Nuevas tendencias de la Minería Subterránea profunda Planeación, operación y estabilización del macizo rocoso

By

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Chair in Rock Mechanics
WA School of Mines, CRC Mining & Curtin University Australia
The overall objective is to characterize rock masses and their response to mining activities, so that *stable excavations* can be designed, constructed and supported.
Introduction

Flowchart of mine planning process (Villaescusa, 1998).
Introduction – Mining at depth

Conditions often become difficult beyond a 1000m or so

Golden Grove Mine, Western Australia (Thompson, 2011)
Maximum recovery – minimal dilution

Continuous extraction sequence required to avoid pillars

Golden Grove Mine, Western Australia (Thompson, 2011)
Mining method selection & infrastructure

Change of the mining method or infrastructure location

1000m

SLC/SLOS

SLOS
Geotechnical monitoring requirements

A need to understand the overall failure process and instability
Large scale geological discontinuities

The global stability may be controlled by large scale structures

Mount Charlotte Mine, Western Australia (Corskie, 2013)
Seismic response of large scale structures

The structures may become seismically active
Mining method multiple lift - sublevel open stoping

Used for tabular or massive – steeply dipping orebodies
Case study - sublevel open stoping at depth

Callie Mine, NT Australia (Graf, 2013)
Multiple lift - Sublevel open stoping

Primary-secondary extraction sequence

Original designed primary-secondary stoping sequence

Mining method changed a rib pillar method

Creation of large voids by firing secondary stopes into the primary stopes

Existing primary stope voids

Pillars created by leaving behind ore from secondary stopes

Final stopes (cavity monitoring survey)

Cavity monitoring survey

Section view, looking east

80247E +110m

Kernil Fault

Callie Mine, NT Australia (Graf, 2013)
Multiple lift - Sublevel open stoping

Cemented rock fill of stoping voids
In-situ stress measurements - a key requirement

Acoustic Emission from oriented core samples – No access required – only deep core
In-situ stress measurements - a key requirement

Orientation and magnitude with depth determination
- For all the stoping block areas planned

Principal Stress with Depth
Magnitude (MPa)

Depth below Surface (m)

Lantin North
Auron
Wilson Upper
Wilson Lower

Callie Mine, NT Australia (Graf, 2013)
Intact rock strength determination

For all rock types

UCS with depth

UCS (MPa)

Depth below surface (m)

UCS results for the Callie Boudin Chert in fresh rock (not weathered)

UCS results for the Magpie Schist in fresh rock (not weathered)
Intact rock strength determination

For all rock types
Intact rock strength determination

For all rock types

UCS results for the Callie Laminated Beds in unweathered rock

UCS results for the Auron Beds in unweathered rock
Joint set number and orientation – block shape

From development exposure and diamond drilled core
Joint condition determination

From development exposure and diamond drilled core
# Joint set characteristics

<table>
<thead>
<tr>
<th>Joint Set</th>
<th>Dip (°)</th>
<th>Dip Direction (°)</th>
<th>Average Spacing (m)</th>
<th>Average Trace Length (m)</th>
<th>Average Macro/Micro Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Kerril-parallel</td>
<td>65 (-17/+14)</td>
<td>160 (-26/+24)</td>
<td>0.5</td>
<td>3.5</td>
<td>Planar – Undulating / Rough</td>
</tr>
<tr>
<td>2</td>
<td>32 (-15/+13)</td>
<td>308 (+27)</td>
<td>0.6</td>
<td>1.7</td>
<td>Planar / Rough</td>
</tr>
<tr>
<td>3 Bayban-parallel</td>
<td>72 (-11/+12)</td>
<td>028 (-10/+9)</td>
<td>0.7</td>
<td>3.5</td>
<td>Planar – Undulating / Smooth – Rough</td>
</tr>
</tbody>
</table>

Callie Mine, NT Australia (Graf, 2013)
RQD from exploration core

Changes with depth
Correlation with large scale structures
Rock mass classification

Callie Mine, NT Australia (Graf, 2013)
Excavation performance under increased stress
Excavation performance under increased stress

<table>
<thead>
<tr>
<th>Load (kN)</th>
<th>INSTRON Compression (mm)</th>
<th>$\sigma_c/\sigma_{ave}$</th>
<th>$\sigma_c/\sigma_{max}$</th>
<th>Spalling on the left wall (4:18)</th>
<th>Spalling on the right wall (4:33)</th>
<th>Crush on the pillar (5:50)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>672</td>
<td>1.42</td>
<td>1271</td>
<td>1226</td>
<td>1584</td>
</tr>
<tr>
<td>$\sigma_c/\sigma_{max}$</td>
<td>-</td>
<td>2.22</td>
<td>1.17</td>
<td>2.28</td>
<td>2.28</td>
<td>1.22</td>
</tr>
<tr>
<td>$\sigma_c/\sigma_{ave}$</td>
<td>-</td>
<td>5.00</td>
<td>2.64</td>
<td>2.74</td>
<td>2.74</td>
<td>2.15</td>
</tr>
</tbody>
</table>

Start loading (0:00)
Ground support strategy for an increasing stress

\[ \sigma_1 = \text{In-situ main principal stress} \]
\[ \sigma_c = \text{Uniaxial Compressive Strength of intact rock} \]

- Heavy rockburst zone
- High stress
- Medium confining stress
- Low confining stress

\[ \frac{\sigma_c}{\sigma_{\text{max}}} \]

<table>
<thead>
<tr>
<th>Near Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.5 – 5.0</td>
</tr>
</tbody>
</table>
Ground support strategy for an increasing stress

The walls of the excavations become unstable due to vertical stress.

Time dependent slow deformation

Sudden, violent failure
Ground support strategy for an increasing stress

Rock bolting - with or without welded wire mesh
A generalized form of support effective for shallow to moderate depths.
Ground support strategy for an increasing stress

At greater depths bolts, shotcrete and mesh required for backs and walls.
Ground support strategy for an increasing stress

Fibrecrete energy dissipation is not enough under high stress conditions
Ground support strategy for an increasing stress

Fibcrecrete energy dissipation is not enough under high stress conditions
Ground support strategy for an increasing stress

Bolts + mesh embedded shotcrete + cables

Sudden failure
Ground support strategy for an increasing stress

Rock mass demand

<table>
<thead>
<tr>
<th>Demand category</th>
<th>Reaction pressure (KPa)</th>
<th>Surface displacement (mm)</th>
<th>Energy (KJ/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>&lt;100</td>
<td>&lt;50</td>
<td>&lt;5</td>
</tr>
<tr>
<td>Medium</td>
<td>100-150</td>
<td>50-100</td>
<td>5-15</td>
</tr>
<tr>
<td>High</td>
<td>150-200</td>
<td>100-200</td>
<td>15-25</td>
</tr>
<tr>
<td>Very High</td>
<td>200-400</td>
<td>200-300</td>
<td>25-35</td>
</tr>
<tr>
<td>Extremely High</td>
<td>&gt;400</td>
<td>&gt;300</td>
<td>&gt;35</td>
</tr>
</tbody>
</table>

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(Modified from Thompson et al, 2012)
Ground support strategy for an increasing stress

Example of low demand – unsupported lower walls
Ground support strategy for an increasing stress

Example of low to medium demand – fibrecrete and walls
Ground support strategy for an increasing stress

Example of low to medium demand – fibrecrete
Ground support strategy for an increasing stress

Example of high to very high demand – mesh embedded chain link
Ground support strategy for an increasing stress

WASM ground support design chart

Reinforcement types

- 2.4m 550MPa 20mm threaded bar – T20
- 2.4m 550MPa 20mm threaded bar – T20-no plate
- 2.4m 550MPa 20mm threaded bar – T20
- 2.4m 550MPa 20mm threaded bar – Secura T20 – resin
- 2.4m 550MPa 20mm threaded bar – Secura R27 – resin
- 2.4m 550MPa 25mm threaded bar – JTECH – resin-SE
- 2.4m 550MPa 20mm threaded bar – T20 – 1.0m centrally decoupled mine nut
- 2.4m 550MPa 20mm threaded bar – T20 – 1.0m centrally decoupled integrated nut/washer
- 2.4m 550MPa 20mm threaded bar – T20 – 1.0m centrally decoupled Posinut Bolt – resin
- 3.0m 280MPa 22mm threaded bar – Safegal – four buffer
- 3.0m 280MPa 22mm threaded bar – Safegal – two buffer
- 2.4m 280MPa 22mm threaded bar – Safegal – HC (weak grout)
- 2.4m 580MPa 22mm Garford solid yielding bolt Version 1
- 2.4m 580MPa 22mm Garford solid yielding bolt Version 2
- 2.4m 580MPa 22mm Garford solid yielding bolt Version 2 – resin
- 2.4m 580MPa 22mm Garford solid yielding bolt Version 2
- 2.4m 400MPa 22mm cone bolt >40 MPa grout
- 2.4m 400MPa 22mm cone bolt >40 MPa LE grout
- 2.4m 400MPa 22mm cone bolt >40 MPa HE grout
- 2.4m 400MPa 22mm cone bolt 25 MPa grout
- 3.0m Roofex 12.3mm – cement grout
- 3.0m 450MPa D-Bolt 22mm – cement grout
- 3.0m Yield-Lok 17.2mm – 77mm yield length - cement grout
- 2.6m Cablebolt-A 15.2mm – plain strand – 2.6m toe anchor rupture
- 2.6m Cablebolt-A 15.2mm – plain strand – 1.5m toe anchor
- 2.6m Cablebolt-A 15.2mm – plain strand – 1.0m toe anchor
- 2.6m Cablebolt-A 15.2mm – plain strand – 0.5m toe anchor
- 3.4m Cablebolt-A 15.2mm – plain strand – 0.6m collar slid
- 3.4m Cablebolt-A 15.2mm – plain strand – 1.7m centrally debonded
- 3.4m Garford yielding cablebolt - Version 2
- 3.4m Garford yielding cablebolt - Version 2
- 3.0m Cablebolt-C 15.2mm – plain strand – two buffer LC
- 3.0m Cablebolt-C 15.2mm – plain strand – four buffer LC
- 3.0m Cablebolt-C 15.2mm – plain strand – damaged wire
- 2.6m cablebolt – 1.8m average toe anchor
- 2.6m cablebolt – 1.8m average toe anchor
- 2.6m cablebolt – 1.8m average toe anchor

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Energy dissipated (kJ)

Deformation at failure (mm)

Very significant damage to surface support

High

Medium

Low

Rock Mass Demand

Reinforcement Design Region

Failure by rupture

High impact testing
Ground support strategy for an increasing stress

Excavation shape at depth will require changes

Square

Shanty back

Oval

Semi-circular (flat floor)
Conclusions

• Rock mass characterization from exploration core.
• Selection of mining method with geotechnical considerations.
• Geotechnical monitoring for global stability.
• Strength vs induced stress ratios become unfavourable.
• Mode of failure anticipation required.
• Ground support strategy for high energy dissipation.
• Change of excavation shape may be required.