Mining Deeper: The Importance of Understanding Brittle Failure Mechanisms

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Presentation Outline

- Motivation & Challenges

- Lessons Learned
  - Importance of Geological Characterization
  - Importance of Behaviour Model (Brittle Failure)
  - Importance of Confinement

- Need for New Tools
  - Continuum
  - Discontinuum

- Conclusions and Looking Forward
Block Cave 101: Economy of Scale

Data from: USGS/Brook Hunt/CRU (2009)

- Copper Price
- Operating Costs

- Age of the Giant Porphyries
- Development of Block Caving

Renewables are 5 times more copper intensive than conventional systems.
Block Cave 101: Economy of Scale

Going Bigger: Block Cave Mining

UNPRECEDENTED SIZE

Current Operations

Step Change in Scale

Being constructed/advance planning

Daily Production (tpd)

Relative Frequency

Historic/Present Caves

Future Caves

1880 1900 1920 1940 1960 1980 2000 2020 2040

YEAR

TONNES PER DAY

Climax

Salvador

Kiruna

Mount Isa

San Manuel

Miami

Ridgeway

Olympic Dam

Andina

Freeport IOZ/DOZ

Henderson

Kidd Creek

Kidd Creek

"Conventional"

underground

Open pits

Super caves

NPM

Oyu Tolgoi

Cadia

ET

Resolution

Grasberg

El Teniente

Argyle

Super caves

NPM

Oyu Tolgoi

Cadia

ET

Resolution

Grasberg

El Teniente

Argyle

Increased geological uncertainty

Increased parameter uncertainty

Increased model uncertainty
Block Cave 101: Mining Method

Hormazabal et al. (2018)
Block Cave 101: Mining Method

Hormazabal et al. (2018)
Moss (2014): The next generation of “super caves” planned to ramp up copper production to 400,000 tpd over the next 15 years, will involve the construction of more than 1000 km of development tunnels, 12,000 drawpoints and 3,000 pillars to manage and support.
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Getting the Characterization Right
Getting the Characterization Right

(Rio Tinto Best Practice Guidelines)
Challenges: Caving in Stronger Rock (Fragmentation)

Paredes et al. (2018)
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Getting the Behaviour Model Right

Experience Base = Lower Stresses or Weaker Rock under Moderately Higher Stresses

Hoek (2001)
Getting the Behaviour Model Right

Martin (1997)

Kaiser et al. (2000)

<table>
<thead>
<tr>
<th>Behaviour Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low In-Situ Stress ($\sigma_3 / \sigma_h &lt; 0.15$)</td>
</tr>
<tr>
<td>Massive (JMR &gt; 75)</td>
</tr>
</tbody>
</table>

- Linear elastic response
- Falling or sliding of blocks and wedges
- Building failure and collapse from the excavation surface
- Brittle failure adjacent to excavation boundary
- Localized brittle failure of intact rock and movement of blocks
- Localized brittle failure of intact rock and movement of blocks
- Squeezing and swelling rocks, failure of plastic continuum

Kaiser et al. (2000)
Interlude:

What We’ve Learned About Brittle Failure
Reference Case – AECL Underground Research Laboratory

Martin (1997)

240 m Level

420 m Level

300 Level

130 Level

420 m Level
Brittle Fracture – Early Paradox

At the atomic level, the development of interatomic forces in a crystal lattice is controlled by the atomic spacing which can be altered by means of external loading ... 

... on extension, the material fractures in tension when the interatomic force is exhausted (i.e., the theoretical tensile strength)
Brittle Fracture – Early Paradox

However, in compression ...

... displacement is countered by an inexhaustible repulsive force.

This suggests that interatomic bonds will only break when pulled apart (i.e., in tension), yet we know rock can fail in compression.
To explain this discrepancy, Griffith (1920) postulated that in the case of a linear elastic material, brittle fracture is initiated through tensile stress concentrations that develop at the tips of small, thin cracks randomly distributed within an otherwise isotropic material.
Fracture Initiation & Griffith Cracks
Brittle Fracture Observations - Initiation

Crack Initiation = 40% UCS

Spalling Initiation = 40% UCS

Eberhardt et al. (1998)

Martin et al. (1999)
Brittle Fracture Observations - Directionality

In a compressive stress field...

- Cracks propagate in the direction of the maximum principal stress ($\sigma_1$).
- In other words, they open in the direction of the minimum principal stress ($\sigma_3$).
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Importance of Confinement

Importance of Confinement

Eberhardt et al. (1998)
Importance of Confinement

Kaiser et al. (2000)
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Footprint Reliability
Fewer delays due to support rehabilitation; more consistent access to the drawpoints.

Support Vulnerability
Stress-induced bulking and damage to support resulting from excessive deformations.

Displacement-Based Support Design
Current State-of-Practice: Numerical Tools

Increasing Confinement

Paterson (1958)

failure occurs if:

\[ \tau_{\text{max}} \geq c + \sigma \tan \phi \]

tension cutoff

Mohr-Coulomb criterion

\[ \sigma_{\text{f}} = \frac{c + \sigma \tan \phi}{2} \]

\[ \sigma_{\text{f}} = \frac{c + \sigma \tan \phi}{2} \]
Current State-of-Practice: Numerical Tools

\[ \psi_1 = 0 \]

\[ \psi_2 = 20 \]

\[ \psi_3 = 40 \]

Dilation (\( \psi \)) affects both:
- extent/depth of failure
- displacement

Rahjoo & Eberhardt (2018)
Need for New Tools – Mechanism Focussed

σ₁

spalling and geometric bulking

Inner Zone  Outer Zone

shear through rock mass

σ₁

shear limit

spalling limit

damage initiation

σ₃

UCS/10
Need for New Tools – Mechanism Focussed

Diederichs (2002)
Need for New Tools – Perspective of Scale

Footprint Scale
Continuum Based
Footprint Reliability

Pillar Scale
Discontinuum Based
Support Vulnerability
New Brittle Failure Numerical Tools - Continuum

Diederichs (2002)

3D Confinement

Rahjoo & Eberhardt (2019)
3-D Extensional-Shear Fracturing Criterion

\[ \sigma_1 \sigma_3 > \text{UCS/10} \]

- **Shear Failure**
  - \( \sigma_1 \) > UCS/10
  - \( \sigma_3 \) < UCS/10

- **Spalling Limit**
  - \( \sigma_1 \) < UCS/10
  - \( \sigma_3 \) > UCS/10

**High Confinement**

**Low Confinement**

Rahjoo & Eberhardt (2019)
New Brittle Failure Numerical Tools – Continuum

Directional dilation
New Brittle Failure Numerical Tools – Continuum

Directional Dilation

Rahjoo & Eberhardt (2019)
New Brittle Failure Numerical Tools – Continuum

Continuum Based → Footprint Reliability

Hopkins et al. (2018)

initial state

Rahjoo & Eberhardt (2018)

after undercut advance
New Brittle Failure Numerical Tools - Discontinuum

Discontinuum Based → Support Vulnerability

Pillar Scale

Draw Drift

Pillar

Extract Drift

Bull Nose

Camel Back

Lavoie & Eberhardt (2019)

Intact and Vein Strength

Lavoie & Eberhardt (2019)
Brittle Failure Numerical Tools - Discontinuum

Lavoie & Eberhardt (2019)

Key Finding #1: Adding a small amount of support pressure (100 kPa) can have a significant impact on the performance of the excavation; however, increasing this pressure can have a less dramatic impact on limiting spalling damage and bulking.

Cave Stress Path Simulated

Stress

undercutting

post undercut

production

Time

DE-COMPRESSION 0.5 MPa

No Support

100 kPa Pressure

1 MPa

production

Stress

undercutting

post undercut

Time

Key Finding #1: Adding a small amount of support pressure (100 kPa) can have a significant impact on the performance of the excavation; however, increasing this pressure can have a less dramatic impact on limiting spalling damage and bulking.
Brittle Failure Numerical Tools - Discontinuum

Key Finding #2: The models have shown that it is crucial to install appropriate support before the undercut passes over the extraction level pillars (Stage 3 decompression).
These models have been used to establish that:

- The skin **bulks** during both loading and unloading.
- Unloading seems to cause more bulking than loading.
- Confinement is a controlling parameter.
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Conclusions

• As underground mines and tunnels push deeper, the risk related to geological uncertainty and especially model uncertainty becomes more pronounced. It must be understood that these projects are operating outside the current experience base.

• At these depths, strong rock becomes susceptible to stress-induced brittle failure, which is driven by extensional fracturing as opposed to the more familiar shear. Fracture initiation leading to spalling can begin at stresses of 50% UCS; this process is highly sensitive to confinement.

• Experiences to date have proven that our existing “shear-based” design tools are insufficient for robust prediction and engineering design under these conditions.
Conclusions

• New tools are now being developed that can capture the initiation of spalling and the directional dilation of the subsequent post-peak bulking process. These warn of the potential for highly localized stretching and shearing developing across the support system, threatening its integrity.

• To address this, there is a need to shift to a deformation-based ground support design strategy. Support must be designed to prevent the spalling rock from bulking during load cycling, keeping the skin as stiff and strong as possible, as well as adding confinement to suppress the spalling process preventing further fracturing deeper into the rock mass.
1. **Orebody Knowledge** to improve characterization of the rock mass properties for more accurate fragmentation prediction and draw control, with opportunities to cross-link to ore grade.

2. **Grade Management** through sensor-based sorting to evaluate bulk and particle sorting systems for integration with underground mobile equipment and material handling systems.

3. **Cave Mine Design** to facilitate effective and efficient underground sorting systems and improved footprint reliability.

4. **Cave-to-Mill** involving the integration of processes to enhance mine and mill performance and bulk sorting to provide selectivity options and reliable feed to the process plant.

5. **New Measurement Technologies** through implementation of advanced instrumentation to monitor drawpoint muck grade, cave loads, and excavation displacements and pillar bulking.

6. **Hazard Management Strategies** to more effectively monitor, forecast and mitigate undercut and extraction-level hazards such as rock bursting and mud rush, to improve safety and production reliability by reducing interruptions.
Thank You