Site Investigations and Geotechnical Risk For Underground Construction

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August 14, 2017
Develop Preliminary Geologic / Geotech Conceptual Model for the Project

Goal is to:
- identify the primary technical considerations,
- limitations/constraints,
- scope,
- purpose,
- geotechnical targets,
- and site conditions that must be resolved.
Identify/Collect Available Geotechnical Data in the Project Area

Information can include:
- Geologic maps
- Data from previous reports
- Drill hole data
- Preliminary mapping

Compile available local data into a database for further evaluation.
Field Geologic Mapping
Typical Drill Hole Logs

**General:**
- Drill rate
- Rig Behavior
- Circulation return
- Depth to water
- Instrumentation
- Drill difficulties
- Shift changes
- Testing intervals and results

**Soil:**
- Lithology
- Soil type (USCS)
- Color
- Consistency / density
- Grain size distribution
- Moisture
- Cementation
- Plasticity (clays)
- Roundness

**Rocks:**
- Rock Type
- Recovery, RQD, GSI
- Color
- Texture
- Degree of weathering
- Strength
- Hardness
- Structure
- Discontinuities:
  - Type
  - Width
  - Infilling Amount & Type
  - Surface Shape
  - Roughness
  - Spacing (Joint Sets)

**Typical Roughness Profiles for JRC**

<table>
<thead>
<tr>
<th>RANGE</th>
<th>Roughness Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-2</td>
<td>Slickensided Polished</td>
</tr>
<tr>
<td>6-8</td>
<td>Smooth</td>
</tr>
<tr>
<td>16-18</td>
<td>Rough Very Rough</td>
</tr>
</tbody>
</table>

Depth to first water (time and date)

Depth to water after drilling (time and date)
Types of Samples – Drive Samplers (SPT, MC, LPT)

Can be performed in most soil types, difficult in gravel-cobbles. Provides information relating to relative density, strength, and applicability of some ground improvement methods (e.g., soil mixing, jet grouting, chemical grouting)
Types of Samples – “Undisturbed” Samples

- Shelby Tube
- Pitcher Sampler
- Piston Sampler

Typically applied to soft-medium, stiff cohesive soils in order to test strength, stiffness, consolidation, etc…
Types of Rigs –

Some typical methods to drill the subsurface include:

- Auger
- Mud/Air Rotary
- Mud/Air Rotary with Casing Advance
- Reverse Circulation
- Sonic
- Becker Penetration
- Large Diameter
- Cone Penetration Tests (CPT)
- Rock Core

Each of these methods have pros and cons and are well suited for specific exploration programs, depending on both the subsurface conditions as well as the data needs for the program.
Typical Drill Hole Logs

Rock Log

Soil Log
Cone Penetration Test (CPT)

Pros:
- Widely available
- Efficient
- No water, mud or air
- Advance many holes in comparison

Cons:
- No samples
- Push depth limitations
Borings Reduce Cost Uncertainty
Geophysics

- Down hole geophysics
- Seismic reflection
- Seismic refraction
- Resistivity
- Ground penetrating radar
- Seismic tomography
- Bathymetry
- Magnetics
Reflection Profile
Marine Geophysics

<table>
<thead>
<tr>
<th>SYSTEM</th>
<th>INFORMATION</th>
<th>DEPTH/RANGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Echo Sounder</td>
<td>Water Depth</td>
<td>0-10 km below water surface</td>
</tr>
<tr>
<td>2 High-Resolution Sub-Bottom Profiler</td>
<td>Shallow Geology</td>
<td>2-20 m below sea floor</td>
</tr>
<tr>
<td>3 Seismic Reflection Profiling System</td>
<td>Medium to Deep Geology</td>
<td>10-1000 m below sea floor</td>
</tr>
<tr>
<td>4 Side Scan Sonar</td>
<td>Sea-Floor Topography and Discrete Objects</td>
<td>50-500 m left and right of trackline</td>
</tr>
<tr>
<td>5 Magnetometer</td>
<td>Magnetic Characteristics of Geology or Discrete Objects</td>
<td>Variable depending on feature</td>
</tr>
<tr>
<td>6 Sonobuoy</td>
<td>Compressional Velocity of Geologic Units</td>
<td>10-1000 m below sea floor</td>
</tr>
<tr>
<td>7 Navigation System</td>
<td>Horizontal Position</td>
<td>10-200 km range</td>
</tr>
</tbody>
</table>
Marine Seismic Refraction
Typical Lab Testing

• Soil
  – USCS classification
  – Strength & Modulus
  – Moisture/density
  – Plasticity
  – Gradation

• Rock
  – Rock classification
  – Compressive/shear strength
  – Tensile strength
  – Moisture/density
  – Durability, abrasivity, slake, toughness
Geologic Profiles –
Understand Geologic Setting
Risk Topics

- Settlement
- Flowing Ground
- Soft Soil Settlement
- Faults and Joints
- Heavy Ground
- Squeezing Ground
- Rock Burst
- Mixed Face
- Mixed Ground
- Obstructions
- Water bearing features & Water Table
- Groundwater Control
- Natural Gas
- Friction
- Stickiness
- Sensitive Soils
- Impacts of fines on slurry separation
- Soil Conditioning
- Abrasion
- Invert Degradation
Settlement

Average Slope = \( S_{\text{max}} / W \)

\[ S = \frac{-Y^2}{2 \cdot i^2} \]

\[ D = 2R \]

\[ \beta \]

\[ W \approx 2.5i \]

\[ 0.05 S_{\text{max}} \]

Ground Surface

Adjacent Structure

Influence Line
Settlement Mechanisms

- Tunneling operations have inherent risks of settlement from:
  - Excessive overcut
  - Excessive or uncontrolled spoil removal
  - Driving of temporary soil supports
  - Inflow of water in granular soils
Settlement Monitoring

- Settlement should be controlled by:
  - Designing construction methods to prevent settlement
  - Continued monitoring of surface and subsurface conditions for settlement or indicators
  - Extensometers:
Flowing Ground in TBM
## Tunnelman’s Ground Classification

*after Heuer and Virgens (1987) and Brandt (1970)*

<table>
<thead>
<tr>
<th>Ground Class</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hard or Firm</td>
<td>Heading may be advanced without roof support. Firm tunnel heading can be advanced without roof support, and the permanent roof support can be constructed before the ground will start to move.</td>
</tr>
<tr>
<td>Slow Raveling to Fast Raveling</td>
<td>Chunks and flakes of material drop out of the roof or the sides. In fast raveling ground, the process starts within a few minutes. In slow raveling ground, the process takes longer.</td>
</tr>
<tr>
<td>Squeezing</td>
<td>Ground slowly advances into the tunnel without fracturing and without a perceptible increase of water content in the ground surrounding the tunnel.</td>
</tr>
<tr>
<td>Swelling</td>
<td>Like squeezing ground, swelling ground moves slowly into the tunnel, but the movement is associated with a very considerable volume increase in the ground surrounding the tunnel.</td>
</tr>
<tr>
<td>Cohesive Running to Running</td>
<td>Material “runs” into the tunnel like granulated sugar until a natural slope is established. If the “run” is preceded by a brief period of raveling, the ground is called cohesive running.</td>
</tr>
<tr>
<td>Very Soft Squeezing</td>
<td>Ground advances rapidly into the tunnel in a plastic flow.</td>
</tr>
<tr>
<td>Flowing:</td>
<td>Flowing ground moves like a viscous liquid and can completely fill the tunnel in a short time if not stopped.</td>
</tr>
</tbody>
</table>
Soft Soil and Ground Consolidation

- **Normally Consolidated Clay**: The present overburden pressure is the most the soil has ever seen.

- **Overconsolidated Clay**: The present overburden pressure is less than the soil has experienced in the past.
Soft Soil Settlement

Figure 4. Schematic of Jet Grout Procedure (Mitchell, 1981)
Faults
Fault Inflow into Tunnel

STARTER TUNNEL RECOVERY
8/23/10 Graveyard
TBM chamber and starter tunnel
Heavy Ground

• Unable to advance TBM due to immense pressures
• Encountered in deep, fault zones
Terzaghi’s Rock Load Classification

Terzaghi’s Rock Load Classification; after Terzaghi (1946), Deere et al. (1970), and Rose (1982)

<table>
<thead>
<tr>
<th>Rock Load Class</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intact</td>
<td>Contains neither joints nor hair cracks. Hence, if it breaks, it breaks across sound rock. On account of the injury of the rock due to blasting, spalls may drop off the roof several hours after blasting. This is known as spalling condition. Hard, intact rocks may also be encountered in the popping condition involving the spontaneous and violent detachment of rock slabs from sides or roof.</td>
</tr>
<tr>
<td>Stratified</td>
<td>Consists of individual strata with little or no resistance against separation along the boundaries between strata. The strata may or may not be weakened by transverse joints. In such rock, the spalling condition is quite common.</td>
</tr>
<tr>
<td>Moderately jointed</td>
<td>Contains joints and hair cracks, but the blocks between joints are locally grown together or so intimately interlocked that vertical walls do not require lateral support. In rocks of this type, both the spalling and the popping condition may be encountered.</td>
</tr>
<tr>
<td>Blocky and seamy</td>
<td>Consists of chemically intact or almost intact rock fragments, which are entirely separated from each other and imperfectly interlocked. In such rock, vertical walls may require support. Moderately blocky and seamy rock has no side pressure; very blocky and seamy rock has little or no side pressure.</td>
</tr>
<tr>
<td>Crushed</td>
<td>Crushed but chemically intact rock has the character of a crusher run. If most or all of the fragments are as small as fine sand grains and no re-cementation has taken place, crushed rock below the water table exhibits the properties of water-bearing sand.</td>
</tr>
<tr>
<td>Squeezing</td>
<td>Slowly advances into the tunnel without perceptible volume increase. Prerequisite for squeeze is a high percentage of microscopic and sub-microscopic particles of micaceous minerals or of clay minerals with a low swelling capacity.</td>
</tr>
<tr>
<td>Swelling</td>
<td>Advances into the tunnel chiefly because of expansion. The capacity to swell seems to be limited to those rocks that contain clay minerals with a high swelling capacity, such as montmorillonite.</td>
</tr>
</tbody>
</table>
Faults and Joints - Outcrop Mapping
Faults and Joints - Cross Hole Geophysics / Tomography

- Approximate existing (red) and planned (gray) tunnel
- Sources
- Receivers
- Depth of inferred range
- Elevation/depth, feet
- Possible breccia "chimney" - total surveyed volume below elev. 600 ft estimated at 6,000 to 7,000 cu yd
- Possible tectonic fracture planes
- Tunnel anomaly

Locations:
- CH#1, CH#2, CH#3
- 32°54'00"N, 088°16'00"W
- 32°54'00"N, 088°16'00"W
- 32°54'00"N, 088°16'00"W
- 32°54'00"N, 088°16'00"W
Squeezing Ground
Rock Burst Potential

- In-situ Stress
- Brittleness
- Stored Energy
- Released Energy
Typical Lab Testing

• Rock
  – Rock classification
  – Compressive/shear strength
  – Tensile strength (Brazilian)
  – Moisture/density
  – Durability, abrasivity, slake, toughness
Mixed Face / Line and Grade

Jet Grouting
West Bank Relief Interceptor, Dallas, Texas

Cross Section

Clay

Rock

6 ft min.
Mixed Face - Seismic Refraction
Mixed Ground Conditions

Soil and Rock Symbols:
- Fill
- Silty Clay to Clay
- Silt
- Sand
- Gravel
- Clayey Silt
- Clayey Sand
- Silty Sand & Sandy Silt
- Mudstone
Obstructions

- Abandoned Ground Support Systems
- Old Foundation Block
- Piles and Building Foundations
- Wells and Casings
- Boulders
Obstructions - Geology, GPR, Well Records, Utilities

Geologic Environment / Prior Experience

Well Records

Ground Penetrating Radar (GPR)

Pothole Utilities
Obstructions - Test Pits and Large Diameter Borings

Test Pits: Used for soil logging, sample collection and lab testing materials anticipated to be encountered.

Large Diameter Borings
Water Bearing Features & Water Table Location

- Tunnel Alignment
- Shaft
- Fractured Rock
- Highly permeable sand-gravel
- Highly permeable Aquifer
- Unconfined Aquifer
- Confined Aquifer
- Impermeable Strata
- Recharge Area
- Water Table
- Piezometric Surface
- Ground Surface
- Flowing Well
- Water Table Well
- Artesian Well
- Screen
- Clay
Groundwater Characterization

- Characterization
  - Water wells
  - Packer testing
Locate Water - Piezometers

Typical stand-pipe piezometer

Multi-level vibrating wire piezometer

Fully Grouted Multi-level vibrating wire piezometer

Legend:
- Overburden
- Rock
- Bentonite Plug (Hydrated Chips or Pellets)
- Well Graded Filter Sand
- Cement-Bentonite Grout
- Riser Cable
- Pressure Transducer

Notes:
1. Piezometers are installed in-line with the placement pipe.
2. Fully grouted borehole
3. Grout can be delivered through the PVC pipe in installations that are up to 30m (100ft) deep.
4. Pipe & signal cable from piezo below
5. Coupling at bottom of housing
6. Coupling at top of housing
7. PVC “placement” pipe makes it easy to place piezometers at the specified elevations.
8. Signal cables are protected by PVC “placement” pipe.
Packer Testing

- Inflation Tube
- Perforated Screen
- Inflatable Packer
- Test Zone
- End Cap
- Perforated Screen
- End Plug
Groundwater Control

- Grouting inside of tunnel
Hazardous Gases & Contaminants Underground

- Methane (CH4)
- Hydrogen Sulfide (H2S)
- Carbon Dioxide (CO2)
- Gasoline Vapors / Hydrocarbons
- Chlorinated Solvents (PCE, DCE, & TCE)
Gas - Sampling Methods

a. Drive-point sampling tube.
- borehole
- grout
- steel pipe
- SS tubing
- undisturbed soil

b. Deep soil gas well.
- valved probe covers
- sand
- grout
- PVC pipe

C. Combination soil gas and groundwater monitoring well.
- tubing
- well casing
- vapor port
- screen
- filter pack
## Friction

<table>
<thead>
<tr>
<th>General Description</th>
<th>Grain Shape</th>
<th>Loose, $\phi$ (deg)</th>
<th>Dense, $\phi$ (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ottawa Standard Sand</td>
<td>Well Rounded</td>
<td>28</td>
<td>35</td>
</tr>
<tr>
<td>Eroded Sandstone</td>
<td>Rounded</td>
<td>31</td>
<td>37</td>
</tr>
<tr>
<td>Fluvial Silty Sand</td>
<td>Subrounded</td>
<td>33</td>
<td>37</td>
</tr>
<tr>
<td>Glacial Silty Sand</td>
<td>Subangular to subrounded</td>
<td>36</td>
<td>40</td>
</tr>
<tr>
<td>Great Salt Lake Sand</td>
<td>Angular</td>
<td>38</td>
<td>47</td>
</tr>
<tr>
<td>Well-graded, compacted crushed rock</td>
<td>Angular</td>
<td>-</td>
<td>60</td>
</tr>
</tbody>
</table>

*Holtz & Kovacs, 1981*
Large Diameter Pipe Jacking Application

- Backacter Shield
- Cutter Boom Shield
- Slurry
- Earth Pressure Balance
Sticky Soils
Stickiness – Clogging Potential
(Thewes, 2005)

EPBM Clogging Potential

**Soil Data**

<table>
<thead>
<tr>
<th>Boring Number</th>
<th>Sample Number and Type</th>
<th>Sample Depth (ft)</th>
<th>Natural Moisture Content, w (%)</th>
<th>Atterberg Limits</th>
<th>Plasticity Index, PI</th>
<th>$I_c = (LL-w)/PI$</th>
<th>Geologic Unit</th>
<th>Strata Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>DH-1</td>
<td>3-CB</td>
<td>4.0</td>
<td>16.9</td>
<td>23</td>
<td>23</td>
<td>0.27</td>
<td>Sandy Lean Clay</td>
<td>Claystone</td>
</tr>
<tr>
<td>DH-3</td>
<td>7-CB</td>
<td>28.0</td>
<td>13.4</td>
<td>40</td>
<td>23</td>
<td>1.16</td>
<td>Lean Clay</td>
<td>Claystone</td>
</tr>
<tr>
<td>DH-4</td>
<td>6-CB</td>
<td>29.0</td>
<td>17.1</td>
<td>45</td>
<td>25</td>
<td>1.12</td>
<td>Sandy Lean Clay</td>
<td>Claystone</td>
</tr>
<tr>
<td>DH-5</td>
<td>6-CB</td>
<td>29</td>
<td>17.1</td>
<td>47</td>
<td>28</td>
<td>1.07</td>
<td>Lean Clay</td>
<td>Claystone</td>
</tr>
<tr>
<td>DH-6</td>
<td>2-CB</td>
<td>9</td>
<td>21.6</td>
<td>50</td>
<td>33</td>
<td>0.86</td>
<td>Lean Clay</td>
<td>Alluvial</td>
</tr>
</tbody>
</table>
Plasticity Testing
Sensitive Soils / Collapsible Soils

Sensitivity

- Ratio of Unconfined compressive strength of an undisturbed soil specimen to its unconfined strength after remoulding.

$$S_t = \frac{(q_u)_{\text{undisturbed}}}{(q_u)_{\text{remoulded}}}$$

<table>
<thead>
<tr>
<th>St</th>
<th>Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-4</td>
<td>Normal</td>
</tr>
<tr>
<td>4-8</td>
<td>Sensitive</td>
</tr>
<tr>
<td>8-15</td>
<td>Extra-Sensitive</td>
</tr>
<tr>
<td>&gt; 15</td>
<td>Quick</td>
</tr>
</tbody>
</table>
Abrasivity - High Wear from Abrasion
Abrasivity - Cerchar Tests & Thin Section Analysis

The CAI is measured by drawing a sharp steel point across a freshly broken surface.

Granitic Porphyry Thin Section
Abrasivity - Soil Laboratory Testing

Millers Drilling Index (ASTM G75-01)

Fig 1: SAT testing in the NTNU abrasion test rig. The test piece is clamped under the 10kg load and is running on sand supplied on the rotating disc by the vibrating feeder.

RAR - Relative Abrasion Resistance

<table>
<thead>
<tr>
<th>Material</th>
<th>Relative abrasion resistance</th>
<th>Compressive strength $(\sigma = 4)$ (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-crystal quartz</td>
<td>1 ± 0.001</td>
<td>360 ± 120</td>
</tr>
<tr>
<td>Jasplilite</td>
<td>0.809 ± 0.002</td>
<td>489 ± 132</td>
</tr>
<tr>
<td>Granite</td>
<td>0.569 ± 0.003</td>
<td>186 ± 48</td>
</tr>
<tr>
<td>Dark norite</td>
<td>0.470 ± 0.002</td>
<td>287 ± 35</td>
</tr>
<tr>
<td>Light norite</td>
<td>0.440 ± 0.002</td>
<td>209 ± 28</td>
</tr>
<tr>
<td>Quartzite</td>
<td>0.436 ± 0.004</td>
<td>250 ± 87</td>
</tr>
<tr>
<td>Syenite</td>
<td>0.400 ± 0.006</td>
<td>176 ± 27</td>
</tr>
<tr>
<td>Single-crystal felspar</td>
<td>0.395 ± 0.003</td>
<td>219 ± 103</td>
</tr>
<tr>
<td>Sandstone</td>
<td>$c$ 0.04</td>
<td>41 ± 6</td>
</tr>
<tr>
<td>Marble</td>
<td>$c$ 0.03</td>
<td>138 ± 36</td>
</tr>
</tbody>
</table>
Fines in Slurry - Slurry Separation Plant

Diagram showing the flow of slurry through the plant, with labels for the upper and lower discharge, feed inlet, and various components of the separation system. The diagram includes numbered steps from 1 to 7, corresponding to the labels: coarse screen, process tank 1, centrifugal pump, coarse cyclones, dewatering screens, process tank 2, and fine cyclones, with final discharge to the TBM.
Fines in Slurry

Hydrometer Test

Grain Size Analysis
Invert Degradation
“Creates an huge risk to the health and safety of participants told to go into small unworkable spaces for the convenience of an owner trying to avoid any inconvenience to his local traffic. While some times there “is no other way” this has become part of the methodology and will stop suddenly when some one gets killed not to mention the huge cost of retooling by the contractor buying new equipment.
“Surprises Are Inevitable - There will always be unexpected ground conditions and neither the owner nor the design team can completely eliminate surprises from complex underground projects.”

Gould, 1995