Geotechnical Investigations for Tunneling and Underground Construction Projects, Recommended Considerations Based on Recent Case Histories

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1. Introduction

2. Difference between Tunnel Gotech and Other applications

3. Tunneling applications, Methods / Machines

4. Some Case Histories

5. Site Investigation for Tunneling

6. Summary
Tunneling and Underground Space

• The use of Tunneling is on the rise on a worldwide basis due to
  – Urbanization,
    • Mass transits i.e. Subway, road tunnels
    • Water and sewer
    • Utility corridors
    • Living space, Parking, etc.
  – Water management
  – Road, Rail, high speed rail
  – Storage, oil/gas/water, Other
  – Defense and Misc.
Will we move to denser sustainable urban use?

1. Denser urban use more typical of urban areas developed prior to the car
2. Sprawling, less dense cities, more typical of urban areas developed with cars
3. Does sustainability suggest this will change?

Source: Priscilla Nelson
People go underground when uses they desire fit best underground, when severe climate makes the underground desirable, and when earth form (hillsides) create easily exploited opportunities. Most uses have been transportation, parking, shopping.

Source: Priscilla Nelson
Underground Master Plan

Helsinki
Organizations are mandated (and funded) to use geographic information to improve knowledge of their assets in order to

- reduce costs
- ensure regulatory and legislative compliance
- increase customers’ satisfaction
- deliver better services
- communicate more effectively

Source: Priscilla Nelson
Applications

- Underground Parking
- Austria
Utilidor

• Amsterdam under the Mahlerlaan
APPLICATIONS

- Underground Stadium Caverns
Stormwater management and road tunnel (Smart) Kuala Lumpur

Convenient, Faster & Better via SMART MOTORWAY

Largest in South East Asia!
Second Largest in Asia!

- Shield Length: 10,245 m
- Shield Weight: 1,500 tonnes
- Total length: 70.0 m
- Total Weight: 2,500 tonnes
- Cutterhead Diameter: 13.260 m
- Maximum Advance Speed: 30 mm/min
- Minimum Steering Radius: 200 m
- Total Installed Power: 8,200 kVA
- Cutterhead Electrical Power: 4,000 kW
APPLICATIONS

• Railroad Tunnels
APPLICATIONS

- Underground Oil Storage
Difference between Tunneling and other Construction Works

• In typical construction the structure is **ON** the ground,
  – Mostly dealing with foundations on soil or rock

• In tunneling, the structure is **IN** the ground for the entire length
  – Dealing with variations in geology/lithology
  – Variability is given, but alignment is mostly unknown except for locations where borings are available, often at high intervals

• Critical to educate owners/public about this issue
Selection of tunneling method

- Based on stability of the ground
  - Roof and walls
    - Stable ground, standing on its own or for sufficient time to install suitable support
    - Unstable ground → shielded tunneling
  - Face
    - Stable face, → Open face
    - Unstable face, → Shielded
  - Groundwater conditions → Pressurized face
# Machine Selection

General classification scheme for tunnelling machines (AITES / ITA, Working Group No.14).

<table>
<thead>
<tr>
<th>Support System</th>
<th>Excavation Method</th>
<th>Tool</th>
<th>Reaction Force</th>
<th>Machine Category</th>
<th>Machine Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Method</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Cavity</td>
<td>Partial Face</td>
<td>Various</td>
<td>None or Grippers</td>
<td>Special Rock Tunneling Machines - Mobile Miner - Other</td>
<td></td>
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<tr>
<td></td>
<td>Excavating Machines (PFM)</td>
<td></td>
<td></td>
<td>Unshielded TBM</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Full Face Rotating Cutting Head (TBM)</td>
<td>Cutting disk</td>
<td>Grippers</td>
<td>Special Unshielded TBM</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Rod header/Backhoe/Manual excavation</td>
<td></td>
<td>Thrust Jacks</td>
<td>Double Shielded TBM (DS-TBM)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Mechanical</td>
<td>Cutting bits/Cutting knives &amp; teeth</td>
<td></td>
<td>Single Shielded TBM (DS-TBM)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>TBM</td>
<td>Cutting bits/Cutting knives &amp; teeth</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PFM</td>
<td>Road header/Backhoe/Manual excavation</td>
<td>Thrust Jacks</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Compressed Air</td>
<td>Cutting bits/Cutting knives &amp; teeth</td>
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<tr>
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<td>TBM</td>
<td>Cutting bits/Cutting knives &amp; teeth</td>
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<td>PFM</td>
<td>Road header/Backhoe/Manual excavation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fluid</td>
<td>Cutting disk/Cutting bits/Cutting knives &amp; teeth</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Slurry</td>
<td>Cutting disk/Cutting bits/Cutting knives &amp; teeth</td>
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<tr>
<td></td>
<td>PFM</td>
<td>Road header/Backhoe</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Earth Pressure Balance</td>
<td>Cutting disk/Cutting bits/Cutting knives &amp; teeth</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>None or Fluid</td>
<td>TBM</td>
<td>Earth Pressure Balance</td>
<td></td>
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</tr>
</tbody>
</table>
Conventional Tunneling by Drill and Blast
Drilling Equipment
Ground Control, Roof Bolting Equipment

- Jackleg / Jumbo Drills
Ground Support

- This goes along with Rock Mass Classification systems RMR or Q

<table>
<thead>
<tr>
<th>Excavation class *</th>
<th>2-X-F</th>
<th>3-X-F</th>
<th>4-X-F</th>
<th>5-X-F</th>
<th>6-X-F</th>
<th>7-X-F</th>
<th>7-X-F1</th>
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</thead>
<tbody>
<tr>
<td>Rock Class</td>
<td>Good rock</td>
<td>Fair rock</td>
<td>Poor</td>
<td>Poor</td>
<td>Very Poor</td>
<td>Very Poor</td>
<td></td>
</tr>
<tr>
<td>Rock mass behaviour</td>
<td>From stable to local instability</td>
<td>Structural weakness and/or insufficient interlock between blocks</td>
<td>Squeezing ground: stress exceed rock strength</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Shotcrete</td>
<td>5 cm</td>
<td>10 cm</td>
<td>15 cm</td>
<td>15 cm</td>
<td>20 cm</td>
<td>25 cm</td>
<td>25 cm</td>
</tr>
<tr>
<td>Wire mesh (layers)</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Steel Ribs</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Radial Rock bolts 4-6 m in length</td>
<td>Cement grouted (S/N bolts)</td>
<td>Swellex Mn 24</td>
<td>Self Drilling Rockbolts</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Front Consolidation</td>
<td>Spiling steel pipe 4 m long, 10-30 pcs) (Pipe roofing, 15 m long, 20-25 pcs)</td>
<td>Spiling &amp; Pipe Roofing</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Round length (top heading)</td>
<td>3.0-4.0m</td>
<td>2.2-3.0m</td>
<td>1.7-2.2m</td>
<td>1.3-1.7m</td>
<td>1.0-1.3m</td>
<td>0.8-1.0m</td>
<td>0.8-1.0m</td>
</tr>
</tbody>
</table>

* Excavation class according to Austrian standard (Norm B 2203/1994)
Shotcrete
Ground Support

• Final Lining, Cast In Place (CIP) concrete
Partial Face Machine, Roadheader
# TBM Selection

## Application Chart for TBM's by Machine Type

<table>
<thead>
<tr>
<th>Machine Type</th>
<th>Diameter Range</th>
<th>Rock Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open Main Beam (MB)</td>
<td>2.5 - 14</td>
<td></td>
</tr>
<tr>
<td>Open Kelley (MK)</td>
<td>2.5 - 13</td>
<td></td>
</tr>
<tr>
<td>Single Shield (SS)</td>
<td>3 - 12</td>
<td></td>
</tr>
<tr>
<td>Double Shield (DS)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Earth Pressure Balance</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The chart indicates the appropriate diameter range for each type of machine based on the rock strength. Each row corresponds to a different type of machine with its respective diameter range and rock strength characteristics.
Machine selection as a function of rock mass

- Function of Rock Mass Rating (RMR)

* RMR = Rock Mass Rating, geomechanics classification
Tunneling by a Main Beam TBM
Main Beam TBM, single grippers
Double-Shield TBM
Shielded TBMs

PDS 740-OS/RM  HDS 1064/660-OS  HDS 660-OS  ADS 248-LS/BV  MDS 356

Shield & LSK 190/300  PDS 710-GS/EPB  Telescop Shield  Blade shield  Blade shield
Single Shield, Open Type
Tunneling by a Shielded TBM
Closed Face Shield Selection

Function of Soil Type

<table>
<thead>
<tr>
<th></th>
<th>clay</th>
<th>silt</th>
<th>sand</th>
<th>gravel</th>
</tr>
</thead>
<tbody>
<tr>
<td>fine</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>medium</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>coarse</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Conditioning to reduce stickiness and high torque
- Conditioning to improve workability and minimize torque
- Conditioning to impart workability and reduce permeability
- Require soil consolidation, or fine filler injection

EPB

Slurry
Slurry TBM

Slurry Machine
EPB Machine

Earth Pressure Balance Machine
Case Histories
Sequential Excavation Method (SEM)
Challenges

• Crossing of Metro line and station, within 3 ft of the crown
• Close proximity to buildings and active traffic above
• Small footprint for shafts and portals
• Highly variable ground with cobles and boulders
• Shallow depth and changing slopes
• Existence of ancient water conduits (Qanats) and possibility of flash floods at the face
• Leaky old water lines along the tunnel
Crossing of Subway Station

Intersecting Station in

- North
- Middle
- South
Twin Peaks Tunnel, Colorado Spring, CO

- Constructed in early 1990's
- Small 12 ft (3.5 m) diameter tunnel constructed by Morrison Knudsen
- Rock type, Granite / Pegmatite
- Low penetration and advance rate
- High cutting forces, in pegmatite
- Claim for differing site conditions (DSC) for rock being harder than indicated in geotec.
Boston Outfall Tunnel

- 10 mile of 26.5 ft diameter tunnel, lined with segmental lining
- Double Shield TBM was used by Kiewit-Atkinson-Kenny JV
- Geology, mainly argillite, at depth of ~200 ft under the Atlantic Ocean, starting from a shaft in Deer Island
- DSC claim for penetration (got 9 ft/hr instead of expected 15 ft/hr), low penetration attributed to rock anisotropy
- DSC for excessive grouting
Queens Tunnel, New York City

- 5 mile long, 23’2’’ wide, and ~700’ deep tunnel through igneous/granitic rock.
- Contactor was Kiewiet-Shea
- Low penetration rates claim (~6’/hr [actual] vs. ~9’/hr [anticipated]) attributed to changed rock mass conditions, high-grade metamorphism of the rocks
- In other words, harder than expected rock but broken ground with frequent shear zones.

- Earlier tunnel in Queens by Shiavone – Shea had a claim for excessive cutter cost

Merguerian, Charles (primary); Ozdemir, Levent RETC-2003
Symour Capilano Twin Tunnels in Vancouver, BC

- Twin tunnel for Raw and Treated Water from the dam to treatment plant and back
- 7 km each, 3.8 m (~13ft) dia. ~300-600 m deep
- Mainly granite and igneous rocks, some areas with weathered granite
- Spalling and rock falls due to stress concentrations at 5 & 11 O’clock position
- High in situ horizontal stresses of about 2-3.5 time vertical/gravitational stress
- Work was interrupted by rock burst!
  - 1st Contractor stopped due to safety concerns and was terminated,
  - 2nd contractor completed the job.
- Over ~$100 in Claims

Source: Tunnel Talk
The St Gotthard Base Tunnel in the Alps

- Total Tunnel Length
  - Nominal length 57.1 km
  - System length 151.8 km
  - TBM 98.1 km
  - Conventional 53.7 km

- Boring diameter
  - 8.8 / 9.4 / 9.5 / 11

- Overburden(min-max)
  - 100 – 2’350 m

- Characterization scheme
  - 2 single track tubes, connected with crosslinks every 312.5
  - 2 multifunction stations
  - 3 access galleries
  - 2 vertical shafts (800 m)
  - 1 bypass gallery
  - 1 inclined ventilation shaft
The St Gotthard Base Tunnel in the Alps

- Main issue in this project was the In-situ stress and ground squeezing
- Designed for up to 3 ft (~1m) of ground convergence
- Open type TBMs used for excavation, this allowed for convergence without entrapment of the shielded machines
GHOMRUD PROJECT, IRAN

- Overall Tunnel length: >50 km
- Broken into lots I-IV 9 km each + 14 km in lot #V
- Lots IV, III, and part of II excavated by Double Shield TBM for the length of 24+450 m
- TBM manufacturer: WIRTH Co.
- Diameter: 4.5 m (OD) 3.8 m (ID)
- Support: Hexagonal Segmental lining
- Start of excavation: Spring 2004
- End of excavation: Spring 2009
Convergence & TBM jamming

Tunnel length

Predicted

Actual

Severe Squeezing

Predicted

Actual

$C_i > 2.5$

$C_i > 1$

Radial Convergence (mm)

Distance from Tunnel Outlet (Km)

Chainage (Km)

Real Lithology

Legend

- Topography Line
- Apparent dip of Layers (In Section)
- Main Fault
- Foccces change
- Qts. Vein
- Tunnel Alignment
- Debris
- Quartzite
- State
- Massive Limestone
- Sandstone
- Quartz veins
- Alteration of Rock, Graphite Schist, Slate & Sandstone
- Alteration of State, Graphite Schist & Sandstone Fault Zones
- Crushed Zones
- Dolomite
TBM Jamming due to Squeezing

- Boring diameter: 4,525 mm
- New cutters: 65 mm
- Worn-out cutters: 35 mm
- Overcut over cutter head: 145 mm
- Front shield diameter: 4,460 mm
- Outer diameter: 4,380 mm
- Tail shield diameter: 1,380 mm
- Max overcut measured at the tail shield: 145 mm
The Zagros tunnel is the largest water transfer project in western Iran situated within the Zagros mountain range.

The second lot of tunnel is approximately 26 km long and 6.73 m in diameter, currently under construction using a double shield (DS) TBM.

The tunnel passes through a variety of sedimentary rock formations with frequent changes in rock mass qualities from poor to very good.

The machine encountered many adverse geologic conditions, all of which resulted in reduced TBM utilization.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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<tbody>
<tr>
<td>Machine diameter</td>
<td>6,730 mm</td>
</tr>
<tr>
<td>Number of cutters</td>
<td>42</td>
</tr>
<tr>
<td>Cutter diameter</td>
<td>432 mm (17”)</td>
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<tr>
<td>Average cutter spacing</td>
<td>90 mm</td>
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<tr>
<td>Cutterhead torque</td>
<td>4,747 kNm</td>
</tr>
<tr>
<td>Thrust force</td>
<td>29,038 kN</td>
</tr>
<tr>
<td>Rotational speed</td>
<td>0-9 rpm</td>
</tr>
</tbody>
</table>
### Geology

<table>
<thead>
<tr>
<th>No</th>
<th>Engineering Geological Unit</th>
<th>Equivalent Stratigraphic Units</th>
<th>Main Lithology</th>
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</thead>
<tbody>
<tr>
<td>1</td>
<td>S1</td>
<td>( PE_{Pd}^{4a} )</td>
<td>Shale</td>
</tr>
<tr>
<td>2</td>
<td>SL1</td>
<td>( PE_{Pd}^{5} )</td>
<td>Argillaceous Limestone</td>
</tr>
<tr>
<td>3</td>
<td>S2</td>
<td>( PE_{Pd}^{6} )</td>
<td>Shale</td>
</tr>
<tr>
<td>4</td>
<td>LS1</td>
<td>( PE_{Pd}^{7} )</td>
<td>Limy Shale</td>
</tr>
<tr>
<td>5</td>
<td>LS2</td>
<td>( PE_{Pd}^{8} )</td>
<td>Limy Shale</td>
</tr>
<tr>
<td>6</td>
<td>S3</td>
<td>( PE_{Pd}^{3} )</td>
<td>Shale</td>
</tr>
<tr>
<td>7</td>
<td>SL2</td>
<td>( PE_{Pd}^{2} )</td>
<td>Argillaceous Limestone</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>( PE_{Pd}^{1} )</td>
<td>Argillaceous Limestone</td>
</tr>
<tr>
<td>9</td>
<td>S4</td>
<td>( K_{Gu}^{5a} )</td>
<td>Shale</td>
</tr>
<tr>
<td>10</td>
<td>LS3</td>
<td>( K_{Gu}^{4} )</td>
<td>Limy Shale</td>
</tr>
<tr>
<td>11</td>
<td>S5</td>
<td>( K_{Gu}^{3} )</td>
<td>Shale</td>
</tr>
<tr>
<td>12</td>
<td>LS4</td>
<td>( K_{Gu}^{2a} )</td>
<td>Limy Shale</td>
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<tr>
<td>13</td>
<td></td>
<td>( K_{Gu}^{1} )</td>
<td>Limy Shale</td>
</tr>
<tr>
<td>14</td>
<td>L1</td>
<td>( Ki (Kl_{5}) )</td>
<td>Limestone</td>
</tr>
</tbody>
</table>

**Legend:**
- Unit Boundary
- Fault
- Tunnel alignment
- Borehole
- Selected tunnel sections
- Crushed zone
Gas emission incident in Zagros long tunnel

- The toxic hydrogen sulfide (H₂S) and explosive methane (CH₄) are the gases mainly encountered along the tunnel route.
- The gas origin was existing sulfide minerals and in particular Pyrite and also natural gas and oil bearing formations along the tunnel alignment which are known as the typical host of oil reservoirs in western Iran.
- Seepage of black tarry liquids into tunnel is an indicator of existing oil (gas)-bearing formations.
- The gas is highly soluble in water and is often brought into the tunnel by seepage, where it is then released into the atmosphere.
Gas emission incident in Zagros long tunnel

Gas concentration changes with water inflow rate
Difficult ground conditions and TBM utilization

Gas concentration vs TBM utilization
Gas emission related problems

- Health and Safety problems and hazards
- Difficult working conditions for tunnel crew
- 2 Fatalities due to negligence by the crew
Oma-Uya Project, Sri Lanka

- Components:
  - 2 dams
  - 4 km transfer tunnel
  - 15 km Headrace Tunnel
  - Surge Shaft,
  - Drop Shaft
  - Powerhouse
  - Access tunnels
  - 4 km Tailrace tunnel
  - Misc. Access or maintenance facilities
Uma Oya Multipurpose Project
Powerhouse

- Underground Powerhouse/Transformer
  - Excavation Finished: January 4th, 2016
Headrace Tunnel - Outlet
Headrace Tunnel

• Disc cutter wear in hard abrasive rocks
Headrace Tunnel,

- Flooding and Water Issues
Escandida Project, Chile

- 3 Microtunnels, 2.5 m (~8 ft) diameter, with total length of 1750 m, from shore to Pacific Ocean
- Complex geology, including fresh/weathered igneous rocks, Diorite and Gabbro, lumped into competent and weathered
- Highly jointed rock, no joint set specified
- Penetration rate claim due to low penetration, attributed to harder rock than reported, 61
Seattle, Northgate tunnel project

- Typical Subway tunnel, ~20 ft Dia (6.3m), twin bore, in soft ground,
- 4.2-mile extension adds to the recently completed University Link tunnels running 3.2 miles
- Geology: various soils, sand, silty sand, clay. Under groundwater table, pressurized face
- Two machines, one by Robbins one by Hitachi Zosen
- Tunnels are completed,
- Wear on the tools and cutterhead
- Issues with ground freezing for cross passages, and resulting heave
Seattle, University Link and Northgate tunnel project

- Wear of cutterhead and tools due to soil abrasivity and Boulders
Seattle, SR-99 Alaskan Way Viaduct Replacement

- Twin-deck highway with a world record-breaking 17.4-m (57.3-ft) bored tunnel, Nearly 3.2 km (2 miles)
- Largest EPB machine in the world
- Tunnel is lined with segmental lining
- Geology: mainly sandy/silt soil/fill plus cobbles & boulders, under water table
- Passing under the existing viaduct, high rises of downtown Seattle, close to Seattle fish market, aquarium, and the ferry terminal

<table>
<thead>
<tr>
<th>Table 1. EPBM specifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter</td>
</tr>
<tr>
<td>TBM length + back-up</td>
</tr>
<tr>
<td>TBM weight</td>
</tr>
<tr>
<td>Min horizontal radius</td>
</tr>
<tr>
<td>Min vertical radius</td>
</tr>
<tr>
<td>Max pressure in chamber</td>
</tr>
<tr>
<td>Max thrust</td>
</tr>
<tr>
<td>Cutterhead displacement</td>
</tr>
<tr>
<td>Cutterhead power</td>
</tr>
<tr>
<td>No of disc cutters</td>
</tr>
<tr>
<td>No of replaceable knife bit cutters</td>
</tr>
<tr>
<td>No of thrust cylinders</td>
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<tr>
<td>Rotation speed</td>
</tr>
<tr>
<td>Max torque at 0.88 rev/min</td>
</tr>
<tr>
<td>Break-out torque</td>
</tr>
<tr>
<td>Screw conveyor diameter/ type/length</td>
</tr>
<tr>
<td>Total power installed</td>
</tr>
</tbody>
</table>
Seattle, SR-99 Alaskan Way Viaduct Replacement

**Recommended TBM Face Pressure at Tunnel Springline (psi):**

- **Max Pressure (Emergency Mode):** 145.0 psi = 10 bar
- **Max Pressure (Normal Mode):** 101.5 psi = 7 bar
- **Full Hydrostatic Pressure:** Max = 81.5 psi = 5.6 bar
- **Anticipated Max Work Pressure:** Max = 62.4 psi = 4.3 bar

**Potential pressure increase if heavily slickensided/fractured clays encountered in full TBM face and residual strength governs.**

Source: TunnelTalk
Seattle, SR-99 Alaskan Way Viaduct Replacement

- Boring started in Sept. 2013
- Machine advanced ~1000 ft encountered problems with the main bearing, had to stop
- Difficult soil conditioning to regulate the flow due to high water pressure and sandy soil
- A rescue shaft was constructed to remove the cutterhead
- Replaced the bearing/head repair in 2014-15
- Restarted in Jan 2016, almost 3500 ft (1100 m) completed
- Faster tunneling in clay and fine soil
Site Investigation
Laying a Water Main in Hampstead 1851

Underground New York City – turn of the century
Composite Utility Plan
Site Investigation

• Soil boring, delineation of soil/rock or Top of Rock interface
• Trenches, sampling shafts (for boulders), . . .
• Core logging
• Lab Tests
  – Soil, Rock, Groundwater
• In situ Testing
  – Groundwater table monitoring, Slug/Pump tests. ..
  – Borehole logging, Optical/Sonic televiewer
  – Dilatometer, Pressure meter tests
  – In-situ stress measurements
**Laboratory Soil Testing**

- Sieve
- Hydrometer
- Density / Specific Gravity
- Atterberg Limits
- Water Content
- Compaction
- PH measurement
- Permeability
- USCS
- Compressive Strength UU
- Compressive Strength CIU
- Organic Content
- Salinity
- Clay Minerals
- Shear Tests
- Soil Abrasion testing
Soil Abrasion

• Typically a non-issue in geotech investigation
• Very critical to tunneling due to implications of tool change under hyperbaric conditions, high cost, risk, and safety issues
• Relatively new, no standard testing, still under study.
A unique testing device was designed and built specifically for this study.

The proposed test device consists of a cylindrical chamber (14 in diameter and 18 in length, 350×450 mm) where the in-situ conditions of the soil can be simulated.

The chamber dimensions were selected to allow for soils potentially containing large gravel size particles, to simulate the in-situ conditions of the soil as closely as possible and avoid altering grain size distribution as in some other tests.
The propeller, which is intended to create maximum contact forces with the soil, is attached to a drive shaft and rotates inside the cylindrical chamber.

The propeller has three blades with the radius of 150 mm.

This leaves an annular space of about 12 mm between the edge of the propeller blades and the walls of the chamber that allows for limited material flow inside the chamber.

To avoid severe wear on the blades and also allow for more accurate measurement of the weight loss on the tools, the blades are fitted with steel covers. The covers weigh much less than the blades and can be easily removed and weighed using a high-precision scale and provide protection to the blade.
Study of the Effect of Soil Conditioning on Soil abrasion


Soil Conditioning Tests on Silica sand

<table>
<thead>
<tr>
<th>Soil</th>
<th>Moisture Content (%)</th>
<th>Testing Time (min)</th>
<th>Weight Loss (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica sand</td>
<td>0 - Dry</td>
<td>30</td>
<td>12.9313</td>
</tr>
<tr>
<td>Silica sand</td>
<td>10% W</td>
<td>30</td>
<td>22.0670</td>
</tr>
<tr>
<td>Silica sand</td>
<td>15% W</td>
<td>30</td>
<td>10.4559</td>
</tr>
<tr>
<td>Silica sand</td>
<td>15% W, Meyco SLF 47</td>
<td>30</td>
<td>0.6453</td>
</tr>
<tr>
<td>Silica sand</td>
<td>15% W, ABR5</td>
<td>30</td>
<td>3.9132</td>
</tr>
<tr>
<td>Silica sand</td>
<td>15% W, AQF-2</td>
<td>30</td>
<td>2.9787</td>
</tr>
<tr>
<td>Silica sand</td>
<td>15% W, Quik Mud D-50</td>
<td>30</td>
<td>13.3139</td>
</tr>
<tr>
<td>Silica sand</td>
<td>15% W, Quik Mud D-50+AQF-2</td>
<td>30</td>
<td>2.9530</td>
</tr>
</tbody>
</table>

Mixing soil with conditioner:

- W = 15% mixed with 3% Conc. ABR5, FIR=25%, FER=17
- W = 15% mixed with 3% Conc. Meyco SLF 47, FIR=25%, FER=17
- W = 15% mixed with 1% Conc. AQF-2, FIR=30%, FER=17
- W = 15% mixed with 0.125% Quik Mud D-50 mixed with water and mixed with dry sand
- W = 15% mixed with 0.125% Quik Mud D-50 mixed with water and mixed with dry sand + 1% Conc. AQF-2, FIR=28%, FER=14
Physical Property Testing for Rocks

- Uniaxial Compressive Strength (UCS)
- Brazilian (Indirect) Tensile Strength (BTS)
- Cerchar Abrasivity Index (CAI)
- Punch Penetration Test
- Thin Section Petrographic Analysis
- Acoustic Velocities
- Point Load Index Test
- Triaxial Compression Test
- Static Elastic Modulus
Sample Logging

EARTH MECHANICS INSTITUTE
Colorado School of Mines

Sample Logging

Project: QUEENS WATER TUNNEL, NO. 3 – STAGE #2
Rock Type: Metamorphic

Core ID: Core #14
Station: 10450

Characteristics:

Moisture Condition: As-received
Air-dried
Over-dried
Saturated
Frozen

Moisture Content: Yes
No

Sample Length: 11.5" Sample Weight: N/A

Diameter 1: ~2.7" Diameter 2:
Diameter 3:

Core mapping:

Notes:
Tests tube performed

DES
Bore hole
Punch, Perforation
Boat load
Ceramic, obsidion, index

Top:
Bottom:

Operator: Michael Tullo
Date: 8/27/1997

Supervisor:
Date: 8/27/1997

Principal Investigator: Janet Gell
Date: 8/27/1997

Version: August 97
Sample Preparation
Uniaxial Compressive Strength (ASTM 7012)

\[ \sigma_c = \frac{F}{A} \]

Where,

- \( \sigma_c \) \( \rightarrow \) Compressive Strength of the Core Sample (MPa or psi)
- \( F \) \( \rightarrow \) Applied Force at Failure (N or lb.)
- \( A \) \( \rightarrow \) Initial Cross-sectional Area (mm\(^2\) or in\(^2\))

Non-structural Failure

Structural Failure
Brazilian Tensile Strength (ASTM D3967-95)

\[ \sigma_T = \frac{2F}{\pi LD} \]

\( \sigma_T \rightarrow \) Tensile Strength (psi)
\( F \rightarrow \) Failure Load (lbs.)
\( L \rightarrow \) Thickness of the disk (in.)
\( D \rightarrow \) Diameter of the disk (in.)

Effect of Foliation on Tensile Strength
Effect of Foliation/Bedding on Disc Cutting

**Tunneling perpendicular to foliation**

**Tunneling parallel to foliation**
Abrasivity Index (CAI) has proven to be fairly accurate and is commonly used for cutter life estimation. A series of three 90° hardened pins of heat treated alloy steel are pulled across a freshly broken surface of the rock. The average dimensions of the resultant wear flats are related directly to cutter life in field operation. This allows calculation of the expected cutter costs per unit volume of material.
Cerchar Index

<table>
<thead>
<tr>
<th>Category</th>
<th>NTNU Classification CAI (pin hardness 43)</th>
<th>CSM Classification CAI (pin hardness 56)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Not very abrasive or Non-Abrasive</td>
<td>0.3 - 0.5</td>
<td>&lt; 1.0</td>
</tr>
<tr>
<td>Slightly abrasive</td>
<td>0.5 - 1.0</td>
<td>1.0 - 2.0</td>
</tr>
<tr>
<td>Medium Abrasiveness to Abrasive</td>
<td>1.0 - 2.0</td>
<td>2.0 - 4.0</td>
</tr>
<tr>
<td>Very abrasive</td>
<td>2.0 - 4.0</td>
<td>4.0 - 5.0</td>
</tr>
<tr>
<td>Extremely abrasive</td>
<td>4.0 - 6.0</td>
<td>5.0 - 6.0</td>
</tr>
<tr>
<td>Quartzitic</td>
<td>6.0 - 7.0</td>
<td></td>
</tr>
</tbody>
</table>

There has been much discrepancies in testing procedures about the pin hardness, surface conditions of the sample, measurement method, etc. that has caused problems, be careful in recording testing details.
Thin-Section Petrographic Analysis (Suggested method by ISRM)

- Plane Polarized Light 20x.
- Notice Garnet Wrapping

The thin section analysis of rocks for engineering purposes includes the determination of parameters, which cannot be obtained from strength test of rock samples, such as mineral content, matrix characteristics grain size and texture. This analysis also helps identify any unusual rock microscopic features (i.e. grain suturing/interlocking, grain elongation), which may have an impact on its boreability.

- Plane Polarized Light, 20x
- Notice Elongation
The velocities of compressive and shear ultrasonic waves through the core sample are measured and used to calculate the elastic modulus and Possion’s ratio. This method indicates the competence of the rock.

\[
E = \frac{\rho V_S^2 \left(3V_P^2 - 4V_S^2\right)}{V_P^2 - V_S^2}
\]

\[
\mu = \frac{V_P^2 - 2V_S^2}{2\left(V_P^2 - V_S^2\right)}
\]

- \(V_S\) = Shear wave velocity (in./s or m/s)
- \(V_P\) = Compressive wave velocity (in./s or m/s)
- \(E\) = Elastic modulus (psi or Pa)
- \(\mu\) = Possion’s ratio
- \(\rho\) = Density (lb/in\(^3\) or kg/m\(^3\))
Point Load Index (ASTM D5731)

\[ I_s = \frac{F}{D_e^2} \]

Where
- \( I_s \) \( \Rightarrow \) Point load index (psi)
- \( F \) \( \Rightarrow \) Failure load (lbs.)
- \( D_e \) \( \Rightarrow \) Distance between platen tips (in.)
- \( D_e^2 = D^2 \) \( \Rightarrow \) for diametrical test
  - \( = 4A/\pi \) \( \Rightarrow \) for axial, block and lump test
- \( A = W.D = \text{minimum cross-sectional area of a plane through the platen contact points} \)
In the Punch Penetration Index test, a standard indenter is pressed into a rock sample that has been cast in a confining ring. The load and displacement of the indenter are recorded with a computer system. The slope of the force-penetration curve indicates the excavatability of the rock, i.e., the energy needed for efficient chipping.
SINTEF / Norwegian Boreability Test Procedures and Apparatus

1. Brittleness Test
   - Brittleness factor calculation: $S_{20}$
   - Flakiness measurement
   - Sample weight calculation

2. The Sievers' Miniature Drill Test
   - Drill bit specifications
   - Rock sample setup

3. Abrasion Test
   - Abrasion test apparatus
   - Rock and soil particle size specifications

AV (or ASV)
The tests yield three indices:

- Drilling Rate Index (DRI)
- Cutter Life Index (CLI)
- Bit Ware Index (BWI)

Combined with joint info (spacing, orientation), and TBM specs and operational info, can be used for performance prediction.
Core Scanning

"unrolled" image of the core mantle
Core Storage

Virtual Drill Core Library

Drill Core Storage House

Virtual Drill Core Library
Core logs

CoreLog-Integra & Fracture Analysis™ Evaluation Software

- DMT CoreScan was developed for the use in both reservoir classes:
  - Fractured Reservoirs
  - Clastic Reservoirs

- Important parameters for the calculation of Fluid Flow of "fractured deposits" can be measured with CoreLog-Integra:
  - Geometric relationship of productive fractures (connectivity)
  - Quantifying the storage capacity
  - Visualisation of fracture distribution and locate productive fractures (aperture estimates, fracture characterisation at different scales)

- Fluid flow in "Fractured Reservoirs" is mainly based on quantitative derivation of required data from fracture orientation, fracture density and fracture spacing (estimates aperture).
In situ testing

- Logging boreholes to see voids/measurement of rock properties/joint density/joint orientation
  - Sonic/ acoustic /optical televiewers
- In-situ stresses measurement in rock, over-coring/fracing
- Pressure tests for in-situ Elastic property measurements
- Groundwater monitoring
  - Groundwater table, Perched/artesian aquifers need multiple level piezometers
  - Monitoring for extended period of time to see seasonal fluctuations,
  - Measuring permeability is critical, slug / pump tests
  - Check water salinity and flow rates for ground freezing
Geotech Cost, Reports and Risk Management for Tunneling Projects
Goetech Site Investigations

- Prospective and Interest
  - Owner (private, public, quasi-government)
  - Engineer / Designer
  - Contractor (single or joint)
  - Construction Management (CM)

- Phases of Site Investigation
  - Phase I – Feasibility
  - Phase II – Preliminary Design
  - Phase III – Final Design
  - Phase IV – Construction
Geotechnical Reports

- Geotechnical Site Investigation Planning, typically at early design stage, never published
- Geotech Data Report (GDR), Contract documents
- Geotechnical Interpretive Report (GIR), contract doc, mostly for soil and shallow structures
- Geotechnical Data Summary Report (GDSR),
- Geotech Baseline Report (GBR), Contract document, higher risk more expensive projects, a risk sharing scheme, and a legal framework
Risk Assessment

• Geotech site investigation should be based on **Risk Assessment and Risk Management**

• This means being prepared for higher cost test where the consequence of missing a feature is very detrimental to the project
Risk Management

- Can you or can you not live with your residual risks? Use a Risk Profile/Matrix to decide.
- (Use as a starter kit e.g. ISO Guide 51:1999 / ISO TS 14’798:2000)
Planning Site Investigation for Tunneling

• **Spacing of Borings: General Rule of Thumb!**
  - For uniform and consistent grounds: 0.7 ft/ft tunnel (m/m)
  - For typical ground conditions: 1-1.5 ft/ft tunnel (m/m)
  - For very variable and changing grounds or for very sensitive structures: 1.5-2 ft/ft tunnel (m/m)

  – Shafts need one boring at the center line and at least one more at the edge or preferably 2-3 on the periphery to identify transitions

  – For example for a 20,000 ft tunnel 30 ft dia.
    - If tunnel is shallow ~150 ft and in typical geology, go for 210 ft borings then we need 90 borings meaning average of ~200 ft interval
    - For a 500 ft deep tunnel in consistent geology, boring depth of 560 ft and we may need 27 borings at 750 ft interval.

  – Target to extend the borings 2D below invert

  – However, if the proposed vertical alignment is subject to modifications, it may be more economical to extend these depths to 3 times the tunnel diameter, for contingency purposes

  – Use inclined boring as needed
**Cost of Geotech Investigation for Tunneling**

- Reasonable range 3-7% total construction

<table>
<thead>
<tr>
<th>Tunnel</th>
<th>Start of the works</th>
<th>Type</th>
<th>Total Length</th>
<th>Cumulated length of boreholes</th>
<th>Cost of explorations / cost of tunnel</th>
<th>Invest. Cost [ME]</th>
<th>Constr. method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lötschberg</td>
<td>1994</td>
<td>Railway</td>
<td>34,6 km</td>
<td>N/A</td>
<td>2,8 %</td>
<td>N/A</td>
<td>Gripper TBM / DB</td>
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<tr>
<td>Gothard</td>
<td>1998</td>
<td>Railway</td>
<td>53,9 km</td>
<td>N/A</td>
<td>1,4 %</td>
<td>N/A</td>
<td>TBM / DB</td>
</tr>
<tr>
<td>Brenner</td>
<td>2011</td>
<td>Railway</td>
<td>57,0 km</td>
<td>~ 36 km</td>
<td>8,7 % i including exploratory galleries</td>
<td>0,63</td>
<td></td>
</tr>
<tr>
<td>LTF</td>
<td>Detailed design phase</td>
<td>Railway</td>
<td>57,1 km</td>
<td>~ 62 km</td>
<td>8,9 % i including exploratory galleries</td>
<td>1,08</td>
<td></td>
</tr>
<tr>
<td>Koralm Base Tunnel</td>
<td>In construction</td>
<td>Railway</td>
<td>33 km</td>
<td>~ 21 km</td>
<td>1,9 %</td>
<td>0,64</td>
<td>N/A</td>
</tr>
<tr>
<td>Semmering Base Tunnel</td>
<td>In construction</td>
<td>Railway</td>
<td>27 km</td>
<td>~ 38,5 km</td>
<td>1,7 %</td>
<td>1,43</td>
<td>N/A</td>
</tr>
</tbody>
</table>

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<thead>
<tr>
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<th>Type</th>
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<th>Cost of explorations / cost of tunnel</th>
<th>Invest. Cost [ME]</th>
<th>Constr. method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saint Vallier</td>
<td>2002</td>
<td>Road</td>
<td>178 m</td>
<td>225 m</td>
<td>2,6 %</td>
<td>1,26</td>
<td>D&amp;B</td>
</tr>
<tr>
<td>Schirmbeck</td>
<td>2003</td>
<td>Road</td>
<td>550 + 150 m</td>
<td>704 m</td>
<td>3,7%</td>
<td>1,01</td>
<td>D&amp;B</td>
</tr>
<tr>
<td>Bois du Peu</td>
<td>2004</td>
<td>Road</td>
<td>2*600 + 90 m</td>
<td>886 m</td>
<td>2,2% Excluding costs for exploratory gallery</td>
<td>1,09</td>
<td>D&amp;B</td>
</tr>
<tr>
<td>Peute Combe</td>
<td>2009</td>
<td>Road</td>
<td>2*600 + 120 m</td>
<td>1219 m</td>
<td>3,85%</td>
<td>0,95</td>
<td>D&amp;B</td>
</tr>
<tr>
<td>Saint Béat</td>
<td>2010</td>
<td>Road</td>
<td>110 + 310 m</td>
<td>1586 m</td>
<td>2,1%</td>
<td>1,12</td>
<td>D&amp;B</td>
</tr>
</tbody>
</table>

Source: ITA work group #2 on Geotech Investigations
Summary

• Geotech Investigation for Tunnel and Underground Construction is more critical/sensitive than other construction projects
• Specialized tests are necessary, depending on construction method
• The lower the investment in Geotech investigations, the higher the probability and magnitude of the Claim
• Owners: Do not pressure the Geotech to reduce the budget, Pay back is a b…..
• Consultants/designers: Make sure to educate your clients, properly plan the Geotech work with sufficient time for proper investigation ahead of design
• Contractors: it is worthwhile to spend some money to identify the ground condition issues beforehand
• Geotech Engineers, You are going to be blamed for all the construction problems no matter what!! :o)
THANKS FOR YOUR ATTENTION & QUESTIONS