STRUCTURAL CONTROL ON STRESS VARIABILITY AT FORSMARK

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SKB is the Swedish Nuclear Fuel and Waste Management Company

- Responsible for management and safe final disposal
- Site selected in 2009
- Construction application for repository submitted in 2011
- Located in Forsmark, Sweden
- Construction to take ca. 10 years
- Ca. 6000 canister capacity
- Depth ca. 470 m
SITE CHARACTERIZATION

• Began in the 1970’s
• Geological, hydrological, ecological and social impacts studied
• On-going investigations include:
  • Geology
  • Thermal properties
  • Rock Mechanics
  • Hydrogeology
  • Hydrogeochemistry
  • Transport properties
• Resulted in regional and local geological models
• Rock mass quality good, stiff, strong and homogeneous
• Lower quality largely related to fault zones (110)
**IN SITU STRESS STATE**

- Good understanding required for safe final disposal
- Fennoscandian area dominated by plate tectonics:
  - Mid-Atlantic ridge-push
  - Collision of the Eurasian and African plates in the alps
- Glaciation effects significant
- Thrust fault conditions promoted shear of brittle fault zones
- Stress state affected
OBJECTIVES & METHODS

- Better understanding of observed variation
- Verification of rock and fault parameters

- Current stress interpretation (Martin 2007) based on 130 overcoring and 240 hydraulic stress measurements
- Indicates NW-SE orientation of $\sigma_H$
- Mean magnitudes of $\sigma_H$ and $\sigma_h$ 41 and 23 MPa, respectively
GEOMETRY

• Simulations performed using 3DEC
• Performed in two phases
  • Phase 1:
    • Planar & undulating fault zone geometry
    • Shear strength
  • Phase 2:
    • Affect of thrust simulation
    • Thrust orientation varied
    • Glaciation simulated

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GEOMETRY / ZONING
SIMULATION PARAMETERS

- Isotropic and elastic rock mass
- Divided into four domains
  - Main rock mass
  - Three fracture domains
- Fault zone parameters varied in individual cases
- Friction and cohesion maintained after failure

<table>
<thead>
<tr>
<th>Parameter</th>
<th>kn</th>
<th>ks</th>
<th>coh</th>
<th>fric</th>
<th>ten</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(MPa/mm)</td>
<td>(MPa/mm)</td>
<td>(MPa)</td>
<td>(°)</td>
<td>(MPa)</td>
</tr>
<tr>
<td>Deformation zone</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All, except Singö</td>
<td>80</td>
<td>20</td>
<td>0.7</td>
<td>36</td>
<td>0.001</td>
</tr>
<tr>
<td>Singö</td>
<td>0.2</td>
<td>0.01</td>
<td>0.4</td>
<td>31.5</td>
<td>0.001</td>
</tr>
</tbody>
</table>
TARGET *IN SITU* STRESS STATE

- Full gravitational water pressure applied
- Variable excess pore pressure applied when simulating glaciation

<table>
<thead>
<tr>
<th>Depth range</th>
<th>$\sigma_h$</th>
<th>$\sigma_h$ trend</th>
<th>$\sigma_h$ trend</th>
<th>$\sigma_v$</th>
</tr>
</thead>
<tbody>
<tr>
<td>(m)</td>
<td>(MPa)</td>
<td>(°)</td>
<td>(°)</td>
<td>(MPa)</td>
</tr>
<tr>
<td>0-150</td>
<td>19+0.008z</td>
<td>145</td>
<td>11+0.006z</td>
<td>55</td>
</tr>
<tr>
<td>150-400</td>
<td>9.1+0.074z</td>
<td>145</td>
<td>6.8+0.034z</td>
<td>55</td>
</tr>
<tr>
<td>400-600</td>
<td>29.5+0.023z</td>
<td>145</td>
<td>9.2+0.028z</td>
<td>55</td>
</tr>
</tbody>
</table>

$z$ is depth below rock surface in metres
Glacial stress evolution

- **sH**
- **sh**
- **sV**
- **Ice thickness**

**Simulated phases**
- **Start of simulation**
- **Forebulge**
- **Maximum**
- **Edge passing**
PHASE 1

- Seven cases as both undulating and planar = 14 cases
- Largely varied fault zone shear strength: $\phi = 10 - 36^\circ$, $c = 0.3 - 0.7$ MPa
- Applied in situ stress directly
PHASE 2

- Lower stress values with narrow variation in Phase 1 -> boundary thrust
- Glaciation cycle also added
- Only undulating geometry
- 15 cases
RESULTS: PHASE 1

- **Planar**: Max 0.5 m
- **Undulating**: Max 0.8 m

**Cumulative magnitude of slip (m)**

<table>
<thead>
<tr>
<th>Depth range (m)</th>
<th>Planar</th>
<th>Undulating</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 100</td>
<td>400 m</td>
<td>1600 m</td>
</tr>
<tr>
<td>100 - 200</td>
<td>200 m</td>
<td>1200 m</td>
</tr>
<tr>
<td>200 - 300</td>
<td>100 m</td>
<td>800 m</td>
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<tr>
<td>300 - 400</td>
<td>40 m</td>
<td>400 m</td>
</tr>
<tr>
<td>400 - 500</td>
<td>0 m</td>
<td>0 m</td>
</tr>
<tr>
<td>500 - 600</td>
<td>0 m</td>
<td>0 m</td>
</tr>
</tbody>
</table>
RESULTS: PHASE 1

- $\phi 36^\circ$ & 0.7 MPa
- $\phi 20^\circ$ & 0.3 MPa
RESULTS: PHASE 2

- Planar vs Undulating geometry
- Effect of glaciation with undulating geometry
RESULTS: PHASE 2

- > ± 20 MPa
- ± 15 – 20 MPa
- ± 10 – 15 MPa
- ± 5 – 10 MPa
- ± 5 MPa

- ± 75° – ± 90°
- ± 60° – ± 75°
- ± 40° – ± 60°
- ± 20° – ± 40°
- ± 20°
CONCLUSIONS

• The measured stress state can be considered reliable:
  o Best match with observed variation using thrust
  o Glaciation disturbances required as well
  o Undulating fault geometry recommended

• Resulting mean stresses insensitive to parameters

• Lower yet realistic parameters mainly increase variation

• Fairly good correlation with stress measurements

• Low magnitudes near the surface possible → low stress measurements not to be discarded

• High magnitudes possible, but not to the level observed → some measurements affected by heat → reliability ranking for all stress measurements in progress