

Quantification of Optimum Lead-lag Distances in South African Gold Mines

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ABSTRACT

Many South African tabular gold mining operations have layouts where different mining advances in adjacent panels result in panels “leading” or “lagging” each other. It is believed that the lead-lag distance between adjacent panels can affect the distribution and characteristics of fracturing and damage within the mining faces, and may affect roof conditions and hence safety. The normal procedure is to minimise the lengths of lead-lags. Mines have generally adopted layouts where optimum lead-lags between adjacent panels are deemed to be between 5 and 10 m. However, these values are based on experience rather than on detailed measurements or an understanding of the deformation processes. There was thus a need to scientifically quantify the effects of lead-lags on fracturing, stability, support and seismicity to either confirm or modify current design guidelines. The research findings contained in this paper aim to provide quantified guidelines on acceptable lead-lag lengths in gold mines.

This paper describes some of the problems associated with lead-lags and resulting strike gully instability. Current industry practice around lead-lags was evaluated by reviewing codes of practice (COPs) to determine the currently adopted inter-panel lead-lag distances. The stipulated lead-lag lengths range between 4.5 m and 10 m.

Detailed fracture mapping around lead-lags was undertaken at 14 sites across eight gold mines representing a variety of reef types, depths and mining methods. The fracture mapping work produced convincing evidence that optimal lead-lags are in the range 4 m – 16.5 m, depending on the reef type. However, the guidelines for the selection of lead-lag lengths relate only to quasi-static conditions and any potentially damaging seismic events will impose further restrictions on the choice of optimum lead-lag length.

Seismicity associated with lead-lags was identified from mine seismic catalogues. Moment tensor inversions were used to calculate the source mechanisms of the lead-lag events. Fault plane solutions were used to confirm the selected seismicity as lead-lags events and to determine the focal mechanisms. Results from one mine showed that most events occurring on lead-lags were of the oblique-slip type. The largest lead-lag event had a magnitude $M_L=1.7$ and it occurred on a lead-lag that was only 15 m long. The mechanisms of the lead-lag events were mostly implosive and had lower energy/moment ratios than shear or tensile events occurring on the faces or abutments. Lead-lags in the range 14 m to 23 m generated larger seismic events than lead-lags outside of this range. There was evidence of a seismic event occurring on a flat-dipping failure plane that cut obliquely across the corner of a 22 m long lead-lag.

The effect of varying lead-lag length on the rock mass was simulated in two stages of numerical modelling: elastic modelling using MINSIM and inelastic modelling using Elfen. The results from the MINSIM modelling showed, as expected, that increases in lead-lag length resulted in large increases in the vertical stresses, energy release rates (ERRs) and elastic convergence. It was concluded that short lead-lags should be used to reduce the vertical face stresses and ERR. The intensity of fracturing and the absolute values of the vertical stresses and ERRs cannot be predicted by MINSIM. However, the results seem to indicate extreme vertical stresses and ERRs for lead-lags greater than 10 m at 3000 m depth. The discrete fracture generation capability of Elfen was used to simulate damaged and failed regions around lead-lags. The Elfen model showed that damage increases as the lead-lag distance increased. However, the modelled fracture extents were much smaller than the underground observations because the increase in the friction angle (with increasing plastic strain) of the Mohr-Coulomb strain softening model needs to be less severe than has been modelled here. Further work is required to carefully calibrate the

material model with both lab test data and underground observations to obtain a reliable indicator of the extent and magnitude of damage.

While the results are not definitive, the findings in this paper confirm the currently adopted lead-lag guidelines of 4.5 m to 10 m stipulated in COPs. In particular, the fracture mapping work provided some compelling results. Although not extensive, the seismic findings seem to corroborate the guidelines derived from the fracture mapping work. The Elfen model needs to be further calibrated for the study of fracturing around lead-lags before it can be successfully used as a forward modelling tool to determine optimal lead-lag lengths during mine design.

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1 INTRODUCTION

South African tabular gold mining operations typically involve different mining advances in adjacent panels, resulting in panels “leading” or “lagging” each other. It is believed that the lead-lag distance between adjacent panels can affect the distribution and characteristics of fracturing and damage within the mining faces, and may affect roof conditions and hence safety.

The creation of lead-lags is an unavoidable part of underground mining. From an operational point of view, lead-lags are required to provide sufficient overlap of the dip and strike scraper lines for face cleaning purposes. From a production perspective, lead-lags can allow a lagging panel to continue mining in the event of stoppages in the leading panel. As a safety measure, lead-lags are deliberately created to break a longwall up into segmented panels to provide sufficient isolation between panels and to confine damage to as few panels as possible in the event of a rockburst. In practice, lead-lag design requires trade-offs between practical production constraints and the theoretical ideals.

The normal procedure is to minimise the lengths of lead-lags. Mines have generally adopted layouts where optimum lead-lags between adjacent panels are deemed to be between 5 m and 10 m. However, these values are based on experience rather than on detailed measurements or an understanding of the deformation processes. Guidelines of minimum lead-lags of 40 m, where the 5 m to 10 m “rule” is exceeded, have also been suggested. These guidelines are intuitive, have not been quantified and are restrictive with respect to production flexibility.

A number of problems have been experienced with ground stability and seismicity when lead-lags become long. Typically, increased cross-fracturing with resulting difficulties in controlling the hangingwall has been observed as lead-lags become longer. Excessive lead-lags can also result in seismicity being generated on the abutment. When exactly this can be expected to occur is unclear and may vary for different types of reefs.

There was thus a need to scientifically quantify the effects of lead-lags on fracturing, stability, support and seismicity to either confirm or modify current design guidelines. The research findings contained in this paper aim to provide quantified guidelines on acceptable lead-lag lengths in gold mines. This work was undertaken as part of a research project (SIM 04-03-03 “Lead-lag design criteria and seismicity patterns”) funded by the Mine Health and Safety Council.

2 RESEARCH METHODOLOGY

The following research methodology was adopted:

- a literature survey of previous work on lead-lags was undertaken;
- on-mine staff were interviewed regarding their experiences with lead-lags;
- a number of past accident investigations where lead-lags were a factor were reviewed;
- aspects of codes of practice that relate to lead-lags were summarised;
- underground observations and measurements using detailed fracture mapping around lead-lags were performed;
- seismic data was acquired from mines and the occurrence of seismicity and potential seismic mechanisms associated with lead-lags were analysed; and
- suitable numerical modelling codes were used to understand lead-lag behaviour and to assess the potential of numerical modelling to simulate underground observations.

3 PROBLEMS ASSOCIATED WITH LEAD-LAGS

The main finding from the available published material is that most lead-lag problems are associated with strike gully stability. Unstable hangingwall conditions frequently occur near the lead-lag corner and the inter-panel lead-lag length seems to affect the severity and extent of the instability. Fractures ahead of the face are face-parallel and roughly vertical, but curve around lead-lags and become flat-dipping in the strike gully. Such fractures are not stabilised as much by the horizontal stresses in the hangingwall and they can break the hangingwall into semi-detached keyblocks, which have the potential to fall out making them difficult to support, thus contributing to an increased fall of ground (FOG) risk (Figures 1 and 2). As a result many FOG accidents have occurred near the lead-lag corner or in the strike gully of the lead-lag.

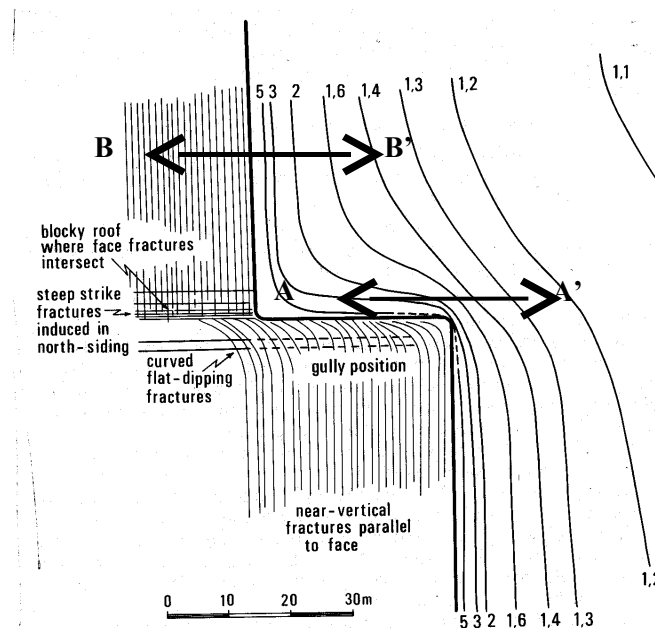


Figure 1. Maximum principal stress contours around a 30 m long lead-lag and the resultant induced fractures. Sections A-A' and B-B' are shown in Figure 2 (after Smith and Ortlepp, 1978)

Hagan (1980) showed that the inter-panel lead-lag length (which influences the energy release rate, or ERR, and mining-induced fracture distribution) was probably the most controllable factor affecting rockfall accidents and production losses on gold mines using segmented longwall mining layouts. Analysis of production figures and mine accident data confirmed that a strong relationship exists between inter-panel lead-lag length and hangingwall stability (Figure 3). Hagan (1980) also modelled the effect of inter-panel lead-lag on ERR using a computer program (Figure 4). Figure 4 shows that the average ERR in a lagging panel increases rapidly up to about 40 m lead-lag length, after which there is a gradual flattening. Figure 5 shows the local effects of inter-panel lead-lag on ERR. There is a rapid increase in ERR from the lightly stressed upper corners to the highly stressed lagging corner of the individual panels. The value of the ERR in the lagging corner increases with increasing lead-lag. Hagan (1980) believed that the local effect of a long inter-panel lead-lag leading to large increases in ERR at the lagging corner caused the intense fracturing in this location, resulting in the consequent rockfall production losses.

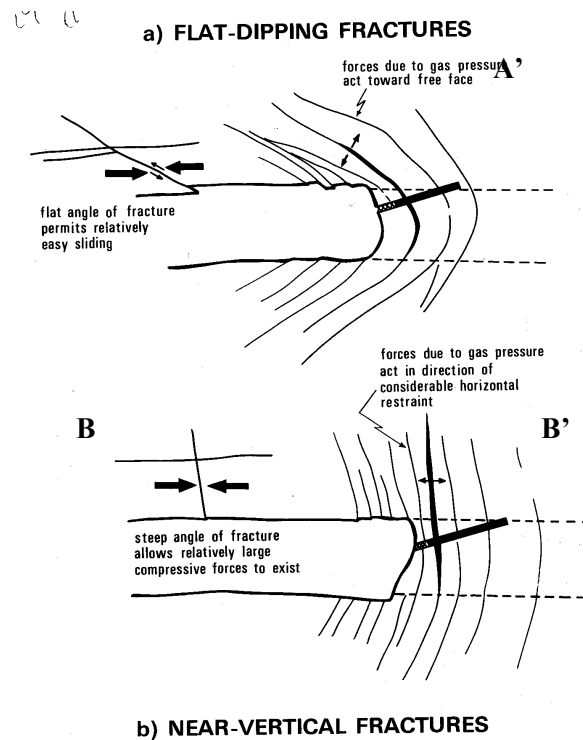


Figure 2. Maximum principal stress contours around a 30 m long lead-lag and the resultant induced fractures (after Smith and Ortlepp, 1978)

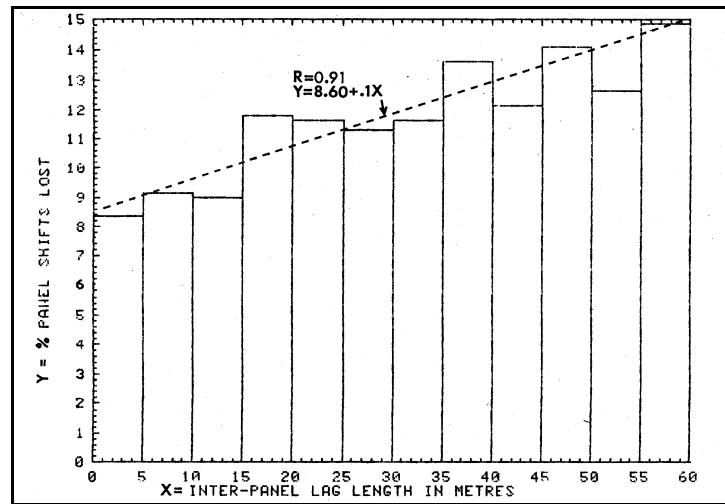


Figure 3. Panel shifts lost due to rockfalls vs. lead-lag length (after Hagan, 1980)

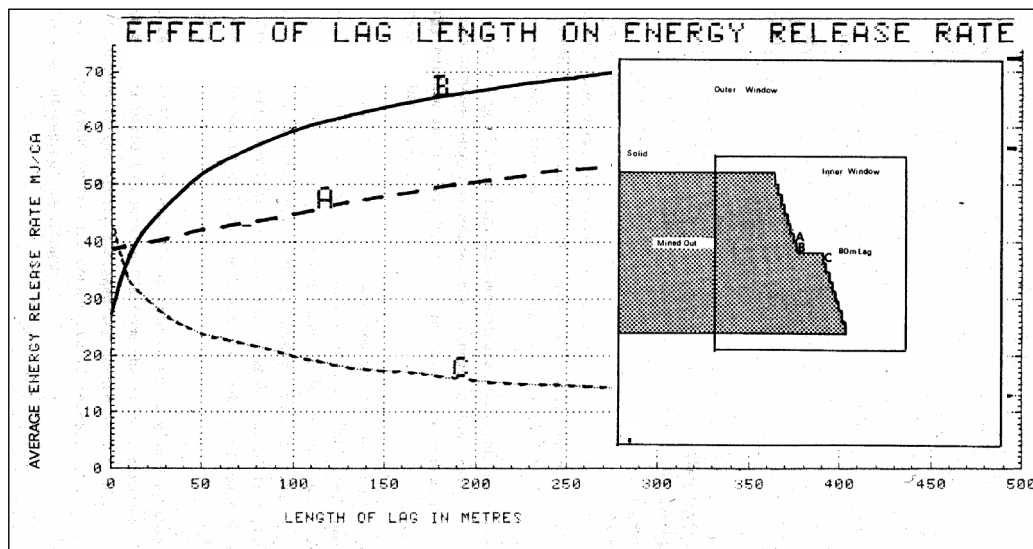


Figure 4. Numerically simulated effect of lead-lag length on ERR (after Hagan, 1980)

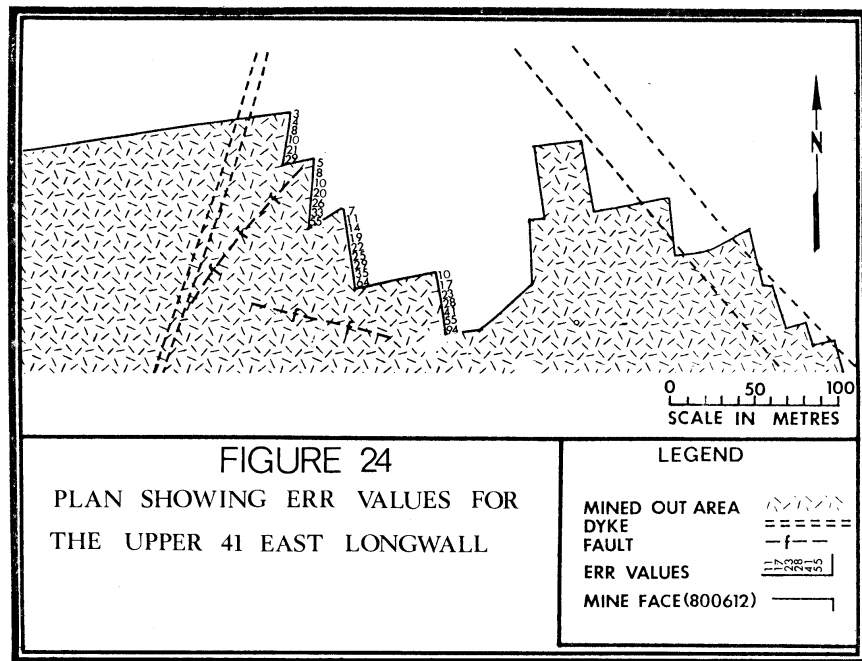


Figure 5. Plan showing the ERR values along panels of a longwall (after Hagan, 1980)

Heunis (1980) suggested that trailing panels immediately adjacent to a long lead-lag would always be subjected to extremely high ERRs and intense cross-fracturing would be observed in the acute intersection between the long lead-lag and the panel faces. The most undesirable situation appeared to be the presence of cross-fracturing, i.e. where two fracture systems intersected at an acute angle in the hangingwall. Such a condition was often found in the strike gullies of panels having excessively long lead-lags, particularly in overhand and underhand breast mining layouts (Figure 6).

Turner (1989) performed detailed mapping of fractures, particularly siding-parallel fracturing, which formed up-dip of the siding (parallel to the lead-lag), associated with lead-lags on three gold reefs (Figure 7). Of particular interest for Turner (1989) was that the siding-parallel fractures in the lead-lag (type C) occurred progressively deeper into the lagging panel as the length of the inter-panel lead-lag increased. The data from 59 panels on six mines and three reefs where the mining depth ranged between 1800 m and 3200 m are shown as a composite plot in Figure 8. Turner (1989) observed that the siding-parallel fractures in the lead-lag occurred progressively deeper into the lagging panel as the length of the inter-panel lead-lag increased; however, the rate of fracture depth seems to decrease with increasing lead-lag length, tending towards an asymptotic value. The work done by Turner (1989) formed the basis of some important conclusions derived from detailed fracture mapping undertaken in this project.

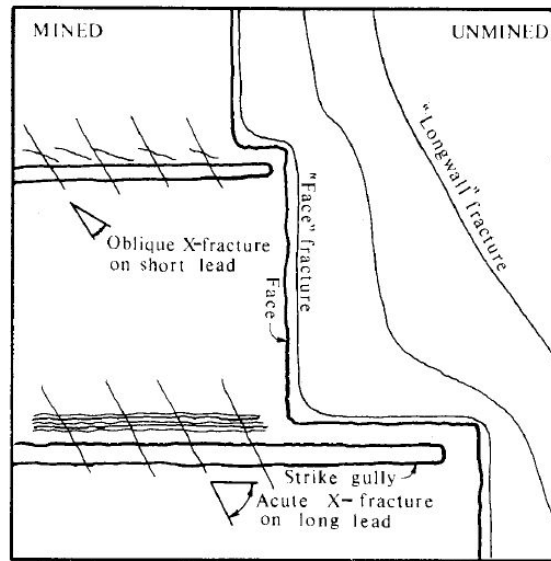


Figure 6. Plan showing the interaction of various fracture generations and resulting hangingwall conditions for a short and a long inter-panel lead-lag (after Heunis, 1980)

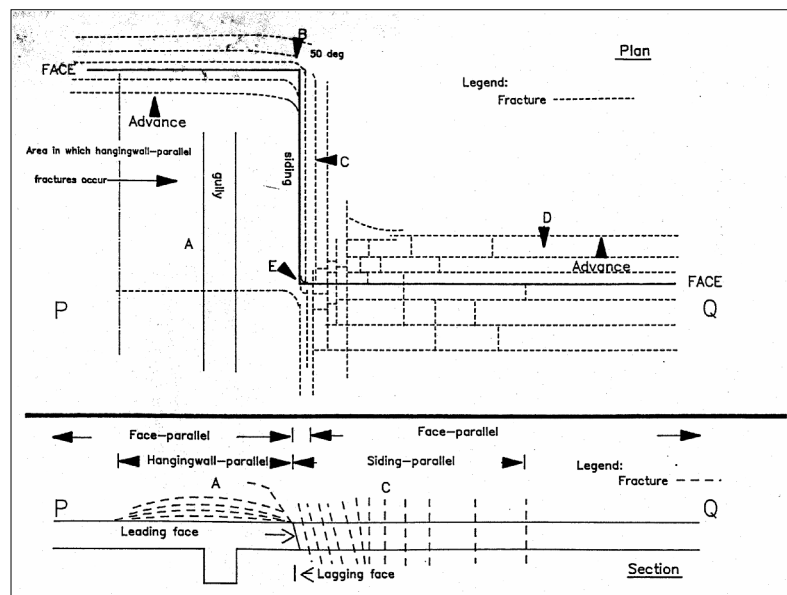


Figure 7. Fractures associated with inter-panel lead-lags – type C are siding-parallel fractures (after Turner, 1989)

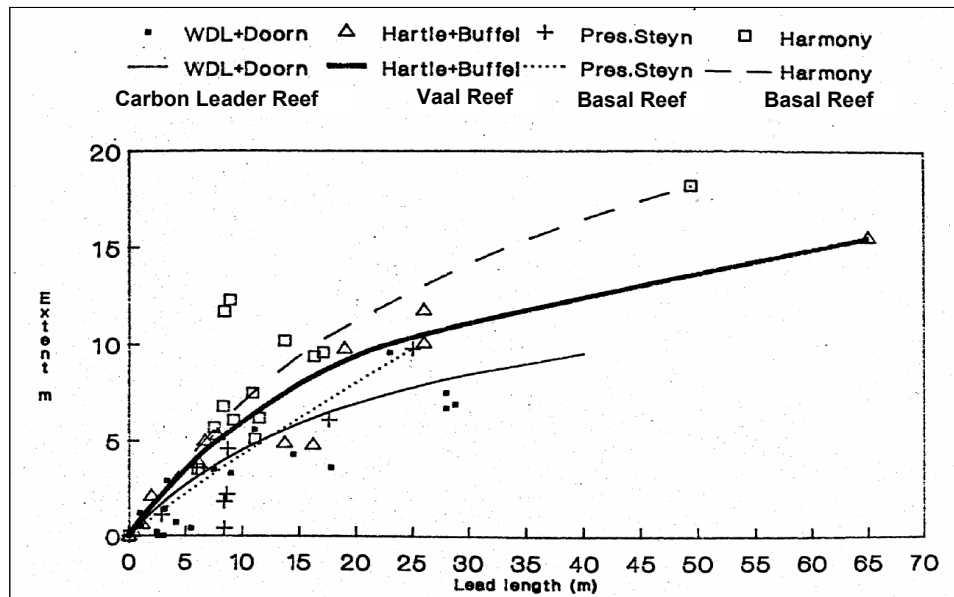


Figure 8. Extent (depth) of siding-parallel fractures as a function of inter-panel lead-lag length (after Turner, 1989)

Because of the tendency of long lead-lags to generate adverse fracturing, which can result in problematic hangingwall stability, many references in the literature recommend that lead-lags should be “kept to a minimum” (generally <10 m) where stress levels are high (Anon., 1988, Jager and Ryder, 1999, Naidoo et al., 2002). The inclusion of a supported siding (advanced in line with the face and the gully) is recommended and the gully should be positioned an adequate distance (3 – 4 m) from the top of the leading panel to avoid the low-angle fractures that curve around the corner of the panel in the lead-lag area.

A review of a number of accident investigations where lead-lags were a contributing factor showed that many accidents were caused by seismically-induced falls of ground associated with excessive lead-lags (>20 m).

4 CURRENT INDUSTRY PRACTICE

In order to evaluate current industry practice around lead-lags, codes of practice (COP) of various gold mines were reviewed to determine the currently adopted inter-panel lead-lag distances. The stipulated lead-lag lengths ranged between 4.5 m and 10 m (Table 1). None of the reviewed mines advocated the use of inter-panel lead-lags greater than 10 m and none provided any rationale for the selection of the stipulated inter-panel lead-lags. In most instances, a statement on keeping lead-lags to a minimum is made without stipulating specific minimum distances.

In addition to formulating the required codes of practice, many mines have implemented rock-related risk management systems in order to meet the requirements of the South African Mine Health and Safety Act and, in particular, in terms of devising strategies to treat rock-related risks arising from the stoping operations. Many rock-related risk management systems devised by various mines specifically list lead-lags as one of the risk assessment parameters.

Information captured by mines in stope assessment sheets and panel rating systems was used to establish the current in-situ practices around lead-lags in the gold mining industry. The purpose of the exercise was to compare in-situ lead-lag lengths with the design criteria, so that levels of compliance or adherence to standards could be determined. The in-situ lead-lags on all mines that participated in the survey deviated from the lead-lag design guidelines. In some cases the deviation from the guideline range was considerable. However, in all cases the adherence to the recommended standard was seldom above 50% (Table 2).

Table 1. Inter-panel lead-lag distances stipulated in mine codes of practice

Mine	Region	Reef mined	Mining method	Average operating depth (m)	COP stipulated lead-lag length (m)
A	Free State	Kalkoenskraan	Longwall	1800	6
B	Free State	Basal	Scattered	1700	5
C	West Wits	VCR	Longwall	2800	10
D	West Wits	CLR	Longwall	3200	10
E	Klerksdorp	Vaal Reef	Scattered	2400	4.5
F	Klerksdorp	Vaal Reef	Scattered	2200	4.5
G	West Wits	CLR	Sequential grid	2800	10
H	Far West Rand	VCR	Sequential grid	3000	10
I	Far West Rand	VCR	Longwall	2650	7

Table 2. Summary of in-situ vs. design lead-lag practice

Mine	Reef	Period of assessment	Mining method	Average stoping width	Lead-lag design guidelines	Actual lead-lag range	Compliance/adherence to standard
J	VCR	June 04 to May 05	Sequential grid	150 cm	3-10 m	0-15 m	50-80%
K	VCR	June 04 to May 05	Sequential grid	150 cm	5-10 m	0-15 m	25-55%
L	CLR	Jan 04 to Oct 04	Longwall	100 cm	5-10 m	0-25 m	25-50%
M	VCR	June 99 to Oct 04	Longwall	120 cm	5-10 m	0-40 m	15-75%
N	VCR	Oct 97 to Aug 99	Longwall (dip pillar)	140 cm	4-8 m	0-60 m	20-50%
O	VCR, Composite, Elsburgs	Jan 98 to Sept 98	Scattered	170 cm	4-8 m	0-60 m	8-30%
P	VCR, Composite, Elsburgs	Sept 97 to Sept 99	Scattered	160 cm	4-8 m	0-30 m	0-90%
Q	LCL	Jan 04 to Sept 04	Longwall	90 cm	5-7 m	0-20 m	5-25%
R	UCL	Jan 04 to Dec 04	Longwall	90 cm	5-10 m	0-20 m	25-45%

5 FRACTURE MAPPING

Fracture mapping was performed in the face and gully areas of a number of panels in a wide range of gold mines in the Witwatersrand Basin. The intention of the fracture mapping work was to establish whether lead-lag distances had an influence on the spatial distribution, frequency and orientation of fractures and whether the fracture imprints could be used to allow for an appropriate selection of inter-panel lead-lags.

Detailed fracture mapping around lead-lags was undertaken at 14 sites across eight gold mines representing a variety of reef types, depths and mining methods (Table 3). Scan line fracture was used to establish relationships between:

- rock mass ratings (RMR) and lead-lag length;
- fracture spacings and lead-lag length;
- the potential for keyblock failure and lead-lag length; and
- siding-parallel fracture extent and lead-lag length (building on the work done by Turner, 1989).

Table 3. Fracture mapping sites

Mine	Reef mined	Mining method	Inter-panel lead-lag (m) at time of survey	Approximate depth below surface (m)
S1	Ventersdorp Contact Reef	Sequential grid	7.6	2950
T	Basal Reef	Longwall	7.6	3172
S2	Ventersdorp Contact Reef	Sequential grid	7.9	2352
S3	Ventersdorp Contact Reef	Sequential grid	8.2	2848
S1	Ventersdorp Contact Reef	Longwall	8.4	2573
U	Carbon Leader Reef	Longwall, sequential grid	10.0	3200
S1	Main Reef	Sequential grid	10.2	2035
T	Basal Reef	Longwall	11.7	3161
V	Basal Reef	Scattered	18.2	1940
V	B Reef	Scattered	19.8	1810
W	Vaal Reef	Scattered	20.0	2274
W	Vaal Reef	Scattered	24.0	2287
X	Ventersdorp Contact Reef	Longwall	34.2	2424
S1	Main Reef	Sequential grid	55.0	2453

The trend of RMR (Bieniawski, 1976) vs. lead-lag length shows that the RMR decreases with increasing lead-lag length. For the sparse dataset analysed, the average RMR value of 68 (for 26 scan lines) suggests that an inter-panel lead-lag distance of 15 m should not be exceeded (Figure 9). The MRMR (Laubscher and Taylor, 1976) analysis yielded similar results: for an average MRMR of 45 (for 26 scan lines), the corresponding lead-lag distances should be kept to below 17 m (Figure 10).

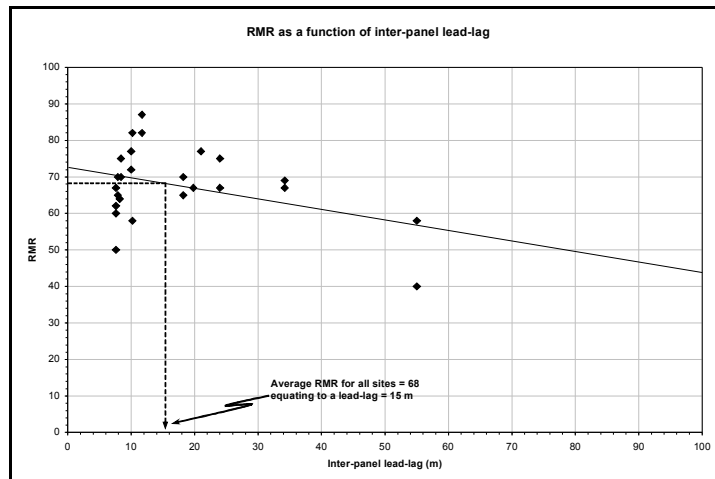


Figure 9. RMR related to inter-panel lead-lag distances

The relationship between lead-lag length and fracture spacing indicated that a rapid decrease in the spacing of fractures occurs for lead-lag distances greater than 10 m (Figure 11). The curve representing the upper bound values suggests, at its inflection point, that a lead-lag distance of 16.5 m is synonymous with a significant change in gradient of fracture spacing; this suggests that optimum lead-lag distances, irrespective of reef type mined and mining method adopted should be less than 16.5 m.

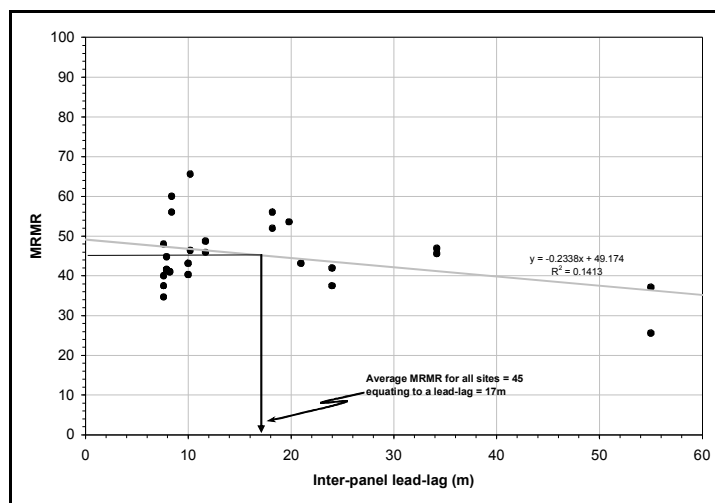
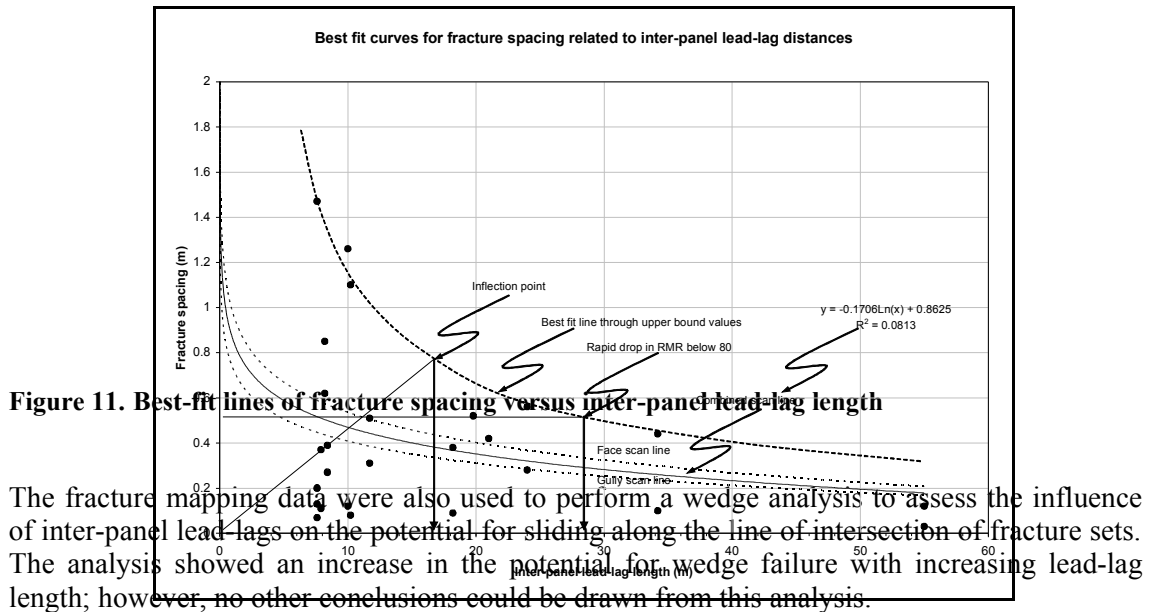


Figure 10. MRMR related to inter-panel lead-lag distances



However, the strongest evidence of a relationship existing between inter-panel lead-lag distances and fractures was provided in the siding-parallel fracture analysis. Siding-parallel fractures, together with face-parallel fractures, form a complex network of cross-fracturing that is initiated at the confluence of the toe of the panel and gully and progresses into the face area of the panel. This cross-fractured zone is often the likely site for rockfall and rockburst incidences due to the friable, broken nature of the rock mass. Thus, if this zone of highly fractured rock mass is kept to a minimum, then it follows that the extent of the hangingwall subjected to rockfalls and rockbursts will be potentially limited.

Turner (1989) showed that the spatial extent of this zone is directly related to the inter-panel lead-lag length, i.e. the greater the inter-panel lead-lag, the greater the extent of the zone until a limiting lead-lag length is reached when the siding-parallel fractures do not propagate any deeper into the rock (see Figures 7 and 8). It is suggested here that a reasonable area to limit the extent of siding-parallel fractures into the face would be 12 m² – 20 m², which for a face to last line of support distance of 4 m, equates to 3 – 5 m measured from the intersection of the face and gully.

For a limiting siding-parallel fracture extent of 3 – 5 m, the analysis suggests optimum inter-panel lead-lags of:

- 5.5 m – 10.5 m for the Ventersdorp Contact Reef;
- 9.5 m – 16.5 m for the Carbon Leader Reef;
- 4.0 m – 9.0 m for the Vaal Reef; and
- 6.0 m – 11.0 m for the Basal Reef.

An example of the analysis for the Carbon Leader Reef is given in Figure 12. A range in lead-lag distance of 6.5 m to 12.0 m is suggested from the composite data (Figure 13).

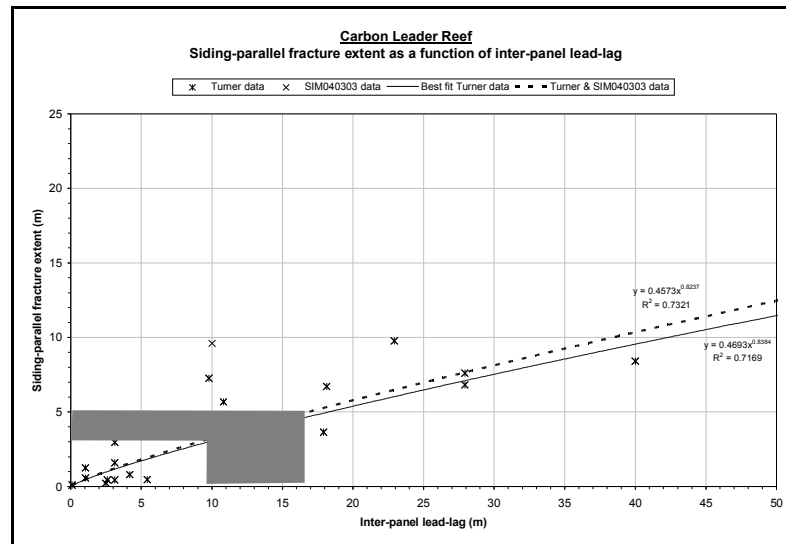


Figure 12. Siding-parallel fracture extents as a function of inter-panel lead-lags for the CLR

It is recommended that the lead-lag distance ranges for the siding-parallel fracture analysis be adopted in the South African gold mining industry. However, the fracture mapping study relates only to quasi-static conditions and any potentially damaging seismic events will impose further restrictions and requirements for selecting optimum lead-lags. For reef types not addressed in this analysis, a match for similarities in geotechnical settings should be checked against the four reef types analysed and the appropriate range chosen. If no match is established, the ranges suggested for the combined reef should be used.

The following conditions apply and must be evaluated prior to using the suggested lead-lag distance ranges:

- The analysis is based solely on the physical presence of stress fractures and does not account for the influence of seismicity on rock mass stability. For seismically active mines, the appropriate analysis must be done to ascertain the rockburst risks associated with the selected lead-lag range.
- The analysis is based on a tolerable siding-parallel fracture extent (or cross-fractured ground) of 3 – 5 m. The requirements on a particular mine may be more stringent. The design charts should be consulted to establish the appropriate lead-lag distances if the criteria for selecting lead-lags are different from those proposed in this report.
- The suggested lead-lag ranges can only be implemented once the support capacity required to maintain stability has been designed using appropriate methods.
- The augmenting of the datasets used in this analysis with new fracture information could lead to changes in interpretation of the results. The user of these graphs is encouraged to collect fracture data from his/her mine to augment and improve the design charts provided.

- Any sound scientific motivation for adopting a lead-lag distance other than that suggested in this report can supersede the suggestions of this report.
- Certain geotechnical environments may not be suited to the distances suggested in this report. If this is the case, the user can follow the same methodology adopted in this report and derive his/her own range of lead-lag distances.
- If the application of the lead-lag ranges suggested in this document results in the relaxing of currently adopted lead-lags, then an issue-based and continuous risk assessment must be conducted to ensure that the “relaxed distances” do not cause a deterioration in ground conditions. If conditions deteriorate, the original distances should be reverted to.

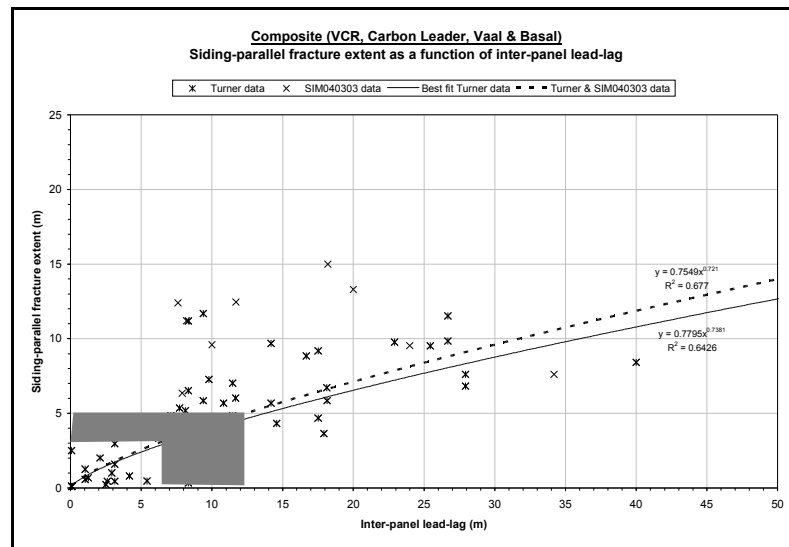


Figure 13. Siding-parallel fracture extents as a function of inter-panel lead-lags collectively for the VCR, CLR, Vaal Reef and Basal Reef

Although fracture mapping was performed on a relatively small sample population (26 scan lines), relationships were established between inter-panel lead-lag distances and RMR, fracture spacing and siding-parallel fracture extents. The augmenting of the Turner (1989) data with the data from this project provided a combined dataset slightly in excess of 80 sites. Although the data for the rock mass rating and fracture spacing analysis was sparse, the magnitude of the lead-lag values suggested by the analysis is in general agreement with that obtained from the siding-parallel fracture analysis. The results of the RMR, MRMR and fracture spacing analyses thus validate the results obtained using the relationship between siding-parallel fracture extents and inter-panel lead-lags. A comparison of the inter-panel lead-lag distances suggested from the four methods for quasi-static conditions is shown in Table 4.

Table 4. Comparison of proposed optimal inter-panel lead-lag distances from the scan line fracture mapping results

Reef type	Approx. depth (m)	Proposed optimal inter-panel lead-lag distances for quasi-static conditions from fracture mapping analysis (m)					
		RMR	MRMR	Fracture spacing	Siding-parallel fractures	Wedge analysis	Current practice
VCR	2400 - 3000	Lack of sufficient data	Lack of sufficient data	Lack of sufficient data	5.5 – 10.5	Inconclusive	5 – 10
CLR	3200				9.5 – 16.5		10 – 15
Vaal Reef	2300				4.0 – 9.0		5 – 10
Basal Reef	2000 - 3200				6.0 – 11.0		5 – 10
Combined reefs	2000 - 3200	15	17	<16.5	6.5 – 12.0		5 – 15

6 LEAD-LAG SEISMICITY AND SOURCE MECHANISMS

Seismicity associated with lead-lags was identified from three mine seismic catalogues. The seismograms of these events were reprocessed using AURA, the CSIR's seismic processing software. Potential lead-lag events were identified by correlating seismicity with monthly advances of the mining face. Moment tensor inversions were used to calculate the source mechanisms of the potential lead-lag events. Fault plane solutions were used to confirm the selected seismicity as lead-lags events and to determine the focal mechanisms. Where possible, the Doppler shift in frequencies (Brawn, 1989) was used to resolve ambiguity in fault plane solutions. The source parameters were then studied for any correlations with lead-lag length.

The results from one mine are presented here, which were most representative of lead-lags.

Eighty-nine seismic events were spatially associated with lead-lag geometry (Figure 14). The magnitudes of these events ranged from $M_L = -1.8$ to $M_L = 1.7$. It was possible to calculate moment tensors for 22 out of 52 events with $M_L \geq -1.0$. The fault plane solutions were classified into fault types according to the orientations of the fault planes, and the most likely fault plane solution that is associated with the mining geometry (Figure 15).

In Figure 15, the striped arrows indicate the most likely fault planes, which were manually selected as being parallel to some aspect of the mining layout or to geological features. The solid arrows (blue or red) indicate the fault planes that showed a Doppler shift in frequencies. The radiation patterns and fault plane solutions were rotated into the plane of the reef, so that the fault plane solutions could be more readily associated with the on-reef mining geometry.

Table 5 shows a number of parameters calculated from the decomposed moment tensors, indicating the relative proportion of volume change components (i.e. the percentage isotropic component), as well as parameters showing how closely the deviatoric portion of the moment tensor (i.e. the non-volume change, shearing component) resembles a pure double-couple source (Dahm, 1996, Jost and Hermann, 1989). In addition, the moment tensors were classified according to their dominant mechanism using the R-value defined by McGarr (1992) and Feignier and Young (1992).

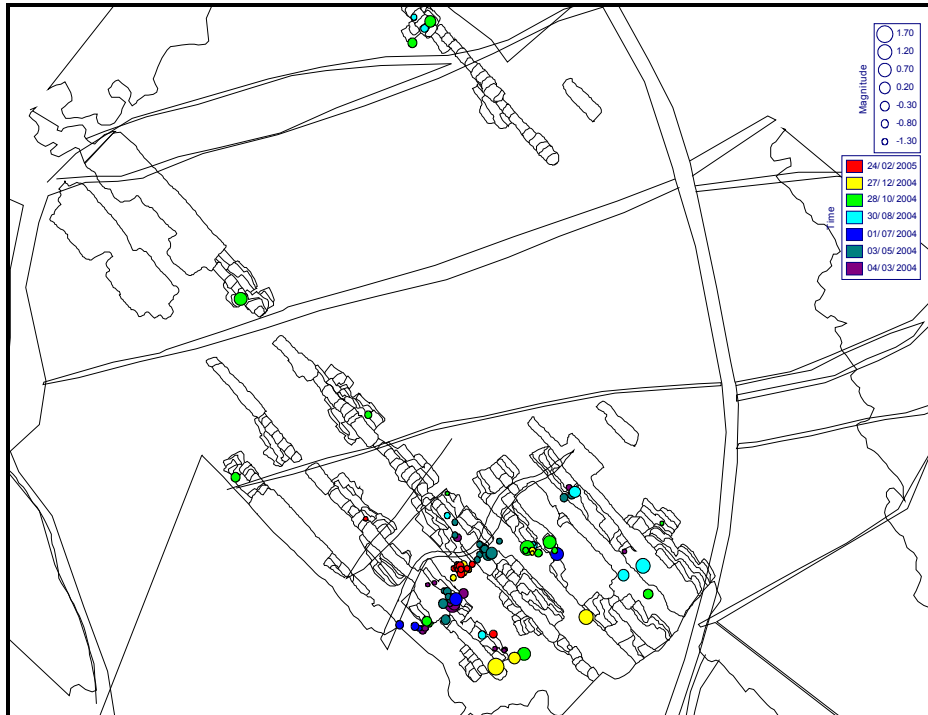


Figure 14. Study area with 89 seismic events spatially associated with lead-lags

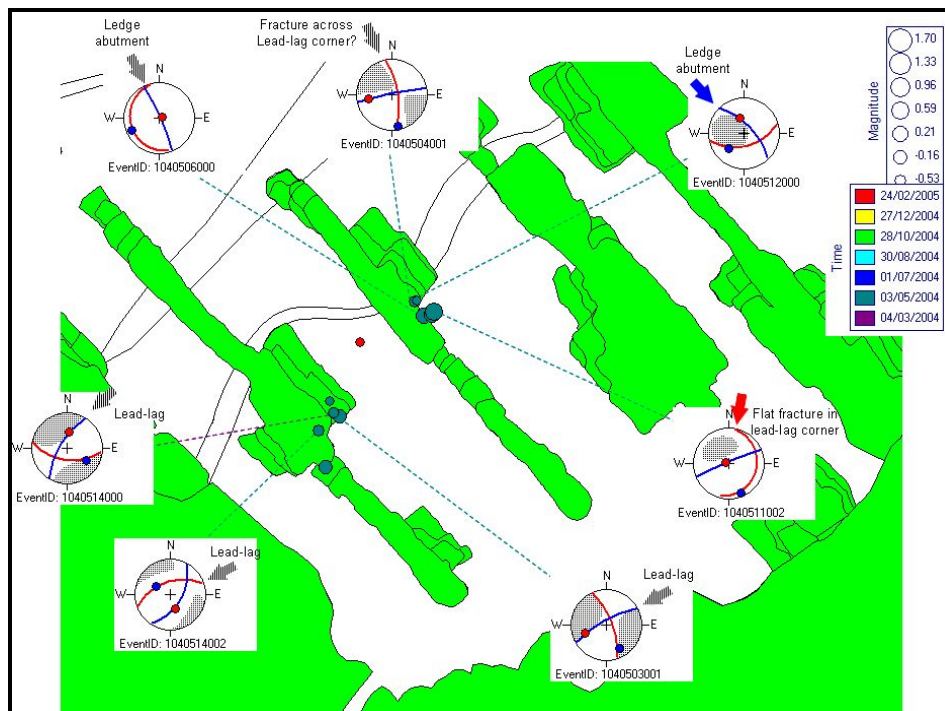


Figure 15. Example of moment tensor solutions for seismic events associated with lead-lags during May 2004. Solutions rotated into the plane of the reef

Table 5. Moment tensor decomposition and source classification (sample only)

Event ID	M _L	%ISO	DevDC	%DC	%CLVD	R	Dominant fault type	Associated feature
1040304000	0.9	-68.37	0.1	80.64	-63.24	Implosive	Thrust	Lead-lag
1040406000	-1.0	-0.20	0.18	63.16	-4.86	Shear	Strike-slip	Ledge abutment
1040503001	-0.2	-0.57	0.17	65.01	-7.87	Shear	Oblique-slip	Lead-lag
1040504001	-0.4	-12.67	0.19	61.19	-30.00	Shear	Strike-slip	Corner cutting fracture in lead-lag corner
1040506000	0.0	-76.55	0.03	93.54	-68.53	Implosive	Dip-slip	Ledge abutment
1040511002	-0.1	-26.98	0.12	76.11	-41.32	Implosive	Dip-slip	Corner cutting flat fracture in lead-lag corner
1040512000	-0.7	-6.25	0.33	33.65	-21.81	Shear	Oblique-slip	Ledge abutment
1040514000	-1.0	-0.55	0.41	18.8	-7.36	Shear	Oblique-slip	Lead-lag
1040514002	-0.4	-29.90	0.36	27.37	-41.22	Implosive	Oblique-slip	Lead-lag
1040612000	0.6	17.64	0.40	20.92	33.08	Tensile	Normal	Lead-lag
1040722000	-0.6	-22.31	0.30	40.50	-36.86	Implosive	Oblique-slip	Face
1040728000	0.4	-16.87	0.33	34.13	-32.75	Implosive	Oblique-slip	Face
1041013000	0.2	-21.26	0.16	68.70	-37.22	Implosive	Oblique-slip	Lead-lag

%ISO: Percentage isotropic component of full tensor (Dahm, 1996)

%DC: Percentage DC contribution of deviatoric tensor (Jost and Hermann, 1989)

%CLVD: Percentage CLVD contribution of deviatoric tensor (Jost and Hermann, 1989)

DevDC: Deviation from a pure DC source (Jost and Hermann, 1989)

R: R-ratio (McGarr, 1992). Classification using R: dominant mechanism according to R value, where Tensile: $R > 30$; Shear: $-30 \leq R \leq 30$; Implosive: $R < -30$ (Feignier and Young, 1992).

The main observations of the moment tensor inversion analysis are as follows:

- The most likely fault plane solutions were associated with either the mining face, ledge abutment or lead-lag geometry for all 22 solutions. The ambiguity of the fault plane solution could be resolved for seven of the 22 solutions using the Doppler shift in corner frequencies. The ambiguity of the remaining 15 solutions was resolved by considering the location of the events relative to the mining geometry. Twelve of the 22

events were associated with lead-lags, six events were associated with the face, and four were associated with ledge abutments.

- The fault plane solution for one event ($M_L = -0.1$) was particularly interesting because the fault plane indicated by the Doppler graphs had a strike (on-reef) that cuts across the corner of a 22 m long lead-lag and dips at a low angle. A second corner-cutting fault plane was observed in the same lead-lag for another event ($M_L = -0.4$), however this fracture had a much steeper dip. Both these events are shown in Figure 15. Various references in the literature review have reported that curved, flat-dipping fractures and cross-fracturing can occur near lead-lags, resulting in a rock mass that is difficult to support. It is also noteworthy that the two seismic events located in the highly-stressed open corner of the lead-lag, where the ERR values ahead of the face are highest. The above two examples appear to confirm the existence of flat-dipping and cross-fracturing in a lead-lag. It has also shown that seismicity can occur on this type of fracturing in a lead-lag (even though the two events in this instance were small in magnitude).
- There was a mixture of different focal mechanisms, although most events occurring on lead-lags were of the oblique-slip type.
- The largest lead-lag event had a magnitude $M_L = 1.7$ and seismic moment $M_0 = 7.69 \times 10^{11}$ Nm. It is significant that this seismic event occurred on a lead-lag that was only 15 m long.
- The mechanisms of the lead-lag events were mostly implosive, indicating that movement towards the source was occurring (Figure 16). This could result from co-seismic convergence. The source mechanism of face events was a mixture of shear and implosive, while most ledge abutment events had a shear mechanism. The mechanism of lead-lag events did not vary with lead-lag length (Figure 17).
- Lead-lag lengths in the range 14 m to 23 m generated larger seismic events than lead-lags outside of this range. In particular, an increase in seismic events with $M_L > 0.5$ (considered to be damaging or potentially fatal if they were to occur on a lead-lag) is observed for this range of lead-lag lengths (Figure 18). The lead-lag range 14 m to 23 m also generated seismic events with larger moments, in particular those with $M_0 > 1 \times 10^{10}$ Nm (Figure 19). This observation suggests that lead-lags at the selected mine should be maintained below 14 m to avoid the increased risk of larger, damaging seismic events when the lead-lag length becomes longer.

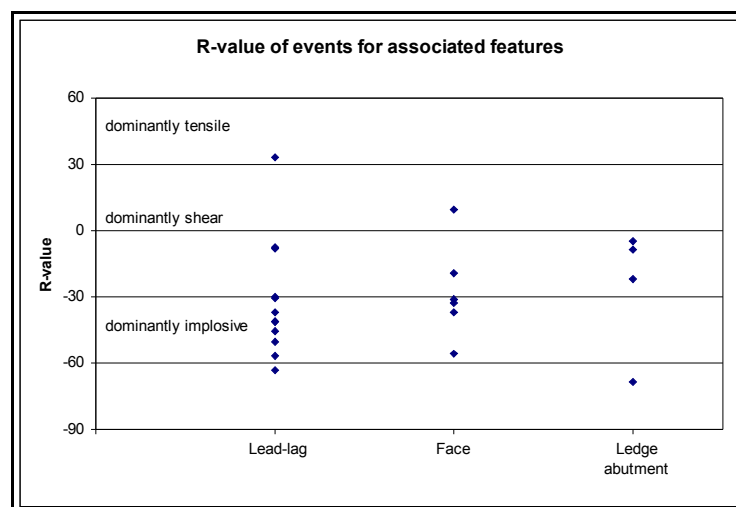


Figure 16. Dominant mechanism of lead-lag, face and ledge abutment events

7 NUMERICAL MODELLING OF LEAD-LAGS

In order to numerically simulate the effect of varying lead-lag length on the rock mass, two stages of numerical modelling were undertaken: elastic and inelastic modelling. The MINSIM 2000 boundary element program was used for elastic conceptual modelling of lead-lags. The analysis provided a basic understanding of the behaviour of lead-lags. Non-linear finite/discrete element modelling with discrete fracture generation capability (Elfen) was used to simulate damage around lead-lags of varying length at different depths. In addition, the capabilities of the CSIR-developed MINF cap stress model with edge weakening in simulating damage around a simple lead-lag geometry were explored.

The objective of performing the MINSIM modelling was to demonstrate the conceptual behaviour of lead-lags, albeit in an unrealistic elastically modelled environment. The elastic results were compared with results from Elfen that can incorporate inelastic behaviour in the rock mass.

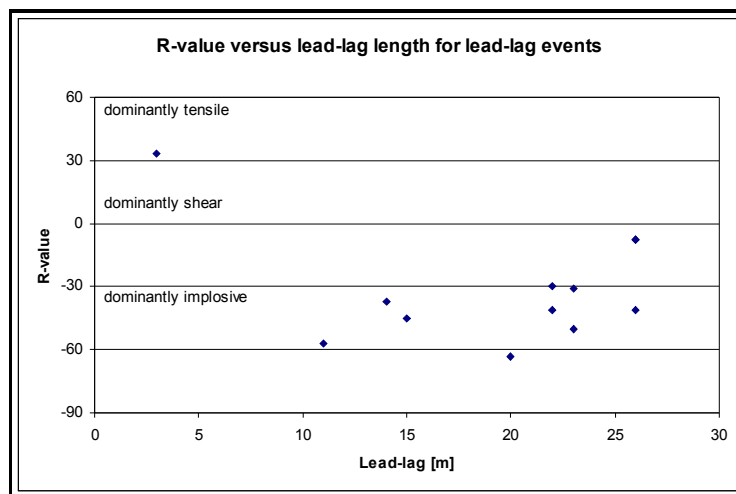


Figure 17. R-value versus lead-lag length for lead-lag events

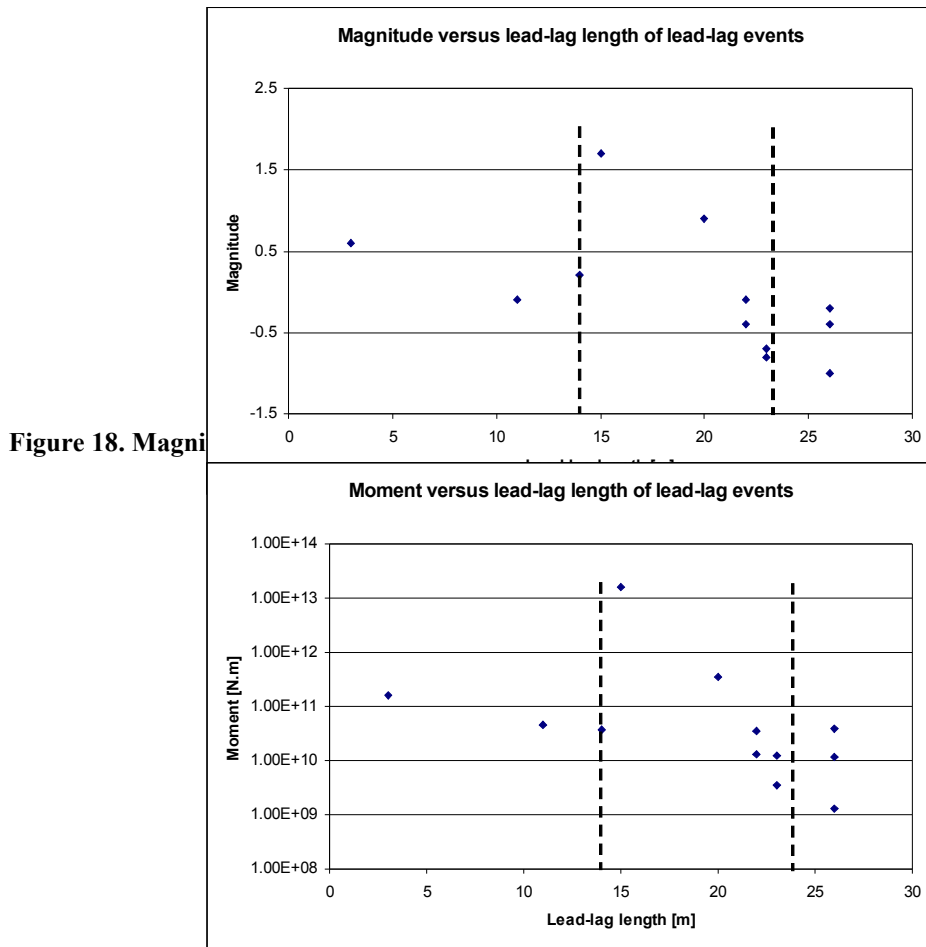


Figure 18. Magni

Figure 19. Moment versus lead-lag length for lead-lag events

7.1 Elastic modelling using MINSIM

In order to obtain a basic understanding of the behaviour of lead-lags and the potential problems they can create, a conceptual model representing mining geometries of typical lead-lag situations was set up using the MINSIM 2000 boundary element program. It is appreciated that deviations of observed rock mass behaviour from that predicted by boundary element codes indicate that inelastic processes dominate the physical reality (Lightfoot and Maccelari, 1999).

An attempt was made in the model to quantify the optimum lead-lag distances by studying the modelled stress distributions, stope convergence and ERR with respect to different lead-lag distances. The layout of the numerical model has three 240 m wide longwalls with 40 m wide panels and 40 m wide strike stabilising pillars between the longwalls (Figure 20). The panel used to gauge the effect of increasing lead-lag was taken centrally to minimise any edge effects. The conceptual layout was used to numerically model the effect of increasing depth and lead-lag length between panels on stress, convergence and ERR. The position of the line along which the stress, convergence and ERR were taken was placed 3 m away from the lead-lag face.

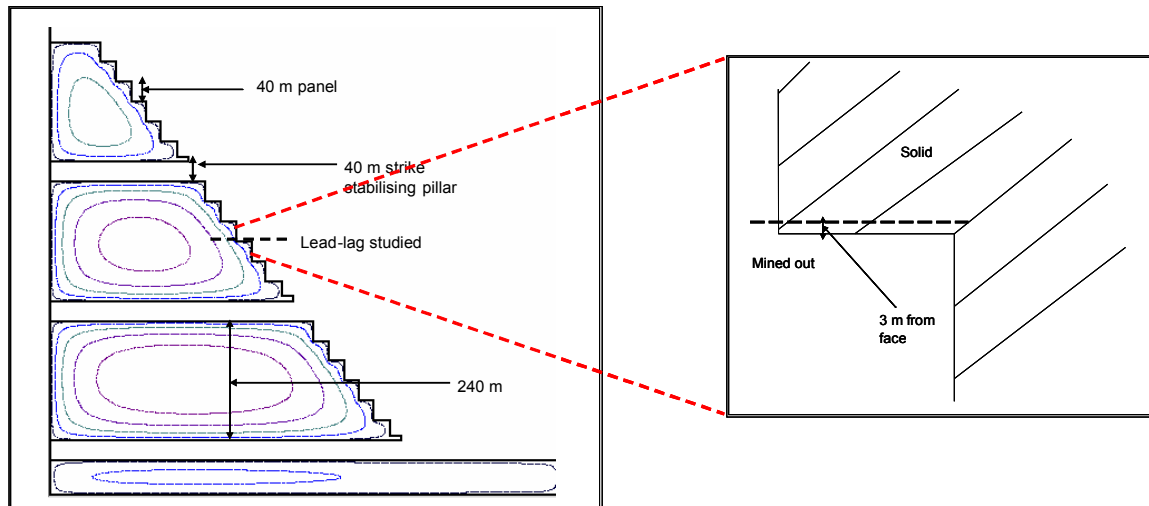
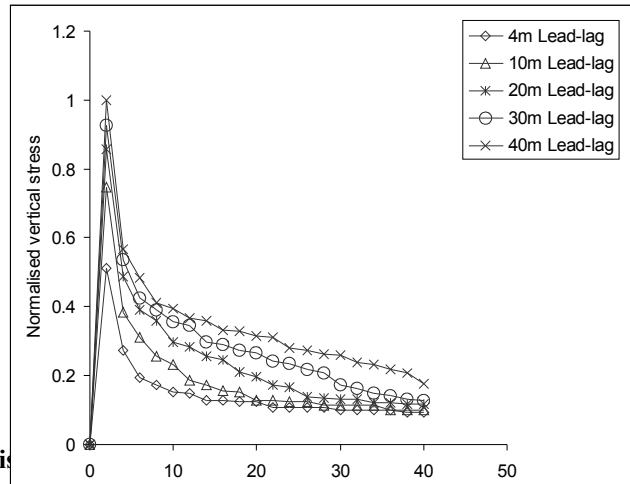


Figure 20. MINSIM model mining layout

The results from the MINSIM elastic modelling showed, as expected, an increase in the vertical stresses ahead of the mining face, ERRs and elastic convergence in the back area with depth. Increases in lead-lag length also resulted in large increases in the vertical stresses, ERRs and elastic convergence (Figures 21 to 23). It was concluded that short lead-lags should be used to reduce the vertical face stresses and ERR.

Previous work has shown that high ERRs cause intense mining-induced cross-fracturing and seismic activity. This implies that mining-induced fracturing, and possibly the associated seismic activity, will also be reduced by using short lead-lags. While the intensity of fracturing and the absolute values of the vertical stresses and ERRs cannot be predicted by MINSIM, the elastic modelling could be used as an indicator of the expected difficult mining conditions should long lead-lag lengths be used. While it was difficult to derive an optimal lead-lag length from the MINSIM modelling, the results seem to indicate extreme vertical stresses and ERRs for lead-lags greater than 10 m at 3000 m depth.

Figure 21. Normalised



ags at 3000 m depth

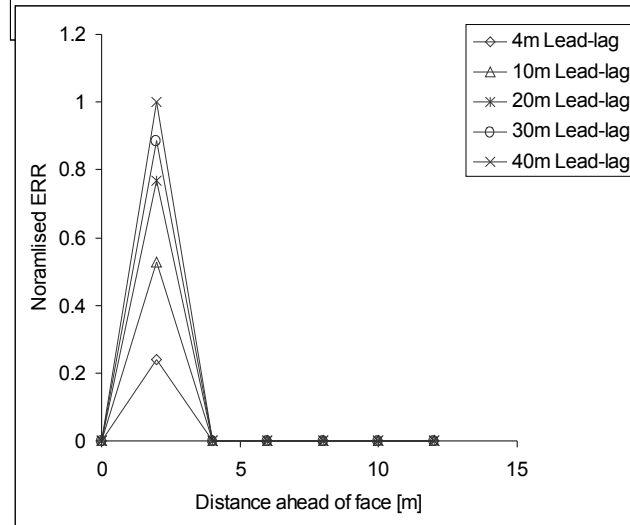


Figure 22. Normalised ERR ahead of the face at 3000 m depth

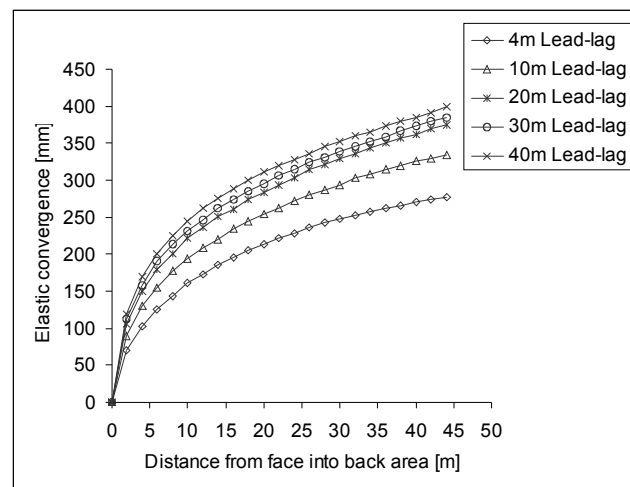


Figure 23. Elastic convergence into the back area at 3000 m depth

7.2 Inelastic modelling using Elfen

The discrete fracture generation capability of Elfen was used to simulate damaged and failed regions around lead-lags. The aim of the Elfen modelling was to determine the relationship between lead-lag distance and damage levels. This involved full three-dimensional modelling and non-linear plasticity of the rock mass.

Elfen uses a Mohr-Coulomb continuum material model to simulate damage and failure propagation. A strain-softening formulation is employed, which allows the cohesion, friction angle and dilation angle to be varied as a function of plastic strain.

The simple case of a junction between two longwall mining panels was modelled (Figure 24) where the face of one panel leads the second panel by various distances (ranging from 2 m to 40 m) at depths between 1000 m and 3000 m. The results were plotted as contours of plastic strain and as graphs of plastic strain parallel and perpendicular to the mining face (examples are shown in Figures 25 and 26).

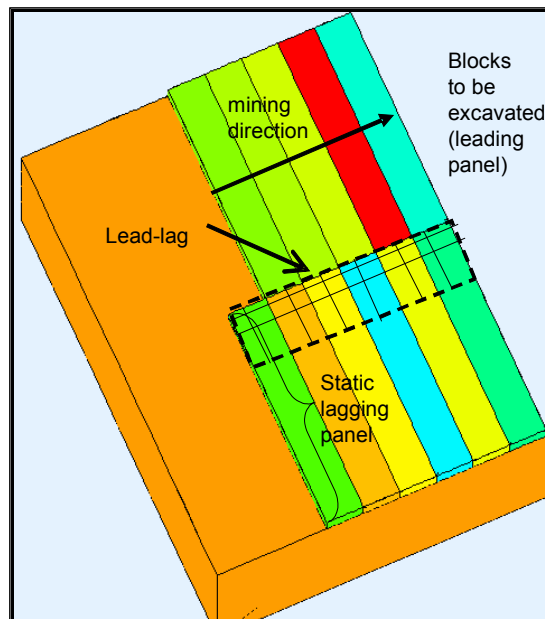


Figure 24. Lead-lag model geometry used for Elfen modelling. The dashed rectangle represents an area with a fine mesh density. Solid lines represent lines along which data were analysed and presented graphically (parallel and perpendicular to the lagging panel face)

The Elfen model showed that damage increased as the lead-lag distance increased. This was indicated by the high concentration of contours around the lead-lag corners. At 1000 m depth, the failed region (fractured zone) represented by an effective plastic strain of 0.01 to 0.02 extended to about 7 m perpendicular to the lagging face and 0.6 m parallel to the face for a 40 m long lead-lag. This was supported by the graphical plots of effective plastic strain parallel and perpendicular to the mining face.

The modelled effective plastic strain showed that shorter lead-lags generated less damage compared to the longer lead-lags (as expected). However, the modelled fracture extents were much smaller than the underground observations, where the depth of siding-parallel fracturing has been reported to be up to 20 m wide for long lead-lags (> 50 m). Also, the models of the same lead-lags at different depths (i.e. at 1000 m, 2000 m and 3000 m) generated similar damage levels. This is not necessarily representative of in situ rock mass behaviour.

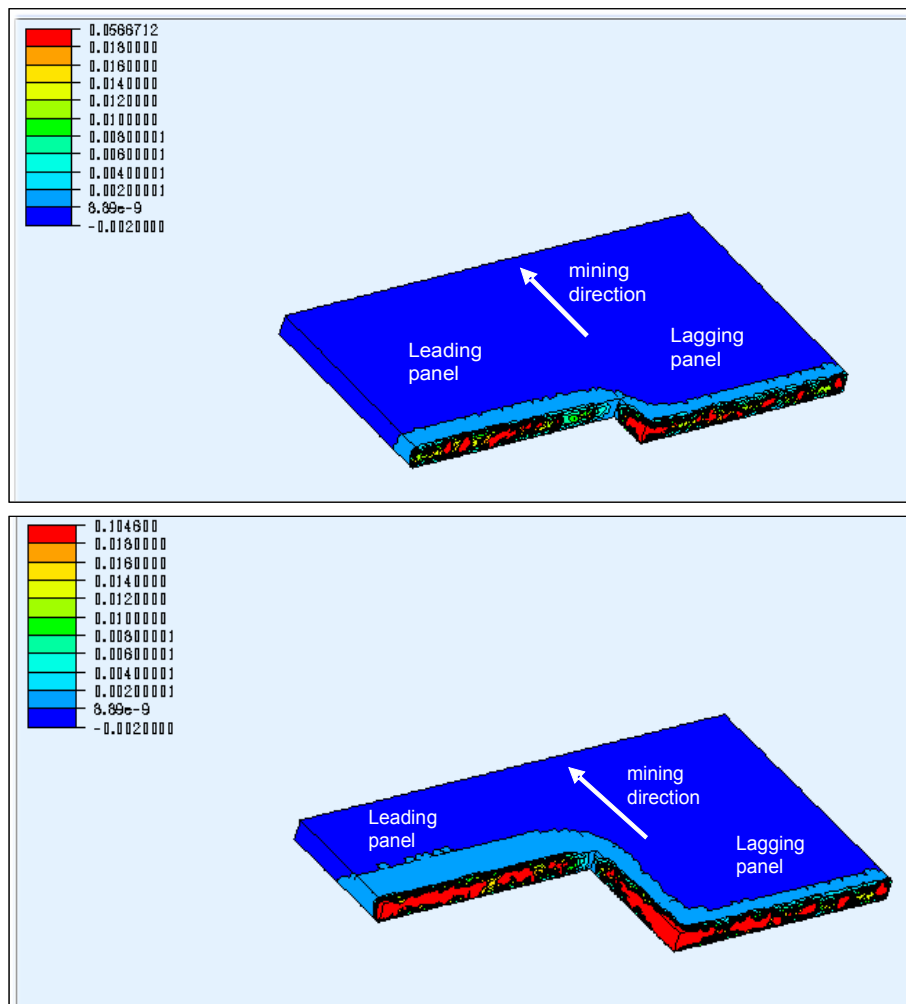


Figure 25. Contours of effective plastic strain for a 2 m lead-lag (top) and a 6 m lead-lag (bottom) at a depth of 1000 m (light blue = damaged zone, red = fractured zone)

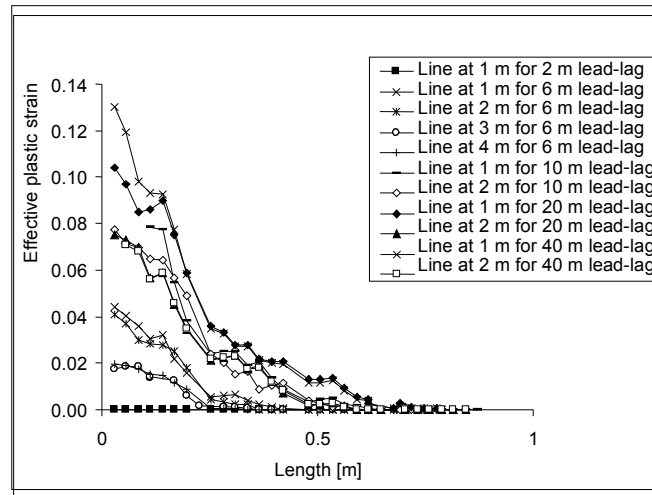


Figure 26. Effective plastic strain as a function of length parallel to the face at a depth of 1000 m

While the usefulness of the Mohr-Coulomb model in predicting the extent of damage has been demonstrated, it is critical that the material properties used in Elfen need to be carefully calibrated with both lab test data and underground observations. This work has to be undertaken before Elfen can be used to as a reliable indicator of the extent and magnitude of damage.

7.3 Inelastic modelling using MINF

Currently only advanced 3-D inelastic models such as 3DIGS and Elfen can model fracturing around lead-lags. The CSIR-developed MINF cap stress model with edge weakening may offer an alternative way of modelling observed fracturing around lead-lags.

A shortcoming of a pure cap stress model is that it does not account for the effects of increasing confinement ahead of the face. The edge weakening capability of the new cap stress model allows for increasing strength ahead of the face, but two strengths are necessary to provide for a drop in strength after failure (Figure 27).

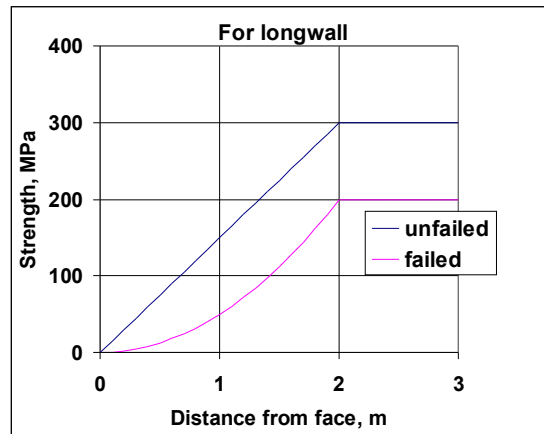


Figure 27. Edge weakening of MINF cap stress model incorporating a pre- and post-failure strength

In the case of an infinite longwall, the edge-weakening model results in much more realistic representations of stress and convergence ahead of the face than either an elastic or pure cap stress model (Figure 28).

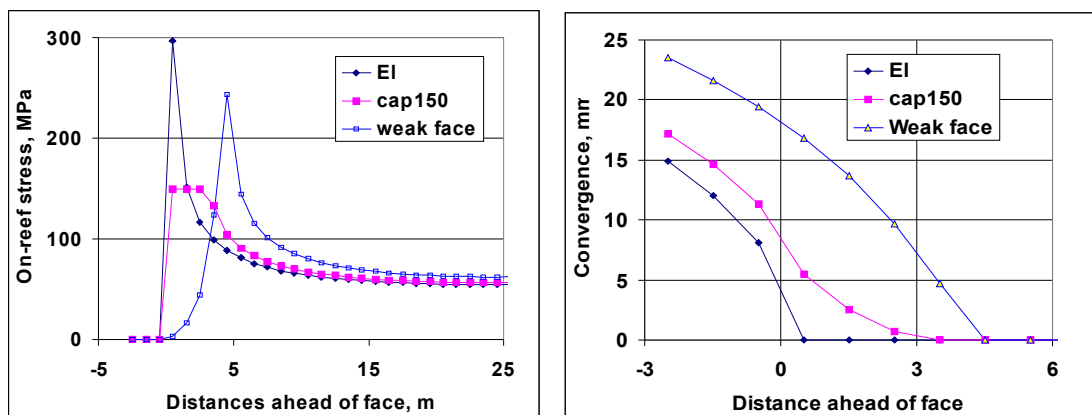


Figure 28. Comparison of the stress profile (left) and convergence (right) ahead of the face of a longwall between an elastic model (“EI”), a pure cap stress model (“cap150”) and an edge weakening model (“weak face”)

Initial results from applying the cap stress model with edge weakening to a simple lead-lag layout show that it generates much more realistic stress contours around the lead-lag than a pure cap stress model (Figure 29). The peak stress is well defined ahead of the face and the stress decreases towards the face.

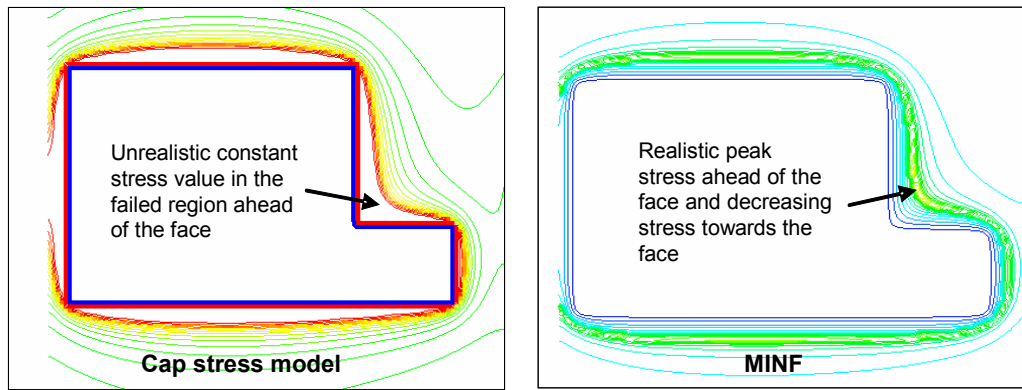


Figure 29. Stress contours ahead of the face around a lead-lag (left: pure cap stress model; right: edge weakening model)

The convergence ahead of the face can be represented as contours of face crushing using the edge weakening model to simulate the depth of fracturing. The model provides a more realistic contrast in the depth and intensity of crushing around the lead-lag than a pure cap stress model (Figure 30).

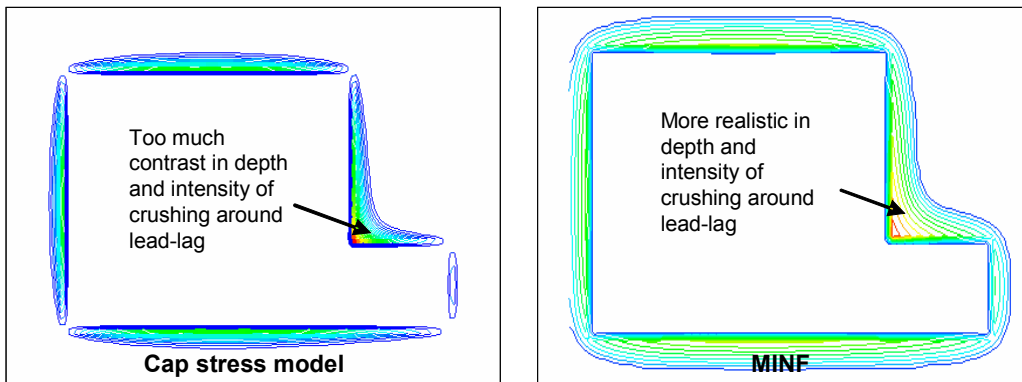


Figure 30. Contours of face crushing ahead of the face around a lead-lag (left: pure cap stress model; right: edge weakening model)

The brief examples shown here illustrate that the MINF cap stress model with edge weakening may be able to simulate the effect of various lead-lag lengths on fracturing around a lead-lag. This capability needs to be explored further.

8 CONCLUSIONS

While the results are not definitive, the work undertaken in this project indicates that the currently adopted lead-lag guidelines of 4.5 m to 10 m stipulated in COPs are similar to the findings in this project. In particular, the fracture mapping work provided some compelling

results. It is suggested that the lead-lag distance ranges listed in Table 4 for the siding-parallel fracture analysis be adopted in the South African gold mining industry. For reef types not addressed in this project, a match for similarities in geotechnical settings should be checked against the four reef types analysed and the appropriate range chosen. If no match is established, the ranges suggested for the combined reef should be used. Although not extensive, the seismic findings seem to corroborate the guidelines derived from the fracture mapping work. The Elfen model needs to be further calibrated for the study of fracturing around lead-lags before it can be successfully used as a forward modelling tool to determine optimal lead-lag lengths during mine design.

ACKNOWLEDGEMENTS

The authors thank the CSIR and the Mine Health and Safety Council for granting permission to publish this paper.

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