Informing Infrastructure Decisions through Large-Amplitude Forced Vibration Testing

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Outline

- NSF EAGER Project – Objectives and general scope of activities
- Foundation dynamics and dynamic soil-foundation-structure interaction (DSFSI)
- Numerical simulation of the dynamic response of a bridge-soil system
- Field implementation using UTA NHERI mobile shakers

Informing Infrastructure Decisions through Large-Amplitude Forced Vibration Testing

Motivation - Civil Infrastructure Evaluation

Aging Infrastructures

- Need for the development of reliable safety assessment approaches
- Structural-Identification (St-Id) has evolved over the past few decades as a result of:
  - Adoption of sensing technologies (global and local)
  - Development of highly refined simulation models
  - Development of model calibration techniques (both deterministic and probabilistic)

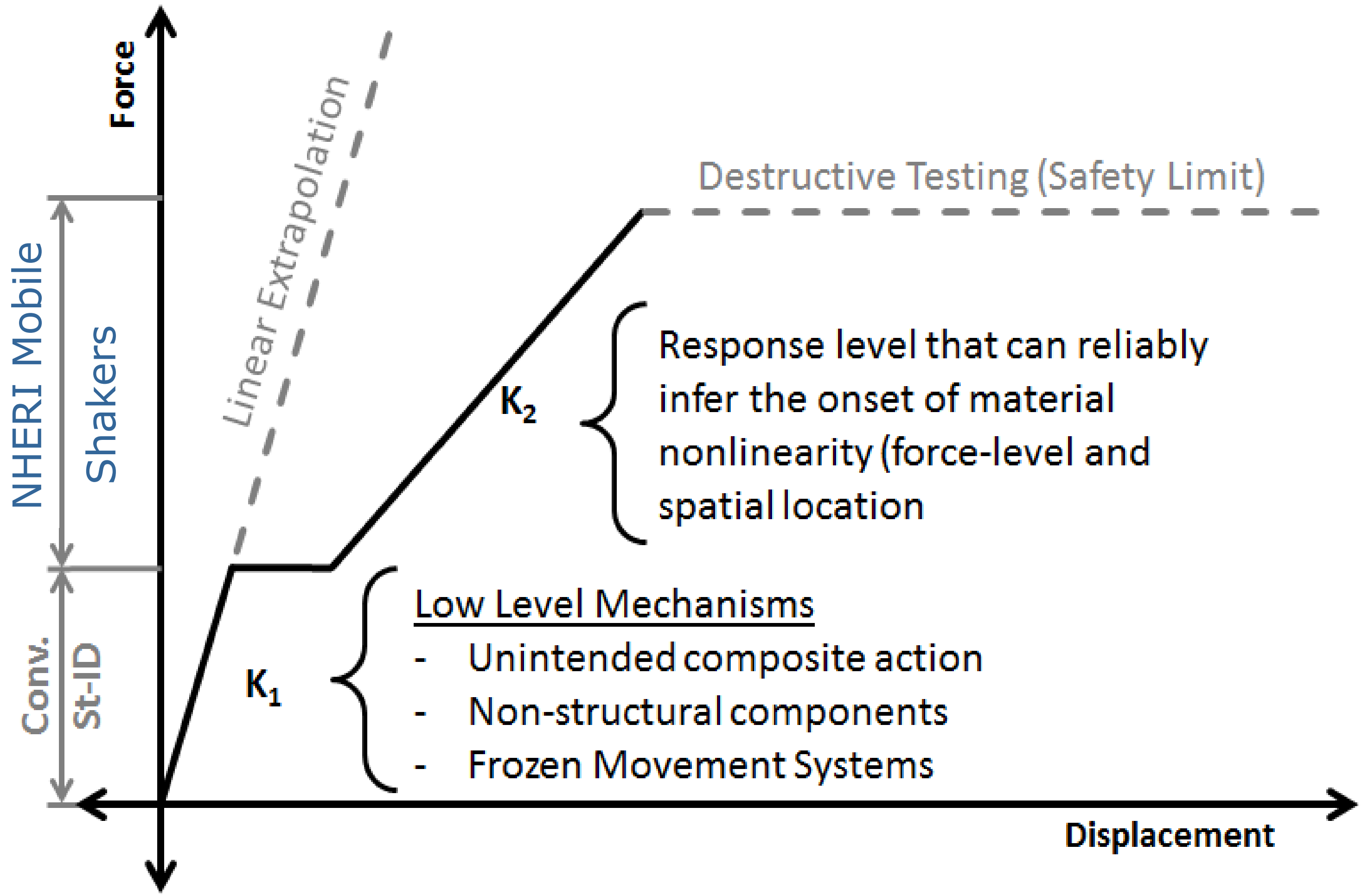
Motivation - Civil Infrastructure Evaluation

Current St-Id for Structure-Foundation Systems

- Based largely on the response data using various inputs (static loading, wind, temperature changes, pull-release, impact, shakers, etc.)

- Those low-level demand inputs are leading to responses similar to operational limit states =>the use of such responses to inform the safety assessment of systems under extreme events requires significant extrapolation

Motivation - Civil Infrastructure Evaluation



=> Large-amplitude mobile shakers offer significant potential to improve the reliability of St-Id by overcoming low-level mechanisms in a controlled manner

NSF EAGER (Early-concept Grants for Exploratory Research) Project

Overarching Aim

- To explore and establish the ability of large-amplitude, forced vibration testing to reveal the current performance and forecast the future system performance of structures, with the consideration of dynamic soil-foundation-structure effects.

NSF EAGER (Early-concept Grants for Exploratory Research) Project

More Focused Objectives

- Develop, evaluate, and refine a series of:
  1. Forced vibration testing and control strategies to capture response measurements indicative of key performance attributes of substructure/foundation and superstructure systems
  2. Data interpretation frameworks for structural system identification and assessment
- Perform a validation of the testing/control strategies and data interpretation frameworks on an operating structure with known substructure, foundation, and soil characteristics.

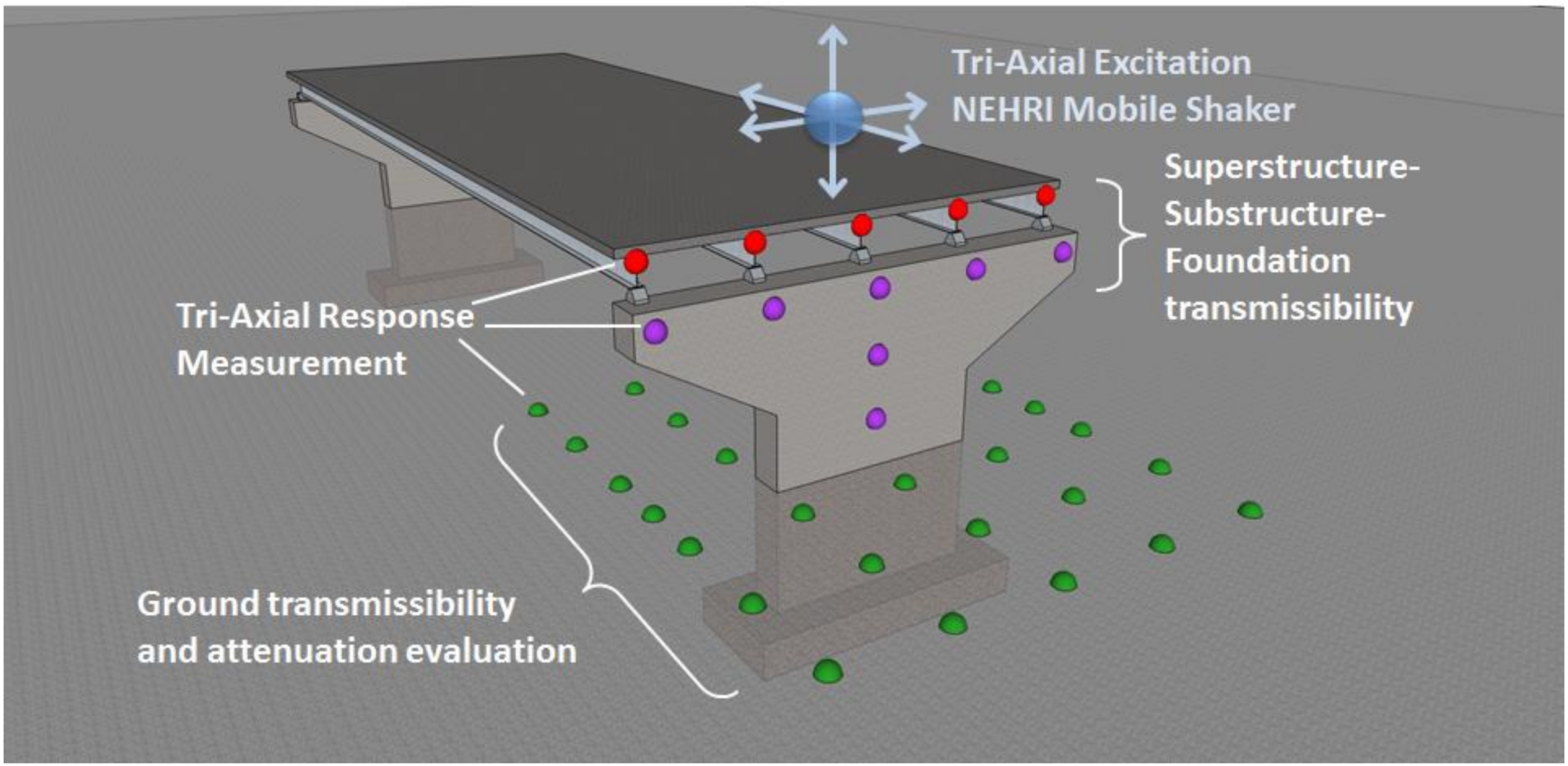
Research Plan

- Development of Forced-Vibration Testing Strategies
  - Parametric study to examine the correlation between certain measurable responses (both foundation and superstructure) and the foundation/substructure type/condition
- Development of Data Interpretation Frameworks
  - Model-Free Frameworks - Methods based primarily on data processing, data visualization, and data fitting techniques
  - Model-based Frameworks - Methods that update simulation models of the system being identified, and then employ these to examine behaviors that cannot be directly observed (St-Id)

Research Plan

- Field Implementation and Validation
  - Field implementation of the most promising testing strategies and data interpretation frameworks
  - Since the deployment of large shakers is the easiest to accomplish on bridges (A bridge in Hamilton, NJ was selected as the implementation structure)
  - To be carried out with a UTA NHERI shaker (T-Rex) and dense instrumentation arrays

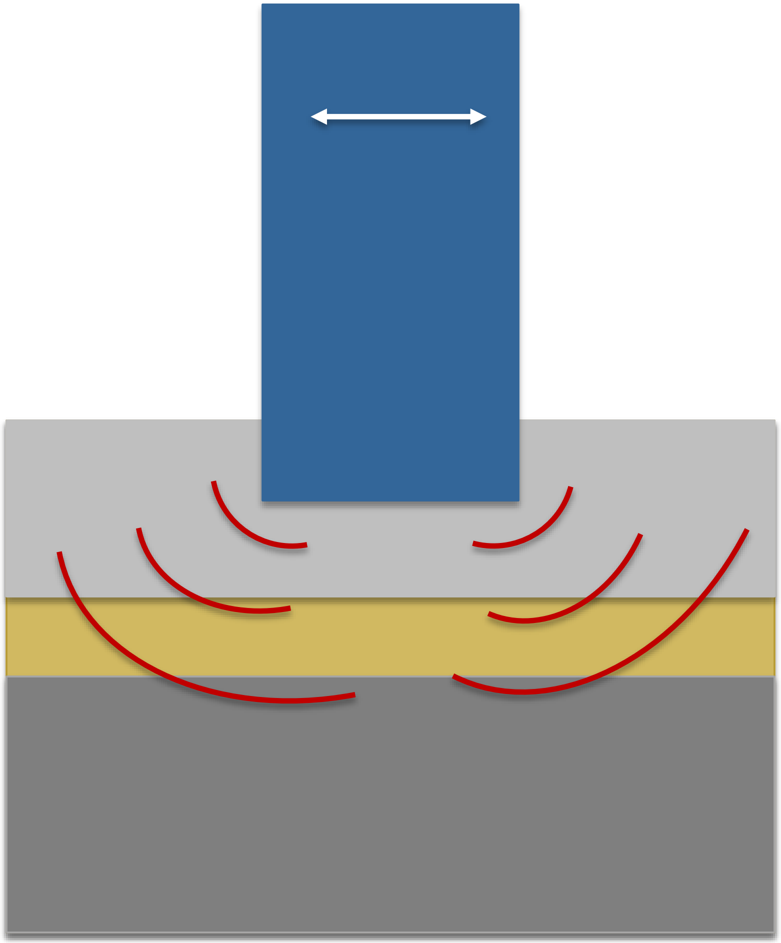
Envisioned Field Implementation



Foundation Dynamics and Dynamic Soil-Foundation-Structure Interaction (DSFSI)

Objective of Dynamic Soil-Foundation-Structure (DSFS) Interaction Analysis

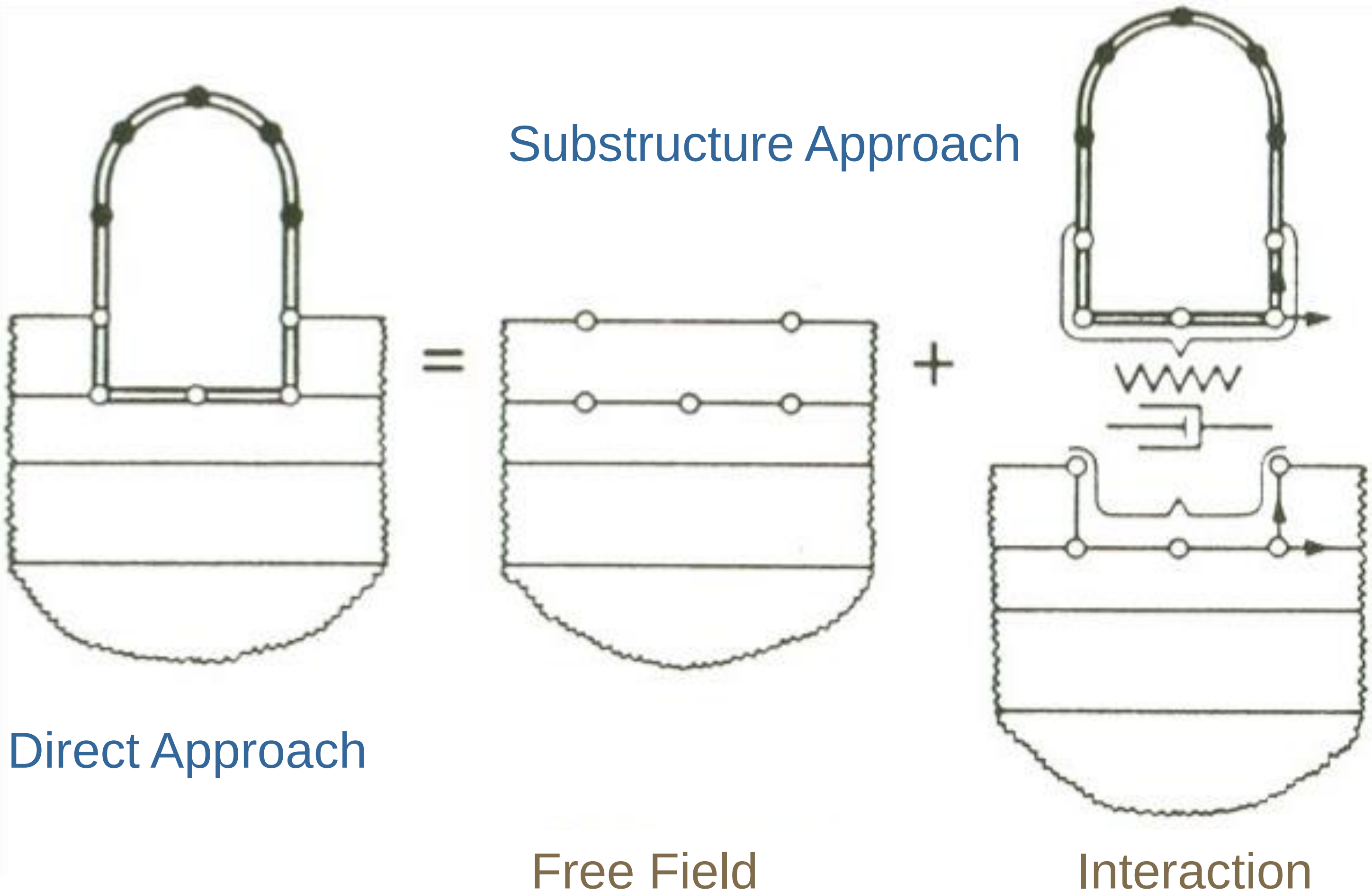
The fundamental objective of soil-foundation-structure interaction analysis is to evaluate the dynamic response by encompassing the radiation of energy of the waves propagating into the soil.



Effects of Soil and DSFSI on the Response

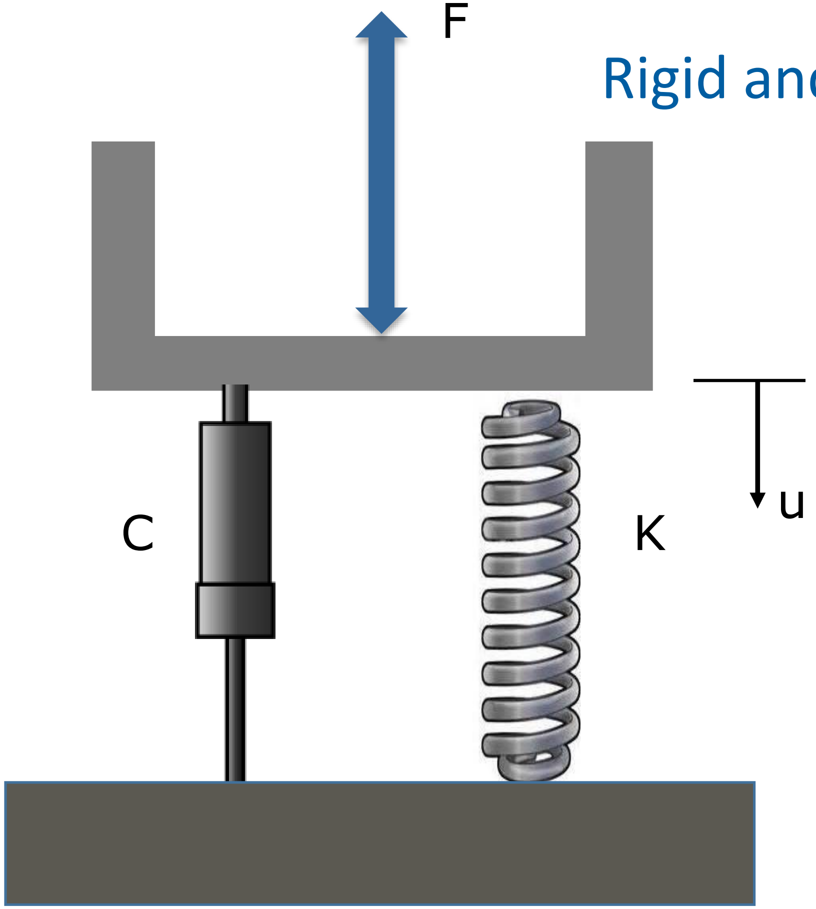
- Site amplification of ground motion (earthquake loading).
- Soil flexibility will effect the flexibility of the overall SFS (Soil-Foundation-Structure) system and, thus, reduce the fundamental frequency. (In comparison to a structure founded on rock.)
- Radiation of energy through soil will lead to a significantly higher damping. (Exceptions are shallow soil layers.)
- DSFSI (Dynamic SFS Interaction) increases as soil becomes softer, and the structure becomes more rigid. And vice versa.
- Generally, DSFSI gives smaller response amplitudes under earthquake and other dynamic loads than modeling on a rigid base. Displacements at the top of a structure may be larger due to rocking of the structure (foundation).

Modeling of DSFSI Problems - Direct and Substructure Methods



(after Wolf, 1985)

Foundation Dynamics Problem – Impedance Functions



$$u = \frac{\boldsymbol{F}}{\boldsymbol{K} + \boldsymbol{i\omega C}}$$

Impedance

Response of Foundations to Vertical Loading

$$K_v = K_{vs}(k + ia_0 c)$$ - vertical impedance

K_{vs} - static stiffness

k - stiffness impedance coefficient

c - damping impedance coefficient

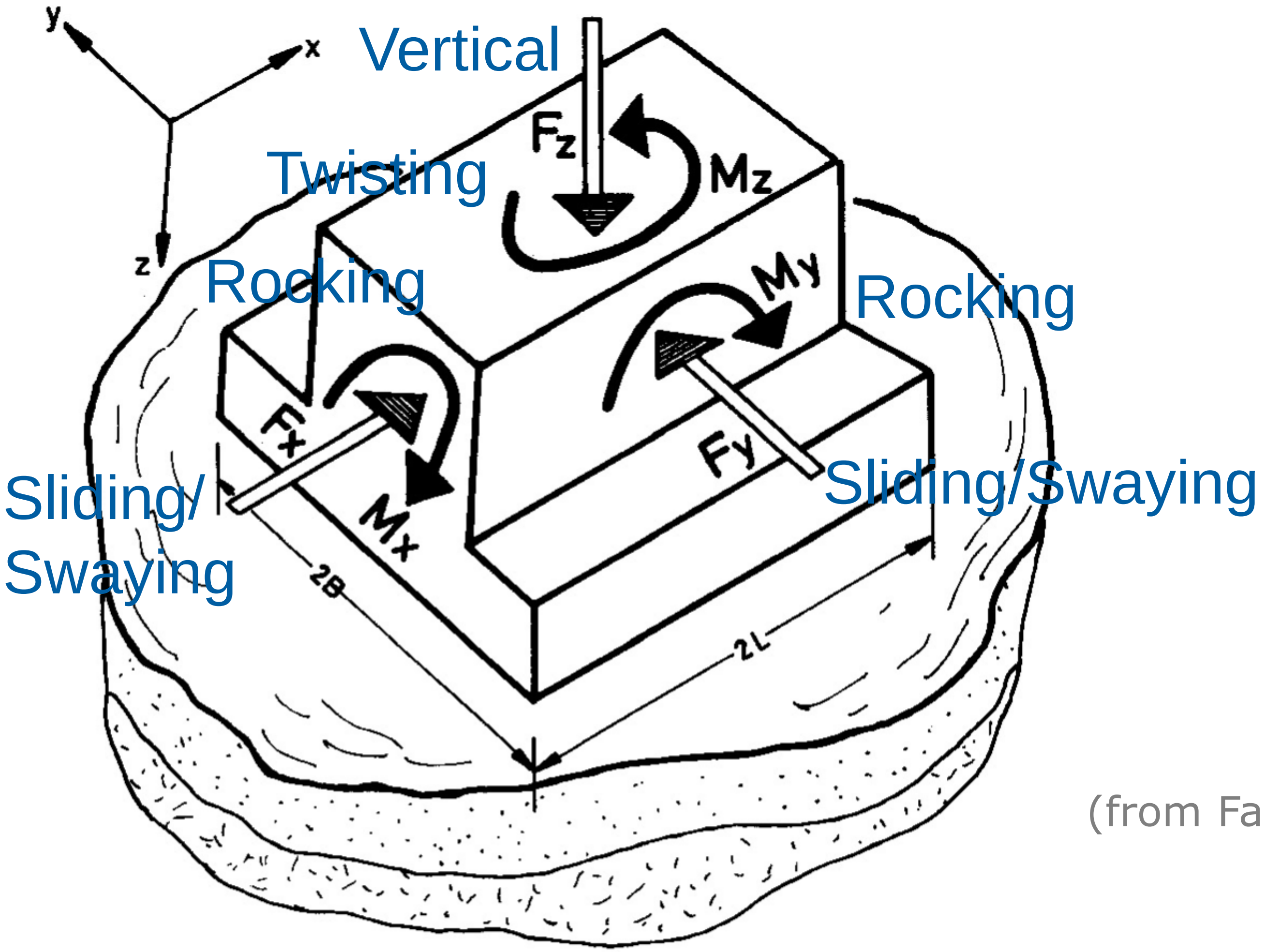
a_0 - dimensionless frequency ($\omega R/V_s$)

Impedances are functions of frequency!

Factors Affecting Dynamic Response of Foundations

- Soil properties (primarily shear modulus, damping and Poisson's ratio)
- Geometry (shape) of the foundation
- Depth of embedment of the foundation
- Presence of a rigid base
- Mode of vibrations (translation or rotation)
- Dynamics and frequency of loading
- Foundation flexibility (stiffness)

Modes of Vibrations



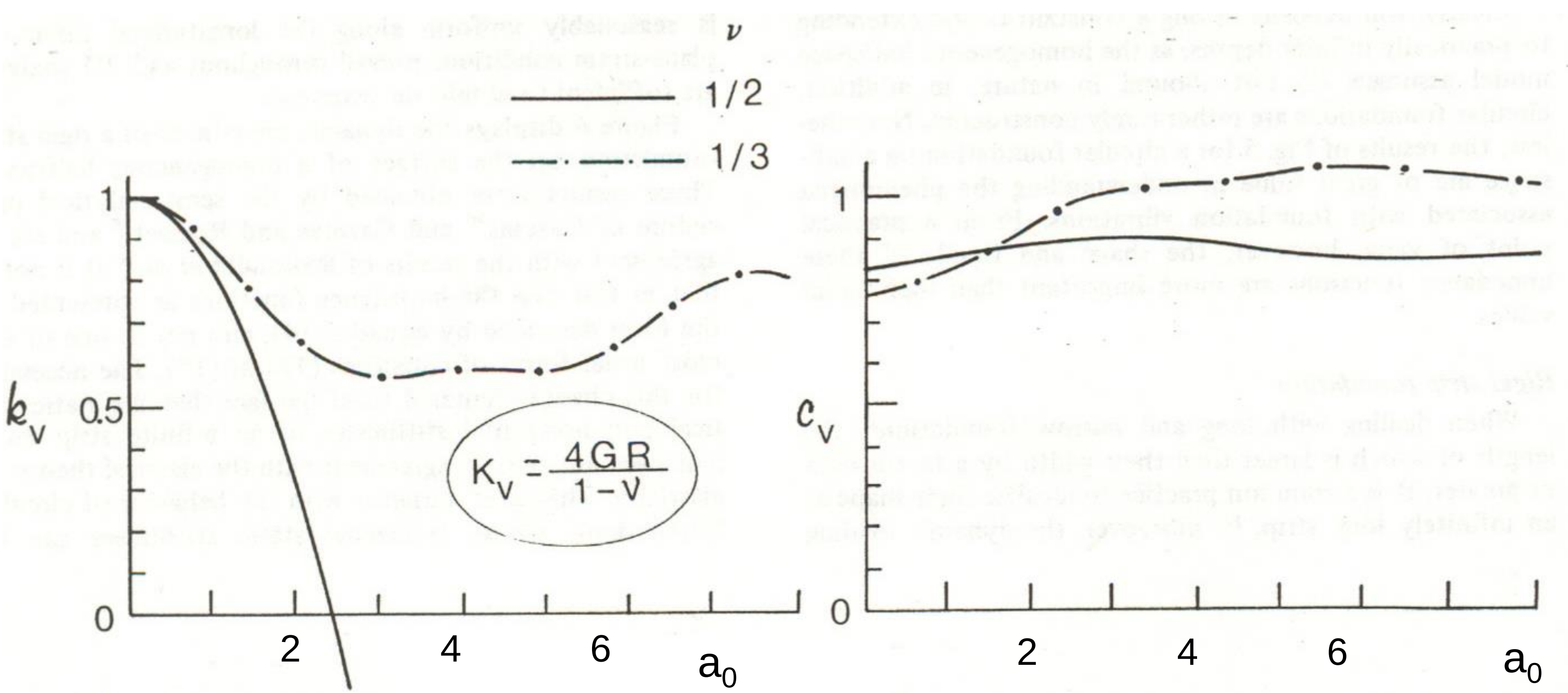
(from Fang, 1991)

Static Stiffness for a Rigid Circular Footing on an Elastic Half-Space

Mode	Vertical	Horizontal	Rocking	Torsion
Stiffness:	$\frac{4GR}{1-\nu}$	$\frac{8GR}{2-\nu}$	$\frac{8GR^3}{3(1-\nu)}$	$\frac{16GR^3}{3}$

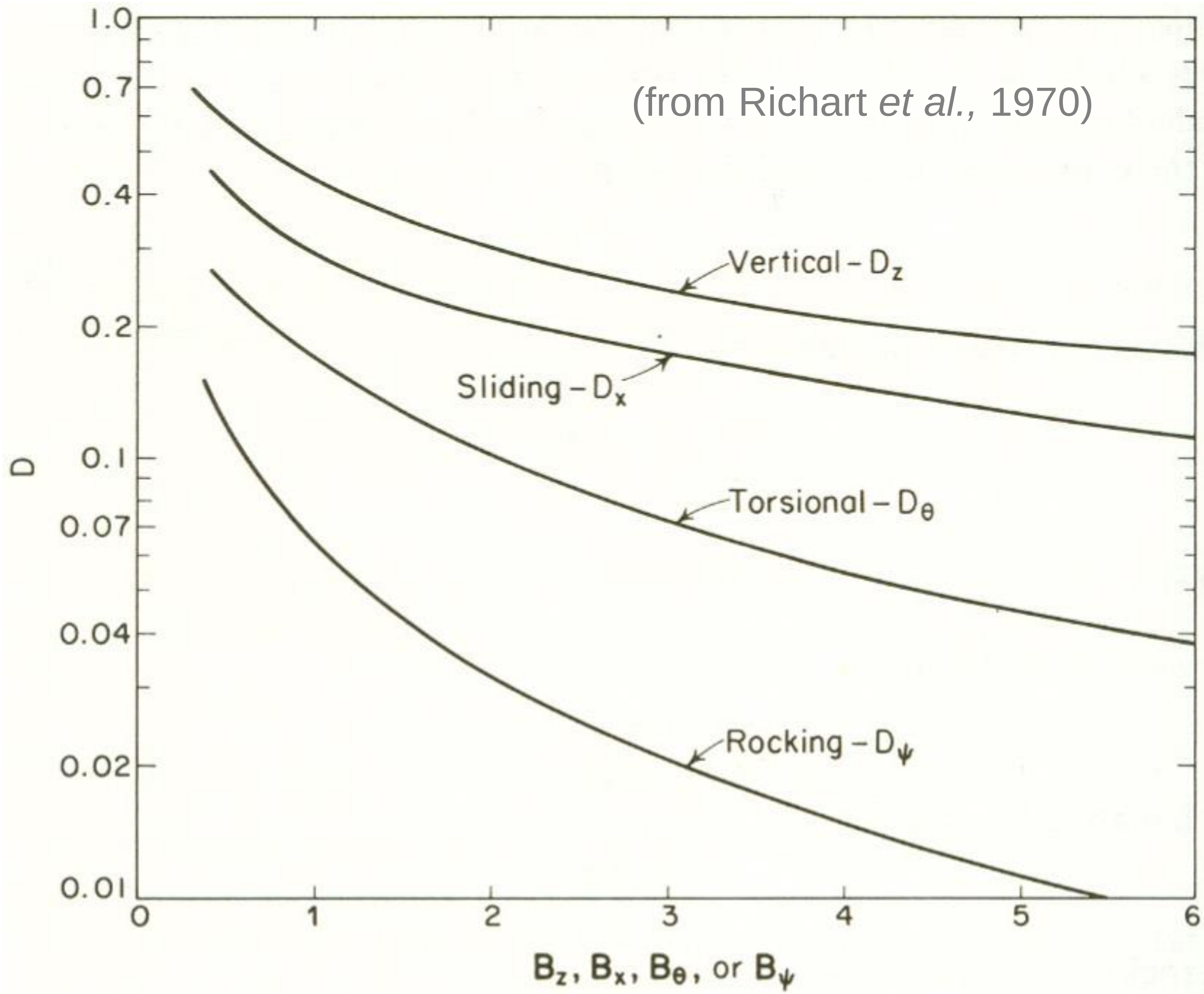
(from Gazetas, 1983)

Impedance Coefficients for a Circular Footing on an Elastic Half-Space - Vertical



(Luco and Westman 1971, from Gazetas 1983)

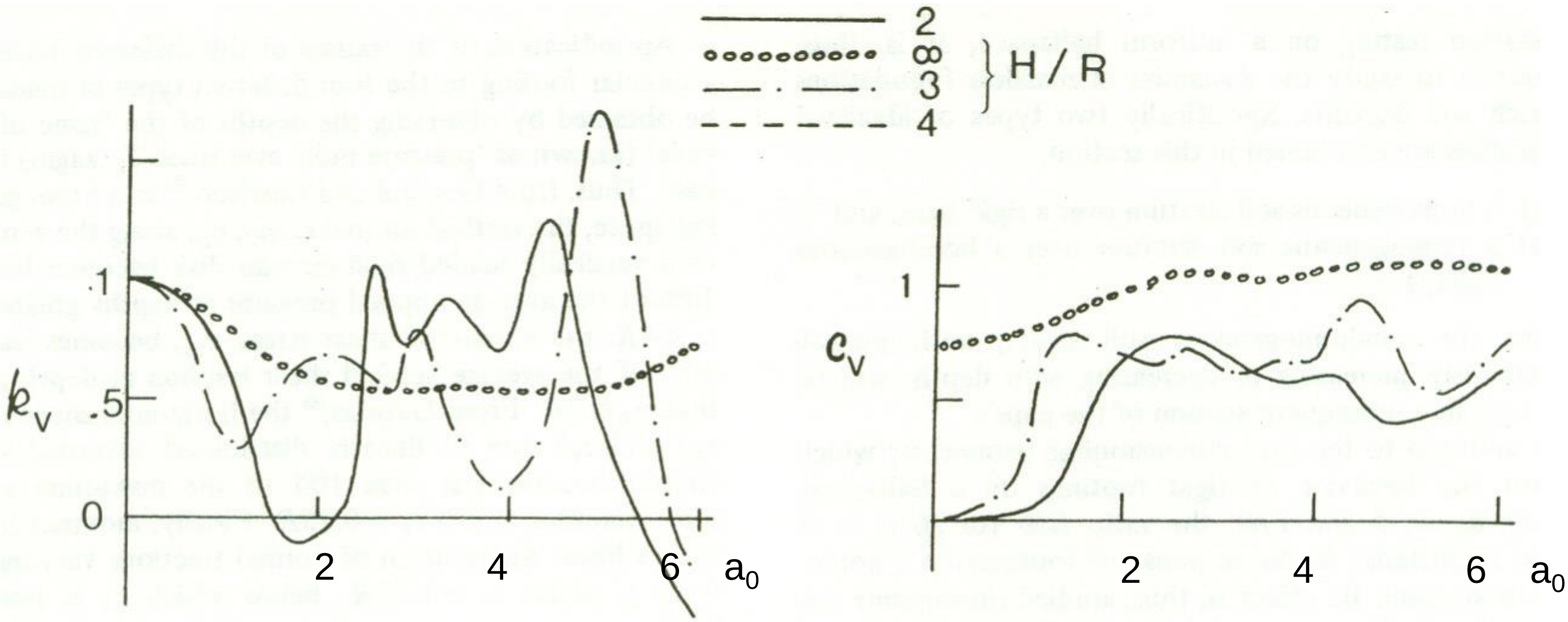
Damping Ratio for Surface Foundations



Some Elements Affecting Foundation Impedance Functions

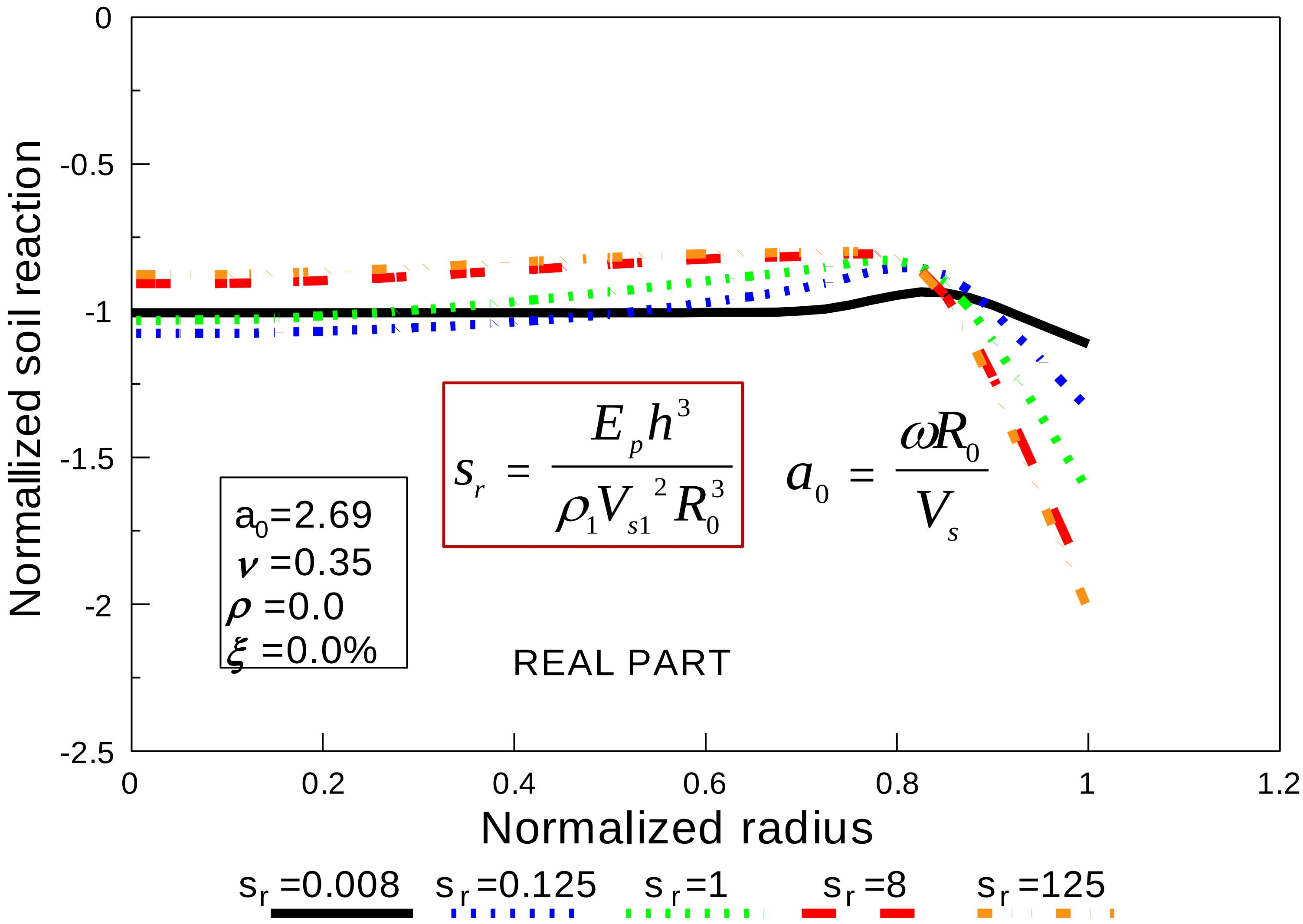
- Embedment significantly increases the dynamic stiffness and equivalent damping ratio. => An effective way to reduce the anticipated high amplitudes of vibrations.
- For a foundation on a stratum, static stiffness in all modes increases (more for translational than rotational modes) with the relative radius to depth to bedrock ratio R/H.
- Impedance coefficients have undulations (instead of smooth functions for H-S) associated with natural frequencies of the stratum.
- Below the first resonant frequency of each mode of vibration, c is zero or negligible. (No surface waves to radiate energy, while bedrock prevents “vertical” radiation.) Vertical and sliding modes affected more.
- Foundation flexibility affects soil reaction and displacement distributions, and impedance coefficients.

Impedance Coefficients of a Rigid Circular Foundation on a Stratum - Vertical

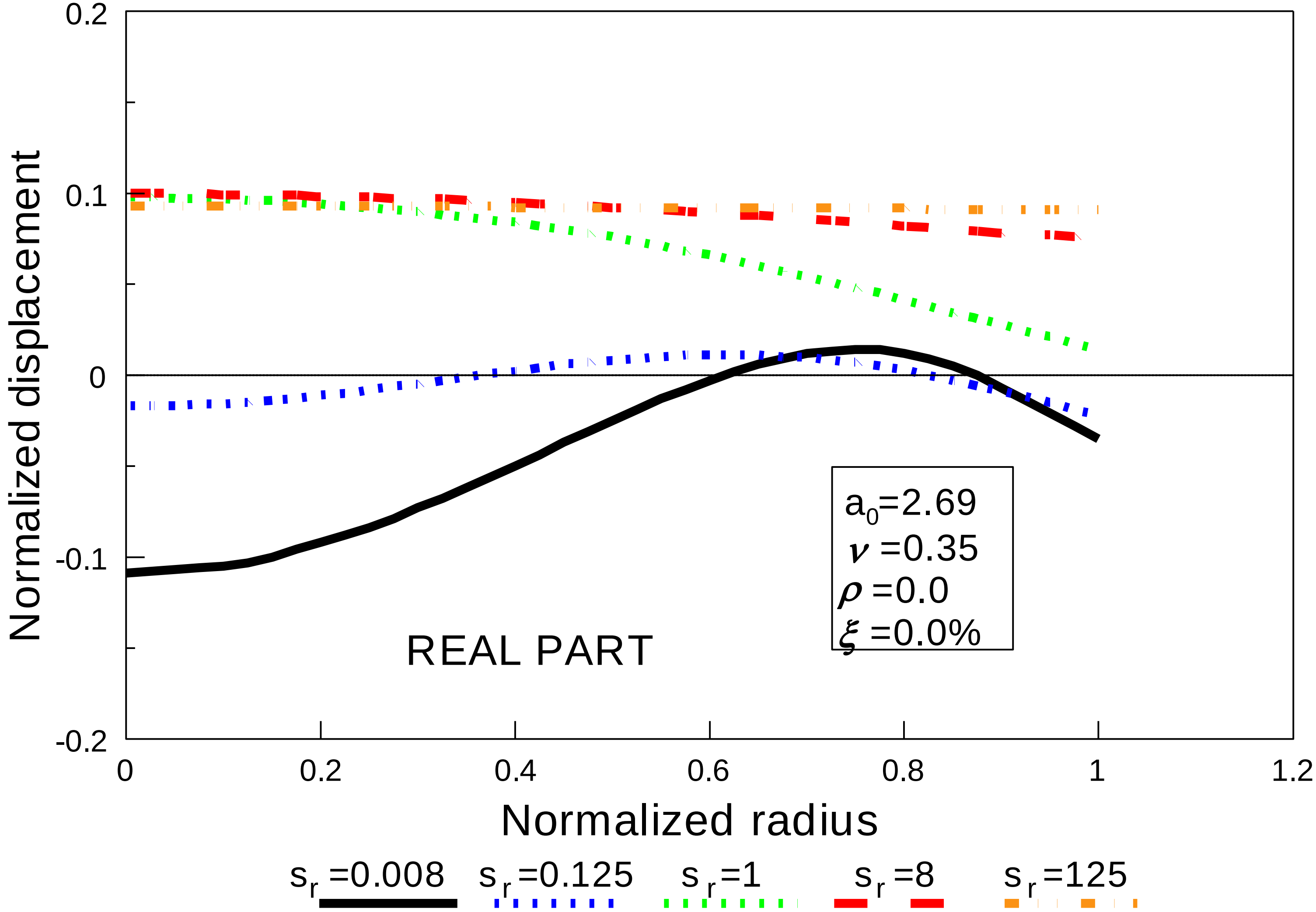


(after Kausel and Ushijima, 1979)

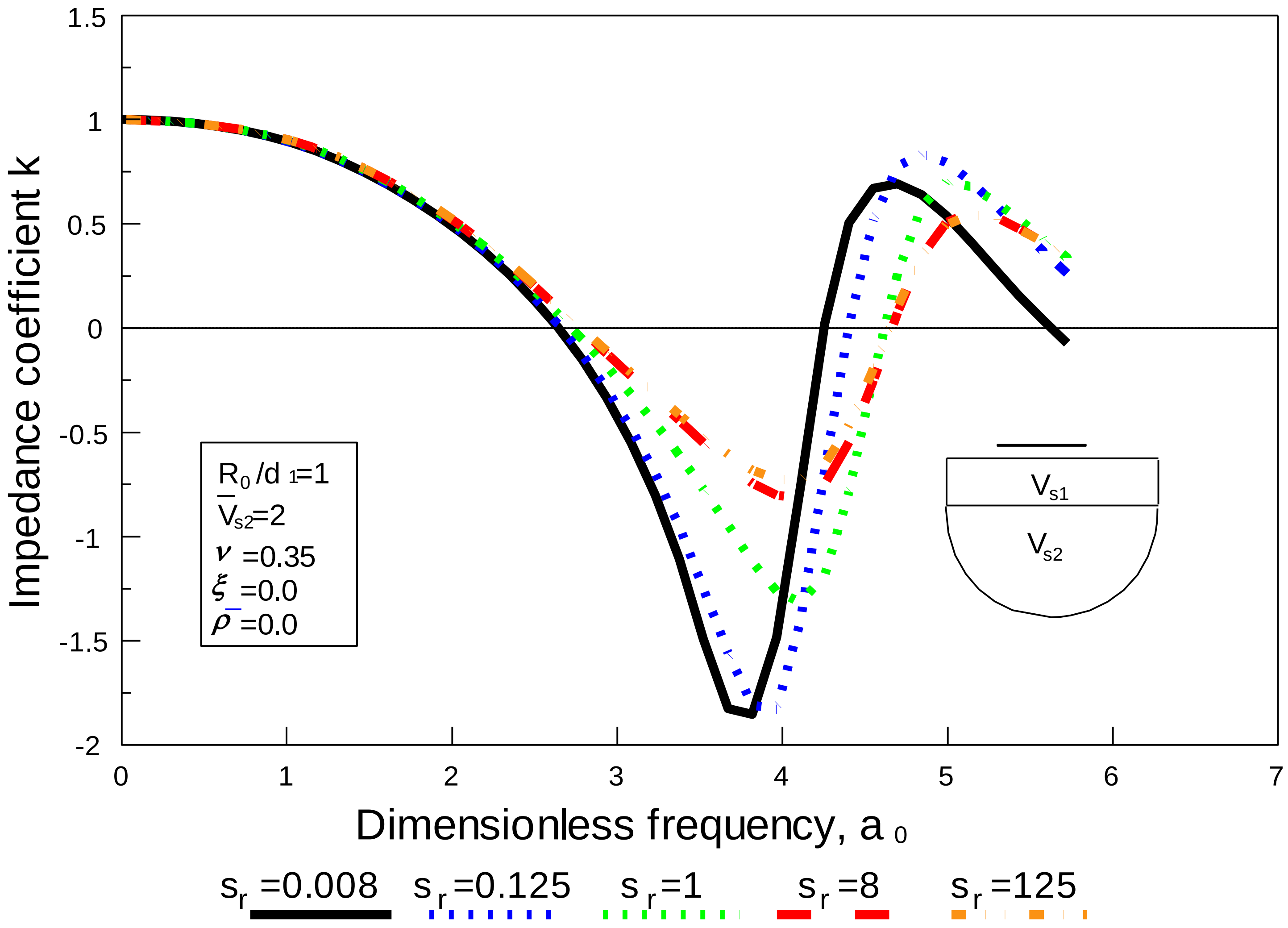
Effect of Foundation Flexibility Expressed Through Stiffness Ratio on Soil Reaction Distribution



Effect of Stiffness Ratio on Displacement Distribution

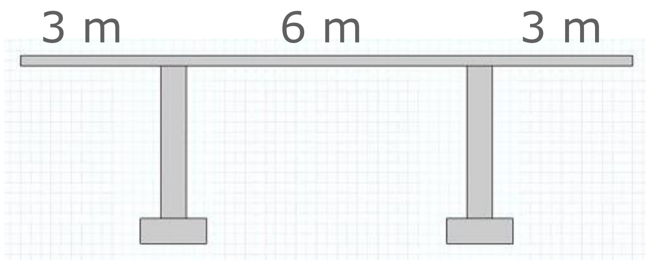


Effect of Stiffness Ratio on Impedance Functions

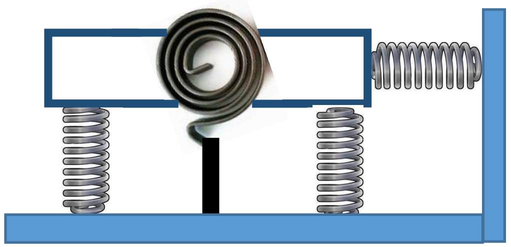


Numerical Model and Parametric Study of Dynamic Response of Bridge-Soil Systems

Parametric Study - 2D Model of Hypothetical Bridge



Foundation



Variables

V_s: Soil S-Wave Velocity; 200-400 m/s

R: Footing Radius; 2-4 m

H_c: Column Height; 3-12 m

Constants

W_f: Footing Width; 1.3m

T_f: Footing Thickness; 0.5 m

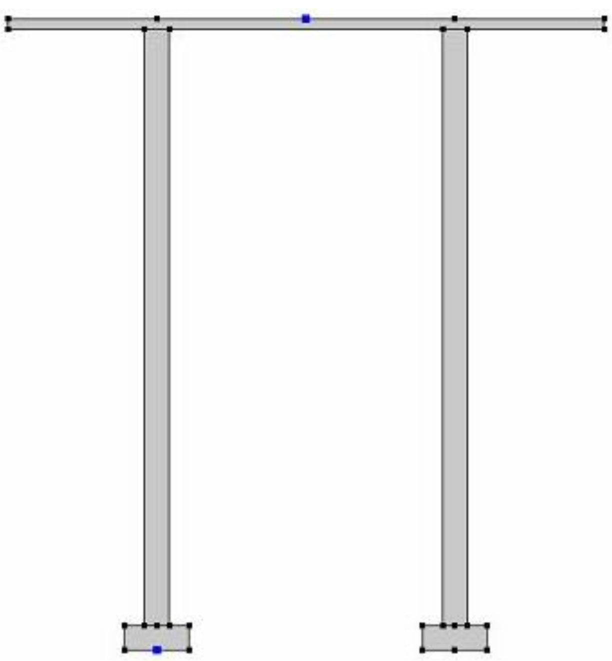
W_c: Column Width; 0.5 m

T_s: Slab Thickness; 0.2 m

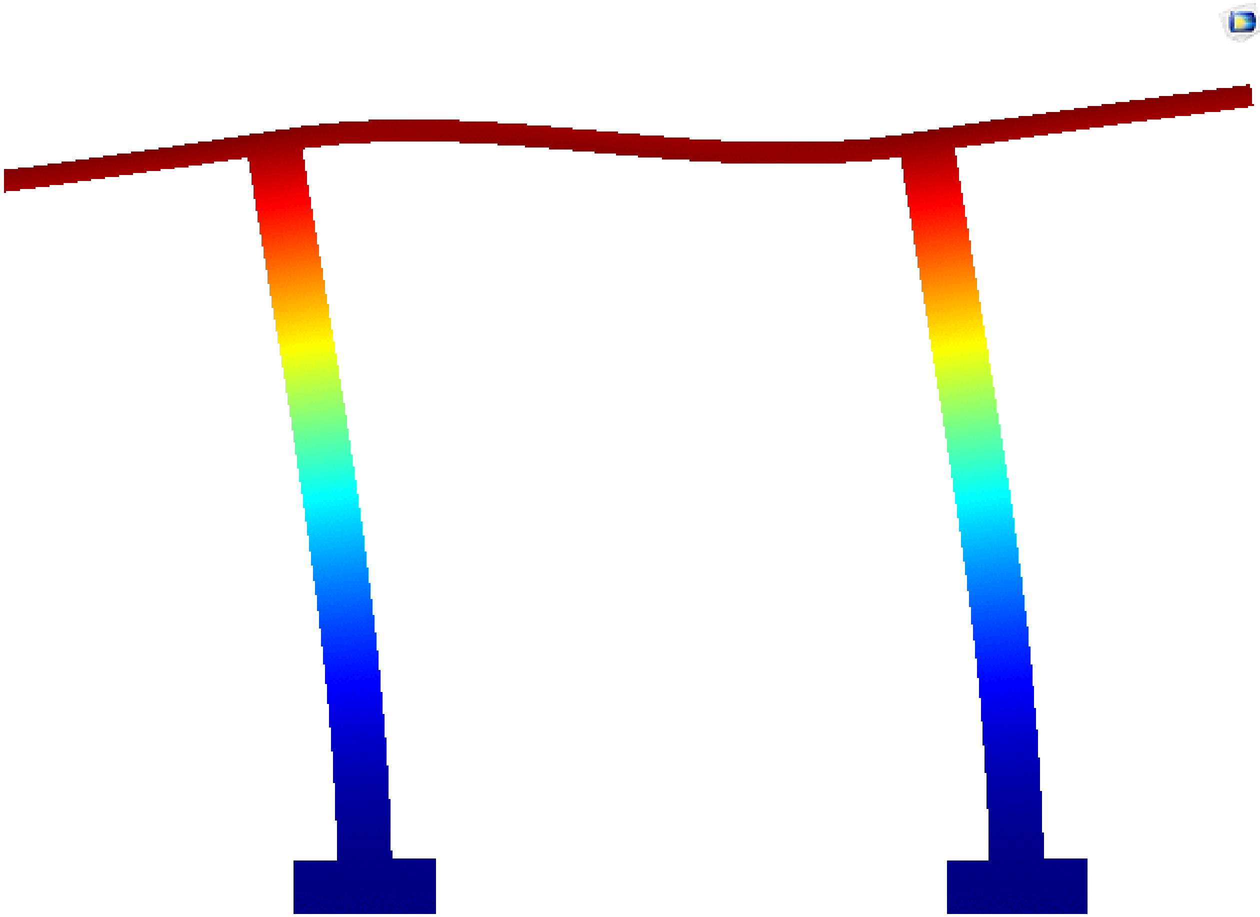
F_s: Half Column Spacing, 3 m

ρ_s: Soil Density; 1900 kg/m^3

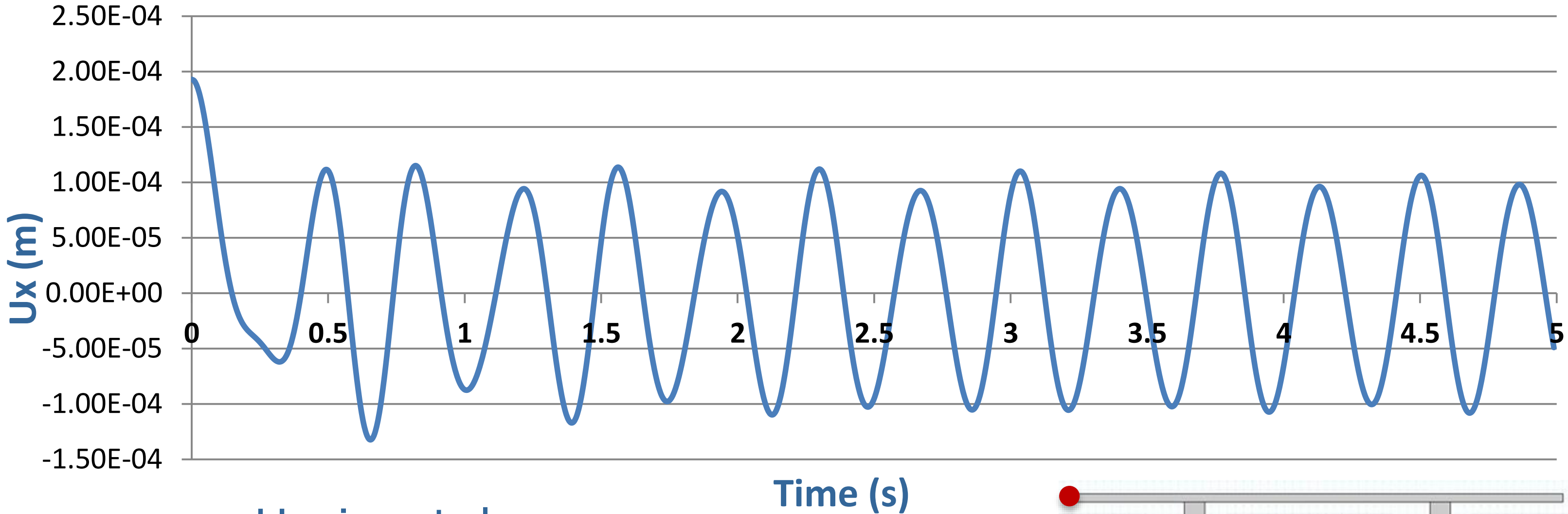
v : Poisson’s ratio; 0.333

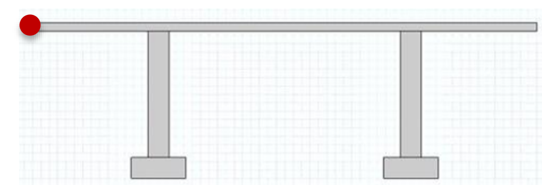


Bridge Swaying Response Under Horizontal Harmonic Loading



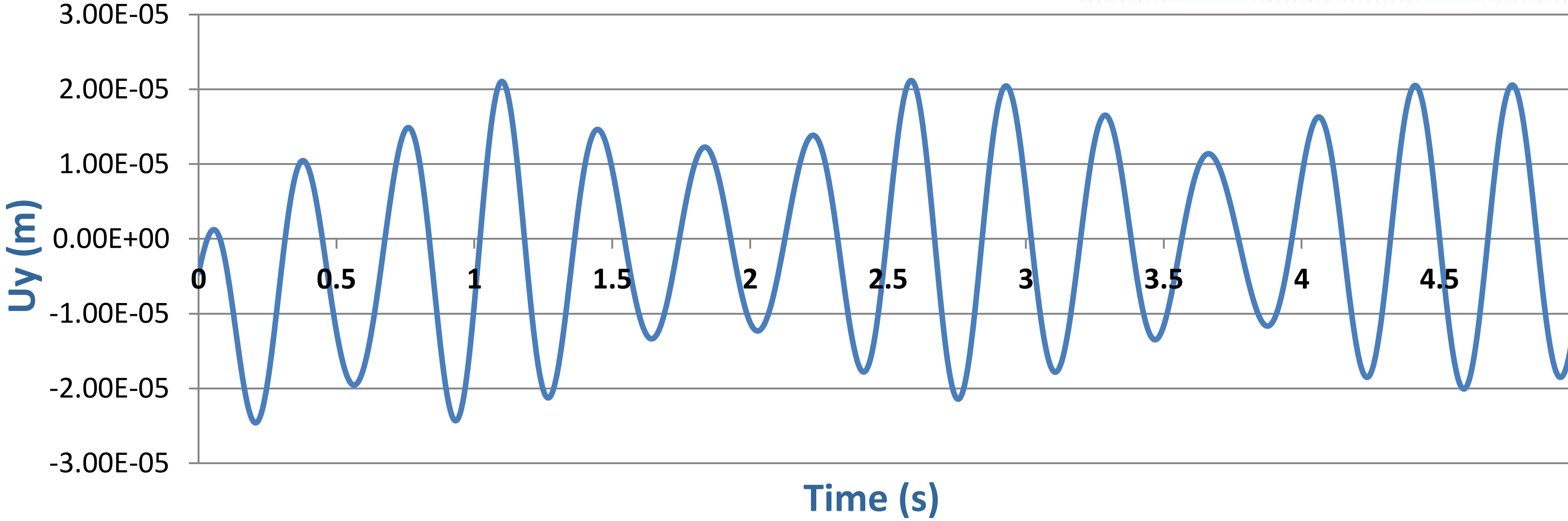
Sample Displacement Time Histories - Deck



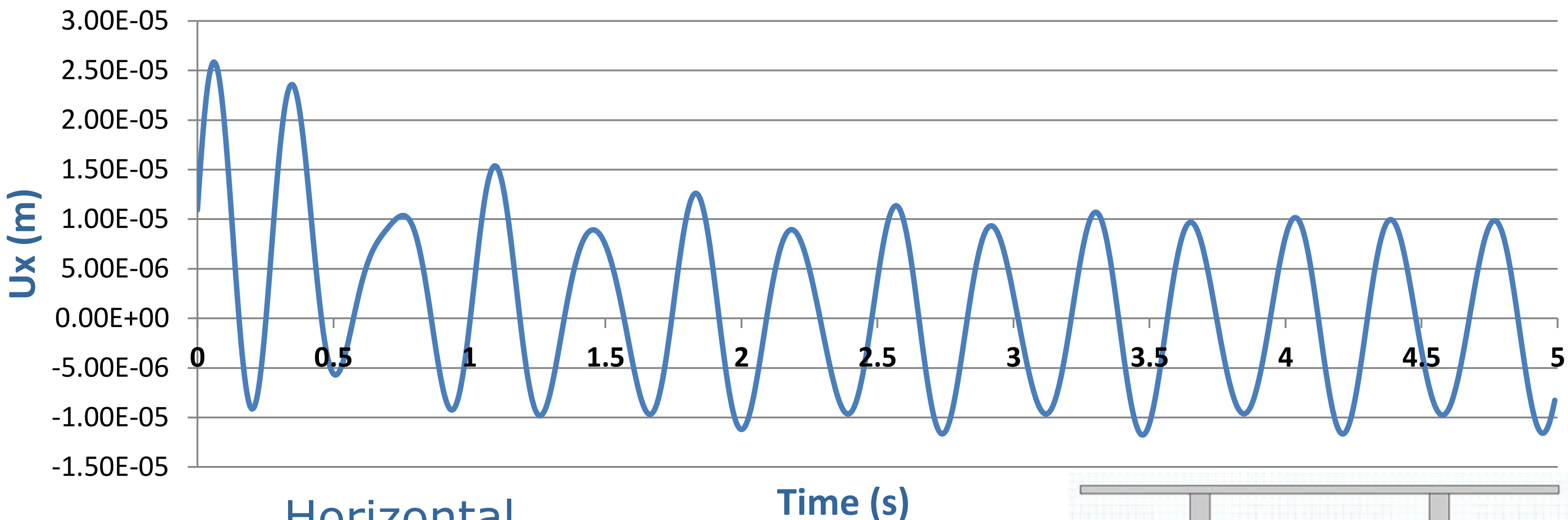


Horizontal

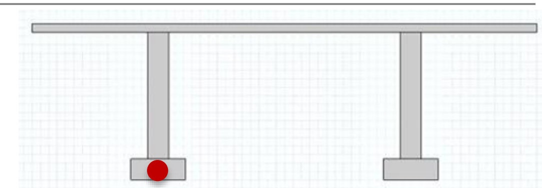
Vertical



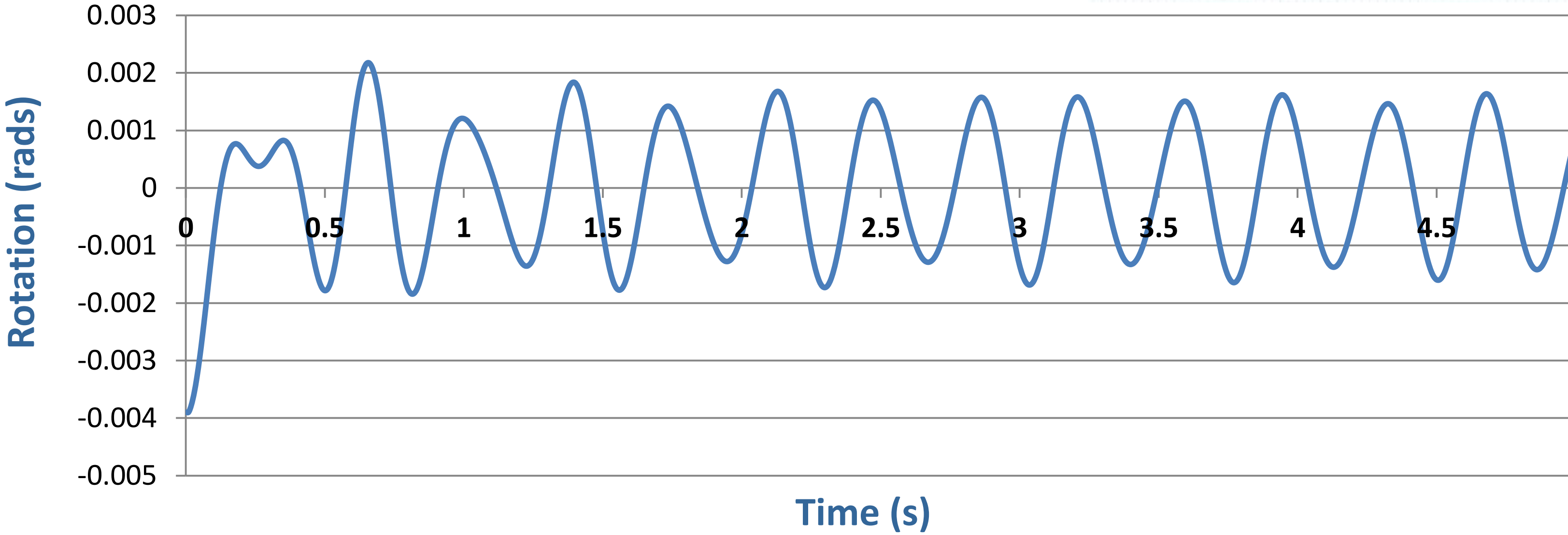
Sample Displacement Time Histories - Foundation



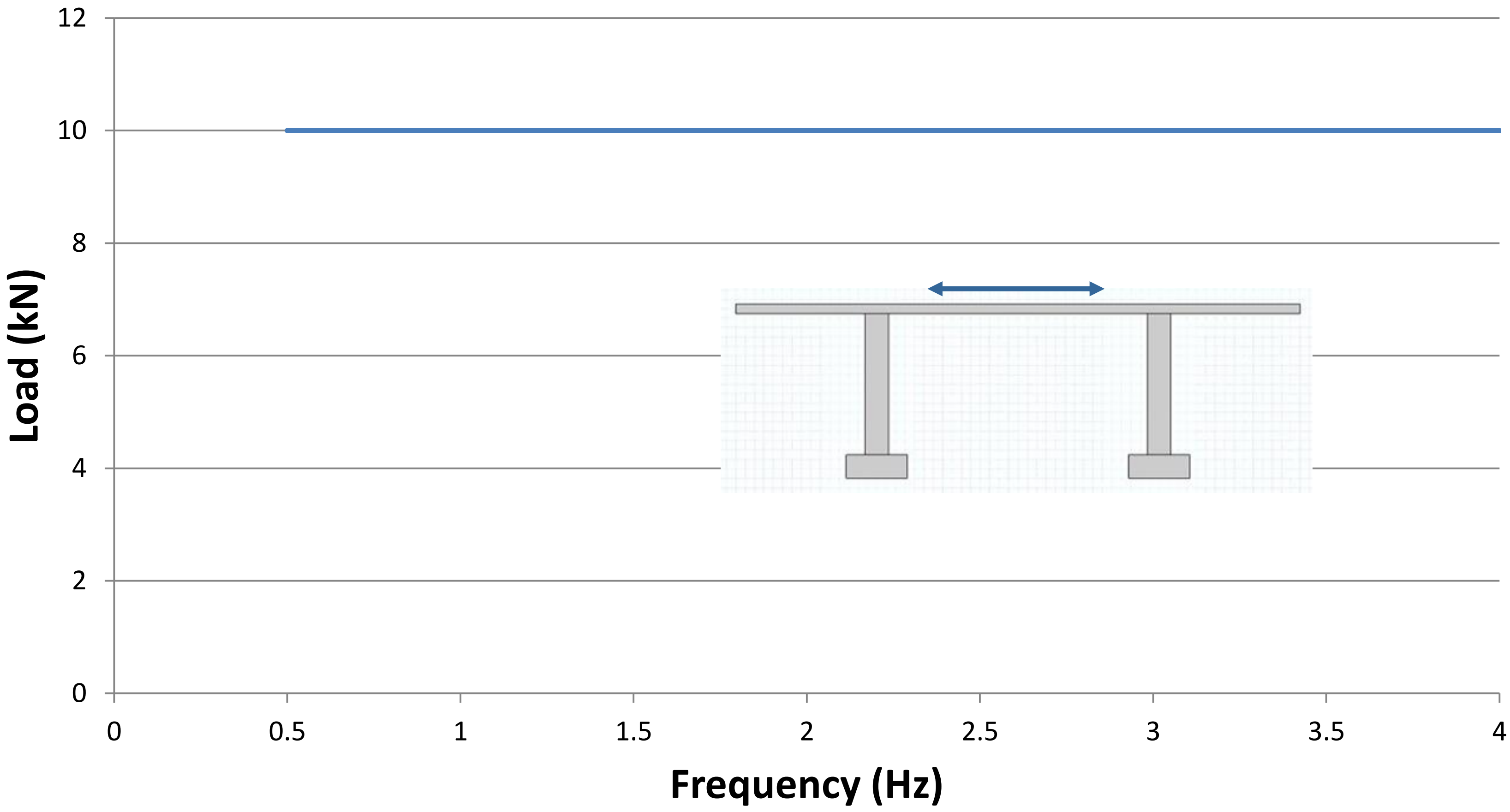
Horizontal



Rotation

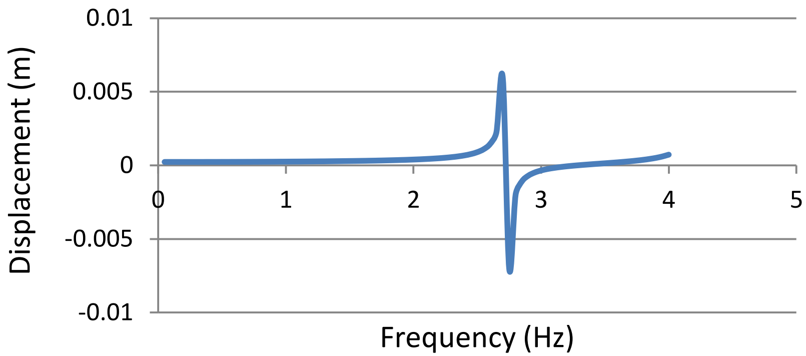


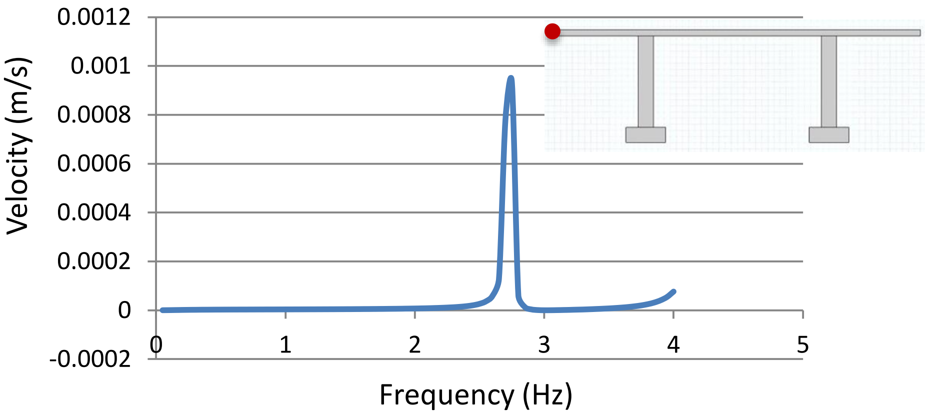
Sample Loading Spectrum

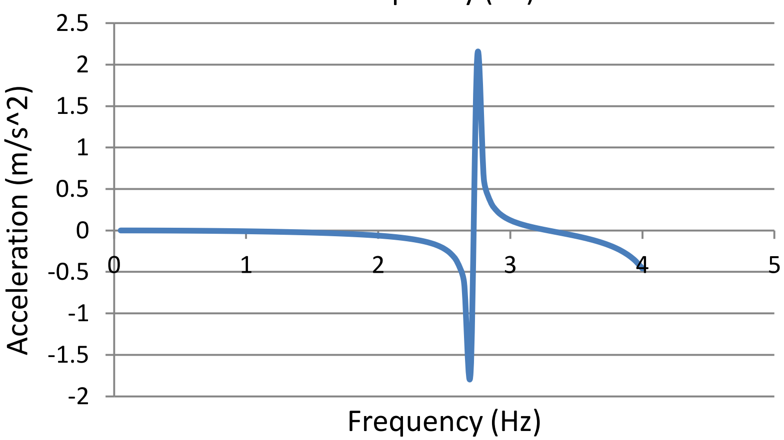


Sample Horizontal Displacement, Velocity and Acceleration Response Spectra

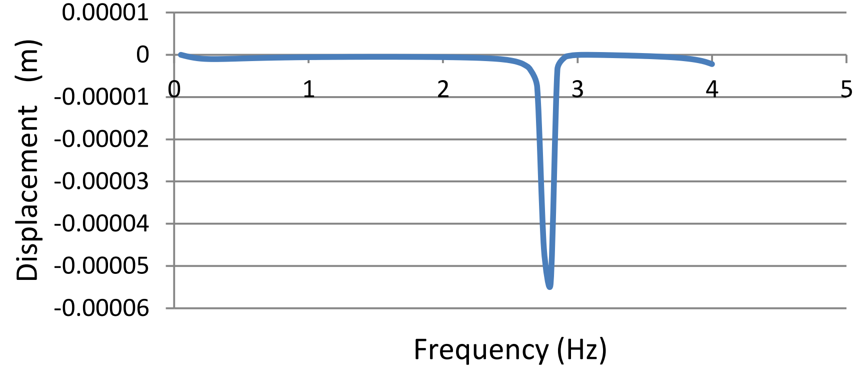
Real Part

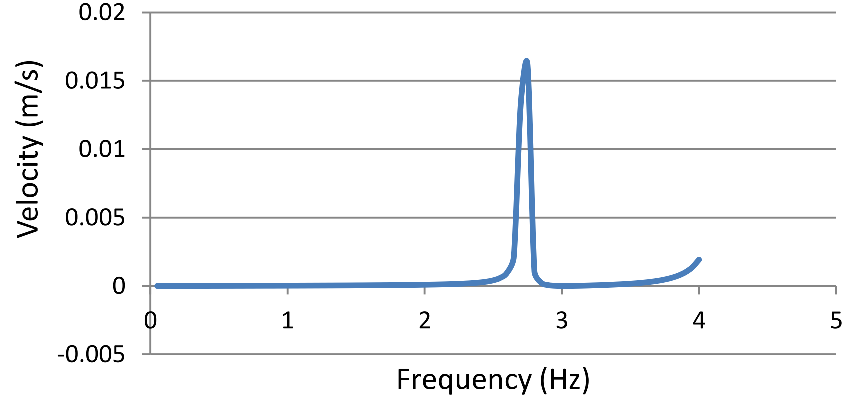


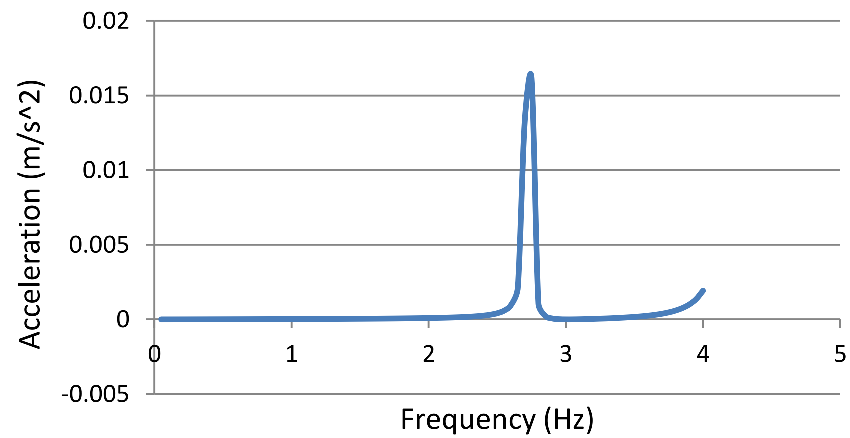




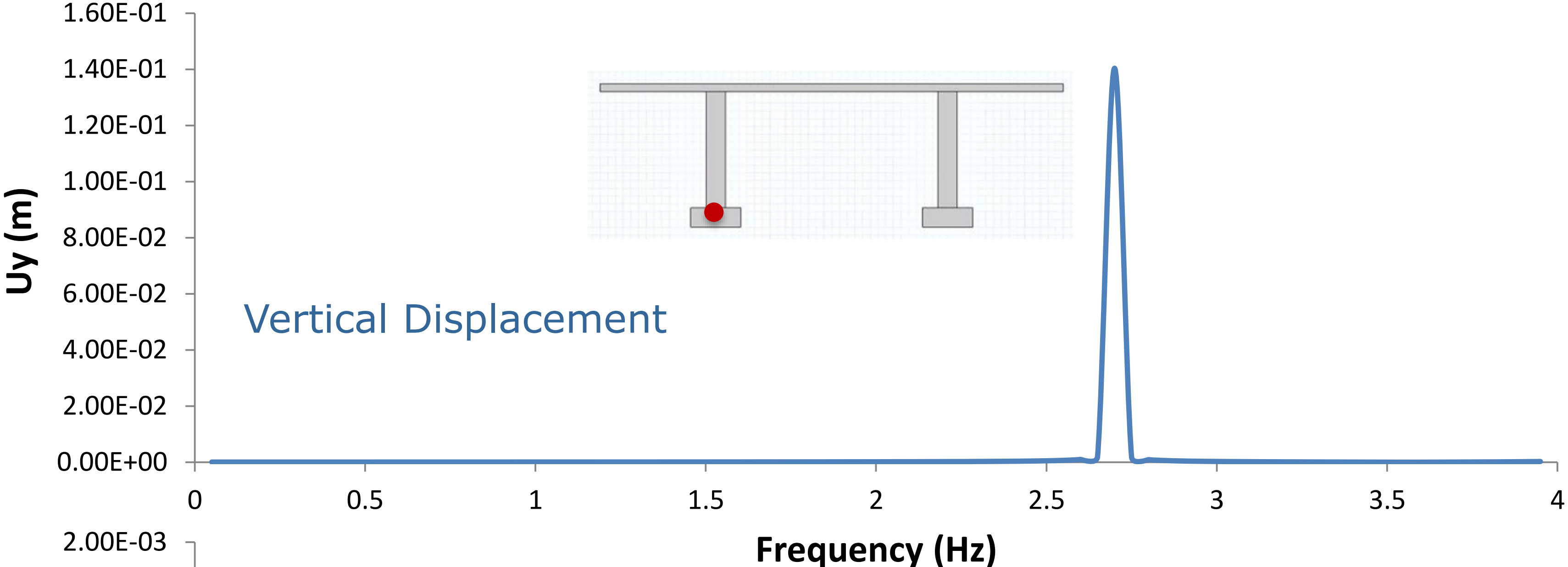
Imaginary Part

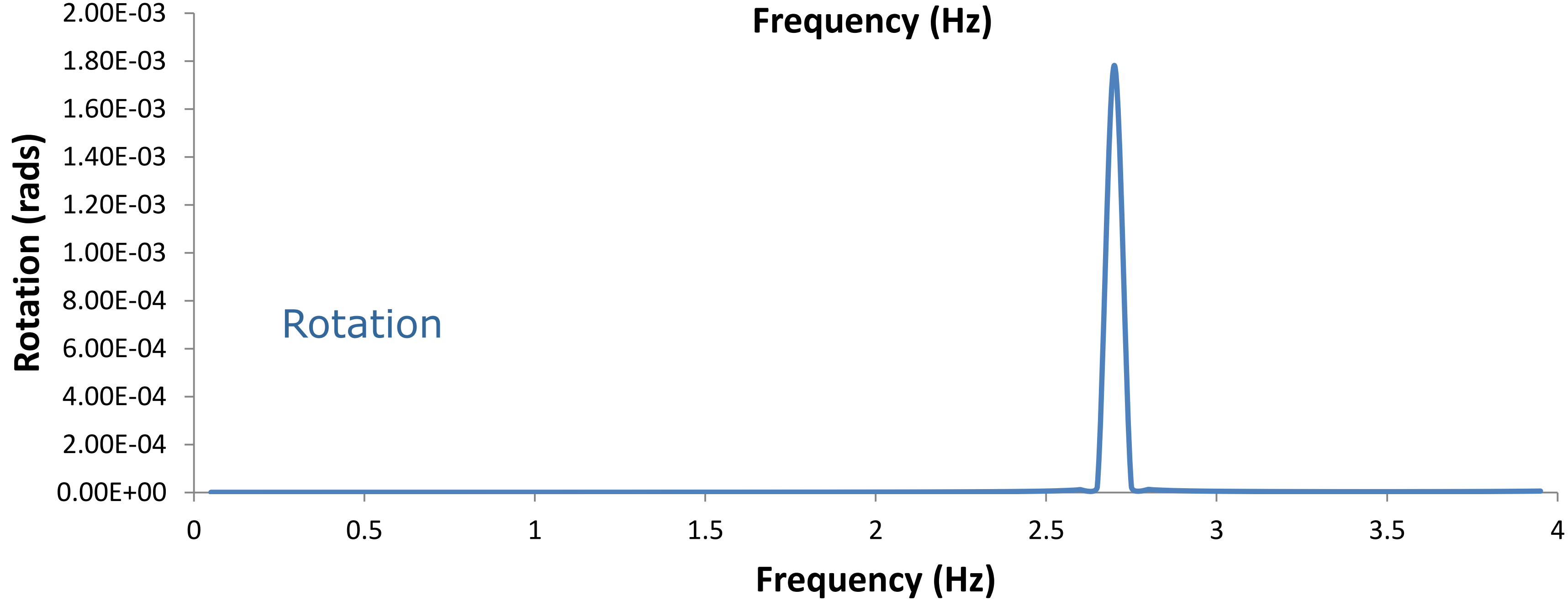




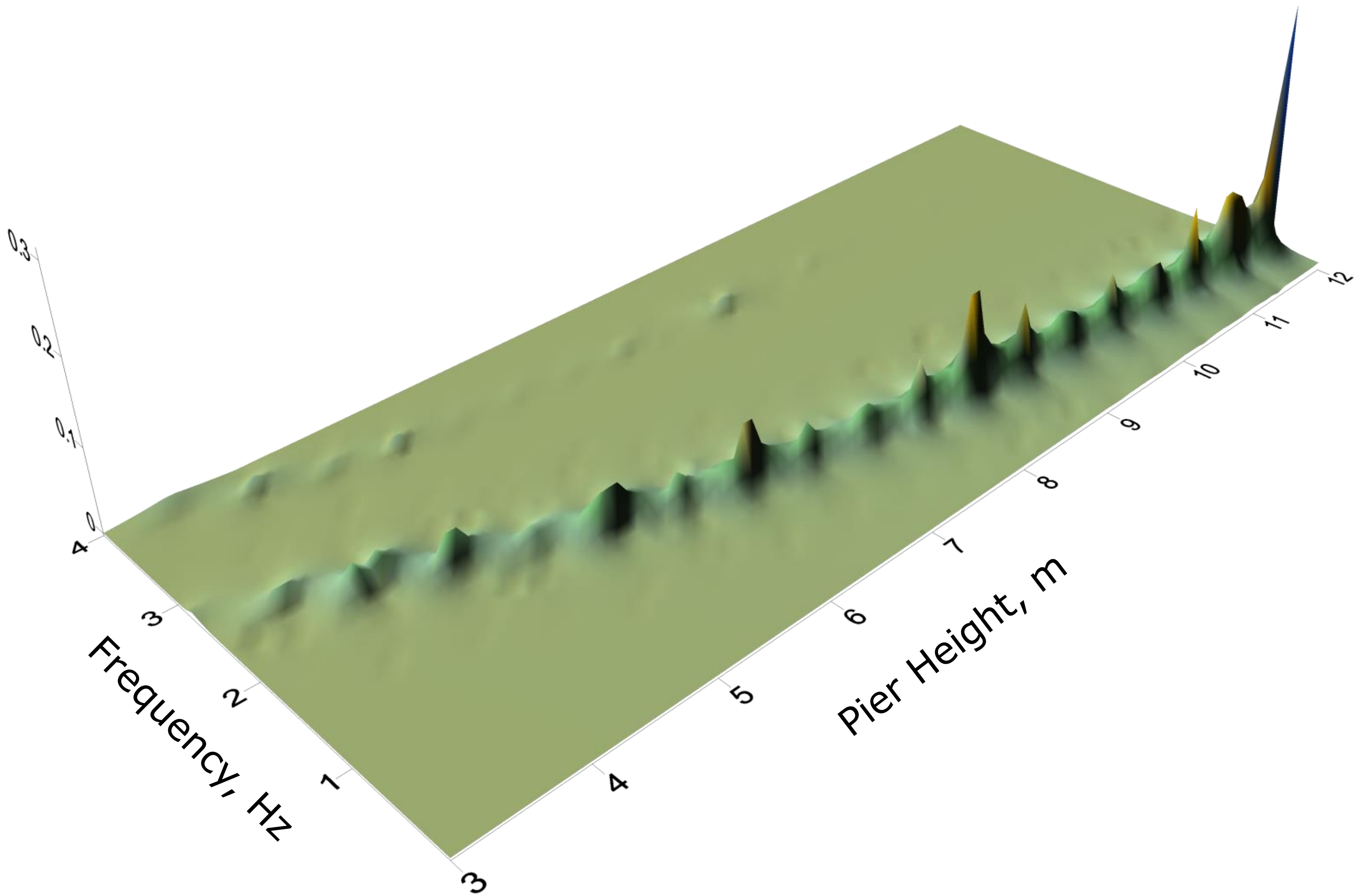


Sample Foundation Vertical Displacement and Rotation Response Spectra

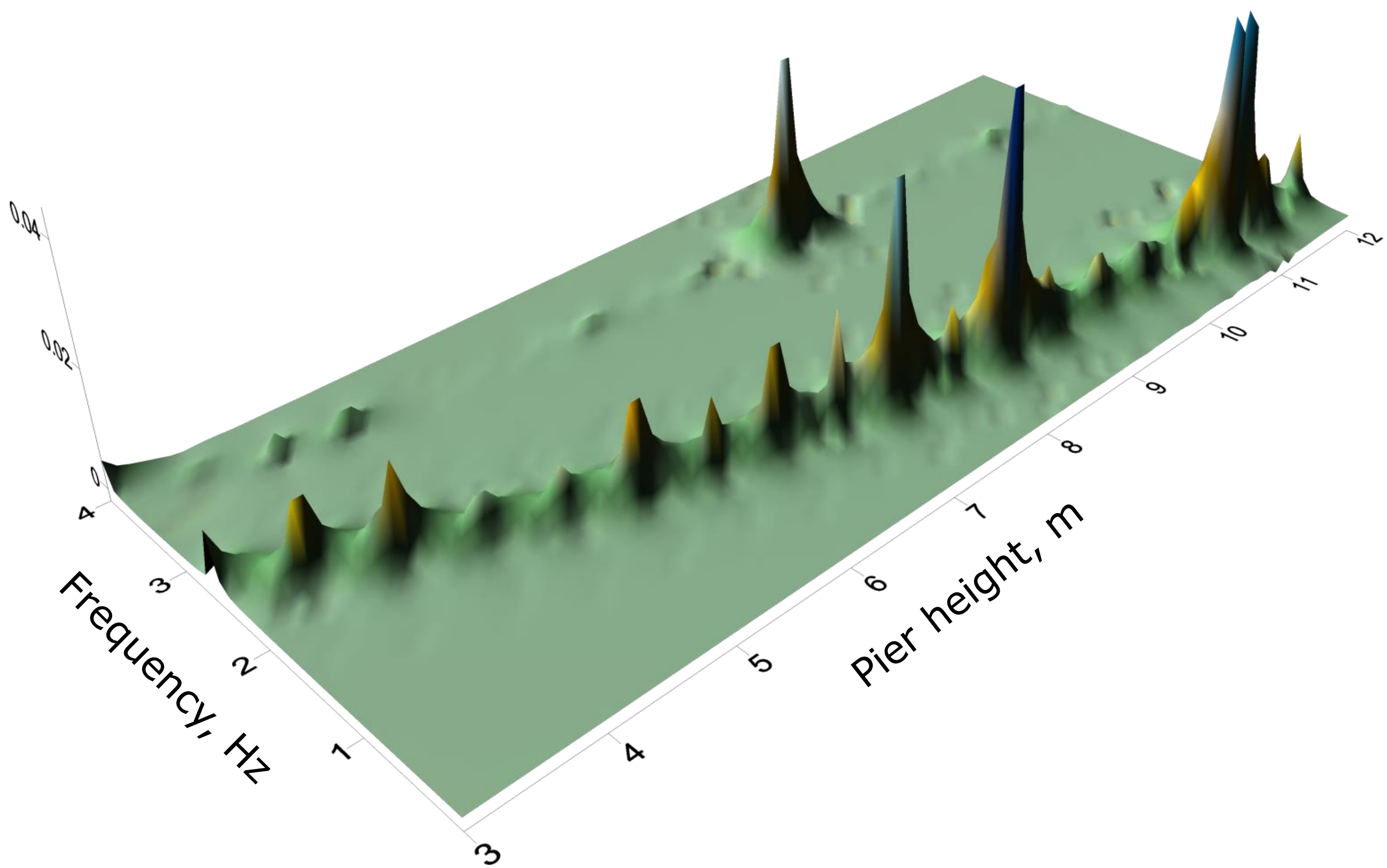


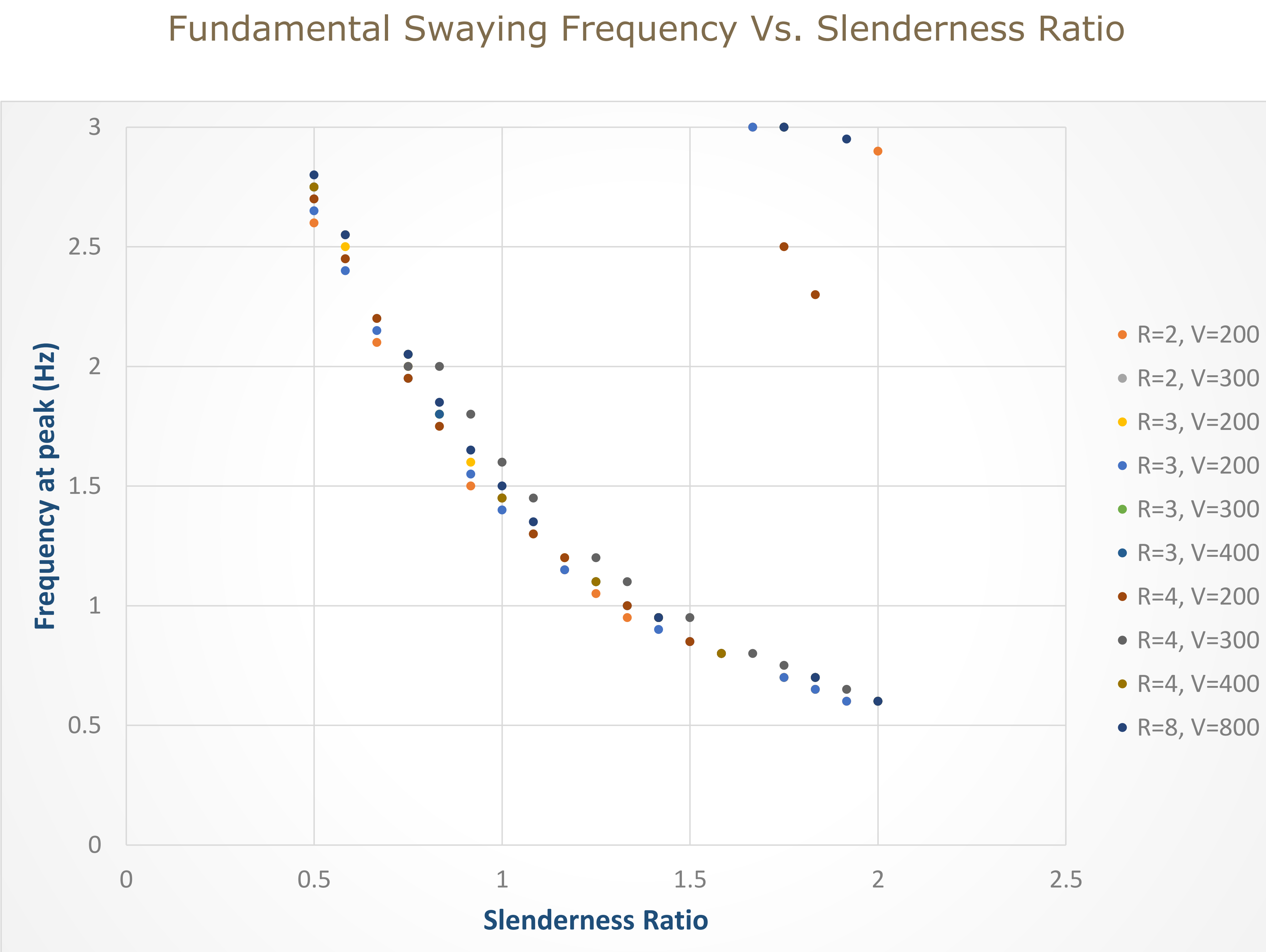


Fundamental Swaying Frequency Vs. Pier Height Rigid Base



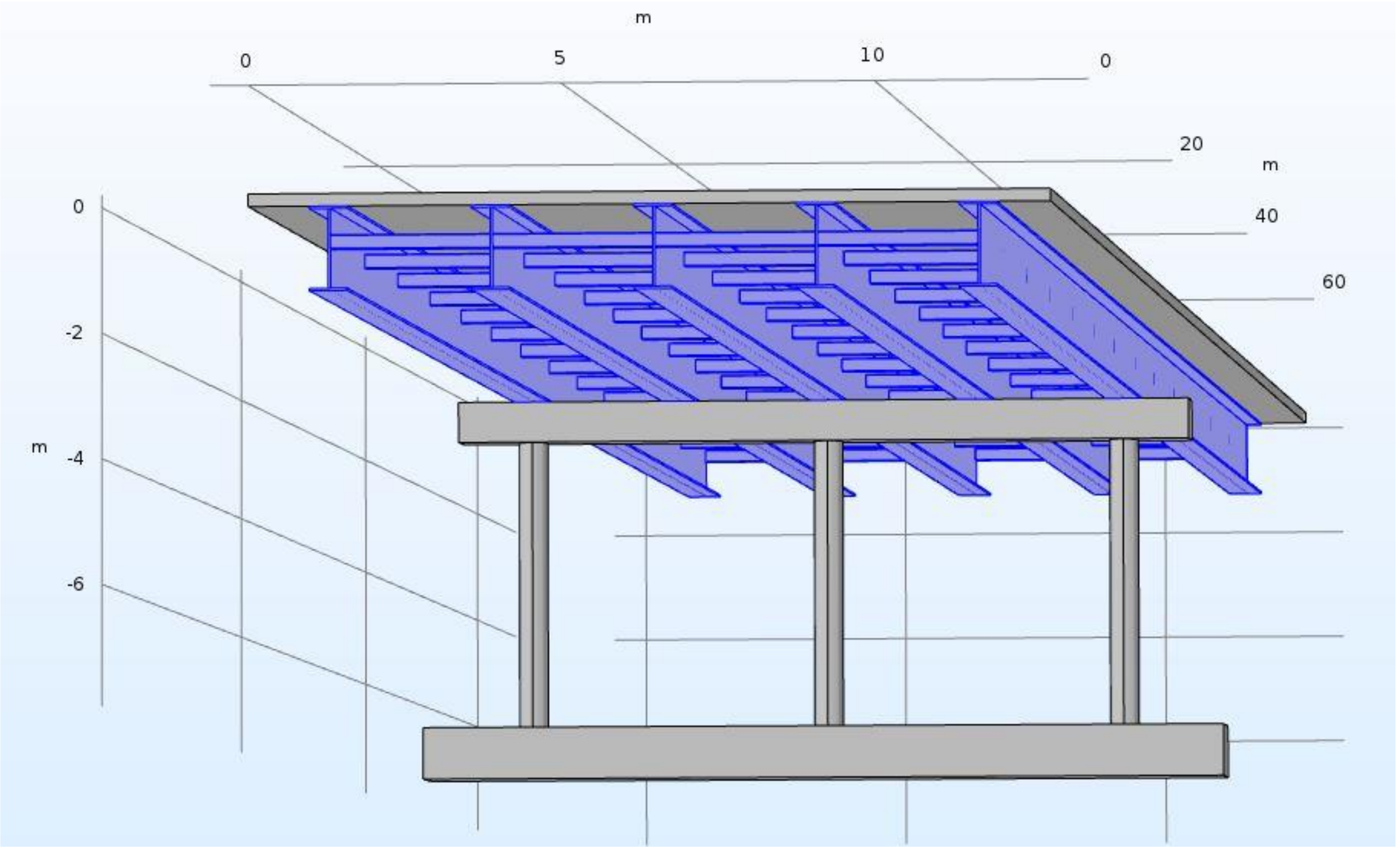
Fundamental Swaying Frequency Vs. Pier Height Flexible Base (R=2 m, V_s=200 m/s)



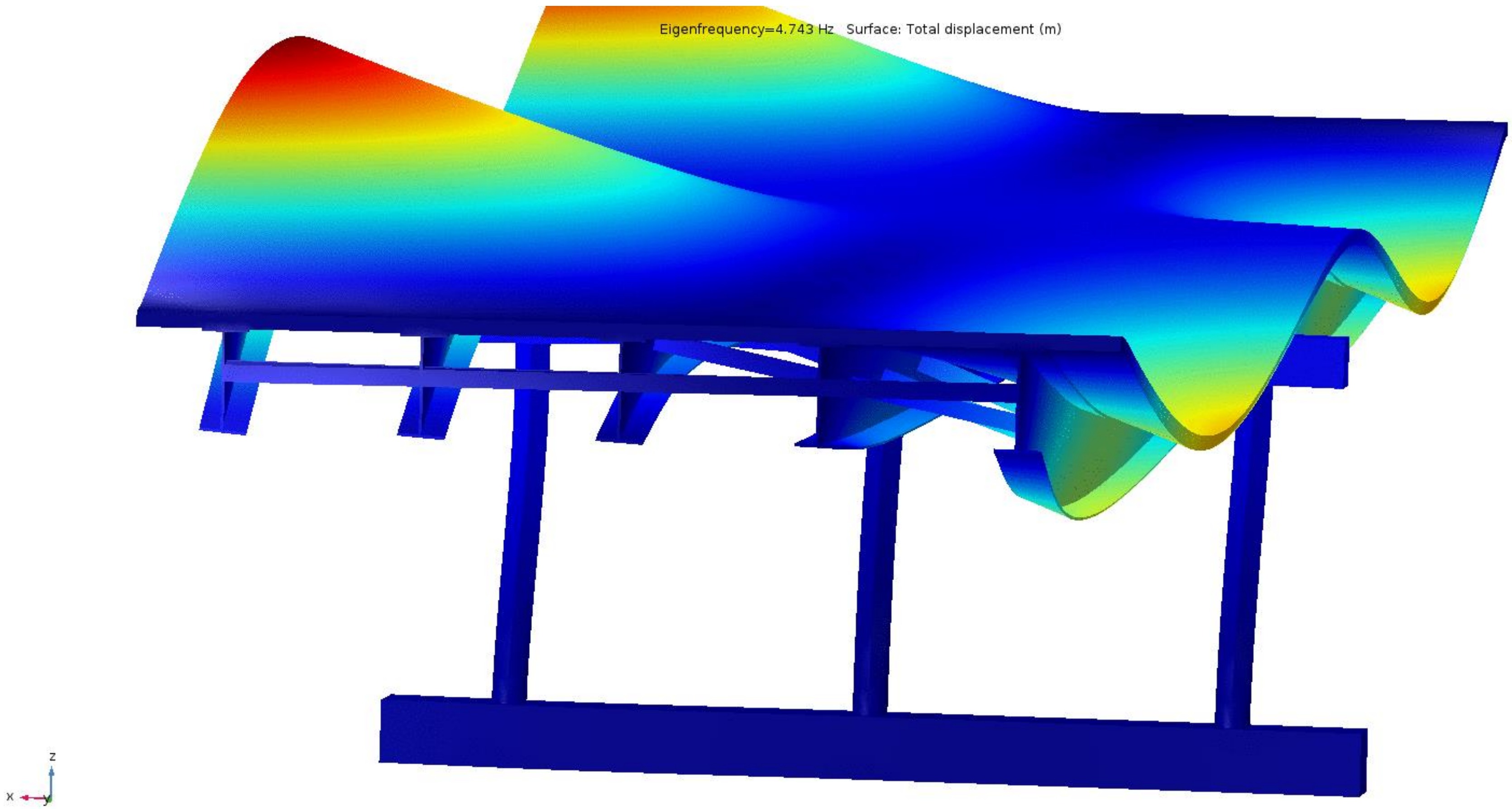


Fundamental Swaying Frequency Vs. Slenderness Ratio
Frequency at peak (Hz)
3
2.5
2
1.5
1
0.5
0
0.5
1
1.5
2
2.5
Slenderness Ratio
R=2, V=200
R=2, V=300
R=3, V=200
R=3, V=200
R=3, V=300
R=3, V=400
R=4, V=200
R=4, V=300
R=4, V=400
R=8, V=800

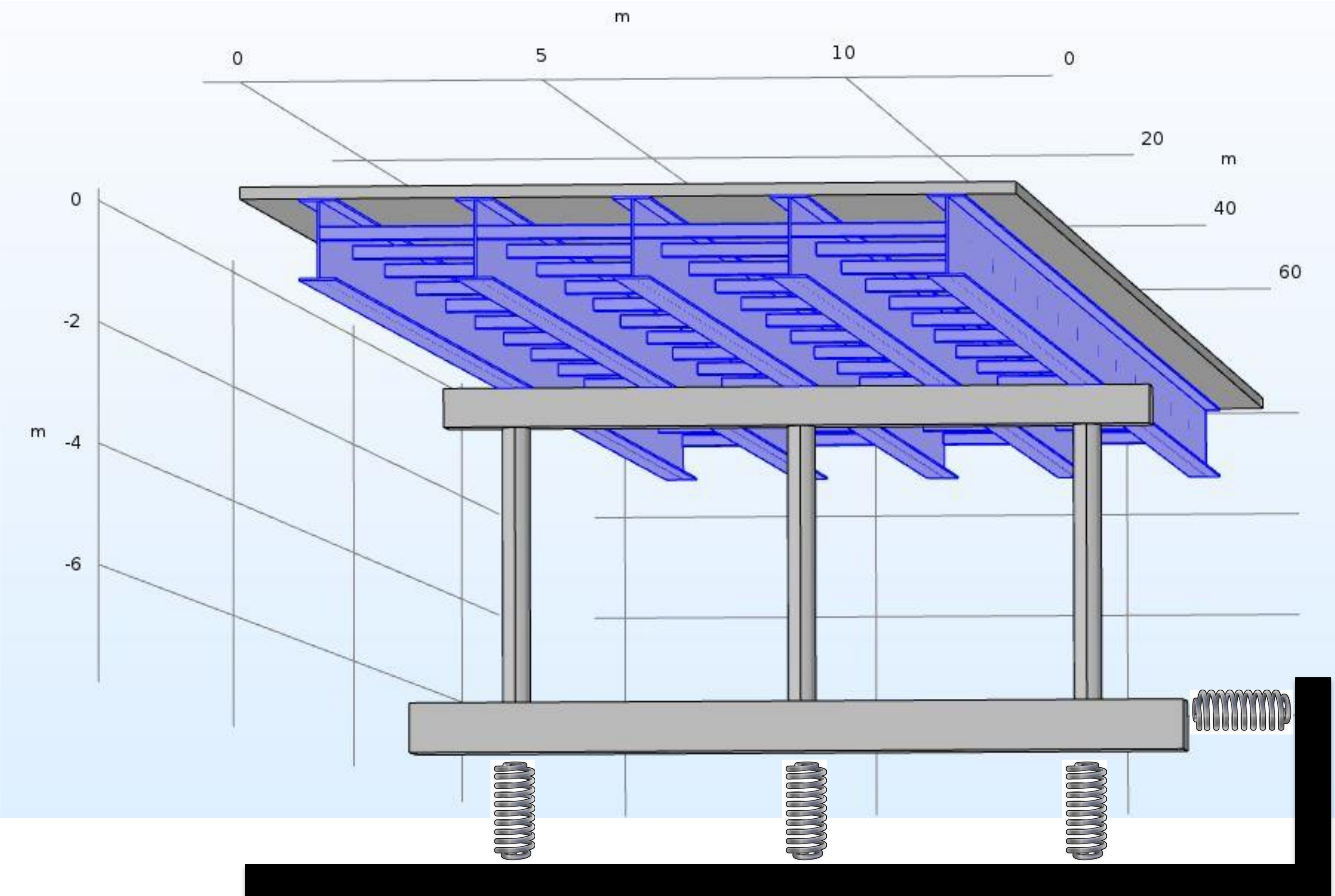
Finite Element Model of Hobson Avenue Bridge



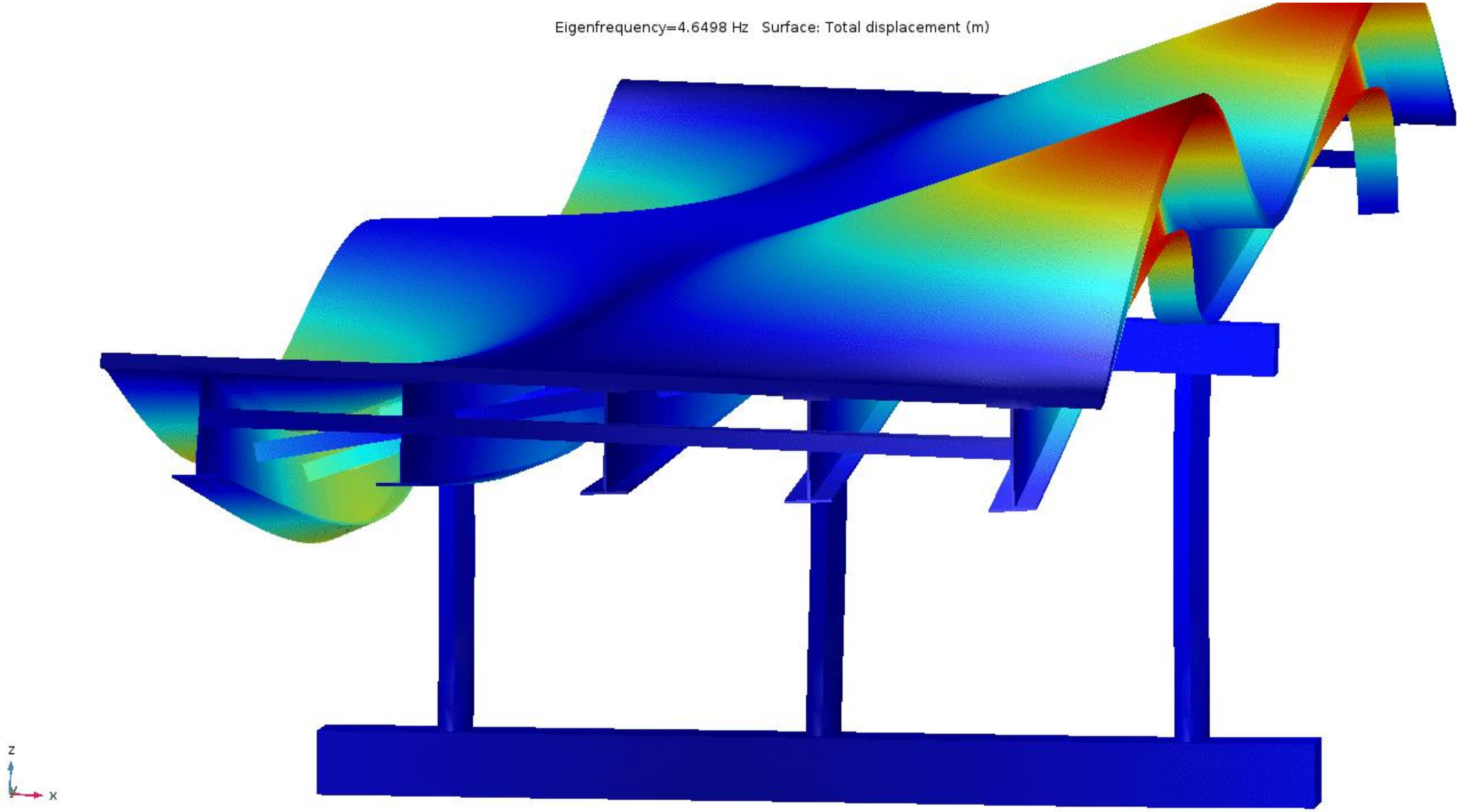
Fundamental Swaying Mode for Rigid Base



Finite Element Model of Hobson Avenue Bridge



Fundamental Swaying Mode for Flexible Base



Field Implementation Using UTA NHERI Mobile Shakers

Field Implementation and Validation

- Objectives :
  - To measure the response of all components: ground, foundation, substructure and superstructure in both vertical and horizontal directions, to infer the contributions of soil-foundation-substructure interaction on the overall response of the superstructure.
  - To enable assessment of transmissibility (motion transfer) and force transfer between superstructure and foundation, and from the foundation to surrounding soil.
  - To enable assessment of foundation impedance functions for both vertical and rocking motion.
- The results will be compared against the models within the parametric study to place the field test in context
- Secondary objective: The results obtained from the bridge excitation using a NHERI shaker (vertical mode only) and THMPER will be compared

Hobson Avenue Bridge over I-195, Hamilton, NJ

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MASW (Multichannel Analysis of Surface Waves) Testing

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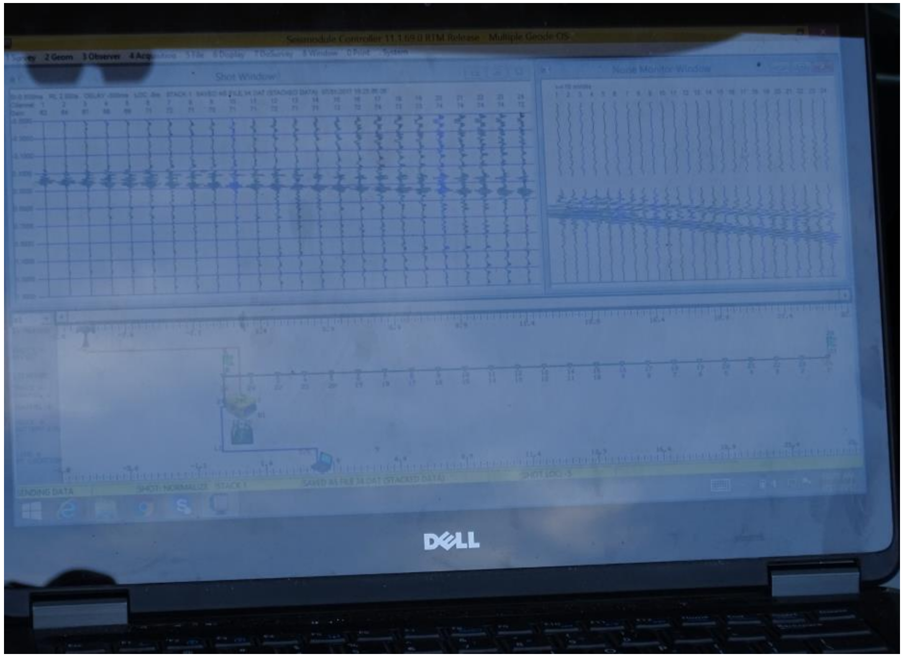


Swaying Test – Center Pier

T-Rex position
Deck Triaxial Accelerometers
Substructure and Ground Triaxial Geophones
Deck Triaxial Geophones

Swaying Test – Middle of South Span

T-Rex position
Deck Triaxial Accelerometers
Substructure and Ground Triaxial Geophones
Deck Triaxial Geophones

Swaying Test – South Abutment

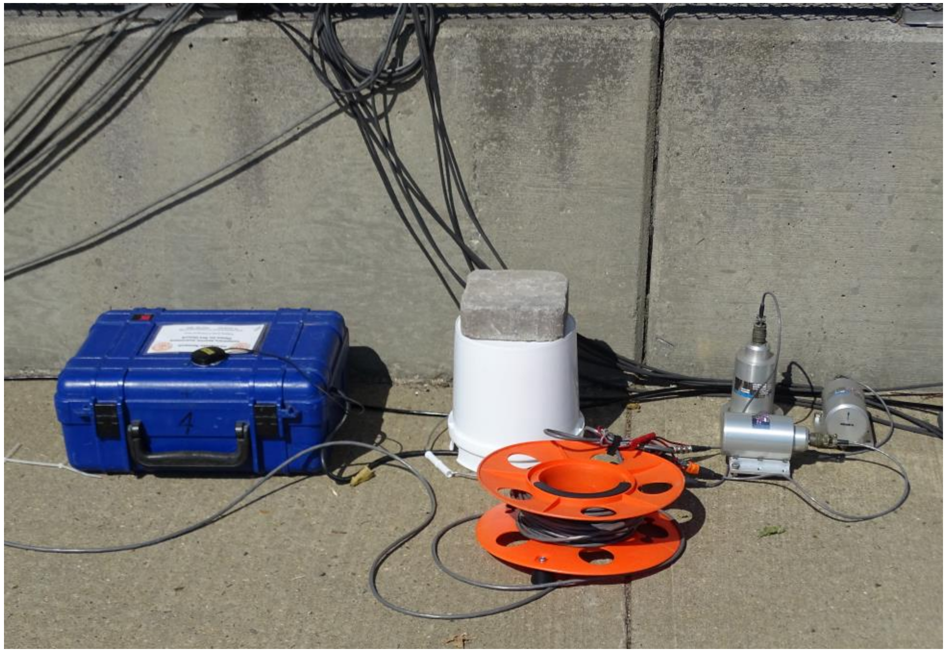
T-Rex position
Deck Triaxial Accelerometers
Substructure and Ground Triaxial Geophones
Deck Triaxial Geophones

T-Rex Mobile Shaker

T-Rex in Position for Testing

T-Rex and THMPER

Geophones and Accelerometers on Bridge Deck



Central Pier

Ground Triaxial Geophone Array

What Are the Questions We Are Trying to Answer?

- Can we infer the contributions of soil-foundation-substructure interaction on the overall response of the superstructure?
- Can we develop data interpretation frameworks for structural system identification and assessment that will take into consideration DSFSI?
- Can large-amplitude, forced vibration testing using NHERI shakers (in a fully controlled manner) reveal the performance of structures beyond operational limit states? Are we entering a nonlinear range?

Acknowledgements

- NSF EAGER– Project support through Award Id. 1650170 (Program officer: Dr. Richard J. Fragaszy)
- NSF NHERI (Natural Hazards Engineering Research Infrastructure) – Provided access to UTA NHERI mobile shakers
- NJDOT – Support in bridge selection, and providing documentation and access to Hobson Avenue Bridge (Mr. Eddy Germain)
- UTA NHERI team


Thank You
NEES@UTexas