EIGHTH G.A. LEONARDS LECTURE

GROUND SETTLEMENT

FROM PILE DRIVING

May 1, 2010
Richard D. Woods
MY CONNECTIONS TO JERRY

- Research Engineer, AF Weapons Lab 1963
  My first job after M.S. as project monitor on Jerry’s AFWL research.

- Invited to apply to Ph.D. program at Purdue.

- Tokyo ISSMFE Conference 1977, post conference tour with Jerry and Beryl, Jorg Osterberg and others.
GROUND SETTLEMENT FROM PILE DRIVING

- GENERAL CONCEPTS
- EXAMPLES FROM PRACTICE
SHEAR STRAIN
\(< 10^{-3} \%\)

SHEAR STRAIN
\(10^{-1} \% – 10^{-3} \%\)

ELASTIC ZONE

PLASTIC ZONE

\(\dot{z} \approx 1 \text{ m/s}\)

ELASTO-PLASTIC ZONE

SHEAR WAVE VELOCITY

PARTICLE VELOCITY
COMPONENTS OF PILE VIBRATION ANALYSIS

- Transfer of energy from pile to soil
- Dissipation of energy through soil
- Threshold of settlement causing vibrations
GENERATION OF GROUND DISTURBANCE

TRANSFER OF DRIVING ENERGY INTO SURROUNDING GROUND
$D = f(\mu)$

- **Cylindrical Shear Wave Front**
- **Shaft Resistance**
- **Tip Resistance**
- **Spherical Wave Front**
TIP RESISTANCE

GOBLE (1980)  \[ R_T = J Z^P \dot{z} \]
- **J** = Damping or loss factor
- **Z^P** = Pile impedance
- **\dot{z}** = particle velocity in pile

IWANOWSKI AND BODARE (1988)

- **J** = ratio of pile and soil impedance and also related to “K” in Heckman & Hagerty (1978)

MASSARSCH AND FELLENIUS (2008)

\[ R_T = Z_P v_o \]
- **Z_P** = \( A^P v_{ps} \rho_s \)
- **v_o** = Hammer impact velocity
SHAFT RESISTANCE

MASSARSCH AND FELLENIUS (2008)

\[ R_S = z_s \dot{\gamma} A^C \]

- \( z_s \) = specific impedance of soil
- \( \dot{\gamma} \) = particle velocity in pile
- \( A^C \) = contact area between soil and pile

\[ \dot{\gamma} = \frac{t_f}{v_s \rho} \quad \text{(often} > 12 \text{ in/sec)} \]

- \( t_f \) = shearing strength of soil
- \( v_s \) = shear wave velocity
- \( \rho \) = mass density of soil

\[ \{(\dot{\gamma})_{\text{max}} \approx 1 \text{ m/s} \quad \text{Observed in densification studies}\} \]
DISSIPATION OF ENERGY WITH DISTANCE

GEOMETRICAL AND MATERIAL DAMPING
EQUATIONS DESCRIBING ENERGY DISSIPATION

BORNITZ EQUATION

\[ w = w_1 \left( \frac{r_1}{r} \right)^n \exp[-\alpha(r - r_1)] \]

- \( w_1 \) = amplitude at known distance \( r_1 \)
- \( w \) = amplitude at any distance \( r \)
- \( r_1 \) = distance from source to point of known amplitude
- \( r \) = distance from source to any point
- \( n \) = coefficient depending on type of wave
  - \( n = 1 \) for body waves in half-space
  - \( n = 2 \) for body waves along surface
  - \( n = 0.5 \) for Rayleigh waves
- \( \alpha \) = coefficient of attenuation
PROPOSED CLASSIFICATION OF EARTH MATERIALS BY ATTENUATION COEFFICIENT

<table>
<thead>
<tr>
<th>CLASS</th>
<th>ATTENUATION COEFFICIENT</th>
<th>DESCRIPTION OF MATERIAL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\alpha \ (1/\text{ft})$</td>
<td>5 Hz 50Hz</td>
</tr>
<tr>
<td>I</td>
<td>0.003 0.03</td>
<td>Weak or Soft Soils—lossy soils, dry or partially saturated peat and muck, mud, loose beach sand, and dune sand, recently plowed ground, soft spongy forest or jungle floor, organic soils, topsoil. $N &lt; 5$ (shovel penetrates easily)</td>
</tr>
<tr>
<td>II</td>
<td>0.001 0.01</td>
<td>Competent Soils—most sands, sandy clays, silty clays, gravel, silts, weathered rock. (can dig with shovel) $5 &lt; N &lt; 15$</td>
</tr>
<tr>
<td>III</td>
<td>0.0001 0.001</td>
<td>Hard Soils—dense compacted sand, dry consolidated clay, consolidated glacial till, some exposed rock. (cannot dig with shovel, must use pick to break up) $15 &lt; N &lt; 50$</td>
</tr>
<tr>
<td>IV</td>
<td>&lt;0.0001 &lt;0.001</td>
<td>Hard, Competent Rock—bedrock, freshly exposed hard rock. (difficult to break with hammer) $N &gt; 50$</td>
</tr>
</tbody>
</table>
EQUATIONS DESCRIBING ENERGY DISSIPATION

PSEUDO - ATTENUATION

\[ \dot{z} = k \left[ \frac{D}{\sqrt{E}} \right]^{-N} \]

\( \dot{z} \) = peak particle velocity
k = intercept at 1 energy unit
D = distance from source
E = energy of source
N = slope of line on log-log plot of \( \dot{z} \) vs scaled distance
PSEUDO ATTENUATION PEEK PARTICLE

Upper Bound Solution
\[ V = 0.137 \left( \frac{D}{E} \right)^{1/2} - 1.27 \]

\[ \text{Scaled Distance} \quad \left( \frac{D}{\sqrt{E}} \right) \]
VIBRATIONS CAUSING SETTLEMENT

SHEARING STRAIN
AND
VOLUMETRIC STRAIN
SHEARING STRAIN

\[ \gamma = \frac{\dot{z}}{v_s} \]
(For harmonic motion only)

\[ \gamma \text{ equivalent for non-harmonic vibrations, displacement gradient suggested by Brandenberg et al (2009)} \]
\[ \frac{\partial u_z}{\partial y} \]

\[ \dot{z} = \frac{\sigma_z v_p}{E_p} \]
(free end of pile)
THRESHOLD STRAIN

- SILVER & SEED (1971) \( \gamma_t \approx 0.01\% \)
- YOUD (1972) \( \gamma_t = 0.01 \% \) (limit of his tests)
- DOBRY (1983) \( \gamma_t = 0.01\% \) (for liquefaction)
- HSU & VUCETIC (2004) \( \gamma_t = <0.01\% \) (10 cycles)
- MASSARSCHE (2008) \( \gamma_t = 0.001\% \) (many cycles)
- BRANDENBERG ET AL (2009) \( \gamma_t = <0.01\% \)
FIG. VERTICAL SETTLEMENT—SHEAR STRAIN RELATIONSHIP FOR SILICA SAND ($D_r = 60\%$)
VARIABLES AFFECTING $\gamma_t$

- RELATIVE DENSITY
- VOID RATIO
- EFFECTIVE CONFINING PRESSURE

- NUMBER OF CYCLES
- STRAIN LEVEL
EXAMPLE 1

BLACKWATER RIVER BRIDGE
I-10
PENSACOLA, FLORIDA
BLACKWATER RIVER BRIDGE looking SOUTH
ELEVATION THROUGH TEST PILE SECTION
TYPICAL CROSSHOLE WAVE FORMS

(Repetitions to show reproducibility)
PRE-DESIGN SOIL DATA

- $V_s$
- SPT #1
- SPT #3
EMPIRICAL EQUATIONS FOR $V_s$ AND $V_v$

$V_s = a + bN^n(\sigma_0)^m$

where $N$ is SPT Blow Count
$\sigma_0$ is effective octahedral confining pressure
and $a$, $b$, $n$, & $m$ are empirical constants

$V_v = a (\text{dist.}/\sqrt{\text{energy}})^{-n}$

where $a$ & $n$ are empirical constants
dist. is source to receiver distance
and energy is enthru per blow
MEASURED & PREDICTED SETTLEMENT

- PREDICTED
  
  \[(\Delta H)_{max} = 1.47 \text{ ft}\]

- MEASURED
  
  \[\Delta H < 0.01 \text{ ft}\]
Effect of Fines on Dynamic Settlement

BORDEN & SHAO (1995)
EXAMPLE 2

INFRASTRUCTURE
REHABILITATION
INTERSTATE BRIDGE
REPLACEMENT
DEPTH (ft)

- CL
- SP
- SP-ML
- SP
- HP 12x53
- PILES VIBRO DRIVEN
- TO THIS LAYER
- IMPACT DRIVEN
- TO FINAL DEPTH

8 < N < 12

(N) avg = 6

N > 15

1
2a
2b
2c
3

0 20 40 60 80 100 120 140 160
### DYNAMIC PILE ANALYSIS

GRLWEAP(TM) Version 2005

**DELMAG 19-42 : 40 kip-ft**

<table>
<thead>
<tr>
<th>Comp. Stress ksi</th>
<th>Tension Stress ksi</th>
<th>Stroke ft</th>
<th>ENTHRU kips-ft</th>
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<tbody>
<tr>
<td>0.000</td>
<td>0.000</td>
<td>10.60</td>
<td>0.0</td>
</tr>
<tr>
<td>0.000</td>
<td>0.000</td>
<td>10.60</td>
<td>0.0</td>
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<tr>
<td>15.879</td>
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<td>4.46</td>
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<tr>
<td>21.333</td>
<td>-3.802</td>
<td>5.24</td>
<td>20.8</td>
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<tr>
<td>21.303</td>
<td>-3.663</td>
<td>5.20</td>
<td>20.6</td>
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<td>23.891</td>
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<td>19.6</td>
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<td>25.728</td>
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<td>28.075</td>
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<td>29.923</td>
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<td>30.011</td>
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<td>30.211</td>
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<td>30.310</td>
<td>-2.580</td>
<td>7.92</td>
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DRIVING 5 PILES WITH D 19-42 HAMMER, 300 BLOWS EACH
40 K-FT

<table>
<thead>
<tr>
<th>shearing strain (in/in)</th>
<th>shearing strain (in/in)</th>
<th>1-D vert vol. chg (in/in)</th>
<th>1-D vert vol. chg (in/in)</th>
<th>Vertical Settle (in)</th>
<th>Vertical Settle (in)</th>
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<tbody>
<tr>
<td>0.000849</td>
<td>0.00043078</td>
<td>0.005</td>
<td>0.003</td>
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<td>0.000739</td>
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<td>0.00087</td>
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<td>0.0025</td>
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<td>0.000864</td>
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<td>0.0025</td>
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<td>0.000442</td>
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<tr>
<td>sum</td>
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<td>19.608</td>
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<tr>
<td>Ultimate Capacity kips</td>
<td>Maximum Compression Stress ksi</td>
<td>Maximum Tension Stress ksi</td>
<td>Blow Count blows/in</td>
<td>Stroke ft</td>
<td>Energy kips-ft</td>
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<tr>
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<tr>
<td>400.0</td>
<td>27.12</td>
<td>2.56</td>
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<td>17.97</td>
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<tr>
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<td>30.44</td>
<td>2.77</td>
<td>4.2</td>
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<td>22.57</td>
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<tr>
<td>400.0</td>
<td>31.96</td>
<td>2.82</td>
<td>3.7</td>
<td>8.87</td>
<td>24.36</td>
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<tr>
<td>400.0</td>
<td>33.39</td>
<td>2.90</td>
<td>3.3</td>
<td>9.49</td>
<td>26.11</td>
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<tr>
<td>400.0</td>
<td>34.77</td>
<td>3.42</td>
<td>3.0</td>
<td>10.11</td>
<td>27.86</td>
</tr>
<tr>
<td>400.0</td>
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<td>4.35</td>
<td>2.7</td>
<td>10.73</td>
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<td>39.89</td>
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<td>12.60</td>
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DRIVING 3 PILES WITH D30-32 HAMMER, 300 BLOWS EACH
70 K-FT

<table>
<thead>
<tr>
<th>shearing strain</th>
<th>shearing strain</th>
<th>1-D vert vol. chg</th>
<th>1-D vert vol. chg</th>
<th>Vertical Settle</th>
<th>Vertical Settle</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 Hz (in/in)</td>
<td>50 Hz (in/in)</td>
<td>5 Hz (in/in)</td>
<td>50 Hz (in/in)</td>
<td>5 Hz (in)</td>
<td>50 Hz (in)</td>
</tr>
<tr>
<td>0.000338</td>
<td>8.50834E-05</td>
<td>0.0018</td>
<td>0.0004</td>
<td>1.641</td>
<td>0.3648</td>
</tr>
<tr>
<td>0</td>
<td><strong>0.000085</strong></td>
<td></td>
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<tr>
<td>0.000199</td>
<td>2.28521E-05</td>
<td>0.001</td>
<td>0.0001</td>
<td>0.91</td>
<td>0.0912</td>
</tr>
<tr>
<td>0</td>
<td><strong>0.000023</strong></td>
<td></td>
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<td>0.000339</td>
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<td>0.0018</td>
<td>0.0004</td>
<td>1.641</td>
<td>0.3648</td>
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<td><strong>0.000085</strong></td>
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<td></td>
<td></td>
<td>4.195</td>
</tr>
</tbody>
</table>


SUMMARY

\[ D = f(\mu) \]

CYLINDRICAL SHEAR WAVE FRONT

SHAFT RESISTANCE

TIP RESISTANCE

SPHERICAL WAVE FRONT
SHEAR STRAIN

10^{-1} \% - 10^{-3} \%

SHEAR STRAIN

< 10^{-3} \%

THREE ELEMENTS TO PREDICT SETTLEMENT

1) Pile to Soil Energy Transfer

2) Transmission of Energy through Soil

3) Vibration Level Required to Cause Settlement

\{ \dot{z} \approx 1 \text{ m/s} \}
ACKNOWLEDGE CONTRIBUTORS

- John Schmertmann
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- Larry Jedele
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- Robert Rabeler
- Rainer Messarsch (Vibisol International Sweden)
CONGRATULATIONS TO VINCE AND ROXANNE ON A BRILLIANT CAREER

FINALLY

THANK YOU!

DICK