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Characterisation of Hazards and Rockmass Response During Remnant Mining in South African Gold Mines

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A three year research project has been undertaken to evaluate the rock related hazards in remnant mining. Preliminary findings are reported in this paper. A study of accident databases identified that stope faces and gullies are the most hazardous regions and are relatively more hazardous than all other mining conditions. The remnants are classified into four classes based on geology and reason for formation to assist the evaluation of the hazard. Continuous closure measurements indicate considerable time dependent closure and significant closure associated with blasting and strong seismic events. The peak particle velocities differ between remnants classes and can regularly reach up to 3m/s in some remnants, particularly shaft pillars. New design criteria need to be developed.

1 INTRODUCTION

As deep level ore bodies become depleted, the only remaining reserves exist as pieces of ground that were left behind due to difficult mining conditions. These areas tend to be in shaft pillars, adjacent to geological features or even within fault zones. Hill (1942) studied remnant mining on East Rand Proprietary Mines and found that most remnants exhibited an increase of seismic activity at a particular stage, followed by very little seismicity as the final remnant was removed. The increased hazards of remnant mining were used by Hill (1942) to justify the introduction of longwalls on East Rand Proprietary Mines. Also, Durrheim et al. (1997) found increased rockburst hazards associated with remnant mining. However, at high percentage extractions, mining of these remnants becomes the only option to extend the life of an old mine.

Until now, although there is a considerable amount of remnant extraction, very little research has been done to evaluate the risks involved. This paper reports on some preliminary findings of a three year research project undertaken to understand and quantify the hazards associated with remnant mining.

The questions that need to be answered include:

- Is remnant mining more hazardous?
- Does the hazard depend on region, reef or type?
- Is the dynamic rock response different in comparison to non-remnant conditions?
- Does the time between leaving the remnant and the current mining increase or decrease the hazard?

A hierarchical approach to data collection has been taken in trying to answer these questions. At the broadest level, the accident databases from the Department of Minerals and Energy have been studied to identify the main problem areas. At the next level of detail, 144 remnants were studied from plans with input from rock engineers, seismologists and production personnel to characterise the typical remnants and to try to relate parameters such as size and mining rate to the remnant type, mining rate and reason of creation and to identify typical hazards. The third level of detail was to monitor about 25 different sites in various regions. The time dependent closure and peak particle velocity were monitored at one or more positions within each remnant and related to the far-field seismicity. Many of the sites in the current project have been monitored throughout the mining of the remnant and the data, therefore, provides a unique insight into the dynamic and quasi-static deformations associated with remnant mining in the Vaal, Basal and Carbon Leader reefs. The final level involves additional instrumentation, geotechnical and geological mapping combined with numerical modelling and detailed seismic hazard assessments for a few of the remnant sites.

Comparisons with the dynamic rockmass response observed from the mine-wide seismic system will allow the quantification of the site effect and the ability to determine the expected maximum ground velocities for input into support design methodologies. The time dependent closure, the seismic energy release and the moment distributions are compared with numerical simulations to investigate the ability of various numerical models to predict the amount and severity of seismic activity.

2 HAZARD IDENTIFICATION FROM DATABASES

The database of accidents from 1990 to 1999 that was compiled by Miningtek for a previous SIMRAC project was used to try to identify the main causes of accidents and to try to determine where the accidents were occurring. The accidents were grouped by the reported area of occurrence. The remnant accidents were separated from the others and expressed as a percentage of the total number of accidents in the relevant class. Figure 1 shows that the stope face and gullies are in general the most hazardous places, but that gullies, raises, pillars and ledging are relatively more hazardous in remnants.

The accidents are reported in a single sentence and often there is little or no information provided. This makes identification of the causes very difficult. As a first step to identify the causes of the accident, 20 appropriate keywords were selected and a spreadsheet was set up to identify the number of times these keywords were matched in the one sentence accident descriptions. This obviously can be biased based on the way the keywords were selected and the way in which accidents were reported. Figure 2 shows the results of the analysis and indicates the number of times the keywords were reported for each category as a percentage of the total number for all accidents in that region.

Figure 2 indicates that the presence of weak strata and seismic events are more likely causes of accidents in remnants as compared to all the rock-related accidents. When scaled by

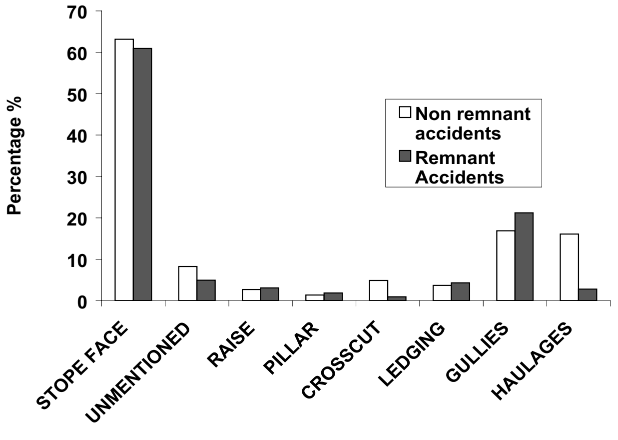

FIG. 1 Position of accidents in remnants compared to all other areas

the number of fatalities per accident, both 'seismicity' and 'weak planes' are emphasised and show that these are the main causes of multiple fatal accidents in remnants.

3 CLASSIFICATION OF REMNANTS

With the permission obtained from the relevant mines, the respective mine plans and seismic data were analysed in the context of the newly developed method for classification of remnants, so that hazards that are generic to all remnants or specific to certain cases can be identified. Initially eight different categories where developed to classify remnants according to the reason for their creation (Rangasamy and Jager, 2002). This was reduced to four categories to simplify the analysis process. The revised classification (which relates to Figure 3) for remnants is as follows:

1. bounded by a structure on one side;
2. bounded by two or more geological structures;
3. required for regional stability (shaft pillar, dip/strike pillar, etc);
4. created by mining layouts.

Figure 3 shows the classification of the various remnants selected for this study. Of the 144 remnants that were assessed, 46% are presently being extracted with another 27% in the planning stages. A further 27% of the remnants were stopped for a variety of reasons. A larger percentage of remnants exist at mining depths between 1500 m to 2500 m below surface. Of the sites that were assessed, only 24% of remnants were at depths below 2500 m. An interesting trend was the size of these remnants when compared to the depth of the mining activity. The shallower mines (depth range of 1000 m to 1500 m below surface) have an average pillar of 3200 m^2, which increases to 6261 m^2 for the deeper mining operations. The possible reason for the larger pillar sizes is due to the increased requirement of regional stability pillars (shaft and dip/strike) in number as well as size. There is only a slight reduction in stoping width when comparing the shallower operations to that being mined below 2500 m. The final part of the empirical analysis of remnants was based on conducting interviews with mine personnel with the focus on obtaining information relating to the conditions of access ways (both on and off reef), mining layouts (both support and extraction methodology) and the related ground conditions.

Figure 4 shows sections through remnants from each of the classes (Classes 3 and 4 being considered to have similar sections). The main difference is in the distance to the previous mining. In Class 1, mining takes place from existing faces and the old faces on the far side of the structure are at some distance. In Class 2, the remnant is an isolated block of ground in between the two faults and the relationship to previous mining depends on the throw on each of the structures. The mining related remnants of class 3 and 4 are usually surrounded by mined-out faces. The relationship between the remnant and the mined-out areas will affect

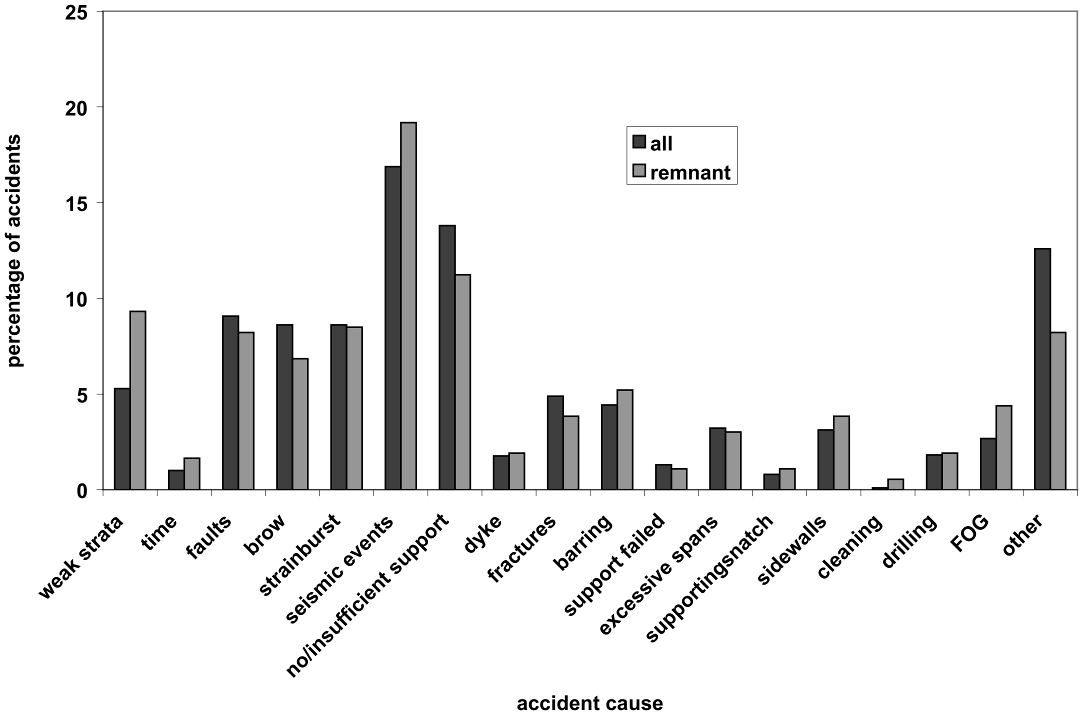

FIG. 2 Causes of accidents in remnants compared to all other areas

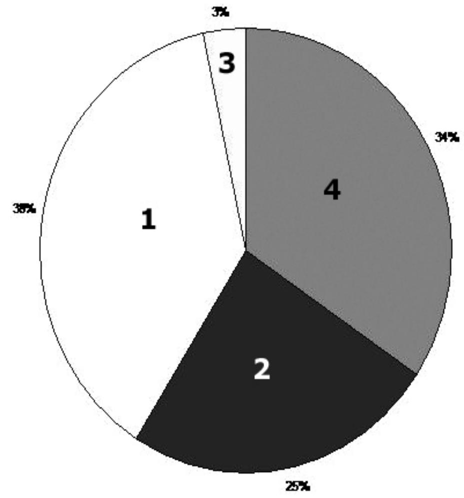

FIG. 3 Classification of selected remnants

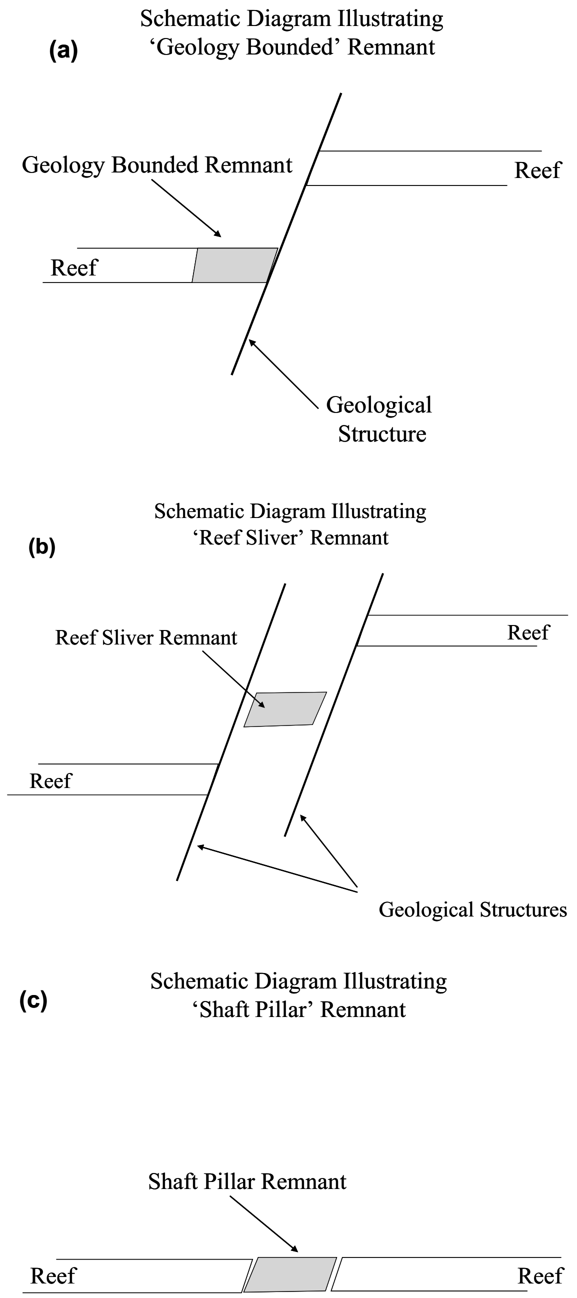

FIG. 4 Classification of selected remnants

the stress transfer around the remnant and the transfer of load to surrounding regions as the remnant is mined. Since the induced seismicity will be related to the load transfer, the different classes should exhibit different seismic hazard characteristics and this will be investigated further in this study.

4 TIME DEPENDENT ROCKMASS RESPONSE

Time-dependent rockmass behaviour may have a significant influence on the hazards of remnant mining and the findings of the various case studies are presented in terms of the different time scales. These are the long-term effects of time between creation and extraction, the medium term effects of mining rate and the very short-term dynamics. Mulder (1999) described two main effects of time that can cause hazardous situations during re-establishment of mining in a remnant. There is time-dependent degradation of the timber supports implying that it is impossible to judge how well the previously mined areas are supported. Also, there is deterioration of the rockmass and a small disturbance is sufficient to cause instability. It is suggested that old areas be considered to be unsupported. Brently and Lucas (1999) reported a sudden increase in closure rate in the days prior to a collapse during scattered mining on Harmony. This was accompanied by "talking" of the hangingwall and difficulty with drilling and cleaning of blast holes. For large collapses with spans greater than 90 m, warning occurred up to 7 days in advance. No warning was evident when geological features controlled the collapse.

The effect of mining rate has been mentioned more often, but is still unclear. Berrange (1956) describes experiences at West Rand Consolidated mines where the 'north face method of extracting a remnant does permit almost continuous working and this speeds up the rate of face advance, which is universally accepted as of primary importance'. In the discussion (Berrange, 1956), Hendersen noted that for the Luipaardsvlei Gold mine, 'hangingwall conditions are invariably good due to rapid face advances and b) the advancing faces being kept at right angles to the shear planes in the old mined out region'. Also, Rouillard (Berrange, 1956) noted his experiences on ERPM where "from our experience, although face advance is a major factor, a steady rate of advance is preferred to a rapid intermittent advance".

The Department of Mines (1964) report noted that 'it is not possible to make a definite recommendation regarding rate of face advance, but it is sound practice for face advance to be regular and continuous.' (Department of mines, 1964). Hill (1942) examined eight remnants with a face advance of over 25′ (7.5 m) per month, all resulting in pressure bursts and concluded that 'Speed is not the solution, though quick extraction gives a better hangingwall and reduces the time during which men working the remnant are exposed to danger.' Unwin in discussion of Hill (1942) said 'am still of the opinion that speed of removal does help to prevent serious consequence' and also 'approximately thirty remnants were removed last year. Speed was insisted upon and, although bursts did occur, damage to personnel and material was much less than usual.' Hill and Denkhaus (1961) found that research from 1956 showed no significant relationship between rate of face advance and severity of bursts. The number of bursts per 1000 m^2 mined was higher for lower mining rates (0.38 vs. 0.25).

Ebrahim-Trollope (2001) noted a change in the character of small seismic events when the mine moved to a cycle mining system where each panel was blasted in turn so that a single face was only blasted every three days. This was ascribed to migration of fractures away from the face softening the rockmass. No conclusions could be drawn on the effect on the hangingwall conditions.

Malan (1999) proposed that the time dependent response was caused by viscoplastic failure of the rockmass surrounding the excavation. By measuring the closure in a continuous manner, it would be possible to characterise the response of the rockmass to mining. By evaluating changes in the response, it may be possible to identify the onset of hazardous situations.

Closure has been measured from at least 25 sites, some for at least a year. Closure curves from a shaft pillar remnant in the Klerksdorp region are shown in Figure 5. The data spans sixteen weeks prior to the site being abandoned for economic reasons. The curves show the typical instantaneous increase after a blast followed by a decrease in closure rate until an almost steady state closure rate is achieved. The curves indicate that the mining rate significantly influences the overall closure. Curve 3 has a rate that is ten times the final steady state closure of curve 7. Theoretically, the closure rate should decrease with distance from face (i.e after each blast). However, the closure rate tends to increase. This phenomenon needs to be understood, but is similar to that observed in caving stopes on the nearby Hartebeesfontein Mine by Malan (1999). The maximum steady state closure rates of about 0.6mm/hour are also similar to those observed at Hartebeesfontein. At this stage, there seems to be no effect of the mining rate on the seismicity as the event rate and the cumulative moment per unit time remained approximately constant in this period.

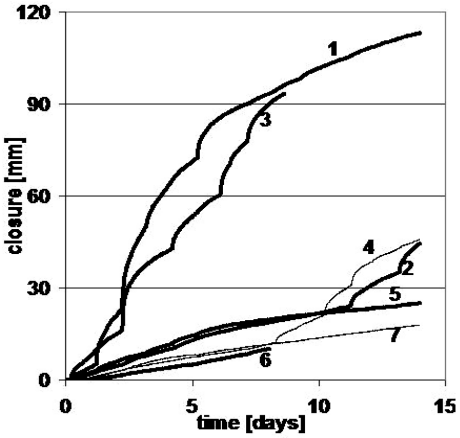

FIG. 5 Closure monitored at a remnant site over sixteen weeks from 20 Jan 2003 to 21 May 2003. Note that a two week gap occurred between curves 3 and 4. Numbers on curves denote sequence of fortnights

Malan (2003) defined the closure ratio as the ratio of the instantaneous closure to the total closure over a single day. This can be expressed as:

$$CR = \frac{1}{n}\sum_{j=1}^{n}\frac{\Delta S_{i_q}^{j}}{\Delta S_{T}^{j}} \qquad [1]$$

Where $\Delta S_{i_q}^{j}$ is the instantaneous closure, ΔS_{T}^{j} is the total closure for *n* days. Using the process for analyzing continuous stope closure behaviour based on the methodology described by Malan (2003), it was possible to determine closure ratios for each data set using Equation 1. Some examples of the closure ratios observed can be seen in Table 1 below. The closure ratio ranges from 0 to 1 and the low values in Table 1 indicated that large time dependent deformations occur subsequent to blasting. High ratios would suggest most of the deformation occurs at blasting and that there is a potential for face bursting (Malan, 2003). There is considerable variability in the closure ratios between and within remnants and it is not clear if the ratios have sufficient resolution to indicate specific changes in rockmass conditions. It is suggested that the closure rate is more important in the remnant conditions.

TABLE 1 Closure ratios for various remnant sites

Class	Remnant	Closure ratio
1	b	0.06
1	b	0.04
1	c	0.21
1	c	0.49
2	d	0.19
2	e	0.71
2	e	0.22
3	a	0.19
3	f	0.15
3	f	0.27
3	g	0.22
3	g	0.13
3	g	0.08

5 RELATIONSHIP BETWEEN CLOSURE AND PEAK PARTICLE VELOCITY

On 18 and 19 September 2003, two large seismic events were recorded in the vicinity of one of the instrumentation sites. The continuous closure monitoring for the period 10 to 18 September, shown in Figure 6, indicates relatively small amounts of instantaneous closure. The large increase in the closure on the 18 September is indicative of a seismic event of magnitude $M_L = 2.7$ at 20:09:10. The event was located within 105 m of the instrumentation site.

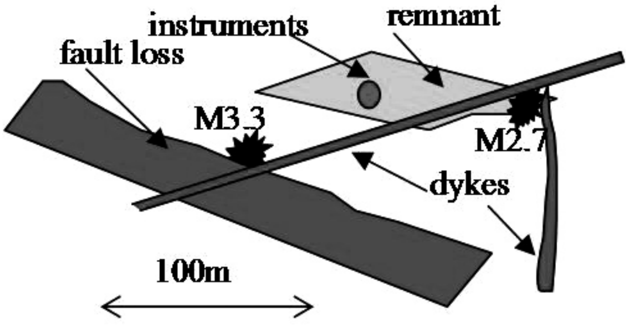

FIG. 6 Schematic plan of the remnant site and two events

The dynamic closure is of the order of 90 mm, with the closure meter situated approximately 15 m behind the face. A second jump in the closure profile is on the afternoon of the 19th September at approximately 16:38:23 and is associated with an event with a magnitude $M_L = 3.3$ at a distance of 124m from the closure and PPV meters. Data from the closure meter shows an increment of only 6 mm for this event. Superimposing the peak particle velocities (PPVs) as obtained from the hangingwall PVD installed in the area, there is a clear correlation with the increase in the recorded PPV values at the time of the dynamic closure for both the 18th and 19th September. This can be seen in Figure 7 where the maximum PPVs recorded for both events were approximately 157 mm/s and 131 mm/s, respectively.

There is significantly less closure and reduced PPV levels associated with the second event. The reduction in the value of the second PPV reading may be attributed to the fact that the second event was on a structure that did not intersect the

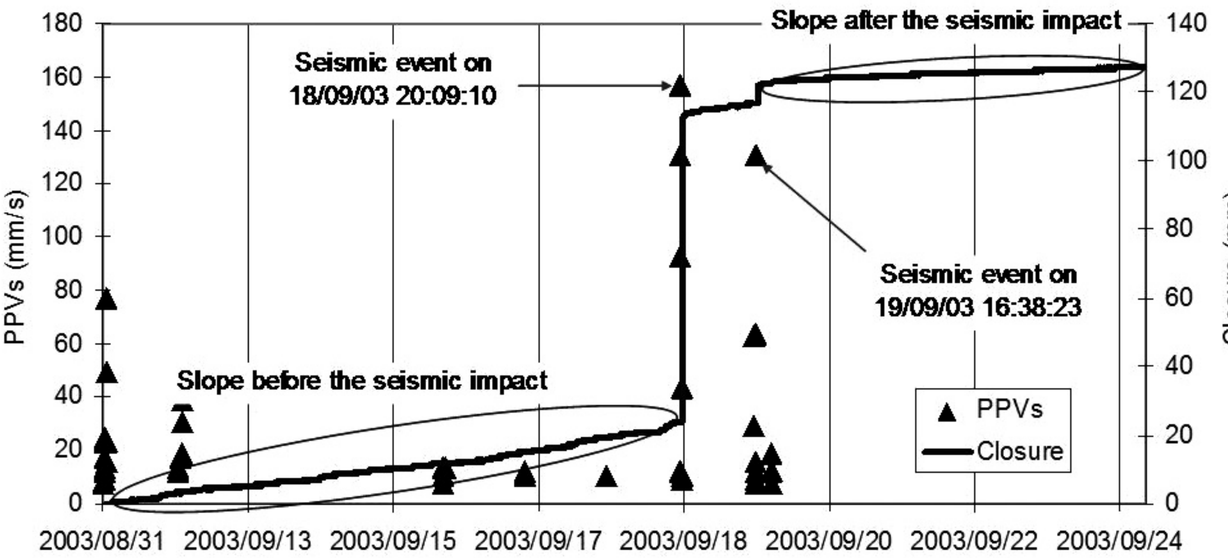

FIG. 7 Closure and peak particle velocity measurements for a remnant that experienced a magnitude 2.7 event at a distance of 50 m from the face

remnant. From discussions with both the seismologist and the rock engineer it was established that extensive footwall heave was evident in the area in particular 20-30 m behind the advancing face. The stoping width in this back area had reduced to 400 mm and some 50 mm of dynamic closure was observed to have taken place. Sporadic falls of ground were observed, with the most significant being the failure of a brow that was created because of undercutting. The support used was 90 x 90 cm Durapaks for the stope face area whilst the gully was supported with the 90 x 120 cm variations.

No precursory information is observed from the PPVs, but there is an increase in closure rate prior to the events that may be significant. A reduction in slope of the closure curve is observed after the event. The cause and implications of the variable closure rates need further investigation.

6 PEAK PARTICLE VELOCITY FOR VARIOUS REMNANT CLASSES

Recorded peak particle velocities are analysed in a form of power-law distribution in each monitoring site. The 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 last group of seismic events was considered as damaging. The values of 100 mm/s and 800 mm/s used for definition of these groups were based on the observations obtained from the simulated rockburst experiment made under the SIMRAC project GAP 530 and published by Milev et al. (2001). In this experiment, 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, which have an insignificant effect on the support system. However, in some isolated cases, damage was observed at PPVs in the range of 100 mm/s.

Additional analyses were carried out in order to characterize the hazard conditions for each type of remnant defined in Section 3. The 'Shaft pillar' type of remnant was additionally separated into three subdivisions as they were mined on different reefs. The recorded PPVs are analysed in a form of power-law distribution plot per monitoring area. The number of events was normalised by the period of observations and then multiplied by 365 to obtain the annual figures. The distribution of the PPVs shown in Figures 8 to 10 follows a power-law with slope close to one.

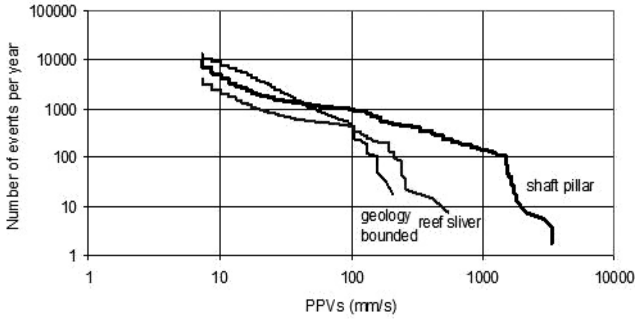

FIG. 8 Power law distribution plot for PPV recorded in some Klerksdorp remnants

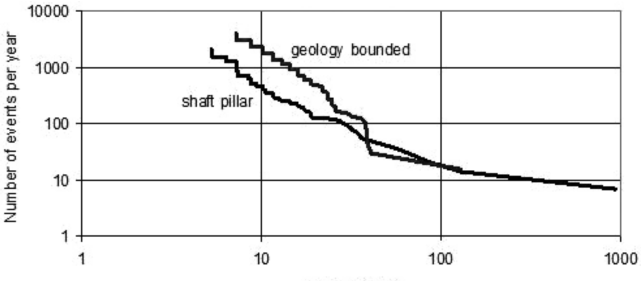

FIG. 9 Power law distribution plot for PPV recorded in some Free State remnants

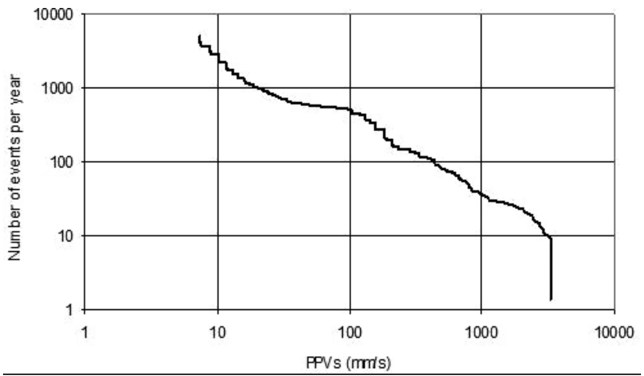

FIG. 10 Power law distribution plot for PPV recorded in a Carletonville 'shaft pillar' remnant

The results have shown that the 'shaft pillar' type of remnants indicated the higher PPVs followed by 'reef sliver' type remnant and lastly 'geological bounded' type of remnants. The hypothesis of early slip on the geological structure during the formation of the 'geological bounded' type of remnant could explain the absence of extremely high PPVs in the presence of a large number of moderate events. The maximum PPV recorded at any site was about 3m/s. This value is consistent with the PPVs measured in the other areas at this mine and is consistent with values reported in SIMRAC project GAP 709 (Milev et al., 2002). The limitation of maximum PPVs at about 3 m/s is interesting as it corresponds to the value previously reported in GAP 709 and proposed by Wagner (1984) as dynamic criteria for support design. The analysis and interpretation are in their initial phase and additional analyses to understand the behaviour of each individual remnant monitored in this project.

The measured peak particle velocity needs to be related to the far-field events so that some predictions can be made regarding the expected hazard for any particular remnant, even if the mining has not yet started. This work is in progress at present.

It is also important to understand the relationship between the peak particle velocity and the potential for damage. A preliminary assessment of 140 damage reports has been carried out for the 5 sites where instrumentation is installed and considering events with magnitudes greater than 2. About 42% of the events resulted in no damage and all but 3 events had a far-field PPV of greater than 100 mm/s. Minor damage occurred in 29% of the cases and most had PPVs greater than 100 mm/s. Moderate damage occurred for 18% of the events and the majority had a PPV of more than 200 mm/s. Severe damage happened at 8% of the cases with most having PPVs of greater than 100 mm/s. Thus, higher PPVs seem to lead in general to more damage, but the full picture of the correlation between damage and PPV is not clear at this stage.

7 NUMERICAL MODELLING

Classical design criteria (e.g. Average Pillar Stress, Energy Release Rate and Excess Shear Stress) for the planning of the size and spacing of final pillars are based on elastic models. There is a strong emphasis to integrate information provided by seismic activity, which represents a direct measurement of the historical rockmass response, with numerical models to predict the stresses and deformations induced by any future mining scenario (Spottiswoode, 2001). The relevance of the classical design parameters must be evaluated and the relevance of new integration schemes tested. To do this, the outputs from a numerical code called MINF (Spottiswoode, 2001) are used to investigate the elastic criteria and to simulate and quantify inelastic effects associated with observed seismicity.

The cumulative volume of elastic convergence is closely related to Energy Release Rate (ERR), (Milev and Spottiswoode, 2001), which is the most widely used criterion for design of mining layouts in the South African Gold mines. Seismic energy was empirically related to the volume of elastic convergence by McGarr (1976) as:

$$\gamma_E = \sum Mo/G\Delta V_E \qquad [2]$$

where ΣMo is the cumulated seismic moment, G is an average modulus of rigidity of rockmass (3.0 x 10^{10} N/m^2), and ΔV_E is the volume of elastic convergence due to mining. This γ_E value represents the level of seismicity due to mining. A linear relationship between seismicity and elastic closure was reported by McGarr (1976). This relationship can be simplified by considering ΔV_M as the total volume of mining and written as:

$$\gamma_M = \sum Mo/G\Delta V_M \qquad [3]$$

where ΣMo is the cumulated seismic moment, G is an average modulus of rigidity of rockmass (3.0 x 10^{10} N/m^2), and ΔV_M is estimated from the volume of rock mined out assuming a constant stope width (Spottiswoode et al., 2000). Table 2 shows the γ_E and γ_M values for different shaft pillars analysed so far in this project. If γ_E is less than γ_M the volume of elastic convergence (ΔV_E) is greater than the volume of area mined (ΔV_M) and thus the mining is being conducted at an extreme ERR (Spottiswoode et al., 2000).

The remnants all exhibit such behaviour, confirming the suspicion that the elastic ERR concept is not relevant under these remnant conditions. Alternatively, this could imply that energy is not being released or energy is being released but not radiated seismically. Further inelastic numerical modelling incorporating closure meter readings will be performed to confirm these observations and to attempt to provide consistent methods for design under remnant mining conditions.

TABLE 2 Relationship between volume of closure and ERR for some remnants and some other mining areas (denoted as class 0)

Reef	**Av. Depth** [m]	**Class**	**$\Sigma\Delta V_E$** [10^3 m^3]	**ΣMo** [TN-m]	γ_E	γ_M	**ERR** [MJ/m^2]
Carbon leader	2608	0	860.4	787.2	0.30	0.04	14
Carbon leader	2615	3	41.5	247.7	0.20	0.32	134
Basal	1445	3	409.6	56.8	0.007	0.04	263
Basal	1445	3	409.6	56.8	0.007	0.02	263
VCR	1741	0	131.3	813.9	0.4	0.26	31
Carbon leader	2506	3	80.5	286.3	0.1	0.15	94
Vaal Reef	2315	3	133.6	38.4	0.01	0.02	196
Vaal Reef	3083	2	9.95	3.31	0.006	0.03	

8 CONCLUSIONS

A three year research project has been undertaken to evaluate the rock related hazards in remnant mining. Preliminary findings are reported in this paper. A study of accident databases identified that stope faces and gullies are the most hazardous regions and are relatively more hazardous than all other mining conditions. When scaled by the number of fatalities per accident, both 'seismicity' and 'weak planes' are indicated as the main causes of multiple fatal accidents in remnants. The remnants are classified into four classes based on geology and reason for formation to assist the evaluation of the hazard.

The effect of the rate of mining on hazards remains unclear due to the limited data. Time dependent degradation of support and the rockmass can lead to unstable situations, although time dependent closure can also lead to increased stability due to the increased region of complete closure. Continuous closure measurements indicate considerable time dependent closure in all remnants and significant closure associated with seismic events. It is suggested that the closure rate is a more important indicator of rockmass conditions than the closure ratio in the remnant conditions. The peak particle velocities observed in the stopes differ between remnants classes and can regularly reach up to 3m/s in some remnants. Shaft pillars exhibited the highest PPVs. The hypothesis of early slip on the geological structure during the formation of the 'geological bounded' type of remnant could explain the absence of extremely high PPVs in the presence of a large number of moderate events. Small, and nearby events cause the highest observed local amplification of peak particle velocities. The correlation between damage and PPV is not clear at this stage.

Elastic numerical modelling emphasised that the remnant mining is being conducted at extreme energy release rates. This confirms that the elastic ERR concept is not relevant under these remnant conditions. Further inelastic numerical modelling incorporating closure meter readings will be performed to confirm these observations and to attempt to provide consistent methods for design under remnant mining conditions.

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