



Field Nonlinear Cyclic Measurement in Soil



Outline

- Importance of Nonlinear Soil Characterization
- Laboratory vs Field
- Conventional Field Nonlinear Testing
 - Shallow Ground Improvement Evaluation Project
- Field Nonlinear Testing using Helical Pile
 - Sunderland Site
- Conclusion

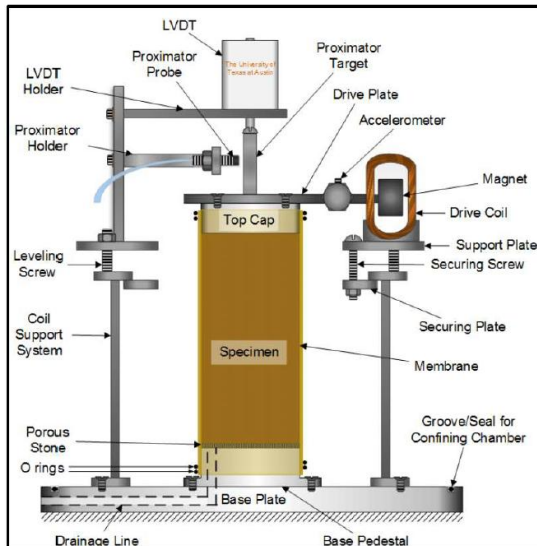


Importance of Nonlinear Soil Characterization

Why Nonlinear Soil Properties?

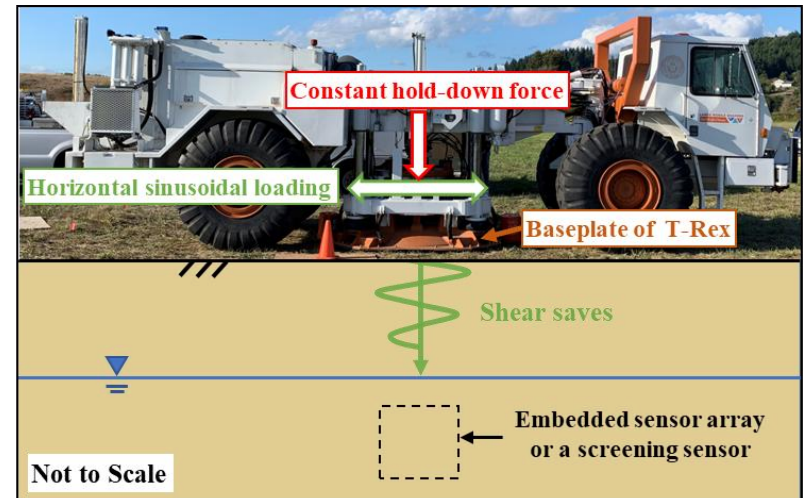
- Soils exhibit **strain-dependent behavior** under seismic loading: stiffness (G) decreases and damping increases with shear strain.
- **Accurate $G/G_{max} - \log \gamma$ curves** are essential for reliable site response analysis and liquefaction assessment.
- Analysis of the Kokusho, T. (2004) and Cubrinovski et al. (2011) revealed that damage distribution was controlled by nonlinear site response, particularly widespread soil liquefaction.
- Neglecting nonlinear soil behavior can lead to **inaccurate ground motion predictions**. (Hashash et al., 2010; Kaklamanos et al., 2015)

Laboratory vs Field Testing



Laboratory testing (e.g., RCTS):

- Provides controlled, high-precision measurements
- Can reach **moderate to large shear strains (up to ~0.1%)**
- Limited by idealized samples
- Laboratory tests often cannot fully replicate field condition



Field testing (e.g., Surface shaking using T-Rex):

- Captures realistic field conditions (e.g., K_0 condition, confining stress, saturation, and natural layering)
- low to moderate strain levels (≤ 0.01 – 0.05%).



Shallow Ground Improvement Evaluation Project Christ Church Earthquake

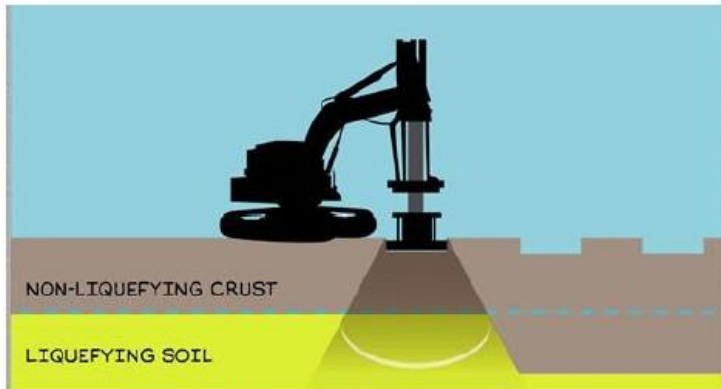




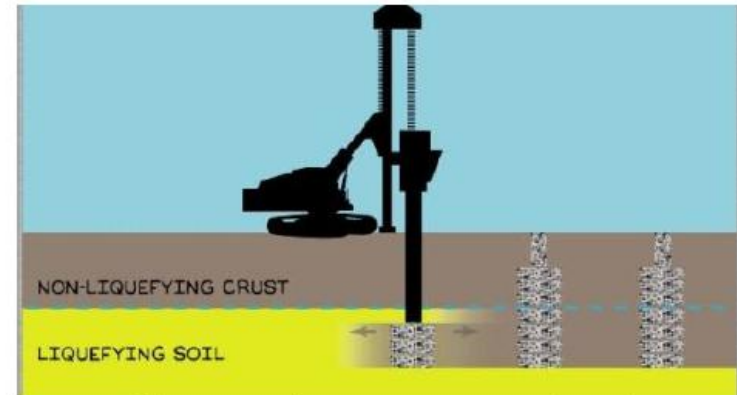
Shallow Ground Improvement Evaluation Project Christ Church Earthquake



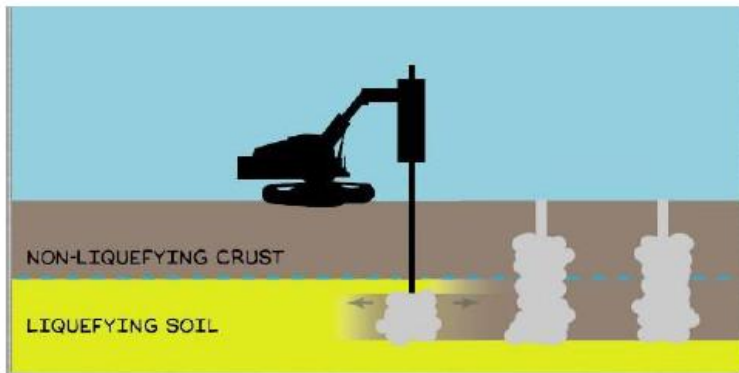
Shallow Ground Improvement Evaluation Project



(a) *Rapid Impact Compaction (RIC)*



(b) *Rammed Aggregate Piers (RAP)*



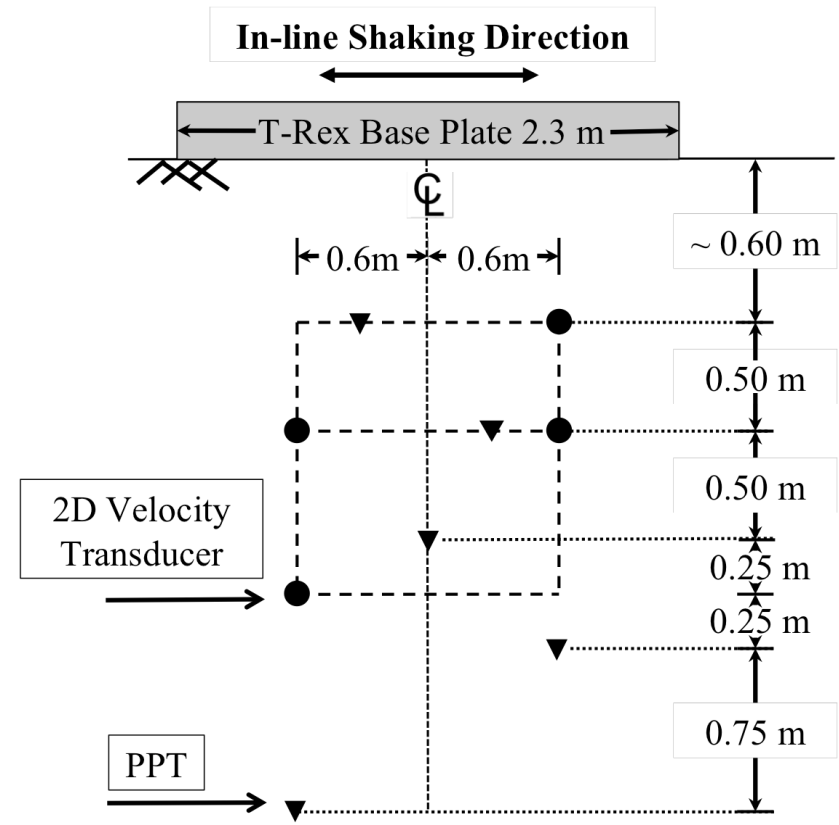
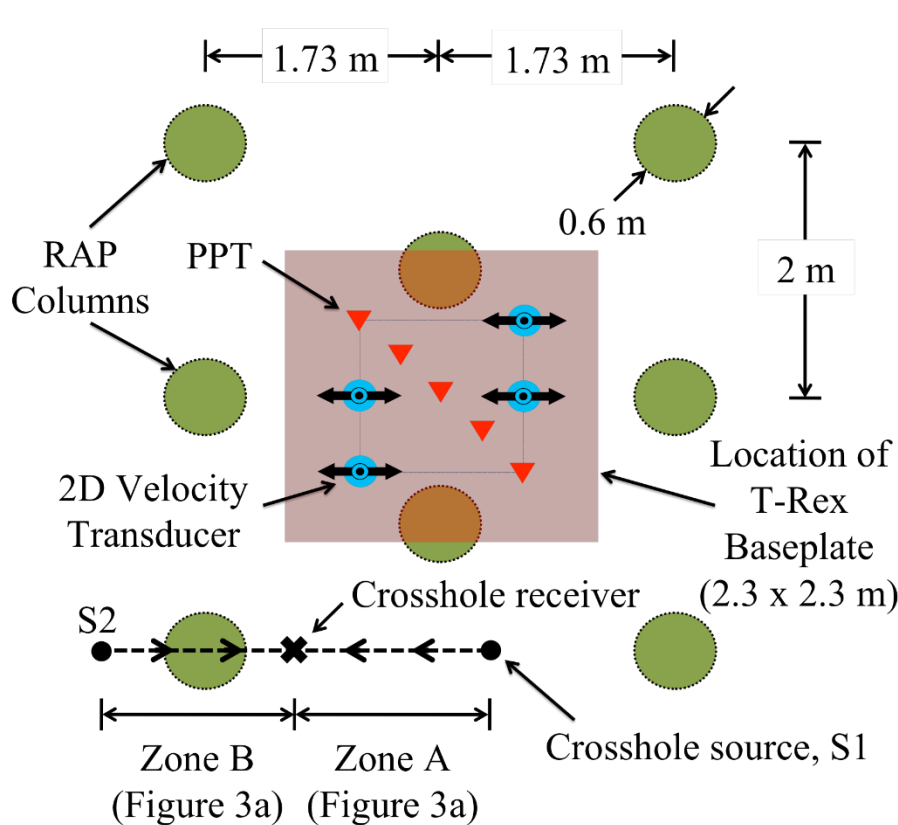
(c) *Low Mobility Grout (LMG)*



(d) *Single Row or Double Row of Horizontal Beams (SRB or DRB)*

Illustration of the four ground improvement methods evaluated in the field trial

Shallow Ground Improvement Evaluation Project

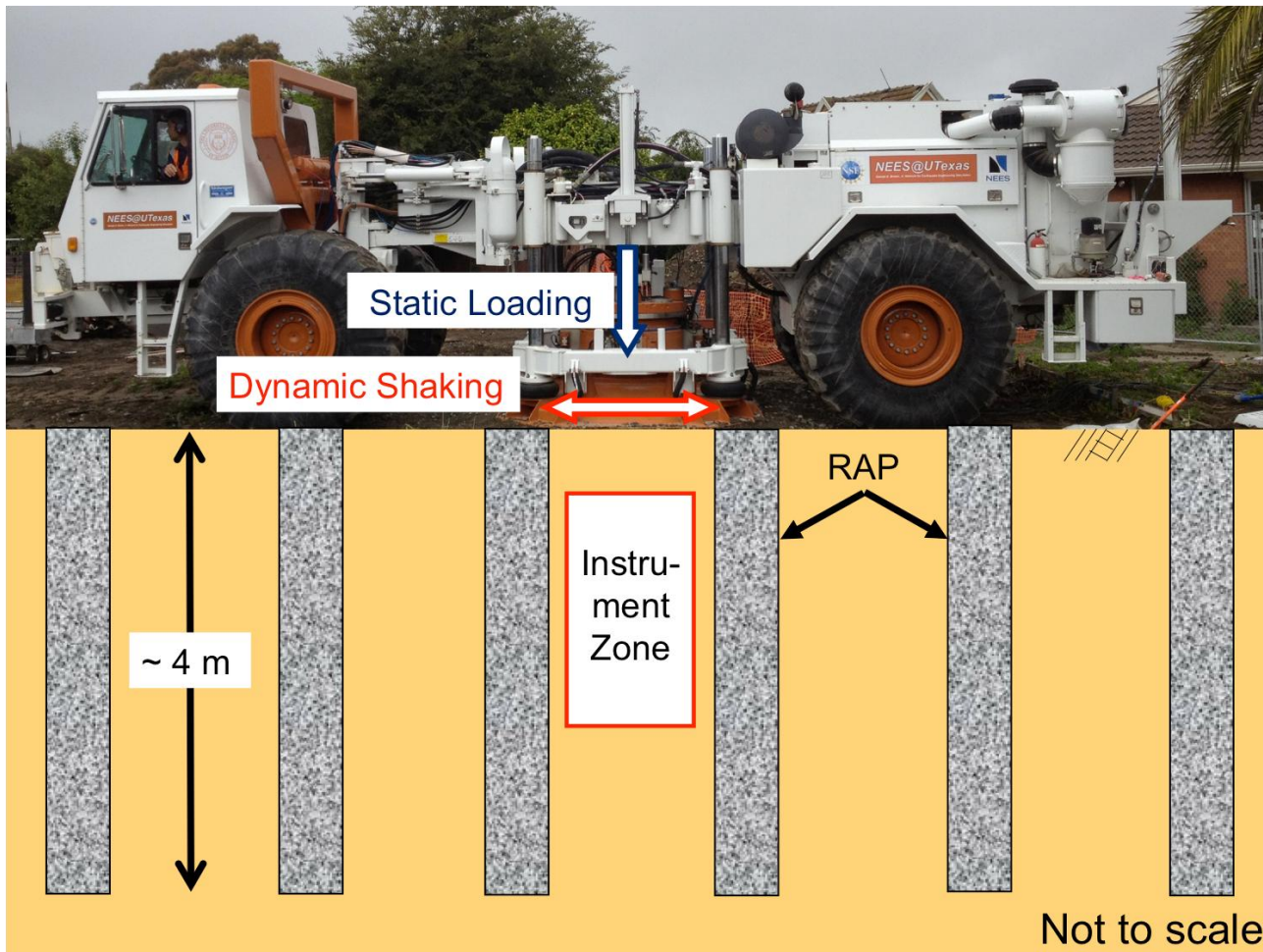


(a) Plan view of central portion of RAP test panel with locations of T-Rex baseplate and pre-shaking crosshole seismic tests.

(b) Instrumentation array created in soil subsequently shaken by T-Rex



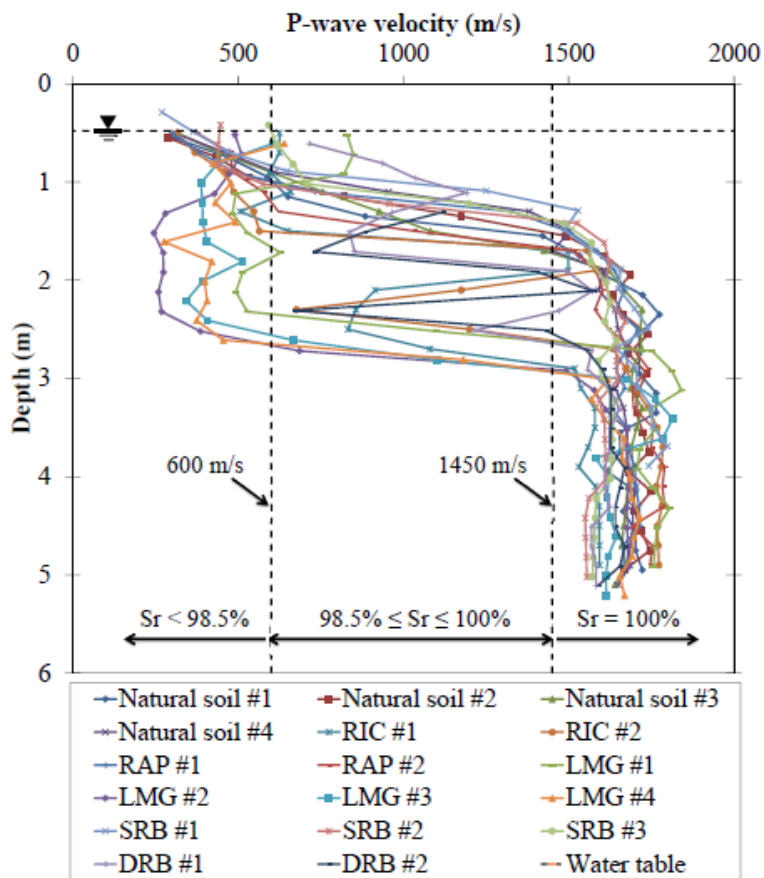
Shallow Ground Improvement Evaluation Project



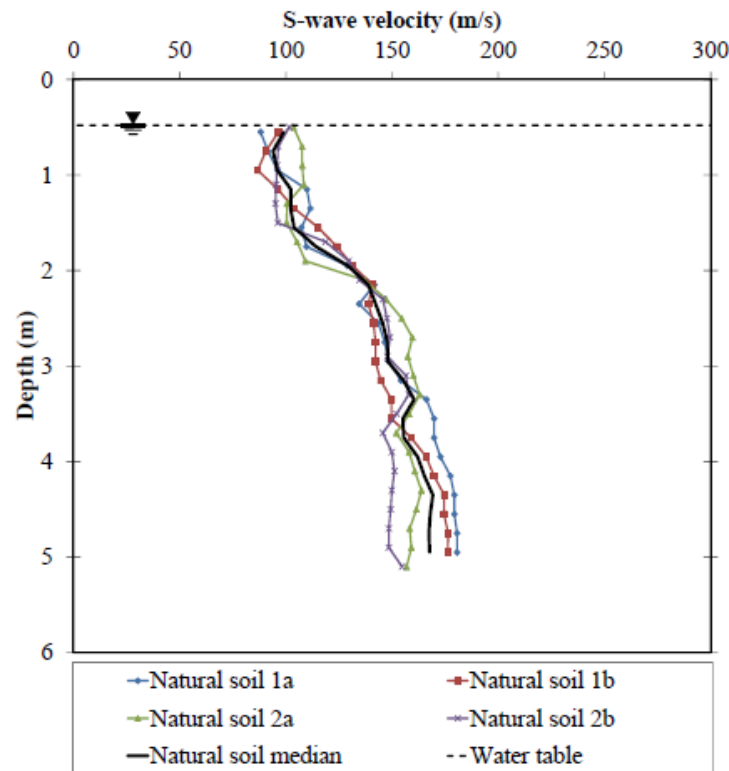
Cross-sectional perspective of T-Rex in place to shake the RAP test panel



Shallow Ground Improvement Evaluation Project

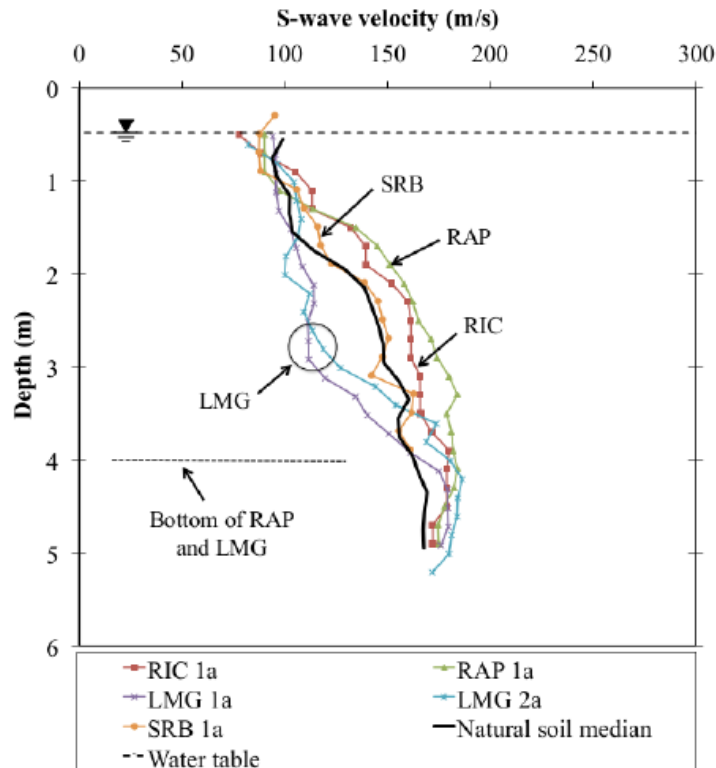


(a) P-wave velocity profiles at each test panel

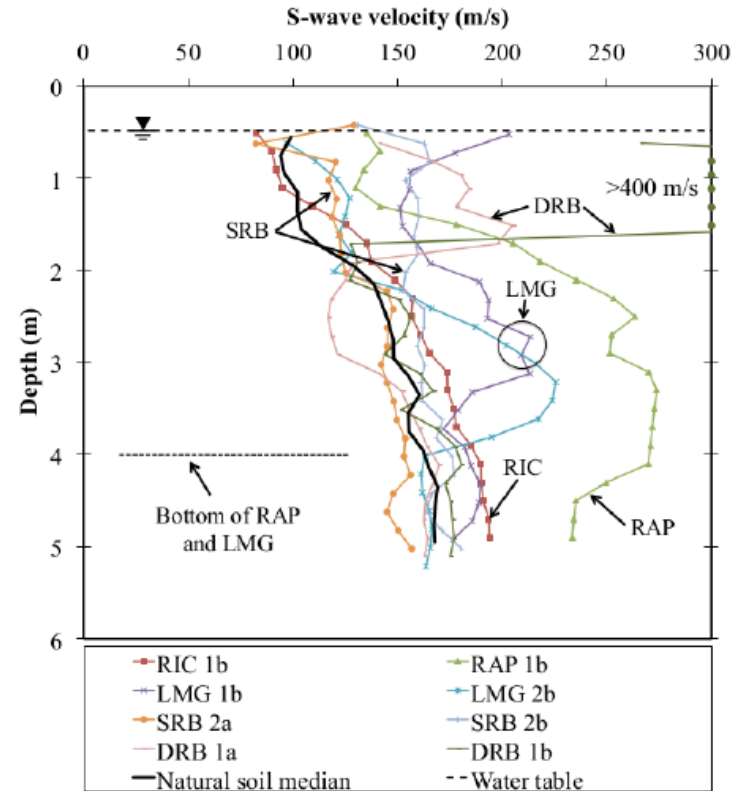


(b) S-wave velocity profiles of both unimproved natural soil test panels with median profile

Shallow Ground Improvement Evaluation Project

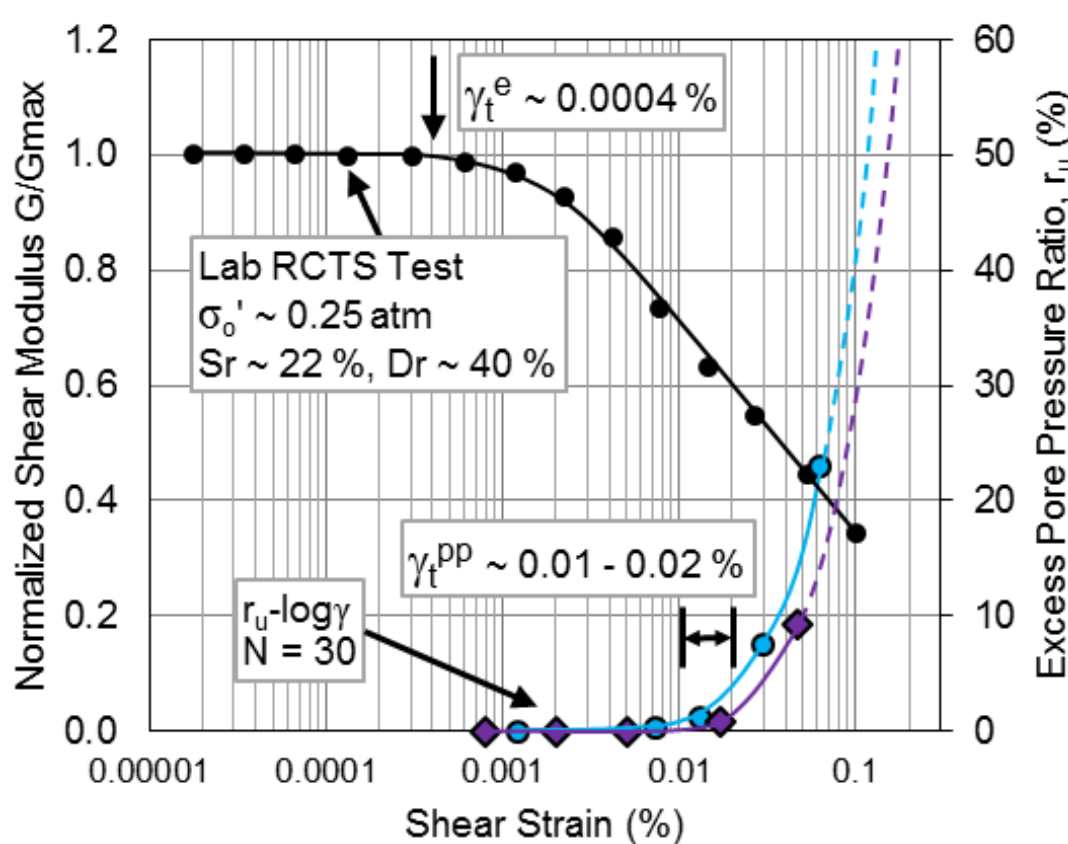


(a) S-wave velocity profiles of soil between improvements compared with median unimproved natural soil profile



(b) S-wave velocity profiles across the improvements compared with median unimproved natural soil profile

Shallow Ground Improvement Evaluation Project



Comparison between the G/G_{max} - log γ curve from RC testing and the r_u - log γ relationships at natural test panel



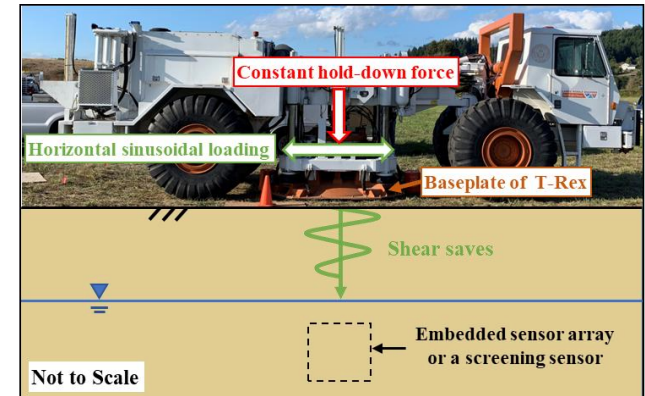
Limitation of Conventional Method

Conventional Surface Shaking

- Shaking applied at the surface.

Key Limitations:

- Varying stress across layers during surface excitation
- Rapid attenuation of cyclic strain with depth
- Effective testing zone restricted to approximately 2 meters



Research Objective:

- Develop and validate a field nonlinear cyclic test method using a helical pile.
- Overcome existing limitations (depth, strain range).
- Soil nonlinearity at a target depth.

Field Nonlinear Cyclic Measurement Using Helical Pile

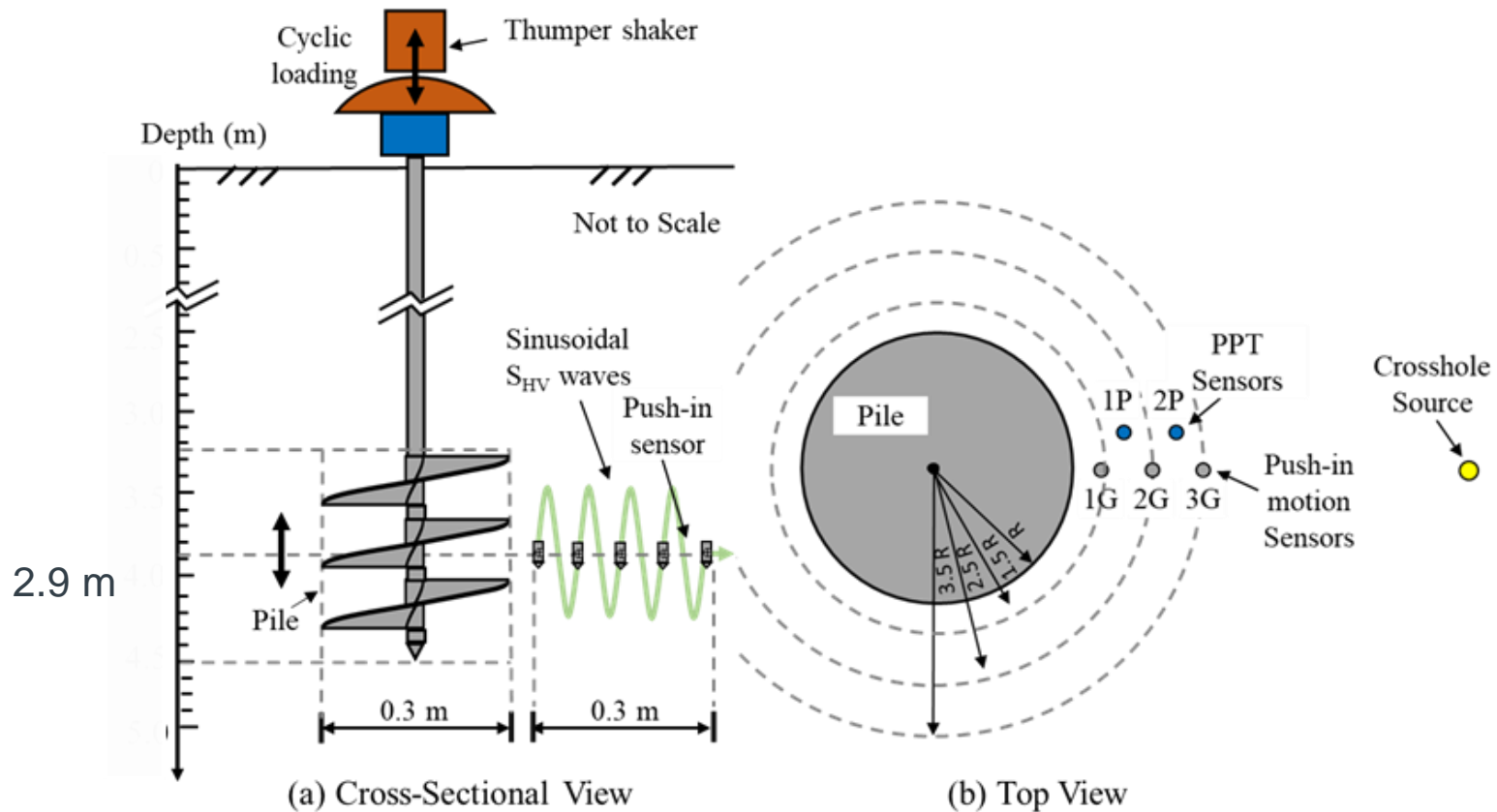


Illustration of the basic arrangement and instrumentation array employed in the field nonlinear cyclic test using a helical pile generating horizontally propagating, vertically polarized waves



What is Helical Pile

Helical pile (also called a screw pile) is a type of deep foundation system used to support loads from structures. It consists of a central steel shaft with one or more helical (spiral-shaped) plates welded to it, resembling a large screw.

Key Advantages

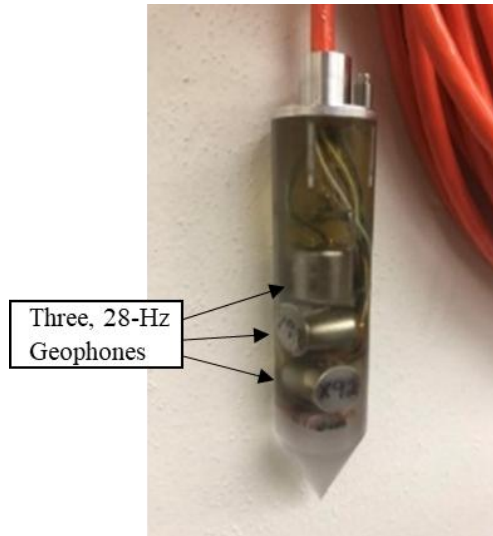
- **Screw-In Mechanism** – The helical plates cut through the soil as they advance, rather than displacing or hammering.
- **Preserves Soil Structure:** The helical blades essentially "slice" through soil rather than shoving it aside. This preserves the surrounding soil fabric and stress conditions, which is important when you want minimal impact on soil properties
- **Localized Disturbance:** Any disturbance that occurs is confined to the narrow path of the helical plates. Beyond this immediate area, the soil structure remains largely unaffected.



Helical Pile Installation

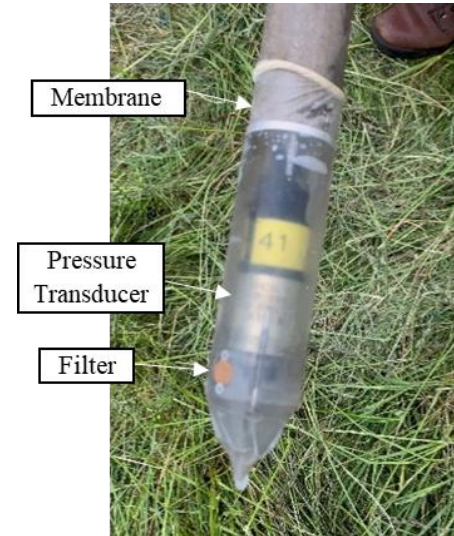


Testing Equipment



3-D Motion Sensors:

- Custom built
- Polycarbonate casing
- Three orthogonal 28-Hz geophones to measure particle velocity in three directions.



Pore-Water Pressure Transducers (PPTs):

- Custom-Built
- Monitor dynamic pore pressure changes during shaking.



Testing Equipment

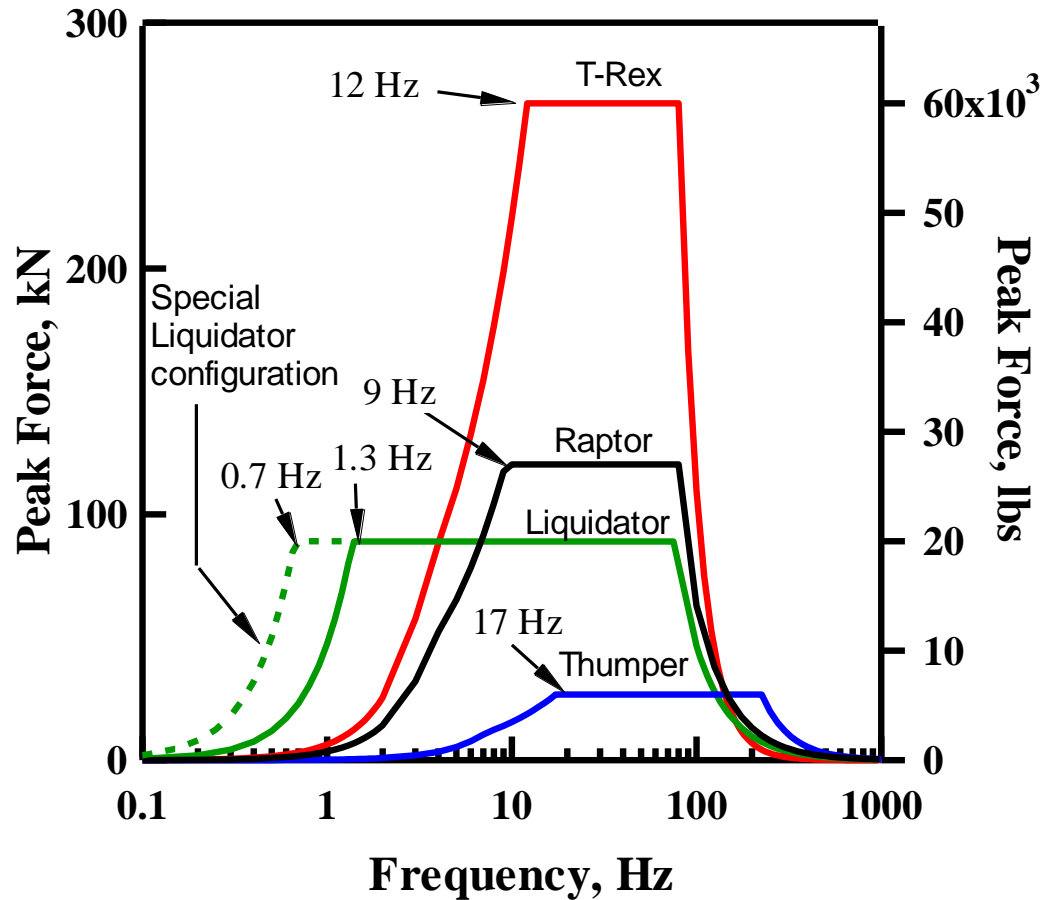


Thumper (Urban Shaker)

- Built on a International 4300 truck;
- 27-ft long, 8.5-ft wide, weight = 24,800 lbs
- Three vibrational orientations
- Four hours field transformation of shaking orientation
- Shear-mode Peak Force = 6,000 lbs
- Vertical-mode Peak Force = 6,000 lbs



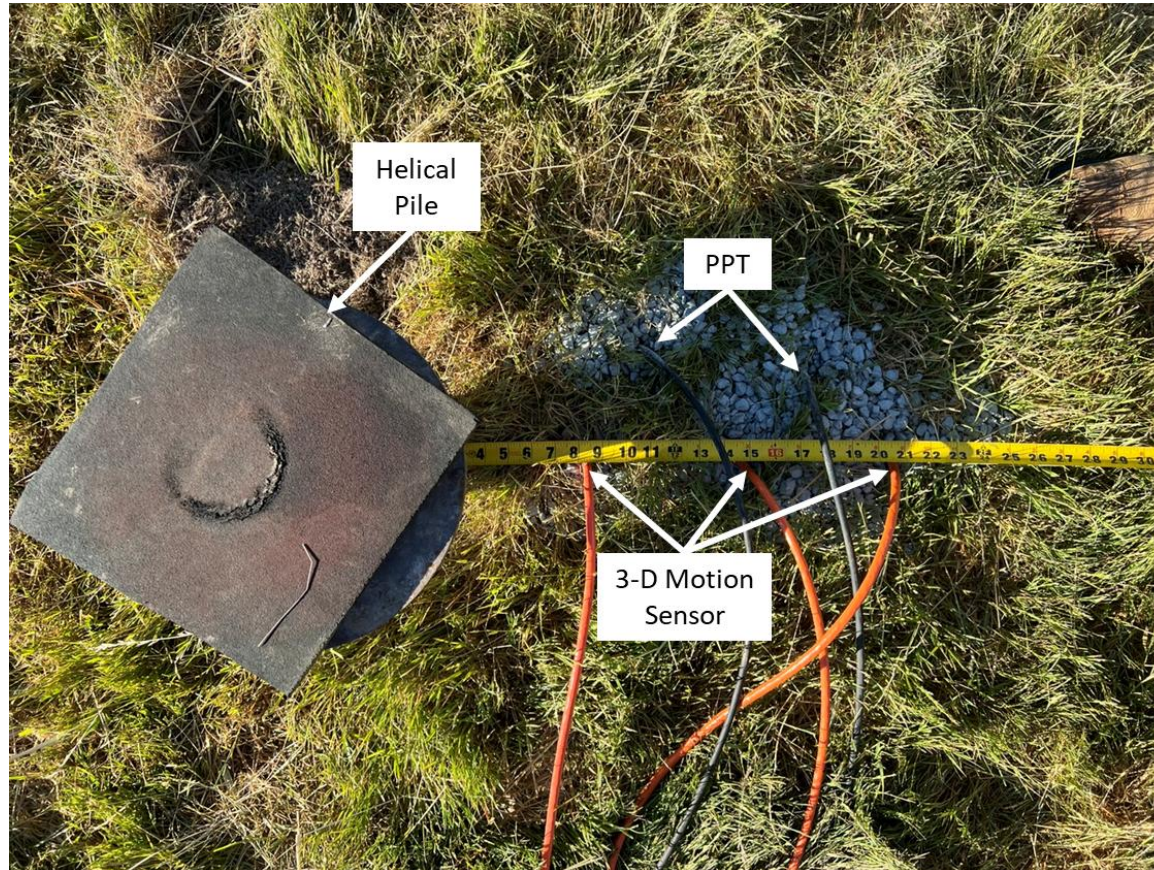
Testing Equipment



Theoretical vertical force outputs of the five mobile shakers available at NHERI@Utexas facility



Field Nonlinear Cyclic Measurement Using Helical Pile



Instrumented array in the field nonlinear cyclic tests using a helical pile at the untreated pad



Application Case Study - The Sunderland Site

Objective: To demonstrate and validate the field nonlinear cyclic test method

Test Site: The Sunderland site in Portland, Oregon, composed of low-plasticity silty soil

Test Beds: The method was applied at two adjacent locations to test its ability to differentiate:

- **Untreated Pad:** The natural, in-situ soil, serving as a baseline
- **Treated Pad:** A location that had been treated with the Microbially Induced Desaturation (MID) method



Application Case Study - The Sunderland Site



An aerial view showing the location of the MID-treated pad. The test pad is located in the Sunderland neighborhood of Portland, OR, and treatment was performed in 2019.



Application Case Study - The Sunderland Site





Application Case Study - The Sunderland Site





Application Case Study – Cone Penetration Test (CPT)

Four CPTs conducted: CPT1 through CPT4

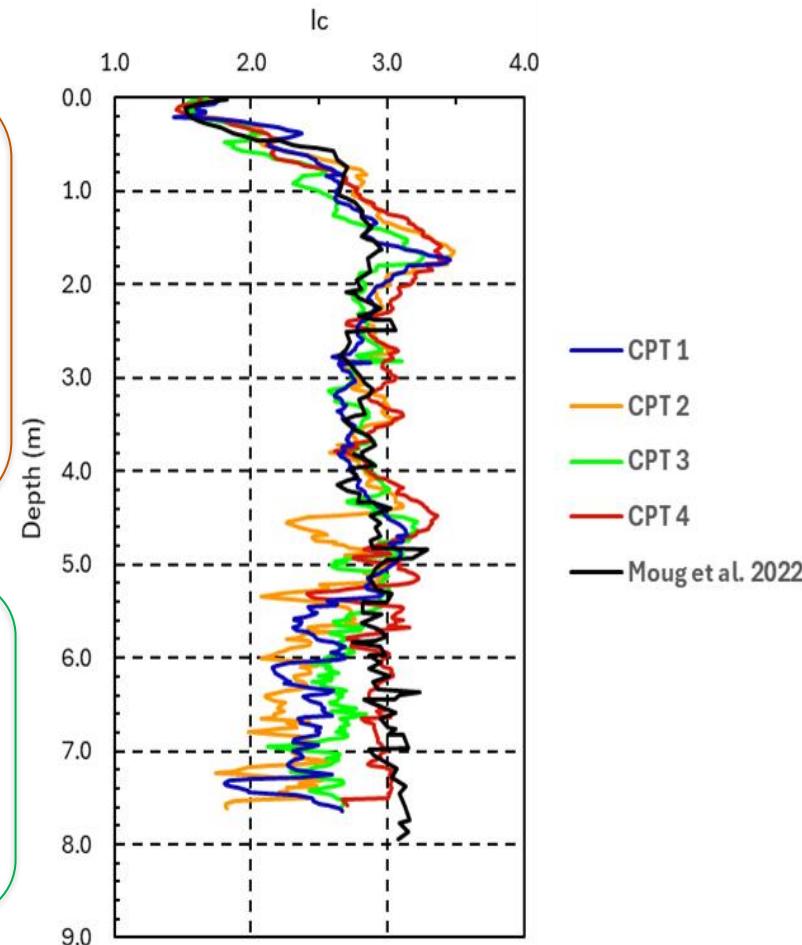
Soil behavior type index (I_c): 2.60 to 2.95

Material: Clayey silt to silty clay

Target depth: 2.5 to 4 m for testing

CPT1 location selected as untreated pad

- Similar I_c values to treated pad
- Adequate distance from MID treatment zone
- Reliable comparison baseline established



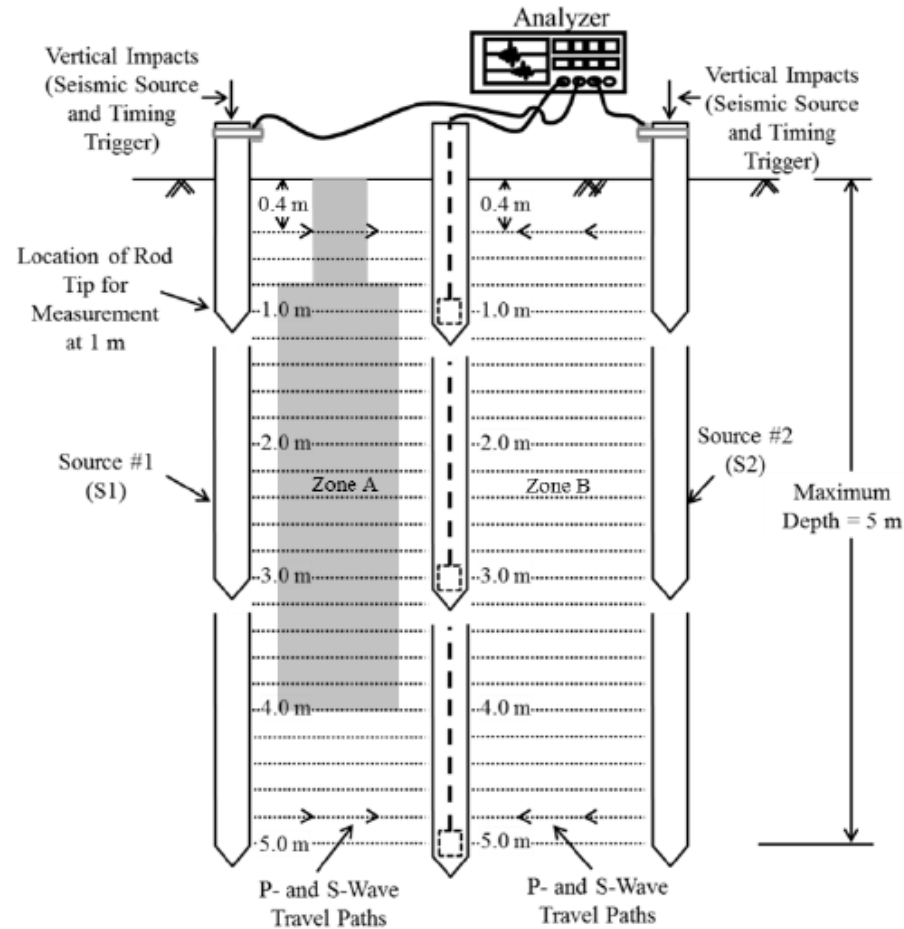
Result of the CPT testing performed at the Sunderland site: (a) comparison between CPT1 through CPT4 conducted in 2024, and (b) comparison between CPT1 through CPT4 and MID CPT result.



Application Case Study – Untreated Pad



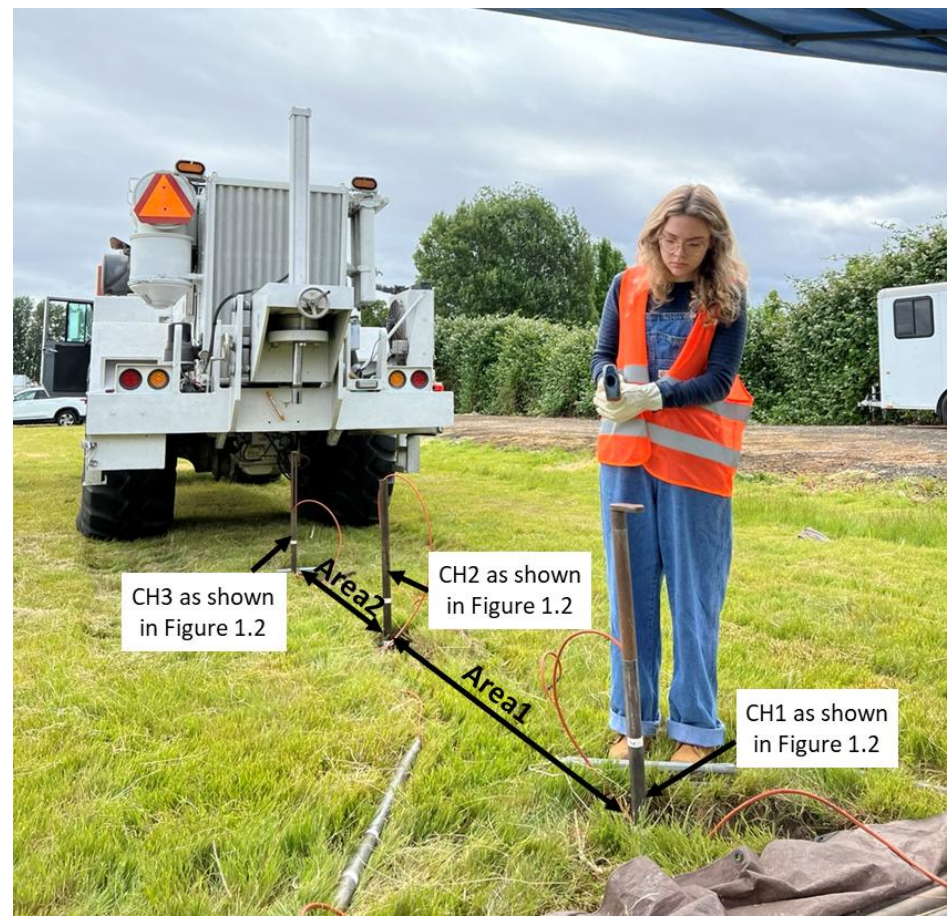
Application Case Study – Direct Push Crosshole Testing



Schematic of generalized arrangement for small-strain direct push crosshole seismic testing



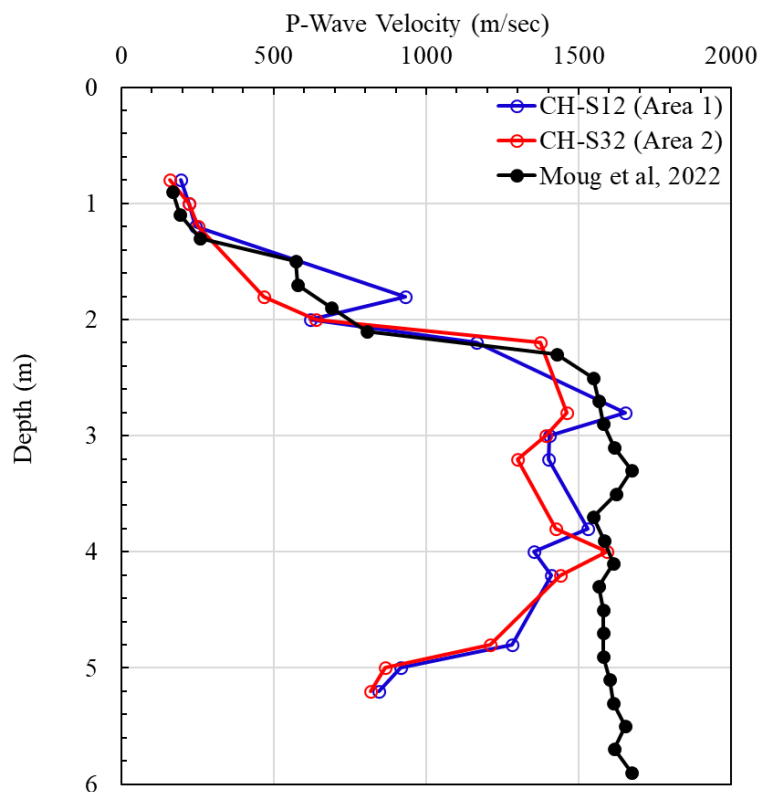
Application Case Study – Direct Push Crosshole Testing



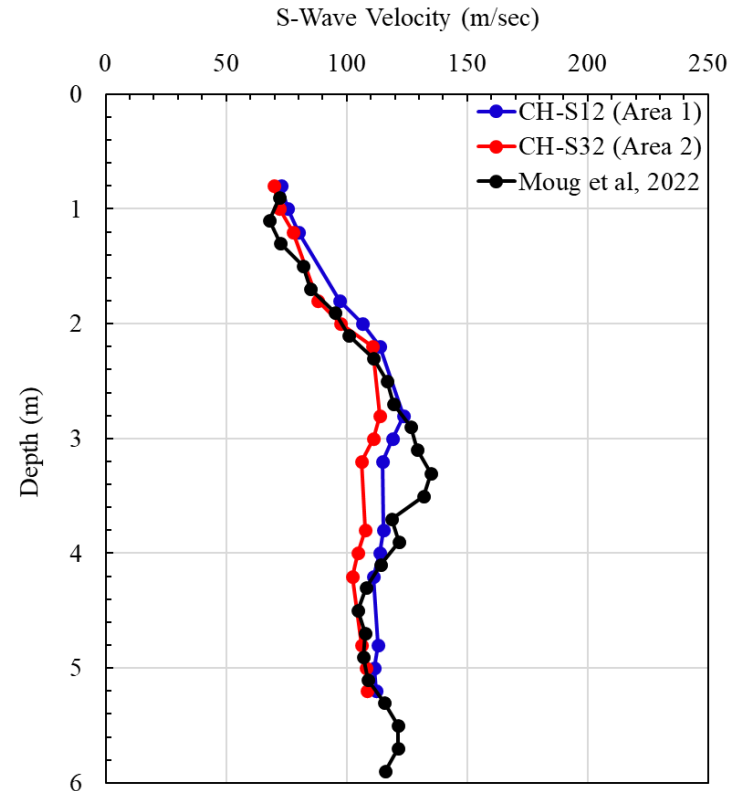
A photograph of direct-push crosshole (DPCH) seismic testing at the untreated pad.



Untreated Pad – Direct Push Crosshole Testing



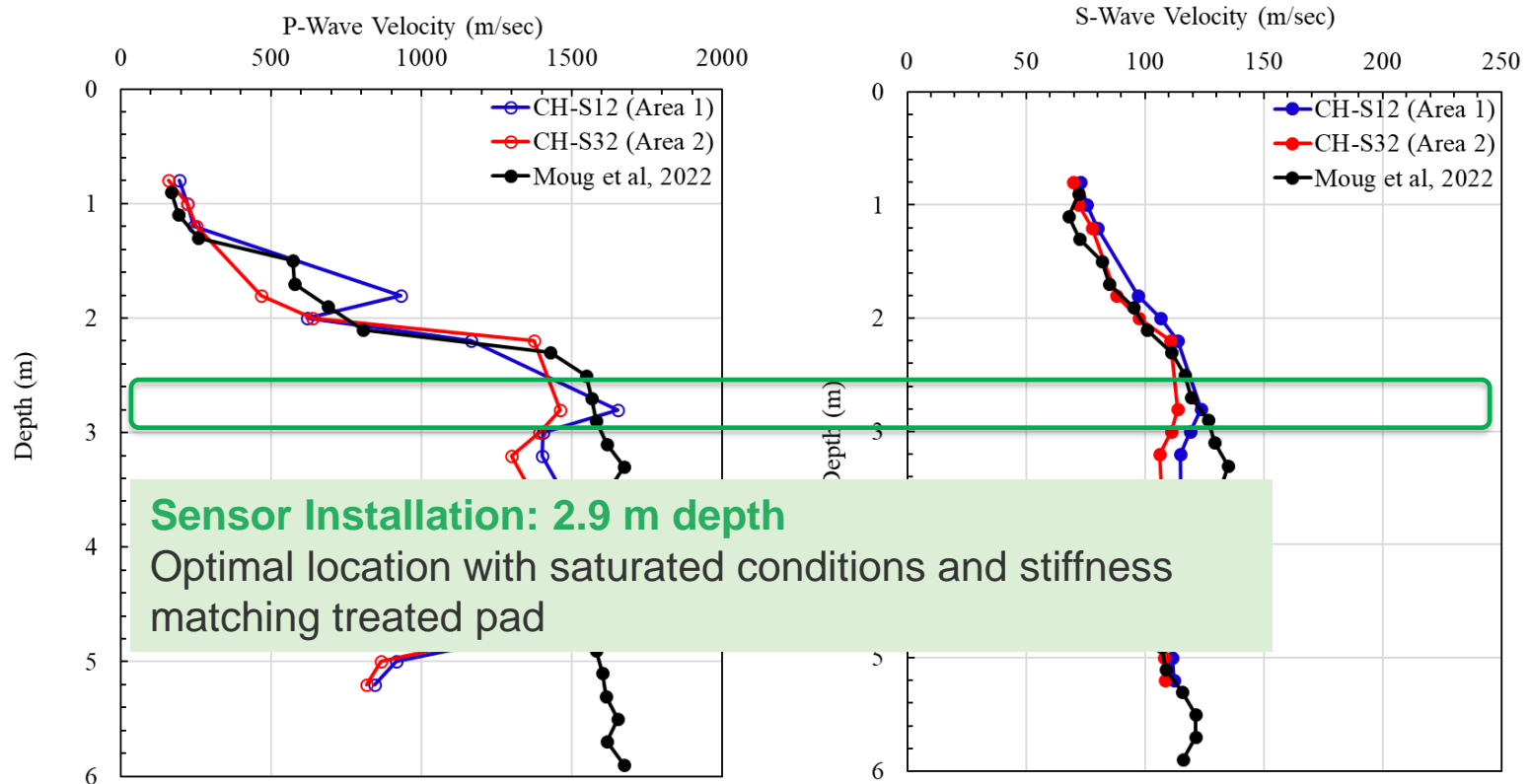
(a) P-wave Velocity at Untreated Pad



(b) S-wave Velocity at Untreated Pad

P- and S-wave velocity profiles from DPCH Testing at the untreated pad compared with DPCH results from Diane et al. (2022)

Untreated Pad – Direct Push Crosshole Testing



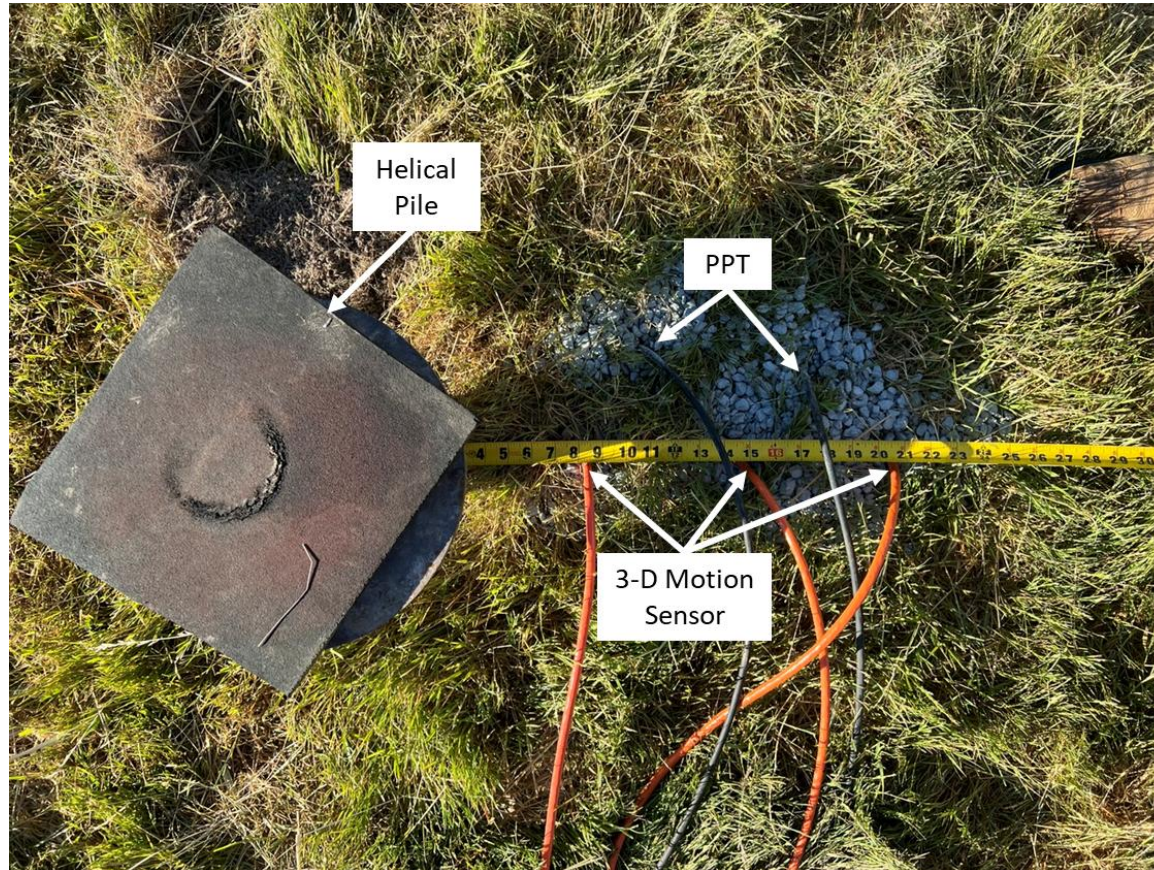
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P- and S-wave velocity profiles from DPCH Testing at the untreated pad compared with DPCH results from Diane et al. (2022)



Field Nonlinear Cyclic Measurement Using Helical Pile



Instrumented array in the field nonlinear cyclic tests using a helical pile at the untreated pad

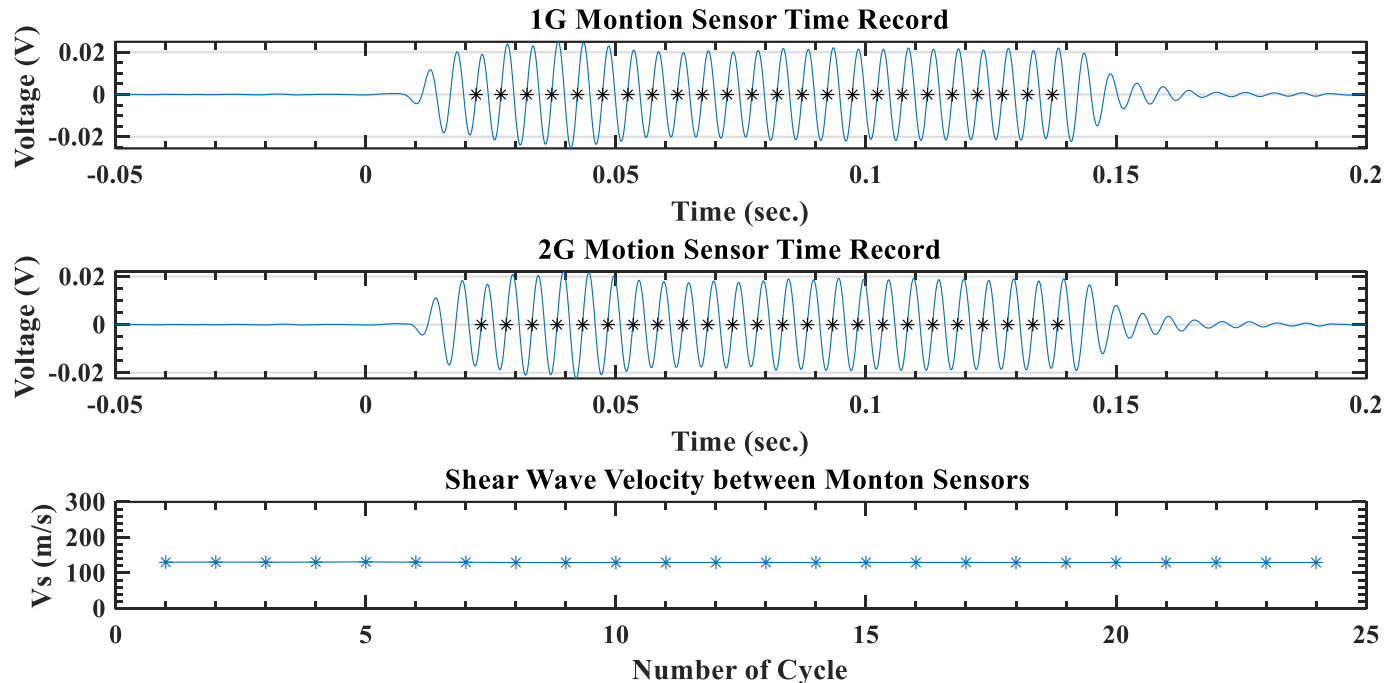


Field Nonlinear Cyclic Measurement Using Helical Pile





Field Nonlinear Cyclic Measurement Results



Analysis Process

100 Hz wave: 24 full + 3 taper cycles

Drive Voltage : 0.5V

Phase difference between 1G and 2G

Average V_s from all cycles = 125 m/sec

Unit weight: 1776 kg/m³

Shear Modulus Calculation

$$G = \rho \times V_s^2 = (\omega/g) \times V_s^2$$

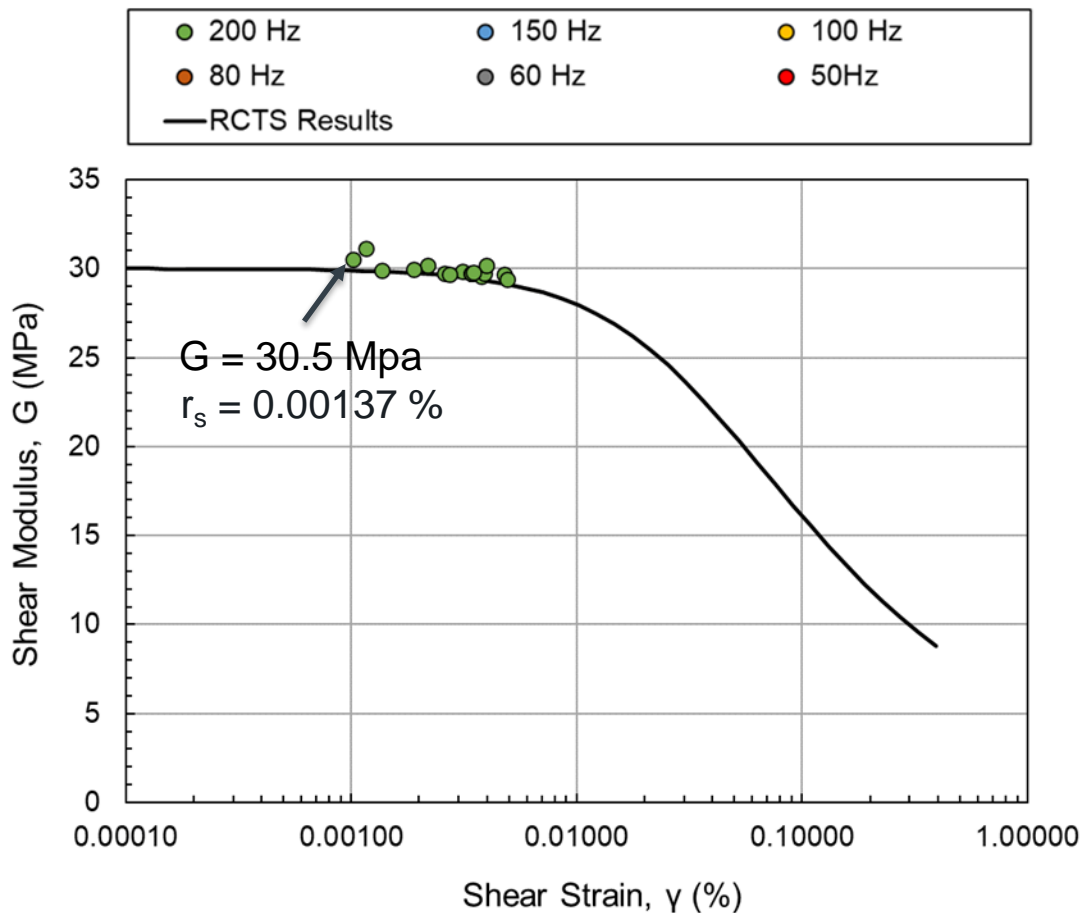
$$G = 30.5 \text{ Mpa}$$

$$r_s = 0.00137 \%$$



Field Nonlinear Cyclic Measurement Results

- Untreated Pad



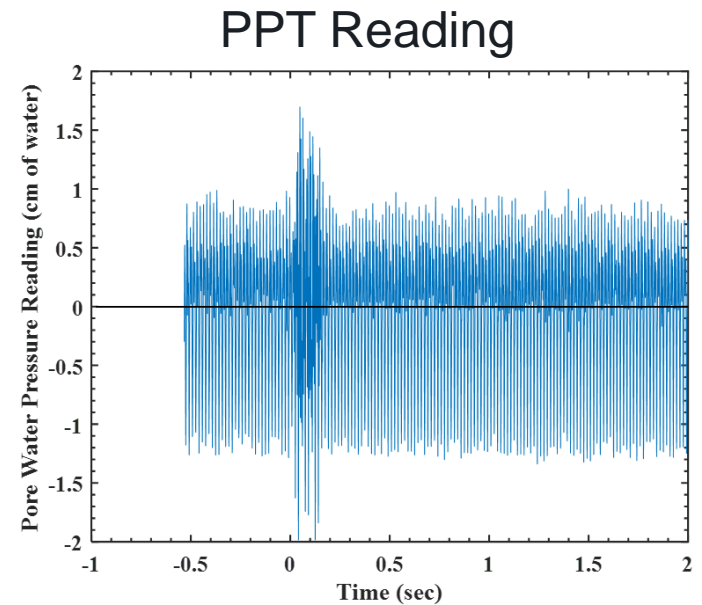
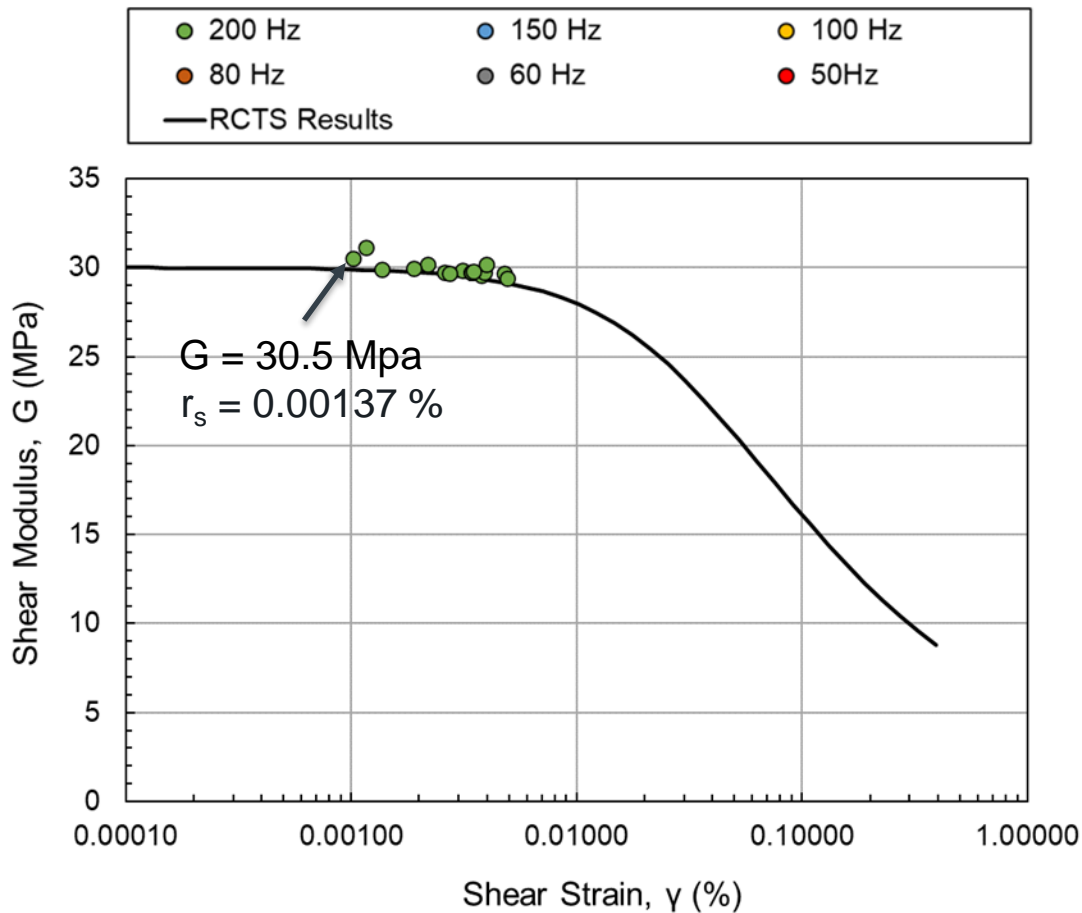
G_{\max} Comparison

Field Testing: 30.5 MPa
RCTS Laboratory: 30.0 MPa
Minimal disturbance from pile installation



Field Nonlinear Cyclic Measurement Results

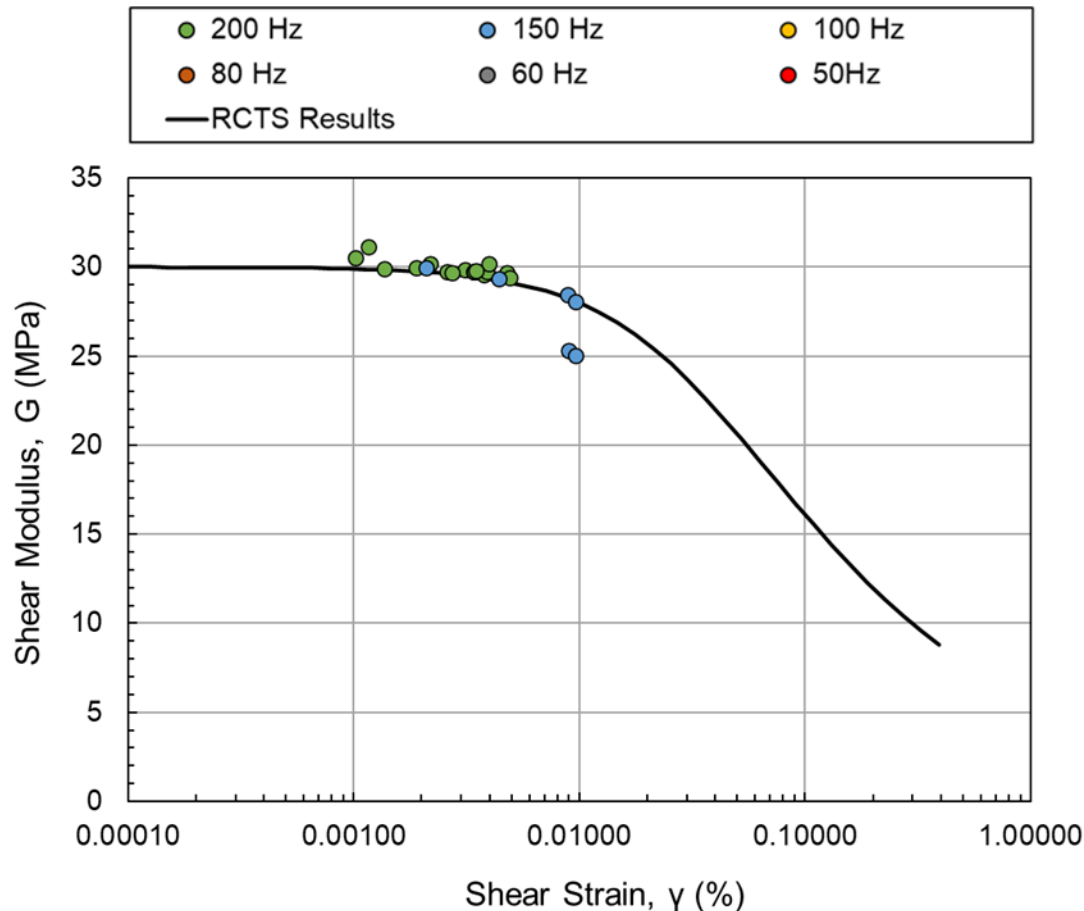
- Untreated Pad





Field Nonlinear Cyclic Measurement Results

- Untreated Pad



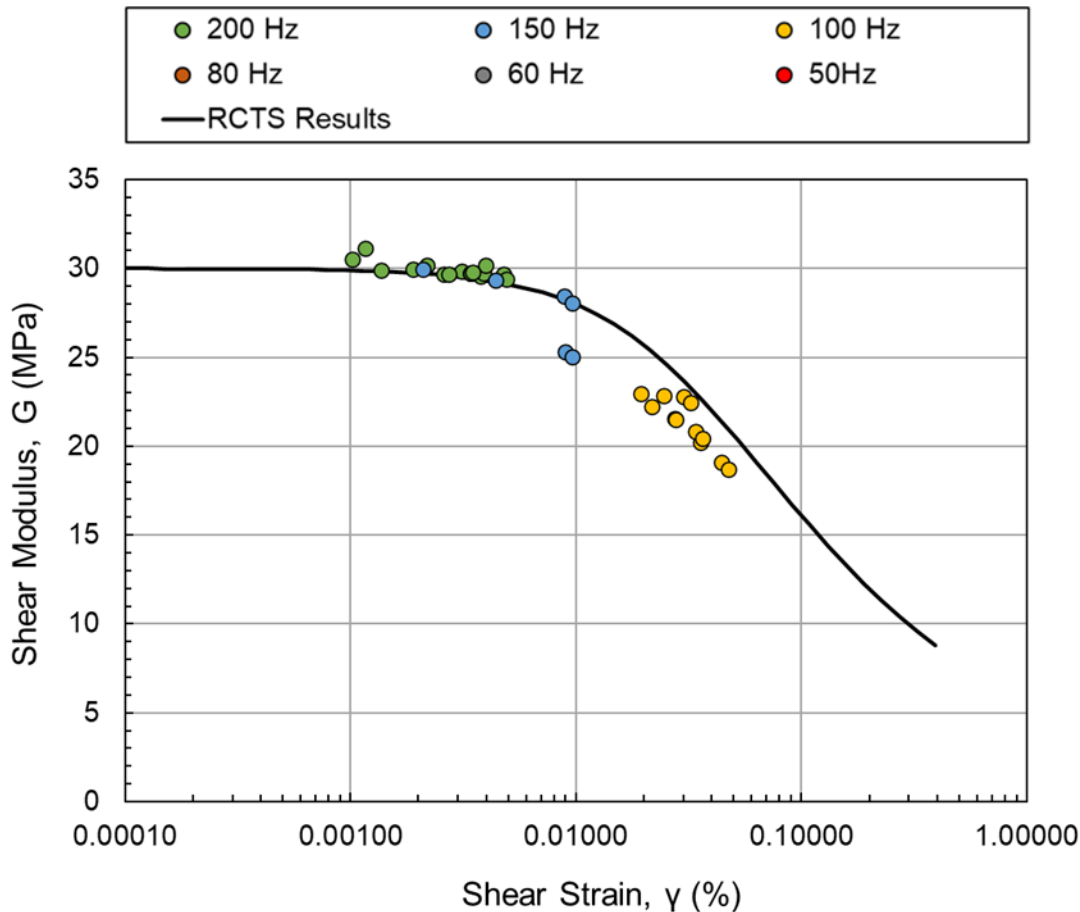
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Field Nonlinear Cyclic Measurement Results

- Untreated Pad



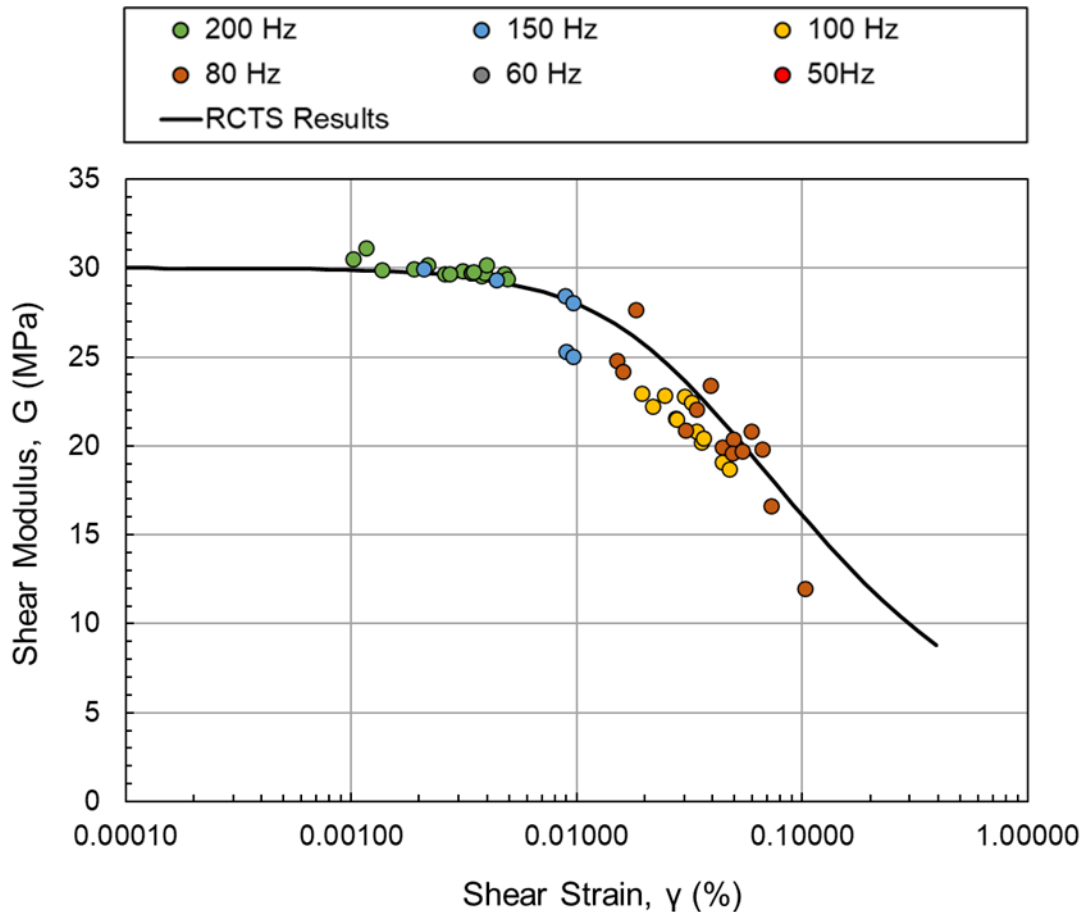
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Field Nonlinear Cyclic Measurement Results

- Untreated Pad



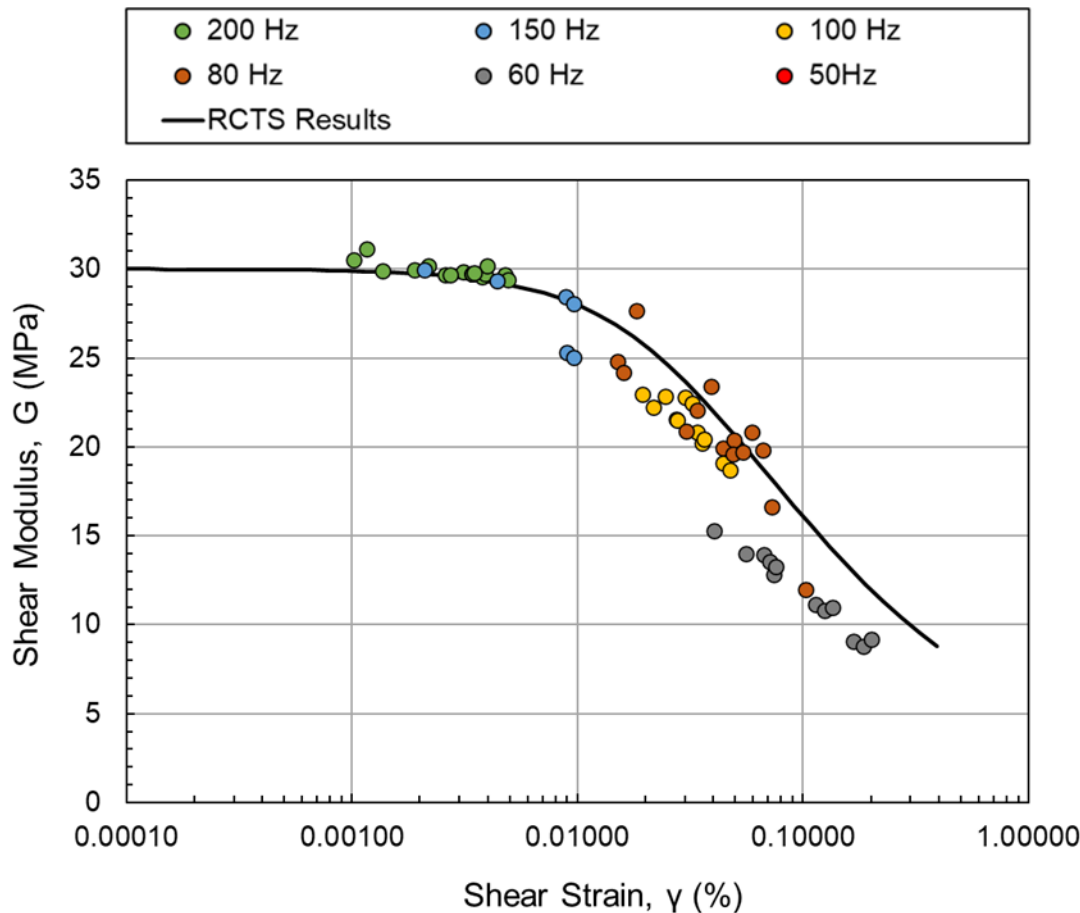
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Field Nonlinear Cyclic Measurement Results

- Untreated Pad

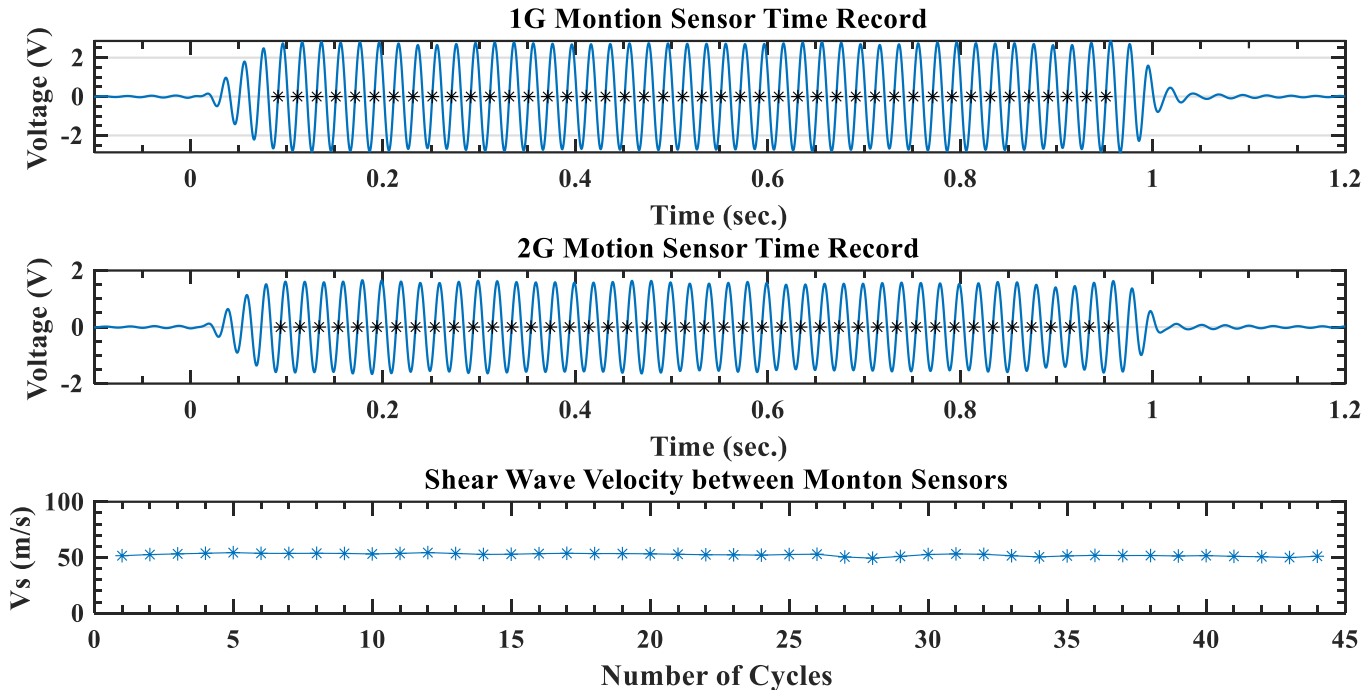


G_{\max} Comparison

Field Testing: 30.5 MPa
RCTS Laboratory: 30.0 MPa
Minimal disturbance from pile installation



Field Nonlinear Cyclic Measurement Results



Analysis Process

50 Hz wave: 44 full + 3 taper cycles

Drive Voltage : 4V

Phase difference between 1G and 2G

Average V_s from all cycles = 50 m/sec

Unit weight: 1776 kg/m³

Shear Modulus Calculation

$$G = \rho \times V_s^2 = (\omega/g) \times V_s^2$$

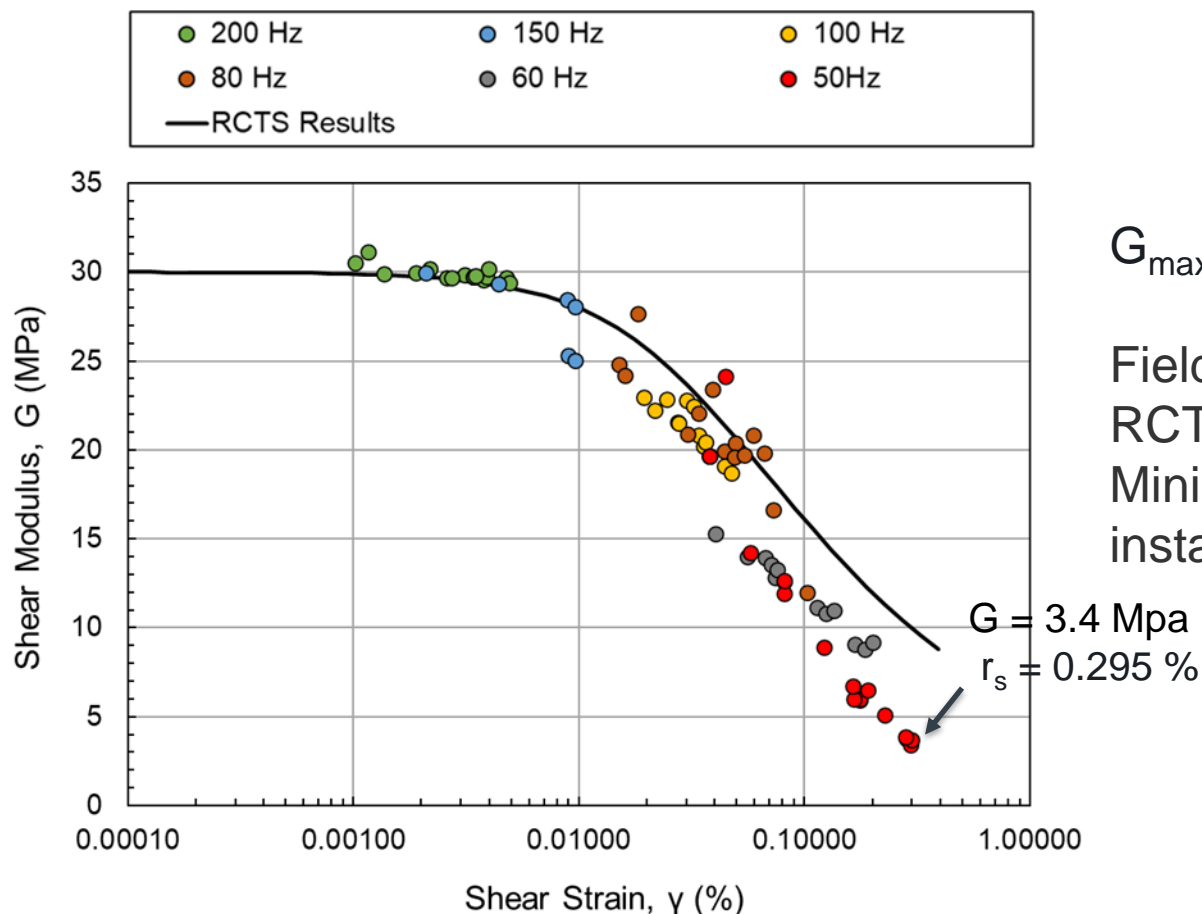
$$G = 3.4 \text{ Mpa}$$

$$r_s = 0.295 \%$$



Field Nonlinear Cyclic Measurement Results

- Untreated Pad



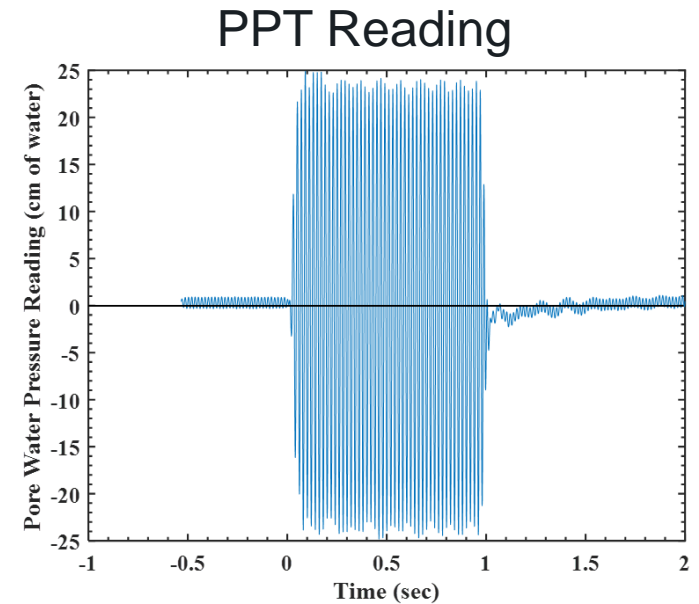
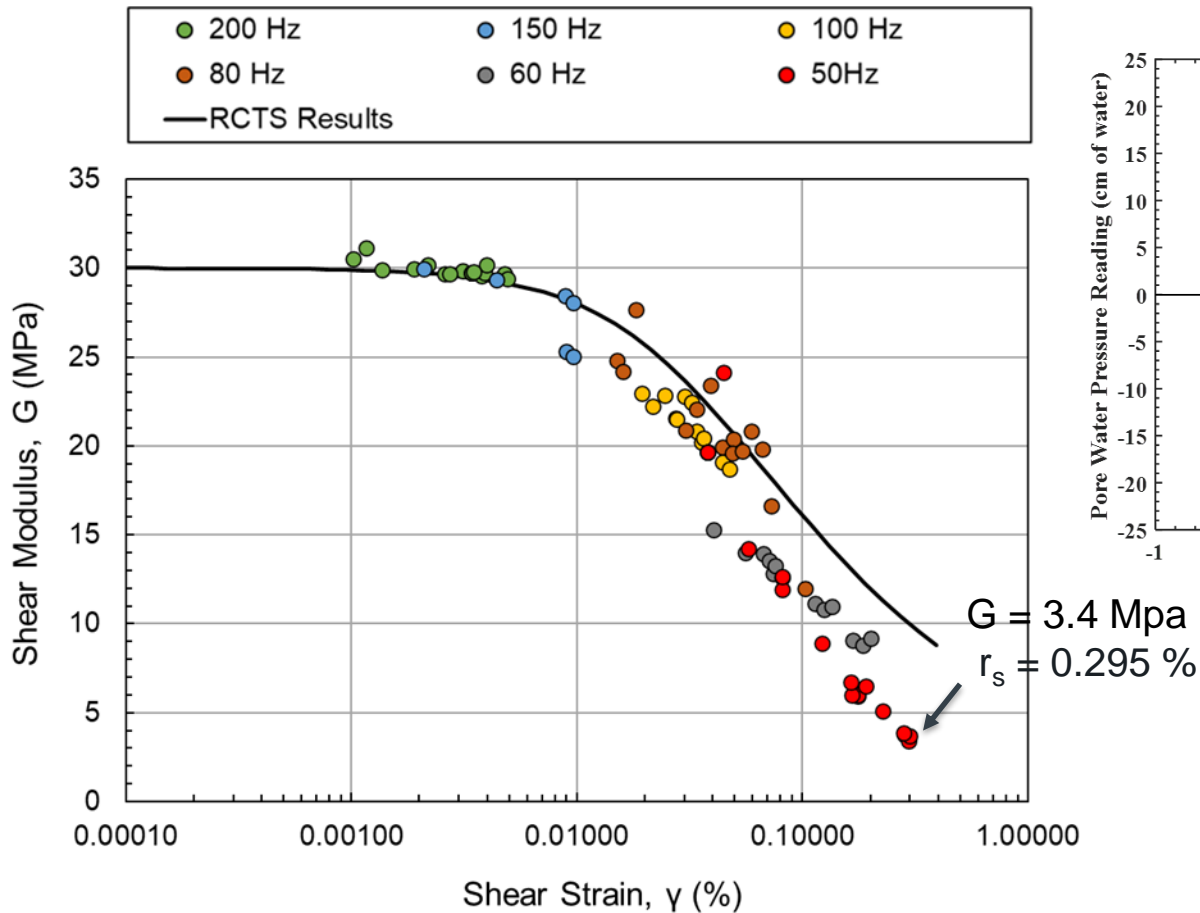
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Minimal disturbance from pile installation



Field Nonlinear Cyclic Measurement Results

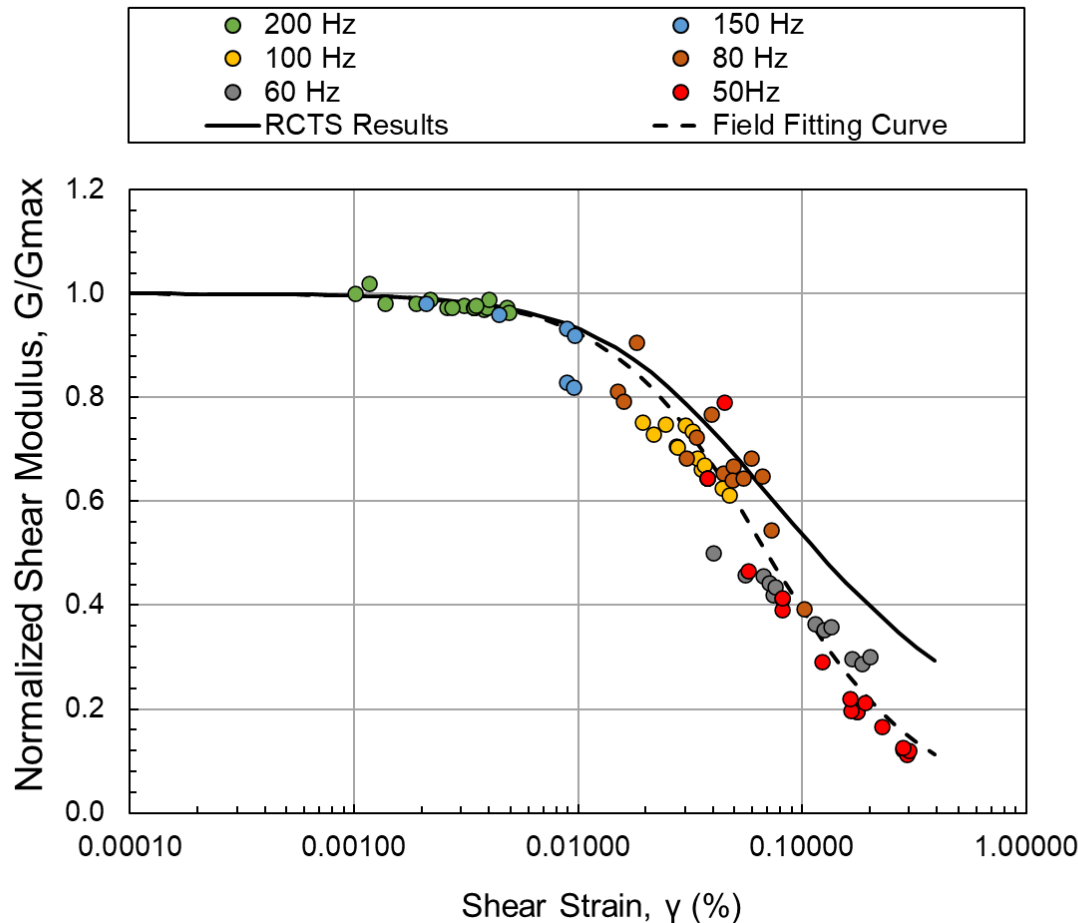
- Untreated Pad





Field Nonlinear Cyclic Measurement Results

- Untreated Pad



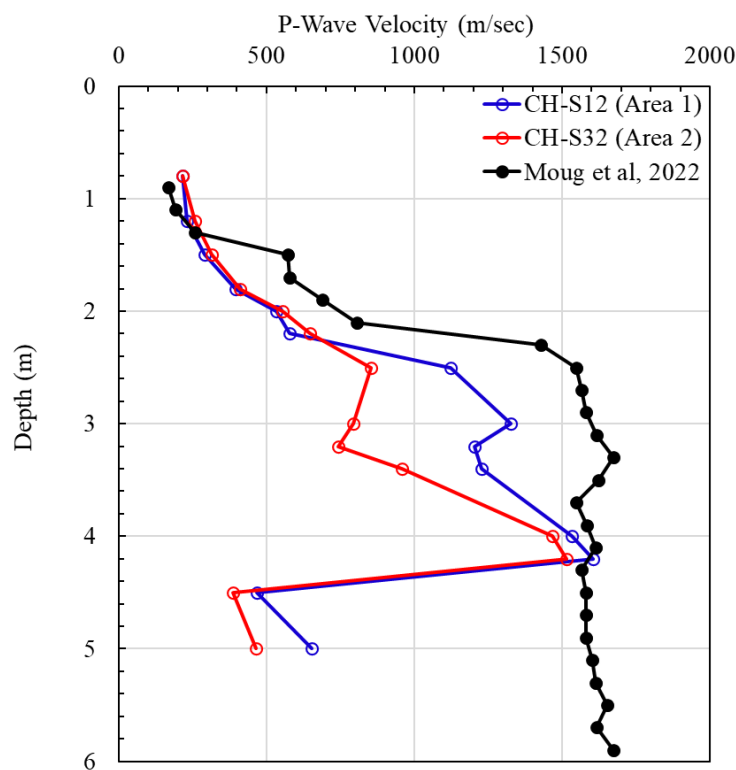
Modified Hyperbolic Model

$$G/G_{max} = 1/[1 + (\gamma/\gamma_r)^a]^b$$

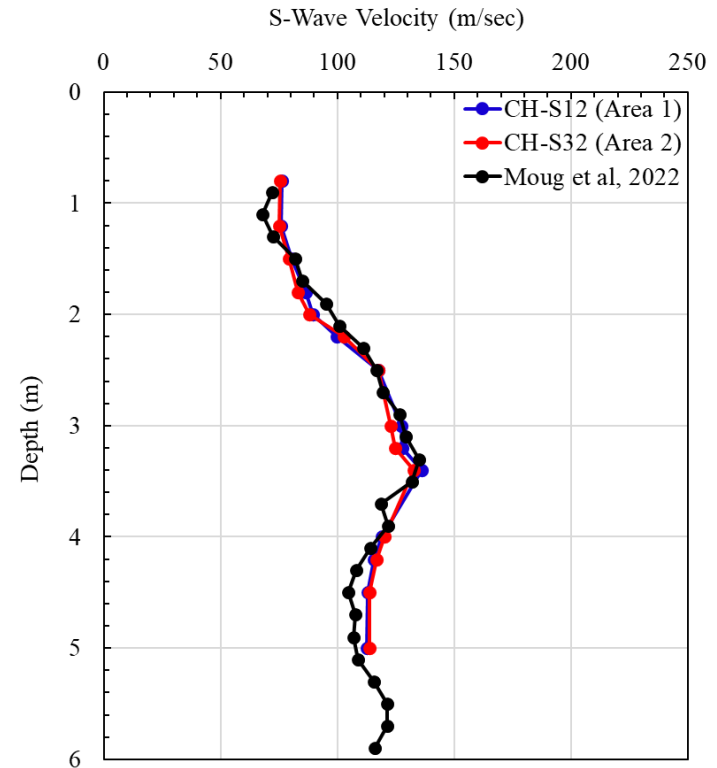
$\gamma_r = 0.058, a = 1.319, b = 0.841$



Treated Pad – Direct Push Crosshole Testing



(a) P-wave Velocity at Treated Pad



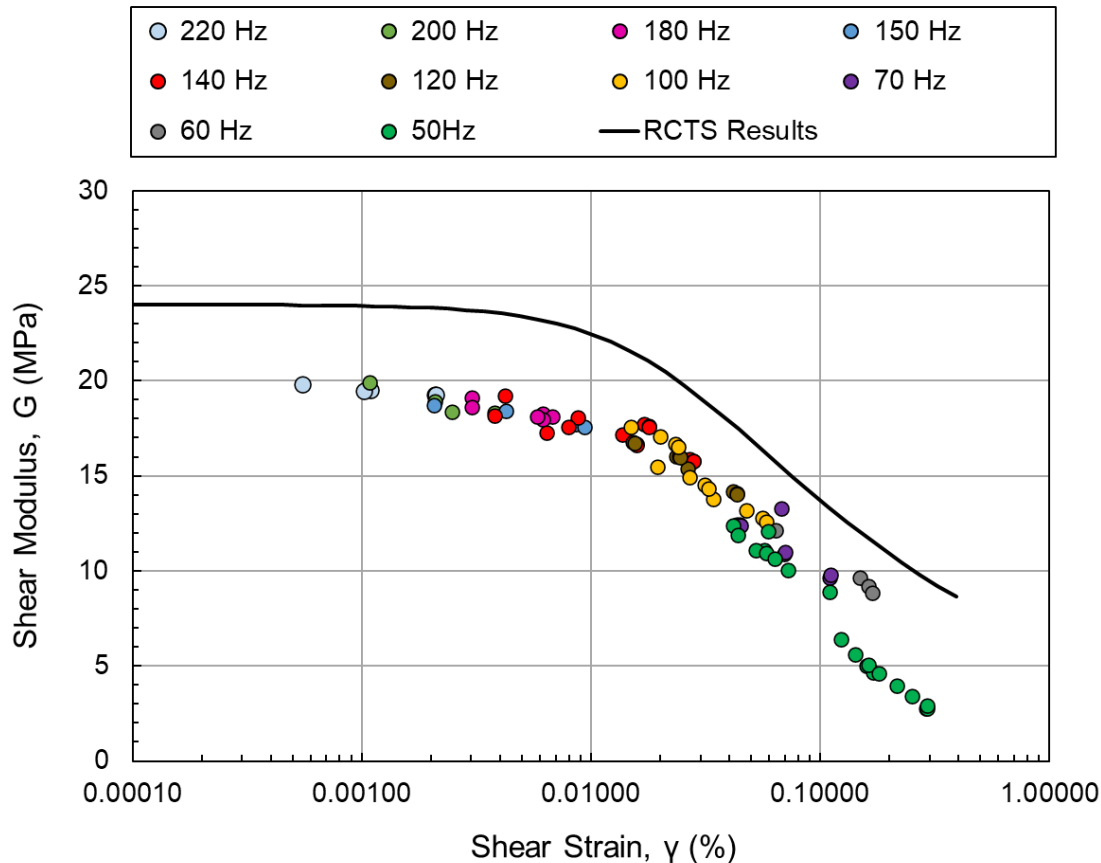
(b) S-wave Velocity at Treated Pad

P- and S-wave velocity profiles from DPCH Testing at the treated pad compared with DPCH results from Diane et al. (2022)



Field Nonlinear Cyclic Measurement Results

- Treated Pad



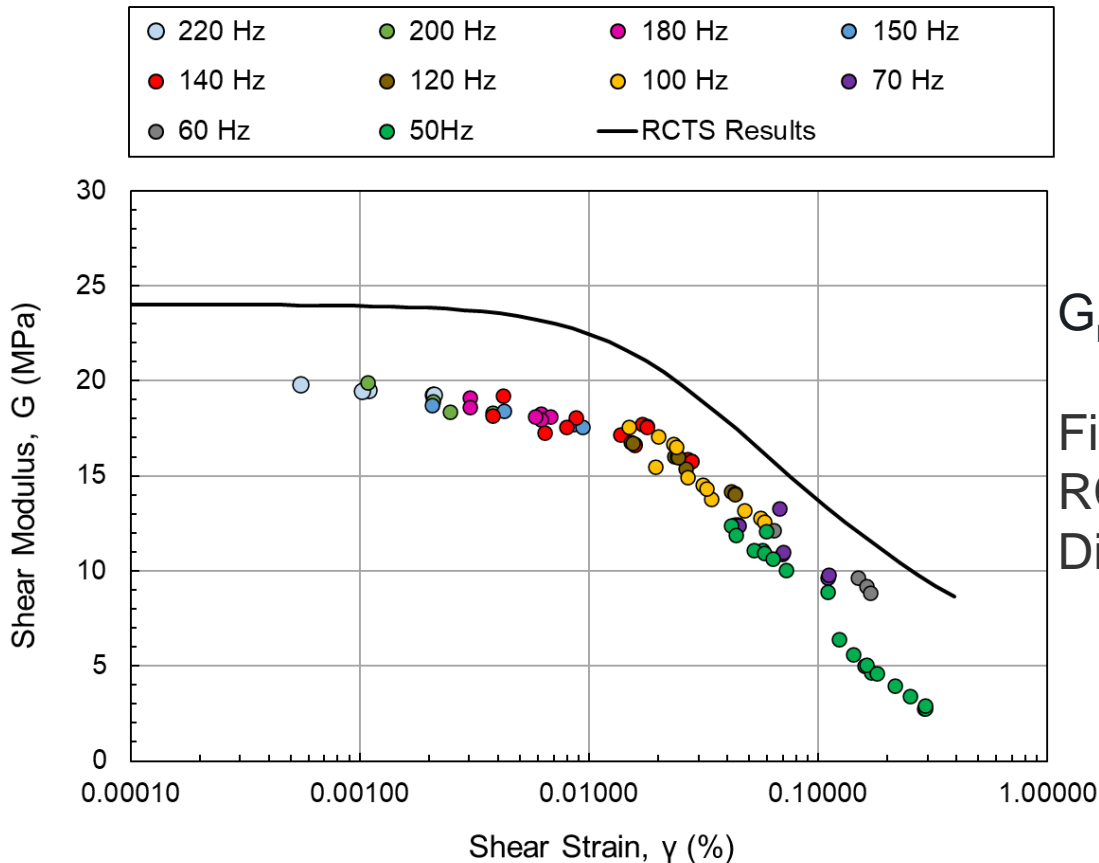
G_{\max} Comparison

Field Testing: 20 MPa
RCTS Laboratory: 24 MPa
Disturbance from pile installation



Field Nonlinear Cyclic Measurement Results

- Treated Pad



G_{max} Comparison

Field Testing: 20 Mpa (106 m/s)

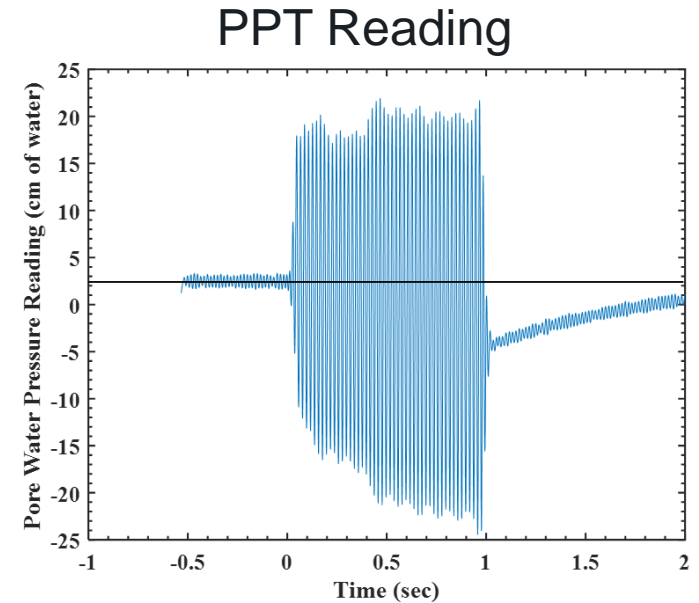
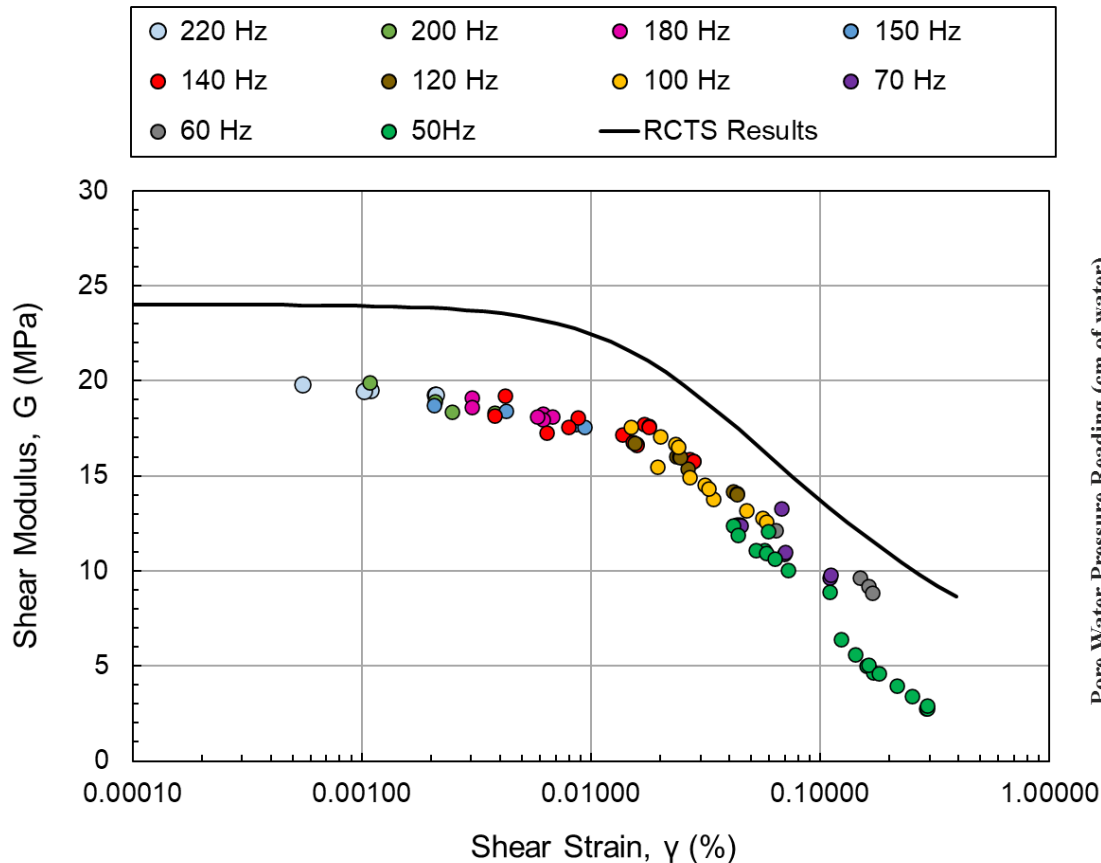
RCTS Laboratory: 24 Mpa (117 m/s)

Disturbance from pile installation



Field Nonlinear Cyclic Measurement Results

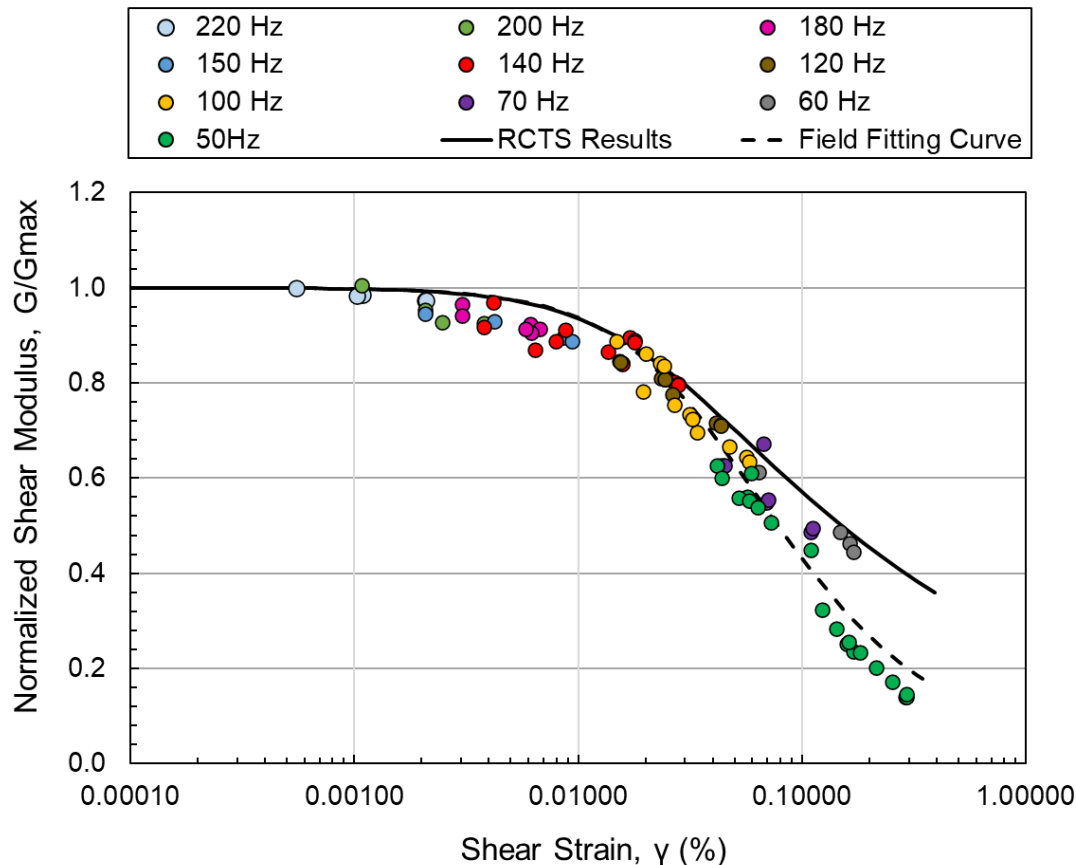
- Treated Pad





Field Nonlinear Cyclic Measurement Results

- Treated Pad



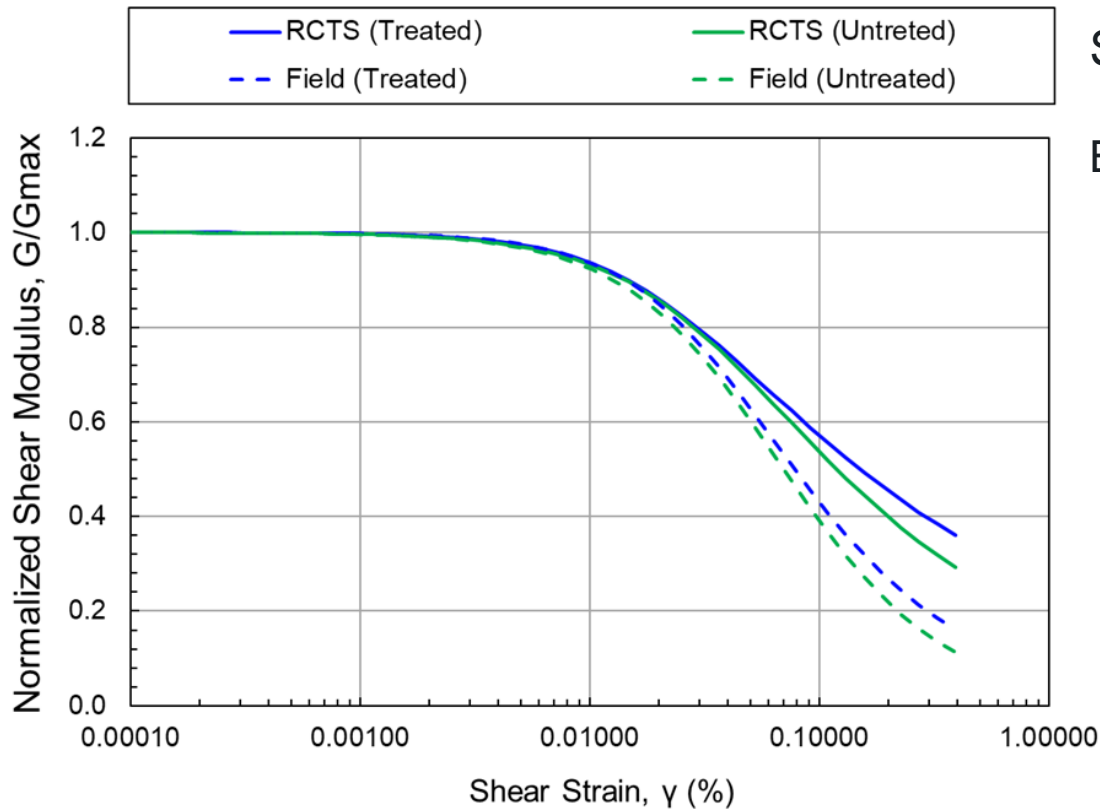
Modified Hyperbolic Model

$$G/G_{max} = 1/[1 + (\gamma/\gamma_r)^a]^b$$

$\gamma_r = 0.041, a = 1.466, b = 0.545$



Comparison of Normalized G/G_{max} – $\log \gamma$ Relationships at the Untreated and Treated Pads from RCTS and Field testing



Strain-Dependent Performance

Below 0.001% strain:

- Both methods exhibit similar behavior
- Minimal differences between pads

Above 0.01% strain:

- Field tests exhibit greater nonlinearity than laboratory tests
- Treated pad demonstrates slightly higher stiffness
- Both test methods show consistent trends



Summary and Conclusion

- Field seismic tests were conducted at the Sunderland site in Portland, OR, to evaluate the effectiveness of the Microbially Induced Desaturation (MID) method that was applied in 2019 to reduce the liquefaction potential of the site.
- Field nonlinear cyclic testing using a helical pile was conducted at both pads and successfully measured the nonlinear soil response, which is comparable to the RCTS testing results.
- No excess pore-water pressure buildup was observed in either pad, although a maximum pore-water pressure of approximately 23 to 25 cm was recorded during maximum shaking events.
- The normalized $G/G_{max} - \log \gamma$ relationships for the untreated and treated pads, derived from RCTS and field testing, were compared. Results from both tests indicate that the treated pad exhibits slightly greater liquefaction resistance at strains exceeding 0.1%.
- However, the desaturation effect of the MID method was not evident in the treated pad, limiting the reliability of the results. Further studies will be pursued to better evaluate the effectiveness of the MID treatment in mitigating soil liquefaction.



Acknowledgements

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Thank You



Reference

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