Rock Engineering for an Underground Storage Facility in Singapore

Dr Zhou Yingxin
Underground Technology & Rock Engineering Programme
Defence Science & Technology Agency
Email: zyingxin@dsta.gov.sg

Outline

- Brief project introduction
- Site characterisation and rock mass classification
- Tunnel design and construction
- Instrumentation and monitoring
- Conclusions
A Completed Cavern

Site Characterisation for the UAF

We don't take everything for Granite!
What Is Site Characterisation

- Engineering geological investigation of the rock, rock discontinuities and rock mass at site and in laboratory
- Integral part of the engineering design process for any projects involving the ground
- Important for layout planning, support design and costing
- Also an important tool for construction safety

Phases of Site Characterisation

- Desk studies and site reconnaissance
- Site investigations
- Data analysis and geological modelling
- Reporting
Desk Studies and Reconnaissance

- Acquire maps, papers, air photographs, imagery and satellite data
- Site visits and renaissance to confirm data and identify areas where engineering difficulties may exist and areas for focused investigation

Site Investigations

- Rock material and rock mass properties
- Discontinuities and their conditions (joints, faults, shear zones)
- Ground water and water pressure
- In-situ stress
## Techniques for Site Investigation

- Geological mapping (exposure and discontinuities)
- Geophysical surveys (detective work)
- Exploratory drilling (soil drilling and diamond core drilling)
- In-situ testing (rock mass properties)
- Laboratory testing (rock material properties)

## Geophysical Surveys

- Seismic refraction and reflection
- Electrical resistivity
- Coupled seismic reflection (good vertical resolution) and electrical resistivity (good horizontal resolution) strongly recommended
- Obtains data on overburden thickness, bedrock elevation, seismic velocities of geological layers, and major geological structures
Methods of Investigation for UAF

<table>
<thead>
<tr>
<th>Type</th>
<th>Methods</th>
<th>Objective</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drilling</td>
<td>Soil boring; diamond core drilling</td>
<td>Overburden, and rock cores</td>
</tr>
<tr>
<td>Surface geophysical</td>
<td>Seismic refraction/reflection; electric resistivity tomography</td>
<td>Main geological structures; overburden depth</td>
</tr>
<tr>
<td>surveys</td>
<td>Borehole logging; seismic logging; borehole camera acoustic imaging;</td>
<td>Ground temperature; Seismic velocities; joints; ground temperature; Seismic velocities; joints; and permeability; geological structures</td>
</tr>
<tr>
<td>and testing</td>
<td>impression packer; borehole radar; Lugeon tests; rising head/falling</td>
<td></td>
</tr>
<tr>
<td></td>
<td>head tests; cross-hole tomography</td>
<td></td>
</tr>
<tr>
<td>Laboratory tests</td>
<td>Point load; uniaxial/triaxial compression; Brazil tensile; 3-point</td>
<td>Mechanical properties of intact rock and rock joints</td>
</tr>
<tr>
<td>In situ stress</td>
<td>flexural</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Hydraulic fracturing; 3-D overcoring</td>
<td></td>
</tr>
</tbody>
</table>

Seismic Refraction

When a sound wave crosses an interface between layers of two different velocities, the wave is refracted.
Seismic Reflection

By measuring the arrival time at successive surface locations we can produce a profile.

Electrical Resistivity

Electrical conductivity (resistivity) can also be measured by applying a current directly into the ground through a pair of electrodes.
Cross-hole Tomography

Cross-hole Tomography

Cross hole Tomography
Borehole Radar Image

Borehole Radar Imaging
Vertical Seismic Profiling

Damaged dry wall

Un-damaged wall
Composite Geological Profile

Core Drilling - Fresh Granite
## Intact Rock Properties

<table>
<thead>
<tr>
<th>Properties</th>
<th>Range</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cm³)</td>
<td>2.62 ~ 2.67</td>
<td>2.65</td>
</tr>
<tr>
<td>Uniaxial compressive strength (MPa)</td>
<td>108.09 ~ 224.89</td>
<td>163.83</td>
</tr>
<tr>
<td>Young’s modulus (GPa)</td>
<td>37.10 ~ 111.25</td>
<td>65.87</td>
</tr>
<tr>
<td>Poisson’s ratio</td>
<td>0.14 ~ 0.35</td>
<td>0.24</td>
</tr>
<tr>
<td>Cohesion (MPa)</td>
<td>—</td>
<td>24.51</td>
</tr>
<tr>
<td>Internal friction angle (°)</td>
<td>—</td>
<td>59.02</td>
</tr>
<tr>
<td>Point load index</td>
<td>5.6 ~ 16.1</td>
<td>8.7</td>
</tr>
<tr>
<td>Brazil tensile strength (MPa)</td>
<td>8.46 ~ 14.30</td>
<td>11.71</td>
</tr>
<tr>
<td>Three-point tensile strength (MPa)</td>
<td>13.25 ~ 27.30</td>
<td>19.94</td>
</tr>
</tbody>
</table>

---

## Core Drilling - Weathered Granite

---

---

---
Outcrop of a Weathered Trench

Weathered Trenches

<table>
<thead>
<tr>
<th>Trench</th>
<th>Strike</th>
<th>Extent, m</th>
<th>Depth, m</th>
<th>Weathering Grade</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1</td>
<td>SN to NE30°</td>
<td>750</td>
<td>39</td>
<td>II, III</td>
</tr>
<tr>
<td>T2</td>
<td>NNW to NE30°</td>
<td>950</td>
<td>80</td>
<td>II, III, IV</td>
</tr>
<tr>
<td>T3</td>
<td>NE25</td>
<td>900</td>
<td>47</td>
<td>II, III</td>
</tr>
</tbody>
</table>
Predominant Sub-vertical Joints

Rock Joints

- Quarry wall mapping; Acoustic imaging; Impression packer; Video camera; borehole radar

Acoustic imaging & impression packer

Borehole radar
### Geometries of Rock Joints

<table>
<thead>
<tr>
<th>Joint Set</th>
<th>Video logging</th>
<th>Impressio n packer</th>
<th>Acoustic imaging</th>
<th>Borehole radar</th>
<th>Qry wall mapping</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub-vertical</td>
<td>310/70</td>
<td>278/70</td>
<td>233/74</td>
<td>239/80</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>311/77</td>
<td>308/71</td>
<td>110/79</td>
<td>9/83</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>68/79</td>
<td>178/83</td>
<td></td>
</tr>
<tr>
<td>Sub-horizontal</td>
<td>98/6</td>
<td>0/0</td>
<td></td>
<td>23/10</td>
<td>231/11</td>
</tr>
<tr>
<td>Medium dip angle</td>
<td>115/37</td>
<td></td>
<td>282/65</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>292/55</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Rock Joint Properties

<table>
<thead>
<tr>
<th>Joint conditions</th>
<th>Friction Angle, $\phi$ ($^\circ$)</th>
<th>Cohesion, $C$ (KPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Freshly fractured and dry</td>
<td>45.6</td>
<td>258</td>
</tr>
<tr>
<td>Freshly fractured and saturated</td>
<td>42.6</td>
<td>172</td>
</tr>
<tr>
<td>Freshly fractured and dry (weathered rock)</td>
<td>36.8</td>
<td>183</td>
</tr>
<tr>
<td>Natural and dry</td>
<td>36.5</td>
<td>266</td>
</tr>
<tr>
<td>Natural and saturated</td>
<td>33.4</td>
<td>108</td>
</tr>
<tr>
<td>Mineral filled and dry</td>
<td>32.5</td>
<td>71</td>
</tr>
<tr>
<td>Mineral filled and saturated</td>
<td>27.3</td>
<td>52</td>
</tr>
<tr>
<td>Weathered and dry</td>
<td>27.6</td>
<td>200</td>
</tr>
<tr>
<td>Weathered and saturated</td>
<td>20.1</td>
<td>136</td>
</tr>
</tbody>
</table>
Characteristics of Rock Joints

- Two dominant sub-vertical joint sets (9-70 deg N & 230–310 deg N)
- One major near-horizontal joint sets
- Vertical strips of densely jointed rock
- Seismic velocity of densely jointed rock about 80% of that in massive rock
- Reduction of shear strength of about 8-16% even for mineral filled joints

Permeability

<table>
<thead>
<tr>
<th>Type</th>
<th>Permeability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil</td>
<td>$10^{-05} - 10^{-06}$ cm/s</td>
</tr>
<tr>
<td>Heavily weathered rock</td>
<td>$10^{-06}$ cm/s</td>
</tr>
<tr>
<td>Jointed rock mass</td>
<td>$10^{-08} - 10^{-09}$ cm/s</td>
</tr>
</tbody>
</table>

>> No major water inflow expected during construction
In situ Stress

- Stresses before excavation (virgin stress)
- Vertical stress $\sigma_v = \gamma H$
- Horizontal stress $\sigma_h = K \sigma_v$
- Strong influence of local variations
- Estimate of average horizontal stress factor:
  
  $$K = 3 - H/500 \text{ (for depth < 1000 m)}$$
  $$K = 9/8 - H/800 \text{ (for depth > 1000 m)}$$

<table>
<thead>
<tr>
<th>Test Method</th>
<th>Hydraulic Fracturing</th>
<th>3-D Overcoring</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Stress, Mpa</td>
<td>Orientation</td>
</tr>
<tr>
<td>Vertical stress</td>
<td>2.25</td>
<td>---</td>
</tr>
<tr>
<td>Maximum horizontal stress</td>
<td>7.3</td>
<td>13°</td>
</tr>
<tr>
<td>Minimum horizontal stress</td>
<td>4.56</td>
<td>103°</td>
</tr>
</tbody>
</table>

**Horizontal stress ratio:** $\sigma_v : \sigma_{hmin} : \sigma_{hmax} = 1:2:3$
Summary of Geological Properties

- No major tectonic faults
- Three-layer geological profile
- Deep weathering trenches
- Sub-vertical strips of densely jointed rock
- Favourable high horizontal stresses
- Relatively low permeability
- Rock mass generally good to very good for cavern construction

Geological Model

- Three layer formation
  - Residual Soil
  - Weathered granite
  - Fresh granite
- Weathering trenches & dense joint strips
Rock Mass Classification - Q system

- Rock Tunnelling Quality Index:

\[ Q = \frac{\text{RQD}}{\text{Jn}} \left( \frac{\text{Jr}}{\text{Ja}} \right) \left( \frac{\text{Jw}}{\text{SRF}} \right) \]

Relative block size: (RQD/Jn)
Inter-block shear strength: (Jr/Ja)
Active stress: (Jw/SRF)

<table>
<thead>
<tr>
<th>Q Value</th>
<th>Rock Mass Quality</th>
<th>Percent, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01 – 0.1</td>
<td>Extremely poor</td>
<td>1.9</td>
</tr>
<tr>
<td>0.1 – 1.0</td>
<td>Very Poor</td>
<td>3.7</td>
</tr>
<tr>
<td>1 – 4</td>
<td>Poor</td>
<td>5.8</td>
</tr>
<tr>
<td>4 – 10</td>
<td>Fair</td>
<td>13.6</td>
</tr>
<tr>
<td>10 – 40</td>
<td>Good</td>
<td>51.8</td>
</tr>
<tr>
<td>40 – 100</td>
<td>Very Good</td>
<td>19.3</td>
</tr>
<tr>
<td>&gt; 100</td>
<td>Extremely Good</td>
<td>3.8</td>
</tr>
</tbody>
</table>
Rock Mass Classification

Very Good 19%

Extremely Good 4%
Extremely Poor 4%

Concrete 2%

Fair 14%

Poor 6%

Good 51%

Tunnel Design and Construction
Typical Tunnel Dimensions

<table>
<thead>
<tr>
<th>Tunnel Parameters</th>
<th>Type I</th>
<th>Type II</th>
<th>Type III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width, m</td>
<td>10</td>
<td>15</td>
<td>30</td>
</tr>
<tr>
<td>Wall height, m</td>
<td>4.5</td>
<td>6.5</td>
<td>8.5</td>
</tr>
<tr>
<td>Crown height, m</td>
<td>8.1</td>
<td>11.2</td>
<td>13.5</td>
</tr>
<tr>
<td>Area, m²</td>
<td>62</td>
<td>115</td>
<td>275</td>
</tr>
</tbody>
</table>

The Cycle of Tunnel Excavation

- Survey/navigation
- Drilling
- Charging & Blasting
- Ventilation
- Mucking out
- Scaling
- Initial support
- Tunnel mapping and support design
Typical Blasting Patterns

- Perimeter holes
- Production holes
- Cut holes
- Lifter holes

- 65 m² with 12 holes
- 125 m² with 17 holes

Chamber section: 275 m²
Bench, 3.5-m high

Drilling
- Computerised 3-boom drilling jumbos
- Critical operations requiring skilled operators (drilling accuracy vs blasting design & tunnel section)
- Horizontal benching required for cavern of 12.5 m height
Production Blasting

- Bulk emulsion
- On-site storage
- Low-risk blasting

Benefits of Using Bulk Emulsion

- Stringent law concerning use of explosives (licensed storage magazine and escorts)
- On-site storage of bulk emulsion reduced cost for magazine rental and long lead time to withdraw explosive for daily consumption
- Reduced emission of toxic gas and ventilation time
Blasting Efficiency and Overbreak

<table>
<thead>
<tr>
<th>Tunnel Type</th>
<th>% of Overbreak</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pilot Phase</td>
</tr>
<tr>
<td>Type I</td>
<td>13.54</td>
</tr>
<tr>
<td>Type III</td>
<td>6.732</td>
</tr>
</tbody>
</table>

Blasting Design Issues

- “Low risk” blasting design: excessive damage; increased support
- Perimeter blasting generally poor (very few half holes)
- Low cost blasting design: limited experience in bulk emulsion.
- Inefficient benching due to limited bench height (3.5 m) and horizontal drilling
- Blasting vibrations
**Trim Blast Using Emulsion**

Emulsion in 32 mm PVC pipe at bottom of 51 mm drill hole

**Blasting Vibrations**

\[ V = H \left( \frac{R}{Q^B} \right)^{-n} \]

H = constant; B = scaling law;  
\( n = \) attenuation coefficient

**Bukit Timah Granite Test:**

\[ V = 1099 \left( \frac{R}{Q^{\frac{1}{3}}} \right)^{-1.44} \]
### Blasting Vibration Criteria

<table>
<thead>
<tr>
<th>Country</th>
<th>PPV (mm/s)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Norway/Sweden</td>
<td>18-70</td>
<td>Specifically stated for vertical PPV for different geological media. Corrections are made for other factors.</td>
</tr>
<tr>
<td>USA</td>
<td>50</td>
<td>Mostly based on US Bureau of Mines studies relating to surface mines</td>
</tr>
<tr>
<td>UK</td>
<td>50</td>
<td></td>
</tr>
<tr>
<td>Switzerland</td>
<td>30</td>
<td></td>
</tr>
</tbody>
</table>

### Observed Threshold Values For RC Structures

<table>
<thead>
<tr>
<th>Material</th>
<th>Building Type</th>
<th>PPV (mm/s)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light concrete</td>
<td>Residential</td>
<td>110</td>
<td></td>
</tr>
<tr>
<td>Old concrete</td>
<td>Industrial</td>
<td>254</td>
<td>Structures expected to crack at 5-18 cm/s in predictions</td>
</tr>
<tr>
<td>Concrete with masonry foundations</td>
<td>Industrial</td>
<td>150-250</td>
<td>Initial concrete block cracks</td>
</tr>
<tr>
<td>Concrete</td>
<td>Industrial</td>
<td>300</td>
<td>Tests showing lowest level corresponding to cracking</td>
</tr>
<tr>
<td>Native stone with mortar joints &amp; rubble foundation</td>
<td>1 1/2-storey residential</td>
<td>180-510</td>
<td>Subjected to progressively more intense blast vibrations until damage was observed.</td>
</tr>
<tr>
<td>Walls</td>
<td>Residential</td>
<td>12.7</td>
<td>Door slams, Converted from strain</td>
</tr>
<tr>
<td>Walls</td>
<td>Residential</td>
<td>22.4</td>
<td>Pounding nails. Converted from strain.</td>
</tr>
<tr>
<td>Walls</td>
<td>Residential</td>
<td>76</td>
<td>Daily environmental changes</td>
</tr>
</tbody>
</table>
Rock Support
(Really Reinforcement)

Initial Support is Gone, Almost

- Shotcrete is used as temporary support
- Pattern bolting used as standard support
- CT-bolts installed (end anchor only) during face drilling for subsequent rounds
- Grouting of CT bolts done later
- Initial support only used in caverns sometimes (more rock bolts)
Support Design Using Q-chart

Q-chart with Energy Capacity for Shotcrete
**Rock Bolt Length**

Roof: \( L = 2 + 0.15B/\text{ESR} \)

Walls: \( L = 2 + 0.15H/\text{ESR} \)

\( L \) = meters; \( B \) = Span; \( H \) = wall height;
\( \text{ESR} \) = Excavation Support Ratio

---

**Quantifying Shotcrete Design**

- Shotcrete not normally modelled as structural element in numerical analysis
- Nominal shear strength = 2 Mpa
- Nominal bonding strength = 0.5 Mpa
- Estimate rock wedge volume
- Compare block weight to shear strength and block weight to bonding strength
- *Shotcrete increasingly accepted as final lining for tunnels*
### Typical Rock Support

<table>
<thead>
<tr>
<th>Class</th>
<th>Q</th>
<th>Type I</th>
<th>Type II</th>
<th>Type III</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>&gt;40</td>
<td>Spot 40 mm</td>
<td>Spot 40 mm</td>
<td>Spot 40 mm</td>
</tr>
<tr>
<td>B</td>
<td>10-40</td>
<td>L3(2.4) 40 mm</td>
<td>L4(2.4) 40 mm</td>
<td>L5(2.4) 50 mm</td>
</tr>
<tr>
<td>C</td>
<td>4-10</td>
<td>L3(2.2) 40 mm</td>
<td>L4(2.2) 40 mm</td>
<td>L5(2.2) 50 mm</td>
</tr>
<tr>
<td>D</td>
<td>1-4</td>
<td>L3(1.9) 50 mm</td>
<td>L4(1.9) 50 mm</td>
<td>L5(1.9) 75 mm</td>
</tr>
<tr>
<td>E</td>
<td>&lt; 1</td>
<td>L3(1.5) 75 mm</td>
<td>L4(1.5) 75 mm</td>
<td>L5(1.5) 100 mm</td>
</tr>
</tbody>
</table>

Note: L3(2.4) = rock bolt length of 3 m at 2.4m center-to-center spacing
Rock Bolts

- 22 mm diameter with 230 KN yield strength and 290 KN failure load

Use of Rock Bolts

- Corrosion protection (polyurethane sleeve, galvanising, cement grout, etc)
- CT Bolts preferred by operators to rebar (bad grout design, lack of physical strength, safety concern, or wrong equipment)
- Pattern bolting or “blind” bolting (angled bolts, penetration at rock joints)
- Cost (material cost small component)
Steel Fibre Reinforced Shotcrete

- Wet mix
- Steel fire: 45 kg/m³
- Alkaline-free accelerators
- Water-cement ratio of about 0.45
- Rebound: 9 – 13%. Avg = 10%
- Energy capacity test

Energy capacity test results (EFNARC, panel: 600 mm x 600 mm @100 mm thick loaded at centre point. Joules)

<table>
<thead>
<tr>
<th>5 mm</th>
<th>10 mm</th>
<th>15 mm</th>
<th>20 mm</th>
<th>25 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>354</td>
<td>641</td>
<td>866</td>
<td>1042</td>
<td>1180</td>
</tr>
<tr>
<td>354</td>
<td>637</td>
<td>862</td>
<td>1047</td>
<td>1198</td>
</tr>
</tbody>
</table>

Grouting

- Used to minimise water seepage, not to stop water completely
- Probe holes of 25 m drilled into face when necessary
- Pre-grouting when flow in three boreholes exceed 15 l/min
- Grouting pressure usually at 30-50 bar (equivalent to 30-50 m water pressure)
Grouting Principles

- Pre-grouting much more effective than post-grouting
- Good penetration (joints aperture and cement type)
- Pressure important (high pressure is better)
- Overlapping of grouting zones (> 5m)
- Thickness must be larger than rock bolts (look out angles).

Excessive Water Seepage

- Normal cement grouting not effective
- Hot bitumen grouting has been used to good effect in controlling water more than 20,000 l/min.
- Water stoppage achieved within hours in dam foundation operations
- Cement grout usually follows to impart strength after initial “plugging” of water seepage.
Rock Mass Classification Method

- General, conservative and may be inaccurate
- Does not consider failure mode, deformation or support interaction
- Cannot consider complex properties of rock mass
- Same rock mass rating with various combinations of rock parameters
- No information on safety margin

Comments about the Q-System

- Easy to use and standardise support design
- Mapping of Q value fairly subjective
- Does not consider orientation of rock joints
- Difficult to account for favourable stress conditions (insufficient resolution?)
Tunnel Geometry Design

- Minimum competent rock cover of 20 m or 1.5 times span
- Empirical rule of 0.2 x tunnel span for arch height results in significant unused tunnel space
- Does not take into consideration of favourable horizontal stresses

Optimisation of Rock Support

- Numerical modelling
  - Geological representation
  - Realistic rock mass properties
  - Tunnel stability criteria (is deformation a good criterion to use in hard rock?)
- Instrumentation and monitoring
  - Use of results
  - Absolute deformation vs measured deformation vs supported deformation
Effects of Joint Orientation

Tunnel Orientations vs Wedge Sizes
Based on Joint Data from Acoustic Imaging BH12: (136/57) (66/73) (280/44)

Volume of Wedges for Different Tunnel Orientations
Rectangle Tunnel (10m Width, 0° Plunge)

Results of UNWEDGE calculations

Instrumentation and Monitoring
Instrumented Cavern Sections

- Instrumentations & monitoring performed during & after construction:
  - Borehole extensometer
  - Convergence (tape)
  - Bolt load (strain gauges)

Cavern Excavation Sequence

slash  

bench  

5 metres
Combined Instrumentation Section

Notes:
The locations of all anchors of multi-point extensometers all displayed with reference to the crown surface of the cavern.

Measured Deformation in Surface MPBX

Displacement and Progress
(Surface MPBX Main Phase Chamber 4--CH50)
“Absolute” Deformation After Grout Setting in Surface MPBX

Displacement and Progress
(Surface MPBX Main Phase Chamber 4--CH50)

Days after 11 December 2001 (8 days after installation)

Displacement (-: into rock; +: into cavern mm)

Excavation Progress (m)

Measured Deformation in Internal MPBX after Installation

Displacement and Progress
(MPBX-BH1 Main Phase Chamber 4--CH50)

Days after 19 March 2002

Displacement (-: into rock; +: into cavern mm)

Excavation Progress (m)
"Absolute Deformation in Internal MPBX" After installation

Displacement and Progress
(MPBX-BH1 Main Phase Chamber 4–CH50)

-4.5 -3.5 -2.5 -1.5 -0.5 0.5 1.5 2.5 3.5
0 50 100 150 200 250 300

Days after 19 March 2002

Displacement (-: into rock; +: into cavern mm)

0 50 100 150 200 250 300

Excavation Progress (m)

2m 6m 12m Pilot Benching Slash

Maximum Roof Deformation

Ratio of Tunnel Span to Q Value (m/Q)

0.0 1.0 2.0 3.0 4.0 5.0 6.0 7.0 8.0

0.0 -1.0 -2.0 -3.0 -4.0 -5.0

Maximum Roof Deformation, mm

square: Measured Data
×: UDEC Predictions

Measured Data
× UDEC Predictions
Summary of Deformation Measurements

- Similar patterns of deformation between internal MPBX and surface MPBX
- Upwards movement of chamber crown observed, peaking when top heading passed measurement position and eventually stabilising at less downward movements
- Inward movement of chamber walls consistently observed

Measured Bolt Loads

Bolt Load vs Time

Compression: -, Tension: +

Bolt Load (kN)

Days after 15 March 2001
Rock Bolts Performance

- Bolt load tends to change considerably before stabilising
- No consistent pattern of maximum bolt loading due to grouting
- Recorded bolt load about 10-25% of design load
- Possible to reduce bolt density and length

Implications for Rock Support

- Rock reinforcement for the cavern roof could be reduced
- Further optimisation of cavern shape is possible (reduced crown height means less excavation cost)
### Comparison with Gjøvik Stadium in Norway (after Broch et al. 1996)

<table>
<thead>
<tr>
<th>Rock Conditions &amp; Bolt Parameters</th>
<th>Gjøvik Stadium, Norway (Based on Broch et al. 1996)</th>
<th>Singapore Site</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical Rock Mass Quality</td>
<td>1 - 30</td>
<td>4 - 36</td>
</tr>
<tr>
<td>Vertical Stress, MPa</td>
<td>1</td>
<td>2 - 3</td>
</tr>
<tr>
<td>Max Horizontal Stress</td>
<td>3.5</td>
<td>8.2</td>
</tr>
<tr>
<td>Minimum Horizontal Stress</td>
<td>2</td>
<td>4.6</td>
</tr>
<tr>
<td>Ratio of Hori. to Vertical Stress</td>
<td>2 - 3.5</td>
<td>2 - 3</td>
</tr>
<tr>
<td>Tunnel/cavern span, meters</td>
<td>61</td>
<td>10 – 30</td>
</tr>
<tr>
<td>Type of Rock Bolts</td>
<td>Fully grouted rebar</td>
<td>Fully grouted CT-bolts</td>
</tr>
<tr>
<td>Lengths, meters</td>
<td>6 m (with alternating 12-m long cables)</td>
<td>3-6 m</td>
</tr>
<tr>
<td>Spacing, meters</td>
<td>2.5 m x 2.5 m</td>
<td>1.5 – 2.4</td>
</tr>
<tr>
<td>Bolt Capacity, KN</td>
<td>220</td>
<td>250</td>
</tr>
<tr>
<td>Minimum Measured Loads, KN</td>
<td>1 – 1.5</td>
<td>3 - 12</td>
</tr>
<tr>
<td>Typical Measured Loads, KN</td>
<td>30 - 60</td>
<td>20 - 60</td>
</tr>
<tr>
<td>Typical Load Percentage</td>
<td>13 – 27%</td>
<td>8 – 24%</td>
</tr>
<tr>
<td>Maximum Measured Load, KN</td>
<td>87</td>
<td>70</td>
</tr>
<tr>
<td>Max Load Percentage</td>
<td>40%</td>
<td>28%</td>
</tr>
</tbody>
</table>

### Back to the Tunnel Cycle

![Graph showing the tunnel cycle activities for 1999 and 2001]
Comparison of World-wide Cost

- Competitive cost in Singapore due primarily to a) large tunnel sections; b) good rock; and c) low labour cost

Conclusions

- No surprises in construction due to good site investigations
- Bulk emulsion explosives proven very beneficial for safety and productivity
- High horizontal stress key factor for stability of large-span rock caverns
- For favourable horizontal stresses, support design using Q-system could be further optimized
“Practical Rock Engineering”

- Very good course notes by Evert Hoek.
- Free download available at:

www.rocscience.com/hoek/PracticalRockEngineering.asp

4th Asian Rock Mech Symposium

Short Courses
- Rock Failure Process Aanalysis (RFPA), by Prof Tang, 7 Nov 06
- Borehole Stability, Earth Stresses and Drilling, by Prof Dusseault, 6-7 Nov 2006

Workshops
- Rock Dynamics, 7 Nov 06 (AM)
- Underground storage facilities, 7 Nov 2006 (PM)

Website: www.arms2006.org
Society for Rock Mechanics & Engineering Geology (Singapore)

- Formerly Engineering Geology and Rock Mechanics Group under TUCSS since 1998
- Registered as new society in July 2006 for better focus on rock mechanics and engineering geology
- Affiliated to ISRM and IAEG
- First AGM to be held on 27 Sept 06
- Contact: Ms An Xinmei. Email: ANXI0001@ntu.edu.sg