Geotechnical Risk for Underground Construction
Agenda

1. Obstructions
2. Mixed Ground / Mixed Face
3. Abrasivity
4. TBM Performance
5. Friction
6. Thrust Restraint
7. Stickiness
8. Sensitive Soils
9. Fines in Slurry
10. Slaking, Raveling, & Invert Degradation
11. Groundwater Control
12. Faults
13. Heavy Ground
14. Squeezing Ground
15. Rock Burst
16. Hydrothermal Conditions
17. Hazardous Gas
18. Settlement
19. Flowing Ground
Obstructions: Risk

Piles and Building Foundations

Abandoned Ground Support Systems

Old Foundation Block
Photo Credit: Stantec

Steel Pipe Obstruction
Photo Credit: The Seattle Times

Wells and Casings
Photo Credit: Stantec

Boulders
Photo Credit: Stantec

Photo Credit: TunnelTalk
Obstructions: Characterization
Obstructions:
Mitigation

Photo Credit: Akkerman

Photo Credit: Herrenknecht

Photo Credit: Stantec

Photo Credit: Akkerman
Mixed Ground: Risk

Photo Credit: Soumagne Tunnel

Photo Credit: GeoHazards

Photo Credit: Stantec

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

MTBM PIPELINE CROSSING AT .25% SLOPE

Photo Credit: Portland Water Bureau
Mixed Face: Characterization

Photo Credit: Stantec
Mixed Face: Mitigation

Jet Grouting
West Bank Relief Interceptor, Dallas, Texas

Cross Section

Clay
6 ft min.

Photo Credit: Hayward Baaker
Photo Credit: Stantec
Photo Credit: Daegu Metropolitan
Photo Credit: Stantec
Abrasivity:
Risk

Photo Credit: Stantec

Photo Credit: Stantec

Photo Credit: Stantec
Abrasivity: Characterization

Photo Credit: Colorado School of Mines

Granitic Porphyry Thin Section
Photo Credit: Colorado School of Mines
Abrasivity: Characterization

Millers Drilling Index (ASTM G75-01)

RAR: Relative Abrasion Resistance
Abrasivity: Mitigation

TBM/Disc Cutter Mechanic Shop

Photo Credit: Alimneti Madhava Reddy Tunnel Project

Photo Credit: Trakkom
Abrasivity: Mitigation
TBM Performance: Risk

Photo Credit: Stantec
Unconfined Compressive Strength

Brazilian Tensile Strength

Resiliency (Toughness)
TBM Performance: Mitigation

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>

Photo Credit: Holtz & Kovacs, 1981
Friction: Characterization

Photo Credit: Stantec

Photo Credit: Retsch

Photo Credit: Stantec

Photo Credit: Stantec
Friction: Mitigation

Interjack Installation

Intermediate Jacking

Automated Pipe Lubrication
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

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

- \( P_{\text{ult}} \): 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 Block Deformation

For a square thrust block of \( B \), it is

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

- \( q \): Bearing pressure on thrust block
- \( u \): Poisson’s Ratio
- \( E_s \): Young’s Modulus of the soil

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

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

Photo Credit: Stantec

Photo Credit: Collucio Construction

Photo Credit: Collucio Construction
Stickiness: Risk
Stickiness: Characterization

### 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>Liquid Limit, LL (%)</th>
<th>Plastic Limit, PL (%)</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>0</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>17</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>20</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>29.0</td>
<td>17.1</td>
<td>47</td>
<td>19</td>
<td>28</td>
<td>1.07</td>
<td>Lean Clay</td>
<td>Claystone</td>
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<td>DH-6</td>
<td>2-CB</td>
<td>9</td>
<td>21.6</td>
<td>50</td>
<td>17</td>
<td>33</td>
<td>0.86</td>
<td>Lean Clay</td>
<td>Alluvial</td>
</tr>
</tbody>
</table>

Photo Credit: Stantec
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.
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>

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

Photo Credit: GN Solids Control

Diagram of slurry system with labels:
1. coarse screen
2. process tank 1
3. centrifugal pump
4. coarse cyclones
5. dewatering screens
6. process tank 2
7. fine cyclones
8. process tank 3

Photo Credit: GN Solids Control

Diagram showing upper and lower discharge points:
Upper Discharge (Liquid, Small Particles, Air)
Lower Discharge (Liquid, Large Particles)

Photo Credit: GN Solids Control
Slaking, Raveling, & Invert Degradation: Risk
### Slaking, Raveling, & Invert Degradation: Characterization

![Photos](photo-credit-colorado-school-of-mines)

<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>
Slaking, Raveling, & Invert Degradation: Mitigation
Groundwater Control: Risk
Groundwater Control: Characterization

Typical stand-pipe piezometer

Multi-level vibrating wire piezometer

Fully Grouted Multi-level vibrating wire piezometer
Groundwater Control: Characterization

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

Photo Credit: Newman Dewatering

Photo Credit: Herrenknecht
Faults:
Risk

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

Fault “A”
Fault “B”
Fault “B” right side Chamber
High Angle Normal Fault

Photo Credit: Stantec
Faults: Characterization

Fault exposed in tunnel & discontinuity data collected to document it.
Faults: Mitigation

Probe Drill/Grout

Grouting Array
Photo Credit: TunnelTalk

High Groundwater Inflows
Photo Credit: Trevor Carter
Heavy Ground: Risk

- Unable to advance TBM due to immense pressures
- Encountered in deep, fault zones
Heavy Ground: Characterization

- Drill hole through faults from surface
- RQD values
- Probe drilling in tunnel
Heavy Ground: Mitigation

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

Photo Credit: J.F. Shea – 2012 NAT
Heavy Ground: Mitigation

Photo Credit: McMillen Jacobs Associates
Squeezing Ground: Risk

Photo Credit: Stantec

Photo Credit: Squeezing Soil Image Search
Squeezing Ground: Characterization

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

Photo Credit: Trevor Carter

Photo Credit: Tunneling in Squeezing Ground

Photo Credit: Stantec
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
- Brittleness
- Stored Energy
- Released Energy
Rock Burst: Characterization

Photo Credit: Goodman Jack - DGSI

Photo Credit: Stantec

Photo Credit: Hydrofrac

Diagram showing equipment and rock formations with labels for EW-rod, core barrel, orienting device, installation rod, stabilizer, reamer, EX-bit, overcoring bit, deformation gage, water swivel, and sigma values.
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: Mirarco

Photo Credit: Stantec
Hydrothermal Conditions: Risk

Photo Credit: Stantec

Geothermal Inflow, Iceland

Photo Credit: Tunneltalk

Photo Credit: Stantec
Hydrothermal Conditions: Characterization

Geothermal Gradient Map, CO

Temperature Gradient w/ Depth

Upper Colorado River Hot Spring

Mapped Hot Springs
Hydrothermal Conditions:
Mitigation

Increased ventilation
Photo Credit: SRK Consulting

Mandatory Breaks & Limited Working Hours
Photo Credit: Utrop

Ice Vest
Photo Credit: Glaciertek
Hazardous Gas: Risk

Photo Credit: TunnelTalk

Hazardous Gases Underground
Applications to Tunnel Engineering

Barry R. Doyle
Hazardous Gas: Characterization

Bacteria
Photo Credit: MicrobeWiki – Kenyon College

Geothermal fields: CO₂
Photo Credit: Geothermal Education Office

Hydrothermal Alteration: H₂S
Photo Credit: James Maynard

Petroleum fields: CH₄
Photo Credit: KQED Science

Gas station: gasoline vapors
Photo Credit: flickr

Aerobes: CO₂
Sulfate reducers: H₂S
Methanogens: CH₄
Hazardous Gas: Characterization

Pore gas sampling

Sample Screening

Groundwater sampling

Photo Credit: Stantec
Hazardous Gas: Mitigation

System Monitoring

Methane Gas Detection

Mechanical Controls

Crew Training
Settlement: Risk

King Street in Seattle, above Bertha TBM
Settlement: Characterization

![Diagram of tunnel construction and settlement characterization](Photo Credit: Stantec)

- **Average Slope**: \( \frac{S_{\text{max}}}{W} \)
- **Settlement Influence Line**: 
  \[ S = \frac{-Y^2}{2i^2} \frac{V_s}{i \sqrt{2\pi}} \]

Where:
- \( V_s \): Shear wave velocity
- \( W \): Width
- \( S_{\text{max}} \): Maximum settlement
- \( Y \): Distance from the ground surface
- \( i \): Inclination angle
- \( D = 2R \): Diameter of the tunnel

![Diagram of tunnel construction and settlement characterization](Photo Credit: Stantec)
Settlement: Mitigation

EPB Shield

Mixshield

Variable Density System

Photo Credit: Dragageshk

Photo Credit: Dogus

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

Photo Credit: Stantec

Flowing Ground in TBM
Photo Credit: Stantec
Flowing Ground: Mitigation

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