Characterization of Dynamic Soil-Pile Interaction by Random Vibration Methods: Experimental Design and Preliminary Results

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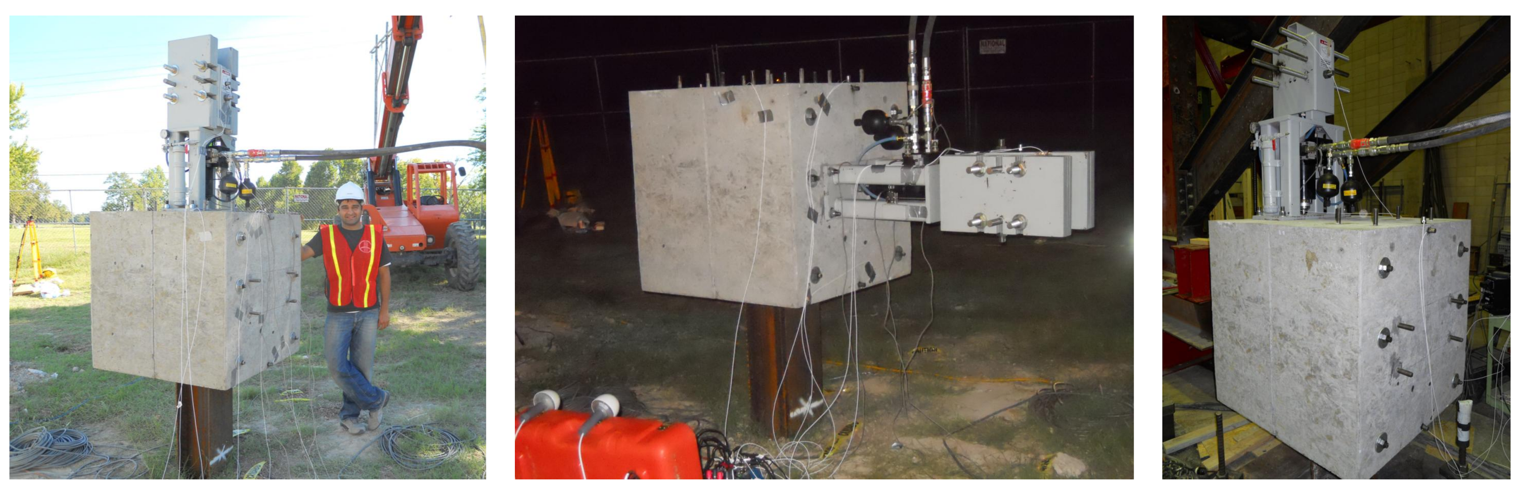
Background and Research Need

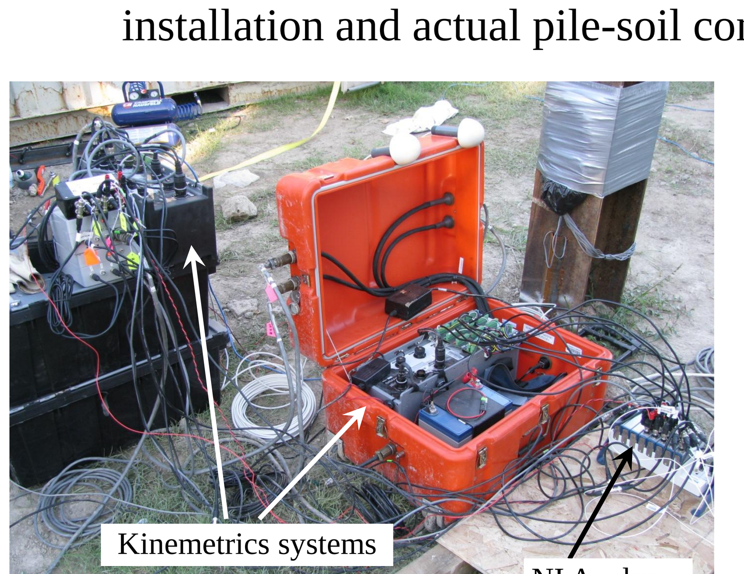
Dynamic foundation testing has traditionally involved the use of single mode tests, with vertical and horizontal loading cases examined separately, often with sinusoidal tests performed sequentially at discrete excitation frequencies (i.e. stepped-sine testing). However, dynamic loads in nature such as those caused by earthquakes, wind, waves, explosions or traffic are inherently multi-directional and contain a wide range of frequency components simultaneously. As has been shown in recent studies of the dynamics of surface as well as deep foundations, the halfspace models commonly used to calculate frequency dependent impedance functions (stiffness and damping) of the soil or soil-foundation system can usually be fit to only a single mode of vibration at a time, with significant error resulting for the other modes. While others have suggested the use of different half-space models for different vibration modes, such a philosophy is not sufficiently general for arbitrary loading conditions, and misses the opportunity to advance our understanding of the mechanics of soil-structure interaction at a fundamental level. To address the problem, experimental and computational capabilities are being developed in this investigation to provide realistic multi-modal dynamic modeling of full-scale pile foundations over a wide range of frequencies.



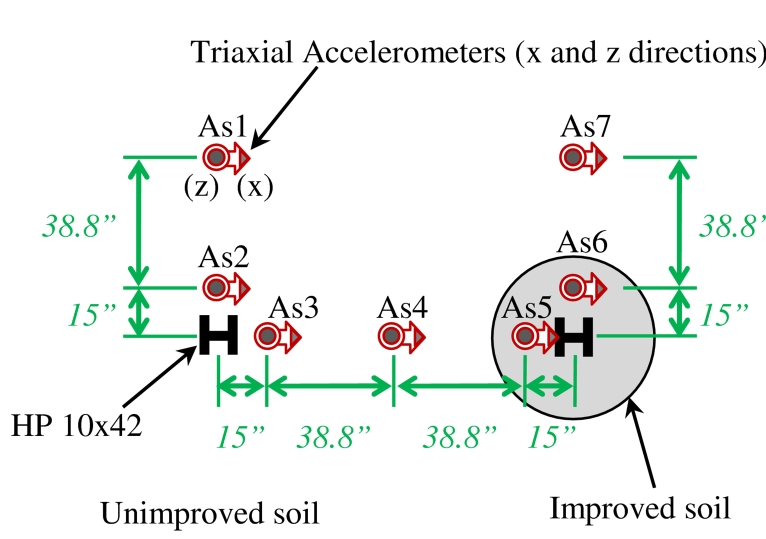
(a) VC test (b) HC test (c) VE test
Inertial shaker configurations for the three test types

Overview

- A total of 109 full-scale vibration tests were performed on HP 10x42 piles with 20 ft embedment using random vibration methods and a newly developed servo-hydraulic inertial shaker testing system
- **Pile U (unimproved soil)**: tested in the natural soft clay soil profile
- **Pile I (improved soil)**: surrounded by a 48" diameter, 13 ft deep cement deep soil mixed (CDSM) improved zone within the soft clay layer
- Three excitation techniques were examined using a range of forcing intensities to determine optimal testing configuration;
  Random (R), Chaotic Impulse (C) and **Swept-sine (S)**
- The multi-modal vertical-eccentric **(VE)** test format was investigated as an efficient alternative to traditionally separate vertical-centric **(VC)** and horizontal **(HC)** forcing tests
- VE test minimizes stress history effects that are unavoidable when VC and HC tests are performed sequentially on the same pile
- VE test alleviates concerns over the equivalence of test conditions when VC and HC tests are performed on separate piles and combined to determine pile response to general multi-directional excitations
- The approach developed in this study uses small-strain wave propagation to infer information about the soil properties (similar to non-destructive geophysical techniques), but also inherently includes the effects of pile installation and actual pile-soil contact conditions



National Instruments dynamic signal analyzer and Kinemetrics Granite data acquisition systems



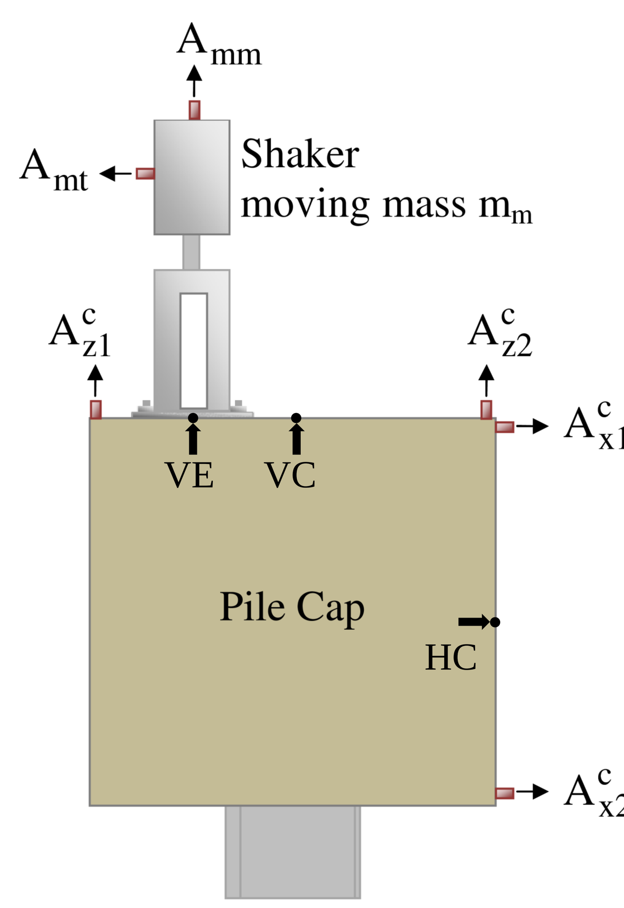
Plan view showing layout of the two test H-piles and accelerometers in the soil

Experimental Approach

- National Instruments hardware and LabVIEW software were used to build a dynamic signal analyzer
- Accelerations of shaker, pile cap and soil surface were recorded under ambient and forced vibrations
- Time-histories, spectral densities, FFTs, transfer functions, and coherence functions were recorded and examined in real-time
- For Transfer and Coherence functions, acceleration A_{mm} of shaker's moving mass was taken as the stimulus, with all other pile-cap and soil accelerations treated as response quantities

Transfer function: $H_{xy}(f) = \dfrac{\bar{G}_{xy}(f)}{\bar{G}_{xx}(f)}$, Coherence: $\gamma_{xy}^2(f) = \dfrac{\left|\bar{G}_{xy(f)}\right|^2}{\bar{G}_{xx(f)}\bar{G}_{yy(f)}}$

- Complete time-histories of all data were also recorded by the nees@UCLA seismic monitoring systems for NEEShub users to analyze with their choice of techniques and sampling parameters



Orientation and notation for accelerometers on shaker and pile cap (shaker in VE test position)

- **Pile-cap transfer function notation**:

  XFER = $\dfrac{\text{response type}}{\text{stimulus type}}$

  e.g.,

  VC/VE = $\dfrac{\text{VC acceleration of pile cap}}{A_{mm} \text{ of shaker in VE position}}$

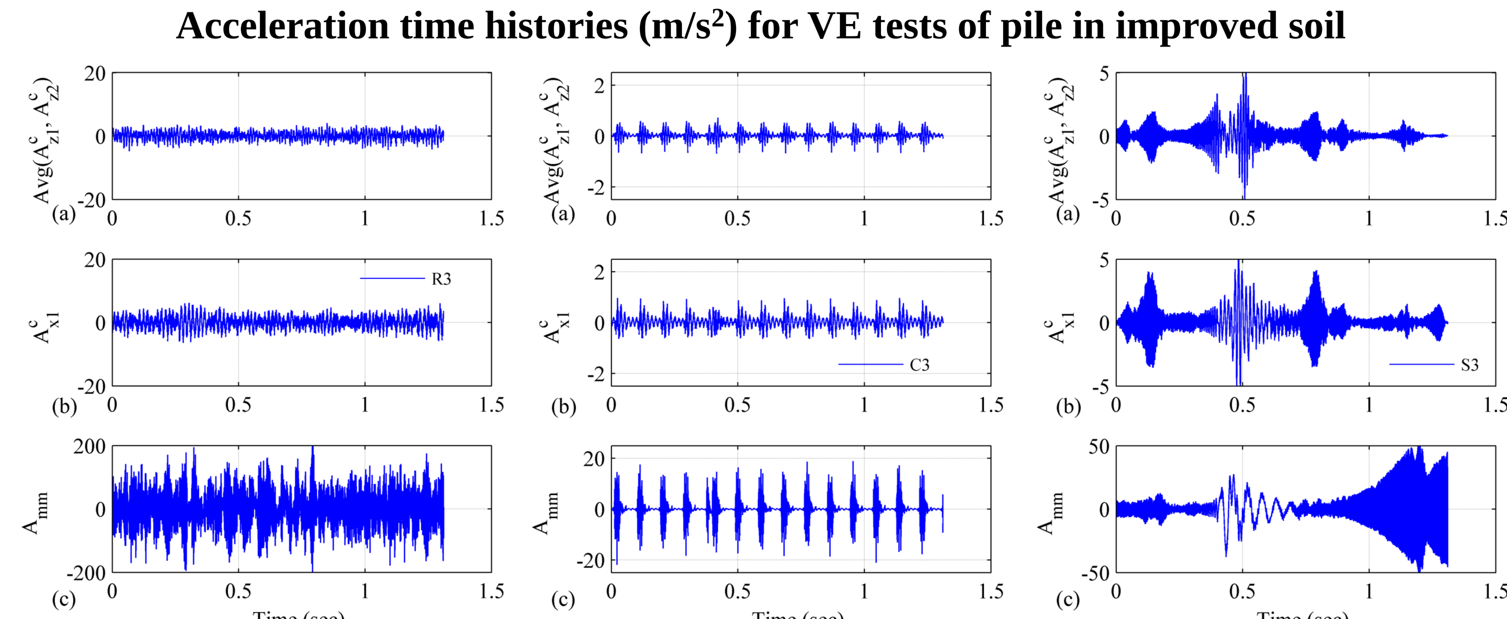
  HC/HC = $\dfrac{\text{HC acceleration of pile cap}}{A_{mm} \text{ of shaker in HC position}}$

  etc…

- **Test naming convention**:
  (Pile)-(Test type)-(Excitation type & level)
  e.g., test **I-VC-R1** = test on Pile I in VC configuration with Random loading at intensity level 1

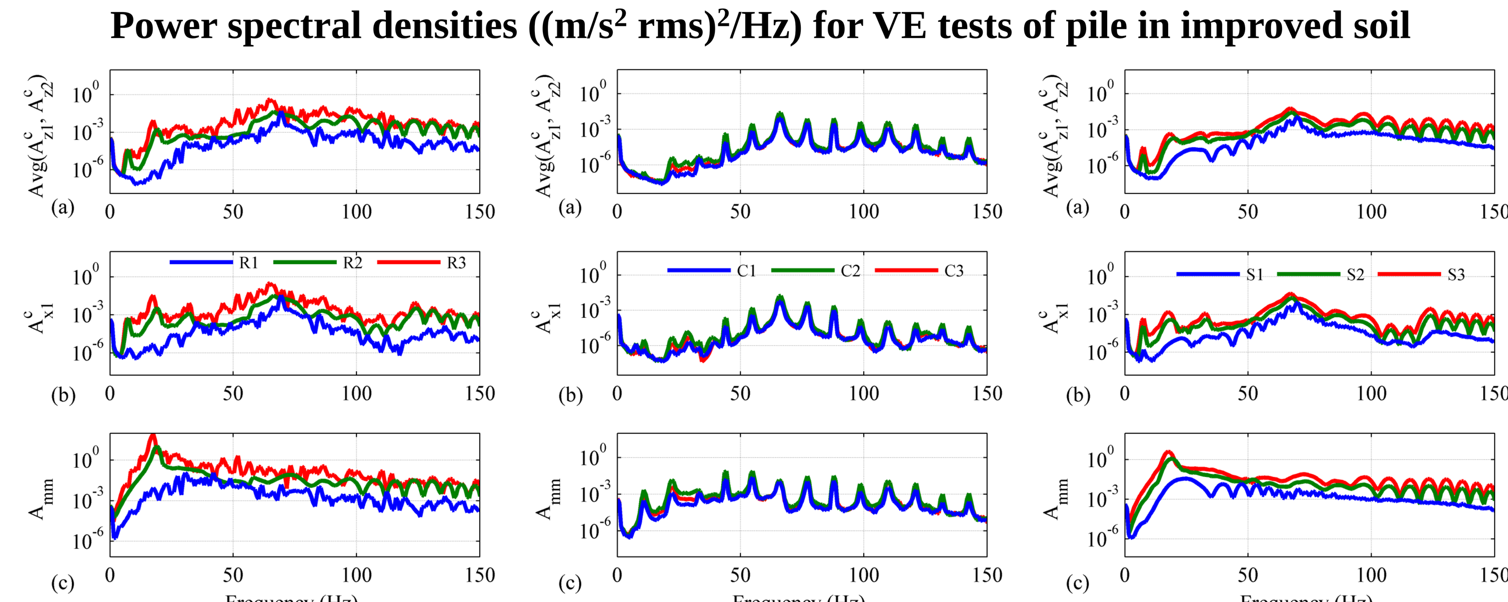
Representative Test Results

Acceleration time histories (m/s²) for VE tests of pile in improved soil



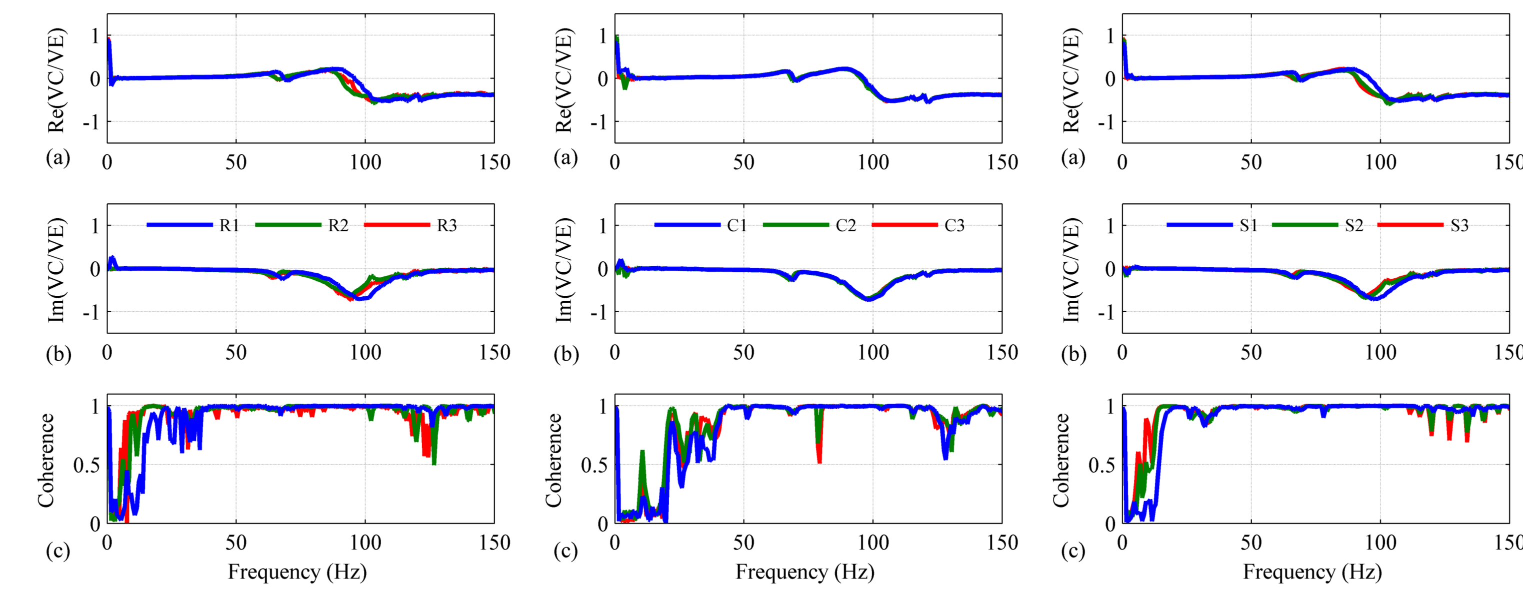
Random excitation, test I-VE-R3 — **Chaotic impulse excitation, test I-VE-C3** — **Swept-sine excitation, test I-VE-S3**

Power spectral densities ((m/s² rms)²/Hz) for VE tests of pile in improved soil



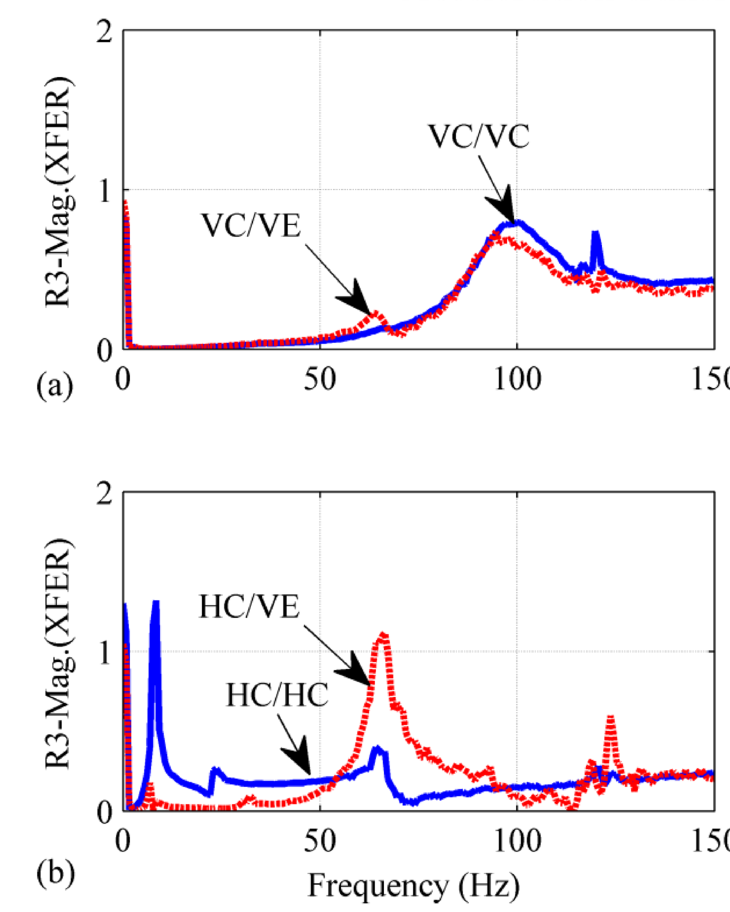
Random excitation, tests I-VE-R1, R2 & R3 — **Chaotic impulse excitation, tests I-VE-C1, C2 & C3** — **Swept-sine excitation, tests I-VE-S1, S2 & S3**

Acceleration transfer functions and Coherence for VE tests of pile in improved soil

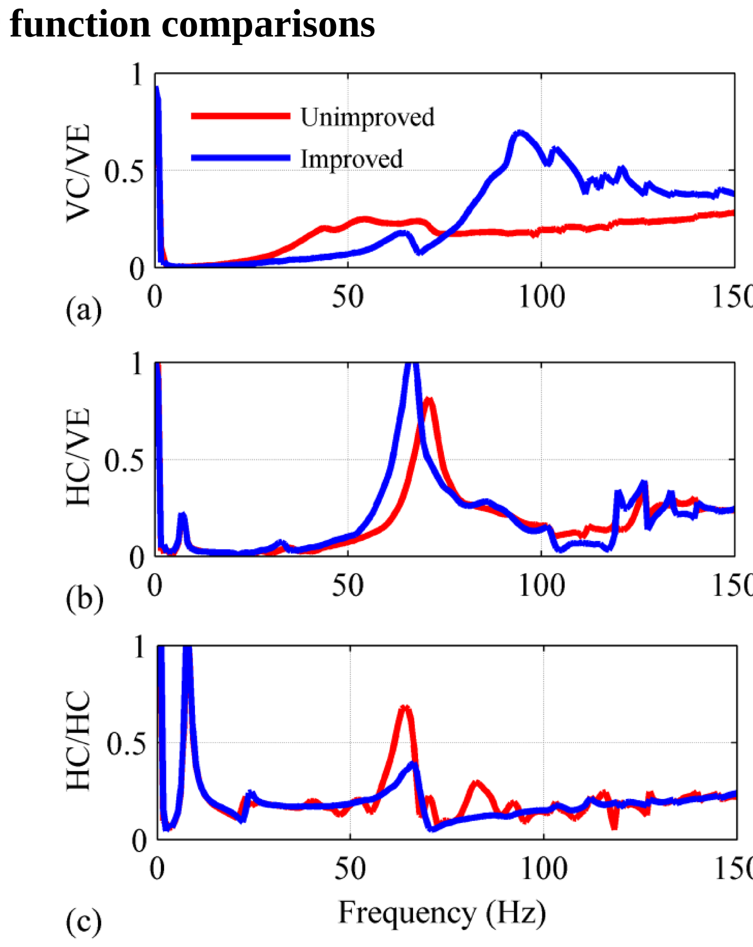


Random excitation, tests I-VE-R1, R2 & R3 — **Chaotic impulse excitation, tests I-VE-C1, C2 & C3** — **Swept-sine excitation, tests I-VE-S1, S2 & S3**

Acceleration transfer function comparisons



Comparison of VE test to combination of VC and HC tests (random excitation) (a) VC response from VC and VE tests, (b) HC response from HC and VE tests



Comparison of transfer functions for pile in unimproved vs. improved soil (swept-sine excitation at intensity level 3)

Preliminary Findings and Interpretation

- Shapes of measured transfer functions were as anticipated
- VE tests successfully generated significant horizontal-rocking motions
- Vertical response from hybrid-mode VE tests closely followed that of the purely vertical VC tests
- Similar peak frequencies of the coupled horizontal-rocking responses were exhibited between VE and HC tests. The different amplitudes can be shown to be a result of the different orientation and location of the shaker.
- CDSM improved soil zone provided significantly stiffer vertical response, but fundamental peak frequency of horizontal-rocking response was unchanged (for VE as well as HC tests)
- Data from this Payload project is currently being analyzed to provide;
  1. The first full-scale verification of numerous experimental findings from centrifuge studies of pile vibration tests performed at CU Boulder
  2. Further refinement of advanced computational continuum boundary element models developed to simulate the observed dynamic behavior of the soil-pile system
  3. The first full-scale calibrations for the Impedance Modification Factor (IMF) approach to rectifying the poor performance of continuum theories for dynamic pile-soil interaction

Acknowledgements

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