Nondestructive Testing to Predict the Embedded Depth of Pile Foundation

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Thanks to: Shamim Rahman, Mervyn Kowalsky, Rudi Seracino (NCSU)
Mohammed Mulla (NCDOT)

Motivation

- Piles are used widely in bridges \(^1\)
  - Average age of 607,380 bridges is 42 years
  - One in every nine bridges is structurally deficient
- Bearing capacity directly related to the embedded length
  - Important: embedded length of in-tact pile
  - Sometimes even the original length is not recorded
- Objective: An effective nondestructive testing (NDT) technique for estimating pile length

1. ASCE – 2013 Report Card for America’s Infrastructure
Existing Techniques

- Longitudinal waves – Impact on top (not always feasible)
- Flexural waves – Impact on Side (complex waves)
- Modal analysis – Sensitivity to boundary conditions
- Parallel Seismic – Requires borehole
- Borehole Sonic/Radar – Requires borehole
- Induction method for steel piles – Requires borehole

**Flexural wave testing is the only feasible method that is inexpensive**

Flexural Wave NDT

- Examine the peaks at the two accelerometers
  - Pulse velocity = ratio of distance and travel time (lag in the peaks)
- Look at the peaks associated with reflections
  - The lag of reflection to first arrival depends on the length
- Back-calculate the length
  - \((\text{Lag} \times \text{pulse\_velocity}) / 2\)
An Example Signal from an Accelerometer

Peaks are impossible to pick directly.

State of the Art: Short Kernel Method (SKM)

Smooth the signal with the help of cross-correlation with a short waveform.

SKM – Results from Lab Testing

| SKM Frequency (Hz) | Estimated Length (m) | Actual Length (m) | Error  
<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>7.13</td>
<td>4.94</td>
<td>44 %</td>
</tr>
<tr>
<td>200</td>
<td>11.5</td>
<td>4.94</td>
<td>&gt; 100%</td>
</tr>
<tr>
<td>250</td>
<td>6.30</td>
<td>4.94</td>
<td>30 %</td>
</tr>
<tr>
<td>300</td>
<td>4.49</td>
<td>4.94</td>
<td>31 %</td>
</tr>
</tbody>
</table>

- Soft tip results show error range from 15 to 45%
- Significant errors even in highly controlled lab setting
- Wide variation of prediction accuracy in the field
  - Sometimes even the peaks are not clearly defined
- Need for a more accurate technique

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Issues Addressed

- Better capture the dispersion properties
  - Effective Dispersion Analysis of Reflections (EDAR)
- Include the effect of soil
  - First arrival does not include effect of soil, but arrival time of reflections are affected by the soil
- Using optimization techniques
- Lab validation of EDAR
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Effect of Dispersion

- Clear peaks from longitudinal waves
- Peaks are dispersed
  - Energy at each frequency travels at a different velocity (wave dispersion)
- SKM convolution has the tendency to shift peaks
EDAR: Effective Dispersion Analysis of Reflections

- Frequency domain analysis
  - As opposed to time-domain approach of SKM
  - Indirectly linked to travel time

- Key: Dispersion properties are explicitly incorporated

- Processing of repeated patterns results in the embedded length

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Effect of Soil

- Soil offers resistance to movement of the pile
  - Winkler foundation type resistance to translation [and damping too]
  - Also resistance to rotation of the pile due to shear
- Translational stiffness from plane strain
- Rotational stiffness from anti-plane shear

Soil Stiffness

- Rotational and translational springs
- Spring stiffness function of soil properties and frequency
  \[ K_T = f(\lambda, \mu, R, C_R, C_P, \omega) \]
  \[ K_R = f(\mu, R, C_R, \omega) \]
- Modified Flexural wave model incorporating the above soil stiffness

\[ \text{Soil Stiffness} \]
Soil Stiffness

Rotational Stiffness

Translational Stiffness

Rotational and Translational stiffness of the soil with Young’s modulus of 45 MPa, Poisson’s ratio .3, and the pile radius of .178m.

What if Soil Stiffness is Ignored?

- Up to 60% error in group velocity
- In the frequency range of interest
- Translation: there can be up to 60% error in predicted length if soil effect is not included (in this case)
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Optimization

- Minimize objective or Misfit function: \( F_{\text{obj}} = \| u_{\text{exp}} - u_{\text{model}} \| \)
  - Can not only minimize to get length, but integrity (modulus)
- Underlying model: Modified Flexural wave model
- Key contribution: can work even in the absence of the excitation signal
  - Different from other optimization methods
  - May be used to fine-tune EDAR for assessing the extent of damage
Objective Function Variation

![Graph showing the objective function as a function of length L (Actual Length = 2 m)]

Objective function as a function of length L (Actual Length = 2 m)

[Real signals will likely not result in such a nice objective function due to noise]

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Lab Validation of EDAR

- Flexural wave testing of pile
  - Installed in NCSU Constructed Facilities Laboratory
- Loose soil
  - Soil stiffness can be ignored

Thanks to Mervyn Kowalsky and Rudi Seracono for setup and equipment

Preliminary Testing

- Data collected using 5 accelerometers for potential use in future algorithm development and validation.
- Only two accelerometer signals are utilized for this work.
EDAR Results from Lab Testing

- **EDAR** has < 3% error, compared to 15 to 100% error from SKM!
- Use of a different hammer does not alter the results from EDAR, but SKM is sensitive to the hammer

<table>
<thead>
<tr>
<th>Cycle Frequency</th>
<th>Wiggle Frequency (m)</th>
<th>Estimated Length (m)</th>
<th>Actual Length (m)</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>81.6</td>
<td>9.89</td>
<td>5.04</td>
<td>4.94</td>
<td>2.1 %</td>
</tr>
</tbody>
</table>

Summary

- Three contributions for flexural wave testing of piles
  - **EDAR**: Effective Dispersion Analysis of Reflections
    - signal processing that respects physics
    - Requires minimal user intervention
    - Incorporation of soil effects including stiffness and damping
    - Optimization technique
- Preliminary lab testing of EDAR
  - High accuracy irrespective of the hammer type
  - **EDAR** has 3% error (vs. 15-100% from SKM)
Future Work

- Continued laboratory verification of EDAR
  - for composite piles
- Further reduction in user intervention for wiggle and cycle analysis
- Development of a portable testing system
- Field testing
- Enhancing EDAR
  - By including soil stiffness and damping
  - Further refinement through optimization
- Extension to concrete, steel and timber piles

Thank You.