NC STATE UNIVERSITY

Nondestructive Testing to Predict the Embedded Depth of Pile Foundation

Murthy Guddati *and* ***Vivek Samu***
NCSU – Civil Engineering
mguddat@ncsu.edu

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

NC STATE UNIVERSITY

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

NC STATE UNIVERSITY

Existing Techniques

- Longitudinal waves – Impact on top (not always feasible)
- Flexural waves – Impact on Side (complex waves)
- Modal analysis – Sensitivity to boundary conditions

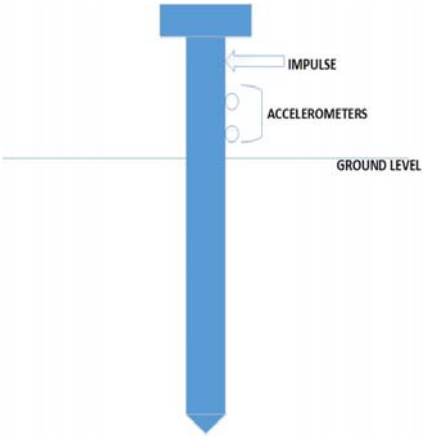
- Parallel Seismic – Requires borehole
- Borehole Sonic/Radar – Requires borehole
- Induction method for steel piles – Requires borehole

Flexural wave testing is the only feasible method that is inexpensive

NC STATE UNIVERSITY

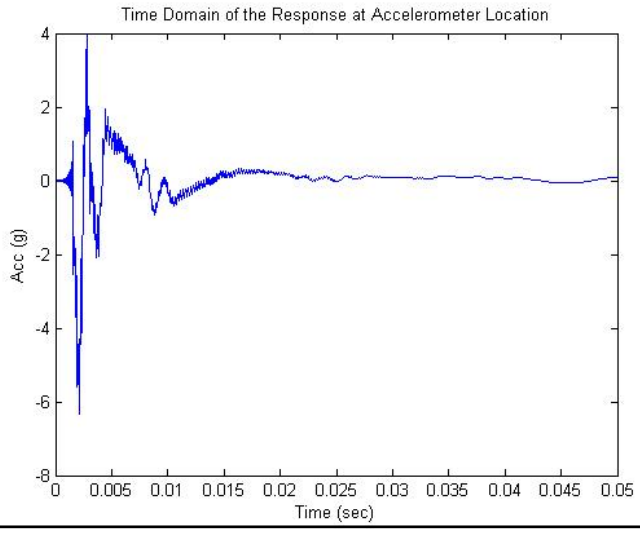
Flexural Wave NDT

- 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
  - (Lag x pulse_velocity) /2



NC STATE UNIVERSITY

An Example Signal from an Accelerometer

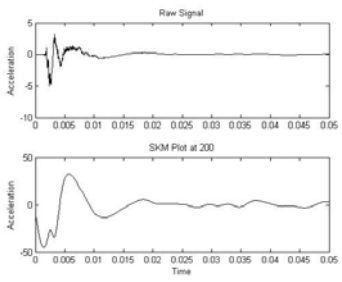


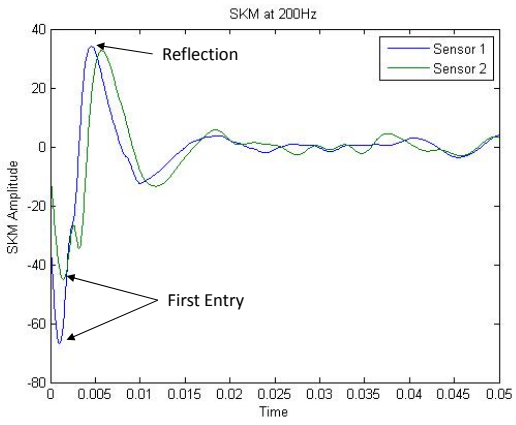
Peaks are impossible to pick directly

NC STATE UNIVERSITY

State of the Art: Short Kernel Method (SKM)

Smooth the signal with the help of cross-correlation with a short waveform [1]





1. Douglas, R. A., and Holt J. D., "Determining Length of Installed Timber Pilings by Dispersive Wave Propagation Methods." (1994)

NC STATE UNIVERSITY

SKM – Results from Lab Testing

SKM Frequency (Hz)	Estimated Length (m)	Actual Length (m)	Error
150	7.13	4.94	44 %
200	11.5	4.94	> 100%
250	6.39	4.94	30 %
300	6.49	4.94	31 %

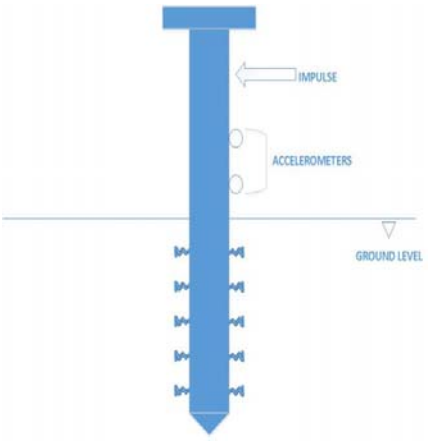
- Soft tip results show error range from 15 to 45%
- Significant errors even in highly controlled lab setting
- Wide variation of prediction accuracy in the field [1]
  - Sometimes even the peaks are not clearly defined
- Need for a more accurate technique

1. Subhani, M., et al (2013). "Determination of the embedded lengths of electricity timber poles utilizing flexural wave generated from impacts."

NC STATE UNIVERSITY

Issues Addressed

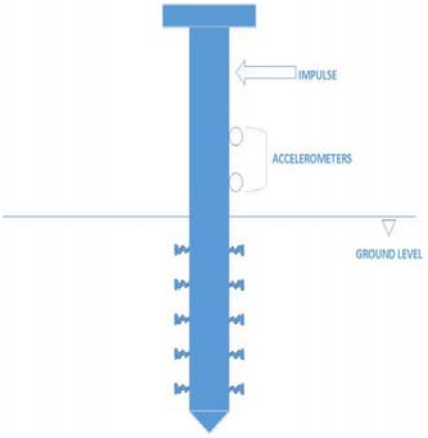
- Better capture the dispersion properties
  - Effective Dispersion Analysis of Reflections (EDAR)
- Include the effect of soil
  - First arrival does not include effect of soil, but arrival time of reflections are affected by the soil
- Using optimization techniques
- Lab validation of EDAR



NC STATE UNIVERSITY

Issues Addressed

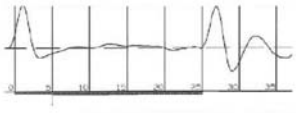
- Better capture the dispersion properties
  - Effective Dispersion Analysis of Reflections (EDAR)
- Include the effect of soil
  - First arrival does not include effect of soil, but arrival time of reflections are affected by the soil
- Using optimization techniques
- Lab validation of EDAR



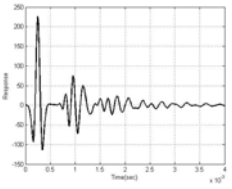
NC STATE UNIVERSITY

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



Longitudinal wave in a bar
Typical Signal from PIT test

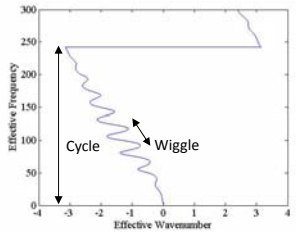


Flexural wave in beam
(synthetic data)

NC STATE UNIVERSITY

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



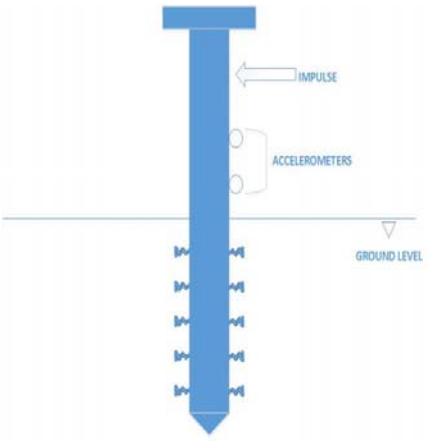
Dispersion relation Partially Embedded Pile (synthetic data)

Wiggle Frequency	24.73
Estimated Length (m)	1.96
Actual Length (m)	2
Error	2 %

NC STATE UNIVERSITY

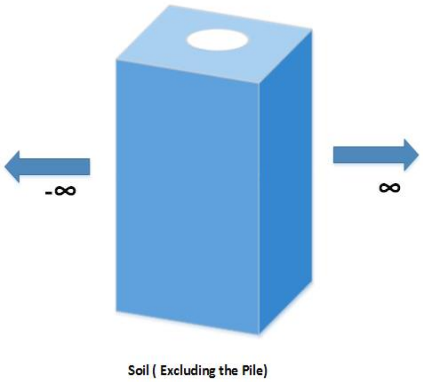
Issues Addressed

- 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



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

$$K_T = f(\lambda, \mu, R, C_s, C_P, \omega)$$

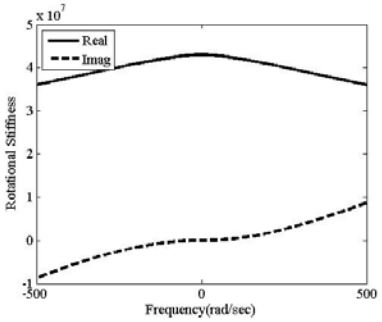
$$K_R = f(\mu, R, C_s, \omega)$$

- Modified Flexural wave model incorporating the above soil stiffness

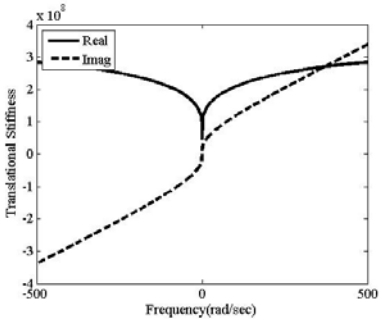
NC STATE UNIVERSITY

Soil Stiffness

Rotational Stiffness



Translational Stiffness

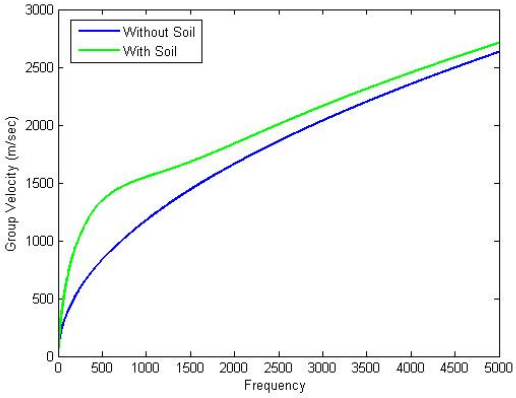


Rotational and Translational stiffness of the soil with Young's modulus of 45 MPa, Poisson's ratio .3, and the pile radius of .178m.

NC STATE UNIVERSITY

What if Soil Stiffness is Ignored?

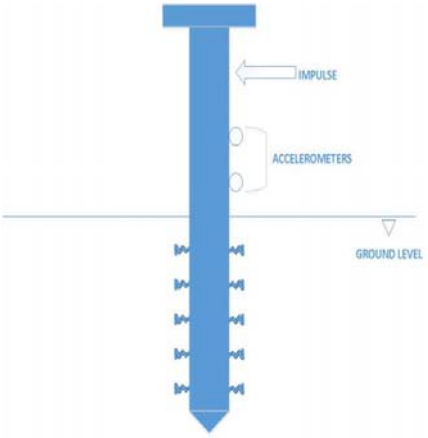
- Up to 60% error in group velocity
  - In the frequency range of interest
- Translation: there can be up to 60% error in predicted length if soil effect is not included (in this case)



NC STATE UNIVERSITY

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



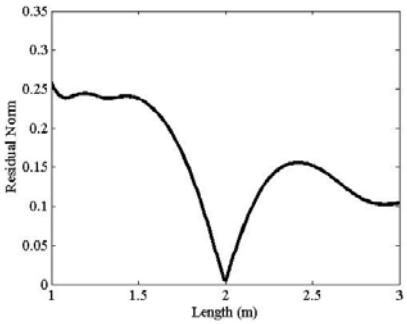
NC STATE UNIVERSITY

Optimization

- Minimize objective or Misfit function: $F_{obj} = \left\| u_{\exp} - u_{model} \right\|$
  - 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

NC STATE UNIVERSITY

Objective Function Variation



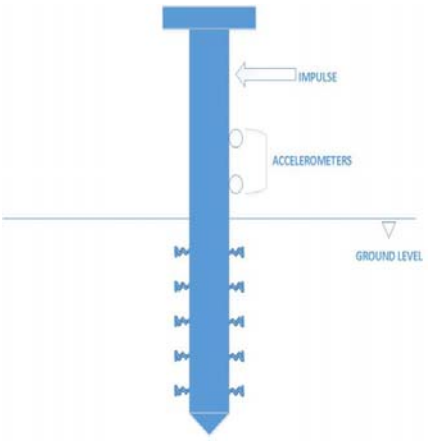
Objective function as a function of length L (Actual Length = 2 m)

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

NC STATE UNIVERSITY

Issues Addressed

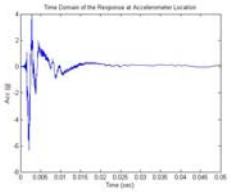
- Better capture the dispersion properties
  - Effective Dispersion Analysis of Reflections (EDAR)
- Include the effect of soil
  - First arrival does not include effect of soil, but arrival time of reflections are affected by the soil
- Using optimization techniques
- Lab validation of EDAR



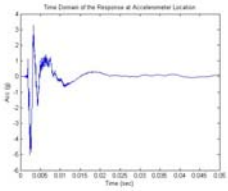
NC STATE UNIVERSITY

Lab Validation of EDAR

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



Top Sensor

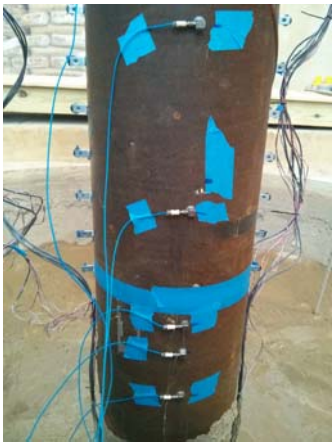


Bottom Sensor

Thanks to Mervyn Kowalsky and Rudi Seracino for setup and equipment

NC STATE UNIVERSITY

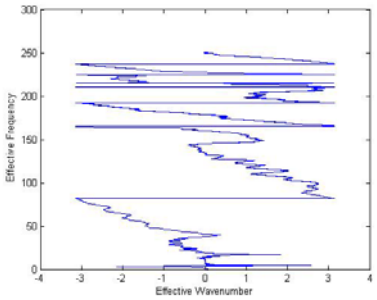
Preliminary Testing



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

NC STATE UNIVERSITY

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

Cycle Frequency	Wiggle Frequency (m)	Estimated Length (m)	Actual Length (m)	Error
81.6	9.89	5.04	4.94	2.1 %

NC STATE UNIVERSITY

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)

NC STATE UNIVERSITY

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

NC STATE UNIVERSITY

Thank You.