EFFECTS OF PILE-DRIVING INDUCED VIBRATIONS ON NEARBY STRUCTURES AND OTHER ASSETS

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OBJECTIVES

• Attenuation rates for pile-driving induced vibration waves

• Effect of site conditions and pile/hammer characteristics on the attenuation

• Screening tool for soil shakedown potential during pile-driving
\[ D = f(\mu) \]

**CYLINDRICAL SHEAR WAVE FRONT**

**RAYLEIGH WAVE**

**SHAFT RESISTANCE**

**TIP RESISTANCE**

**SPHERICAL WAVE FRONT**
NON-LINEAR ZONE

{ \dot{\varepsilon} > 1 \text{ m/s} }

SHEAR STRAIN

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

NEARLY ELASTIC ZONE

SHEAR STRAIN

< 10^{-3} \%
• Field Testing: Sensor installation and data acquisition

• Data processing and synthesis from all sites

• Development of screening tool for soil shakedown potential during pile-driving
Sensors & Data Acquisition System

Cone casing and adaptor used to push the sensors to depth of interest

Cone casing with attached geophone

Geophone and Triaxial accelerometer

Cone casings with attached accelerometers
Sensors & Data Acquisition System

Surface geophone

Data acquisition system used to record the signals from sensors
Sites Monitored and Procedure

Positions for sensor installation

Installation of casing
Sites Monitored and Procedure

Pile driving and monitoring
Sites Monitored and Procedure

Data acquisition
Field Testing Sites
Site M-25 (Harbor Beach)
Site M-25 (Harbor Beach)

Plan view of sensor locations

Cross-Section of sensor locations
Site M-66 (Battle Creek)

Plan view of sensor locations

Cross-Section of sensor locations
Site M-66 (Battle Creek)

Plan view of surface geophone sensor locations
Site M-66 (Battle Creek)

Welding the second piece after completion of pile driving and monitoring again
Site US-131

Tested at both abutments
Site Conditions

- **Boring 5**
  - Depth of sensors
  - 41 ft: Dense silt
  - 100 ft: Hard silty clay

- **Boring 1**
  - Depth of sensors
  - 14 ft: Medium dense fine and medium sand
  - 3 ft: Very loose fine and medium sand
  - 9 ft: Loose fine and medium sand
  - 3 ft: Medium dense fine and medium sand
  - 100 ft: Sandstone
Site Conditions

Loose fine and medium sand

Depth (ft)

Boring 4

Depth of sensors

Medium dense silt

Loose fine and medium sand

Medium dense fine and medium sand

Dense fine to coarse sand

Very dense fine to coarse sand

M-139

NSPT

Boring 1

Depth of sensors

Loose fine to medium sand

Loose to medium dense fine to coarse sand

Dense clayey fine sand

Very dense fine to medium sand

Hard sandy clay

US 131 A

NSPT
Site Conditions: $V_s$ measurements

**M-139**

**SPT close to pile location**

- 5: Loose fine & med sand
- 7: Med dense silt
- 7: Loose fine & med sand
- 9: Med dense fine & med sand
- 11: Dense fine to coarse sand
- 19: Very dense fine to coarse sand
- 41: Dense silt with clay
- 48.5: Very dense fine sand
- 70:  

**M-139**

**Vs profile**

- Boring 4: adjusted analysis based on profile
- SASW

**Measurements**

- Depth (ft)
- N
- $V_s$ (ft/s)
Field Testing Data
Site M-25 (Harbor Beach)

Record of accelerometers (vertical axis)
Site M-25 (Harbor Beach)

Max spike for pile tip elevation 23-24 ft
Peak Particle Velocity (PPV) Results

![Graphs showing PPV results for different sensors at various elevations.](image)

- US-131 A
- US-131 B
- Depth of sensors represented in the graphs.
Peak Particle Velocity (PPV) Results
(Surface geophones)
D = f(\mu, z)

CYLINDRICAL SHEAR WAVE FRONT FROM SHAFT

RAYLEIGH WAVE

SPHERICAL WAVE FRONT FROM TIP

MOTION SENSOR

HAMMER
Site M-139

max spikes of A3 sensor (ALL spikes)

- Tip above A3
- Tip below A3

Depth of sensor = 25.5 ft
Distance from pile = 0.5 ft

PPV (in/sec)

Diagonal distance from sensor to pile tip (ft)
max spikes of A4 sensor (ALL spikes)

- tip above A4
- tip below A4

depth of sensor = 25.5 ft
distance from pile = 2.5 ft
max spikes of A5 sensor (ALL spikes)

- Tip above A5
- Tip below A5

Depth of sensor = 25.5 ft
Distance from pile = 6.5 ft
M-139

10 ft above and 10 ft below depth of sensors (track ALL blows)

depth of sensors = 25.5 ft

PPV (in/sec)

Diagonal distance from sensor to pile tip (ft)

above sensor A3

below sensor A3

below sensor A5

below sensor A4

A3 (horizontal distance=0.5 ft)
A4 (horizontal distance=2.5 ft)
A5 (horizontal distance=6.5 ft)
Data Processing
Wave Attenuation Coefficients

Site US-131A

<table>
<thead>
<tr>
<th></th>
<th>Distance from pile (ft)</th>
<th>$\dot{z}$ (in/sec)</th>
<th>$\gamma$</th>
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</thead>
<tbody>
<tr>
<td>PILE</td>
<td>0.1</td>
<td>23.80</td>
<td>0.2220569</td>
</tr>
<tr>
<td>A2</td>
<td>0.5</td>
<td>9.74</td>
<td>0.1322479</td>
</tr>
<tr>
<td>A4</td>
<td>2.5</td>
<td>3.34</td>
<td>0.1895872</td>
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<tr>
<td>SG2</td>
<td>6.5</td>
<td>0.97</td>
<td>0.1704741</td>
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<tr>
<td>PILE</td>
<td>0.1</td>
<td>23.80</td>
<td>0.1472161</td>
</tr>
<tr>
<td>PILE</td>
<td>0.1</td>
<td>23.80</td>
<td>0.1736980</td>
</tr>
</tbody>
</table>

Pile Tip Elevation 34-35 ft

Distance from pile (ft) vs. $\dot{z}$ (in/sec) for different piles and distances.
ENERGY DISSIPATION

Bornitz Equation: \[ A_2 = A_1 \left( \frac{r_1}{r_2} \right)^n \exp[-\alpha(r_2 - r_1)] \]

- \( A_1 \) = amplitude at known distance \( r_1 \)
- \( A_2 \) = amplitude at any distance \( r_2 \)
- \( r_1 \) = distance from source to point of known amplitude
- \( r_2 \) = 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 replaced by: \( \Upsilon \) determined from this study
Shearing Strain Calculation

\[ \phi \approx \tan^{-1}\left(\frac{N_{SPT}}{12.2 + 20.3 \sigma_v'/\text{Pa}}\right)^{0.34} \]

\[ \phi \Rightarrow K \Rightarrow \sigma_h' \Rightarrow \text{shear stress, } \tau \]

Best estimation based on using 3 layers with:

- 1\text{st} layer \Rightarrow K_o
- 2\text{nd} layer \Rightarrow 1.1K_o
- 3\text{rd} layer \Rightarrow 1.2K_o

\[ \text{maxPPV} = \frac{\tau_{\text{max}}}{(V_s \rho)} \text{ at pile face} \]

\( (V_s \text{ reduced appropriately}) \)
Shearing Strain Calculation

\[ \phi \approx \tan^{-1}\left[ \left( \frac{N_{SPT}}{12.2 + 20.3\sigma_v' / \text{Pa}} \right)^{0.34} \right] \]

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\[ \text{maxPPV} = \frac{\tau_{\text{max}}}{V_s \rho} \] at pile face

\( V_s \) reduced appropriately
φ≈tan⁻¹\left[\frac{N_{SPT}}{(12.2+20.3σ_v'/Pa)}\right]^{0.34}

φ => K => σ_h' => shear stress, τ

Best estimation based on using 3 layers with:

1\textsuperscript{st} layer=>K_0
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\[ \text{maxPPV} = \tau_{\text{max}} / (V_s \rho) \quad \text{at pile face} \]

\( V_s \) reduced appropriately
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)

• MASSARSCH (2008) $\gamma_t = 0.001\%$ (many cycles)

• BRANDENBERG ET AL (2009) $\gamma_t < 0.01\%$
Effect of Fines on Dynamic Settlement

AFTER BORDEN & SHAO (1995)
Spreadsheet

- Input = Soil Profile, Pile Type and Size, Hammer
- Output = Yes or No to likelihood of shakedown settlement at selected distances from pile
- Not considered – number of piles or blows
- Not considered – amount of settlement
Conclusions

• In situ ground vibration measurements during pile driving extended our understanding and helped improve and refine the hypothetical model of energy transfer from pile to ground.

• The Bornitz form of equation was determined to be the best way to most accurately represent attenuation. However, the conventional way of including material damping through the coefficient of attenuation, $\alpha$, was determined to be too simple for driven piles as a source of energy, so a different symbol for coefficient of attenuation, $\gamma$, has been chosen.

• A spreadsheet calculation tool was developed for identifying potentially troublesome sites. This tool requires input of only a basic soil stratigraphy, blow counts (N) for each strata, pile section and pile driver rated energy. Soil and attenuation properties are derived from correlations with blow count (N).
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