Assessment of the risk of plug or water barrier failure due to seismicity at South Deep Mine

by W.D. Ortlepp* and T.R. Stacey†

Synopsis

As part of a comprehensive risk analysis which was carried out into the effectiveness of the water barrier between South Deep and Randfontein Estate mines, the potential threat posed by large seismic events was assessed.

The study covered several aspects. Firstly, an estimate of the maximum credible earthquake was obtained from a probabilistic analysis of the regional seismicity of the previous 25 years. Allowance was made for 'reservoir-induced' effects by increasing the estimate of the size of the maximum credible earthquake from M_L = 5.1 to M_L = 5.5.

Based on available knowledge of the geological structure, the possibility of such an event occurring in the vicinity of the barrier pillar was estimated. The possibility of substantial damage to the barrier rock mass, resulting as a consequence of a large event, was assessed.

The likely damage to the concrete control plugs installed in five tunnels that penetrated the barrier, which might result from a 'near-miss' by the largest possible seismic event or from a 'direct hit' by a smaller event, was also considered.

It was concluded that there was a negligibly small possibility that the maximum credible earthquake could occur close enough to the barrier, and in such a manner, as to cause any damage to it or to the plugs in the tunnels passing through it. The possibility of serious plug damage occurring as a result of a 'direct hit' by a smaller event was slightly greater, but still sufficiently remote as to be of no practical concern at all.

Introduction

A comprehensive analysis was undertaken by Placer Dome Western Areas Joint Venture (PDWAJV) to determine the risks associated with high pressure water plugs that would control water inflow from abandoned mines on the up-dip side of South Deep Mine. This risk analysis identified seismic activity as a potential threat to the five control plugs installed in the boundary pillar zone.

Consequently, in December 2001, on behalf of PDWAJV, SRK Consulting (SRK) commenced a comprehensive assessment of all aspects of the seismic threat.

In considering the strategy to be followed, the following facts and premises were recognized:

- Significantly large natural earthquakes were, historically, not expected in the Kaapvaal craton
- Several medium-sized earthquakes (perhaps better referred to as 'mine quakes') have occurred since mining became widespread in the Witwatersrand basin
- Events of Richter local magnitude between M_L = 4.4 and M_L = 5.2 have occurred perhaps as often as 40 times in the last 32 years in the Free State and Klerksdorp gold fields. During this period only two very large events occurred in the Carletonville area, one of M_L = 4.4 and one of M_L = 4.9
- In the Free State and Klerksdorp areas these large events have been shown to result from slip on faults with strike extent of many kilometres and 'throws' of hundreds of metres, where the reef on either side has been mined extensively. In neither of the two Carltonville events was the source mechanism determined but it is thought also to have been due to slippage on large faults
- The co-seismic slip can be as much as 400 mm across a single narrow fault zone. Importantly, tunnels intersected by such faults are often not seriously damaged by this amount of dislocation.

In broad terms, an assessment of the seismic risk would need to address the following questions:

- How large a seismic event might be expected to occur?
- What was the chance that it would occur close to the boundary pillar area?
- What modes of failure might affect:
  - the plugs and
  - the pillar?

* *SRK Consulting.*

† *University of the Witwatersrand.*

 Paper received Nov. 2004; revised paper received May 2006.

- ➤ What would be the estimated overall likelihood that these postulated damage mechanisms might actually occur?
- ➤ What would be the consequences of each such occurrence?

Consideration of these issues suggested that both a probabilistic and a deterministic approach would be necessary.

Probabilistic study

Seismological analysis and prognosis

A statistical review of the seismic history of the previous 25 years in the region defined by a 50 km radius circle centred on the barrier pillar, was requested from the SA Council of Geoscience. Based on the Gutenberg-Richter relationship, using a b-value of 1.38 they determined that the maximum credible magnitude earthquake was M_{max} = 4,87 with a standard deviation (SD) of 0.25. Conservatively then, the assessment of future risks could be based on an M_{max} value of 5.1.

The seismic expectancy rates calculated by the Council were expressed as probabilities that specified magnitudes between M_L = 3.5 and M_{max} = 5.1 would be exceeded in particular periods of time. Thus it can be seen from Table I that M_L = 4.0 events occur sufficiently often to suggest, with a very strong probability (96%), that 3 would occur every year, on average. It would require a much longer period, viz. 75 years, to ensure the same near-certainty that a magnitude 5.0 event would occur. Over the same long period there would be about a one in three chance that the maximum credible earthquake of M_{max} = 5.1 would occur somewhere within 50 km of the plugs.

The above analyses were based on two complete catalogues of events which had been recorded by the national network during the period January 1971 to December 1995 from within a 50 km radius circle centred around the boundary pillar area. The first period, which ended 31 December 1985, included 429 events from M_L = 3.5 upwards. After December 1985, improvements in the national seismic network enabled all events above the threshold of M_L = 2.7 to be located, yielding 2 184 events in total.

Using the probabilities of exceedence of the various magnitudes listed in Table I for the 75-year period covering the life-of-mine, an attempt was made to address the questions and implications listed in broad terms in the introduction above.

During preliminary discussions of the proposed seismological analyses, Dr A. Kijko of the SA Council for Geoscience suggested that reservoir-induced seismicity might be a relevant issue that could not be taken into account by his approach.

Because of the need to consider every conceivable threat to the integrity of the plugs and barrier pillar, PDWAJV decided that the first assessment should be re-appraised to take account of the fact that the reservoir-induced phenomenon might be invoked. If the water compartment to the north was allowed to flood completely, the barrier pillar and plugs would essentially represent the impoundment of a reservoir 1 500 m deep. An appropriate literature survey was done to determine the nature of the phenomenon and a second data survey was requested from the SA Council for Geoscience.

The re-appraisal of risks which resulted from analysis of this second data set, is described in this paper.

Table I

Expected number of seismic events

Magnitude	Time period—years (average expected no. of events)			
	1	5	10	75
3.5	1.000 (17)	1.000 (83)	1.000 (166)	1.000 (1244)
4.0	0.964(3)	1.000 (17)	1.000 (33)	1.000 (250)
4.5	0.446 (-)	0.948 (2–3)	0.997 (5)	1.000 (37)
4.8	0.155	0.568	0.814 (0–1)	0.999 (7)
5.0	0.043	0.197	0.356	0.963 (1)
5.1	0.006	0.031	0.060	0.373

Fluid-triggered seismicity

Reservoir-induced seismicity is the term used to denote earthquakes typically observed after filling of large reservoirs. The two largest events of M_L = 6.5 and M_L = 6,3 were in earthquake-prone regions (India and Greece). The third largest (M_L = 6.2) occurred at Kariba in 1963 in a region which is not considered earthquake prone. Other Southern African examples are those of Khatse in 1996 and Gariep in 1971.

McGarr and Simpson (1997) have suggested that when the stress change that causes a seismic instability is small compared with the ambient stress state, the resulting earthquake should be said to be triggered. An induced event, by contrast, requires a perturbing stress change that is relatively large compared with prevailing crustal stresses.

What is of relevance to the present study is the fact that areas considered to be non-seismic might have latent faults that are close to instability in terms of stress level but very remote in terms of time. With the introduction of fluid at the pressure of 15 MPa expected to develop behind the barrier pillar, such an otherwise stable fault might be activated to fail prematurely and cause a triggered earthquake.

To gain greater insight into the possible existence of faults that could be the cause of natural earthquakes in the normal course of geologic time, the second data set of the Council for Geoscience was examined. The intention was to form an estimate of the frequency of non-mining related, neo-tectonic seismicity in this portion of the Kaapvaal craton.

The first output of this study is represented in a location map of all events larger than M_L= 3.5 that occurred since 1952 within a 100 km radius circle centred on Potchefstroom. This is produced in Figure 1. The lower magnitude limit of M_L = 3.5 was thought appropriate because the study would include a reasonable number of events (378) but these would be of magnitude large enough to exclude all events which resulted from purely mine-related source mechanisms such as pillar bursts.

A good insight into the incidence of natural seismicity, as opposed to the much more frequent mining-induced seismic activity, could thus be gained from examining the spatial distribution of the events in Figure 1.

The dashed outlines in Figure 1 enclose all the fault-slip events that can confidently be said to be induced by mining. These comprise 85% of the total. With a generous allowance made for possible location error, another 9% (34 events)

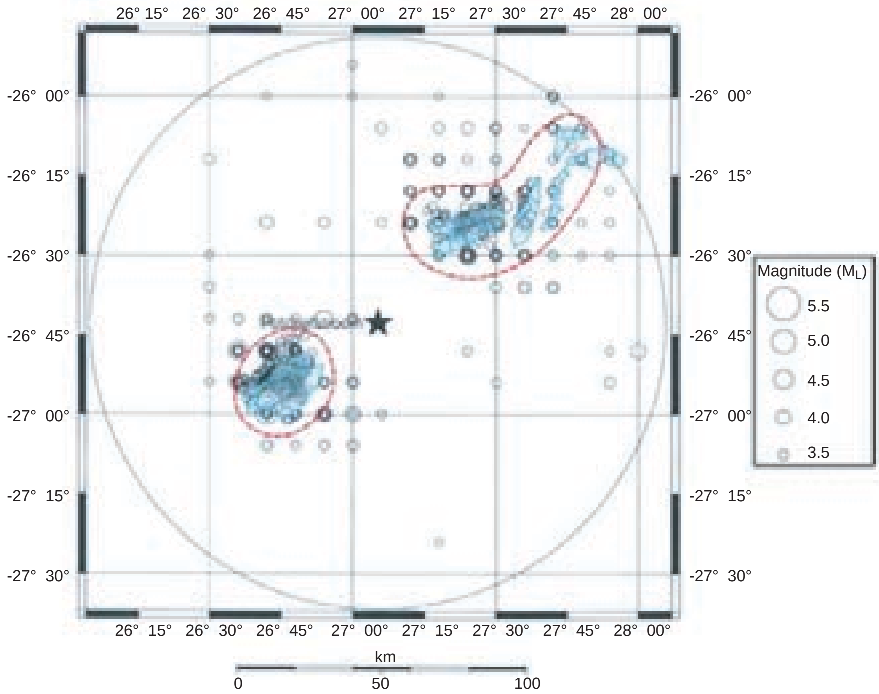

Figure 1—Location of event data in relation to mining outlines and the two main seismogenic areas of approximately 1 840 km^2 in extent

which lie within 15 km of the mining-induced seismogenic area could be said to be probably related in some way to the mining activity.

Twelve events (3%) fall within the next 15 km wide peripheral area and 8 events occur beyond that limit. These 20 events are considered to be not related to mining.

Thus during a period of 50 years some 20 seismic events greater than M_L = 3.5, which can be considered to be of totally natural origin have occurred in an area of 31 400 km^2. Four of these were larger than M_L = 4.0 and one was of magnitude M_L=4.5.

If this very sparse activity is assumed to represent the natural background level of crustal seismicity in the western half of the Witwatersrand basin, then it is self-evident that neo-tectonic earthquakes represent only the remotest threat to the SDWA water barrier. To evaluate how remote this threat would be, assume that the natural activity is randomly distributed over the area. Possibly two or three additional natural events might have been coincidentally located within (and been obscured by) the relatively intense seismicity in the mine-induced seismogenic regions. Thus there may have been seven or eight natural events larger than ML = 4.0 in 50 years or, say, ten events in the 75 years of the expected life-span of the South Deep mine, occurring in the total sampled area.

To estimate the probability that one such event of M_L = 4.5 might occur close enough to the plugs to cause damage requires, first of all, a decision as to what constitutes significant damage and how close must the event be to cause such damage.

The most widely accepted understanding of the mechanics of a seismic source is due to J.N. Brune (1970). The Brune model assumes a circular planar fault surface with the amount of slip greatest at the centre, decaying outwards, parabolically, to zero at the edge of the circular surface. The radius of the circular surface (*r*) is a function of the magnitude of the event, the rock type and the stress drop. With a stress drop of 10MPa, which is considered to be a typical value for a large damaging event in quartzite, the source radius for M_L = 4.5 would be about 500 m. It would be about 1100 m for an event of M_L = 5.1 and about 1 700 m for M_L = 5.5 (Mendecki, 1997).

Thus if an event of M_L = 4.5 originated more than 500 m away from a water control plug the reactivated slip front would not reach the plug position. Therefore the shear movement could not cause any differential displacement or strain at the plug or create a permeable fracture path through the surrounding rock, even if the extended plane of the existing fault passed through the plug site. Similarly an event of M_L = 5.1 would have to originate within a circle of 1 100 m centred on the plug to cause direct damage to it or the nearby rock surround (Figure 2).

The significant area for a M_L = 4.5 event (r = 500 m) is thus 0.785 km^2. There are 31 400 km^2 in the sampled area in which it is estimated that less than one natural event of that magnitude would occur each year (Table I). In 10 years, 5 events of M_L = 4.5 could be expected, randomly distributed throughout the sampled area of 31 400 km^2. The chances that one of these would occur in the significant area during that time is 0.785 ÷ 31400 x 5=0.000125.

The significant area for an event of M_L = 5.1 (source radius of 1 100 mk) is 4.23 km^2. Because of this larger 'target' area there is a considerably greater geometrical chance or geographic probability that the M_{max} = 5.1 event will hit within that area. However, the Gutenberg-Richter size-frequency law indicates that the probability of the maximum event occurring in the 75-year period is only 0.373 (Table I).

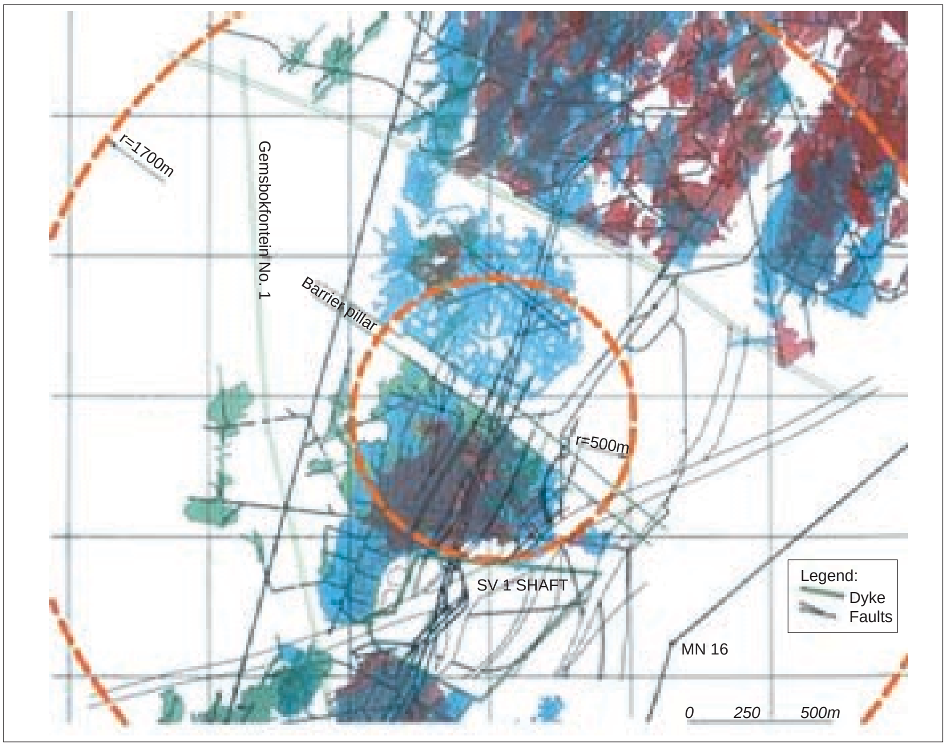

Figure 2—Structural geology interpretation showing significant areas for M_L=4.5 (*r*=500 m) and M_{max} = 5.5 (*r* = 1700 m) earthquake

The expectancy that it should occur in that particular small area where it might cause damage during the life of mine is thus 4,23 ÷ 31 400 x 0,373 = 0,00005. Both of these calculated probabilities are so small that it can be concluded that the chance that damage to plug or barrier pillar could result from a natural earthquake is so slight as to be completely negligible for practical purposes.

Local geological structure

However, the vital question still remains whether a nearby existing fault that is tectonically stable but which might have some obscure hydraulic connection to the impounded reservoir, might be induced to slip by the presence of water at 15 MPa together with relatively large mining-induced stresses. Consideration of this issue requires a deterministic, rather than a probabilistic, approach and leads to the following thoughts:

- ➤ What is the state of mining-induced stress on the existing faults?
- ➤ If the stress component perpendicular to the fault surface (the 'clamping' stress) was reduced by the 15 MPa fluid pressure of the flooded compartment, would slip occur?
- ➤ For this to happen the water would have to penetrate into the fault in such a pervasive way as to exercise its full destabilising effect by acting against the greater part of the surface area of the fault. Water pressure which is confined to a braided system of narrow sinuous channels along the fault surface would presumably not have the same effect
- ➤ If moderately sized mining-induced events (say M_L = 2.5 to 3.5) were to cause small displacements (50 mm to 100 mm, say) on existing faults cutting through the barrier pillar zone, might these become more vulnerable to a later large event? Water penetrating through fault gouge made permeable as a result of the small displacement on these reactivated faults would tend to increase the pore pressure and reduce friction. This would increase the tendency of the fault to slip.

In the face of so many unknowns with so many permutations, it is not possible to do better than make an informed guess when attempting to estimate the influence of these imponderables.

The first assessment of overall risk examined the possible consequences of slippage on such faults in a conceptual, non-explicit way. It would seem reasonable, then, to make a further allowance for an increased frequency of occurrence and an increase in the size of the largest event, in order to cater for the additional threat imposed by unknown fluid-triggering factors such as those listed above.

This has been done by allowing the maximum credible earthquake to have a value of M_L = 5.5 instead of M_L = 5.1. The probability of exceedence of this magnitude in 75 years (Table I) is assumed to remain at 0.373. Usually the considerably larger M_L = 5.5 would be expected to have a correspondingly lower probability of occurrence in a given time period than the M_L = 5.1. To allow it to have the same probability of 0.373 recognizes that the fluid triggering mechanisms could cause the larger event to slip much sooner than would be the case with the same amount of mining disturbance but without the presence of water under pressure.

The circular significant area of 3.4 km diameter into which the origin of this maximum credible earthquake should fall in order for it to cause significant damage in the boundary pillar zone is outlined in Figure 2 together with the larger known geological structures.

In the light of the above reasoning, the possibility of damage resulting from slip occurring on any of the three most significant sets of structures which are known to exist in the area of the barrier pillar is examined more explicitly in the following sections.

Method of assessment of hazard occurrence

The starting point for estimating the probabilities of actual occurrence of any of the hazards that might be identified, is the table of exceedences given in Table I.

In order to reflect the likelihood that an event (of a given size) could occur within a particular area, the actual listed probability values (which are based on the premise of random spatial occurrence anywhere in the mining-affected area in the project study region) have to be discounted appropriately. This is done by applying a 'geographical likelihood' factor in column 2 in Table II in the same way as was done earlier for the probability of a natural event occurring close to the plugs. The factor is determined from the ratio between the area considered significant for a particular size of seismic event and the total area seismically-activated by mining. The area within which mining-induced seismicity has been activated during the sample period is estimated at 1 840 km2.

If, for example, it was considered that an event of maximum credible magnitude M_{max}=5.5 would have to occur within 1 700 m of any plug (as measured from the nearest point on the fault surface) in order for damage to result, then the significant area would be 9.1 km2. The geographic likelihood factor would be 9.1 km divided by 1 840 km2 or 0.005.

Because of the possibility of fluid triggering it has been assumed that the probability of an M_L = 5.5 event occurring somewhere within the seismogenic region within a 75-year period is 0,373. The chance that it will then occur within the very specific small area that lies within the significant distance of 1 700 m from the plugs on SDWA is 0.005 x 0.373, i.e. only 0.0019.

The significant area would logically reduce quite rapidly for smaller magnitude events since they would have to be much closer to the plugs to cause shock or vibrational type damage. An event of M_L = 3.5 has only about 0.10% of the energy content of the M_L=5.5 event and would obviously have to be much closer to the plugs to cause damage. The slip radius of the M_LL = 3.5 event is 160 m so its hypocentre would need to be within 160 m from the plug for it to reach close enough to cause damage. The significant area would thus be 0.08 km2. The geographic likelihood would be 0.08/1840 = 0.00004. This is a much smaller probability than that which governs the likelihood of the very much larger M_L = 5.1 event occurring significantly close to the plug sites. However, the frequency of occurrence of the smaller events is so much greater that it is possible (from Table I) that some 1250 M_L = 3.5 events might occur in the seismogenic region during the 75-year life of mine. The chance of one occurring close to the plugs is thus 0,00004 x 1 250 i.e. 0.05. This is about 25 times more likely than the largest possible event occurring within 1 700 m of the plugs

Thus, it is evident that one should estimate the risks associated both with smaller-sized major seismic events, (viz. those over M_L = 3.5) as well as the threat of the very largest events. The further moderation of the hazard because of geometric or other constraints must then be done in a manner that is appropriate for the kinetics and consequences of the smaller sizes and the different mechanisms of these relatively lesser events.

Deterministic study of possible damage to barrier pillar or plugs

Once it is accepted that an event may occur close to a plug it has to be assumed that it may actually intersect the plug.

Table II

Risks, probability and consequences

1		2	3	4	5		6	7
Item	Identified Hazard	Seismic-statistical probability (2)	Geometrical probability (kinetic (3) freedom)	Overall likelihood (4)	Potential for increased leakage rate (1)		Severity of consequence (5)	Overall risk rating (6)
					rapid flow	slow flow		
1	**Fault slip: M_L = 5.5 r = 1700 m** 1.1 fault within one source dimension 1.2 ENE fault intersects barrier 1.3 fault transects barrier pillar along its length 1.4 fault transects plug	**0.0019 (0.37 x 0.005)**	0.0001 0.00005 0.00005 0.00001	**1.9×10^{-7} 9×10^{-8} 9×10^{-8} 1.9×10^{-8}**	(see items 3 and 4) unlikely unlikely likely	 likely possible very likely	- marginal 3 negligible 1 severe 100	 **2.7×10^{-7} 9×10^{-8} 1.9×10^{-6}**
2	**Pillar failure: M_L = 3.5 r = 160m** 2.1 'pillar-crush' failure due to critical width : height ratio 2.2 'foundation' failure due to high stress	**0.05 (1250 x 0.00004)**	0.00001 0.00001	**5×10^{-7} 5×10^{-7}**	possible unlikely	very likely possible	substantial 20 marginal 3	**1.0×10^{-5} 1.5×10^{-6}**
3	**Plug destruction: M_L = 5.5 r = 1700m** 3.1 plug ejection through shear failure of interface 3.2 complete crushing of matrix 3.3 pervasive shearing due to axially-directed shear wave from near-field M_{max} event	**0.0019 (0.37 x 0.005)**	0.0001 0.00001 0.00001	**1.9×10^{-7} 1.9×10^{-8} 1.9×10^{-8}**	certain certain very likely	- - certain	disastrous 1000 catastrophic 10000 disastrous 1000	**1.9×10^{-4} 1.9×10^{-4} 1.9×10^{-5}**
4	**Plug damage: M_L = 4.0 (7) r = 270m** - plug sheared/dislocated by transecting fault surface 4.1 along horizontal axial plane (bedding plane fault) 4.2 along steeply inclined ENE fault surface 4.3 along steeply – inclined structure parallel to boundary pillar	**0.031 (250 x 0.00012)**	0.0001 0.0001 0.001	**3.1×10^{-6} 3.1×10^{-6} 3.1×10^{-5}**	likely likely possible	very likely very likely likely	severe 100 severe 100 substantial 20	**3.1×10^{-4} 3.1×10^{-4} 6.2×10^{-4}**

Notes: (1) These terms, descriptive of relatively high likelihood, apply only in the extremely unlikely event that the identified hazard actually **does** occur.

(2) The seismic-statistical probability is the product of the two values in parentheses: the likely number of occurrences in the 75 year life-of-mine, and the 'geographic' likelihood.

(3) The estimated likelihood that all of the necessary causative factors to 'drive' the fracture or slip, and to give it the 'kinetic freedom' to move, are actually present in the significant area.

(4) Product of column 2 and column 3 gives overall estimated probability of occurrence (overall likelihood).

(5) 'Consequence' values for risk rating – based on Table 16 of RAMP.

(6) Overall risk rating = overall likelihood (4) x consequence value (5) .

(7) If the 'boundary dyke' fault should slip, the largest possible magnitude event that could be 'kinetically accommodated' would be < 4,0 with a slip radius of <270 m.

Therefore the consequences of this happening need also to be examined. Similarly, a major fault or induced fracture may transect the boundary pillar and thereby endanger its integrity as a water barrier—see the schematic depiction in Figure 3.

The approach that then needs to be adopted becomes deterministic rather than probabilistic and all the possible modes of failure, both of the plugs and that part of the surrounding rock mass that constitutes the boundary pillar, need to be considered. This has been done in Table II and some of the possible modes of failure of the pillar have been diagrammatically illustrated in Figures 4(a) to (c).

It was thought prudent in the case of each of the envisaged failure mechanisms to consider the minimum size of the major event that would pose a threat in each case. It would then be necessary to assess the geographical likelihood on the basis of a smaller associated significant area as discussed above. Two values are given in parentheses behind the probability value in column 2 in Table II.

The first number is the likely number of times these smaller major events might occur somewhere in the seismogenic area during the 75-year life of mine. These estimates are determined from Table I.

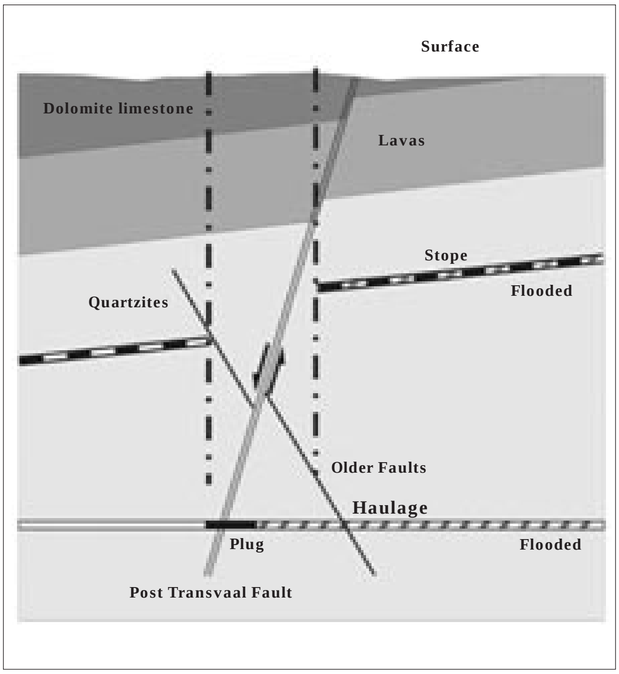

Figure 3—Linking of compartments across boundary pillar

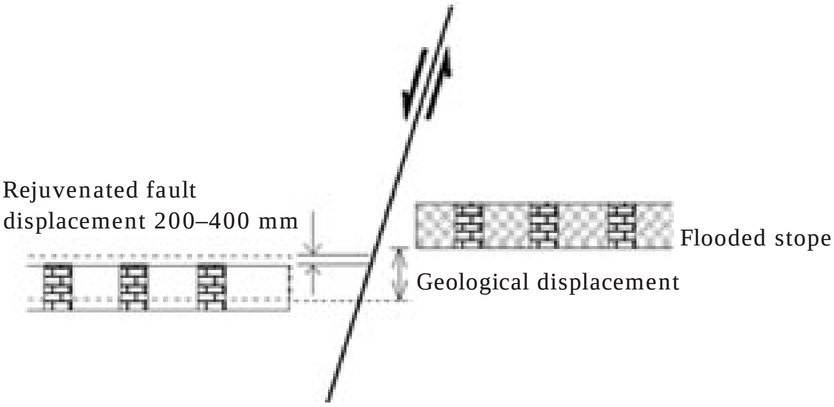

Figure 4(a)—Movement on fault through pillar

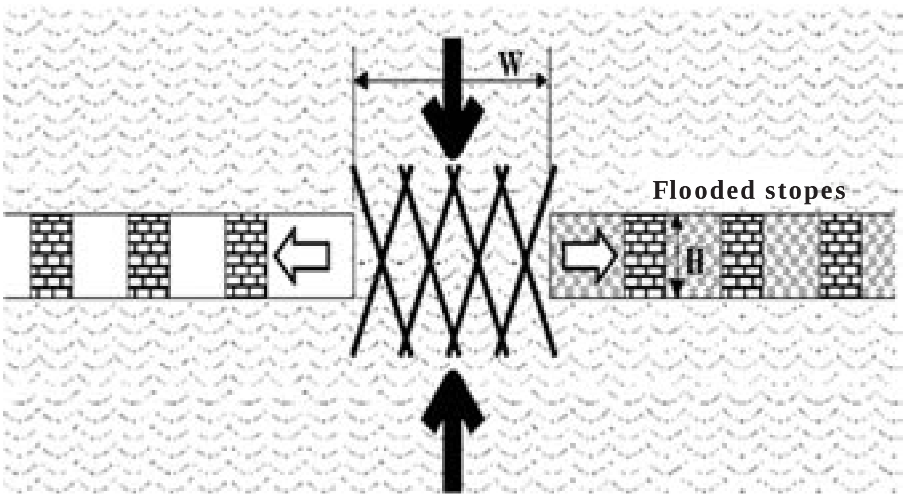

Figure 4(b)—Pillar-crush failure

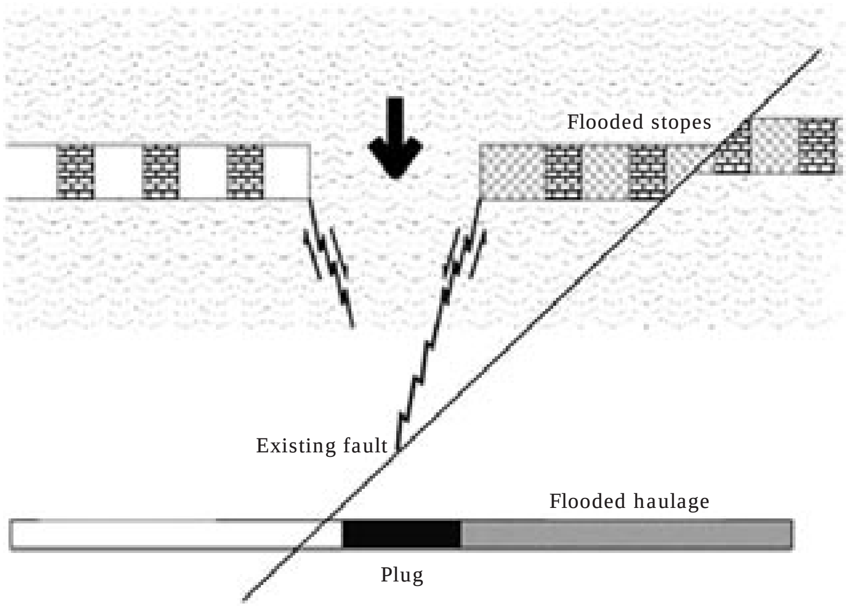

Figure 4(c)—Pillar-foundation failure

The second number in parentheses is the ratio of the relevant significant area to the 1 840 km^2 seismogenic area.

More important, however, is the factor listed under the heading Geometrical probability (kinetic freedom) in column 3 of Table II. This is intended to reflect the cumulative effect of the various geometrical and physical constraints that co-exist in the actual underground situation. This geometric factor is effectively an assessment of the inhibiting or, sometimes, the totally proscriptive effect that the combined constraints will have on the physical possibility that the postulated movement or failure mechanism can occur at all.

Examples of these constraints are, for instance, whether or not the necessary source radius of a particular fault rupture surface can actually be accommodated in the perturbed zone of the overall stoping span or whether the intensity of stress required to cause a pillar foundation rupture (as in Figure 4 (c)) can possibly be generated by the prevailing pillar geometry.

There were very few discontinuities that could be classed as large faults which were encountered during the mining of the relatively small E-W span of 800 m flanking the barrier pillar—see Figure 2. This lack of large geological structure and the limited area of mining differs totally from the situation in the Free State or the Klerksdorp region where re-activated slip on the major faults such as the Dagbreek Fault and the Number 5 Shaft Fault have been the cause of the largest mine-related earthquakes (M_L = 5.2) that have so far been experienced in South Africa. Here the very extensive mining, which extends on either side of the faults, affords them the opportunity (kinetic freedom) to slip over a large area of fault surface. The Dagbreek has been the source of 3 events of M_L=5+ during the last 30 years. We accordingly rate the geometric probability of a M_L 5+ event actually occurring within the significant area surrounding the South Deep pillar as being extremely unlikely. It was therefore given a value of 0.0001 in column 3 for the identified hazard 1.1, see Table 15 in Appendix 1. For this hypothetical fault to be so specially orientated as to intersect the barrier pillar somewhere along its 600 m exposed length is even more unlikely. We therefore accorded it one-fifth of the likelihood of it being the cause of the maximum credible (fluid-triggered) earthquake in the first instance, and it was given a value of 0.00005 in column 3, item 1.2.

Thus the product of the statistical probability and the geometrical probability (or kinetic freedom) gives values of overall likelihood of 1.9 x 10^{-7} and 9 x 10^{-8} respectively for the two examples outlined above and listed as items 1.1 and 1.2 in Table II.

So little is actually known about the physical mechanisms at the source of large events that the basis on which these assessments are made is, ultimately, entirely one of engineering judgement. The probabilistic forecasts of the seismological analyses are essentially an extrapolation into the future, based on a well-known history of thousands of events which occurred over 25 years of reliable monitoring. But it is entirely devoid of any physical basis. The engineering judgements, on the other hand, are based on very little history—only a few actual observations have been recorded in the literature.

However, a significant percentage of these observations have either been made by the authors of this paper or by peers and colleagues of close acquaintanceship. A considerable understanding of the physical processes of failure in rock masses has, similarly, been acquired by the authors during a combined total of some 60 years of experience.

Damage to plug

Plug destruction by crushing or shearing of matrix

Because of the totally catastrophic consequence to the entire SDWA operations (Table II, item 3, column 6) if any plug should be completely destroyed, it was deemed necessary to examine this hypothetical case particularly carefully. Indeed it was probably the vision of such an extreme *force majeur* happening that led to the identifying of seismicity as a potential hazard in the first place.

Three conjectural modes of destruction of the plugs are postulated in items 3.1 to 3.3 in Tab1e II and illustrated in Figures 5(a) and 5(b).

Little is known about how inhomogeneous or non-uniform the process is that generates the vibrational wave in the rock close to the sheared surface, when the sudden slip movement occurs on the fault. The problem of what upper bounds can be placed on the effect, has been considered by McGarr (2001). He has shown that the quantities that determine the maximum values for strong ground motion are the amount of movement on the fault, and its rise time and duration. The peak ground velocity adjacent to the surface of slip or rupture is typically 1.5ms^{-1} for a reactivated ancient fault and as much as 5 ms^{-1} where fracture occurs through intact rock.

How this is manifested as deformation or strain, which can damage the fabric of the rock mass or the matrix of a concrete structure that is an integral part of the rock mass, is largely determined by the dominant frequency and wave length of the seismic waves, the length of the wave path along which the PPV will decay and the site response of the affected 'structure'. The very large mine quakes that have occurred in the Free State and Klerksdorp goldfields have had measured co-seismic slip displacements of 400 to 500 mm. The dominant frequency usually lies between 1 Hz and 10 Hz with wave lengths of many hundreds to possibly a few thousands of metres.

Compressive and shear strains are consequently likely to be in the order of one to a few millistrains at most, even within a few hundreds of metres from the point of origin of the fault movement. While microcracks may form in concrete at that level of strain, the driving stress would have to be sustained for some time for small cracks to grow, coalesce and lengthen sufficiently to cause structural damage. In the actual situation a few cycles of alternating high stress might recur but the total duration would be no more than two or three seconds. There is thus insufficient time for pervasive damage to occur.

A major mitigating effect occurs because the tunnel containing the plug has dimensions that are small compared with the wavelength of the seismic pulse. Typically the tunnel is 4.5 to 5.0 m in diameter at the plug position and the plug is 30m long. The spreading stress wave responds to the inertial and dampening effects of the semi-infinite rock mass and is oblivious to the presence of the insignificantly small 'worm-hole' represented by the tunnel. When the direction of propagation of the wave is transverse to the tunnel axis it is easy to visualize how the entire rock mass, together with the tunnel, would move up and down through an amplitude of two or three millimetres at most, with no difference between its roof and floor—see Figure 5 (a). There would thus be no discernible differential movement or significant compressive strain within the concrete mass of the plug.

Also, because of the lower modulus of the concrete (0.7 GPa) relative to that of the rock (>50 GPa), the plug is a 'low-modulus inclusion,' which therefore experiences a much lower induced compressive stress than is felt by the surrounding strong rock.

It is therefore considered impossible for any pervasive compressive failure or crushing to occur within the body of the plug. The 'kinetic freedom' for crushing failure is accordingly given a near-zero value in Table II.

If the wave propagation direction is parallel to the tunnel axis—Figure 5(b)—the situation might appear to be more complex and there might be a tendency for surface waves such as Rayleigh or Love waves, to develop along the tunnel surface. Again, because the tunnel surface area is extremely small compared with the very large cross-sectional area of the rock mass, the tendency for the surface of the tunnel to move differentially, is considered to be negligibly small.

The shear component of the body waves induced in the concrete by the shear wave in the rock has, for the above reasons, too small a strain value to cause any pervasive shear failure in the concrete core of the plug. The identified hazard 3.3 is consequently accorded a near-zero value in column 3 of Table II.

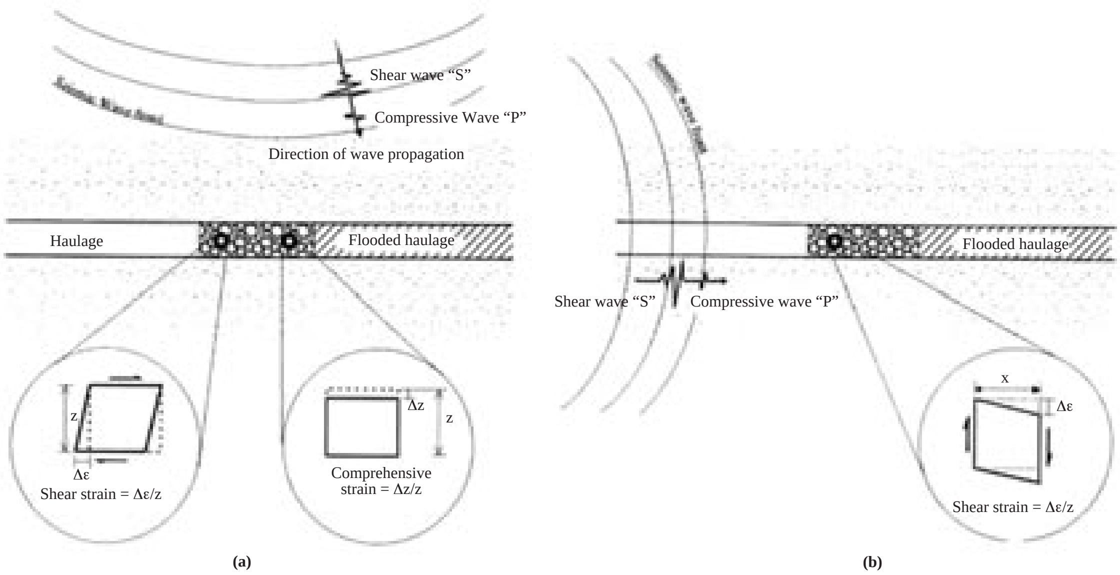

Figure 5—Schematic of seismic transient effects on plugs

Therefore crushing or shearing of the matrix are not possible mechanisms for the destruction of the plug

Plug ejection by shear failure of interface

Following from the above reasoning, it would seem physically impossible, despite the big difference in compressive modulii, for a shear stress along the plug/rock interface to be large enough or be sustained for long enough to cause any weakening of the shear bond between rock and concrete. The design value for the strength of the shear bond was 830 kPa whereas a realistic laboratory strength would probably be 8000 kPa. The design rationale also does not recognize that the interface is not ideally cylindrical or smooth but irregular and rough. Thus, in reality, the basis of the design is extremely conservative and the 'kinetic freedom' for failure along the interface is accorded an extremely low value of 0.0001.

Therefore ejection is not a possible mechanism for destruction of the plug.

Partial damage to plugs

The above arguments effectively dismiss any possibility of sliding displacement of the plug or of pervasive damage to the plug material from nearby large seismic events. Therefore it follows that smaller fault-slip events, while they have a much greater chance of occurring, also have a negligibly small chance of destroying the plug. This is because the magnitudes of the transient stresses and accompanying strains are considerably smaller than with the very large events, and stress and energy levels are more strongly attenuated at the higher frequencies associated with smaller events.

However, if the plug is intersected by such a fault then the plug will be subjected to the same step displacement or dislocation as the rock mass itself—Figure 6.

Several variations of such a possible eventuality have been listed in Table II. Of these, only 4.3 poses a possibility of partially destroying the plug or causing severe damage to it. If the fault transected the plug within, say, one-third of the plug length or less, from the dry face (as illustrated in Figure 6), it is conceivable that the full hydrostatic pressure might be experienced on the surface of dislocation. This would require that the fault surface, which is now permeable because of the crushing and grinding of a plane that was previously sealed by mylonite or other type of ancient fault gouge, is connected directly to the flooded excavations or via some other permeable fracture or discontinuity.

If the full hydraulic demand or thrust were resisted by only one-third or less of the rock/concrete interface strength, the smaller portion of the plug might be ejected. This failure mechanism was the cause of the violent failure of the plugs placed in the concrete-lined vertical shafts that led to the catastrophic flooding of the Merriespruit gold mine in the Free State in the early 1960s.

The other modes of damage considered in items 4.1 and 4.2 of Table II, if they were to occur, would not destroy the plug but would seriously increase leakage. It should be emphasized here that we consider the overall likelihood of occurrence to be extremely low or, in practice, virtually impossible. The amount of leakage would depend on factors such as the amount of dislocation and the thickness and size distribution of the comminuted material enclosed by the shear surfaces. The consequences of such lesser damage are dealt with in the right-hand half of Table II. It is only because these consequences are potentially substantial, or perhaps even severe, that the overall risk is rated as slightly greater than negligible.

Tabulation of risks, probability and consequences

Table II essentially attempts to synthesize and summarize the discussions and speculations of the preceding sections in such a way as to facilitate comparison of the total risks and consequences.

Broadly outlined, the left half of the table (columns 1 to 4) is devoted to the description of the various potential hazards and the estimation of the likelihood that they might actually occur. Columns 5 and 6 roughly describe the nature and potential severities of the consequences that would follow if a particular type of hazard or mode of failure should take place.

In order to enable a broad-brush hierarchical assessment to be made, scale values of severity of consequences have been listed in column 6. It is here that the method of approach of the Risk Analysis and Management of Projects (RAMP, 1988) has been used as a guideline. When this value is multiplied by the total likelihood value, an estimated overall risk rating is obtained—column 7.

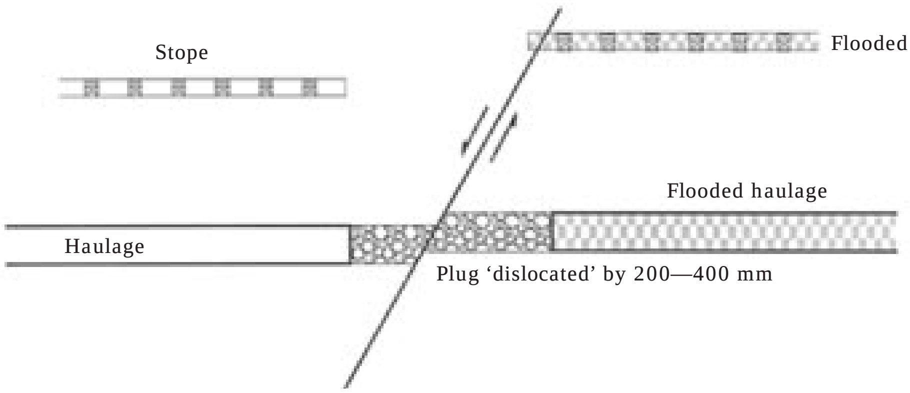

Figure 6—Plug intersected by fault

Transaction Paper

Table III

Summary of probabilities

Item	Identified hazard	Overall likelihood
1	Fault slip: M_L = 5.5	
	1.1 fault within one source dimension	1.9 x 10^{-7}
	1.2 ENE fault intersects barrier pillar	9 x 10^{-8}
	1.3 fault transects barrier pillar along its length	9 x 10^{-8}
	1.4 fault transects plug	1.9 x 10^{-8}
2	Pillar failure: M_L = 3.5	
	2.1 'pillar-crush' failure due to critical width : height ratio	5 x 10^{-7}
	2.2 'foundation' failure due to high stress	5 x 10^{-7}
3	Plug destruction: M_L = 5.5	
	3.1 plug ejection through shear failure of interface	1.9 x 10^{-7}
	3.2 complete crushing of matrix	1.9 x 10^{-8}
	3.3 pervasive shearing due to axially-directed shear wave from near-field M_{max} event	1.9 x 10^{-8}
4	Plug damage: M_L = 4.0	
	- plug sheared/dislocated by transecting fault surface	
	4.1 along horizontal axial plane (bedding plane fault)	3.1 x 10^{-6}
	4.2 along steeply inclined ENE fault surface	3.1 x 10^{-6}
	4.3 along steeply inclined structure parallel to boundary pillar	3.1 x 10^{-5}

The same scale values have been used as appear in Tables A1 and A2 RAMP, (see 1988), which are reproduced in Appendix 1, except that an even more severe category of consequence has been introduced. Catastrophic would refer to an incident that would result in the loss of hundreds of lives and the permanent loss of the entire asset. It has been accorded a scale value of 10 000 on the RAMP scale.

Conclusions

By the end of an appraisal exercise such as the one outlined in this paper it becomes very evident that most of the questions posed cannot be expected to have explicit answers. The largest mine-induced seismic events are nothing more or less than the lower end of the spectrum of crustal earthquakes, albeit with a more clearly identifiable causative origin, namely the stress perturbation induced by mining. Consequently, details of the mechanisms prevailing at the source (e.g. the area of dislocation along the fault surface) and the phenomena determining the nature and extent of damage are little better known than is the case with large catastrophic earthquakes.

Most of the ideas incorporated in this analysis have been derived directly from discussions with local seismologists or have at least been exposed to their critical review. However, the choice of the quantities that are finally expressed as probabilities of actual occurrence, are based on the experience and engineering judgement of the authors.

The important value of the whole exercise is that a wide-ranging enquiry has been applied to every aspect of the problem and a broad consensus has been reached. There is agreement that the overall likelihood of any serious damage to plugs or barrier pillar is extremely remote.

The range of possible damage mechanisms is summarized in Table III together with numerical values describing the respective probabilities that these eventualities might actually occur. It needs to be emphasized, however, that there has not been, and can never be, any history of precedents that can validate the numbers used. Ultimately these almost astronomically small values are simply saying that it is extremely unlikely that the underlying engineering logic, based on experience and broad understanding that has been diligently applied, can be significantly wrong.

Additional measures are being implemented by the Mine to minimize the risks even further. A risk assessment has been carried out, and some of the additional measures include seismic monitoring, regular physical inspections to detect the presence of any leaks, water level monitors, and warning systems.

Acknowledgements

Valuable insight has been provided by friends in the seismological community, principally Steve Spottiswoode, Gerrie van Aswegen, Andresj Kijko and Alexander Mendecki. Discussions with SRK colleagues Awie Swart, Peter Labrum and Alan White have been very helpful.

The permission of Placer Dome Western Areas Joint Venture for the publication of this information is gratefully acknowledged.

References

BRUNE, J.N. Tectonic Stress and the Spectra of Seismic Shear Waves. *Journ.Geophys. Res.* 75, 1970. pp. 4997–5009.

MCGARR, A. Control of Strong Ground Motion of Mining-induced Earthquakes by the Strength of the Seismogenic Rock mass. *5th Int. Symp. on Rockbursts and Seismicity in Mines*. SAIMM 2001.

MCGARR, A. and SIMPSON, D.W. A broad look at induced and triggered seismicity. *Rockbursts and Seismicity in Mines*, Gibowicz & Lasocki, Balkema, 1997.

RAMP, Risk Analysis and Management of Projects. Published by Thomas Telford, 1988.

Seismic Monitoring in Mines. A.J. Mendecki (ed.) Published by Chapman & Hall, London, UK, 1997. ◆

Appendix 1
RISK ASSESSMENT TABLES

This Appendix outlines an approach that is intended to assist in the prioritisation of risks for analysis. It is based on the method of Risk Analysis and Management of Projects (RAMP, 1988).

Set out below are some specimen risk assessment tables. However, it should be emphasised that there is a variety of ways in which such tables can be drawn up, so as to meet the needs of the particular project, with different categories and differing decision rules about which risks should be eliminated, managed or ignored.

To explain the use of the specimen tables, suppose that particular risk event has a 30% chance of occurring at least once during the project's life cycle. If it occurs, it will be a serious threat to the investment. It will be awarded a score of 8 in Table A1 and a score of 100 in Table A2, leading to a combined score of 800 (see Table A3). According to the suggested decision rule, this risk event would come into the category of undesirable, i.e. a risk which one should attempt to avoid or transfer if at all possible (Table A4). Suppose, however, that the same risks event had been assessed as having a disastrous consequence if it occurs. Then the combined score would have been 8000, which means it is an intolerable risk. If it cannot be eliminated, transferred or avoided, the whole future of the project may be in doubt.

Table A1. Risk assessment table – likelihood (RAMP, 1988)
(This table categorises risk according to their probability of occurring at least once at some point during the whole project life-cycle)

Description	Scenario	Probability	Scale Value
Highly likely	Very frequent occurrence	Over 85%	16
Likely	More than evens chance	50 – 85%	12
Fairly likely	Quite often occurs	21 – 49%	8
Unlikely	Small likelihood but could well happen	1 – 20%	4
Very unlikely	Not expected to happen	0.01 – 1%	2
Extremely unlikely	Just possible but very surprising	Less than 0.01%	1

Table A2. Risk assessment table – consequence (RAMP, 1988)

Description	Scenario	Scale Value
Disastrous	Business investment could not be sustained (e.g. deaths, bankruptcy)	1000
Severe	Serious threat to business or investment	100
Substantial	Reduces profit significantly (e.g. injury, damage to equipment)	20
Marginal	Small effect on profit (e.g. minor damage to equipment)	3
Negligible	Trivial effect on profit (e.g. only clean up required)	1

Appendix 1 (continued)
RISK ASSESSMENT TABLES

Table A3. Risk assessment table – acceptance of risk (RAMP, 1988)

Likelihood		Consequence: Disastrous (1000)	Severe (100)	Substantial (20)	Marginal (3)	Negligible (1)
Highly likely	(16)	16 000	1600	320	48	16
Likely	(12)	12 000	1200	240	36	12
Fairly likely	(8)	8000	800	160	24	8
Unlikely	(4)	4000	400	80	12	4
Very unlikely	(2)	2000	200	40	6	2
Extremely unlikely	(1)	1000	100	20	3	1

Table A4. Key to acceptance of risk (RAMP, 1988)

Points	Category	Action required
Over 1000	Intolerable	Must eliminate or transfer risk
101 -- 1000	Undesirable	Attempt to avoid or transfer risk
21 – 100	Acceptable	Retain and manage risk
Up to 20	Negligible	Can be ignored

Anglo Coal stays with limestone technology to treat acid water*

For the past five years, several mines around South Africa have been quietly implementing what was, at the time, revolutionary technology for the treatment of acid water using limestone. Developed by the CSIR and implemented by Gauteng engineering firm, Thuthuka Group Limited (TGL), this state-of-the-art technology has proven time and again its efficacy in treating acid effluent.

The very first mine to pioneer this technology was coal-mining company Anglo Coal's Landau Colliery. Implemented at the mine's Navigation Section, the technology hinges on the use of limestone precipitate as a neutralization agent for treating acid leachates and acidic process water to levels that allow for the water's reuse or release into the environment.

Now, TGL has been sub-contracted by engineering company Keyplan to implement this technology at another Anglo Coal mine—this time at Greenside Colliery in what is known as the Emalahleni water reclamation project. The total project, valued at approximately R300 million, will treat water emanating from Anglo Coal's Kleinkopje and Greenside coalmines as well as BHP Billiton's South Witbank coal mine. Keyplan has been contracted to design, engineer and construct a water treatment neutralization and desalination plant, which will produce potable water for the Emalahleni municipality. The limestone washplant that has been sub-contracted to TGL will be incorporated into the multimembrane pretreatment plant fairly early in the process, says TGL's Francois le Roux.

Anglo Coal Environmental Services senior project manager Peter Günther is a strong proponent of the limestone washplant method of treating acid water implemented by TGL as he was closely involved in the pioneering plant installed at Navigation. Le Roux was also involved in that very first implementation of the technology, as well as all subsequent installations. He says, 'Peter has been enormously impressed by the Navigation plant's performance over the past five years, so he was very positive about the technology. Keyplan agreed to incorporate the limestone technology into its greater project as it quickly realized what the plant could achieve in terms of processing acid effluent as well as the cost implications thereof.'

This is the first time that TGL and Keyplan have collaborated on a project and work has already begun on the civil engineering on site, with the plant to be commissioned in 2007. The managing director of Keyplan, Ralph Jones, concludes, 'We at Keyplan are very pleased to be working with TGL on this project and look forward to future collaboration between the two companies. Our technologies are extremely synergistic and we hope to capitalize on this to our clients' benefit.' ◆

* *Issued by: Alison Job, V Squared Marketing*
Tel: +27 11 678 2227,
E-mail: vsquared@telkomsa.net