Analysis of Large-Scale Pit Slope Stability — The Aitik Mine Revisited

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Things we all know…

• Design of overall slopes is important – for open pits of all scales – and further underlined by the push towards larger, and deeper pits.

• Evolution of design tools:
  ❖ From simple empirical and limit equilibrium methods to sophisticated numerical computer modelling.
  ❖ Rapid increase in computer capacity, but also an increased understanding of the behaviour of large-scale slopes.
  ❖ Still severely data- and knowledge constrained…

• Illustration of design development and current state-of-the-art using the Aitik open pit mine as a case in point.
The Aitik Mine

- Owned and operated by Boliden (from the start)
- Mineralization discovered in the 1930s
- Mining commenced 1968 – Boliden’s first open pit
- Currently the largest metal open pit mine in Europe
The Aitik Mine 1968 – 2 Mtpa (ore)
Early 70’s – 6 Mtpa (ore)
2000 – 18 Mtpa (ore)
2010 – 36 Mtpa (ore)

- Workshop
- Mill
- Conveyor belts
- Railway terminal
- Crusher
Today – 40 Mtpa (ore)
3000 x 1000 m, 420 m depth, main pit + satellite pit

Main pit hangingwall
Geological setting

North

Aitik area
Geological legend

Quaternary
187 Overburden

Lina granite suite
125 Pegmatite

Haparanda suite
56 Diorite
57 Gabbro
84 Hornblende banded gneiss

Hydrothermal rocks
325 Feldspar-Epidote zone
121 Amphibolite
155 Muscovite schist
116 Biotite schist
83 Biotite gneiss
87 Amphibole-biotite gneiss

Aitik pit outline
Salmijarvi planned pit outline
Mineralization

1000 m
• Generally strong, metamorphic rock, with some weaker units (biotite/muscovite schist)
• Medium to good rock quality; poor quality in schist units
Structural Characteristics

- Well-developed foliation + cross-joints and vertical jointing
- Hangingwall contact = old thrust fault with clay
- No other large-scale structures identified
The early stages…

- First major design study in 1976 with follow-up in 1985
- Bench design based on structural control; Double-benching (2 x 15 m) with offset chosen to match foliation dip
- Catch bench width based on original Ritchie criterion – 11 m for 90% of the cases
- Overall slopes not assessed
Blasting can make things better…

• Problems:
  ❖ Vertical blast damage
  ❖ Quality control / hole deviation
  ❖ Local crest failures & bench widths not attained

• Solutions:
  ❖ Blast damage model (PPV)
  ❖ More buffer rows
  ❖ Pre-split with decoupled charges
Large-scale slope stability at Aitik…

• Issues for hard rock slopes:
  ❖ No failure observations = no calibration of properties possible (except that failure should not develop for current mining geometries)
  ❖ Failure may be rapid and uncontrollable (brittle rock)

• Remedies:
  ❖ Develop methodology for modeling and parameter assessment and apply to other slopes with failure
  ❖ Design methodology must be conservative => use residual strength parameters
Large-scale and 2D – at Aitik…

- Project on large-scale slope stability in hard rocks (1990s) & revision of overall slope angles:
  - Empirical case study database
  - Updated geomechanical model
  - 2D numerical modeling – continuum models, rock mass strength + residual strength parameters + ubiquitous joints (foliation)

- Results
  - Stability assessment to 500 m depth
  - Increase of interrramp and overall angles (+5°) with drainage program
  - Additional modeling for deeper (750 m) pit => additional drainage
2D and deeper – and the importance of "disturbance"

• New strategic plan – and deeper mining (2015-2016)!
• New analyses:
  ❖ Numerical modeling, Factor-of-Safety calculations, 2D (& 3D)
  ❖ Perfectly-plastic material model (no softening; peak strength = residual strength); Hoek-Brown material model
  ❖ Rock mass strength values estimated empirically using characterization (GSI) and Hoek-Brown failure criterion
  ❖ Experiences and practices from Itasca analysis of large pit slope used to supplement and refine estimates
  ❖ Acceptance criterion: FoS for the Overall Slope Angle > 1.2
2D and deeper – and the importance of "disturbance"…

• Design values for \textit{GSI} and \textit{UCS}:
  
  \begin{itemize}
  \item mean – 0.5 std.dev
  \item Corresponds to 30-35 percentile
  \item Accounts for heterogeneity in large-scale rock masses, and the ability for the rock to fail through the weaker components (based on experience and empirical evidence)
  \end{itemize}

• Variation of \textit{D} (disturbance factor) with depth
  
  \begin{itemize}
  \item $D=1.0$ everywhere proven too conservative
  \item Blast damage highest close to slope face
  \item Stress relief close to slope face
  \item Possible stress damage at depth
  \end{itemize}
2D and deeper – and the importance of "disturbance"…
2D and deeper – and the importance of "disturbance"…

DESIGN PROFILE A

- Current Pit
- Previously Planned Final Pit
- Level 750/800/850 m Pit
2D and deeper – and the importance of "disturbance"…

- Groundwater conditions:
  - Partly depressurized in upper portion; face seepage in lower portion
  - Scenario 1: Depressurized 100 m horizontal distance (upper 2/3 of slope height)
  - Scenario 2: Depressurized 150 m horizontal distance (upper 2/3 of slope height).
# Results & design recommendations

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<thead>
<tr>
<th>HW overall slope angle [°]</th>
<th>Pit bottom [level]</th>
<th>Depressurization [m]</th>
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<tbody>
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<td>800 m</td>
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<td>54 *</td>
<td>600 m</td>
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* Middle-southern portion (lower final slope heights)
2D or 3D? Or both?

• How conservative are 2D-analyses?

• 3D-check for Aitik geometry:
  ❖ Simplified slope, undrained conditions
  ❖ $\text{FoS (3D)} = 2.0 \Leftrightarrow \text{FoS (2D)} = 1.2$ for the same case

• Geometry matters (a lot)!
Aitik findings....

- Increased reliability in bench slope design
  - Presplit blasting on footwall (inclined, 70°) and for modified ramp design
  - Increased safety of benches; maintained catch bench design
  - Revised acceptance criteria

- Improved interramp slope design
  - Increase on footwall interramp slope angle from improved blasting
  - Implemented allowed maximum interramp height = 200 m (6–7 double benches)
  - Rock mass stability => steeper interramp angles allowed

- Overall pit slope design
  - Verified overall pit slope angles: 47° for footwall; 54° for hangingwall, for a maximum pit depth of 850 m
  - Depressurized conditions required (150 m horizontal distance)
The future…

• Analytical methods are standard for bench-scale design
• Numerical modeling remains the preferred tool for large-scale stability assessment
  ❖ 3D models, DFN input, coupled (water-stress) modeling, etc. are all increasingly used
  ❖ Computational speed less of an issue…cloud computing emerging!?
• Advances in data collection not on par with advances in modeling capabilities
  ❖ Are we using the right tools? Volumetric coverage?
  ❖ Is there "unconventional" data to be used? As "proxies" for rock mechanics parameters?
The future…

• Validation efforts required:
  ❖ Partial validation is also of value!
  ❖ Acceptance criteria for validation
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