AN INCONVENIENT GEOTECHNICAL TRUTH

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For many people the term “inconvenient truth” refers to the facts, cause and effects of global warming. This talk is about a different kind of “inconvenient truth,” relevant in the geotechnical world where nature and natural conditions as well as human created conditions control.
A true fact is that even a significant amount of advance testing with soil borings, geophysics, load testing and soil sample laboratory testing can not assure sufficient information to enable precise, accurate prediction of how the natural ground and contained foundation elements will perform under either natural forces or human-engineered forces.
ABSTRACT

However, by following certain rules based on the writer’s 60+ years of foundation design and construction experience, our prediction performance ability can be substantially improved.

This talk will outline the primary points learned and will be illustrated by several well known case histories ranging from Chicago to Kuala Lumpur.
1. Good Communication Between S.E. and G.E.
   a) Competence and experience, mutual confidence.
   b) Develop exploration program together.

2. Adequate Subsurface Investigation
   a) Borings for general stratigraphy
   b) Select borings for special sampling and testing in-situ pressuremeter, cone and dilatometer tests, geophysical testing – shear wave velocity for site specific seismic analysis, triaxial and consolidation testing.
Schematic of Pressuremeter Apparatus

Schematic of Pressuremeter Probe Loading Conditions
PRESSUREMETER RESULTS

Pressuremeter Data Reduction (BX)

- $E_d =$ Deformation Modulus
- $E_o =$ Rebound Modulus
- $E^+ =$ Recompression Modulus
- $P_f =$ Creep Limit
- $P_i =$ Limit Pressure
- $\alpha =$ Soil Type Empirical Factor
  - Often related to $E_d/E^+$

Pseudo-elastic Zone

Plastic Zone

Pressure in TSF

Injected Volume in CC

Creep in CC

Volume

Creep
Dead load pressure
+ long-term real live load pressure
+ effective overburden pressure
must be less than creep pressure.
3. Settlement Prediction and Bearing Capacity Analysis

a) Simple – use approximation for quick order of magnitude

b) Where more complex – finite element, computer
4. Instrumented Load Test Program
   a) Conventional load frame
   b) Osterberg cell
   c) Dynamic
   d) Statnamic
CONVENTIONAL LOAD FRAME
OSTERBERG CELL
OSTERBERG CELL
5. Construction Monitoring and Settlement Monitoring
   a) Experienced observer during excavation, monitoring
   b) Monitoring during loading

6. When Operating at Limit of Past Experience
   a) Take small steps. If large step necessary, be more conservative
   b) Go through “what ifs” and have a Plan B ready if poor performance exceeds acceptable limits
   c) Assume, but verify. If not possible to verify, then above are especially important
1. We may not be as smart as we think we are.
2. Things are not always what they seem.

So....

1. Know and make use of your local geology.
2. Know and calibrate to any local documented case histories in similar geology.
3. When operating at the limit of past experience, take small steps.
CASE HISTORY - PETRONAS TOWERS

- World’s third tallest building (1482’) as of 2008
- World’s deepest high rise foundations up to 430’
- World’s deepest ground improvements up to 530’
TOWER FOUNDATION PROFILE
PRINCIPLES TO REMEMBER

1. There is no geotechnical limit to friction piles. Friction piles can be made long enough so that structural capacity governs, provided the friction deposit is deep enough.

2. For a mat on friction piles in similar material, the load will be shared between mat and piles based on relative modulus and area based on calculations for compression in the piles and compression in the soil, including the zone of significant stress below the piles.

3. Where the ground alone is strong enough to support the building with mat only, but settlement is the issue, the purpose of the piles is primarily to reduce the settlement, i.e. stiffen the ground. The longer the piles, the less the settlement as more of the stress bulb is in the “stiffened” ground.
Use of variable length piles under mat to minimize critical differential settlement of world's tallest building – Petronas Towers.

1. Predict settlement based on modulus values from bored pile load testing and extensive in-situ pressuremeter testing

2. Use simple equivalent footing approach as well as more complete finite element computer programs to predict settlement

3. Monitor settlement and load distribution in piles and on mat during and after construction
## PRESSUREMETER TEST RESULTS

<table>
<thead>
<tr>
<th>Boring</th>
<th>B14</th>
<th>B23</th>
<th>T1-10</th>
<th>T1-24</th>
<th>T1-54</th>
<th>T2-26</th>
<th>T2-54</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_d$ Min.</td>
<td>9.3MPa</td>
<td>10MPa</td>
<td>32MPa</td>
<td>17.8MPa</td>
<td>38.5MPa</td>
<td>18.3MPa</td>
<td>11.7MPa</td>
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<tr>
<td>$E_d$ Max.</td>
<td>99</td>
<td>309</td>
<td>683</td>
<td>222</td>
<td>199.4</td>
<td>157</td>
<td>470</td>
</tr>
<tr>
<td># of Tests</td>
<td>18</td>
<td>15</td>
<td>27</td>
<td>26</td>
<td>26</td>
<td>31</td>
<td>27</td>
</tr>
<tr>
<td>$E_d$ Avg.</td>
<td>37.6MPa</td>
<td>133.9MPa</td>
<td>67.9MPa</td>
<td>109.8MPa</td>
<td>101.8MPa</td>
<td>64.1MPa</td>
<td>149MPa</td>
</tr>
<tr>
<td>$E_R$ Min.</td>
<td>27.5</td>
<td>22.3</td>
<td>55</td>
<td>32</td>
<td>57.7</td>
<td>47.8</td>
<td>68.3</td>
</tr>
<tr>
<td>$E_R$ Max.</td>
<td>479</td>
<td>931</td>
<td>851</td>
<td>496</td>
<td>590.3</td>
<td>495</td>
<td>383.3</td>
</tr>
<tr>
<td># of Tests</td>
<td>17</td>
<td>15</td>
<td>27</td>
<td>25</td>
<td>25</td>
<td>31</td>
<td>27</td>
</tr>
<tr>
<td>$E_R$ Avg.</td>
<td>186.9MPa</td>
<td>391.8MPa</td>
<td>176MPa</td>
<td>226MPa</td>
<td>223MPa</td>
<td>190MPa</td>
<td>535MPa</td>
</tr>
</tbody>
</table>

Overall Weighted $E_d$ Avg. = 94.3

$E_R$ Avg. = 267
STANDARD PENETRATION RESISTANCE PROFILE
STATIC LOAD TEST
BORED PILE INSTRUMENTATION
SIMPLE SETTLEMENT ANALYSIS

FIGURE 12 FOUNDATION SCHEMATIC FOR SIMPLE SETTLEMENT ANALYSIS

P = 2,680,000 KN (BUILDING LOAD)
AVERAGE NAT PRESSURE = 1130 KPa
SETTLEMENT ANALYSIS USING EQUIVALENT FOOTING METHOD

Pressuremeter Data

\[ E_{d, AV} = 94.3 \text{MPa} \]
\[ E^+_{AV} = 267 \text{MPa} \]
\[ \alpha = \frac{E_d}{E^+} = 0.35 \text{ , Use 0.4} \]

Settlement Calculation – Menard Empirical Method

\[ s_{\text{Menard}} = \frac{1.33}{3 \times E_B} q R_0 \left( \lambda_2 \frac{R}{R_0} \right)^\alpha + \alpha q \lambda_3 \frac{R}{R_0} \]
\[ \lambda_2, \lambda_3 = 1 \text{ for a circle} \]
\[ R_0 = 30 \text{cm} \]

\[ s_{\text{Menard}} = \frac{1.33}{3 \times 135} \times 0.610 \times 30 \left( \frac{7,500}{30} \right)^{0.4} + \frac{0.4 \times 0.61 \times 7,500}{4.5 \times 94} \]

\[ s_{\text{Menard}} = 0.55 \text{cm} + 2.16 \text{cm} = 27.1 \text{mm} \]

Settlement Calculation – Elastic Theory

\[ s_{\text{Elastic}} = \frac{\mu_0 \mu_1 q B}{E} \]
\[ s_{\text{Elastic}} = \frac{0.35 \times 0.92 \times 6,100 \times 75,000}{250,000} = 59 \text{mm} \]
Elastic Compression of Shaft Down to Equivalent Footing Level

\[ \Delta \ell = \frac{\sigma L}{E_{conc}} \]

\[ \sigma = \frac{2,680,000 \text{ kN}}{82 \times 1.2 \times 2.8} = 9,727 \frac{\text{kN}}{m^2} \]

\[ E_{conc} \approx 27,000,000 \text{ kPa} \]

\[ \Delta \ell = \frac{9,727 \times 40,000}{27,000,000} = 14.4 \text{ mm} \]

Total Predicted Settlement

By Menard Empirical Method

\[ S = s_{Menard} + \Delta \ell \]

\[ S = 27.1 \text{ mm} + 14.4 \text{ mm} = 41.5 \text{ mm} \]

By Elastic Theory

\[ S = s_{Elastic} + \Delta \ell \]

\[ S = 59 \text{ mm} + 14.4 \text{ mm} = 73.4 \text{ mm} \]
SETTLEMENT MAPS AND ROCK CONTOUR PLAN – TOWER 1

SETTLEMENT mm
TEST 8–28
DL +LL

TOWER 1 ROCK DEPTH, m

80 100 120 140 160 180
TOWER FOUNDATION PROFILE
SETTLEMENT OF TOWER 1 COLUMNS
BEAUTIFUL FINISHED STRUCTURE
1. In-situ testing with empirical correlations works well enough for engineering purposes.

2. Menard empirical procedures yield better settlement predictions compared to elastic theory using test pressuremeter modulus values as the Young’s modulus for the soil and geologic conditions reported herein.

3. Simple hand calculations for settlement and bearing capacity can be as reliable as sophisticated computer solutions.

4. Innovative cost effective foundation solutions are often possible with close interaction of geotechnical and structural engineer and cooperation of experienced contractor.
Chicago Experience in Maximizing Allowable Soil Bearing Pressures for High Rise Foundation Design
TYPICAL DOWNTOWN CHICAGO SOIL PROFILE
LAKE POINT TOWER

- Designed before pressuremeter testing was common.
- Designed based on triaxial compression testing.
WATER TOWER

- Heavy concrete structure
- Settlement predicted based on pressuremeter testing
# Predicted vs. Measured Settlement for Significant Chicago Structures

## Table 1

<table>
<thead>
<tr>
<th>Building</th>
<th>Profile Below Bearing Level*</th>
<th>Bearing Pressure in TSF</th>
<th>Column Load in Tons</th>
<th>Predicted Settlement in Inches</th>
<th>Measured Settlement in inches Range Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>75-story RC Tower</td>
<td>15’ clayey hardpan over 25’ very dense silt over limestone bedrock</td>
<td>14.5</td>
<td>8000</td>
<td>2.00</td>
<td>1.69-2.19 1.94</td>
</tr>
<tr>
<td>50-story steel</td>
<td>25’ very dense silt over limestone bedrock</td>
<td>20</td>
<td>2000</td>
<td>0.5</td>
<td>none reported</td>
</tr>
<tr>
<td>50-story steel</td>
<td>15’ clayey hardpan over 20’ very dense silt over limestone</td>
<td>12</td>
<td>2000</td>
<td>0.56</td>
<td>.48-.54 0.5</td>
</tr>
<tr>
<td>40-story RC with large bays</td>
<td>20’ very dense silt over limestone</td>
<td>20</td>
<td>9000</td>
<td>1.2</td>
<td>0.9-1.0</td>
</tr>
</tbody>
</table>

* Bearing level typically is 80+’ below ground surface

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**Water Tower**
OSTERBERG LOAD CELL TESTING
OSTERBERG LOAD CELL TESTING
OSTERBERG LOAD CELL AT BASE OF REINFORCEMENT CAGE
TRUMP INTERNATIONAL HOTEL & TOWER

Used O-cell in 6-foot deep rock socket to prove 270 tsf end bearing

(Maximum allowed by Chicago Code was 200 tsf)
CHICAGO SPIRE

• 2000 ft tall

• 300 tsf end bearing tested and approved
Utilizing the in-situ pressuremeter test and the Menard empirical settlement calculations and bearing capacity analysis procedures, and by observing building performance over time, we have been successful in increasing allowable bearing pressures on good Chicago hardpan (very dense glacial till) from 12 ksf to 50 ksf on major Chicago high rises and with reliably predicted settlement.

Utilizing the Osterberg Load Cell test we have been able to increase maximum allowable dolomite rock bearing pressures from 200 tsf to 300 tsf.