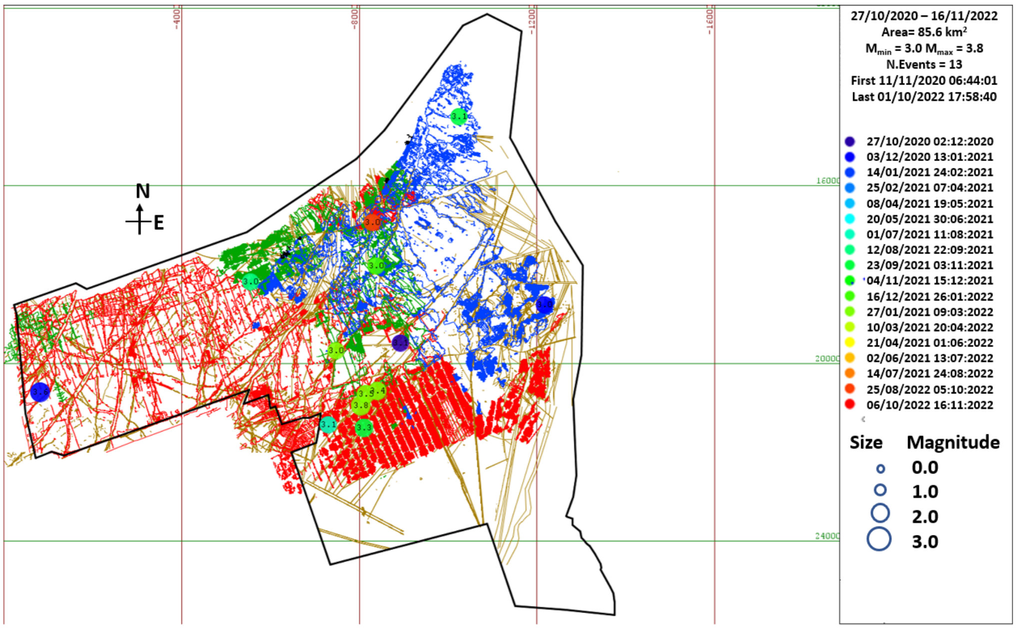


Figure 1. Mining plan of the three tabular reefs extracted at Driefontein Gold Mine. The middling between the reefs is around 60m. Depth of mining increases towards the South with an inclination of approximately 26^0. Major geological features are delineated. The location and magnitude of events M_L3.0 and greater (13 in total) are shown by discs, warmer colours indicating the latest, in the time period 1 November 2020 to 31 October 2022. Frequency-magnitude distributions reveals the sensitivity of the seismic network to events as small as M_{min}-2.0 (or better). Maximum magnitudes (M_{max}) of 3.8 can be expected.

Experience at Sibanye Stillwater deep gold operations has shown that magnitudes less than about M_L1.8 are usually within the expected normal range of energy dissipation around the stope with mining, ordinarily occurring shortly after blasting. Large-scale shear effects along geological discontinuities or through intact rock, typically at highly stressed abutments or along bedding planes, tend to generate much larger seismic events. “Slip” (relative dislocation) of discontinuity surfaces or planar weaknesses is recognised as a common failure mechanism and, fortunately, normally occurs somewhat further from the stope face where the workforce is concentrated. The geometry of mining layout and geological complexity exert great influence on the seismic response, and much consideration and due diligence needs to be expended to contend with this.

The seismic coverage and sensitivity to ground motions are in accordance with the density of the geophone array for the operations and are generally good. Driefontein mine benefits from 42 4.5 Hz ground motion sensors (tri-axial geophones, orthogonally oriented, in a sealed unit), all strategically located for optimum seismic coverage of workplaces. New sensors are installed when the extended mining horizon necessitates it. The seismic system is given high importance and is efficiently maintained. Location accuracy, frequency-magnitude and temporal distributions attest to this.

3 LOCAL MAGNITUDE, SEISMIC POTENCY AND PEAK PARTICLE VELOCITY

The local magnitude (M_L), initially independently calculated for each mine, is now regionally defined, so event sizes are directly comparable not only across Sibanye-Stillwater but also other mining groups employing Institute of Mine Seismology (IMS) systems. It is given by:

$$M_L = A_0*\log(E) + B_0*\log(Mo) + C_0$$

where the regional coefficients are $A_0 = 0.344$, $B_0 = 0.516$ and $C_0 = -6572$; seismic energy (E) and seismic moment (Mo) are obtained from the recorded waveforms.

Peak particle velocity (PPV) expressed in local magnitude and distance from the source (D) is described as:

$$\log(PPV) = A_1*M_L + B_1*\log(D) + C_1$$

where $A_1 = 0.661$, $B_1 = -1.720$ and $C_1 = 1.396$.

Seismic potency (P) is a useful parameter to quantify rockmass strain in response to mining. Comparisons between actual mining production and potency (both in m^3) can identify the onset of deviations from the norm or more hazardous rockmass behaviour, and lead to corrective procedures. The seismic potency per unit area mined was calculated as defined by Mendecki (2016):

$$P = Mo/G = Ad$$

where G = modulus of rigidity (30 GPa), A = area of slip (m^2) and d = slip displacement (m).

PPV expressed in P is given as:

$$\log(PPV) = A_2*\log(P) + B_2*\log(D + D_2*P^{1/3}) + C_2$$

where $A_2 = 0.684$, $B_2 = -1.809$, $C_2 = 1.900$ and $D_2 = 10.000$.

The two expressions of PPV, graphically shown in Figure 2, can be used to differentiate between near- and far-field ground motions.

3.1 Near- and far-field calculations of ground motions

The PPV-magnitude-distance distribution cited above leads to an overestimation of ground motions in the near-field (Jager & Ryder 1999; van Aswegen *et al*., 2018). Using a PPV-potency-distance relationship constrains the ground motions of relatively small and nearby seismic events and produces better results. The relationship can be adjusted in the far-field to coincide with the magnitude-distance distribution calculated using local data. Then, for each damaging event (i.e., $M_L \geq 1.0$), the radius from the source of the event attained when the PPV decays to a level where damage is unobservable or non-consequential (in this case, 0.08 m/s) can be obtained in the constrained near-field, according to Figure 2.

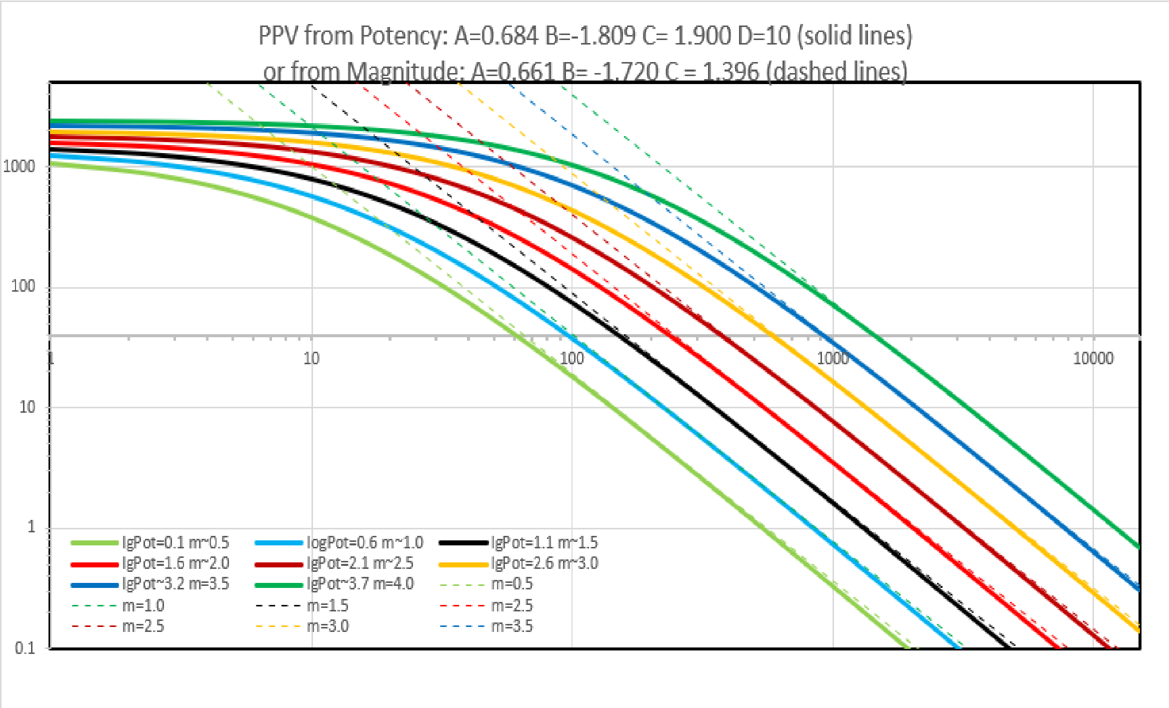


Figure 2. Graphical representation of PPVs for given magnitudes of seismic events. The x-axis refers to ground motion (mm/s); the y-axis refers to distance from the source (m). The PPVs based on P provide a better estimate of ground motions in the near-field.

4 SEISMIC DAMAGE AND THRESHOLD OF OBSERVABLE DAMAGE

Not all seismic events result in damage, but as the magnitude of these seismic events increases, there is a corresponding and exponential increase in reportable damage (Jager & Ryder 1999). An increase in event magnitude is linked to an increase in the dimensions of the source. A larger volume of the mining excavations is affected by higher ground motions and velocities, and a greater likelihood of damage and worker exposure. Accordingly, a withdrawal zone scales according to the magnitude.

The relevant mines' Codes of Practice and internal records reveal M_L2.0 and greater events are more readily associated with damage further afield than the immediate stope face. It further points out that smaller-sized events normally cluster close to the active workings, while a different subset of larger events, with different source mechanisms, are usually associated with more distant geological features or the shearing of intact rock. A typical micro-seismic network as used at Driefontein can provide information on likely modes of deformation and seismic risk. Many factors contribute to rockmass damage. For example, the formation of cracks and fractures as mining disrupts the balance of stress, the ejection of rock from the face, severe excavation deformation, and shakedown when support systems fail. Most seismic activity tends to be centered around the stope face directly after blasting. In these cases, damage, when it happens, is very localized. Mid-range to large events (conservatively M_L1.0 and larger) with possible aftershock occurrence can occur on-shift, and pose a greater potential risk, particularly to the workforce in adjacent areas or further afield.

Here we report on the extent of damage produced by 27 events from one of Driefontein's deeper shafts, spread over a period of 20 months (see Figure 3). The occurrences ranged in magnitude from M_L0.9 to M_L3.4. We recognize the information is limited, but it supports prior knowledge. The interest here, of course, is to establish the distances from event sources to the point where no more damage is apparent to the observer during subsequent *in-situ* investigation.

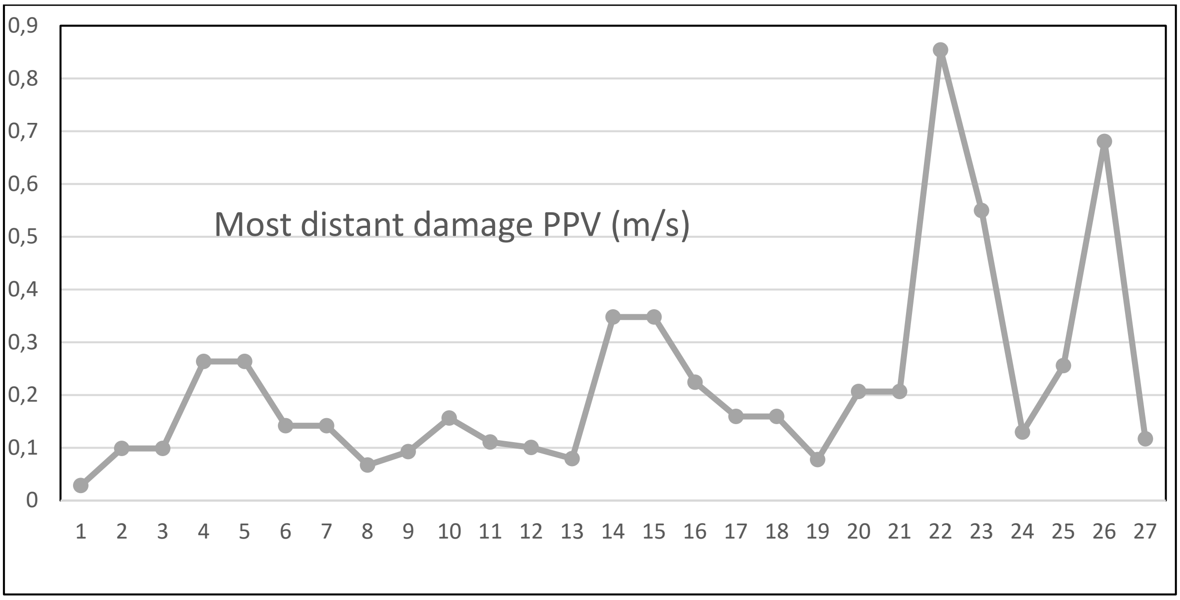


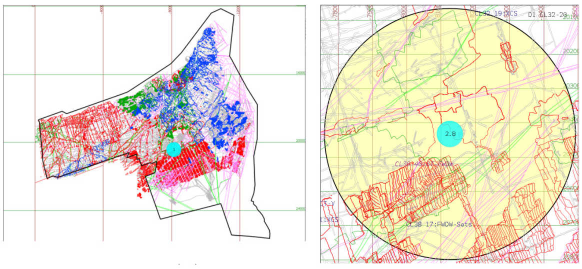
Figure 3. The information provided by in-situ inspection reveals a threshold of ground motion of approximately 0.08 m/s, below which damage in stopes, tunnels and ancillary excavations is not visually apparent anymore. This value is further reduced to 0.06 m/s with a factor of safety of 1.5, to account for various unknowns and wider application across the operations. These quantities should be reviewed whenever the ground motion equations are revised.

5 RADII OF INFLUENCE AND COMMUNICATION WITH THE WORKFORCE

Visual displays on screens at various points on the mines provide a list of all active workplaces located within the volume defined by the PPVs of at least 0.06 m/s following an event of M_L1.0 or greater. Work crews are notified telephonically to withdraw if they locate within the zone of potential damage. The displayed list of affected workplaces may be overwritten in quick succession by subsequent large aftershocks or large tremors elsewhere; to ensure the list is maintained for record-keeping, this information is also relayed by electronic mail. Figure 4 shows an actual example of a seismic event (M_L2.8 in this case; picture cropped to fit) as it would be displayed on remote screens, its location in relation to the entire mine, and a zoomed-in view of the affected areas with a listing thereof. A control facility, manned around the clock, would also feel the tremor on the surface and relay the information to the relevant decision-makers for immediate action.

6 CONCLUDING REMARKS

Production stoppages are very costly, especially for marginal mines. The management of seismic risk should encompass those workplaces affected when seismicity occurs, quickly and effectively. A rock engineering solution needs to define the extent of damage associated with strong dynamic ground motions and evacuate the affected workforce from the zones prone to damage and possible aftershocks. We've presented a practical but robust methodology that considers the historical behaviour of the rockmass and establishes a minimum damaging PPV, which is then translated into an exclusion zone following the occurrence of events $M_L \geq 1.0$. This information is readily and widely communicated across the operations, both electronically and telephonically.



Event Mag=2.8 at 08:37:19 on 19/12/2022
Location = 20433 -8125 -2532
MPot=2.5 Potency=328m3 LogMoment=13.03
LogEnergy=7.59
WorkPlace CL38 40:6T-FWDW dXY=114 HW+188
PPV=272.0 mm/s
Affected Area: Radius = 367 m

Shaft	Affected Work Place / Panel	Distance XY	Elevation
D1	CL38 40:6T-FWDW	114 m	HW +188 m
D1	CL38 17:FWDW-Sets	265 m	HW +257 m

Figure 4. An example of the information communicated via email after a possibly damaging seismic event, showing some event details, the location and a listing of affected workplaces. A similar display appears at remote terminals in multiple office localities and control rooms across the mines, providing information that may be required for rescue or workplace evacuation efforts.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the support of Sibanye-Stillwater for this work. Special thanks to Dewald Lamprecht and Deon Louw for stepping up to the challenge posed by the Government Department of Mineral Resources and Energy, obtaining the all-important underground information and relating damage to minimum ground motions. We recognize also the ready support of Dr Ted Stankiewicz; the enabling software was developed in collaboration with Hamerkop Scientific Services.

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