Risk based design of ground support

William Joughin
Joseph Muaka, Philani Mpunzi, Denisha Sewnun, Johan Wesseloo
Risk based design of ground support

Sub project of “Ground Support Systems Optimization” research project lead by the Australian Centre for Geomechanics (ACG).

Participants
- William Joughin (SRK SA)
- Johan Wesseloo (ACG)
- Joseph Muaka (SRK SA)
- Philani Mpunzi (SRK SA)
- Denisha Sewnun (SRK SA)

Advisors
- Luis-Fernando Contreras (SRK SA)
- Michael Dunn (SRK Australia)
- Dick Stacey (University of the Witwatersrand)
- Shaun Murphy (SRK SA)
- Jeanne Walls (SRK SA)

Data
- IvanPlats Pty Ltd

Major sponsors
Glencore Mount Isa Mines, Independence Group NL, Codelco Chile, MMG Limited, Minerals Research Institute of Western Australian, and the Australian Centre for Geomechanics.

Minor Sponsors
Introduction

• Purpose of Risk Based Design
  – Cater for the inherent variability in rock mass conditions
  – To address uncertainty
  – To apply engineering judgement
  – To enable decisions to made based on the level of risk to the operation
  – Risk = probability x consequence

• Probabilistic vs Deterministic
  – Advantages of probabilistic analysis well known
  – Powerful methods of probabilistic analysis developed

• Not widely applied in underground mining geotechnical applications
  – Additional effort
  – Acceptable probabilities of failure?
Example Mining Layout

- Access Ramp
- Sub-level drive
- Primary stope drive
- Secondary stope drive
Hazards

Tunnel supported with bolts and mesh

Rockfall (joint bounded)

Stress Damage (depth of failure)

Consequences

- Production delays – loss of income
- Rehabilitation costs
- Injuries
- Cost of damage to mobile equipment
Risk Analysis Process

Rockfall Block Analysis

Rock Mass Properties

Loading Conditions

Excavation Geometry & support

Stress Damage Numerical Analysis (Elastic & Elasto-plastic approaches)

PoF Monte Carlo Simulation

Damage Loss Model

Risk Evaluation

PoF Various methods

Various methods
Rockfall Block Analysis

- Rock Mass Properties
- Loading Conditions
- Excavation Geometry & support

PoF Monte Carlo Simulation
Joint Roughness

- 1 POLISHED
- 2 SMOOTH PLANAR
- 3 ROUGH PLANAR
- 4 SLICKENSIDED
- 5 SMOOTH UNDULATING
- 6 ROUGH UNDULATING
- 7 SLICKENSIDED STEPPED

Joint Fill

- 1 GOUGE THICKNESS > AMP
- 2 GOUGE THICKNESS < AMP
- 3 SOFT SHEARED FINE
- 4 SOFT SHEARED MEDIUM
- 5 SOFT SHEARED COARSE
- 6 NON-SOFTENING FINE
- 7 NON-SOFTENING MEDIUM
- 8 NON-SOFTENING COARSE
- 9 STAINING

\[ \varphi = \arctan \left( \frac{J_r}{Ja} \right) \]

Barton
Rockfall

Block Analysis & Monte Carlo Simulation

Simple DFN process to generate blocks using joint data. >100 000 Blocks

Limit equilibrium analysis – Monte-Carlo > 100 000 blocks
Gravity fall, sliding, rotation – effect of support
Keeps track of the surface area exposed for normalisation

Unwedge image
Results
Rockfall
Frequency

Rockfall

Rockfall frequency per 100 m length of tunnel

Block Volume (m³)
Stress Damage

- Rock Mass Properties
- Loading Conditions
- Excavation Geometry & support

Stress Damage Numerical Analysis (Elastic & Elasto-plastic approaches)

PoF Various methods
Stress Damage

Data - GSI

Composite
10m intervals
Stress Damage

Data – Rock Strength

Hoek-Brown failure criterion

Laboratory tests

Fixed $m_i$
Variable UCS

![Graph showing stress-strain relationship](image.png)

![Histogram showing frequency and probability](image2.png)
Stress Damage

Numerical Analysis

Elastic (Johan Wesseloo)
• Unit stress elastic boundary element analyses (Map3D)
• Stress super-position (mXrap)
• Strength Factor (mXrap)
• Monte-Carlo (mXrap)

Depth of failure
Numerical Analysis

Stress Damage

Base case

“-”

“+”

Elasto-plastic

Depth of failure

Monte-Carlo Simulation not practical
Other probabilistic methods required

- Point Estimate method (PEM)
- Response Surface Method (RSM)
- Response Influence Factor (RIF)

Itasca
FLAC/UDEC (Fish/Python) or
RocScience
Phase2 / RS2 (built in functions only - PEM)
Stress Damage

PoF

Pof = 5%
Dof = 2.2m
Stress Damage

PoF = 5%

Use Binomial distribution to determine the probability of various lengths of tunnel damage

\[ Pr = \frac{n!}{k!(n-k)!} p^k (1-p)^{n-k} \]
Probability Distribution

Stress Damage

![Graph showing Stress Damage Probability Distribution with different symbols for Ramp and Primary](image-url)
Damage Loss Model

- Rock Mass Properties
- Loading Conditions
- Excavation Geometry & support

Rockfall Block Analysis

- Stress Damage Numerical Analysis (Elastic & Elasto-plastic approaches)

PoF Monte Carlo Simulation

PoF Various methods
Damage location

Access ramp = Immediate impact 100% of production affected
Sub-level drive = Immediate impact 30% of production affected
Primary stope drive = Possibly delayed impact 1/7 of production affected
Secondary stope drive = Delayed impact 1/6 of production affected

Example is Ramp
# Damage Loss Model

1. Cost of repair \( (\$/m \times \text{length affected}) \)
2. Production loss (duration of rehabilitation where access is prevented = rate of rehabilitation \( \times \text{length of damage} \) \( \times \text{daily tonnage} \times \$/\text{ton} \)

## Stope Production

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stope Height</td>
<td>30 m</td>
</tr>
<tr>
<td>Stope Width</td>
<td>10 m</td>
</tr>
<tr>
<td>Ring spacing</td>
<td>2 m</td>
</tr>
<tr>
<td>Ring volume</td>
<td>600 m³</td>
</tr>
<tr>
<td>Rings</td>
<td>1 Rings/day</td>
</tr>
<tr>
<td>Density</td>
<td>2.7 tonnes/m³</td>
</tr>
<tr>
<td><strong>Daily production</strong></td>
<td><strong>1620 tonnes</strong></td>
</tr>
</tbody>
</table>

## Financial

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grade</td>
<td>6 g/t</td>
</tr>
<tr>
<td>Conversion</td>
<td>31 g/ounce</td>
</tr>
<tr>
<td>Gold Price</td>
<td>1278 $/ounce</td>
</tr>
<tr>
<td>Revenue</td>
<td>247 $/tonne</td>
</tr>
<tr>
<td>Direct Cost</td>
<td>40%</td>
</tr>
<tr>
<td><strong>Loss</strong></td>
<td><strong>148 $/tonne</strong></td>
</tr>
<tr>
<td>Daily Loss</td>
<td>0.240 $M</td>
</tr>
<tr>
<td>30 Day loss</td>
<td>7.2 $M</td>
</tr>
<tr>
<td>365 Day loss</td>
<td>87.6 $M</td>
</tr>
</tbody>
</table>

## Evaluation of damage costs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tunnel length considered (m)</td>
<td>200</td>
</tr>
<tr>
<td>Segment length (m)</td>
<td>10</td>
</tr>
<tr>
<td>Segments</td>
<td>20</td>
</tr>
<tr>
<td>Probability of segment failure (%)</td>
<td>5.0%</td>
</tr>
<tr>
<td>Impact on Daily production (%)</td>
<td>100%</td>
</tr>
<tr>
<td>Time until impact (days)</td>
<td>0</td>
</tr>
<tr>
<td>Rehabilitation Rate (m/day)</td>
<td>1</td>
</tr>
<tr>
<td>Rehabilitation cost ($/m)</td>
<td>1000</td>
</tr>
</tbody>
</table>
Risk Evaluation

Rock Mass Properties

Loading Conditions

Excavation Geometry & support

Stress Damage Numerical Analysis (Elastic & Elasto-plastic approaches)

Rockfall Block Analysis

PoF Monte Carlo Simulation

Damage Loss Model

Risk Evaluation

PoF Various methods

Various methods
Risk Evaluation

Expected losses ($M)

<table>
<thead>
<tr>
<th>Tunnel</th>
<th>Rockfalls</th>
<th>Stress Damage</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Access ramp</td>
<td>$1.92M</td>
<td>$2.41M</td>
<td>$4.33M</td>
</tr>
<tr>
<td>Primary stope drive</td>
<td>$0.02M</td>
<td>$1.78M</td>
<td>$1.80M</td>
</tr>
</tbody>
</table>
# Risk Evaluation

## Risk Matrix

<table>
<thead>
<tr>
<th>Probability of Occurrence</th>
<th>Insignificant &lt;$0.01M</th>
<th>Minor $0.01M-$0.10M</th>
<th>Moderate $0.10M-$1.0M</th>
<th>Major $1M-$10M</th>
<th>Catastrophic &gt;$10M</th>
</tr>
</thead>
<tbody>
<tr>
<td>Certain</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
<td>Extreme</td>
<td>Extreme</td>
</tr>
<tr>
<td>Likely</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
<td>High</td>
<td>Extreme</td>
</tr>
<tr>
<td>Possible</td>
<td>Low</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
<td>High</td>
</tr>
<tr>
<td>Unlikely</td>
<td>Low</td>
<td>Low</td>
<td>Medium</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Rare</td>
<td>Low</td>
<td>Low</td>
<td>Low</td>
<td>Medium</td>
<td>Medium</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Probability Description</th>
<th>Criteria</th>
<th>Probability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Certain</td>
<td>The event will occur. The event occurs daily</td>
<td>&gt;50%</td>
</tr>
<tr>
<td>Likely</td>
<td>The event is likely to occur. The event occurs monthly</td>
<td>10% to 50%</td>
</tr>
<tr>
<td>Possible</td>
<td>The event will occur under some circumstances. The event occurs annually</td>
<td>5% to 10%</td>
</tr>
<tr>
<td>Unlikely</td>
<td>The event has happened elsewhere. The event occurs every 10 years</td>
<td>1% to 5%</td>
</tr>
<tr>
<td>Rare</td>
<td>The event may occur in exceptional circumstances. The event has rarely occurred in the industry.</td>
<td>&lt; 1%</td>
</tr>
</tbody>
</table>
Risk Evaluation

Risk Matrix

- Extreme
- High
- Medium
- Low

- Ramp: Stress Damage
- Rockfalls
- Primary: Stress Damage
- Rockfalls
Factors to Consider

• Types of Uncertainty
  – Aleatoric variability
    • The natural randomness in a system (Data required)
  – Epistemic uncertainty
    • The scientific uncertainty due to limited data and knowledge Sources of Uncertainty (Engineering Judgement)

• Factors to consider
  – Incomplete rock mass data (estimates of confidence)
  – Scale variability
  – Uncertain stress field
  – Influence of major geological structures
  – Time dependant deterioration
  – Model bias (simplification and assumptions)
  – Human error during implementation

Occam’s Razor - increasing complexity does not necessarily increase understanding of the risk
Conclusions

- A preliminary risk based approach to ground support design has been developed
  - Rockfall and stress damage analyses
  - Probabilistic solution techniques
  - Damage Loss Model
  - Risk Evaluation
  - Process could be adapted to other analytical methods
Conclusions

• Probability Interpretation (Vick S.G., 2002)
  – Relative frequency approach:
    • The probability of an uncertain event is its relative frequency of occurrence in repeated trials or experimental sampling of the outcome.
  – Subjective, degree of belief approach:
    • The probability of an uncertain event is the quantified measure of one’s belief or confidence in the outcome, according to their state of knowledge at the time it is assessed.