Development of Nonlinear SSI Time Domain Methodology

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  - Mike Salmon
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Presentation Goals

- Present the need for nonlinear soil-structure interaction (NLSSI) analysis
- Discuss development of a nonlinear seismic soil-structure interaction (NLSSI) methodology
- Discuss future NLSSI development needs

What is the Need?

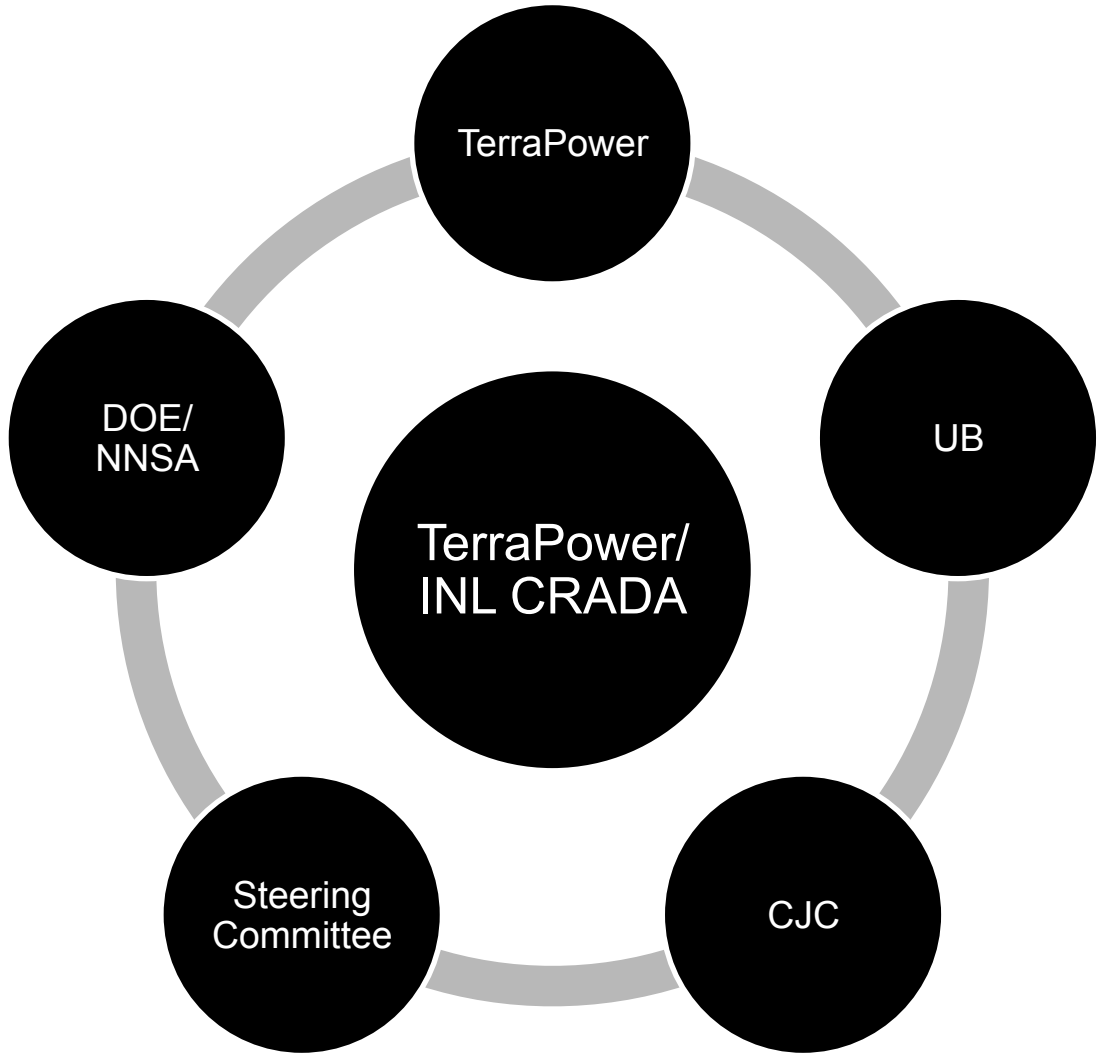
	KK 2007	Fukushima 2011	North Anna 2011
Design Value (g)	0.20	0.26 (Original) 0.45 (Update)	0.18
Recorded Value (g)	0.32	0.56	0.26

- The estimated hazard has recently been exceeded at Nuclear Power Plants
- Uncertainty associated with seismic hazard
- NLSSI needed to capture nonlinear behavior during larger earthquakes
  - Gapping and Sliding
  - Material Nonlinearity

All Exceeded Design Basis Earthquake

Managing Uncertainties is a desirable goal

NLSSI Project Team

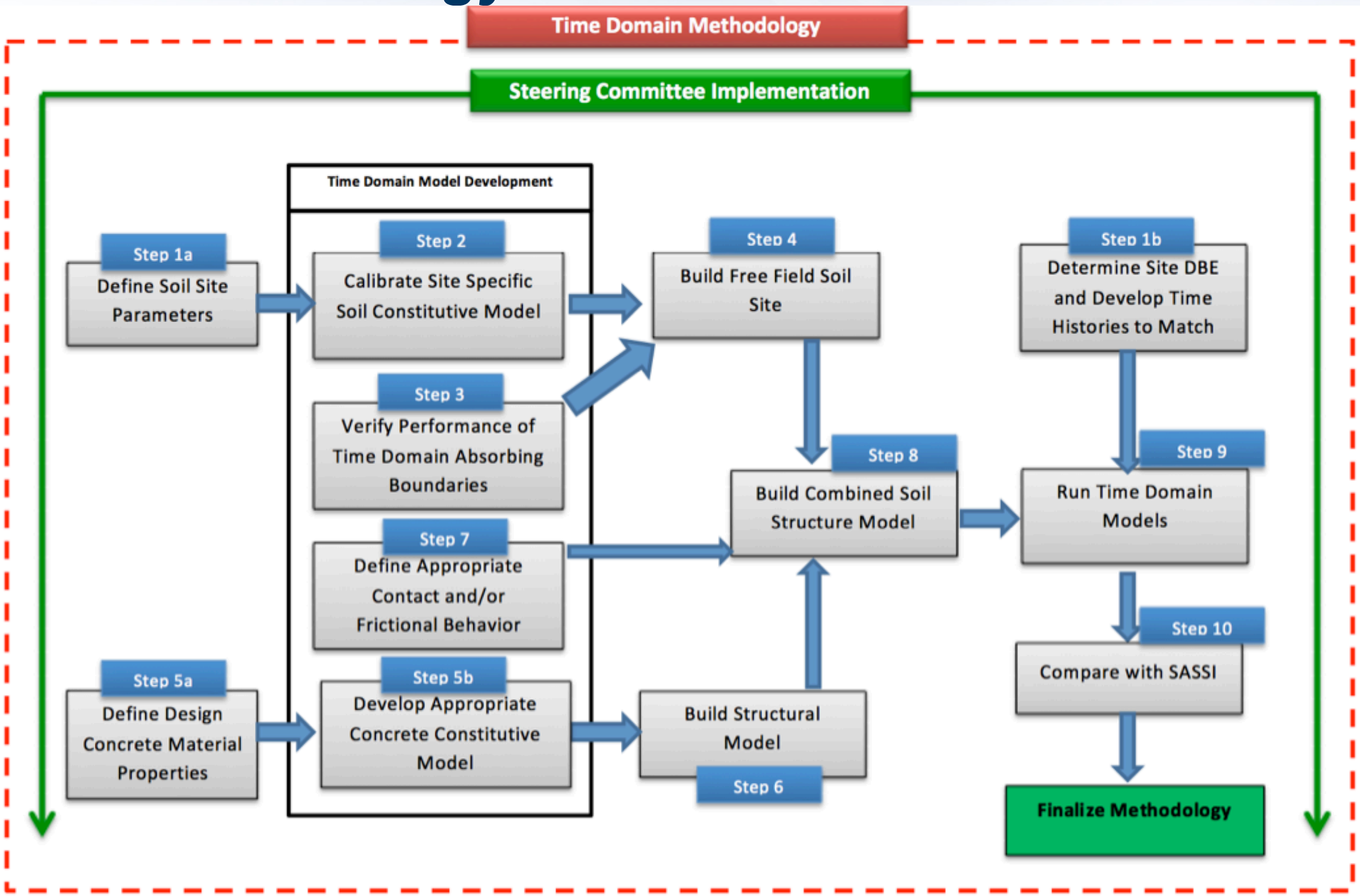


Success achieved by building a team of individuals from different technical backgrounds to guide the process

NLSSI Project Achievements

- Initiated development of NLSSI methodology
- Focused on geometric nonlinear effects of gapping and sliding on in-structure response for increasing levels of earthquake ground motion.
- Demonstrated an approach for calibrating a nonlinear soil constitutive model to recover the free field site response from an equivalent linear code at low levels of soil shear strain.
- Provided a method for identifying the size of a soil-structure model to sufficiently minimize the effect of reflection of radiation waves from soil boundaries.
- Compared results of analysis using a recently verified and validated version of SASSI with those from a NLSSI code using increasing levels of earthquake ground motion.
- Documents an approach for converting rock outcrop time histories to force time histories that are applied in-layer at the top of rock.
- Identifies issues related to the use of piecewise linear hysteresis loops and the generation of artificial high frequency noise in in-structure response.

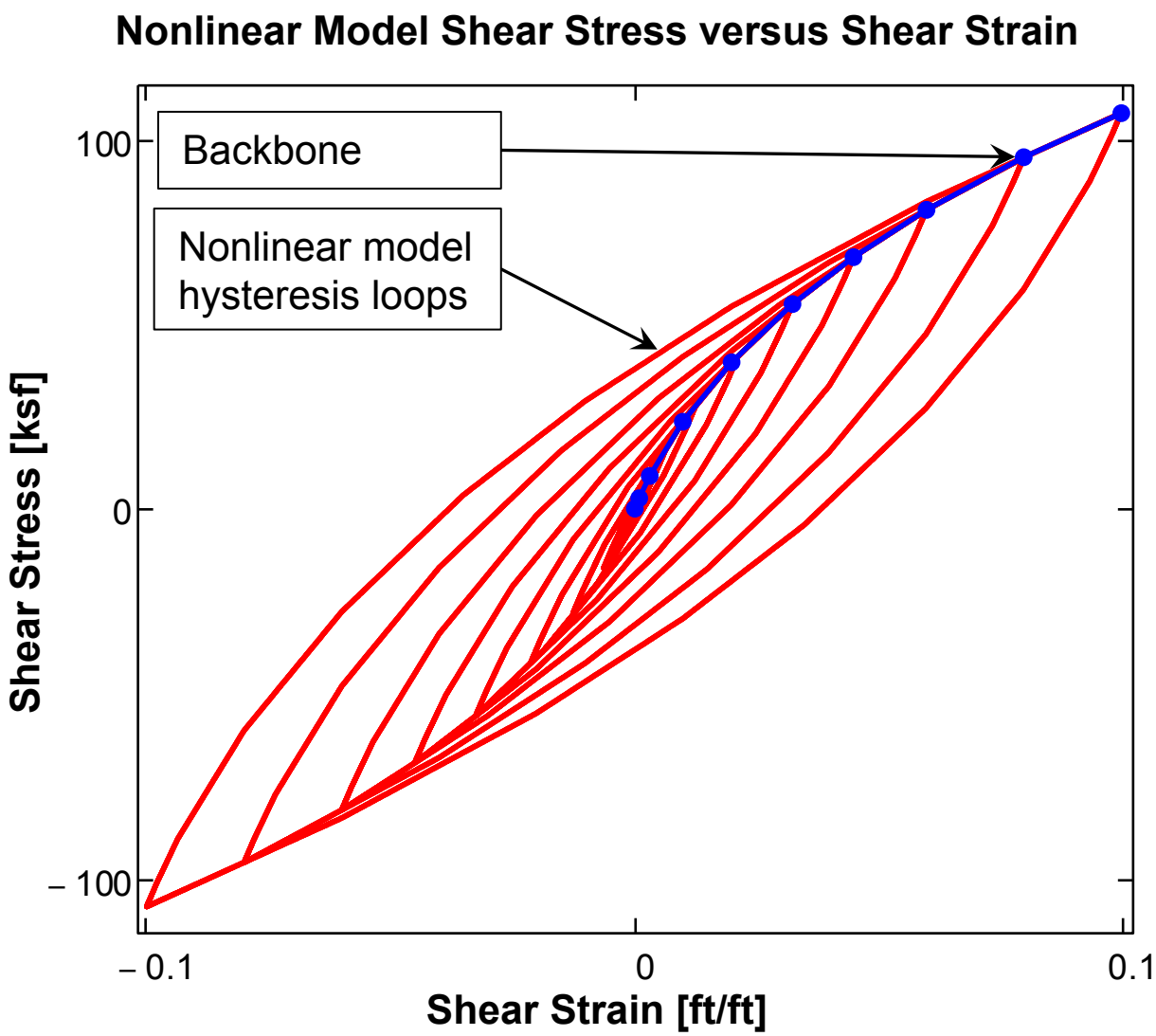
NLSSI Methodology

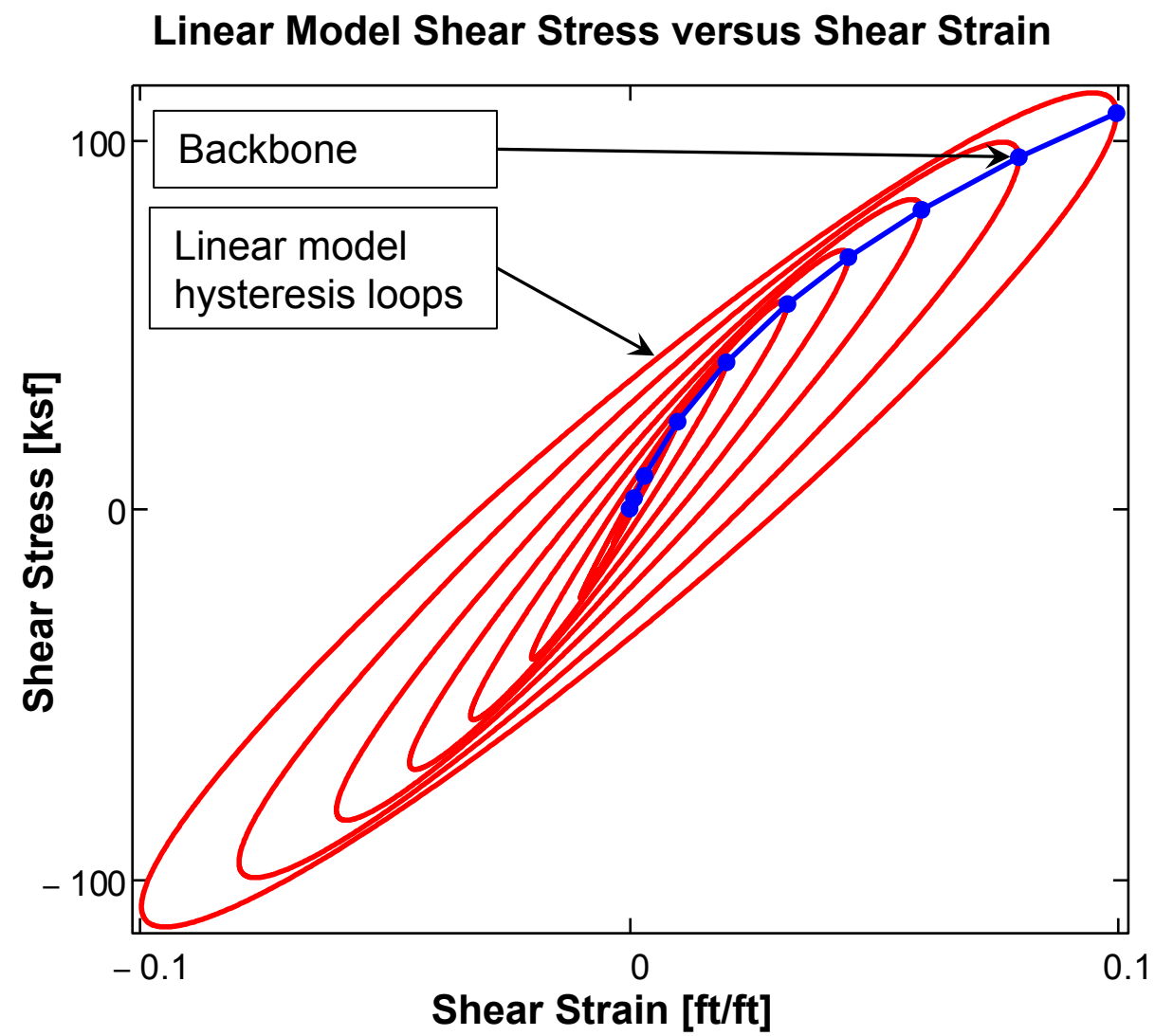


Nonlinear Soil Constitutive Model

- LS-DYNA and ABAQUS have kinematic hardening constitutive soil models that address hysteretic behavior in soil.
- The hysteretic behavior is dictated by post yielding stress versus strain (at a given hydrostatic pressure)
- The yielding and the stress versus strain data vary with changes in hydrostatic pressure (if desired)
- Other soil parameters are also available such as yield function constants, dilation parameters, cut-off pressure, and an exponent for bulk modulus pressure sensitivity (the z-direction must be vertical for these to work correctly)
- This constitutive model is of a form that includes the Drucker-Prager model and is reasonable for nonlinear soil behavior

Hysteresis Loop Comparison for the Nonlinear and Linear Models





The Hysteresis loops above produce the same peak shear stress and the same absorbed energy per cycle for each data point on the backbone curve.

Soil Column Comparison between SHAKE and NLSSI

Both Models

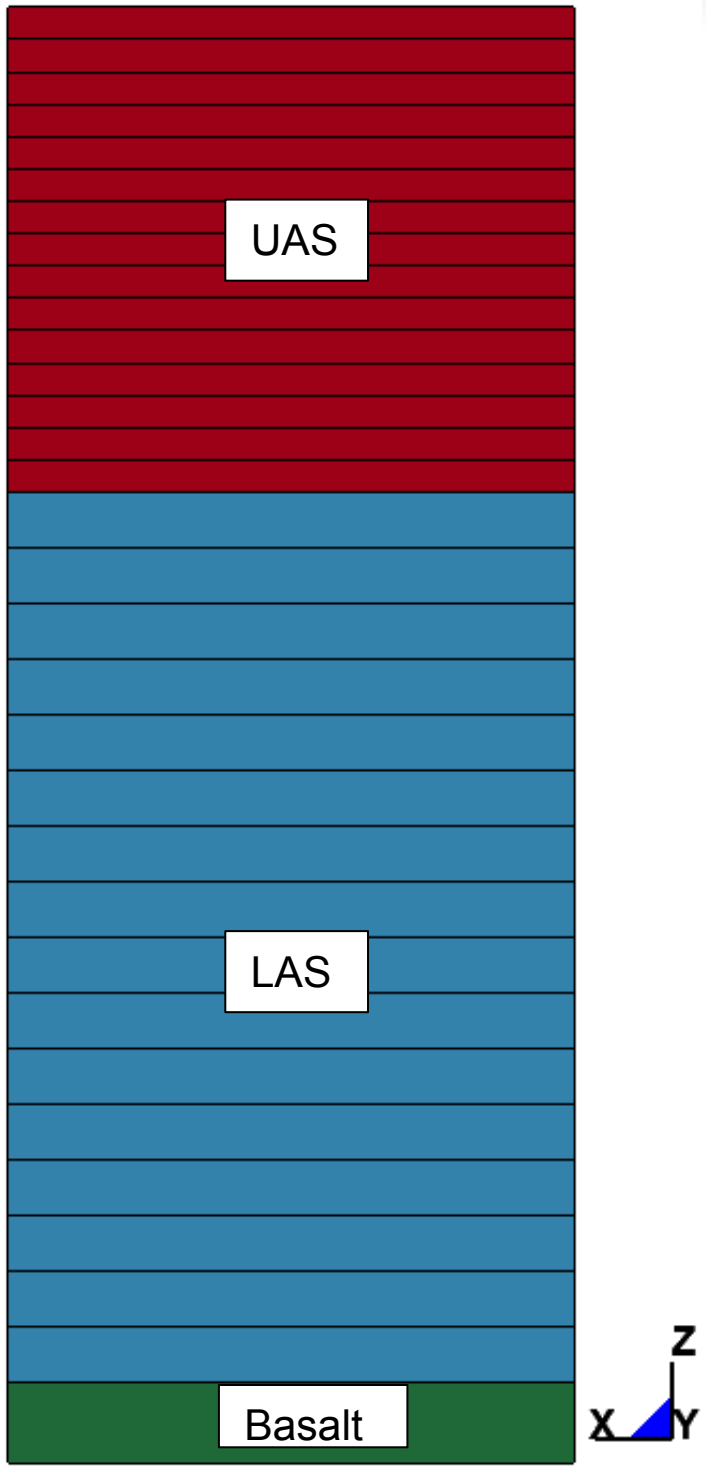
- Include 30 feet of UAS, 55 feet of LAS (modeled using nonlinear hysteretic soil constitutive model), and 5 feet of basalt (modeled as linear with one element/layer)
- Have a rock outcrop time history applied to the top of the basalt and a free boundary condition applied to the top surface of the model

Linear SHAKE Model

- Performed iteratively with a ratio of equivalent uniform strain divided by maximum strain of 0.65
- Uses an acceleration time history as input

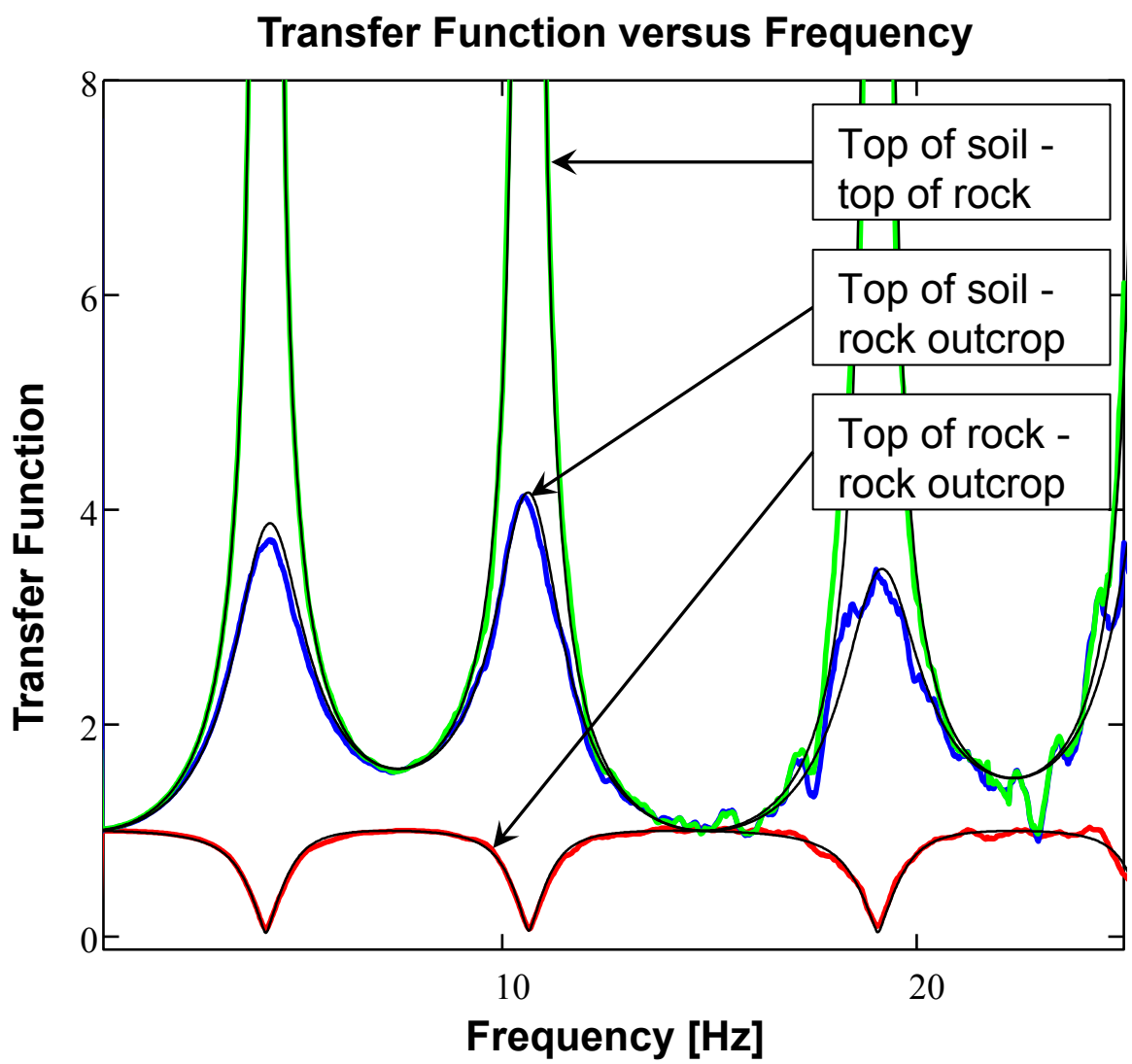
Nonlinear LS-DYNA Model

- Has non-reflective boundary conditions defined at the bottom of the basalt
- Uses a load time history as input

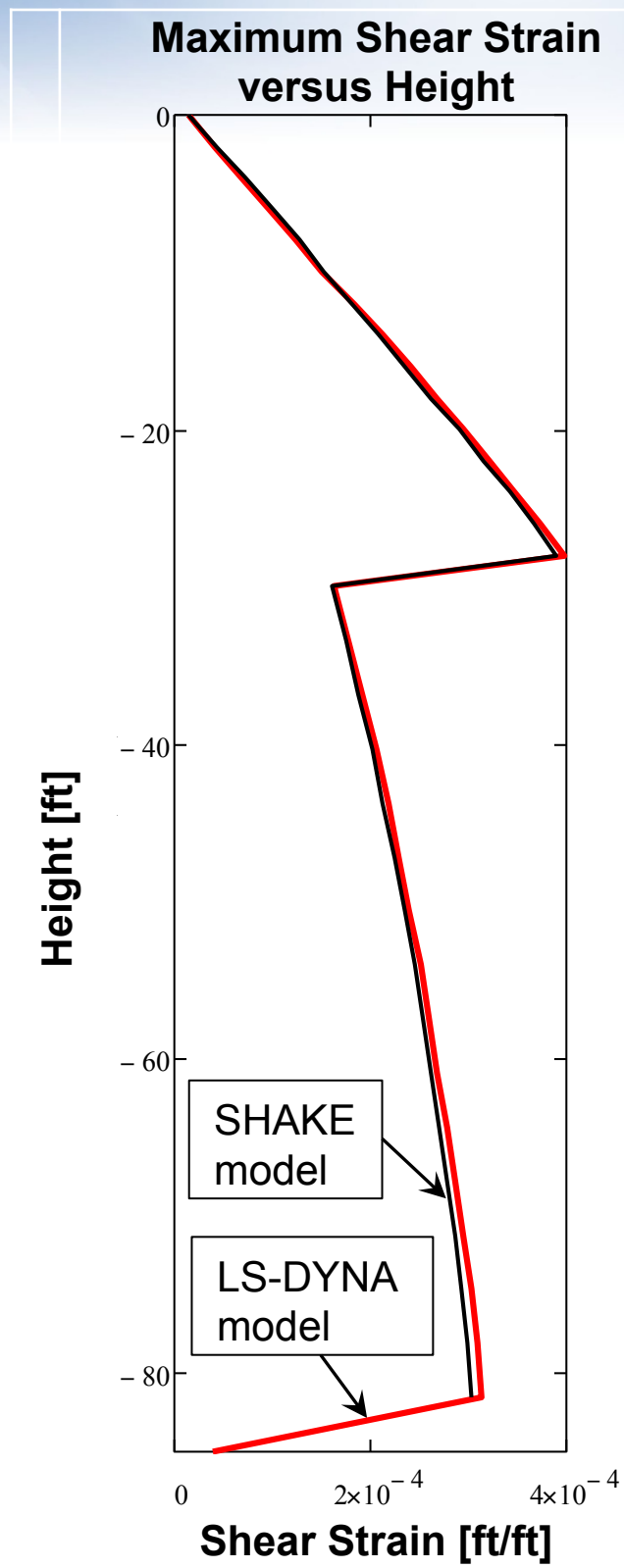


$$\sigma = E\cdot\varepsilon \implies \frac{P(t)}{A} = E\cdot\frac{v(t)}{c} = E\cdot\frac{v(t)}{\sqrt{\frac{E}{\rho}}} = \sqrt{E\cdot\rho}\cdot v(t) \implies P(t) = A\cdot\sqrt{E\cdot\rho}\cdot v(t)$$

Soil Column Comparison between SHAKE and NLSSI

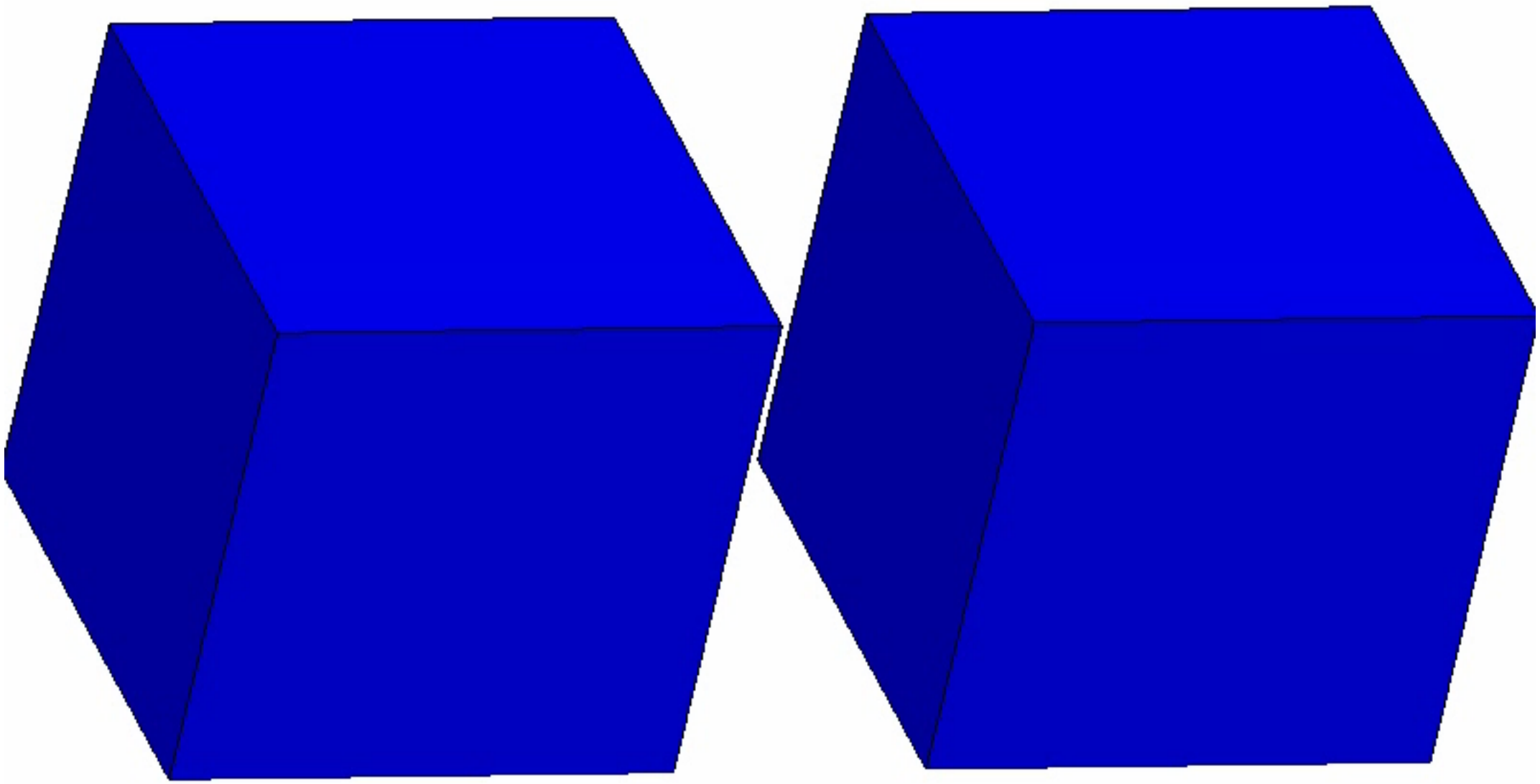


The colored curves above are 0.5 Hz averaged LS-DYNA data. The similar shaped black curves are SHAKE data.



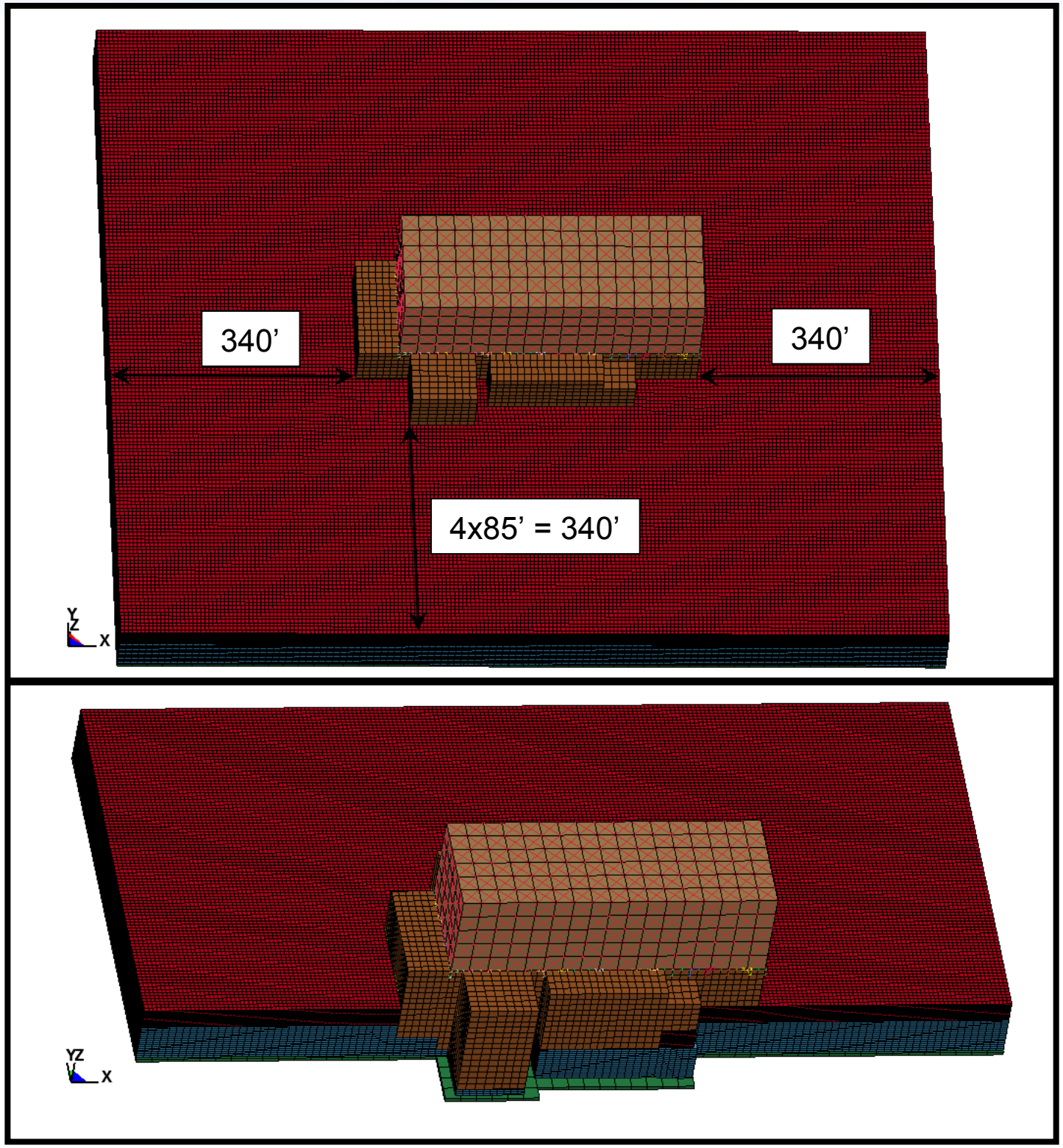
Absorbing Boundary Condition Demonstration

- Both models have: Vertical motion applied to upper left corner, Symmetry restraints on back and left sides and no boundary condition on the top
- Right model has non-reflective boundary conditions on the right, front, and bottom sides
- Left model these sides are fixed



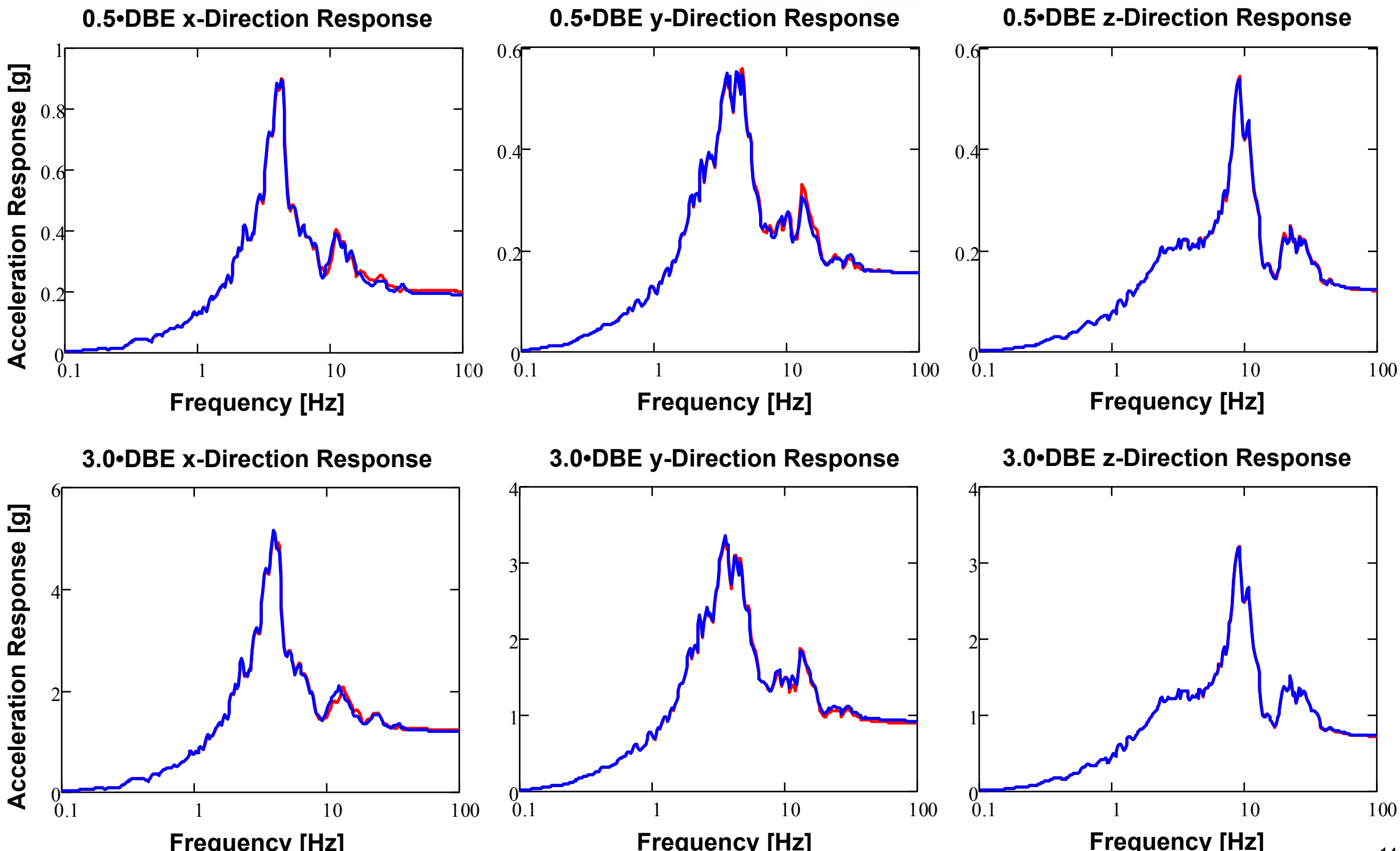
NLSSI Constraint Verification

- Seismic input at the top of the rock including two shearing and one compressive
- Non-reflecting boundary conditions at bottom of rock and free boundary conditions at the top
- Constrained boundary conditions at the sides on each layer of nodes
- Elastic material properties for the structure
- Tied contact attaching soil layers
- Penalty contact defined between the soil and structure of other model runs

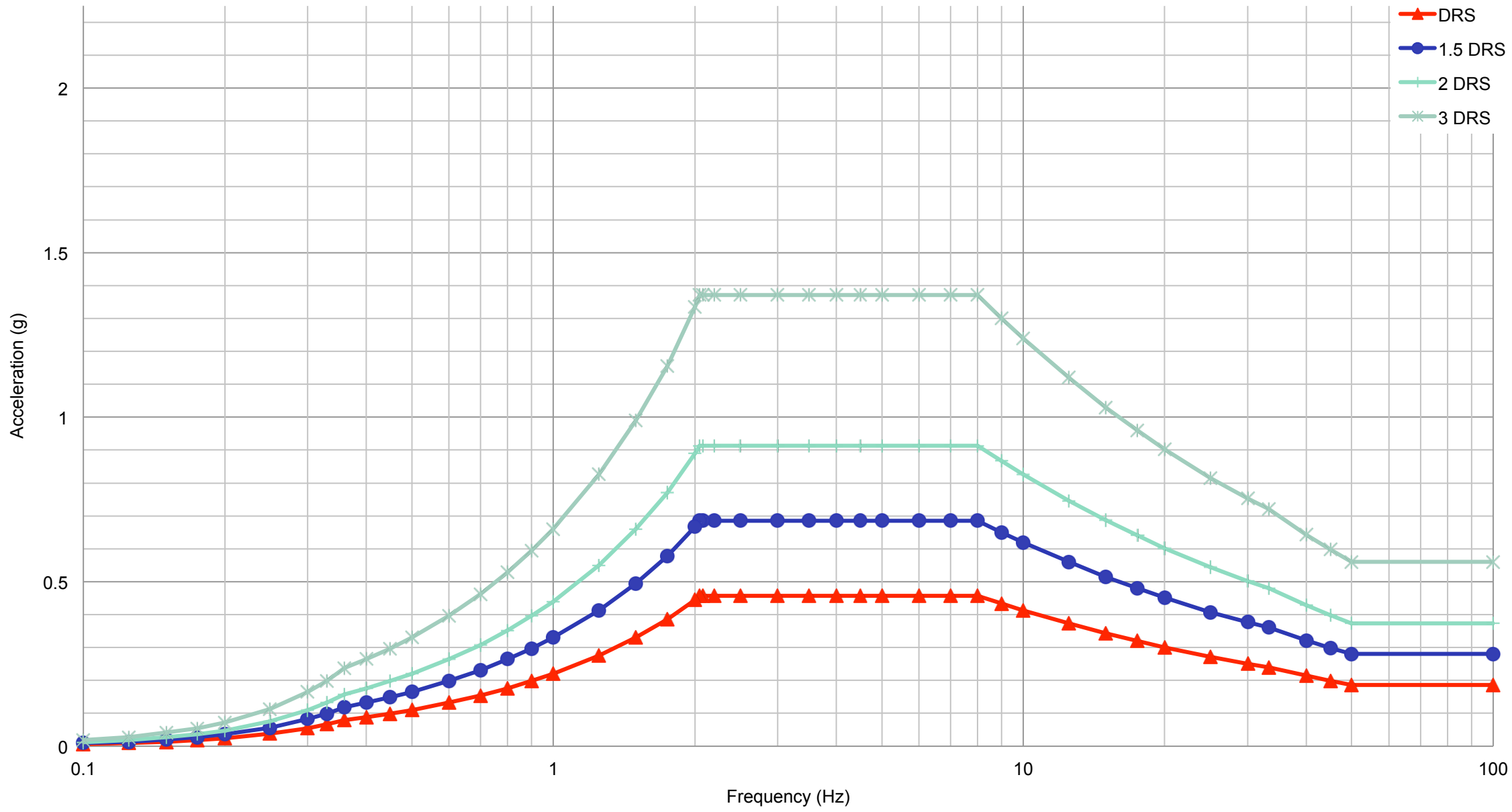


Response Spectra Comparison (Node 1)

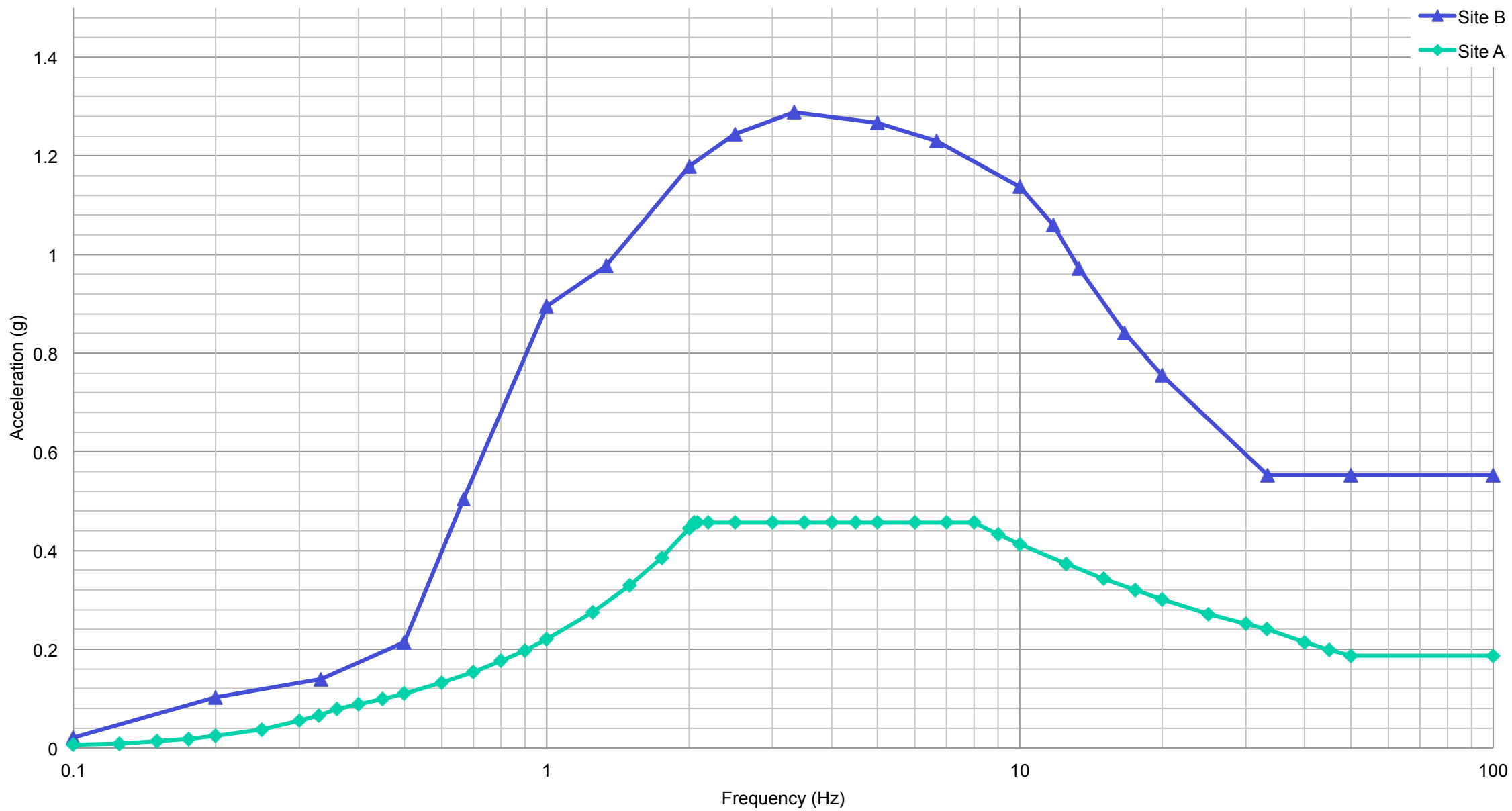
- 4x Model
- 3x Model



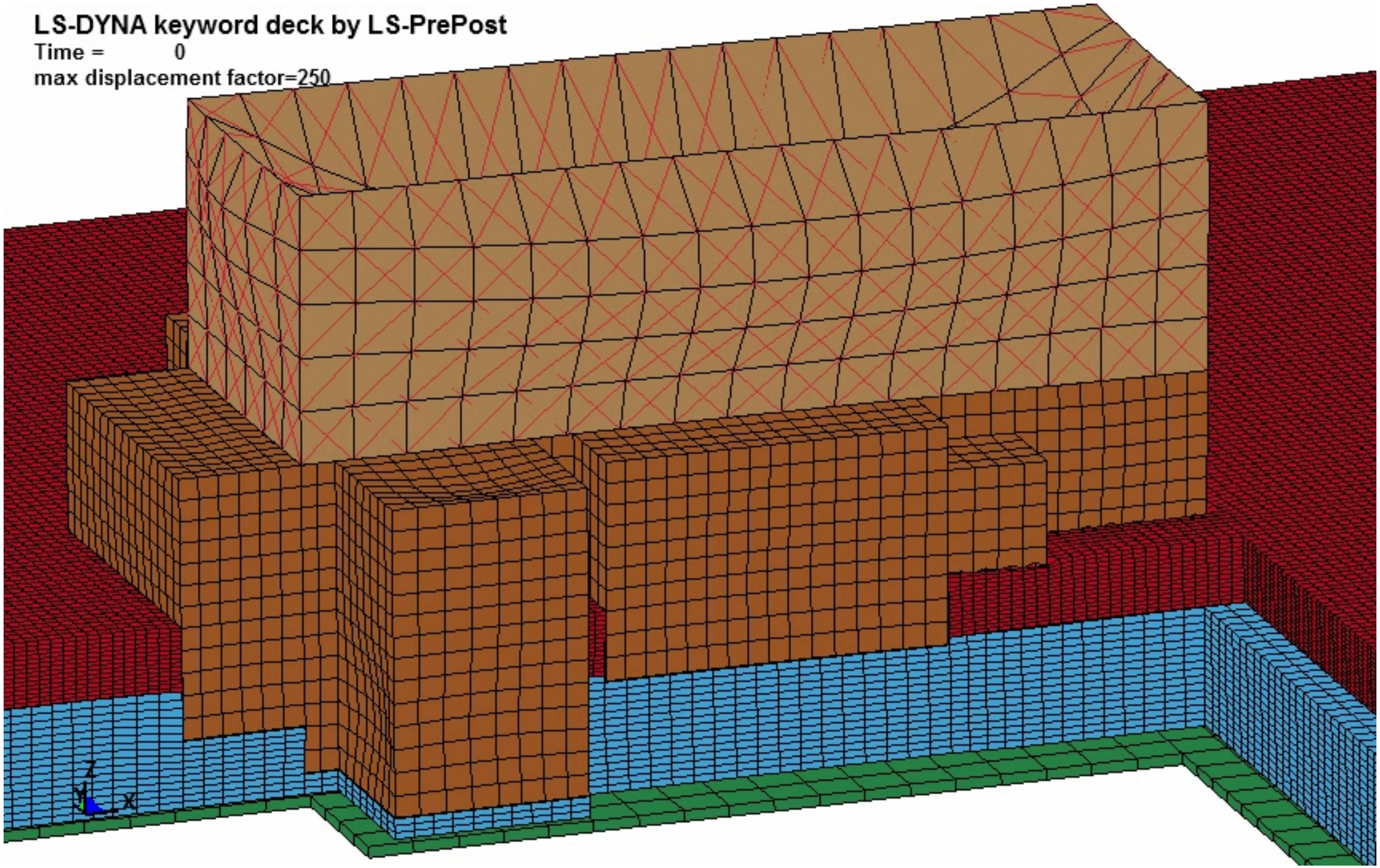
INL DRS used to Define Input Motion



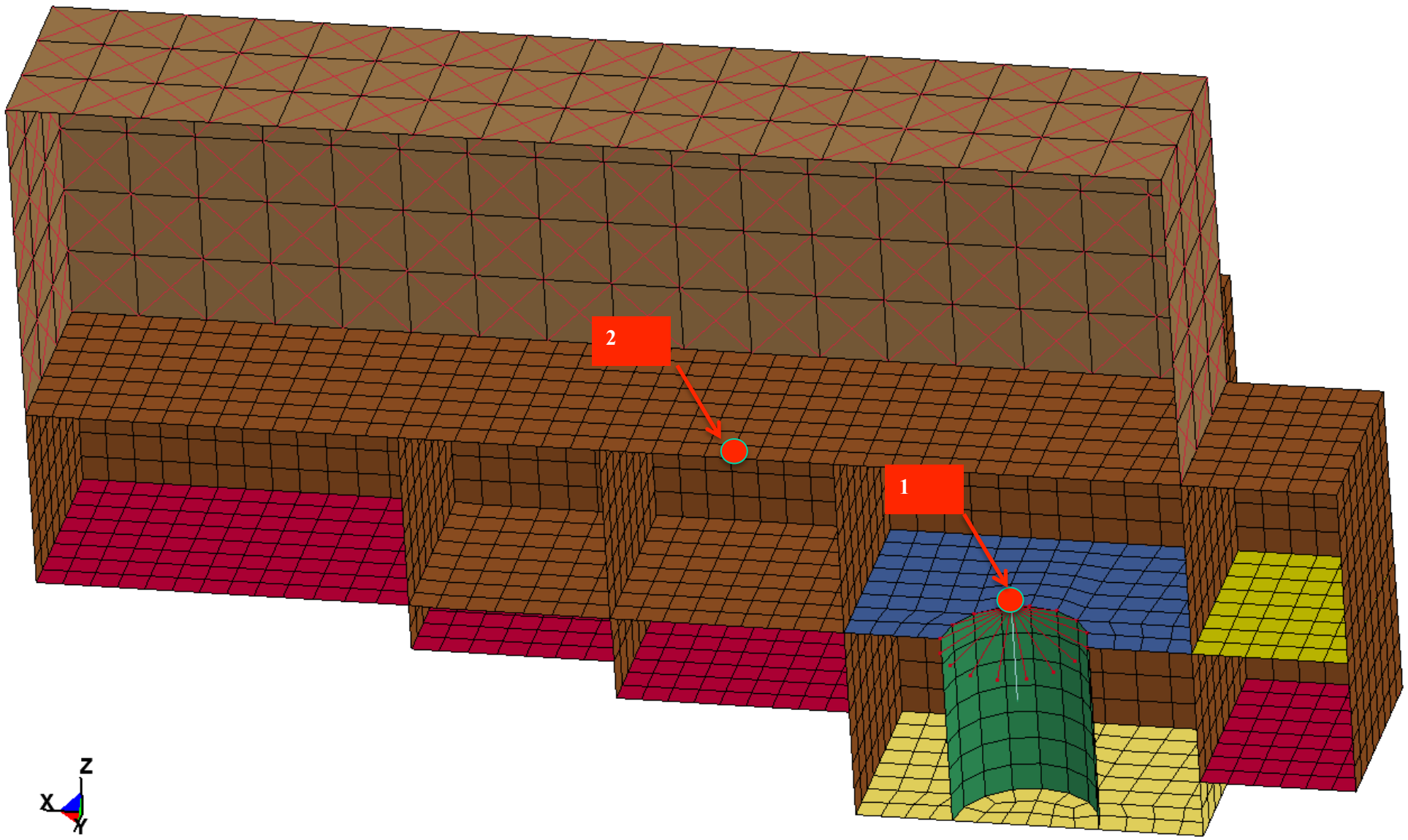
INL 10,000 Year DRS Compared to LANL 2,500



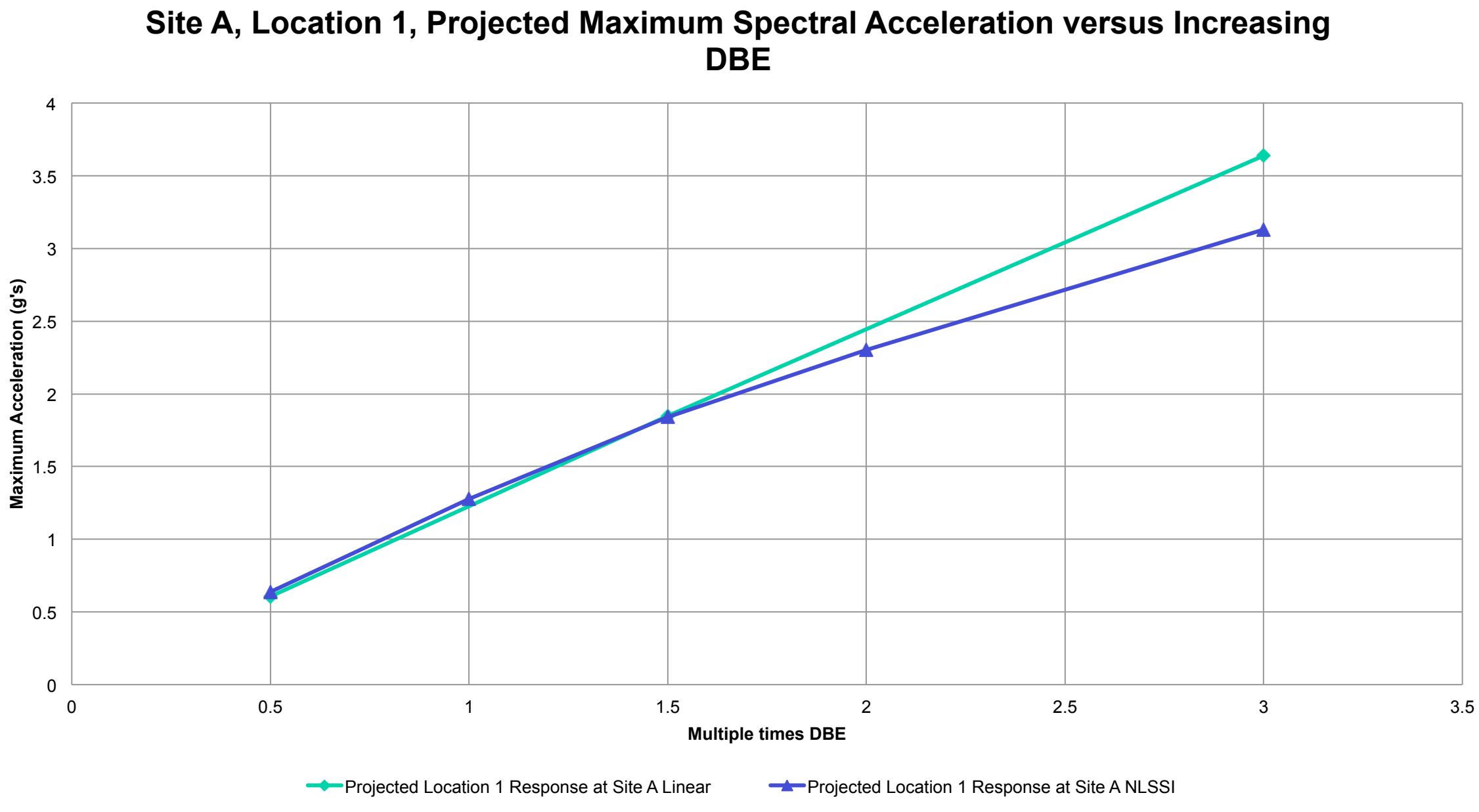
Nonlinear Soil-Structure Interaction Animation



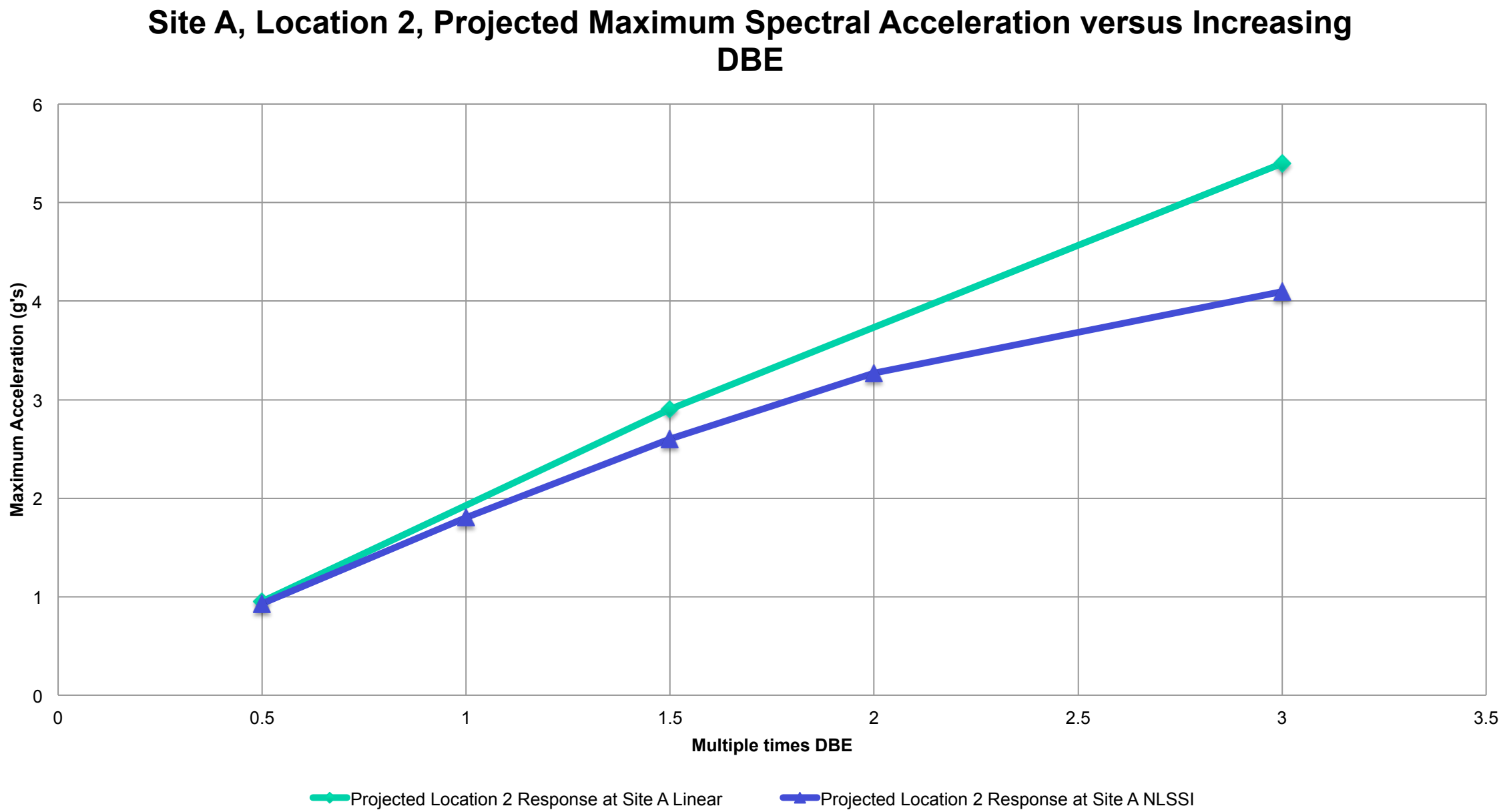
NLSSI Results at Two Locations



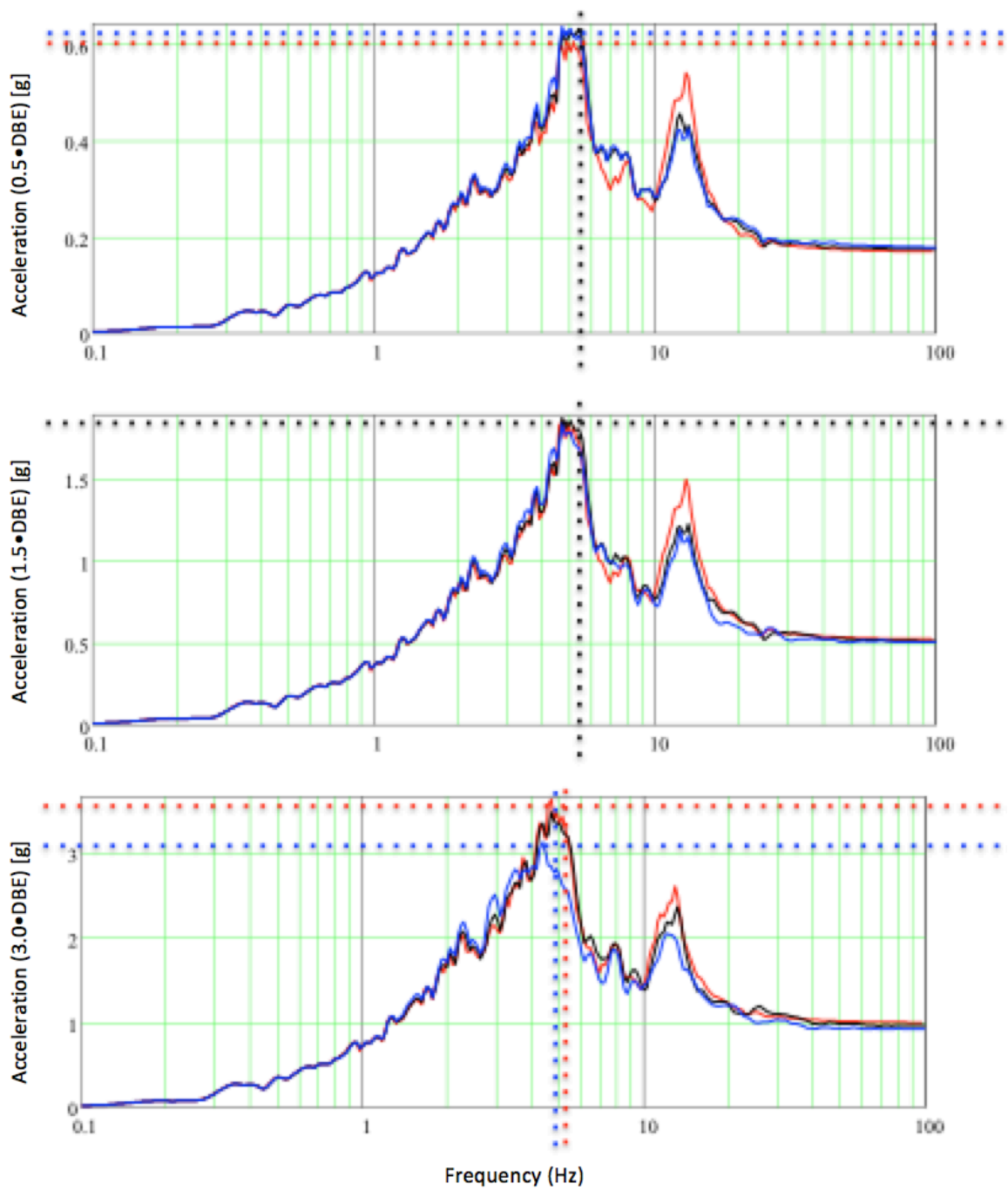
Location 1 Results



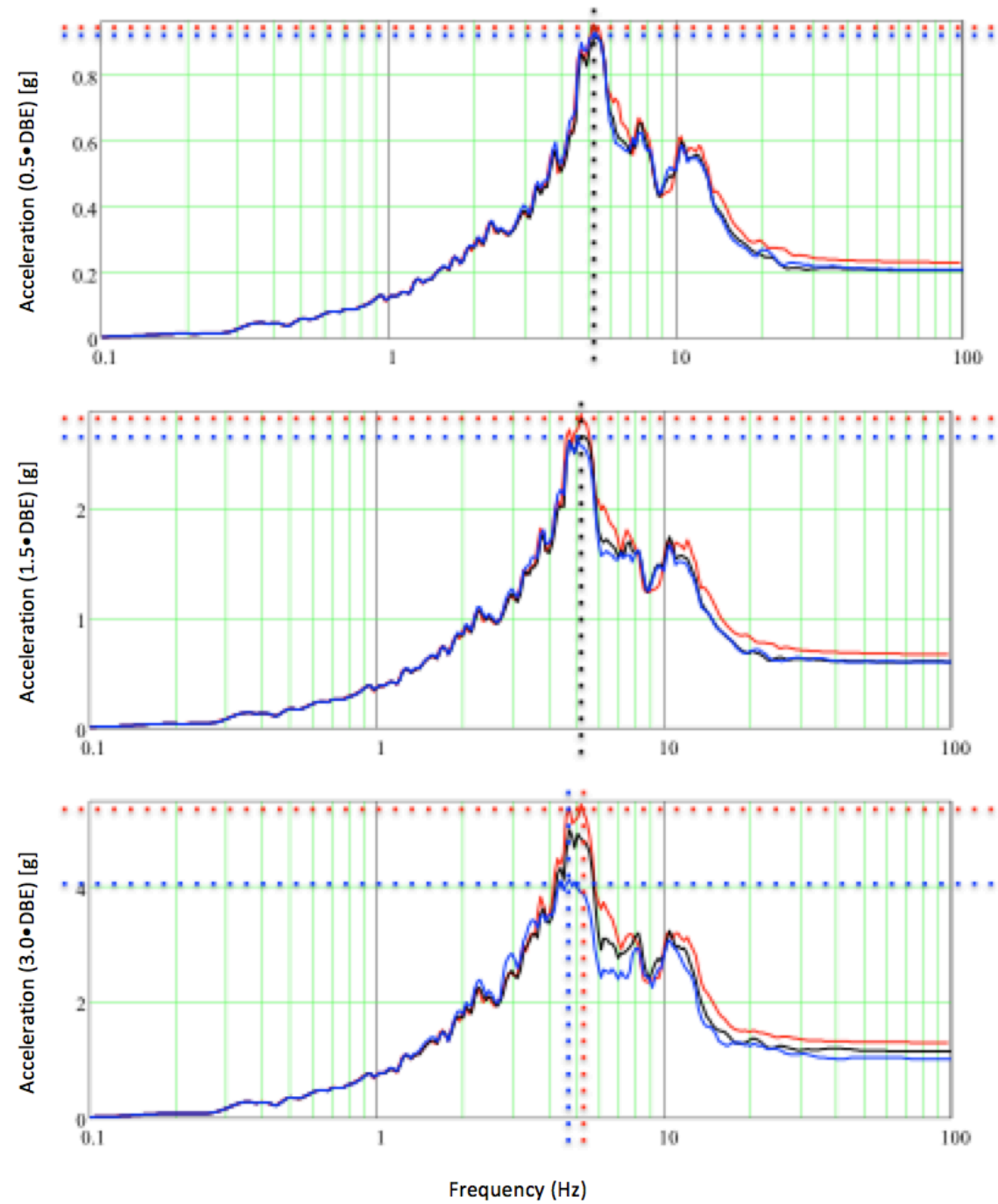
Location 2 Results



Locations 1 and 2 ISRS

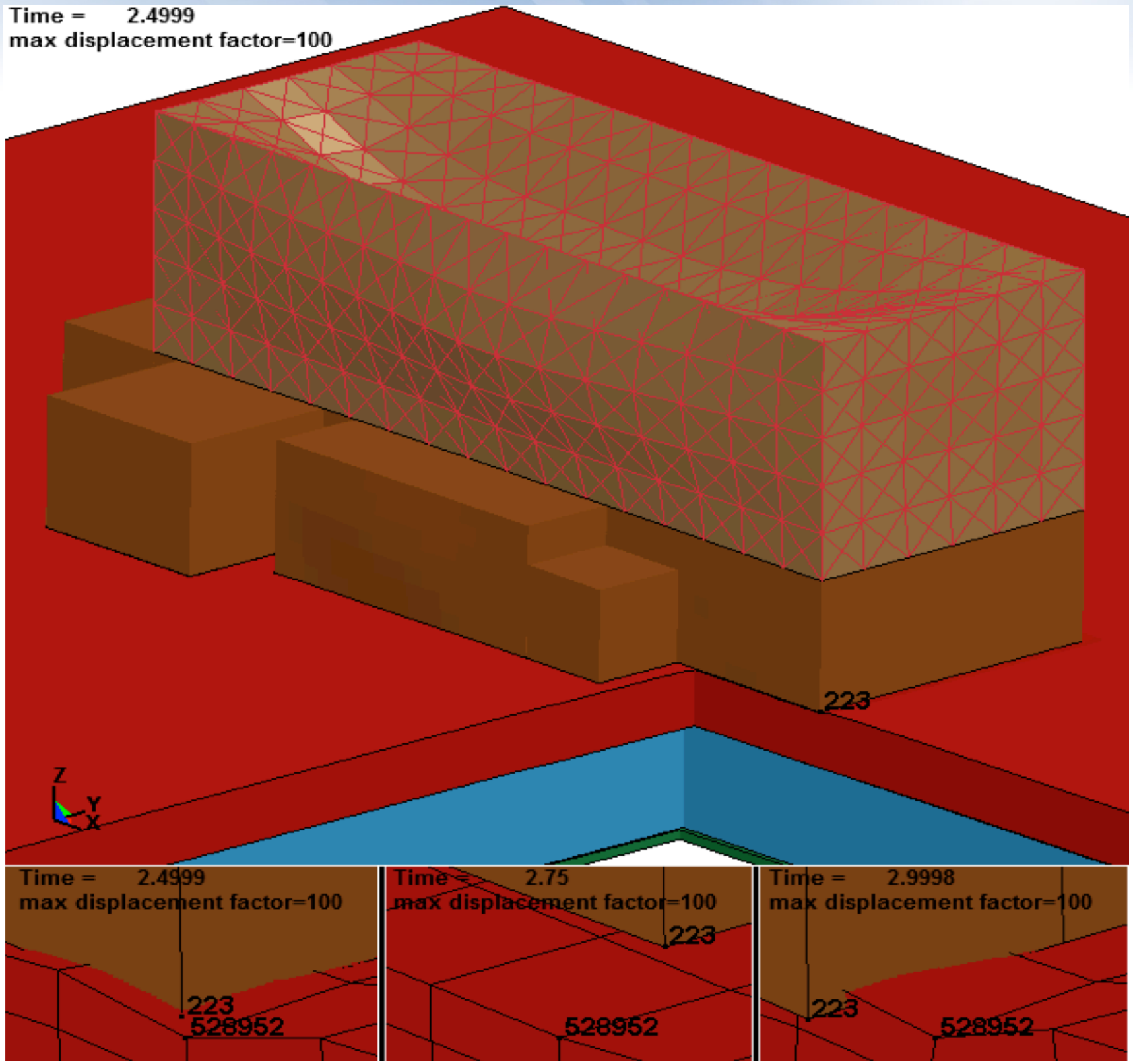


Location 1



Location 2

What is the NLSSI Effect that Causes Reduction?



NLSSI Project Achievements

- Assembled a diverse team to accomplish project
- Developed a methodology for NLSSI analysis
- Focuses on geometric nonlinear effects of gapping and sliding on in-structure response for increasing levels of earthquake ground motion.
- Demonstrated an approach for calibrating a nonlinear soil constitutive model
- Provided a method for identifying the size of a soil-structure model to sufficiently minimize the effect of reflection of radiation waves from soil boundaries.
- Compared results of analysis using a recently verified and validated version of SASSI with those from a NLSSI code using increasing levels of earthquake ground motion.
- Documented an approach for converting rock outcrop time histories to force time histories that are applied in-layer at the top of rock.
- Identifies issues related to the use of piecewise linear hysteresis loops and the generation of artificial high frequency noise in in-structure response.

Next Steps

- Use NLSSI on softer soil site such as SRS
  - Determine NLSSI effects
- Perform nonlinear soil site validation at Lotung
- Perform experimental dynamic, large-strain testing of soils using geotechnical laminar box to characterize soil behavior
  - Compare with NLSSI, SHAKE, DEEPSOIL
- Develop a soil constitutive model that accounts for dynamic changes in mean effective stress
- The nonlinear analysis predicts higher levels of shear strain (in the soil column considered) than the equivalent linear analysis, which will be important for buried structures.
- Verification and validation of the linear and nonlinear codes, in a controlled laboratory environment, is needed.
- Characterizing the strain at which the linear and nonlinear methods start to produce divergent results

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Verification and Validation Process in NLSSI Development

- *verification:* the process of determining that a computational model accurately represents the underlying mathematical model and its solution.
- Verification
  - Using simple benchmark problems to verify the mathematics of the software package.
  - Developed a closed form mathematical solution to the wave equation, which relates shear stress and strain. This closed form solution is then compared to a one element numerical finite element problem defined with the soil nonlinear constitutive model.
  - This is the soil constitutive model used in the analysis

Verification and Validation Process in NLSSI Development

- *validation:* the process of determining the degree to which a model is an accurate representation of the real world from the perspective of the intended uses of the model.
- Validation
  - Using experimental data gathered on INL soil (Torsional shear tests) to develop stress strain curve for numerical model.
  - Running the time domain constitutive model at various shear strains to develop a damping curve and comparing this numerical damping curve result with experimental damping data
  - Using a software package which performs its own internal V&V for its structural dynamics capabilities
  - Will perform validation of the NLSSI methodology for the Lotung site

Seismic Model
Load Time History Application

$$\sigma = E \cdot \varepsilon \implies \frac{P(t)}{A} = E \cdot \frac{v(t)}{c} = E \cdot \frac{v(t)}{\sqrt{\frac{E}{\rho}}} = \sqrt{E \cdot \rho} \cdot v(t) \implies P(t) = A \cdot \sqrt{E \cdot \rho} \cdot v(t)$$

Where:

σ - Stress of concern (shear stress in this case)

E - Stiffness relative to the stress of concern (shear modulus in this case)

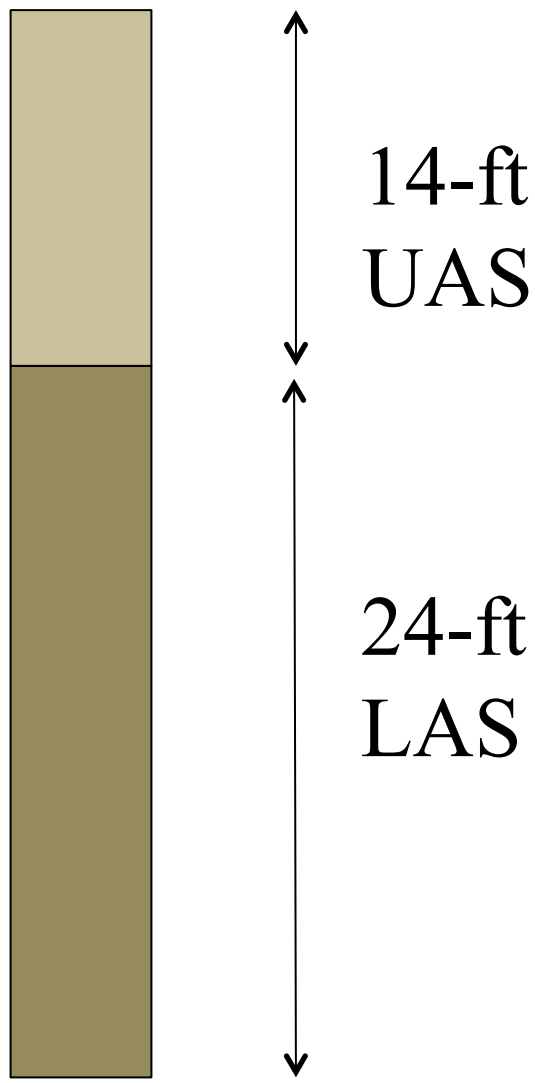
ε - Strain of concern (shear strain in this case)

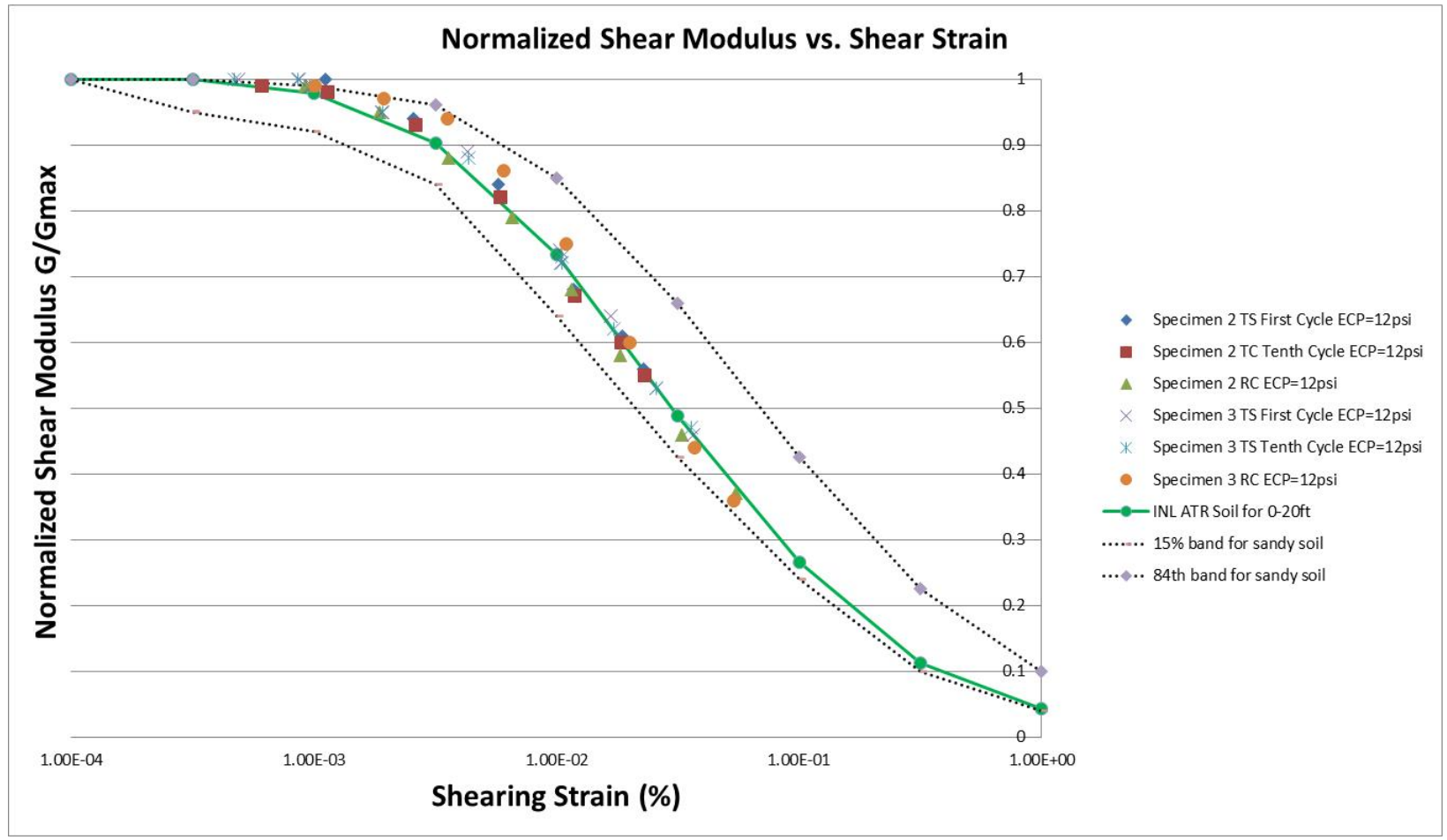
$P(t)$ - Force time history $v(t)$ - Velocity time history where

A - Cross-sectional area c - Speed of sound ρ - Density

- The velocity time history for this portion of the study is rock outcrop
- Applying this load time history to the basalt without soil on top of it produces a rock outcrop motion
- Applying this load time history to the basalt with soil on top of it produces top of rock motion
- This fact can be validated by observing the similarities of the transfer functions used for comparison between the linear SHAKE model and the nonlinear LS-DYNA model

NLSSI Plan…Site 1





UAS: Upper Alluvial Soil
LAS: Lower Alluvial Soil