WASHINGTON MONUMENT
CASE HISTORY

Jean-Louis BRIAUD
Texas A&M University
OUTLINE

• History
• Construction
• Dimensions
• Loading
• Soil Stratigraphy
• Soil Properties
• Bearing Capacity
• Settlement Monitoring
• Consolidation Calculations
• Conclusions
HISTORY

• Built to honor George Washington, the 1st President of USA
• Due to historic events and excessive settlement, the Monument was constructed in three phases:
  • 1848: 1st phase = construction begins
  • 1858: construction stops = no more money
  • 1879: 2nd phase = underpinning
  • 1880: 3rd phase = completion of the shaft
  • 1884: construction completed
• Settlement measurements have been taken since the 2nd phase in 1879, providing a valuable long-term record
1792 map and 2007 map of Federal City - Washington DC
• Recent alluviums deposited by Potomac River (tidal fluctuations and floods)
• Pleistocene terrace deposits
• At that time, sea level varies greatly with abrupt climate changes, resulting in the presence of highly variable medium-plastic and slightly-to-moderately organic clay, sand, gravel, and sometimes boulders.
• Cretaceous soils missing
• Crystalline bedrock = decomposed Wissahickon Schist. metamorphic rock dating from the Ediacaran to the Cambrian age.
Began in 1848 under the supervision of Robert Mills, the architect of the Monument

Original foundation consisted of a stair stepped pyramid made of blue gneiss blocks

Shaft made of marble blocks

Construction was halted in 1858 with the shaft uncompleted at a height of 55.5 m due to lack of funds
Construction did not resume until 1879, after the Civil War when Lt. Col. Casey of the US Army Corps of Engineers took control.

The original foundation was considered inadequate so Casey decided to underpin the foundation and install buttresses:

- Increased foundation area
- Founded on stiffer soil

The Monument was completed in 1884.
DIMENSIONS
PRESSURE vs TIME

- First Phase of Construction
- Underpinning
- Final Phase of Construction

Pressure (kPa)

Time (years)

- Completely Distributed Total Pressure
- Underpinning-Only Total Pressure
• Weight of original foundation: 70 MN (Pressure = 118 kPa)
• Weight at the end of Phase 1: 305 MN (Pressure = 513 kPa)
• Weight of new foundation: 153.8 MN
• Final weight of Washington Monument: 607.7 MN (Pressure = 465 kPa)
  • San Jacinto Monument: 313 MN
  • Tower of Pisa: 142 MN
  • Eiffel Tower: 94 MN
• Earth terrace: 86.4 kPa
51 SOIL BORINGS
DEEPEST 38 m
BEARING CAPACITY

- **Actual Pressure** under old foundation = 513 kPa
- **Ultimate pressure** $P_u$ under old foundation (Clay)
  
  $P_u = N_c S_u + \gamma D$
  
  - $S_u = 72$ kPa (from N=12 bpf, Kulhawy and Mayne, 1990), $D = 2.34$ m (at time of maximum loading), $N_c = 6.2$ (square foundation)
  
  - Then $P_u = 491$ kPa

- **Ultimate pressure** $P_u$ under old foundation (Sand) (Briaud and Gibbens, 1999):
  
  $P_u \left[ \text{kPa} \right] = 75 \times N \left[ \frac{\text{blows}}{\text{ft}} \right]$
  
  - Blow count (N) = 12 bpf, Then $P_u = 900$ kPa

- $FS = 0.96 - 1.75$
• Actual pressure at end of construction = 465 kPa
• Ultimate pressure $P_u$ under new foundation:

$$P_u A_f = P_u (\text{clay}) A_f + \left( p_{\text{inside}} + p_{\text{outside}} \right) H \times k_0 \sigma_{ov}' \tan \phi$$

• $A_f$ = area of the foundation
• $p_{\text{inside}}$ = inside perimeter of foundation
• $p_{\text{outside}}$ = outside perimeter of foundation
• $H$ = thickness of sand layer
• $k_0$ = coefficient of earth pressure at rest in sand layer
• $\sigma_{ov}'$ = vertical effective stress at middle of sand layer
• $\phi$ = effective stress friction angle of the sand layer

• Then $P_u$ under the new foundation = 987 kPa
• Factor of safety = 2.4.
In this case the depth of influence is set by the presence of the shallow bedrock at about 20 m depth.
The depth of influence is defined as the depth where:

- the stress has decreased to 10% of the applied stress
- the settlement has decreased to 10% of the foundation settlement
\[ E(z) = E_0 + E_1(Z/B) \]

**Depth to 10% settlement**
STRESS INCREASE WITH DEPTH BY 3D FEM (ABAQUS)

Old foundation (After Phase 1)

Underpinned foundation (Before & after Phase 3)
CONSOLIDATION CALCULATIONS

• Calculated settlement for:
  • Phase 1 (From 1948 to 1958)
  • Phase 2 (Underpinning of Monument)
  • Phase 3 (Completion of Monument)

• Three methods:
  • Curve method (Method a)
  • Equation method With Cr measured on initial loading curve (Method b)
  • Equation method With Cr measured on unload/reload curve (Method c)
CONSOLIDATION
SETTLEMENTS
PREDICTED VS MEASURED

<table>
<thead>
<tr>
<th>Assumption Case</th>
<th>Settlement (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sub-case</td>
</tr>
<tr>
<td></td>
<td>a</td>
</tr>
<tr>
<td>Phase 1 (calculated)</td>
<td>1.328</td>
</tr>
<tr>
<td>Phase 3 (calculated)</td>
<td>0.116</td>
</tr>
<tr>
<td>Phase 3 (measured)</td>
<td>0.119</td>
</tr>
</tbody>
</table>
RECONSTITUTED SETTLEMENT

Time in Years

C_v = 10.2 m^2/yr

(1) Calculated based on consolidation test data
(2) Inferred from measured creep rate
(3) Measured
SETTLEMENT MONITORING

- Settlement was not measured during Phase 1
- Casey placed reference points at each corner of the top of the original foundation
- The benchmark used is the Meridian Stone which is marked by a bolt in the center of a square granite post set flush with the ground
- Settlement first measured in February 1879
- During underpinning, settlement readings for each corner were taken and recorded once daily, and since that time.
BENCHMARK IS THE MERIDIAN STONE AT THE WHITE HOUSE
MEASURED SETTLEMENT

- Settlement after underpinning = 52 mm
- Settlement after completion = 115 mm
- Settlement after last reading (1992) = 170 mm
Measured vs. Calculated Settlement

- Drainage length ($H_{dr}$) = 10.2 m (one-way)
- $C_v = 10.2 \text{ m}^2/\text{yr}$ (average), $C_v = 3.39 \text{ m}^2/\text{yr}$ (minimum)

\[
T = \frac{t \cdot C_v}{H_{dr}^2}
\]
CONCLUSIONS

• After Phase 1, the pressure was close to the ultimate pressure and the settlement was 1.3 m
• Underpinning saved the monument by reducing the net pressure on the soil and increasing the ultimate bearing capacity (FS = 2.4)
• The calculated settlement for Phase 2 and 3 matched well the measured settlement (?!)
• Creep settlement has been consistent at less than 1 mm/year for 120 years.
• The role played by subsidence continues to be studied.
CONCLUSIONS

• Depth of influence to 10% settlement depends on modulus profile (1B for linear increase and 4B for constant with depth)
• Read the consolidation curve directly for settlement calculation
• Plot the consolidation curve as a stress strain curve.
• Beware of the unload-reload loop as the slope depends on the stress release amplitude
ACKNOWLEDGEMENTS

• Mueser Rutledge Consulting Engineers (MRCE) for sharing their knowledge and data on the Washington Monument (Hugh Lacy, Doug Christie)
• Phil King (Synchropile)
• Jay Padgett Jr. of GeoServices Corporation for his insight and background on the Monument
• Brad Smith and Jennifer Nicks of Texas A&M University
• Funding provided by the Spencer J. Buchanan Chair at Texas A&M University