Stabilizing and bracket pillar design to reduce seismicity

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Synopsis

The work described forms part of a Safety in Mines Research Advisory Committee (SIMRAC) funded project, currently an ongoing programme of research aimed at providing 'improved criteria, guidelines and the use of numerical models to design mine layouts at depth, so as to reduce seismicity and enhance worker safety'. The entire project deals with a number of distinct, albeit interrelated, research areas such as: subsidence and caving in hard rock, general numerical criteria for layout design, regional benefits of backfill, concrete pillars, strike stabilizing pillars and bracket pillars. This paper will focus on the last two items only. New considerations for the design of both stabilizing pillars and bracket pillar layouts are briefly discussed.

Introduction

Strike stabilizing pillars (Figure 1) are used in association with longwalling in deep level gold mines for regional support. They are the most common pillars in deep mines of the Central Rand and Carletonville goldfields. Their purpose is directed at restricting the convergence in the back areas of longwalls, obtaining a reduction in both the stresses and mining-induced seismicity in the stope faces and, thus, contributing a great deal towards lowering the risk of rockbursts in deep stopes.

On another front, it has been commonly accepted that mining in the vicinity of geological structures, such as faults and dykes, leads both to an increase in the number of seismic events along these structures and to a deterioration in local ground conditions in their vicinity. At times, slip on discontinuities may cause rockbursts within stopes, which can cause equipment damage and, more seriously, injury and loss of life. The most accepted practical measure to counter such effects involves the leaving of strips of unmined ground adjacent to the features so as to reduce the potential for them to slip. These strips of unmined reef are termed 'bracket pillars' (Figure 2) and they are intended to exert a 'clamping' effect on the adjacent discontinuity. Central to this rationale is the assumption that, by reducing the potential for slip, the incidence of damaging seismic events along a bracketed structure is also lessened, resulting in better and safer conditions in the nearby stopes.

It needs to be emphasized that seismicity will always occur whenever excavations are made in highly stressed rock masses, such as those of deep level mines. Regional support measures such as the use of strike stabilizing pillars and bracket pillars can only reduce, but not eliminate, the incidence of seismicity in the vicinity of working faces. The objective of optimal layout design will be the one for which such reduction is maximized.

In the absence, at this stage, of unequivocal relationships between geological and rock engineering properties from which design methods could be derived, other parametric interdependencies of equal importance to mine layout design may be found from planned experiments and data analyses from field monitoring, as well as from numerical modelling. A number of observations that may have great impact on the design of both stabilizing and bracket pillars have emerged from a series of such studies. This paper attempts to summarize the most relevant findings from recent research activities.

Stabilizing pillars

Final analysis of the PSS data from Kloof Gold Mine.

A portable seismic system (PSS) was installed on Kloof Gold Mine to monitor the seismicity associated with the continued formation of a strike stabilizing pillar at a depth of 3035 m (see Figure 3).

Seismic events were recorded over a period of three years after which the system was

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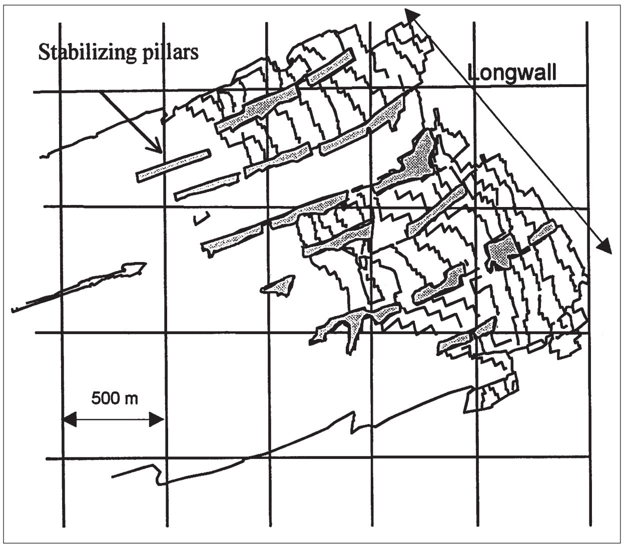

Figure 1—Stabilizing pillar layout

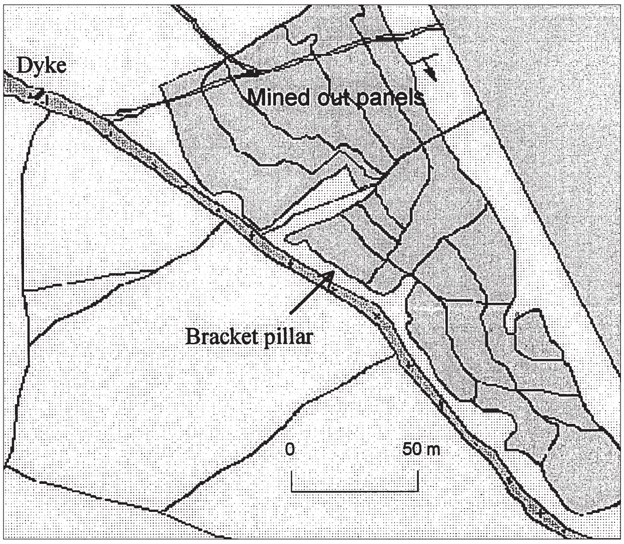

Figure 2—Bracket pillar layout

removed. During that time seismic events were recorded with magnitudes ranging from -1.0 to 2.8. The seismic data collected were analysed to reveal both spatial and temporal trends. This analysis enabled the following conclusions to be made.

➤ From studying the diurnal distribution of the seismic events locating within the vicinity of the stabilizing pillar, Maccelari (1997) observed that the response to face advance at blasting time is longer for the pillar than for the advancing face itself. In other words, a greater proportion of events occurred on the pillar during the working shifts. The fact that a large proportion of seismic events associated with the stabilizing pillar occurred between shifts has negative implications from a safety point of view.

➤ Total closure has taken place in the back areas thus stress-reducing the stabilizing pillar in addition to increasing the horizontal confining stresses acting on it. The net result of this is that there is very little seismicity; approximately 15% of all seismic events recorded within the area of interest were associated with the stabilizing pillar in back areas. We suggest that the pillar has been stress-reduced seismically. That is, there is continued movement or deformation along existing fault planes which releases very small amounts of energy.

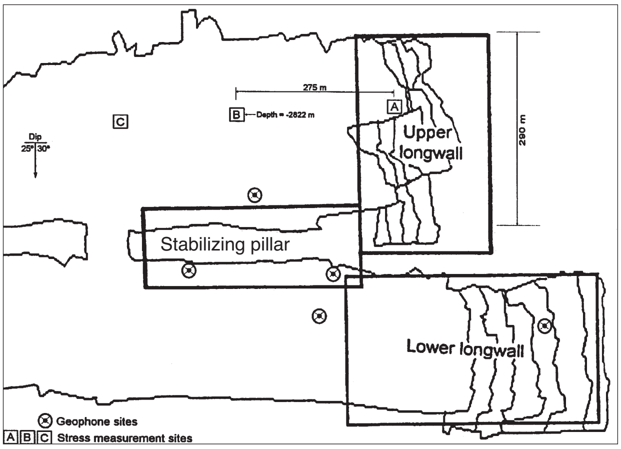

Figure 3—Plan view showing the region of interest indicating the three sub-regions studied in the temporal analysis of the seismicity and the analysis of seismic source parameters. The latest geophone positions and stress measurement positions are marked

Analysis of back area seismicity on Western Deep Levels Gold Mine

Seismicity occurring in the back areas of WDL stabilizing pillar layouts has been analysed using both statistical and neural network techniques. The aim of this study was to identify the influence of geometrical and geological parameters on the stability of strike stabilizing pillars in back areas. From this work the following observations were made.

➤ Increasing the length of a stabilizing pillar will cause seismic events of magnitude 1, ($M \geq 1$) or larger to take place in the back area of the pillar. If mining on adjacent areas is not increased, then the probability of a seismic event $M \geq 1$ occurring in the back area is radically reduced but not totally eliminated since mining in neighbouring regions can induce seismicity on the pillar. On the Carbon Leader Reef horizon (CLR) stabilizing pillars, which increase in length, were associated with an average of three seismic events ($M \geq 1$) per pillar per annum, but those stabilizing pillars which do not increase in length were associated with an average of one seismic event per pillar per annum. On the Ventersdorp Contact Reef horizon (VCR) this difference was not as pronounced; pillars which increase in length are also associated with an average of three seismic events per pillar per annum. However, those pillars which do not increase in length are associated with an average of two seismic events per pillar per annum.

➤ A positive correlation between the rate of face advance, the number of faults and igneous intrusions (dykes) intersecting a stabilizing pillar and the seismic hazard has been noted. Faults and igneous intrusions do not cause seismicity, instead they are concentrators of potential seismic events because they are points of weakness. The level of seismicity is determined by the area of mining that takes place. The influence of such geological features within stabilizing pillars is more localized on the CLR than on the VCR.

- Shape also influences the level of back area seismicity associated with stabilizing pillars. A stabilizing pillar with a regular rectangular shape was found to be associated with a lower seismic hazard than one with an irregular shape. It is suggested that a pillar with a regular shape, having a single plane of failure parallel to the pillar, will enable aseismic deformation to take place. An irregularly shaped stabilizing pillar will have asperities where its shape deviates and hence no single failure plane allowing for aseismic deformation. The implications of this finding are that faults and igneous intrusions need to be negotiated in such a way as to leave a regularly shaped stabilizing pillar. This, of course, may pose serious operational difficulties, since a stabilizing pillar system is, from an operational viewpoint, a 'rigid system', i.e. does not allow freedom of directional mining.
- The traditional stabilizing pillar design parameters of pillar width and dip span of the adjacent longwall stopes are not critical parameters in determining the level of back area seismicity associated with stabilizing pillars. That is, average pillar stress (APS) and energy release rate (ERR) should not provide the only criteria when designing strike stabilizing pillars. Instead, it appears that a change in stress levels drives the seismicity associated with stabilizing pillars as opposed to absolute stress level or APS. This is discussed in the next section.

Investigating stress influence on seismicity. Stress-change as a design parameter

Vieira (1997) tested numerically the possibility that pillar related seismicity in back areas is influenced by the rate of stress change on the stabilizing pillar itself. The analysis was carried out using MINFFT, an elastic boundary element code developed by Spottiswoode (1997) which allows for stress analysis of realistic mine geometries. MINFFT has, in addition, the capability of handling records of seismic parameters with reference to the space-time domains of the layout in analysis. Forty stabilizing pillars were analysed. Stress distributions along the longitudinal axis of each pillar were determined for each incremental numerical step equivalent to annual mining face advances.

As expected, stresses were found to be higher in the back areas of pillars (Figure 4). These back areas, however, are subject to smaller stress changes when compared with areas nearer to mining faces (Figure 5).

As pillars get longer, the rate of stress change in the back area is reduced. Consequently, following Salamon and Wagner's (1979) rationale that seismic events are triggered by stress changes, a corresponding reduction in the seismic activity in the backareas should be observed.

This effect was indeed corroborated in the analysis performed and is shown in Figure 6, which indicates that the spatially distributed seismic moment in the back areas of

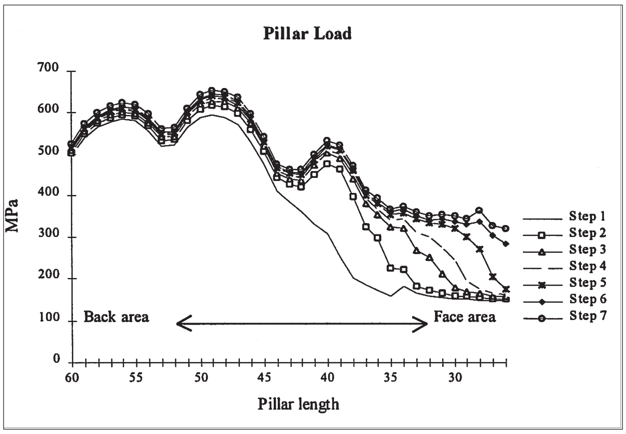

Figure 4—Case example: stress distributions along one analysed pillar over seven mining steps

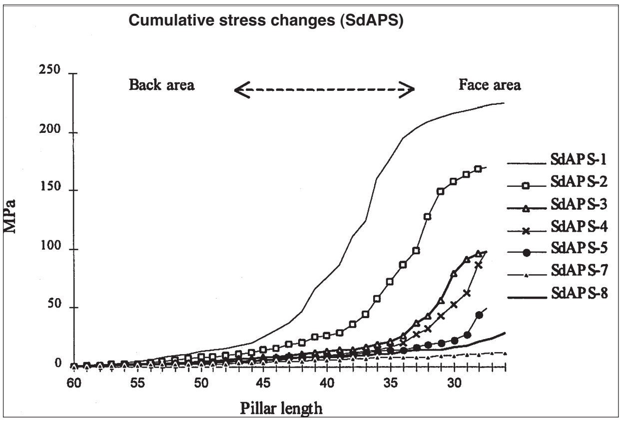

Figure 5—Cumulative stress changes along pillar length for seven mining steps (SdAPS-1 to SdAPS-8)

pillars is reduced when compared with the activity nearest to the longwall mining faces (where stress changes are higher).

On directly comparing the stress changes along pillar length (e.g. Figure 5) with spatially distributed seismic parameters (e.g. Figure 6), reasonable, qualitative agreements between the two were found for various pillars. Figure 7 indicates one such correlation between the stress change and the cumulative seismic moment for one particular pillar, during a certain mining step. Similar patterns were found for other pillars.

Based on the evidence collected, it can be stated that, in general terms, greater values of stress changes are associated with greater values of both the number of events and their corresponding seismic moments. This consideration may have implications for mine layout design in that it may be possible to design mine layouts in such a way as to reduce the rate of stress change along planned structures. This study provided motivation for evaluating a concept for an 'extended ERR', as discussed further in this paper.

Improved design criterion: Energy Release Rate with limits to on-reef stress

For the lack of a design criterion that allows for deformations wherever they might occur, ERR is still the major mine design criterion, although it has a number of major

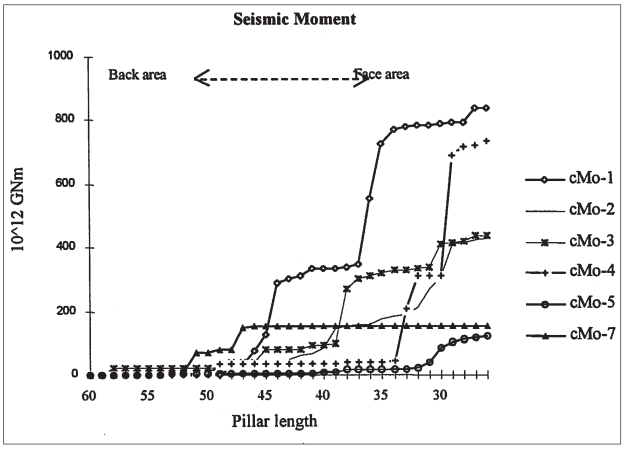

Figure 6—Cumulative seismic moments (represented with the notation cMo-n) for six mining steps (cMo-0 to cMo-7)

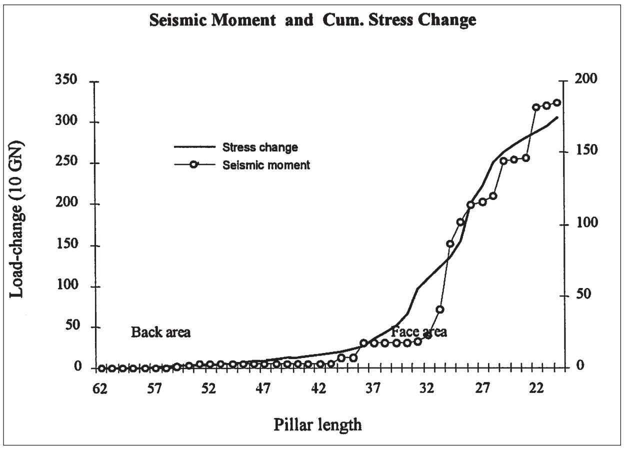

Figure 7—Cumulative stress change along the pillar length with seismic trend superimposed

shortcomings, principally that the rock mass is assumed to be infinitely strong. ERR at any face position is usually calculated by

$$ERR = \sigma D/2 \qquad [1]$$

where σ is the stress before an element is mined and D is the convergence between the hanging- and footwall after the element is mined. On-reef stresses and stope convergences in tabular openings are conveniently calculated using boundary element methods (e.g. Napier and Stephansen, 1987).

It is now proposed (Spottiswoode, 1997) that the concept of ERR be extended by limiting, or capping, the on-reef stress to a certain value (σ_F), which might represent the effective strength of the unmined ground, at the face or at pillars or abutments. Figure 8 is a sketch showing the effect of σ_F on ERR. The motivation for this approach is:

- ERR is well understood and can be applied to very large mining problems with personal computers.
- The 'cap' model will allow for energy release in areas where there is no current mining.
- Existing numerical models can be adapted to apply σ_F.

In the usual case of an elastic rock mass, ERR is most conveniently viewed as the work done on the rock about to be mined at a level of stress much lower than that predicted using elastic theory. In the deep-level gold mines the immediate hangingwall and footwall of the stopes are as fractured as the rock to be mined. It is therefore likely that the vast majority of the energy associated with ERR is not expended in the rock actually removed, but in the hanging- and footwall strata. This would certainly be the case within a stabilizing pillar that is unfractured in the centre, but has associated foundation failure.

The cross-hatched area in Figure 8 is the work done on the element before it is mined and the stippled area is the work done when the element is mined. By comparison, the area under the dotted line would be used to calculate ERR, assuming purely elastic behaviour of the rock mass.

To assess the impact of the extended ERR concept, the code MINFFT, developed by Spottiswoode (1997), was used. This code reads the files generated for MINSIM, and is supported by analysis programs and the display program MINAVS. The MINSIM files contain a 64 by 64 square pattern of percentage mined in each square element. MINFFT simultaneously solves for problems consisting of many of these patterns placed edge to edge. In this study, Spottiswoode (1997) used 12 patterns, four along strike by

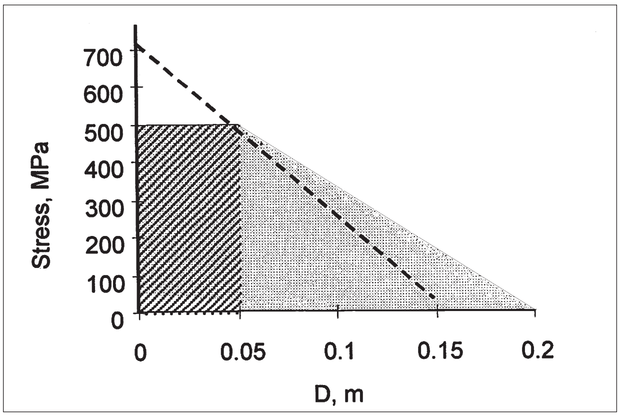

Figure 8—Sketch to illustrate ERR on an element with a limit of σ_F = 500 MPa on the on-reef stress (solid outline) and 'elastic' ERR (dashed line)

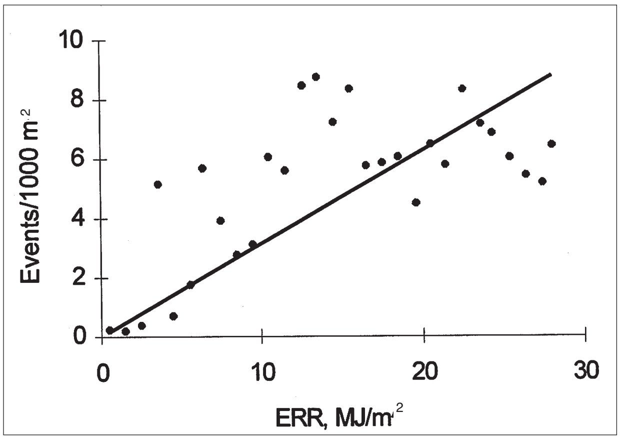

Figure 9—Plot of seismicity per grid block as a function of ERR, averaged into interval of 1.0 MJ/m² σ_C = 250 Mpa

three on dip, gridded into an element grid size of 24 m.

A range of limit stresses (σ_F) was considered, namely 200, 250, 300, 350, 400, 450, 500 and 600 MPa, as well as the conventional model with infinite strength. A limit stress of 250 MPa, as shown in Figure 9 and Figure 10, provided good agreement between the seismicity data and ERR. This value provided a linear fit in Figure 10 and included almost all the events within its spatial coverage.

One of the implications of a finite limit to on-reef stress is an increase in the total energy released. In Figure 11 it can be seen that the energy increases gradually for decreasing limit stress down to about 350 MPa, below which it increases rapidly. The values of limit stress and its effect on the analysis is probably not unique. For example, the extent of abutment failure is reduced by using large element sizes. A higher value of limit stress might be appropriate for a grid size smaller than 24 m. On the other hand, a lower limit stress might be appropriate around dykes and faults.

Bracket pillars

It was noted in the introduction that underground mining can induce sudden slip movements on fault and dyke structures (Hemp, 1994) and these can cause rockbursts. As also mentioned, these effects can potentially be controlled by leaving strips of unmined ground (i.e. bracket pillars) parallel to the dyke or fault in order to inhibit slip movements and thereby reduce the seismic risk. Vital to the successful implementation of bracket pillars is an understanding of the nature of the structure. By understanding what makes one feature rockburst prone and another not, for a particular mine geometry, it is possible that the hazards associated with their failure may be more easily prevented or reduced.

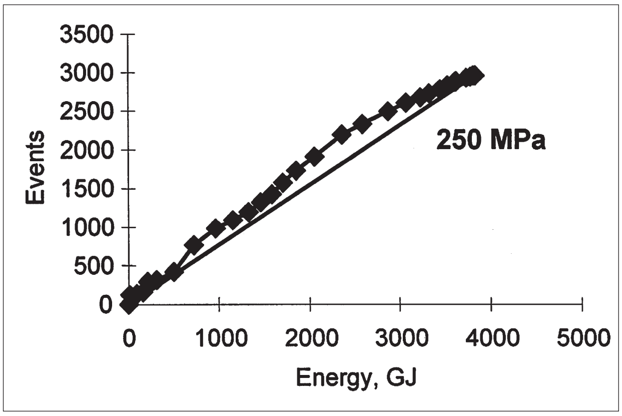

Figure 10—Same values as in Figure 9, cumulated by total energy and by number of event. Plot of seismicity per grid block as a function of ERR, averaged into interval of 1.0 MJ/m2

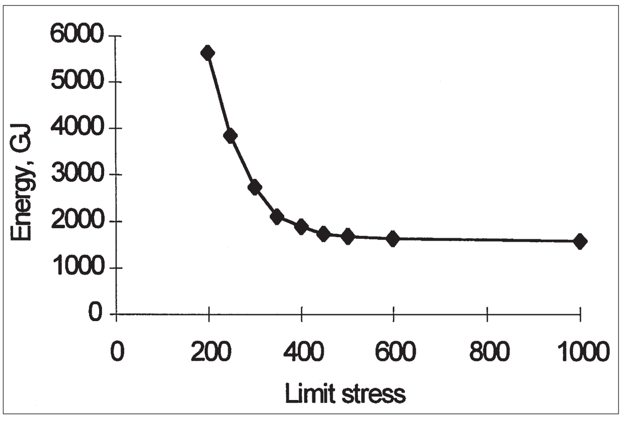

Figure 11—Total released energy as a function of the limit strees σ_F, with the normal elastic ERR being drawn at a value of 1000 (MPa)

Addressing bracket pillar design through modelling

Although bracket pillars are used extensively in the proximity of geological structures, only rudimentary criteria have been available for their design. The most used criteria have been the concept of excess shear stress, and the stress-to-strength ratio of dykes. Numerical modelling can provide some insight into the effects of different layout strategies and basic design criteria (Dede and Handley, 1997).

A methodology that uses design charts, derived from the use of numerical models in plane strain conditions, has been developed to aid the rock engineering practitioner in the design of bracket pillars for certain layout options. These charts provide an initial estimate of the required bracket pillar width based on mining and geological factors that are easily measured. It must be emphasized, however, that the charts are not intended to provide the final estimate of pillar size. They should be interpreted as guidelines. In general, it is difficult to ensure that no movement whatsoever can occur on a bracketed discontinuity. This suggests then that appropriate local support systems and backfill placement should be considered in addition to opting for a layout sequence which moves along or away from the potentially hazardous structure (Hemp, 1994). Mine experience, derived from expert knowledge and historic data of ground behaviour, should also be taken into consideration in the final design.

Some calibration of the developed charts was carried out, in terms of available seismic data and three-dimensional

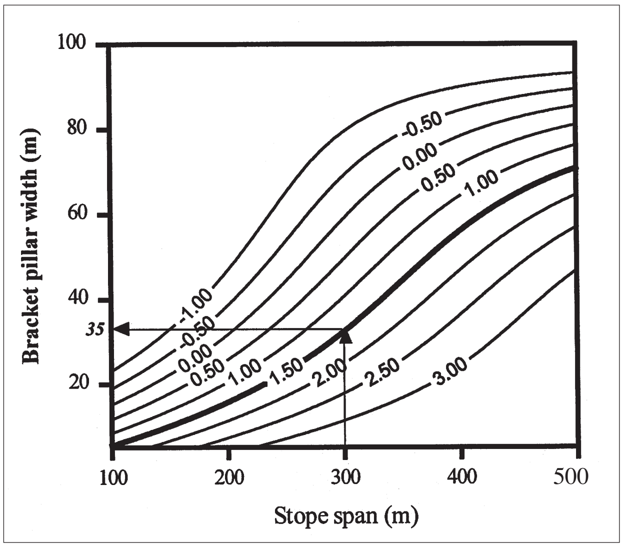

Figure 12—Example of a design chart for a bracket pillar layout at a depth of 2000 m, *k*-ratio = 0.5, discontinuity dip = 75°, stope dip = 0°. Each plot line corresponds to estimated magnitude contours for varying stope spans and pillar widths

modelling of real sites. As a result, it was demonstrated that the three-dimensional analysis validated the two-dimensional results initially obtained for the plane strain conditions. As mentioned, further validation will be possible from back-analysing the bracketed features on the monitoring site described previously.

Numerous combinations of mine geometries were modelled, varying parameters such as dip, stope span, pillar width, discontinuity dip, stress state (*k*-ratio) and depth. Backfill placement in adjacent stopes was also considered. In all, this resulted in at least 7290 combinations of mining configurations, which were analysed using DIGS (Discontinuity Interaction and Growth Simulation) (Napier and Hildyard, 1992). Each run represented a particular combination of the above variables. The solution from each modelled combination would estimate the size of a potential seismic event which, hypothetically, would have occurred due to slip along the discontinuity. Numerous sets of preliminary ‘pillar size’ design charts (e.g. Figure 12) were then drawn up based on the results from the population of all numerical runs.

The principles of new bracket pillar design

The proposed methodology is based on a conceptual model of seismic emission along bracketed discontinuities. The method of application is as follows: A seismic event is considered to be the result of a shear movement along the fault or dyke being bracketed. The induced seismicity due to slip is measured by means of a calculated seismic parameter (e.g. seismic moment or event magnitude). In our case, the seismic moment (M_0) is determined from a well-known relationship

$$M_0 = G\int R dA \qquad (Nm) \qquad [2]$$

where G is the shear modulus (Pa), A is the area of slip (m^2) and R the incremental amount of slip (m) at each point of the discontinuity plane. The plane strain model only provides one slip profile, which is constant in the out of plane direction. The area of integration is assumed to be a Brune type circle, the diameter of which is the dip length undergoing slip. Considering that slip takes place within an interval [*a,b*] of a slip patch, equation [2] can then be rewritten as [3] or [4]:

$$M_0 = GAD \qquad (Nm) \qquad [3]$$

$$M_0 = GV \qquad (Nm) \qquad [4]$$

where

$$D = \frac{1}{b \pm a}\int_a^b R(x)dx$$

is the average slip (m) and

$$V = \frac{\pi}{4}D(b \pm a)^2$$

the entire volume of slip.

The complete distribution of slip generated by the plane strain model is numerically integrated over the length (a, b), which limits the extent of displacement undergone by the discontinuity along its dip direction. The calculated area of the Brune’s circle is subsequently multiplied by the average slip in order to obtain a *volume* of slip, V, reflecting the entire sheared zone of the discontinuity. Lastly, the maximum magnitude (M) of a seismic event that may be triggered by a potential slip along the discontinuity is obtained from an empirical relationship (5), derived by Hanks and Kanamori (1979). The ‘worst case’ is assumed by which all moments lead to the maximum magnitude.

$$M = 2/3[\log(M_0) - 9.1] \qquad (Nm) \qquad [5]$$

The seismic risk (measured by the inferred maximum magnitude) of a given layout is determined for all combinations of the layout geometry, as described. Design charts are then produced which relate all design parameters considered. This is explained in the next section.

Methodology of bracket pillar design

Bracket pillars designed so as to result in ‘no seismicity’ in the vicinity of bracketed features are impractical, as they would have to be very wide (Napier, 1987) and result, consequently, in totally uneconomical layouts. The new approach is that pillars should be designed by taking into account a tolerable level of seismicity in their vicinity. The new design involves the use of pillar ‘design charts’, which will enable rock mechanics engineers to arrive at preliminary pillar dimensions for a given structure with a minimum of effort. For its correct use, the following factors need to be considered:

- The seismic hazard (represented by the seismic moment or event magnitude, as described above) along a bracketed geological structure is assumed to be dependent on the amount of an arbitrary slip displacement on the discontinuity.
- The largest tolerable magnitude for the region is set.

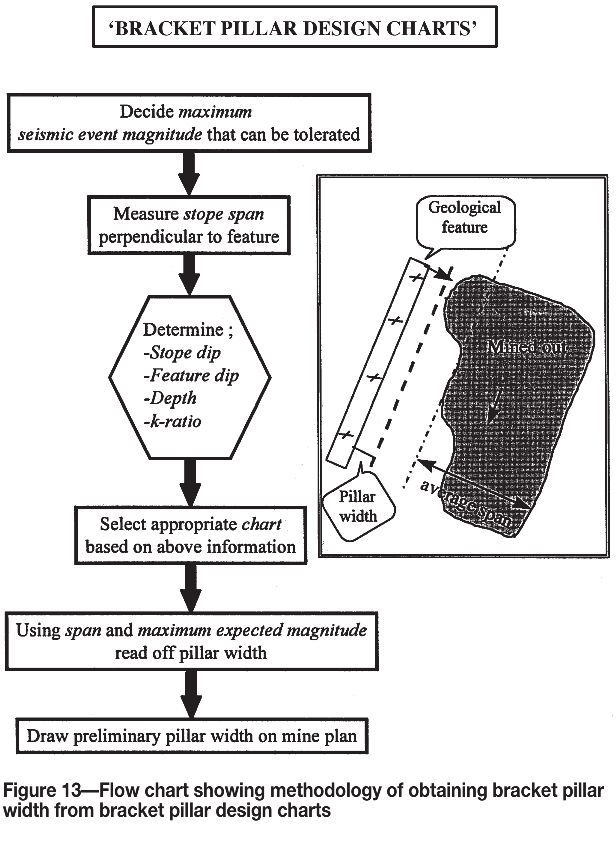

Figure 13—Flow chart showing methodology of obtaining bracket pillar width from bracket pillar design charts

Events of a lower magnitude are assumed to have no significant effect on ground conditions in the nearby stopes. In this case the local stope support would also remain effective for events below the tolerable seismic magnitude. For example, if for a given mine region experience shows that the conditions in the nearby stopes remain acceptable when seismic events of magnitude 2.0 and less occur, then the maximum tolerable event in a structure would be one of magnitude 2.0. The rock mechanics engineer at a mine will have to determine, statistically, the tolerable seismic magnitude for a geotechnical area where bracket pillars are intended.

➤ Knowing the planned span of mining and having established a tolerable seismic magnitude for the respective mine region, the pillar width required may be read off from the appropriate chart that characterizes the prevailing mining conditions (i.e. stope dip, stope span, discontinuity dip, depth, *k*-ratio, backfill). The full process is illustrated in the diagram in Figure 13.

It must be emphasized that bracket pillar design does not stop at this point. The rock engineer must model the situation in greater detail to determine other relevant factors such as, for example, the optimum mining sequence in the vicinity of the structure, and optimize the pillar width.

Conclusion

New approaches to deep mine layout design have been proposed provisionally, and are believed to offer an added advantage to the rock engineering practitioner in the design of regional support systems in a more rational way, potentially contributing to improved ground control measures and, hence, to a safer working environment from a rock mechanics view point.

With regard to stabilizing pillar layouts several design parameters previously not considered in regional stability have now been found to be relevant. Among them are the influence of total closure in pillar confinement and aseismic destressing of pillars; the seismic risk of stabilizing pillar layouts being related to pillar length, the number of intersecting geological features and pillar shape; stress changes that govern pillar stability as opposed to absolute or average pillar stress.

It has been proposed also that a revised model of ERR with a limit of 250 MPa to the on-reef stress may provide an improved predictor of the spatial distribution of seismicity than the normal ERR, which assumes elastic behaviour of the entire rock mass. The standard energy calculation for ERR has been extended by adding the component of work done on the hanging- and footwalls when limiting the on-reef stress.

A methodology was developed to assist the rock engineering practitioner in the design of bracket pillars, based on an expected seismic risk along the bracketed discontinuity.

Acknowledgements:

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Golden future for top Wits mining graduand*

The University of the Witwatersrand mining engineering graduand Grant Davey, 25, with the Chamber of Mines gold medal awarded him at the engineering faculty's annual graduation ceremony on 9 December 1997. Grant was

selected as the most distinguished B.Sc. (Eng) candidate in the branch of mining or metallurgy and materials engineering. Having studied at the University of the Witwatersrand as an Anglo American Corporation in-service bursar, he will be joining Anglo Golds's Vaal Reefs No. 10 shaft at Klerksdorp in January. Grant sees himself as being 'a production man for the rest of my life and following the line management route'. Speaking of his time at Wits, he says, 'I believe my academic grounding was not only of a very high standard but also extremely relevant. Wits University was built around the gold mining industry and the university continues to be deeply committed to the future of gold mining in this country. While at university I chaired the Student Mining Engineers Society and this gave me numerous opportunities to liaise academically and socially with people of vision and commitment'. ◆

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Kelley is first woman to win top Wits Engineering Award*

The University of the Witwatersrand's chemical engineering graduand Kelley McGurk, 21, with the Chamber of Mines gold medal she received at the engineering faculty's annual graduation ceremony on 9 December 1997. Kelley is the first woman in the history of the award to achieve this distinction. The Chamber of Mines award, which includes a R20 000 scholarship, goes annually to the most distinguished B.Sc. (Eng) candidate in any branch of engineering other than mining. A straight 'A' student throughout her four-year engineering degree studies, Kelley is keen to pursue a career in environmental engineering. Kelley, whose father is an engineer, attended a Wits open day while still at school and although her interest lay in science, she found that chemical engineering, and particularly the environmental aspect, appealed to her. Based on her matric marks, Kelley, who entered university in 1994, received a vice-chancellor's scholarship which was renewed each year. 'I enjoyed my time at Wits enormously,' she says. 'The degree course was stimulating and challenging and prepared me academically for the practical experience which I now hope to gain. Once I have achieved this I would like to study for my masters degree through Wits on a part-time basis.' ◆

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