Simulation of Paste Backfill Material with *FLAC3D* at Kittilä

5th International Itasca Symposium on Applied Numerical Modeling

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February 18, 2020

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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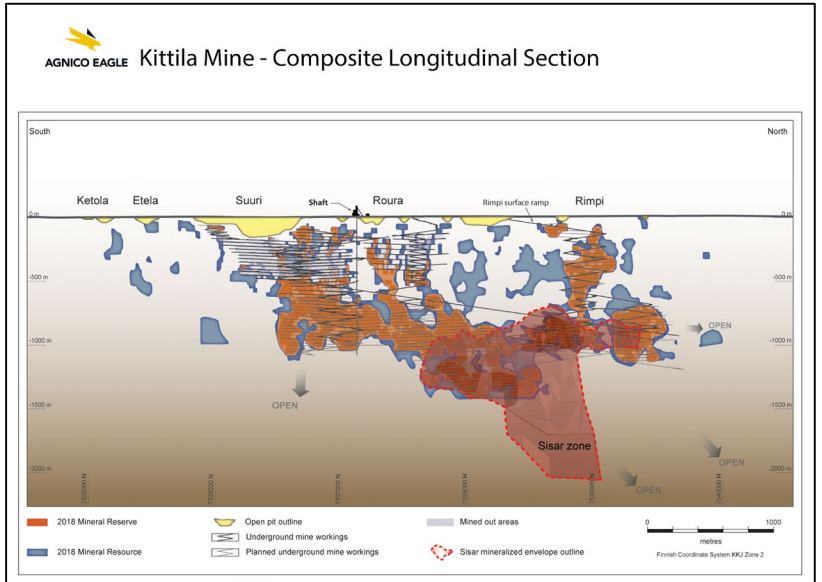
Kittilä Mine Overview

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



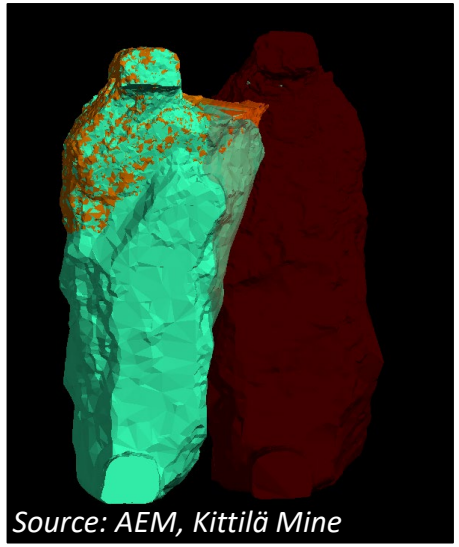
Source: AEM website

- 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

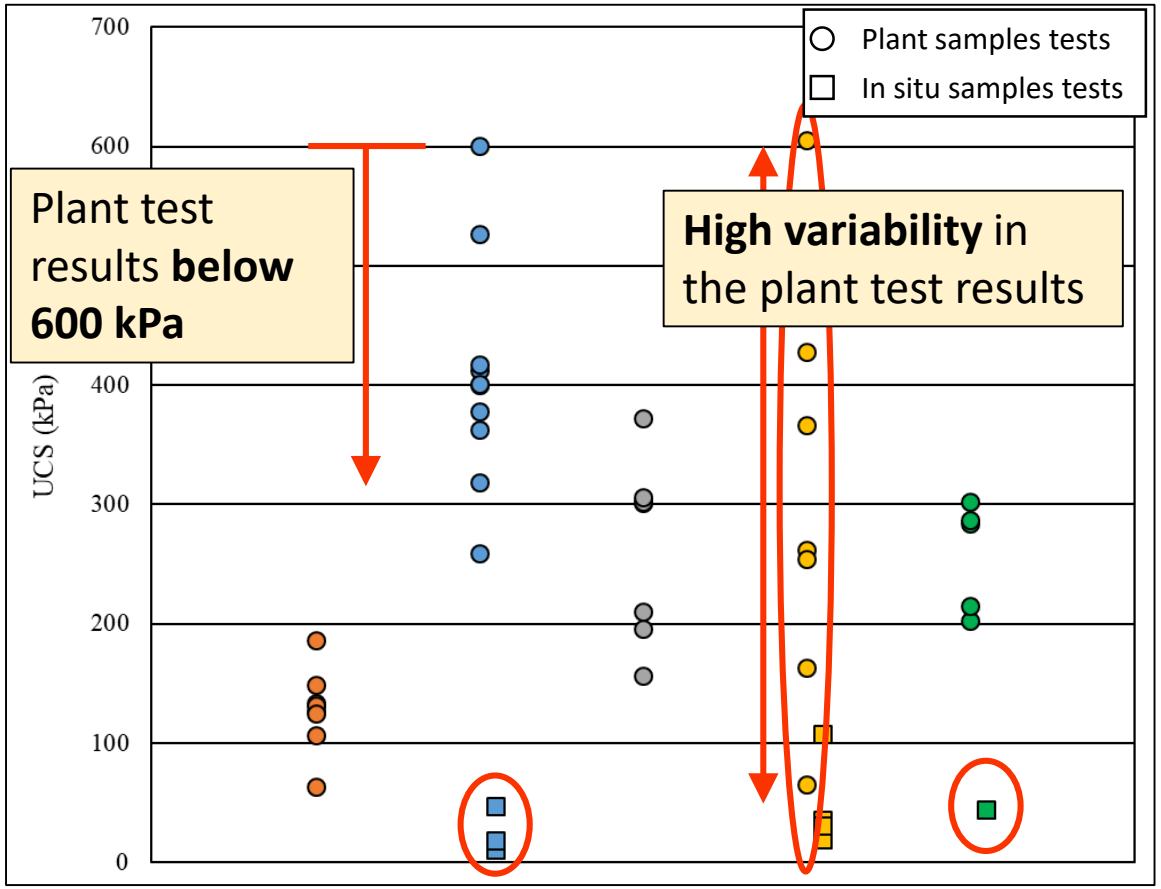
- Malfunction at the paste backfill plant
- Five primary stopes filled with **poor-quality paste backfill material**
- **Paste dilution** observed after poor-quality paste exposed during secondary mining



Source: AEM, Kittilä Mine

- Project objective: evaluate **mining options** for mining next the poor-quality paste

Paste UCS Test Results for Stopes 1 to 5



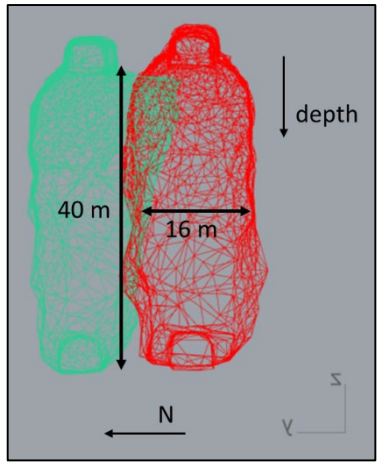
Source: A2GC, Technical Report, 2019

Tests on ***in situ*** samples significantly **weaker**

Modelling Workflow

Calibration

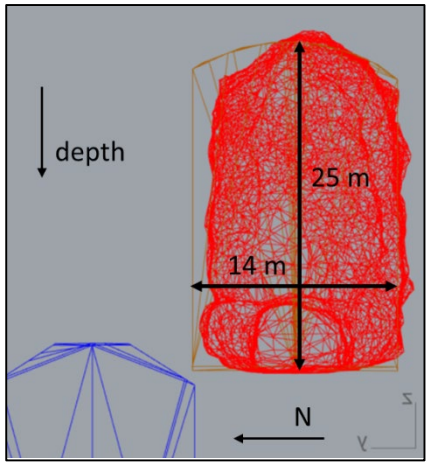
Back-analyses of mining next to poor-quality paste



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

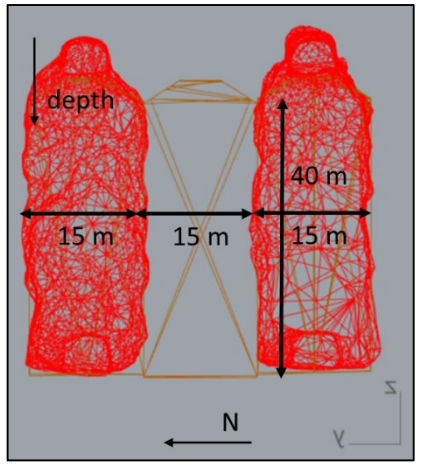
Forward analyses

Undercut paste model



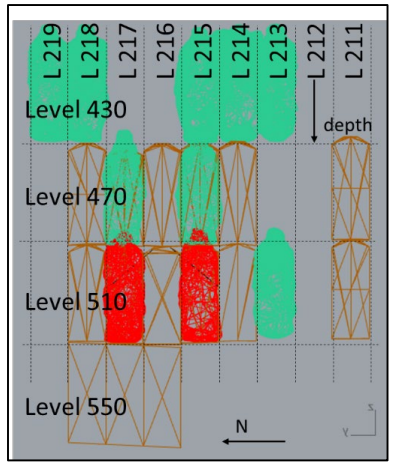
Evaluate the feasibility of removing poor-quality paste by undercutting it and letting it collapse into a void below (to replace with good quality paste)

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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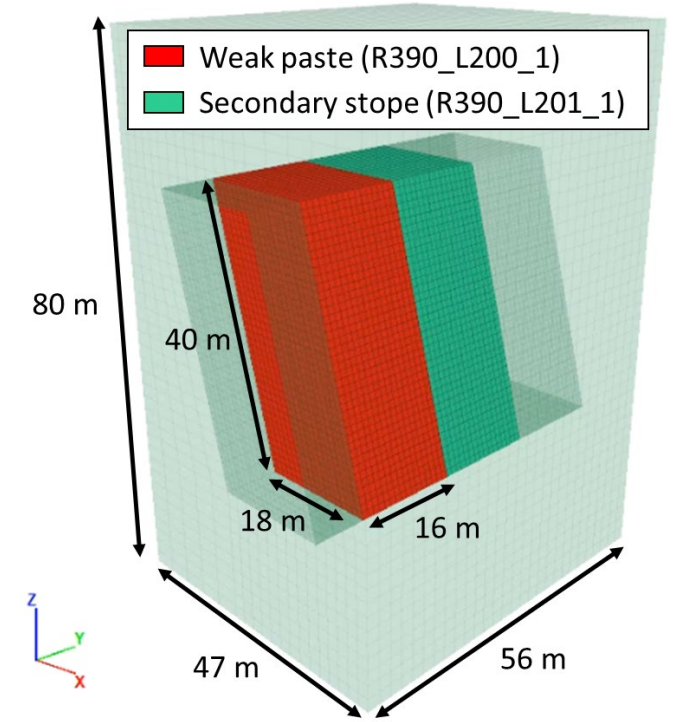
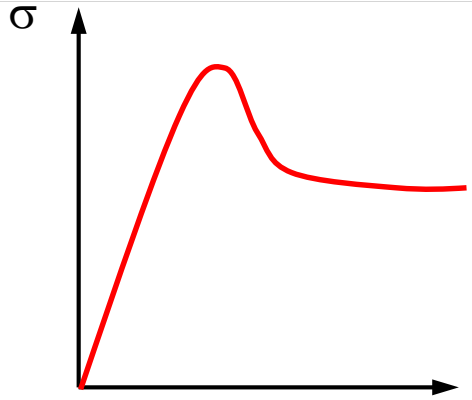
FLAC3D Model Presentation

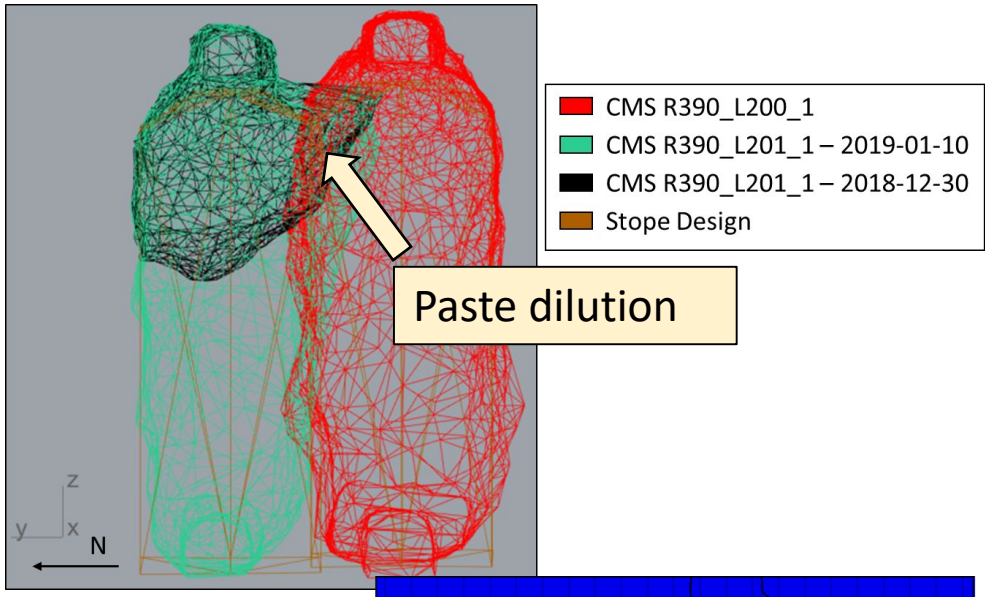
- Small-scale **gravity-loaded** model
- Two stopes included in the model for the back-analysis:
  - One primary stope filled with poor-quality paste (in red)
  - One abutting secondary stope to be excavated (in green)
- Paste material modelled as a **strain-softening Mohr-Coulomb** material
- Surrounding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

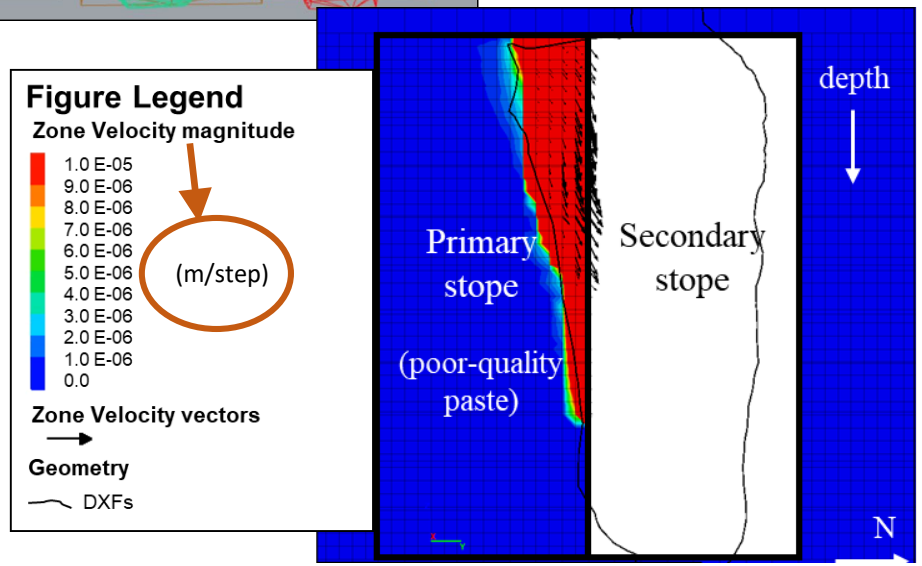




Model Calibration

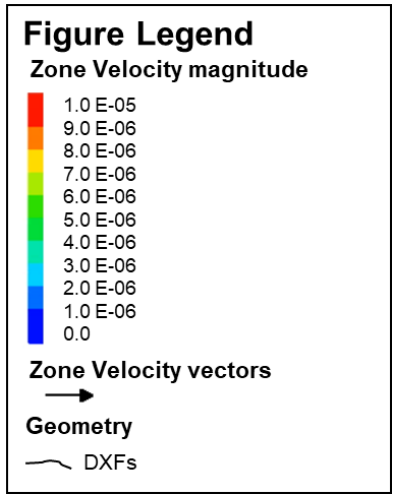
- Calibration case: a secondary stope (in green) mined adjacent to poor-quality paste (in red)
- Available data: **two CMS scans** indicating paste dilution into the secondary stope
- Methodology: **adjustment of the paste strength** (in terms of UCS) and **strength gradation** to best reproduce the 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**

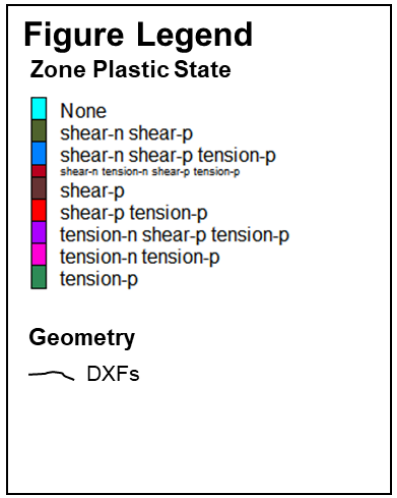




Modelling Results with the Calibrated Properties

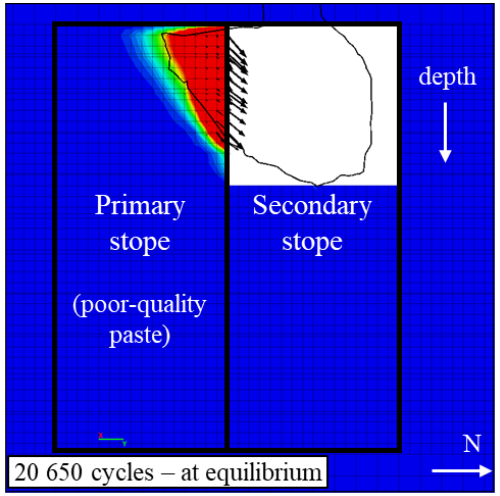
- Gridpoints with a **velocity** greater than 1e-5 at equilibrium **closely matched both CMS shapes**
- **A band of shear failure generally followed the CMS shapes** – the poor-quality paste remained largely intact below that shear band

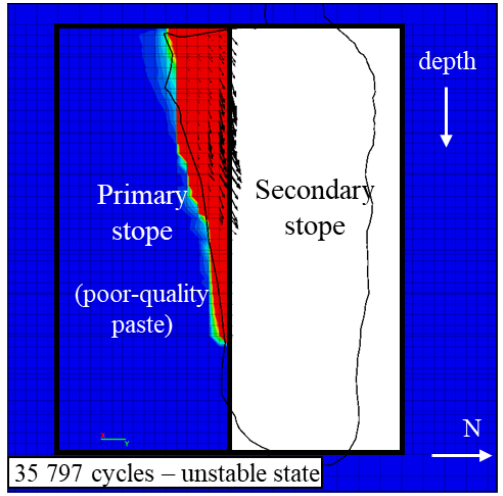


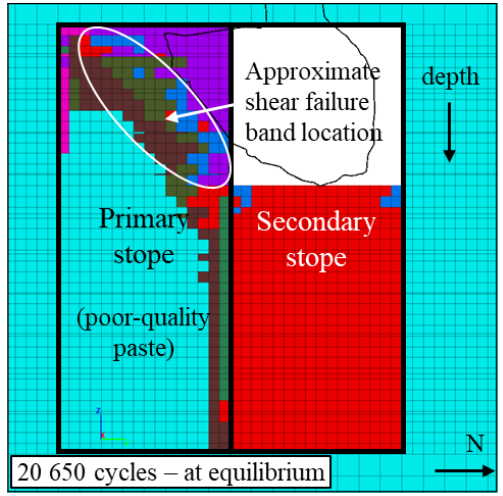


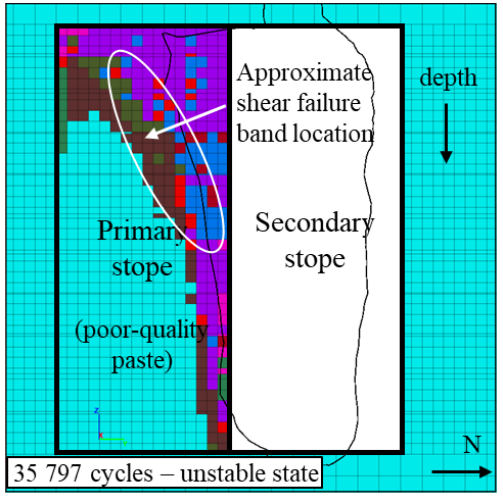
After partial mucking

After complete mucking









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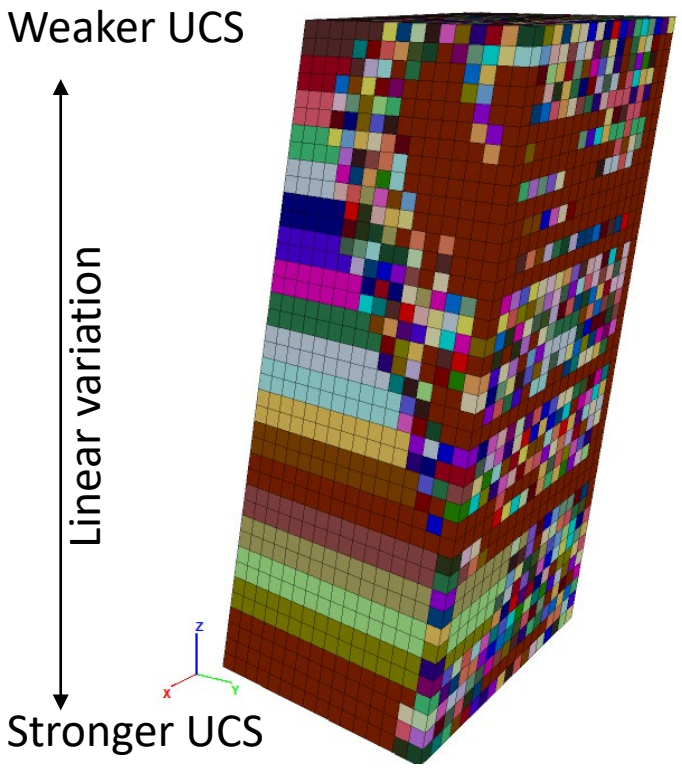
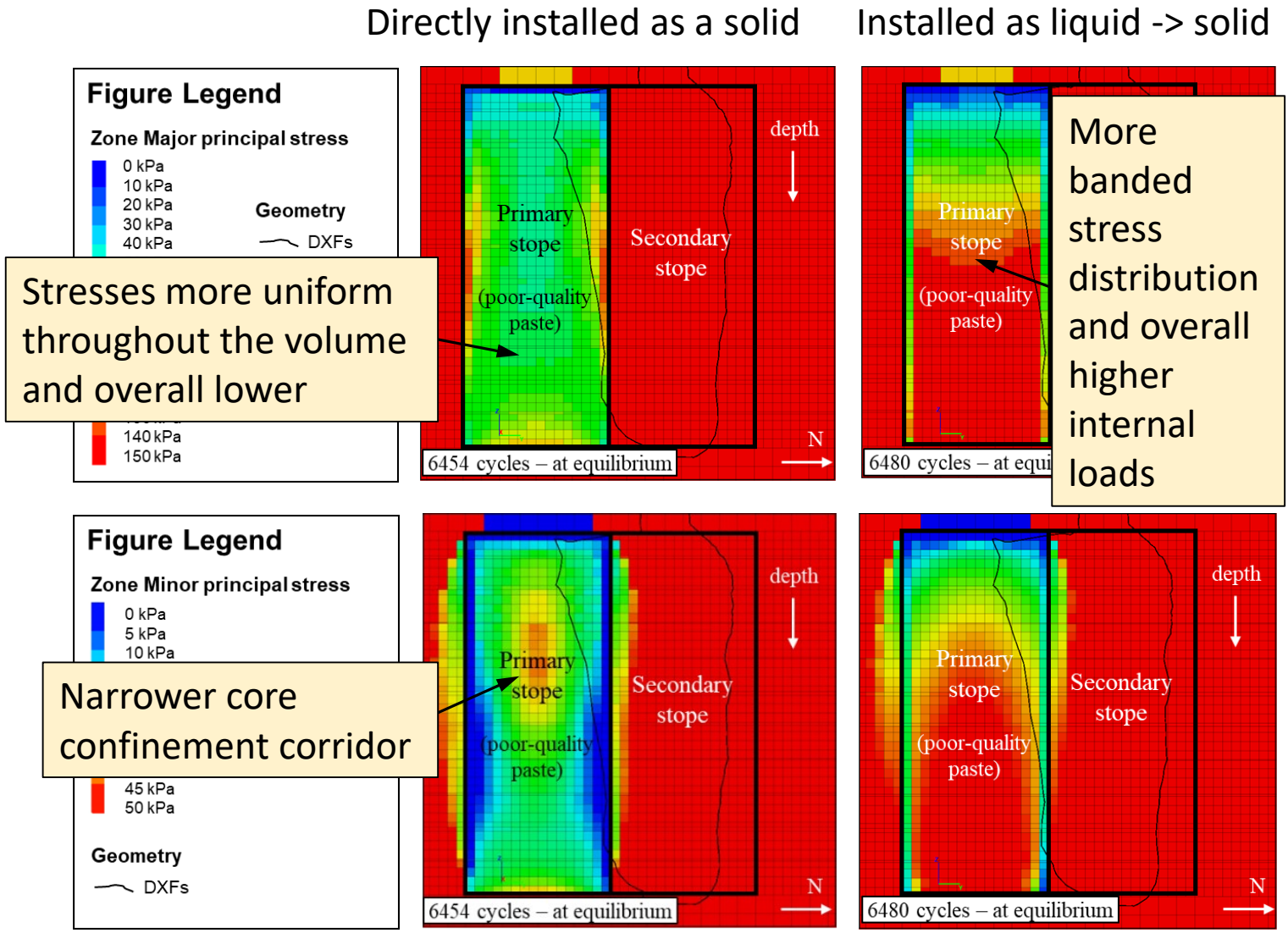
Key Findings for Paste Backfill Implementation

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



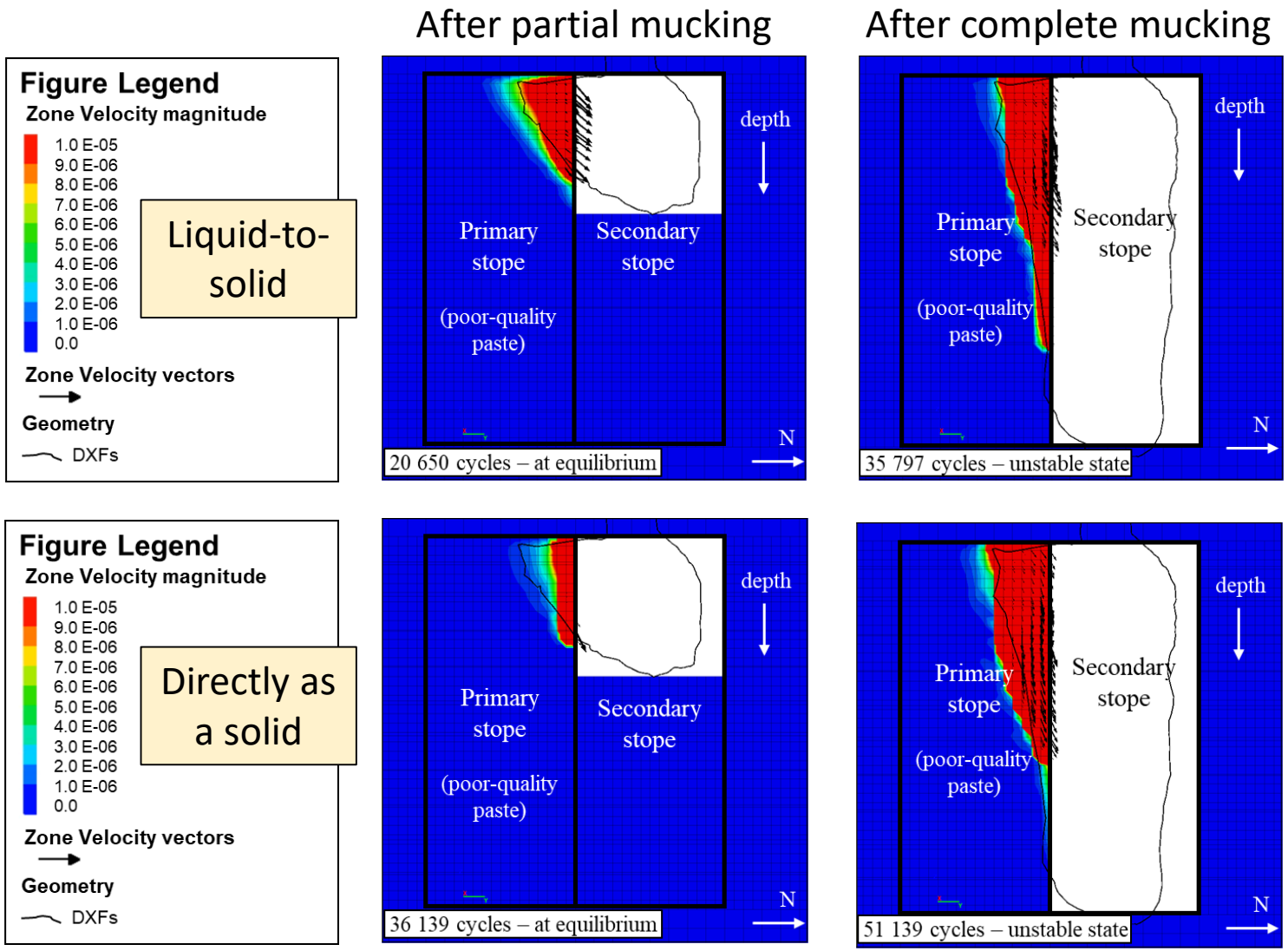
Effect of Liquid-to-Solid Paste Placement Initialization

- **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



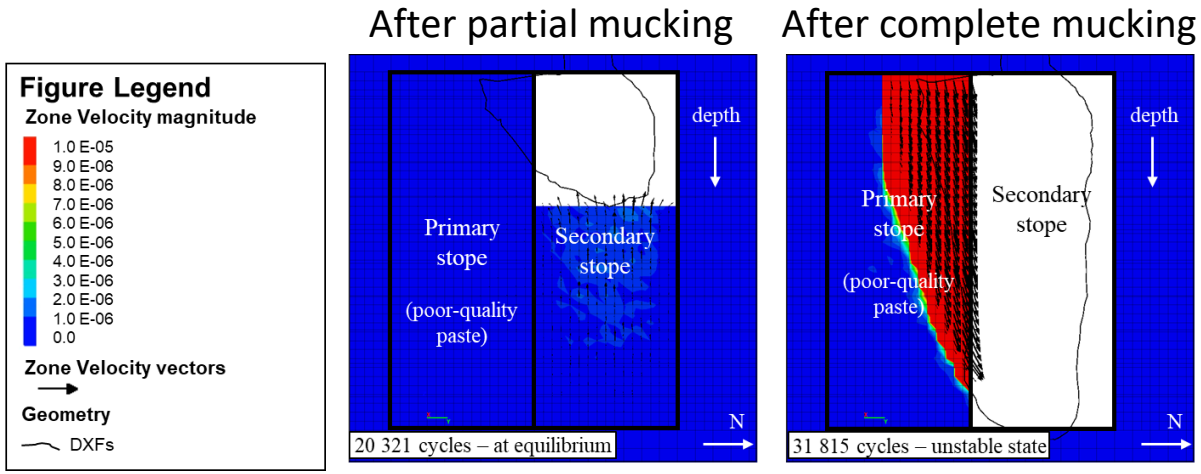
Effect of Liquid-to-Solid Paste Placement Initialization

- 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

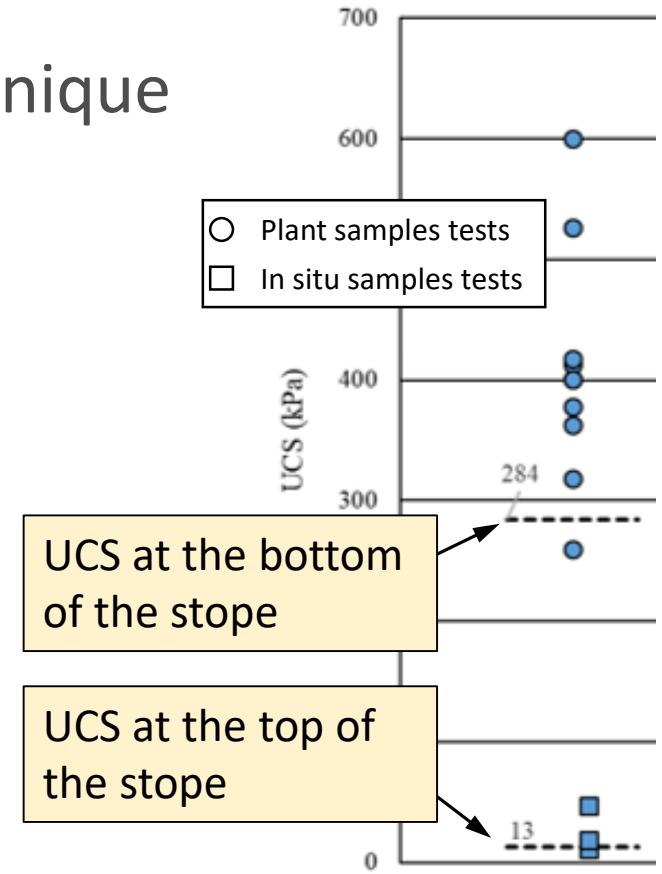


Effect of Strength Variation Along Stope Height

- 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



Comparison between UCS values that best match the CMS data and available UCS tests



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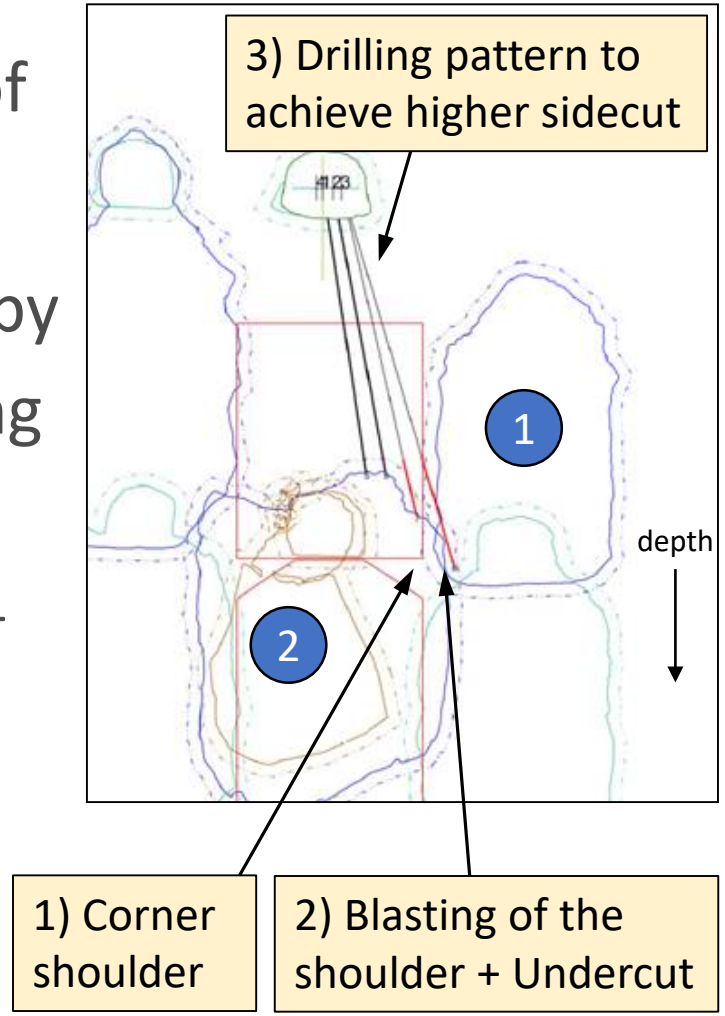
Case Presentation

- Poor-quality paste was placed inadvertently in stope 1
- Blasting (leaving a **corner shoulder**) and partial mucking of stope 2 was done
- It was then attempted to **remove the poor-quality paste** by letting it collapse into the void created by partially mucking Stope 2 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

Source: AEM, Kittilä Mine



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

5 m high undercut

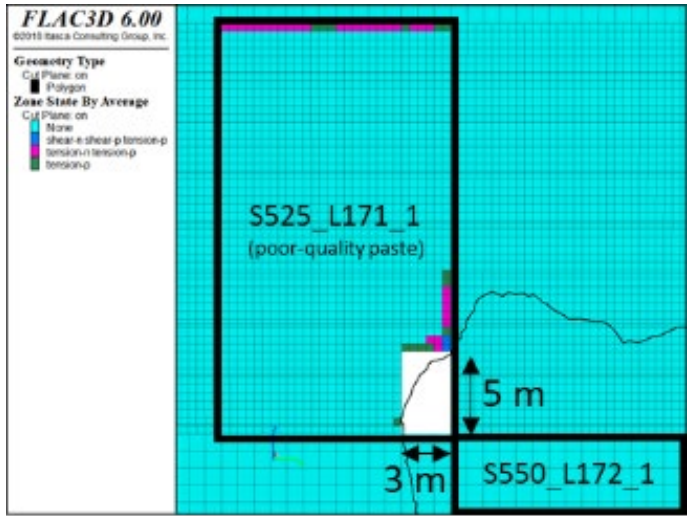


Figure Legend

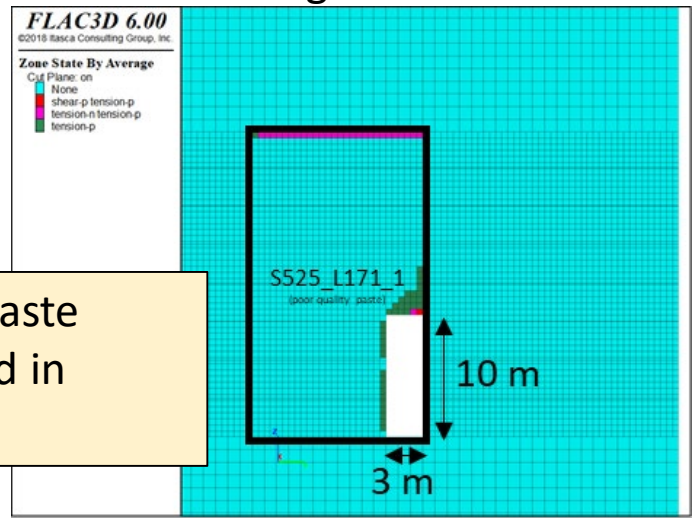
Zone Plastic State

- None
- shear-n shear-p
- shear-n shear-p tension-p
- shear-n tension-n shear-p tension-p
- shear-p
- shear-p tension-p
- tension-n shear-p tension-p
- tension-n tension-p
- tension-p

Geometry

- DXFs

10 m high undercut



No significant paste failure predicted in either case

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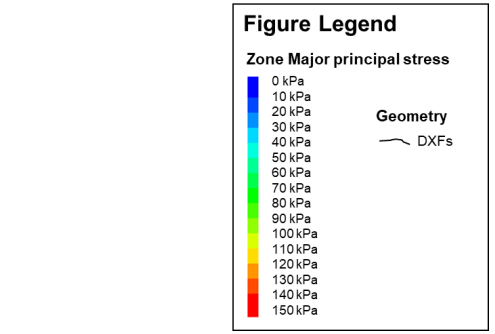
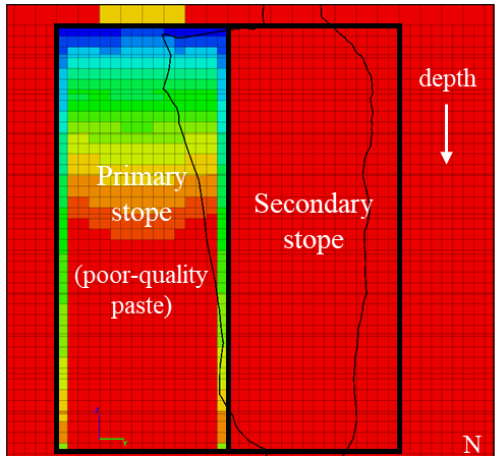
Conclusions

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