Celebrating Houston
Part 3 of 4
March 31 at Rice University
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Responsive ■ Resourceful ■ Reliable

Terracon
GROUND IMPROVEMENT STARTS HERE
Project: King Abdullah University of Science and Technology (KAUST)
Country: Saudi Arabia (Jeddah)
Summary: New University (36M m²) built from scratch in record time in the desert

Main Issues to Solve:
- Local condition: relatively heterogeneous deposits of Sabkha (loose silt deposited by wind)
- Fast track project and project not well defined at time of ground improvement
- High water table
KAUST = King Abdullah University for Science and Technology

- New university campus of 36 million m² (i.e. 6 km x 6 km) to be completed in 26 months
- Located in the desert near Jeddah
- Includes desalination plant, wind turbines, golf course, residences, services, campus, infrastructures
Initial Conditions and Challenges:

- Sabkah: saturated loose fine silty sand – wind blown. On this project, up to 5m thick at surface.
- Fast-track project: project was launched before 100% drawings – Menard needed to propose a ground improvement system without having final structural drawings and loads.
VARIATION IN SOIL PROFILE OVER 30 METERS
DESIGN CONCEPT WHEN LOCATION OF FOOTINGS UNKNOWN

Total settlement < 1 inch (25mm) – max diff 1/500 on footings

150 tons max

200 kN/m² max

Engineered Fill

Working Platform (gravelly sand)

Soft Sabkha (DR)

Loose sand (DC)

Arching layers Minimum 2m

Contour of Subarea
DC treatment area
DR treatment area
HDR treatment area
Green area
DESIGN DECISION TREE

Based on Observational Method

Selection of G.I. method is dependent on site observation during compaction and borings
12 Cranes (LRB 855 & 885) x 2 shifts

12 to 25 tons weight depending on areas

Over 2,500,000 m² (25,000,000 ft²) of DC/DR

Team of 100 persons on site
Project: Fedex Ground Sorting Facility
Country: USA (Jersey City)
Summary: New plant in Greenfield with final grade raised several meters and large net new loads

Main Issues to Solve:

- Local condition: thick deposits of varved soft clay below a layer of thick organics
- Settlement: predicted long term settlement >2ft over 20 years due to deep soft clays
- Construction period – Fast schedule
- Limited budget
Soil profile:
Fill (with some MSW) over Organics (meadow mat) over varved silt and clays

Main Challenge was thickness of compressible soil extending beyond the capacity of classical CMC rigid inclusions elements.
Second challenge was to limit total settlements to under 2 inches long term and differential settlement of ¾ inch between two column footings.

Differential settlement between loaded bay and unloaded bay is also to be studied.

Differential between footings and slab is another focus.
Depth challenge solved
Develop two custom made lead mast systems attached to crawler cranes with high torque / high pull down capacity.
Settlement challenge solve

Combination of Global support (with one added CMC at concentrated loads) and thick LTP to spread load.
Fedex NJ

- Jersey City, NJ
- Warehouse
- 350,000 sf
- 600 psf floor load
- 135 ft max
- 4,150 CMC
LESSONS LEARNED:
- Each site is unique and has its own challenges that lead to unique design-build solutions
- Innovate to find the right solution
- Being entrepreneurial and a risk-taker often pays off

THANKS!
Jean-Louis Briaud, Ph.D, P.E., D.GE.

Distinguished Professor and Spencer J. Buchanan Chair Professor
Texas A&M University
BEHAVIOR OF TWO LARGE MATS UNDER HIGH LOADS

Jean-Louis BRIAUD
Distinguished Professor
Texas A&M University

Jean-Louis Briaud – Texas A&M University
Washington Monument Case History
George Washington, 1st President of USA

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 measured since 2nd phase in 1879
CONSTRUCTION

• Began in 1848 with architect Robert Mills
• 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 at a height of 55.5 m due to lack of funds
CONSTRUCTION

• Construction resumed in 1879, after the Civil War with Lt. Col. Casey of the US Army Corps of Engineers
• Casey considered the original foundation inadequate and decided to underpin it.
  • Increased foundation area
  • Founded on stiffer soil
• The Monument was completed in 1884
DIMENSIONS

Section View

[Diagram showing dimensions in meters]
LOAD vs TIME

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

Graph shows the load (MN) over time (years) from 1845 to 2007. The graph illustrates the progression of load with time for different phases of construction and underpinning.
PRESSURE vs TIME

First Phase of Construction
Underpinning
Final Phase of Construction

Time (years)
1845 1850 1855 1860 1865 1870 1875 1880 1885 1890 2007

Pressure (kPa)
0 100 200 300 400 500 600

Completely Distributed Total Pressure
Underpinning-Only Total Pressure

Blue line: Completely Distributed Total Pressure
Orange line: Underpinning-Only Total Pressure
• Weight of original foundation: **70 MN** (Pressure = **118 kPa**)
• Weight at 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
SOIL PROPERTIES
SOIL PROPERTIES
SOIL PROPERTIES
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.
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 CURVE

- Void Ratio vs Pressure (kPa)
  - 13.9 m - 14 m
  - 31.9 m - 32 m
  - 57.5 m - 57.6 m

- Stress vs Strain (kPa)
  - 13.9 m - 14 m
  - 31.9 m - 32 m
  - 57.5 m - 57.6 m
## 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

Settlement (m)

Cv = 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
Settlement after underpinning = 52 mm
Settlement after completion = 115 mm
Settlement after last reading (1992) = 170 mm
• 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 1.4 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 1mm/year for 110 years.
CONCLUSIONS

• 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
The San Jacinto Monument Case History

Picture obtained from http://www.laanba.net/photoblog/ January05/sanjacinto.jpg
History

• March 2, 1836:
  – Texas declares its independence from Mexico
• March 6, 1836: The Battle of The Alamo
  – Mexico (Santa Anna) defeats Texas
• April 21, 1836: The Battle of San Jacinto
  – Texas (Sam Houston) defeats Mexico
Structural Dimensions
Construction

Reinforcement in the Foundation
(Bullen, 1938)
Construction
Loading

- Gross pressure = 224 kPa
- Max pressure (dead + wind) = 273 kPa
- Excavation = -83 kPa
- Net pressure = 141 kPa
- Net pressure after mat poured = 10 kPa
- Pressure from Terraces = 34 kPa and 85 kPa
## Soil Borings

<table>
<thead>
<tr>
<th>Boring Date</th>
<th>No. of Borings</th>
<th>Boring Depth (m)</th>
<th>Company</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1936</td>
<td>1</td>
<td>6.1</td>
<td>Layne Texas</td>
<td>No. and location unknown</td>
</tr>
<tr>
<td>1938</td>
<td>1</td>
<td>198.2</td>
<td>Unknown</td>
<td>Location unknown, water well</td>
</tr>
<tr>
<td>1948</td>
<td>1</td>
<td>44.2</td>
<td>Unknown</td>
<td>Location unknown</td>
</tr>
<tr>
<td>1953</td>
<td>1</td>
<td>61</td>
<td>Unknown</td>
<td>Likely used by Dawson for teaching purposes</td>
</tr>
<tr>
<td>1964</td>
<td>8</td>
<td>4.5 to 6.1</td>
<td>Golemon &amp; Rolfe</td>
<td>For repairs to the Monument</td>
</tr>
<tr>
<td>1976</td>
<td>13</td>
<td>3 to 12</td>
<td>Murillo Eng.</td>
<td>For new construction around the reflection pool</td>
</tr>
<tr>
<td>1980</td>
<td>3</td>
<td>2.1 to 6.1</td>
<td>McClelland</td>
<td>Study of the movements</td>
</tr>
<tr>
<td>Unknown (&gt;1946)</td>
<td>1</td>
<td>47.6</td>
<td>McClelland</td>
<td>Unknown date and location</td>
</tr>
</tbody>
</table>
Location of Soil Borings

- BM 4
- BM 5
- BM 6
- BM 2

B1 - 1964 (4.57 m)
B2 - 1964 (5.79 m)
B3 - 1964 (5.79 m)
B4 - 1964 (3.96 m)
B5 - 1964 (5.79 m)
B6 - 1964 (4.57 m)
B7 - 1964 (5.79 m)
B8 - 1964 (4.57 m)
B12-1980 (6.10 m)
B13-1980 (2.13 m)

BM 9
1953
(60.98 m)
<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Soil Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-7.5</td>
<td>Very Stiff Clay, red and gray</td>
</tr>
<tr>
<td>7.5-11</td>
<td>Very Stiff Clay, red and gray</td>
</tr>
<tr>
<td>11-15</td>
<td>Very Stiff Clay, red and gray</td>
</tr>
<tr>
<td>15-17</td>
<td>Silty Sand, Very Dense</td>
</tr>
<tr>
<td>17-18</td>
<td>Silty Sand Very Dense</td>
</tr>
<tr>
<td>18-20</td>
<td>Very Stiff Clay</td>
</tr>
<tr>
<td>20-23</td>
<td>Very Stiff Clay</td>
</tr>
<tr>
<td>23-26</td>
<td>Very Stiff Clay, light gray and red</td>
</tr>
<tr>
<td>26-28</td>
<td>Clay with Ferrous nodules</td>
</tr>
<tr>
<td>28-31</td>
<td>Clay, light gray and tan</td>
</tr>
<tr>
<td>31-38</td>
<td>Silty Clay, brown and gray</td>
</tr>
<tr>
<td>38-40</td>
<td>Very Stiff Clay, red and gray</td>
</tr>
<tr>
<td>40-47</td>
<td>Very Stiff Clay, red and gray</td>
</tr>
<tr>
<td>47-53</td>
<td>Very Stiff Clay, red and gray</td>
</tr>
<tr>
<td>53-62</td>
<td>Silty Clay with gray sand</td>
</tr>
<tr>
<td>62-64</td>
<td>Silty Clay with clay stones</td>
</tr>
<tr>
<td>64-75</td>
<td>Stiff Silty Clay, gray</td>
</tr>
<tr>
<td>75-77</td>
<td>Stiff Silty Clay, gray</td>
</tr>
</tbody>
</table>
Consolidation Characteristics
Stress History

Pressure, kPa

σ'_p (kPa)

Depth, m

Consol Curve σ'_p
Estimated σ'_p
σ'_0
Typical Desiccation Profile

Boring in 1953
Boring in 2007
Cone Penetrometer Results

Tip Resistance (kPa)
Friction (kPa)
Pore Pressure (kPa)
Ratio (%)

Depth (m)

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Pressuremeter

$P_L = 2.7 \text{ MPa}$, $P_y = 1.6 \text{ Mpa}$, $E_0 = 54 \text{ MPa}$, $E_r = 145 \text{ MPa}$, $n = 0.022$
Pressuremeter

Limit Pressure (kPa)

$E_0$ (kPa)

$Er$ (kPa)

$n$

Jean-Louis Briaud – Texas A&M University
Undrained Shear Strength

1953

- 1964 Borings
- 1976 Borings
- 1980 Borings
- Boring (Unknown Date/Loc.)
- 0.45*Pocket Penetrometer
- Average

2007

Pocket Penetrometer

CPT

Pressuremeter

Jean-Louis Briaud – Texas A&M University
Ultimate Bearing Capacity

\[ P_L = 680 \text{ kPa at 5 m depth} \]

\[ S_u = 100 \text{ kPa at shallow depth} \]

Total pressure at 5 m = 224 kPa
Net pressure at 5 m = 141 kPa
## Ultimate Bearing Capacity

<table>
<thead>
<tr>
<th>Test Method</th>
<th>Bearing Capacity (kPa)</th>
<th>F.S (Dead Load)</th>
<th>F.S (Hurricane + Dead Load)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$S_U$ from Borings (Skempton, 1951)</td>
<td>721</td>
<td>3.22</td>
<td>2.64</td>
</tr>
<tr>
<td>CPT (Tand et al, 1986)</td>
<td>900</td>
<td>4.02</td>
<td>3.3</td>
</tr>
<tr>
<td>CPT (AFNOR-Frank 2013)</td>
<td>870</td>
<td>3.89</td>
<td>3.19</td>
</tr>
<tr>
<td>PMT (AFNOR-Frank 2013)</td>
<td>935</td>
<td>4.18</td>
<td>3.43</td>
</tr>
</tbody>
</table>
Modulus of Elasticity

Modulus of Deformation (MPa)

Depth (m)

O'Neill (2000)
- Briaud, Little (1988) - 1st Load
- Briaud and Little (1988) - Reload
- Williams, Focht (> 1978 - Obtained From Ken Tand, 2005) - 1st Load
- Williams, Focht (> 1978 - Obtained From Ken Tand, 2005) - Reload
- Back-Calculated Modulus that Best Fits the Observed Avg Settlement
- Calculated Mod. from Consolidation Data (CASE B)
Modulus of Elasticity

- Using the elastic settlement equation,
  \[ s = 0.88(1 - \nu^2)pB/E \]
  the Modulus (E) at the site was back-calculated to be 12.3 MPa based on the last known settlement observation (s) of 0.329 m.
  - \( \nu = 0.35 \)
  - \( p = 138.9 \) kPa (net pressure)
  - \( B = 37.8 \) m
Elastic Settlement

\[ E_0 = 30 \text{ Mpa}, \quad B = 38 \text{ m}, \quad p = 141 \text{ kPa}, \quad \gamma = 0.35 \]

\[ S(t_0) = 0.88(1 - 0.35^2) \times 141 \times 38 / 30000 = 138 \text{ mm} \]

Long Term Settlement

\[ s(t)/s(t_0) = (t/t_0)^n \]

\[ s(t_0) = 138 \text{ mm}, \quad t = 70 \text{ yrs}, \quad t_0 = 5 \text{ min}, \quad n = 0.045 \]

\[ S(70 \text{ years}) = 138 \times (70 \times 365 \times 24 \times 60 / 5)^{0.045} \]

\[ S(70 \text{ years}) = 325 \text{ mm} \]
Modulus of Subgrade Reaction

- \( k = \frac{p}{s} \)
- Using the elastic settlement equation,
  \[ s = 0.88(1-\nu^2)pB/E \]
- Therefore \( k = \frac{1}{E/B} \)
- \( k \) depends on the soil parameter and the size of the foundation
- If \( k = 20000 \text{ kN/m}^3 \) for a 1 m footing
- Then \( k = 2000 \text{ kN/m}^3 \) for a 10 m footing
Modulus of Subgrade Reaction

\[ s = \frac{p}{k} \quad \text{or} \quad s = \frac{IpB}{E} \]

- A 1x1 m footing loaded with 100 kN settles 10 mm. Pressure is 100 kN/m\(^2\).
- A 10x10 m footing loaded with 10000 kN settles 10 mm according to subgrade modulus. Pressure is 100 kN/m\(^2\).
- A 10x10 m footing loaded with 10000 kN settles 100 mm according to elasticity.
Stress Distributions

![Diagram showing stress distributions with labeled distances and areas.

- 18.9 m
- 37.2 m
- 55.5 m
- 2 B (B=37.8m)
- 2.5 B (B=37.8m)
Rigid Foundation
Flexible Fill
(Under Center of Foundation)
Depth of Influence

• Two definitions for the depth of influence:
  – Depth at which the pressure has decreased to 10% of the applied surface pressure
  – Depth at which the settlement is 10% of the settlement at the surface

• The zone of influence depends on which definition is used and on the modulus profile of the soil
## Settlement – consolidation test

### Case 7
- Assumptions:
  - Water at base of foundation
  - Added Fill
  - No rebound

### Case 8
- Assumptions:
  - Water at base of foundation
  - Added Fill
  - Rebound of excavation

<table>
<thead>
<tr>
<th>Case</th>
<th>Subcase</th>
<th>2007 Tests (m)</th>
<th>1953 Tests (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>A</td>
<td>0.353</td>
<td>0.392</td>
</tr>
<tr>
<td></td>
<td>CUNLOAD</td>
<td>0.561</td>
<td>0.481</td>
</tr>
<tr>
<td></td>
<td>CLoad</td>
<td>0.448</td>
<td>0.359</td>
</tr>
<tr>
<td>8</td>
<td>A</td>
<td>0.454</td>
<td>0.602</td>
</tr>
<tr>
<td></td>
<td>CUNLOAD</td>
<td>1.002</td>
<td>0.854</td>
</tr>
<tr>
<td></td>
<td>CLoad</td>
<td>0.781</td>
<td>0.587</td>
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## SETTLEMENT

<table>
<thead>
<tr>
<th>Consolidation Tests</th>
<th>CPT (Schmertmann)</th>
<th>PMT (First modulus)</th>
<th>Measured in 2006</th>
</tr>
</thead>
<tbody>
<tr>
<td>1953 (long term)</td>
<td>Short term</td>
<td>Short term</td>
<td>0.392 m</td>
</tr>
<tr>
<td>2007 (long term)</td>
<td>Long term</td>
<td>Long term</td>
<td>0.353 m</td>
</tr>
<tr>
<td></td>
<td>0.19 m</td>
<td>0.299 m</td>
<td>0.19 m</td>
</tr>
<tr>
<td></td>
<td>0.299 m</td>
<td>0.145 m</td>
<td>0.299 m</td>
</tr>
<tr>
<td></td>
<td>0.145 m</td>
<td>0.291 m</td>
<td>0.342 m</td>
</tr>
<tr>
<td></td>
<td>0.291 m</td>
<td>0.328 m</td>
<td>0.342 m</td>
</tr>
</tbody>
</table>
Reference Points

- Dawson established 50 reference points around the foundation
Benchmarks-6.7 m deep
Actual Settlement

• Dawson established the elevations of the benchmarks and reference points on November 9, 1936 – two weeks after the foundation was poured
• Net soil pressure = 10.4 kPa
• Dawson took 26 settlement readings between 1937 and 1966
Actual Settlement

![Graph showing Actual Settlement over time with different lines representing minimum, average, and maximum settlement. The x-axis represents dates from 1936 to 2006, and the y-axis represents settlement in meters from 0 to 0.4. The graph includes lines for minimum, average, and maximum settlement, each indicated by different symbols and colors.]

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Subsidence

• The areas that have the greatest groundwater extraction have subsided about 3 m.

• The rate of subsidence in the Houston area ranged from 31 to 76 millimeters per year.

• Assuming uniform subsidence around the San Jacinto Monument, the benchmarks and reference points would not see differential settlement.
EFFECTIVE STRESS (kPa)

DEPTH (m)

• EFFECTIVE STRESS IN 1936
• EFFECTIVE STRESS IN 1975
• EFFECTIVE STRESS IN 2007
Stress History

Pressure, kPa

σ_p (kPa)

DEPTH (m)

Depth, m

- Consol Curve σ'_p
- Estimated σ'_p
- σ_0v
- Typical Dewatering Profile

- Boring in 1953
- ▲ Boring in 2007
## SETTLEMENT

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Benchmark Settlement</th>
<th>Monument Settlement</th>
<th>Differential Settlement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Monument only, no subsidence</td>
<td>0.019 m</td>
<td>0.288 m</td>
<td>0.269 m</td>
</tr>
<tr>
<td>Subsidence in the free field, no</td>
<td>2.613 m</td>
<td>2.613 m</td>
<td>0 m</td>
</tr>
<tr>
<td>Monument</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monument plus subsidence</td>
<td>2.617 m</td>
<td>2.919 m</td>
<td>0.302 m</td>
</tr>
</tbody>
</table>
## SETTLEMENT

<table>
<thead>
<tr>
<th>Measured (mm)</th>
<th>CPT (mm)</th>
<th>PMT (mm)</th>
<th>Consolidation (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>After accounting for subsidence – 295</td>
<td>Short term - 190</td>
<td>Short term - 145</td>
<td>Long term - 353</td>
</tr>
<tr>
<td></td>
<td>Long term - 299</td>
<td>Long term – 291</td>
<td></td>
</tr>
</tbody>
</table>
Conclusions

• **Stress increase with depth:**
  – For rigid mats, use flexible stress increase solutions. The soil redistributes the pressure in the long term.
  – Go to a depth of 2B
  – Divide that depth in about 10 layers
  – Calculate the decrease in stress due to excavation in each layer
  – Calculate the increase in stress due to the mat in each layer
  – Calculate the increase in stress due to the structure in each layer
Conclusions

• *Consolidation Testing:*
  – Think about what the soil will go through in the field.
  – Upon extrusion from the Shelby tube the sample is unloaded. Consolidation tests start as reloading tests
  – Apply loading up to the initial vertical stress, $\sigma'_{ov}$, for the sample
  – Unload the sample by an amount equal to the pressure removed due to excavation
  – Reload the sample in steps up to at least $\sigma'_{ov} + \Delta\sigma_{load}$
Conclusions

• *Settlement calculations*:
  – Perform calculations for the center of each layer
  – Use the void ratios from the consolidation curves $s = H \Delta e/(1+e_o)$
  – Calculate separately the rebound during excavation, the settlement of the mat, the settlement of the structure.
  – Remember that heterogeneity is scale dependent.
Conclusions

• *Settlement calculations:*
  – For long term settlement, $E/s_u = 123$
  – If available, use a 3-D numerical method to determine settlement. In this fashion, the stress increase and the stiffness profile are automatically taken care of.
  – Which settlement is important? After the mat is poured, after a few floors, after completion of the structure? Should the recompression settlement be included?
FOUNDATIONS FOR HIGH RISE

\[ R_U = R_{U \text{Mat}} \]

\[ R_U = R_{U \text{Mat}} + \sum R_{U \text{Piles}} \]

\[ R_U = \sum R_{U \text{Piles}} \]
PMT FOR DEEP FOUNDATIONS OF SUPER TALL BUILDINGS

- Burj Khalifa
- Petronas
- Nakheel
PMT FOR DEEP FOUNDATIONS OF BURJ KHALIFA

PMT FIRST MODULUS

SETTLEMENT

AFTER POULOS, 2009
THANK YOU

http://ceprofs.civil.tamu.edu/briaud/
Celebrating Houston
March 31 at Rice University
GEO-HOUSTON 2017