Strike Stabilising Pillars as a Regional Support Strategy for Ultra Deep Gold Mines

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ABSTRACT: Strike stabilising pillars are included in the mine layout of a number of deep South African gold mines as a means of providing regional support with the principal aim of controlling rockbursts. Large seismic events associated with stabilising pillars can cause extensive damage to working areas.

Mining induced seismicity recorded on Western Deep Levels Limited has been analysed in an attempt to improve the design of stabilising pillars and thereby reduce their associated seismic hazard. This work revealed that the vast majority of stabilising pillars, regardless of their dimensions and those of their adjacent stopes, will, at some time, give rise to seismic events of magnitude, \( M \geq 2 \). Contrary to expectations, this work strongly indicates that the rockmass in the near vicinity of the mined areas does not behave in an elastic fashion. Consequently the currently employed design methodologies, based on elastic principles, should not provide the only criteria when designing strike stabilising pillars.

*Key Words*: stabilising pillar, mine seismicity, rockmass behaviour, pillar failure

Introduction

The gold mines of the Witwatersrand Basin in South Africa exploit pebble conglomerate reefs (placer deposits) spread over a wide area as a thin layer, varying in thickness from a few centimetres to several metres. The mining excavations (stopes) remaining after the reef has been extracted are therefore tabular; i.e. having a small height in relation to their lateral extent. This shape generates high stress concentrations at the stope faces, which leads to intense fracturing and to rockbursts (Cook, 1963). In an attempt to reduce the incidence of rockbursts, strips of unmined reef have been left behind along strike in the form of strike stabilising pillars (see Figure 1). From this figure it can be seen that the stabilising pillar width and the stope span along dip are two design parameters that can be varied. Four deep Witwatersrand mines have implemented strike stabilising pillars as a means of providing stiff regional support in the back-areas of stopes so as to reduce the stress concentrations ahead of the stope faces, and consequently to control rockbursts at the stope faces.

A literature survey (Maccelari, 1994) revealed that the implementation of strike stabilising pillars resulted in a reduction in the level of seismicity experienced in those portions of mines protected by stabilising pillars. However, since their
Introduction mine personnel have noted that strike stabilising pillars periodically give rise to large seismic events associated with loss of life and extensive damage to working areas and access routes (Lenhardt and Hagan, 1990). The work presented in this paper has formed part of a project to assess the current criteria for the design of strike stabilising pillars with a view to improving their design, and consequently reducing the seismicity associated with them (Vieira et al, 1998).

![Diagram of mine layout incorporating strike stabilising pillars]

**Figure 1.** Schematic plan view showing a mine layout incorporating strike stabilising pillars. Typical dimensions are 40 m pillar width with stope spans of 240 m between pillars.

**The Current Rationale and Design of Strike Stabilising Pillars**

The motivation for stabilising pillars has been based principally on the concept of energy release rate (ERR): a quantitative design parameter based on elastic theory (Cook, 1963 and Cook et al, 1966). ERR gives the spatial rate at which energy is released during mining. It has been shown that the extent and intensity of fracturing ahead of the face increases with increasing ERR (Adams and Jager, 1979). Moreover, on average, an increased incidence of rockbursts is associated with higher ERR values (Chamber of Mines Research Organization (COMRO), 1988). Thus, if through the implementation of stabilising pillars, the elastic convergence in the stopes can be limited, ERR can be reduced and hence the level of seismicity associated with the stope face should also be reduced.

An important stabilising pillar design guideline has been provided by calculating the average pillar stress (APS) (COMRO, 1988). The understanding is that the APS should not exceed 2.5 times the uniaxial compressive strength of the country rock if the pillar foundations are not to fail. This empirical formula has been derived from a suite of laboratory tests (Ozbay and Ryder, 1989).

Stabilising pillars represent a loss of potential income to a mine since they are formed from gold bearing reef. Consequently their width and spacing need to be optimized to a level commensurate with the safety requirements of the mine as determined by acceptable ERR and APS levels.
Background Information on Western Deep Levels Limited

Western Deep Levels Limited (WDL) gold mine is located approximately 70 km west of Johannesburg. The mine exploits two economic gold bearing reefs, the Ventersdorp Contact Reef (VCR) and the Carbon Leader Reef (CLR). The stopes on the VCR vary between 1.2 and 1.4 m wide, while on the CLR their width is between 0.9 and 1.0 m. The VCR is mined from 1600 to 3050 m below surface, and the CLR from 2300 to 3500 m below surface. Both reefs dip at about 22° in a southerly direction and are separated by approximately 900 m of quartzitic rock.

The strike stabilising pillars on WDL have been designed such that they are 35 to 45 m wide and spaced approximately 240 m apart in the dip direction. This layout was implemented in 1984 and allows for an 85% extraction ratio while limiting the maximum ERR to 30 MJ/m² and the APS to 600 MPa (Macciali, 1994).

Assessment of Strike Stabilising Pillars on Western Deep Levels Limited

Definition of Face Seismicity and Back-area Seismicity

The performance of strike stabilising pillars has two aspects, firstly, their ability to improve conditions at the stope face and secondly, their behaviour in back-areas, i.e. their stability in the long-term. The strike stabilising pillars on WDL have been assessed through studying seismic data recorded by a mine wide seismic network. The system has been recording mining induced seismic events with a location accuracy of about 40 m since 1986. The recorded seismic events of magnitude M ≥ 1 were separated into two groups: face seismicity and back-area seismicity. To determine to which group a seismic event belonged, the recorded data was dealt with on a yearly basis as depicted in Figure 2. All seismic events occurring during the year under consideration that located behind the face advance achieved during that year were considered to constitute back-area seismicity. The remaining seismic events that located within the area mined during that year, as well as those locating ahead of the face, were classed as face-area seismic events. With the seismic events classified in this manner it transpired that the seismicity occurring in back-areas constitutes about 25% and 30% of the total number of seismic events on the CLR and the VCR respectively.

Analysis of the Seismic Data

The seismic data has been analysed using both a statistical and a neural network technique (Vieira et al., 1998). The back-area seismic data was initially analysed statistically. When the conclusions reached were not what had been anticipated and did not support the assumption that the rockmass behaves elastically, it was deemed necessary to reanalyse the data using a different technique in an attempt to verify these conclusions. A neural network was considered to be an appropriate tool for the analysis of mine seismic data. This technique has already been successfully applied in studying other rock mechanics problems related to deep level mining (Cichowicz, 1997). The face seismicity data was analysed using only a statistical approach. In each analysis the two reefs were considered separately.
Figure 2. Schematic showing the definitions of both back-area seismicity and face seismicity.

Statistical Assessment of the Behaviour of Stabilising Pillars in Back-areas

A statistical investigation into the behaviour of stabilising pillars in the back-areas was used to assess the influence of the following factors on the level of back-area seismicity:

- stope span between adjacent stabilising pillars,
- stabilising pillar width, and
- the influence of the presence of igneous intrusions and faults (geological features) within stabilising pillars.

For each of the variables studied a control curve and a sample curve was obtained. The control curves were obtained by superimposing lines, parallel to the dip of the reef, on underground plans of the mine at 75 m intervals. Each time a sample line intersected a stabilising pillar the stabilising pillar width, the span of the stope between adjacent stabilising pillars, and the distance to the closest geological feature intersecting the stabilising pillar was measured. The measurements recorded were then binned and the number of entries per bin was summed. These totals were then cumulated, expressed as a percentage of the total number of control samples, and plotted to provide a control curve.

The sample curves were obtained in a similar fashion. To assess the influence of stope span, for each back-area seismic event the span of the stope they located in was recorded. To determine the influence of pillar width and geological features, only back-area seismic events occurring on stabilising pillars and within 50 m of a stabilising pillar were taken into consideration. For each such seismic event, the width of the stabilising pillar and the distance to the closest geological feature were measured. In each case the measurements recorded were binned, the number of entries per bin was calculated, and these totals were then cumulated, expressed as a percentage of the total number of samples and plotted to yield sample curves. Each sample curve was then plotted on the same chart as its corresponding control curve.

When considering the influence of geological features, the control curves gave a measure of the frequency of geological features intersecting stabilising pillars. Plotting these values on the same chart as the curve describing the frequency of seismic events afforded an understanding of the relationship between the seismicity associated with the stabilising pillars and the presence of geological features (see
Figure 3). The deviation between the two curves was not easy to interpret and so the
data was manipulated using the following equation:

\[
\text{Normalized cumulative seismic event frequency} = \left( \frac{x}{y} \right) \left( \frac{100-x}{100-y} \right)
\]

Equation 1

where: \(x\) = cumulative % of seismic events and \(y\) = cumulative % of samples for each
distance measurement. The plots obtained are shown in Figure 4. From this figure it
is possible to identify that faults and igneous intrusions have a more localized effect
on the level of back-area seismicity on the CLR than they do on the VCR. On the
CLR there is a localized concentration of seismic events in their near vicinity. This
increased level of seismicity tails off to a background value of half the incidence at
distances greater than 50 m from geological features. A similar decrease in the level
of seismicity is not observed on the VCR.

The control curves depicting the stope span measurements gave a measure of
the frequency of the various stope spans, while the sample curves indicated the
frequency of seismic events associated with the different stope spans. (These curves
have not been shown in the text.) Unlike the previous sets of charts, the sample and
control curves obtained were very similar for both the VCR and the CLR. A result of
this nature implies that there is no significant difference between the frequency of
stope span, which ranged from 60 to 420 m, and the frequency of seismic events
associated with the different stope spans on either reef. In other words, the level of
back-area seismicity is independent of the stope span between adjacent stabilising
pillars on WDL.

For the case of pillar width, the control curves gave a measure of the frequency
of the different pillar widths on the mine and the sample curves indicated the
frequency of seismic events associated with the different pillar widths. (These curves
have not been shown in the text.) Again, the sample and control curves for both the
VCR and the CLR are very similar implying that the level of back-area seismicity is
independent of the width of the stabilising pillars used on WDL. The stabilising
pillars analysed varied in width between 35 and 57 m.

Neural Network Assessment of the Behaviour of Stabilising Pillars in Back-areas

A self-organising network, also known as an unsupervised or Kohonen
network (Kohonen, 1983), was applied to the data. Parameters describing the
geometry and geology of the stabilising pillars constituted the input parameters and
the occurrence of seismic events in back-areas formed the output parameters. The
application of a neural network enabled an understanding to be gained of the effect of
each input variable, or combination of input variables, on the output variables using
pattern recognition procedures. That is, it enabled certain design parameters (input
variables) to be correlated with seismic hazard (output variables). This work
confirmed two of the findings of the statistical analysis and identified other factors
that influence the hazard associated with stabilising pillars in their back-areas.

The neural network divided the stabilising pillars into three classes which
correlated with their associated degree of seismic hazard. Neither stabilising pillar
width or the stope span between adjacent stabilising pillars had any influence on this
classification confirming the lack of a relationship between these two variables and
the level of back-area seismicity.
Figure 3. The control and sample curves for the analysis of the influence of geological features on back area seismicity occurring within 50 m of stabilising pillars on (a) the VCR and (b) the CLR.

Figure 4. The increase or decrease in seismicity per unit length of stabilising pillar within any chosen distance in relation to the seismicity beyond that distance as given by Equation 1. Faults and igneous intrusions have a more localized effect on the level of back-area seismicity on the CLR than they do on the VCR.
The rate of increase in the length of stabilising pillars was identified as affecting their associated seismic hazard in back-areas. On both reefs, if the annual increase in stabilising pillar length exceeded 100 m per annum then the seismic hazard in the back-areas of the pillar was high. Further, it was noted that if the length of a stabilising pillar did not increase because the lagging adjacent longwall was not mined, then its seismic hazard was reduced but not eliminated. The VCR stabilising pillars that did not increase in length during the year were, on average, associated with approximately one third the number of back-area seismic events associated with those pillars that did increase in length during the year. A more pronounced situation was found to exist on the CLR where the occurrence of seismic events corresponding to stabilising pillars that did not increase in length was only half of that associated with pillars whose length did increase during the year.

Finally, the neural network identified that the shape of a stabilising pillar has a strong influence on its associated level of back-area seismicity. The ideal shape for a stabilising pillar is one where the sides are straight and the width constant. There are many causes for deviation from an ideal shape including the presence of a geological feature or the loss of a face panel. Figure 5 shows an example of a stabilising pillar with a good shape and one with a very poor shape. It transpired that the more irregular the stabilising pillar shape, the greater its associated seismic hazard in back-areas.

![Figure 5](image)

**Figure 5.** Stabilising pillars of varying shape. (a) Stabilising pillar with a good shape; the sides are approximately straight and the width is fairly constant. (b) Stabilising pillar of very poor shape; the sides are irregular and the width is not constant.

Statistical Assessment of the Behaviour of Stabilising Pillars in the Face-areas

For each stope the annual number of face-area seismic events was plotted as a function of both dip stope span and annual area mined for the CLR and the VCR. In all four cases the plots showed extensive scatter within the data and hence no significant correlation between face seismicity and stope span or area mined. The face seismicity was then normalized for the annual area mined. Annual face advance and stope span was plotted as a function of the normalized seismicity and still no correlation was evident.

The effective stabilising pillar strength was investigated by classifying the longwalls into two groups: those with an adjacent abutment and those bounded only by stabilising pillars. A schematic of this is shown in Figure 6. Numerical modelling of this layout, using the dimensions given in Figure 6 and assuming the stabilising pillars to have infinite strength, was carried out to determine the expected increase in ERR as a result of having stabilising pillars in place of an abutment (Spottiswoode, 1997). The result was that the average ERR for the longwall bounded only by stabilising pillars was 14% higher than it was for the longwall with an adjacent abutment and, thus, a 14% increase in seismicity was expected for the latter.
longwalls. These results were not borne out by the recorded seismicity. On both the VCR and CLR the number of seismic events, per annual area mined, occurring in the face-area of those longwalls bounded only by stabilising pillars was about double that recorded in the longwalls with an adjacent abutment, implying that the stabilising pillars are not infinitely strong.

![Diagram](image)

**Figure 6.** Schematic showing a longwall bounded only by stabilising pillars and a longwall bounded by an abutment and a stabilising pillar. The dashed line formed an axis of symmetry in the numerical model. The dimensions given were those used in the model. The anticipated increase in ERR due to the presence of a stabilising pillar has also been indicated.

**Discussion and Conclusions**

The conventional models used for the design of stabilising pillars allow for only elastic stope convergence and assume pillars to be stiff. The results obtained from the investigations into both the face and back-area seismic data sets from WDL are not in accordance with the behaviour predicted by the numerical models.

Although stabilising pillars do protect the stope face, this work has shown that the traditional design parameters of stabilising pillar width and stope span are not critical parameters in determining the local level of seismicity on either the CLR or the VCR at WDL. Instead it has shown that a system of longwalls and stabilising pillars work as a unit rather than as isolated longwalls. The results also indicate that stabilising pillars do not have infinite strength as is assumed by the design criteria.

According to ERR theory, a stabilising pillar that does not increase in length should have no associated seismicity. This was found not to be the case. If the length of the pillar is not increased then the probability of a seismic event of magnitude \( M \geq 2 \) occurring in the back-area is reduced, but not totally eliminated. Seismicity observed under these conditions is a result of mining in other stope, such as the leading longwall, and the time dependency of the rockmass. If a low seismic hazard in the back-area of stabilising pillars is desirable on WDL, then the annual increase in length (or face advance rate) should not exceed 100 m.
At the depths under consideration, and hence the very high stresses acting on
the stabilising pillars, it is possible that the more localized influence of geological
features intersecting stabilising pillars on the CLR is a result of the softer nature of the
footwall and hangingwall lithologies on that reef in comparison with the VCR. These
softer lithologies enable total closure to take place within the back-areas on the CLR.
Once total closure has taken place the potential region of influence around a
geological feature becomes limited.

An unexpected result from this work was the recognition that stabilising pillars
with an ideal shape are associated with a lower seismic hazard than those with a
highly irregular shape. A possible explanation for this phenomenon is that a regular
pillar may have a single plane of failure enabling aseismic deformation to take place
on an existing plane of failure parallel to the strike of the pillar. An irregularly shaped
stabilising pillar will have asperities where its shape deviates, and hence no single
failure plane enabling aseismic deformation. The presence of such asperities can give
rise to large seismic events. This proposed mechanism of pillar foundation failure is
in accord with the “punch” type of failure put forward by Lenhardt and Hagan (1990).
The importance of this finding, from a mine layout point of view, is that faults and
igneous intrusions that intersect a stabilising pillar should be negotiated in such a way
as to minimise the deviation of the shape of the stabilising pillar.

It can thus be concluded that APS and ERR should not provide the only
criteria when designing strike stabilising pillars. If APS was a valid pillar design
criterion for the range of pillar widths and stope spans analysed, the results presented
here would have supported it. Stress change, or rate of stress change, as opposed to
the absolute stress level given by APS, appears to have a greater influence in the
seismic behaviour of strike stabilising pillars. The assumption that the rockmass
behaves elastically is valid on a regional scale and at a distance from the stope
(Yilmaz et al., 1993), but this work has demonstrated that the inelastic behaviour of
the rockmass extends further than just the “skin” around the stopes.

Finally, in response to the problems discussed, WDI implemented extensive
backfilling of stopes in 1995, and the rate of seismicity on the mine has been reduced
significantly (Handley, pers. com.). Backfill limits the inelastic closure, and thereby
limits the deformation in the rockmass, thus reducing the level of seismicity.

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