FOUNDATION ENGINEERING: RECENT ADVANCES

Downdrag on Piles, Laterally Loaded Pile, Spread Footings on Sand, Large Mat on Stiff Clay

The 32nd Martin KAPP Lecture

by

Jean-Louis BRIAUD, PhD, PE
Professor and
Holder of the Buchanan Chair
Zachry Dept. of Civil Engineering
Texas A&M University

New York City, 14 December 2006
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ACKNOWLEDGEMENTS

• ASCE MET Section and Geo-Institute Local Chapter

• Geoff Meyerhof (too complicated!)

• Louis Briaud (so what!)
• Research Principles
  • Downdrag on Piles
  • Laterally Loaded Piles
  • Spread Footings on Sand
  • Large Mat on Stiff Clay

RESEARCH PRINCIPLES

1. Literature Review
2. Dimensional analysis
3. Test matrix optimization
4. Model scale tests, scaling laws
5. Numerical simulations
6. Method development
7. Full scale field tests, verification
8. Threshold of optimum of simplicity
“Everything should be made as simple as possible but not one bit simpler than that”

Albert Einstein (Safir and Safire, 1982)

- Research Principles
- Downdrag on Piles
- Laterally Loaded Piles
- Spread Footings on Sand
- Large Mat on Stiff Clay
General Observations

1. Downdrag does not reduce the ultimate capacity of a pile

2. Downdrag increases the load in the pile

3. Downdrag increases the settlement of a pile; downdrag is a case where settlement controls the pile design

4. Live loads should not be included in settlement calculations including downdrag
6. Downdrag makes a pile come out of the ground

7. Bitumen reduces downdrag significantly (90%?) when properly chosen and properly applied

8. Bitumen is most easily applied when the air is colder than the soil (winter) but when the temperature is above freezing

9. Piles located on the inside of a pile group experience less downdrag than the perimeter piles
WHEN TO DESIGN FOR DOWNDRAG?

1. The total settlement of the ground surface will be larger than 100 mm
2. The settlement of the ground surface after the piles are driven will be larger than 10 mm
3. The height of the embankment to be placed on the ground surface exceeds 2 m
4. The thickness of the soft compressible layer is larger than 10 m
5. The water table will be drawn down by more than 4 m
6. The piles will be longer than 25 m

WARNING: Downdrag can occur even if the above conditions are not met.

DESIGN TO AVOID THESE THREE CONDITIONS

1. The settlement of the top of the pile after the dead load of the structure is placed will be larger than can be tolerated by the structure
2. The stresses in the pile will exceed the allowable stress for the pile material
3. The load placed at the pile top does not lead to an acceptable factor of safety against plunging of the pile into the soil.
MAXIMUM FRICTION FOR PILES IN CLAY (short term and long term)

\[ f_{\text{max}} = \alpha S_u \]

\[ f_{\text{max}} = \beta \sigma'_{ov} \]

Short Term (Undrained) Friction in Clay

For Driven and Bored Piles

Long Term (Drained) Friction in Clay and Silt

For Bored Piles Use:

\[ f_{\text{max}} \text{ (Bored)} = 0.75 \ f_{\text{max}} \text{ (Driven)} \]

MAXIMUM FRICTION FOR PILES IN SAND

\[ f_{\text{max}} = \beta \sigma'_{ov} \]

\[ f_{\text{max}} \text{ (kPa)} = 5 \ (N)^{0.7} \]

\[ N = \text{SPT blow count} \]
MAXIMUM POINT RESISTANCE
FOR PILES IN SANDS AND IN CLAYS

Clay (short term) \( q_{\text{max}} = 9 \, S_u \)

Clay (long term) \( q_{\text{max}} = \sigma'_{\text{ov}} \, N_q \)

Sand (short & long term) \( q_{\text{max}} = 1000(N)^{0.5} \)

Sand (short & long term) \( q_{\text{max}} = \sigma'_{\text{ov}} \, N_q \)

POINT DISPLACEMENT TO REACH THE MAXIMUM POINT RESISTANCE
FOR PILES IN SANDS AND IN CLAYS

\[ w_{\text{max}} = 0.785 \, (1-\nu^2) \, q_{\text{max}} \, D / E_{\text{soil}} \]

- \( D \) = pile diameter
- \( E \) = soil modulus
- For clays \( E = 100 \, S_u = E_{\text{pmt}} \)
- For sands \( E \) (kPa) = 800 N = 2 \( E_{\text{pmt}} \)
FINDING THE DEPTH OF THE NEUTRAL POINT

Vertical Equilibrium

\[ Q_t + F_n = F_p + Q_p \]

Compatibility of Movement

\[ w_{pile} = w_{soil} \]

\[ w_{soil} = \text{read on consolidation settlement profile} \]

\[ w_{pile} = w_{point} + \text{elastic compression} \]
FINDING THE PILE SETTLEMENT

\[ W_{\text{pile at top}} = W_{\text{pile at bottom}} + \text{elastic compression} \]

FINDING THE LOAD SETTLEMENT CURVE
DOWNDRAG ON PILE GROUPS

After Okabe, 1977
DOWNDRAG ON PILE GROUPS

**AXIAL FORCES IN ENDBEARING SINGLE PILE**

- **PREDICTED**
- **MEASURED**

**DOWNDRAG ON PILE GROUPS**

**AXIAL FORCES IN ENDBEARING GROUP PILES**

- **1** EXTERIOR PILE
- **2, 3, 4** INTERIOR PILES
- **PREDICTED**
- **MEASURED**
REDUCTION FACTORS FOR DOWNDRAG ON PILE GROUPS

EXAMPLE

Pile Ult. Capacity

\[ Q_u = 706 + 1000 \]

\[ Q_u = 1706 \, \text{kN} \]
$w_{\text{top}} = 46 \text{ mm}$ \hspace{1cm} $w_{\text{top}} = 14 \text{ mm}$ \hspace{1cm} $w_{\text{top}} = 14 \text{ mm}$

with bitumen

(a) \hspace{2cm} (b) \hspace{2cm} (c)
WHAT IS BITUMEN?
A black viscous substance. The residue left at the end of the refining process of crude oil, made of high molecular weight hydrocarbons.

WHAT IS A PRIMER?
A liquid made of half bitumen and half solvent to liquefy the bitumen for easy application and filling the holes. The layer left is largely the bitumen after drying.

HOW DOES BITUMEN BEHAVE?
Bitumen is a viscous material
\[ \tau = \eta \left( \frac{d\gamma}{dt} \right) \]
\[ \tau = \eta \left( \frac{d\gamma}{dt} \right) \]

\( \eta \) decreases when \( \frac{d\gamma}{dt} \) increases
\( \frac{d\gamma}{dt} \times 10 \) leads to \( \sim \frac{\eta}{2} \)

\( \eta \) decreases when \( T \) increases
\( T \times 2 \) leads to \( \sim \frac{\eta}{10} \)

\( \eta \) much more sensitive to \( T \) than \( \frac{d\gamma}{dt} \)
HOW TO CHOOSE A BITUMENT THAT WORKS?

\[ \tau = \eta \left( \frac{d\gamma}{dt} \right) \]

- Storing
- Driving
- Reducing downdrag
- Particle penetration
CONSTRUCTION AND SPECIFICATIONS

- Clean surfaces (free of dust and grease)
- Apply the primer (wait 24 hrs for drying)
- Apply the bitumen (10 mm thick)
- Storing (cold, hot)
- Handling in the field (pad eye, no strap)
- Drive the piles (splice, temperature)
• Clean surfaces (free of dust and grease)
• Apply the primer (wait 24 hrs for drying)

Applying the bitumen (10 mm thick)
Applying the bitumen (10 mm thick)

Handling in the field
Storing the coated piles

In hot weather, store under cover away from direct sunlight

In cold weather, wait until bitumen cools down before storing

Driving the piles (splice, temperature)
For more information On Downdrag

PILNEG, free software
http://ceprofs.tamu.edu/briaud/

Videotape on Bitumen Coating
(email Briaud)


• Research Principles
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• Large Mat on Stiff Clay
LATERAL LOAD-DEFLECTION CURVE

LOAD

\[ H_{0w}/F \]

DEFLECTION

\[ y_{o} \]

\[ B/10 \]

SETTLEMENT

\[ S_{o} \]

\[ Q/F \]

\[ B/10 \]

\[ L/AE \]
THE TEXAM PRESSUREMETER
1981

Simple
Safe
Versatile
ULTIMATE HORIZONTAL LOAD, \( H_{ou} \)

\[
H_{ou} = \frac{3}{4} \ p_l \ B \ D_v
\]

- \( p_l \) = limit pressure from PMT
- \( B \) = projected pile width
- \( D_v = (\pi/4) \ l_o \) with \( l_o = (4EI / K)^{1/4} \) for \( L > 3 \ l_o \)
- \( D_v = L/3 \) for \( L < l_o \)
- \( E \) = modulus of pile material
- \( I \) = moment of inertia of pile
- \( K = 2.3 \ E_0 \)
- \( E_0 \) = PMT first load modulus of soil
- \( L \) = pile length

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### SAND (36 sites)

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>$E_O$ (kPa)</th>
<th>$E_R$ (kPa)</th>
<th>$p_L$ (kPa)</th>
<th>$q_c$ (kPa)</th>
<th>$f_s$ (kPa)</th>
<th>$N$ (bl/30 cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>1</td>
<td>0.125</td>
<td>8</td>
<td>1.15</td>
<td>57.5</td>
<td>383</td>
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<tr>
<td></td>
<td></td>
<td>8</td>
<td>1</td>
<td>64</td>
<td>6.25</td>
<td>312.5</td>
<td>2174</td>
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<tr>
<td></td>
<td></td>
<td>0.125</td>
<td>0.0156</td>
<td>1</td>
<td>0.11</td>
<td>5.5</td>
<td>47.9</td>
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<tr>
<td></td>
<td></td>
<td>0.87</td>
<td>0.16</td>
<td>9</td>
<td>1</td>
<td>50</td>
<td>479</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.0174</td>
<td>0.0032</td>
<td>0.182</td>
<td>0.02</td>
<td>1</td>
<td>9.58</td>
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<tr>
<td></td>
<td></td>
<td>0.0026</td>
<td>0.00046</td>
<td>0.021</td>
<td>0.0021</td>
<td>0.104</td>
<td>1</td>
</tr>
</tbody>
</table>

### CLAY (44 sites)

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>$E_O$</th>
<th>$E_R$</th>
<th>$p_L$</th>
<th>$q_c$</th>
<th>$f_s$</th>
<th>$S_u$</th>
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<td>14</td>
<td>2.5</td>
<td>56</td>
<td>100</td>
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<tr>
<td></td>
<td></td>
<td>3.6</td>
<td>1</td>
<td>50</td>
<td>13</td>
<td>260</td>
<td>300</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.071</td>
<td>0.02</td>
<td>1</td>
<td>0.2</td>
<td>4</td>
<td>7.5</td>
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<tr>
<td></td>
<td></td>
<td>0.40</td>
<td>0.077</td>
<td>5</td>
<td>1</td>
<td>20</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.079</td>
<td>0.0038</td>
<td>0.25</td>
<td>0.05</td>
<td>1</td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.010</td>
<td>0.0033</td>
<td>0.133</td>
<td>0.037</td>
<td>0.625</td>
<td>1</td>
</tr>
</tbody>
</table>
VERY POOR CORRELATIONS

HORIZONTAL DISPLACEMENT $y_o$ @ $H_{ou}/3$

$$y_o = 2 \frac{H_o}{l_o} K \quad \text{for } L > 3l_o$$
$$y_o = 4 \frac{H_o}{L} K \quad \text{for } L < l_o$$

$H_o = H_{ou}/3$ = horizontal load at ground surface
$K = 2.3 \quad E_o$ = horizontal modulus (line load/deflection)
INTERACTION DIAGRAM FOR COMBINED HORIZ. LOAD AND OVERTURNING MOMENT

\[ r^2 = 0.355 \]

\[
\begin{align*}
Y \text{ (pred) (mm)} &= 5, 10, 15 \\
Y \text{ (meas) (mm)} &= 0, 5, 10, 15
\end{align*}
\]

**Legend:**
- Clay
- Sand
- Sand over Clay
- Concrete
- Steel
- Timber

ANY COMBINATION OF H AND M ON THE DIAGRAM GIVES THE SAME DEFLECTION

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LONG TERM LATERAL LOAD

\[ \frac{y_0(t)}{y_0(t_0)} = \left(\frac{t}{t_0}\right)^n \]

\( n = 0.01 \) to 0.03 in sands
\( n = 0.02 \) to 0.08 in clays

n VALUES FROM PMT TESTS

\[ \frac{\Delta R(t)}{\Delta R(t_0)} = \left(\frac{t}{t_0}\right)^{-n} \]

\( n = -\log(\frac{\Delta R(t)}{\Delta R(t_0)}/\log(t/t_0)) \)

\( n = 0.01 \) to 0.03 in sands
\( n = 0.02 \) to 0.08 in clays
CYCLIC LATERAL LOAD

\[ y_N = y_1 N^a \]

- \( a \) averages 0.1 for clays (one way and two way)
- \( a \) averages 0.08 for sands under one way loading
- \( a \) averages 0 for sands under two way loading
\[ \frac{\Delta R_N}{\Delta R_1} = N^a \]

\[ a = \log \left( \frac{\Delta R_N}{\Delta R_1} \right) / \log N \]

PMT only applicable to one way cyclic loading
H_{trench} = \lambda \ H_{no\ trench}

For more information
On Laterally Loaded Piles


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TIEBACK WALLS

POST CONSTRUCTION GROUND LEVEL
WAILE

FINAL EXCAVATION LEVEL
SOLDIER BEAM

4 @ 2.4 – 9.6 m
13 @ 2.4 – 9.2 m
4 @ 2.4 – 9.6 m

(a) Elevation View

INCLINOMETER CASINGS

LOAD CELL
WAILE
TUBE BRACKET

5.06 m TENDON UNBONDED LENGTH

7.3 m TENDON BONDED LENGTH

(b) Two Row Anchored Wall – Section View

EARTH PRESSURE COEF. VS MOVEMENT / HEIGHT

Earth Pressure Coefficient (k)

-0.04 -0.035 -0.03 -0.025 -0.02 -0.015 -0.01 -0.005 0 0.005 0.01

Wall Deflection (\(\Delta u_{2D}/H\))

TAMU 1 row, Final Excav.
TAMU 2 row, Final Excav.
TAMU 2 row, 2nd Excav.
Bonneville, 6th Excav.
Boston, 5th Excav.
Lima, 1st Excav.
Boston, 4th Excav.
Boston, 2nd Excav.

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For more information On Tieback Walls


• Research Principles
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THIS BEARING CAPACITY EQUATION DOES NOT WORK

\[ p_u = c N_c + \frac{1}{2} \gamma B N \gamma + \gamma D N_q \]
THIS BEARING CAPACITY EQUATION DOES WORK

\[ p_u = kr \]

\[ r = p_L, q_c, N, s_u \]
3mx3m Footing Load Tests up to 1200 tons

Texas A&M National Site
LOAD SETTLEMENT CURVE METHOD

\[ \frac{s}{B} = 0.24 \ \Delta \frac{R}{R} \]

\[ p_f = \Gamma p_p \]
PROBLEM: A bridge abutment rests on a shallow foundation 15 m long and 3 m wide. The foundation is subjected to a vertical and centered load equal to 9000 kN. The lateral earth pressure generates a load of 900 kN on the back of the abutment. The resultant of the two forces has an eccentricity equal to 0.2 m. The soil is a sand characterized by an average pressuremeter value.

SOLUTION: Load-Settlement Curve Method

\[ f_{cm} = 0.8 \times 0.2 \times 3/15 = 0.064 \]

\[ f_c = 1 \times 0.33 \times 0.33 = 0.098 \]

\[ f_s = 1 - \left( \frac{\text{Minimum Pressure}}{\text{Maximum Pressure}} \right)^{0.5} = 0.999 \]

\[ f_d = 0.8 (1 + 2/3)^{-1} = 0.842 \]

\[ f = f_{cm} f_c f_s f_d = 0.089 \]

\[
\begin{array}{|c|c|c|c|c|c|c|c|}
\hline
\text{AR} & \text{f}_{cm} & \text{f}_c & \text{f}_s & \text{f}_d & \text{f} & \text{S} & \text{Q} \\
\hline
0.025 & 0.015 & 0.009 & 0.78 & 0.82 & 0.598 & 73.0 & 4.18 \\
0.05 & 0.034 & 0.022 & 0.96 & 0.96 & 0.186 & 167.0 & 7.61 \\
0.08 & 0.051 & 0.04 & 1.18 & 1.18 & 0.008 & 180.7 & 11.73 \\
0.10 & 0.055 & 0.043 & 1.19 & 1.19 & 0.009 & 181.9 & 13.32 \\
0.12 & 0.059 & 0.047 & 1.23 & 1.23 & 0.009 & 183.0 & 15.53 \\
0.15 & 0.060 & 0.052 & 1.25 & 1.25 & 0.009 & 183.9 & 21.97 \\
\hline
\end{array}
\]
For more information on Spread Footings


• Research Principles
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The San Jacinto Monument
Case History

History

- March 2, 1836: Independence declared
- March 6, 1836: The Battle of The Alamo
- April 21, 1836: The Battle of San Jacinto
History

Alfred C. Finn
Architect

Raymond F. Dawson
Geotechnical Consultant

Robert C. Cummins
Structural Engineer

From the Air
SAN JACINTO MONUMENT
HOUSTON (1936)

WASHINGTON MONUMENT
WASHINGTON DC (1887)

Dimensions

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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 & 85 kPa
Stratigraphy

Soil Index Properties
Using the elastic settlement equation,
\[ s = 0.88(1-v^2)pB/E \]
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.
- \( v = 0.35 \)
- \( p = 138.9 \text{ kPa (net pressure)} \)
- \( B = 37.8 \text{ m} \)
Modulus of Elasticity

\[ \sigma_0' = \text{stress before anything} \]
\[ \sigma_0' - \Delta \sigma_{\text{exc}} = \text{stress in soil after excavation} \]
\[ \sigma_0' - \Delta \sigma_{\text{exc}} = \text{stress in soil after construction} \]
\[ \Delta \sigma_{\text{exc}} = \text{stress increase corresponding to } E_a \]
\[ \Delta \sigma_{\text{OG}} - \Delta \sigma_{\text{exc}} = \text{stress increase corresponding to } E_c \]
Stress Distributions
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

Using Stress Criterion

Using Settlement Criterion
**Case 7**

- **Assumptions:**
  - Water at base of foundation
  - Added Fill
  - No rebound

<table>
<thead>
<tr>
<th>Sub-Case</th>
<th>RIGID Foundation</th>
<th>FLEXIBLE Foundation</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>0.32</td>
<td>0.37</td>
</tr>
<tr>
<td>b</td>
<td>0.37</td>
<td>0.46</td>
</tr>
<tr>
<td>c</td>
<td>0.45</td>
<td>0.52</td>
</tr>
<tr>
<td>b L</td>
<td>0.27</td>
<td>0.34</td>
</tr>
<tr>
<td>c L</td>
<td>0.34</td>
<td>0.39</td>
</tr>
</tbody>
</table>
Case 8

• Assumptions:
  – Water at base of foundation
  – Added Fill
  – Rebound from excavation

<table>
<thead>
<tr>
<th>Sub-Case</th>
<th>(RIGID Foundation) s (m)</th>
<th>(FLEXIBLE Foundation) s (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>0.52</td>
<td>0.61</td>
</tr>
<tr>
<td>b</td>
<td>0.75</td>
<td>0.90</td>
</tr>
<tr>
<td>c</td>
<td>0.81</td>
<td>0.96</td>
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<tr>
<td>b L</td>
<td>0.49</td>
<td>0.59</td>
</tr>
<tr>
<td>c L</td>
<td>0.54</td>
<td>0.64</td>
</tr>
</tbody>
</table>

Reference Points

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

Actual Settlement

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Summary of Settlement

<table>
<thead>
<tr>
<th>Description</th>
<th>s (m)</th>
</tr>
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<tbody>
<tr>
<td>Case 8a</td>
<td>0.607</td>
</tr>
<tr>
<td>Case 7a</td>
<td>0.370</td>
</tr>
<tr>
<td>Dawson's Prediction</td>
<td>0.187</td>
</tr>
<tr>
<td>Measured Settlement</td>
<td>0.329</td>
</tr>
</tbody>
</table>

Subsidence

Picture obtained from www.ruf.rice.edu/~leeman/aNR.html
Subsidence

• The areas that have the greatest groundwater extraction have subsided about 3 m.
• The rate of subsidence in the Houston area ranges 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.

Lessons learned from this case history

1. For rigid mats, use flexible stress increase solutions and go to 2B
2. Use the void ratios from the consolidation curves $s = H \Delta e/(1+e_o)$
3. Calculate separately the rebound during excavation, the settlement of the mat, the settlement of the structure.
4. For long term settlement,
   
   \[ E/s_u \sim 123 \quad (E_o(pmt)/s_u \sim 100) \]
5. Which settlement is important? After the mat is poured, after a few floors, after completion of the structure? Should the recompression settlement be included?
• Research Principles
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THANK YOU

http://ceprofs.civil.tamu.edu/briaud/

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