Geotechnical Risk for Underground Construction
<table>
<thead>
<tr>
<th>Agenda</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Obstructions</td>
</tr>
<tr>
<td>3. Abrasivity</td>
</tr>
<tr>
<td>4. TBM Performance</td>
</tr>
<tr>
<td>5. Friction</td>
</tr>
<tr>
<td>7. Stickiness</td>
</tr>
<tr>
<td>10. Slaking, Raveling, &amp; Invert Degradation</td>
</tr>
</tbody>
</table>
Obstructions:

- Risk

- Abandoned Ground Support Systems

- Steel Pipe Obstruction

- Boulders

- Piles and Building Foundations

- Old Foundation Block

- Wells and Casings

- Abandoned Ground Support Systems

- Photo Credit: TunnelTalk

- Steel Pipe Obstruction

- Photo Credit: The Seattle Times

- Wells and Casings

- Photo Credit: Stantec

- Boulders

- Photo Credit: Stantec
Obstructions: Characterization
Obstructions: Mitigation

Photo Credit: Akkerman

Photo Credit: Stantec

Photo Credit: Herrenknecht
Mixed Ground: Risk

Photo Credit: Soumagne Tunnel

Photo Credit: GeoHazards

Photo Credit: Stantec
Mixed Face: Risk

MTBM PIPELINE CROSSING AT .25% SLOPE

JACKING SHAFT

Photo Credit: Portland Water Bureau
Mixed Face: Characterization

Photo Credit: Stantec
Mixed Face: Mitigation
Abrasivity:
Risk
Abrasivity: Characterization

Photo Credit: Colorado School of Mines

Photo Credit: St. Cloud Granite

Granitic Porphyry Thin Section

Photo Credit: Colorado School of Mines
Abrasivity: Characterization

Millers Drilling Index (ASTM G75-01)

![Image of Millers Drilling Index](Image)

**RAR:** Relative Abrasion Resistance

**Table: Relative Abrasion Resistance and Uniaxial Compressive Strengths of the Materials Drilled**

<table>
<thead>
<tr>
<th>Material</th>
<th>Relative abrasion resistance</th>
<th>Compressive strength (σ = 4) MPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single-crystal quartz</td>
<td>1 ± 0.001</td>
<td>360 ± 120</td>
</tr>
<tr>
<td>Jasplite</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>

Photo Credit: ASTM
Abrasivity: Mitigation

TBM/Disc Cutter Mechanic Shop

Photo Credit: Alimineli Madhava Reddy Tunnel Project

Photo Credit: Trakkom
Abrasivity: Mitigation
TBM Performance: Risk

[Image of a diagram showing the layout of Cowles Mountain with stations and elevations on the x-axis and elevation on the y-axis.]

[Image of a bar chart showing weekly progress of TBM excavation from March to September 1992.]
TBM Performance: Characterization

Unconfined Compressive Strength

Brazilian Tensile Strength

Resiliency (Toughness)

Photo Credit: Colorado School of Mines
TBM Performance: Mitigation

![Graph showing Normal Force vs Cutter Number]

![Diagram illustrating Geology and Rock Properties]

![Diagram showing Corrected ROP: Cutter Wear, Brittleness, Petrographic Features, Porosity, Foliation/Bedding, Joints/Fissures]

![Diagram explaining Spacing (S) and Chip Formation: \[ \frac{S}{p} = 10 - 20 \]]

Photo Credit: Colorado School of Mines
<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>Sand from St. Peter sandstone</td>
<td>Rounded</td>
<td>31</td>
<td>37</td>
</tr>
<tr>
<td>Silty sand from Franklin Falls Dam site, NH</td>
<td>Subrounded</td>
<td>33</td>
<td>37</td>
</tr>
<tr>
<td>Silty sand from vicinity of John Martin Dam, CO</td>
<td>Subangular to Subrounded</td>
<td>36</td>
<td>40</td>
</tr>
<tr>
<td>Sand from Great Salt Lake</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>
Friction: Characterization
Friction: Mitigation

Intermediate Jacking

Interjack Installation

Automated Pipe Lubrication

Photo Credit: Stantec

Photo Credit: Tunneling and Underground Space Technology

Photo Credit: Herrenknecht
Thrust Restraint

Concrete Thrust Block
THRUST BLOCK RESISTANCE

\[ T_{\text{all}} = \frac{1}{2} K_p \gamma (H^2-h^2)B \]

Factor of Safety

For a square thrust block of B, it is

\[ \delta = \frac{qB(1-u^2)}{E_s} \]

\[ q = \text{Bearing pressure on thrust block} \]

\[ u = \text{Poisson’s Ratio} \]

\[ E_s = \text{Young’s Modulus of the soil} \]

\[ P_{\text{ult}} = \left[ \left( h + \frac{H}{2} \right) \gamma \tan^2 \left( 45 + \frac{\phi}{2} \right) + 2c \tan^2 \left( 45 + \frac{\phi}{2} \right) \right] HB \]

\( P_{\text{ult}} = \) Passive resistance of thrust block

\( \gamma = \) Soil unit weight

\( H = \) Height of thrust block

\( h = \) Depth to top of thrust block

\( B = \) Width of thrust block

\( \phi = \) Soil friction angle

\( c = \) Soil cohesion
Thrust Restraint: Mitigation

Photo Credit: Stantec

Photo Credit: Collucio Construction
Stickiness: Risk

Photo Credit: Stantec

Photo Credit: Stantec

Photo Credit: Stantec
Stickiness: Characterization

![Graph showing stickiness characterization with data table below.](Image)

<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>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Liquid Limit, LL (%)</td>
<td>Plastic Limit, PL (%)</td>
</tr>
<tr>
<td>DH-1</td>
<td>3-CB</td>
<td>4.0</td>
<td>16.9</td>
<td>23</td>
</tr>
<tr>
<td>DH-3</td>
<td>7-CB</td>
<td>28.0</td>
<td>13.4</td>
<td>40</td>
</tr>
<tr>
<td>DH-4</td>
<td>6-CB</td>
<td>29.0</td>
<td>17.1</td>
<td>45</td>
</tr>
<tr>
<td>DH-5</td>
<td>6-CB</td>
<td>29</td>
<td>17.1</td>
<td>47</td>
</tr>
<tr>
<td>DH-6</td>
<td>2-CB</td>
<td>9</td>
<td>21.6</td>
<td>50</td>
</tr>
</tbody>
</table>

Photo Credit: Stantec
Stickiness: Mitigation

Different Conditioners
- Dispersants
- Polymer
- Limited amounts of water
- Jetting or hand removal
Sensitive Soils: Risk

GRANBY STREET SEWER
Hartford, CT

• Encountered very sensitive varved clays.

• Three tunnels constructed via microtunneling for 2,500 linear feet total.

Photo Credit: Stantec
Sensitive Soils: Characterization

Ratio of Unconfined Compressive Strength of an undisturbed soil specimen to its unconfined strength after remolding

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

<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>

Clay Minerals

House of Cards Structure (held together by salts)

After Dissolution of Salts & Compaction

Photo Credit: Soil Mechanics – Soil Classification and Compaction
Sensitive Soils: Mitigation

Photo Credit: Mitchell, 1981

Photo Credit: Stantec
Fines in Slurry: Risk

Photo Credit: Slurry Separation Image Search

Photo Credit: Stantec

Photo Credit: Stantec
Fines in Slurry: Characterization

Hydrometer Test

Photo Credit: International Journal of Geosciences
Fines in Slurry: Mitigation
Slaking, Raveling, & Invert Degradation: Risk
Slaking, Raveling, & Invert Degradation: Characterization

<table>
<thead>
<tr>
<th>ID₂ (%)</th>
<th>Durability classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 - 25</td>
<td>Very Low</td>
</tr>
<tr>
<td>26 - 50</td>
<td>Low</td>
</tr>
<tr>
<td>51 - 75</td>
<td>Medium</td>
</tr>
<tr>
<td>76 - 90</td>
<td>High</td>
</tr>
<tr>
<td>91 - 95</td>
<td>Very High</td>
</tr>
<tr>
<td>96 - 100</td>
<td>Extremely High</td>
</tr>
</tbody>
</table>

Photo Credit: Colorado School of Mines
Slaking, Raveling, & Invert Degradation: Mitigation
Groundwater Control: Risk

Photo Credit: Stantec
Groundwater Control: Characterization

Diagram showing various groundwater control elements including recharge area, piezometric surface, groundwater table, tunnel alignment, shaft, flowing well, artesian well, unconfined aquifer, confined aquifer, impermeable strata, and highly permeable sand-gravel.
Groundwater Control: Characterization

Typical stand-pipe piezometer

Multi-level vibrating wire piezometer

Fully Grouted Multi-level vibrating wire piezometer

Photo Credit: Stantec

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

Notes:
1. Signal cables are protected by PVC “placement” pipe.
2. PVC “placement” pipe makes it easy to place piezometers at the specified elevations.
3. Piezometers are installed inline with the placement pipe.
4. Grout can be delivered through the PVC pipe in installations that are up to 30m (100ft) deep.
Groundwater Control: Characterization

- Packer Testing (Single & Double)
- Constant Head
- Falling Head
- Pump Test
Groundwater Control: Mitigation

Photo Credit: Newman Dewatering

Photo Credit: Herrenknecht

Photo Credit: Robbins

Photo Credit: TunnelTalk
Faults:

Risk

Fault "A"

Fault "B"

High Angle Normal Fault

Fault "B" right side Chamber

Photo Credit: Stantec
Faults:
Characterization

Fault exposed in tunnel & discontinuity data collected to document it

Fault/Lineation Map
Aerial Photo Lineation Map

Photo Credit: Stantec
Faults: Mitigation

Probe Drill/Grout

Grouting Array

High Groundwater Inflows

Photo Credit: TunnelTalk

Photo Credit: Trevor Carter
Heavy Ground: Risk

- Unable to advance TBM due to immense pressures
- Encountered in deep, fault zones

Photo Credit: McMillen Jacobs Associates

Photo Credit: Stantec
Heavy Ground: Characterization

- Drill hole through faults from surface
- RQD values
- Probe drilling in tunnel

<table>
<thead>
<tr>
<th>Box 4</th>
<th>3/27-28/2018</th>
<th>RQD %</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>90.5'-95.5'</td>
<td>50%</td>
</tr>
<tr>
<td>19</td>
<td>95.5'-100.5'</td>
<td>50%</td>
</tr>
<tr>
<td>20</td>
<td>100.5'-104.2'</td>
<td>14%</td>
</tr>
<tr>
<td>21</td>
<td>104.2'-105.5'</td>
<td>92%</td>
</tr>
<tr>
<td>22</td>
<td>105.5'-109.7'</td>
<td>43%</td>
</tr>
<tr>
<td>23</td>
<td>109.7'-110.5'</td>
<td>100%</td>
</tr>
</tbody>
</table>

Photo Credit: Stantec
Heavy Ground: Mitigation

- Heavy support
- Pre-support
- Spiling
- Thicker shield
- Don’t stop progress
Heavy Ground: Mitigation

Photo Credit: McMillen Jacobs Associates
Squeezing Ground: Risk
Squeezing Ground: Characterization

- Rule of thumb—UCS vs overburden stress
- Strength/stress ratio
- Modeling
- Linear into plastic

Photo Credit: Trevor Carter

Photo Credit: Stantec

Photo Credit: Tunneling in Squeezing Ground
Squeezing Ground: Mitigation

- Yielding support
- Ribs w/ slides
- American commercial
- TBM shield is tapered
- Shotcrete—jacks between shotcrete panels
Rock Burst: Risk

- In-situ Stress
- Britteness
- Stored Energy
- Released Energy
Rock Burst: Risk

2nd Video

Video Credit: McNally Support System - Robbins
Rock Burst: Mitigation

Drilling of horizontal and vertical relief holes, and shotcrete application

Photo Credit: Journal of the Southern African Institute of Mining and Metallurgy

Photo Credit: Stantec

Photo Credit: Mirarco
Hydrothermal Conditions:
Risk

Photo Credit: Stantec

Geothermal Inflow, Iceland

Photo Credit: Tunneltalk

Photo Credit: Stantec
Hydrothermal Conditions: Characterization

Geothermal Gradient Map, CO
Photo Credit: Stantec

Temperature Gradient w/ Depth
Photo Credit: Stantec

Upper Colorado River Hot Spring
Photo Credit: Stantec

Mapped Hot Springs
Photo Credit: Stantec
Hydrothermal Conditions: Mitigation

Increased ventilation

Mandatory Breaks & Limited Working Hours

Ice Vest
Hazardous Gas: Risk

Photo Credit: TunnelTalk

Photo Credit: Ashley Pon/Getty Images

Hazardous Gases Underground
Applications to Tunnel Engineering

Barry R. Doyle
Hazardous Gas: Characterization

Bacteria

Geothermal fields: CO₂

Aerobes: CO₂
Sulfate reducers: H₂S
Methanogens: CH₄

Hydrothermal Alteration: H₂S

Petroleum fields: CH₄

Gas station: gasoline vapors

Photo Credit: MicrobeWiki – Kenyon College

Photo Credit: Geothermal Education Office

Photo Credit: James Maynard

Photo Credit: KQED Science

Photo Credit: flickr
Hazardous Gas: Characterization

Pore gas sampling

Sample Screening

Groundwater sampling
Hazardous Gas: Mitigation

Mechanical Controls

Crew Training

System Monitoring

Methane Gas Detection

Photo Credit: Stantec
Settlement: Risk

King Street in Seattle, above Bertha TBM

Photo Credit: KIRO 7 News
Settlement: Characterization

![Diagram showing settlement characterization](image-url)

**Average Slope**

\[ \text{Average Slope} = \frac{S_{\text{max}}}{W} \]

**Settlement Influence Line**

\[ S = \frac{V_s}{\sqrt[4]{2\pi}} \]

**Parameters**

- \( V_s \): Surface settlement
- \( S_{\text{max}} \): Maximum settlement
- \( W \): Wall length
- \( \beta \): Angle of slope
- \( D = 2R \): Diameter
- \( i \): Internal friction angle
- \( z \): Vertical distance

*Photo Credit: Stantec*
Settlement: Mitigation

Photo Credit: Dragageshk

EPB Shield

Mixshield

Variable Density System

Photo Credit: Dragageshk

Photo Credit: Dogus

Backfill Grouting Material

Ground Displacement

Tail Void

Segmental Lining

Advance

Photo Credit: Bft International
Settlement should be controlled by:

- Designing construction methods to prevent settlement
- Continued monitoring of surface and subsurface conditions for settlement or indicators
- Extensometers
Settlement: Mitigation

Photo Credit: Stantec
Flowing Ground: Risk

Clay

Wet fine sand

Wet sand

Silt

Flowing, running ground

Photo Credit: Stantec
Different Conditioners

- Dispersants
- Foam Injection Ratios
- High Density Limestone Slurry
- Bentonite
- Polymer
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
Thank you