Simulation of Paste Backfill Material with *FLAC3D* at Kittilä

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Amélie Ouellet  
Thierry Lavoie  
Antti Pyy  
Louis-Philippe Gélinas  
Véronique Falmagne  
Patrick Andrieux

A2GC, Canada  
A2GC, Canada  
Agnico Eagle, Kittilä Mine, Finland  
Agnico Eagle, Technical Services, Canada  
A2GC, Canada

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Presentation Overview

1. Introduction
   – Kittilä Mine overview
   – Context of the modelling project
   – Modelling workflow

2. Back-analysis methodology
   – FLAC3D model presentation
   – Model calibration

3. Key findings for paste backfill numerical implementation
   – Effects of liquid-to-solid paste placement initialization
   – Effects of strength variation along the stope height

4. Forward analysis example
   – Case presentation
   – Comparison between model predictions and field behaviour

5. Conclusions
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Kittilä Mine Overview

- Operator: Agnico Eagle Mines Limited
- Lapland region of Northern Finland
- Largest primary gold producer in Europe
- Hosts Agnico Eagle’s largest mineral reserves

- Achieved commercial production in May 2009
- Open-pit completed in 2012
- Now underground-only operation
- Mine-life estimated through 2035

Source: AEM, Technical Report, 2010
Context of the Modelling Project

- Malfunction at the paste backfill plant
- Five primary stopes filled with poor-quality paste backfill material
- Paste dilution observed after poor-quality paste exposed during secondary mining
- Project objective: evaluate mining options for mining next the poor-quality paste

Source: A2GC, Technical Report, 2019

Paste UCS Test Results for Stopes 1 to 5

- Plant test results below 600 kPa
- High variability in the plant test results

Tests on in situ samples significantly weaker

Source: AEM, Kittilä Mine

High variability in the plant test results
Modelling Workflow

**Calibration**

**Back-analyses** of mining next to poor-quality paste

Better understand the poor-quality paste properties and how to simulate them

**Forward analyses**

**Undercut paste** model

Evaluate the feasibility of removing poor-quality paste by undercutting it and letting it collapse into a void below (to replace with good quality paste)

**Mining between poor-quality paste**

Evaluate the maximum area of poor-quality paste that can be exposed and remain stable (in the case it is impossible to remove it)

**Rock “skin” model**

Evaluate the minimum dimensions of stable retaining thin rock pillars (“skins”) – tradeoff study with previous case
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**FLAC3D Model Presentation**

- Small-scale **gravity-loaded** model
- Two stopes included in the model for the back-analysis:
  - One primary stope filled with poor-quality paste (in red)
  - One abutting secondary stope to be excavated (in **green**)
- Paste material modelled as a **strain-softening Mohr-Coulomb** material
- Surrounding rock mass modelled as an elastic material
- Paste density of 1.2, rock mass density of 2.7
- Young’s modulus of $\approx 200$ MPa for the paste and 1 GPa for the rock mass
Model Calibration

• Calibration case: a secondary stope (in green) mined adjacent to poor-quality paste (in red)

• Available data: two CMS scans indicating paste dilution into the secondary stope

• Methodology: adjustment of the paste strength (in terms of UCS) and strength gradation to best reproduce the failure shown by the CMS scans
  – Available UCS tests used to guide the calibration process

• Model indicators used to conclude on the fitting of the failure shape: velocity and yielding/plasticity
Modelling Results with the Calibrated Properties

- Gridpoints with a **velocity** greater than 1e-5 at equilibrium closely matched both CMS shapes
- A band of shear failure generally followed the CMS shapes – the poor-quality paste remained largely intact below that shear band
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Key Findings for Paste Backfill Implementation

1. Paste should **initially be placed in the model as a fluid**, which subsequently solidifies into a solid material
   - “Fluid” in **FLAC3D**: cohesionless and tensionless material, with only friction
2. To best represent the poor-quality material placed at Kittilä, it was found its strength had to **vary along the stope height**
   - Stronger paste at the bottom of the stope and weaker paste at the top
Effect of Liquid-to-Solid Paste Placement Initialization

- **Sequence** followed to place paste backfill in the model:
  - Initially placed as a **fluid** (cohesionless and tensionless, with only friction)
  - Then turned into a **solid** material (with the calibrated mechanical properties)
- This affects the initial **stress distribution** throughout the fill material mass

**Figure Legend**
Zone Major principal stress
- 0 kPa
- 10 kPa
- 20 kPa
- 30 kPa
- 40 kPa

**Figure Legend**
Zone Minor principal stress
- 0 kPa
- 5 kPa
- 10 kPa

- Directly installed as a solid
- Installed as liquid -> solid
- Stresses more uniform throughout the volume and overall lower
- Narrower core confinement corridor
- More banded stress distribution and overall higher internal loads
The initial load distribution differences lead to **different** mechanical behaviours once the paste is exposed.

With paste placed directly as a solid, the fitting with the CMS is not as good as with the liquid-to-solid paste placement.
Effect of Strength Variation Along Stope Height

- UCS values that best matched the CMS data:
  - **284 kPa** at the bottom of the stope and **13 kPa** at the top
- Example of a non-conclusive calibration attempt with a unique UCS value of 142 kPa:
  - Final failure shape wider than the actual CMS-derived shape
  - No failure predicted after partial mucking
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Case Presentation

• Poor-quality paste was placed inadvertently in stope

• Blasting (leaving a corner shoulder) and partial mucking of stope was done

• It was then attempted to remove the poor-quality paste by letting it collapse into the void created by partially mucking Stope by
  – Blasting the remaining shoulder, plus a 5m-high x 3m-long x 7m-wide undercut at the corner of the poor-quality paste; or,
  – Making the initial 5m-high undercut 10m-high instead
Comparison of Model Predictions and Field Observations

• Undercutting of paste in the FLAC3D model to evaluate whether the paste would fail based on velocity and yielding/plasticity indicators
  - If the paste volume was found to be in failure, it was assumed that it could be mucked and then replaced by stronger paste
• No paste collapse was predicted from the simulations
• Field results confirmed that assessment: the paste remained stable

Figure Legend
Zone Plastic State
- None
- Shear
- Shear-p
- Tension-p
- Tension-n
- Shear-p
- Tension-p

Geometry
- DXFs

No significant paste failure predicted in either case
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Conclusions

1. To best reproduce the stress distribution in paste material, placing the paste in the model should be done in two steps:
   - First, the paste should be considered as a viscous fluid (cohesionless and tensionless, with only friction) and cycled to equilibrium in that state.
   - It should then be turned into a solid and equilibrated again.
   - That “two-step” paste placement (liquid, then solid) allowed for a more easily attained match with CMS scans than with a more typical “one-step” paste placement (solid only).
   - This modelling approach should be applied regardless of the paste strength whenever the focus of the model is the exposed paste behaviour.
Conclusions

2. For the poor-quality backfill and geometrical conditions at Kittilä, the **strength of the paste had to be varied along the stope height** for the field behaviour to match the numerical simulations
   - The paste had to be stronger at the bottom and weaker at the top
   - Consolidation effects may partially explain such a strength distribution
   - Not yet very well understood