SIM 04 03 03: Lead-lag design criteria and seismicity patterns
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O.D. Goldbach, T. Rangasamy, L.M. Linzer, M.O. Kataka,
S.M. Spottiswoode and P. du Pisani
Introduction

- Creation of lead-lags is a fact of mining
- Problems experienced with ground stability and seismicity when lead-lags become long
- Current guidelines are intuitive – is 5 to 10 m optimum, or 40 m?
- Guidelines based on experience, not detailed measurement and understanding of deformation processes
- Need to scientifically quantify effects of lead-lags on fracturing/stability/support/seismicity to confirm/modify current design guidelines
- Focus on *inter-panel* lead-lags in *gold* mines
Deliverables

- **Output**: to quantify the effects of inter-panel lead-lags on rockfall and rockburst risk under various mining conditions and to develop strategies and guidelines to manage risks associated with lead-lags (mining, seismic and support).

- **Impact**: improved understanding of lead-lag behaviour in terms of influence of lead-lags on ground conditions, support and seismicity, leading to fewer rock-related losses associated with lead-lags.
Methodology

- Review current knowledge (literature review)
- Current industry practice (COPs, \textit{in situ} lead-lag practice)
- Field measurements (fracture mapping)
- Seismicity & seismic mechanisms
- Numerical modelling
- Conclusions
Review current knowledge

- Books, past papers, theses, COM reports, SIMRAC reports, DeepMine reports, FutureMine reports
- Interviews with RE personnel
- Review accident investigations where lead-lags were a factor
Past publications

- Most lead-lag problems are associated with strike gully stability
- Unstable hangingwall conditions often occur near the lead-lag corner
- Inter-panel lead-lag length seems to affect the severity and extent of the instability
- Fractures curve around lead-lags and become flat-dipping in the strike gully → keyblocks, difficult to support
- Many FOG accidents have occurred near the lead-lag corner or in the strike gully of the lead-lag
Flat-dipping fractures

Smith & Ortlepp (1978)
Past publications

- Strong relationship between inter-panel lead-lag length and hangingwall stability
- Average modelled ERR in a lagging panel shows exponential decay
- Increase in ERR from top of panel to lagging corner
Effect of lead-lag length

Hagan (1980)

PLAN SHOWING ERR VALUES FOR THE UPPER 41 EAST LONGWALL

Hagan (1980)

EFFECT OF LAG LENGTH ON ENERGY RELEASE RATE

FOR CONDITIONS DESCRIBED IN TEXT AND SHOWN IN FIG. 23

Hagan (1980)
Past publications

- Depth of siding-parallel fractures shows exponential decay with increasing lead-lag length

Siding-parallel fractures (type C)

Siding-parallel fracture depth vs. lead-lag length

Turner (1989)
Past publications

- Many references recommend lead-lags should be “kept to a minimum” (generally <10 m) where stress levels are high because of their tendency to generate adverse low-angle fractures
- Inclusion of a supported siding (advanced in line with the face and the gully) is recommended
- Gully has to 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
Gully position

(a) Section through stope showing fracture pattern around stope face

(b) Unstable hangingwall Dangerous area

±3 m

Steep dipping fractures, stable hangingwall

60° - 90°

20° - 40°

Curved flat dipping unstable fractures in hangingwall

±70° - 90°

Jager & Ryder (1999)

Plan of stope showing orientation of immediate hangingwall fractures in solid
Accident investigations

- Many accidents due to seismically-induced FOGs associated with excessive lead-lags (>20 m)
Current industry practice

- Inter-panel lead-lags stipulated in mine COPs were <10m

<table>
<thead>
<tr>
<th>Mine</th>
<th>Region</th>
<th>Reef mined</th>
<th>Mining method</th>
<th>Average operating depth (m)</th>
<th>COP stipulated lead-lag length (m)</th>
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<tr>
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<td>J</td>
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<td>CLR</td>
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<td>L</td>
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<td>4,5</td>
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<td>N</td>
<td>Far West Rand</td>
<td>VCR</td>
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<tr>
<td>O</td>
<td>Far West Rand</td>
<td>VCR</td>
<td>Longwall</td>
<td>2650</td>
<td>7</td>
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</tbody>
</table>
Current industry practice

- In-situ lead-lag practice determined from
  - stope assessment sheets
  - panel rating systems

<table>
<thead>
<tr>
<th>Mine</th>
<th>Reef</th>
<th>Period of assessment</th>
<th>Mining method</th>
<th>Average stoping width</th>
<th>Lead-lag design guidelines</th>
<th>Actual lead-lag range</th>
<th>Compliance/adherence to standard</th>
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</thead>
<tbody>
<tr>
<td>P (stoping)</td>
<td>VCR</td>
<td>June 04 to May 05</td>
<td>Sequential grid</td>
<td>150 cm</td>
<td>3-10 m</td>
<td>0-15 m</td>
<td>50-80%</td>
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<tr>
<td>P (ledging)</td>
<td>VCR</td>
<td>June 04 to May 05</td>
<td>Sequential grid</td>
<td>150 cm</td>
<td>5-10 m</td>
<td>0-15 m</td>
<td>25-55%</td>
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<td>Q</td>
<td>CLR</td>
<td>Jan 04 to Oct 04</td>
<td>Longwall</td>
<td>100 cm</td>
<td>5-10 m</td>
<td>0-25 m</td>
<td>25-50%</td>
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<tr>
<td>Q</td>
<td>VCR</td>
<td>June 99 to Oct 04</td>
<td>Longwall</td>
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<td>5-10 m</td>
<td>0-40 m</td>
<td>15-75%</td>
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<td>R</td>
<td>VCR</td>
<td>Oct 97 to Aug 99</td>
<td>Longwall (dip pillar)</td>
<td>140 cm</td>
<td>4-8 m</td>
<td>0-60 m</td>
<td>20-50%</td>
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<tr>
<td>R</td>
<td>VCR, Comp., Elsburgs</td>
<td>Jan 98 to Sept 98</td>
<td>Scattered</td>
<td>170 cm</td>
<td>4-8 m</td>
<td>0-60 m</td>
<td>8-30%</td>
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<td>R</td>
<td>VCR, Comp., Elsburgs</td>
<td>Sept 97 to Sept 99</td>
<td>Scattered</td>
<td>160 cm</td>
<td>4-8 m</td>
<td>0-30 m</td>
<td>0-90%</td>
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<tr>
<td>S</td>
<td>LCL</td>
<td>Jan 04 to Sept 04</td>
<td>Longwall</td>
<td>90 cm</td>
<td>5-7 m</td>
<td>0-20 m</td>
<td>5-25%</td>
</tr>
<tr>
<td>S</td>
<td>UCL</td>
<td>Jan 04 to Dec 04</td>
<td>Longwall</td>
<td>90 cm</td>
<td>5-10 m</td>
<td>0-20 m</td>
<td>25-45%</td>
</tr>
</tbody>
</table>
In-situ lead-lag practice

Monthly compliance

Compliance over time

June 2004

Compliance: 56%
Fracture mapping

- Test the hypothesis that lead-lag distances have an influence on the spatial distribution, frequency and orientation of fractures and hence the fracture imprints can be used to allow for an appropriate selection of inter-panel lead-lags

- 14 sites, eight gold mines, variety of reefs, mining methods and depths

- Use scan line fracture mapping to establish relationships:
  - rock mass ratings vs. lead-lag length
  - fracture spacings vs. lead-lag length
  - potential for keyblock failure vs. lead-lag length
  - siding-parallel fracture extent vs. lead-lag length (Turner, 1989)
## Fracture mapping sites

<table>
<thead>
<tr>
<th>Mine/Shit</th>
<th>Reef mined</th>
<th>Mining method</th>
<th>Inter-panel lead-lag (m) at time of survey</th>
<th>Approximate depth below surface (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kloof 1#</td>
<td>Ventersdorp Contact Reef</td>
<td>Sequential grid</td>
<td>7,6</td>
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<tr>
<td>Bambanani 4#</td>
<td>Basal Reef</td>
<td>Longwall</td>
<td>7,6</td>
<td>3172</td>
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<td>Kloof 3#</td>
<td>Ventersdorp Contact Reef</td>
<td>Sequential grid</td>
<td>7,9</td>
<td>2352</td>
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<td>Kloof 7#</td>
<td>Ventersdorp Contact Reef</td>
<td>Sequential grid</td>
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<td>2848</td>
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<tr>
<td>Kloof 1#</td>
<td>Ventersdorp Contact Reef</td>
<td>Longwall</td>
<td>8,4</td>
<td>2573</td>
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<tr>
<td>Driefontein 5E#</td>
<td>Carbon Leader Reef</td>
<td>Longwall, Sequential grid</td>
<td>10,0</td>
<td>3200</td>
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<tr>
<td>Kloof 1#</td>
<td>Main Reef</td>
<td>Sequential grid</td>
<td>10,2</td>
<td>2035</td>
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<tr>
<td>Bambanani 4#</td>
<td>Basal Reef</td>
<td>Longwall</td>
<td>11,7</td>
<td>3161</td>
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<tr>
<td>Masimong 5#</td>
<td>Basal Reef</td>
<td>Scattered</td>
<td>18,2</td>
<td>1940</td>
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<tr>
<td>Masimong 5#</td>
<td>B Reef</td>
<td>Scattered</td>
<td>19,8</td>
<td>1810</td>
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<td>Great Noligwa</td>
<td>Vaal Reef</td>
<td>Scattered</td>
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<td>2274</td>
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<tr>
<td>Great Noligwa</td>
<td>Vaal Reef</td>
<td>Scattered</td>
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<td>South Deep</td>
<td>Ventersdorp Contact Reef</td>
<td>Longwall</td>
<td>34,2</td>
<td>2424</td>
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<td>Kloof 1#</td>
<td>Main Reef</td>
<td>Sequential grid</td>
<td>55,0</td>
<td>2453</td>
</tr>
</tbody>
</table>
Fracture mapping sites

(S) = Soft
(H) = Hard

Lead-lag length (m)

Number of samples
RMR vs. lead-lag length

- Average RMR (Bieniawski, 1976) of 68 suggests 15 m lead-lag length
MRMR vs. lead-lag length

- Average MRMR (Laubscher & Taylor, 1976) of 45 suggests 17 m lead-lag length

$$y = -0.2338x + 49.174$$

$R^2 = 0.1413$

Average MRMR for all sites = 45 equating to a lead-lag = 17m
Fracture spacings vs. lead-lag length

- Rapid decrease in fracture spacings for lead-lags >10 m (asymptote to 0.2 m)
- Inflection point of upper bound values where lead-lag distance changes from rapid decrease to asymptotic suggests optimum lead-lag distance <16.5 m
Fracture spacings vs. lead-lag length

Best fit curves for fracture spacing related to inter-panel lead-lag distances

\[ y = -0.1706 \ln(x) + 0.8625 \]

\[ R^2 = 0.0813 \]
Potential wedge failure vs. lead-lag length

- Wedge analysis to assess influence of inter-panel lead-lags on potential for sliding along line of intersection of fracture sets
Potential wedge failure vs. lead-lag length

- Increase in potential for wedge failure with increasing lead-lag length, otherwise inconclusive

![Graph showing potential wedge failure vs. lead-lag length](image)
Siding-parallel fracture extent vs. lead-lag length

- Depth of siding-parallel fractures (type C) shows exponential decay with increasing lead-lag length (Turner, 1989)
Siding-parallel fracture extent vs. lead-lag length

- Siding-parallel fractures + face-parallel fractures form complex network of cross-fracturing
- Cross-fractured zone is often the likely site for rockfall and rockburst incidences
- Limit the spatial extent of this zone by controlling the inter-panel lead-lag length
- Suggest limiting cross-fractured zone to 12 m² – 20 m², i.e. for face-to-support distance of 4 m, this means that siding-parallel fracture extent must be limited to 3 m – 5 m
Siding-parallel fracture extent vs. lead-lag length

- In order to limit siding-parallel fracture extent to 3 m – 5 m, inter-panel lead-lags of 9.5 m – 16.5 m for the Carbon Leader Reef are obtained.
Comparison of optimum lead-lag lengths

- Optimum lead-lag distances suggested by fracture mapping analyses

<table>
<thead>
<tr>
<th>Reef type</th>
<th>Approximate depth (m)</th>
<th>Proposed optimal inter-panel lead-lag distances for quasi-static conditions from fracture mapping analysis (m)</th>
</tr>
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<tbody>
<tr>
<td></td>
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<td>RMR</td>
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<tr>
<td>Ventersdorp Contact Reef</td>
<td>2400 - 3000</td>
<td>Lack of sufficient data</td>
</tr>
<tr>
<td>Carbon Leader Reef</td>
<td>3200</td>
<td>Lack of sufficient data</td>
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<tr>
<td>Vaal Reef</td>
<td>2300</td>
<td>4.0 – 9.0</td>
</tr>
<tr>
<td>Basal Reef</td>
<td>2000 - 3200</td>
<td>6.0 – 11.0</td>
</tr>
<tr>
<td>Combined reefs</td>
<td>2000 - 3200</td>
<td>15</td>
</tr>
</tbody>
</table>
Conditions of suggested lead-lag lengths

- Applicable for quasi-static conditions only, i.e. analysis is based on physical presence of stress fractures and does not account for the influence of seismicity on rock mass stability.

- Analysis based on a tolerable siding-parallel fracture extent of 3 m – 5 m (12 m² – 20 m² of cross-fractured ground). Design charts should be consulted to establish appropriate lead-lag distances if the criteria for selecting lead-lags are different.

- Suggested lead-lag ranges can only be implemented once the support capacity required to maintain stability has been determined.
Conditions of suggested lead-lag lengths

- User is encouraged to collect fracture data from own mine to augment and improve the design charts. This could lead to changes in interpretation of the results.

- Certain geotechnical environments may not be suited to the distances suggested in this report. User can follow the same methodology adopted in this report and derive 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.
Seismicity and seismic mechanisms

- Obtained seismic catalogues from three mines: Kloof 3# pillar, Tau Tona, Elandsrand
- Relocated the seismic events using MLOC hybrid relocation program (SIM 02-03-04) and AURA seismic analysis software
- Identified potential lead-lag events by correlating seismicity with monthly mining steps
- Computed source mechanisms for selected lead-lag events using MTlv7.exe moment tensor inversion program (GAP604)
- Analysis of source parameters with lead-lag length
Seismicity and seismic mechanisms

Doppler shift in frequencies used to resolve ambiguity in fault plane solutions
### Seismicity and seismic mechanisms

<table>
<thead>
<tr>
<th>Event ID &amp; magnitude</th>
<th>Radiation pattern &amp; fault plane solution (relative to surface)</th>
<th>Radiation pattern &amp; fault plane solution (rotated to reef)</th>
<th>Dominant fault type (relative to reef plane)</th>
<th>Associated feature</th>
</tr>
</thead>
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<tr>
<td>1040304000 M&lt;sub&gt;L&lt;/sub&gt;=0.9</td>
<td><img src="image1" alt="Radiation pattern 1" /></td>
<td><img src="image2" alt="Radiation pattern 2" /></td>
<td>Thrust</td>
<td>Lead-lag</td>
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<td>1040406000 M&lt;sub&gt;L&lt;/sub&gt;=1.1</td>
<td><img src="image3" alt="Radiation pattern 1" /></td>
<td><img src="image4" alt="Radiation pattern 2" /></td>
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<td>Ledge abutment</td>
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<td>Lead-lag</td>
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Seismicity and seismic mechanisms

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<th>Event ID</th>
<th>M_L</th>
<th>%ISO</th>
<th>DevDC</th>
<th>%DC</th>
<th>%CLVD</th>
<th>Dominant mechanism</th>
<th>Dominant fault type</th>
<th>Associated feature</th>
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<td>10403040000</td>
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<td>0,1</td>
<td>80,64</td>
<td>-63,24</td>
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<td>Thrust</td>
<td>Lead-lag</td>
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<td>10404060000</td>
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<td>-0,20</td>
<td>0,18</td>
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<td>-4,86</td>
<td>Shear</td>
<td>Strike-slip</td>
<td>Ledge abutment</td>
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<td>1040503001</td>
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<td>-0,57</td>
<td>0,17</td>
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<td>0,03</td>
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<td>Dip-slip</td>
<td>Ledge abutment</td>
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<td>0,12</td>
<td>76,11</td>
<td>-41,32</td>
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<td>Corner cutting flat fracture in lead-lag corner</td>
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<td>-6,25</td>
<td>0,33</td>
<td>33,65</td>
<td>-21,81</td>
<td>Shear</td>
<td>Oblique-slip</td>
<td>Ledge abutment</td>
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<tr>
<td>1040514000</td>
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<td>0,41</td>
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<td>Oblique-slip</td>
<td>Lead-lag</td>
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<td>-41,22</td>
<td>Implosive</td>
<td>Oblique-slip</td>
<td>Lead-lag</td>
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<td>1040612000</td>
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<td>17,64</td>
<td>0,40</td>
<td>20,92</td>
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<td>-22,31</td>
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<td>Face</td>
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<td>Oblique-slip</td>
<td>Face</td>
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<td>68,70</td>
<td>-37,22</td>
<td>Implosive</td>
<td>Oblique-slip</td>
<td>Lead-lag</td>
</tr>
</tbody>
</table>
Results from Kloof 3#

- Most lead-lag events were oblique-slip type
- Magnitudes of lead-lag events were $-1.0 < M_L < 1.7$
- Mechanisms of lead-lag events were mostly implosive
Results from Kloof 3#

- Lead-lags in range 14 m to 23 m generated larger seismic events than outside this range.
Results from Tau Tona

- Abutments (>35 m), rather than typical inter-panel lead-lags
- Seismicity associated with abutments, faces or geology
Results from Tau Tona

- Most abutment events were oblique-slip type
- Magnitudes of abutment events were $-0.8 < M_L < 0.5$
- Mechanisms of abutment events were mostly shear
- Poor correlation of seismic parameters with abutment length
Numerical modelling

- Conceptual elastic MINSIM modelling confirmed increase in vertical stress, ERR and convergence with increasing lead-lags.
Numerical modelling

![Graphs showing numerical modelling results.](image-url)
Numerical modelling

- Inelastic modelling using Elfen to simulate damaged/failed regions around lead-lags
  - non-linear finite element modelling package
  - discrete fracture generation capability
  - uses Mohr-Coulomb material model to simulate damage and failure propagation
  - strain softening formulation (cohesion, friction & dilation angle vary with plastic strain)
  - high internal friction angle of failed elements provides too high confinement, limiting depth of damaged zone
  - demonstrated qualitative effect of lead-lags
Numerical modelling

- Lead-lags 2 m to 40 m
- Depths 1000 m to 3000 m
- Contours of plastic strain
- Graphs of plastic strain parallel and perpendicular to lead-lag
Numerical modelling
Numerical modelling

- MINF
  - cap stress model *with edge weakening*
  - increasing strength ahead of face
Numerical modelling

• MINF

  • more realistic representation of stress and convergence ("depth of fracturing") around simple lead-lag than pure cap stress model
Conclusions

- Convincing evidence from fracture mapping work that optimal lead-lags are in the range 4 m – 17 m (depending on reef type)
- In accordance with current lead-lag guidelines (5 m – 15 m)
- However, need stricter adherence to lead-lag standards
- FOGs in long lead-lags due to nearby seismicity
- Lead-lags in range 14 m – 23 m generated larger seismic events ($M_L > 0.5$) than outside this range (Kloof)
- Elfen and MINF show potential to model failed regions around lead-lags
Thank you