Lessons Learned from the Geotechnical Investigation Program
DC Clean Rivers Project

Speaker: William Edgerton, P.E.  October 2, 2013
Agenda

• Project Overview
• Geologic and Hydrogeologic Setting
• Design and Construction Considerations
• Geotechnical Investigation Program
• Issues, Lessons Learned and Observations
• Other General Lessons Learned and Conclusions
## Project Overview

<table>
<thead>
<tr>
<th>Contract Division</th>
<th>Description</th>
<th>Facilities</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Blue Plains Tunnel (BPT)</td>
<td>• 24,200 LF&lt;br&gt;• 23-ft diameter&lt;br&gt;• 110+ ft deep&lt;br&gt;• 5 shafts</td>
</tr>
<tr>
<td>H</td>
<td>Anacostia River Tunnel (ART)</td>
<td>• 12,600 LF&lt;br&gt;• 23-ft diameter&lt;br&gt;• ~100 ft deep&lt;br&gt;• 6 shafts</td>
</tr>
<tr>
<td>J</td>
<td>NE Boundary Tunnel (NEBT)</td>
<td>• 26,700 LF&lt;br&gt;• 23-ft diameter&lt;br&gt;• 50 to 160 ft deep&lt;br&gt;• 5 shafts</td>
</tr>
<tr>
<td>P</td>
<td>First Street Tunnel</td>
<td>• 2720 LF&lt;br&gt;• 18.5-ft diameter&lt;br&gt;• 60 to 140 ft deep&lt;br&gt;• 4 shafts</td>
</tr>
</tbody>
</table>
Geologic and Hydrogeologic Setting

- Coastal Plains Sediments:
  - Fill
  - Quaternary-age Alluvium
  - Cretaceous-age Patapsco/Arundel Formation (undivided) of the Potomac Group
  - Cretaceous-age Patuxent Formation of the Potomac Group
  - Bedrock (approximate 400 ft deep)
- 3 Main Aquifer Systems:
  - Unconfined water table aquifer in the fill and alluvium sediments;
  - Confined conditions in the Potomac Group sediments;
  - Groundwater within the crystalline bedrock (gneiss and schist)
Soil Classification System

- Similar to Washington Metropolitan Area Transportation Authority (WMATA) classification system
- Soil groups used to organize subsurface information in a manner that addresses soil behavior relevant to tunneling and other construction

<table>
<thead>
<tr>
<th>Geologic Unit</th>
<th>Soil Group</th>
<th>USCS Symbol</th>
<th>General Soil Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fill</td>
<td>Fill</td>
<td>Highly variable – see Section 5.2 and site specific borings</td>
<td></td>
</tr>
<tr>
<td>Alluvium</td>
<td>Alluvial Clay and Silt</td>
<td>CL, CH, ML, MH, OH, OL, PT</td>
<td>Clays, Silts, Organic Soils</td>
</tr>
<tr>
<td></td>
<td>Alluvial Sand</td>
<td>SP, SP-SM, SP-SC, SM, SW, SW-SM, SW-SC, SC, SM</td>
<td>Clean Sand, Sand with Clay or Silt, Silty Sand, Clayey Sand,</td>
</tr>
<tr>
<td></td>
<td>Alluvial Gravel</td>
<td>GP, GP-GM, GP-GC,GM, GW, GW-GM, GW-GC, GC, GM</td>
<td>Clean Gravel, Gravel with Clay or Silt, Silty Gravel, Clayey Gravel</td>
</tr>
<tr>
<td>Potomac Group</td>
<td>G1</td>
<td>CH, MH</td>
<td>Clays and Silts of High Plasticity</td>
</tr>
<tr>
<td></td>
<td>G2</td>
<td>CL, ML</td>
<td>Clay and Silts of Low Plasticity</td>
</tr>
<tr>
<td></td>
<td>G3</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>G3A</td>
<td>SM, SC, SC-SM</td>
<td>Silty Sand, Clayey Sand Silty/Clayey Sand</td>
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<tr>
<td></td>
<td>G3B</td>
<td>GM, GC, GC-GM</td>
<td>Silty Gravel, Clayey Gravel Silty/Clayey Gravel</td>
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<tr>
<td></td>
<td>G4</td>
<td>SP, SP-SM, SP-SC, SW SW-SM, SW-SC</td>
<td>Clean Sand, Sand with Clay or Silt</td>
</tr>
<tr>
<td></td>
<td>G5</td>
<td>GP, GP-GM, GP-GC, GW, GW-GM, GW-GC</td>
<td>Clean Gravel, Gravel with Clay or Silt</td>
</tr>
</tbody>
</table>
Soil Profile of Blue Plain Tunnel
Design and Construction Considerations
Tunnels and Microtunnels

- Liner design
- Machine selection and design
- Obstructions along the tunnel alignment
- Tunneling-induced ground settlements
- Ground improvement
- Groundwater Control

Traylor Skanska Jay Dee, JV TBM Blue Plains Tunnel
Shafts and Near Surface Structures

- Excavation support
- Ground deformation
- Groundwater control
Shafts and Near Surface Structures

- Groundwater control
- Excavation bottom stability
- Uplift
- Break-in and break-out for TBMs (shafts only)
Protection of Structures

- Extensive analyses performed for project
- Modeling Soil Movements
- Structural Modeling for existing structures
Protection of Structures

- Mitigation measures
  - Ground Improvement
  - Structural Rehabilitation
<table>
<thead>
<tr>
<th>Proposed Structure</th>
<th>Design</th>
<th>Construction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tunnels</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Shafts</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Shallow Structures</td>
<td>●</td>
<td>●</td>
</tr>
<tr>
<td>Sewers</td>
<td>●</td>
<td>●</td>
</tr>
</tbody>
</table>
Summary of the Geotechnical Investigation Program (Field)

- **Soil Borings**
  - Mud Rotary
  - Hollow Stem Auger
  - **Sonic Drilling**
- **Soil Samples**
  - Disturbed
    - Split Spoon
    - Sonic Core
  - Undisturbed:
    - Shelby Tube Sampler
    - Pitcher Sampler
    - Dension Sampler
- **Rock Samples**
  - Wireline Rock Core
  - Sonic Rock Core
- **Field Testing**
  - Pumping Test
  - Standard Penetration Test
  - Pressuremeter
  - Crosshole and Downhole Seismic Survey
  - Seismic Refraction
  - Seismic Reflection
  - Slug Test
  - Cone Penetration Test (CPT)
- **Groundwater Monitoring**
  - Monitoring Well
  - Vibrating Wire Piezometer
Geotechnical Investigation Program (Lab Testing)

- Laboratory Testing
  - Atterberg Limits Index Testing
  - **Mineralogy (X-ray diffraction & Petrographic)**
  - Soil Abrasion Test
  - Consolidation Test (ILC, CRS)
  - Strength Test (I-CUTX, K₀-CUTX)
  - Swell Test
  - Soil Corrosion
  - Groundwater Quality
  - Dissolved Gas in Water (H₂S, CH₄)
  - **X-Ray Photography**
Issues, Lessons and Observations

• Sonic Drilling
• Marine Survey
• X-Ray Radiography of Soil Samples
• Coefficient of Lateral Earth Pressure at Rest – $K_0$
• Soil Abrasion Test (SAT)
Sonic Drilling
Sonic Drilling – Great for the project

- Provides continuous coring
  - Complete soil profile for deep shafts and identify sand lenses for tunneling – Very important for preparation of the GBR
- Sonic drilling is almost twice as fast as conventional drilling
  - Sonic – ~50 to 100 ft/day
  - Convention – ~25 to 50 ft/day
- Main issue is the size of the equipment, especially support water.
The Problem and Solution

- **Typical Issues:**
  - Sonic drilling is typically used for continuous (disturbed) coring - no undisturbed samples and no SPT
  - (regional) Sonic drillers did not have rigs that were set-up to do both sonic drilling and undisturbed sampling/SPT

- **Solutions:**
  - Retrofit sonic rig to accommodate the use of automatic hammer
  - Modified the sampler (i.e. Shelby tube)
  - Result: SPTs and undisturbed Samples
Comparison of Sonic and Conventional Boring Logs

- **Sonic Drilling (BPC-48)**

  - Wet, dense, bluish gray, fine to medium, SILTY SAND, estimated 15 - 25% fines, (G3A)
  - At 160.0' changes to bluish gray and brown

- **Mud Rotary (BPC-30)**

  - Moist, very dense, bluish gray, fine to medium, SILTY SAND, estimated 15 - 25% fines, (G3A)
  - At 160.3' changes to fine to coarse, estimated <5% fine gravel
  - At 163.0' changes to very dense
Geophysics - Marine Survey
Geophysics (Marine Surveys)

- **Goal:** Better define alluvium/Potomac Contact
Geophysics - A tale of two surveys

- December 2009 Reflection Survey
  - Results: base of alluvium apparent; poor resolution of units w/in P/A and PTX Formations

- October 2010 Reflection Survey
  - “High resolution” survey; increased number of channels to 16 to 24 channels recorded
  - Enhanced digital processing / 3D interpretation
  - Results: base of alluvium apparent; poor resolution of units w/in P/A and PTX Formations

- Survey Comparison
  - Later survey - more sophisticated gear, more sophisticated data processing, cost about 4x more
  - Results were about the same
Lessons Learned & Observations

• Geophysical surveys were useful and cost effective for our purpose to fill the data gap between boreholes - *if the conditions are right.*

• Used other places on the project to identify possible old valleys on the alignment and reduce uncertainty during the contract preparation.

• At the end we decided not to chase the ground or have a conservative baseline condition and handled the potential for the boulders and alluvium in the crown of the tunnel in the Contract.
X-Ray Radiography of Soil Samples
X-Ray Radiography (ASTM 4452)

- X-ray radiography is extremely useful to identify soil structures and selecting good samples for strength test (i.e. locating slickensides and sand pockets)
- The key is to select a lab which has the right equipment and experience in performing X-Ray radiography
- Monitor and quality control
- Spend money to save money and reduce the number questionable results
X-Ray Photos of Soil Samples (ASTM 4452)
Coefficient of at Rest Lateral Earth Pressure – $K_0$
The Problem with $K_0$

- Potomac Clays are highly overconsolidated: $K_0$ greater than 1 for the project, sometimes as high as 1.5
- $K_0$ values have a significant cost impact: thicker walls, thicker slabs, more rebar. Constructability issues
- Field testing for $K_0$ may not correlate well with empirical data – no different for this project
- We used empirical and field test data for $K_0$
  - Consolidation Tests (empirical relationship $(1-\sin\phi')\times OCR^{\sin\phi'}$)
  - Pressuremeter Tests (direct measurement)
- Potential to measure during construction but do not know what happens over time – 100 year design life for the project
Pressure Measured during Construction

Excavation
Consolidation Test (ILC vs CRS)

- Used Constant Rate of Strain (CRS) test over 1-D Incremental Load Consolidation (ICL) test
  - Maximum Past Pressure in Potomac greater than 30 tsf
  - ICL capacity ~30 tsf; CRS capacity of ~100tsf
  - CRS is faster and provides smoother curve
  - Permeability can be estimated by CRS
  - Down side is not a common piece of equipment
- Key test for determination of $K_o$
- Research is being performed to develop a piece of equipment that can estimate $K_o$ directly
Example of ILC vs CRS

Settlement Curve from ILC (same sample)

Settlement Curve from CRS (same sample)
Pressuremeter (PMT)

- Modulus of Elasticity (E)
- Supplemented data for $K_0$
  - Correlated well with empirical relationship

Unload-Reload in Elastic Phase (BPT)
Coefficient of Lateral Earth Pressure at Rest – $K_0$
Soil Abrasion Test (SAT)
Soil Abrasion Test (SAT) – Why we care?

- Abrasive soil can wear out the cutting tools and TBM - Affects pricing and scheduling.
- The abrasiveness of soils was included in the Geotechnical Baseline Report as a soil property.
- Tunneling industry is becoming more familiar with SAT.
- In addition to SAT, Petrographic and X-Ray Diffraction are recommended be performed together to determine the mineralogy of the soil.
- SAT results will become more useful as more correlations are developed.
Soil Abrasion Test (SAT) Results

SAT Value and Descriptor

<table>
<thead>
<tr>
<th>SAT Value and Descriptor</th>
<th>G1/G2</th>
<th>G3A/G4</th>
<th>Completely Weathered Rock</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extremely low (&lt;1)</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Very low (2-3)</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low (4-12)</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium (13-25)</td>
<td>6</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>High (26-35)</td>
<td></td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Very High (36-44)</td>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Extremely high (&gt;44)</td>
<td>1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Soil Abrasion Test Equipment

Test equipment used to determine Abrasion Value Cutter Steel (AVS) and Soil Abrasion Test (SAT™).

Part of a cutter ring, a 10 mm slice taken from the same ring, and two prepared AVS test pieces which are cut out of the centre of the slice.

Photo showing two AVS (to the left) and two SAT™ test pieces (to the right).
Other Lessons Learned and Conclusions

- Get a good Historical Photograph person on your team (old channels, land use (UXO)). Can save you lots of $$$ and better define investigation.
- Sometimes you spend money to save money – X-rays and marine seismic survey.
- More research is needed to determine if and how long it takes $K_o$ to come back onto excavations final liners (tunnels and shafts). The design life for projects can be order of 100 to 200 years.