An Overview of Seismic SSI Analysis for Nuclear Structures

Based on Various Case SSI Studies

Session 1: 9:00am -10:00am

Ghiocel Predictive Technologies Inc.

Dr. Dan M. Ghiocel

Email: dan.ghiocel@ghiocel-tech.com

Ghiocel Predictive Technologies Inc.

http://www.ghiocel-tech.com

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Purpose:

To present a overview of the seismic SSI effects for nuclear structures based on many SSI analysis results accumulated over last ten years from a variety of seismic projects and internal studies (published or unpublished).

From a myriad of factors influencing seismic SSI effects, this presentation focuses on *some relevant factors* that more recently attracted attention of the nuclear engineering community for the new build designs.

DISCLAIMER: Some remarks reflect our experience, not necessarily an industry consensus.

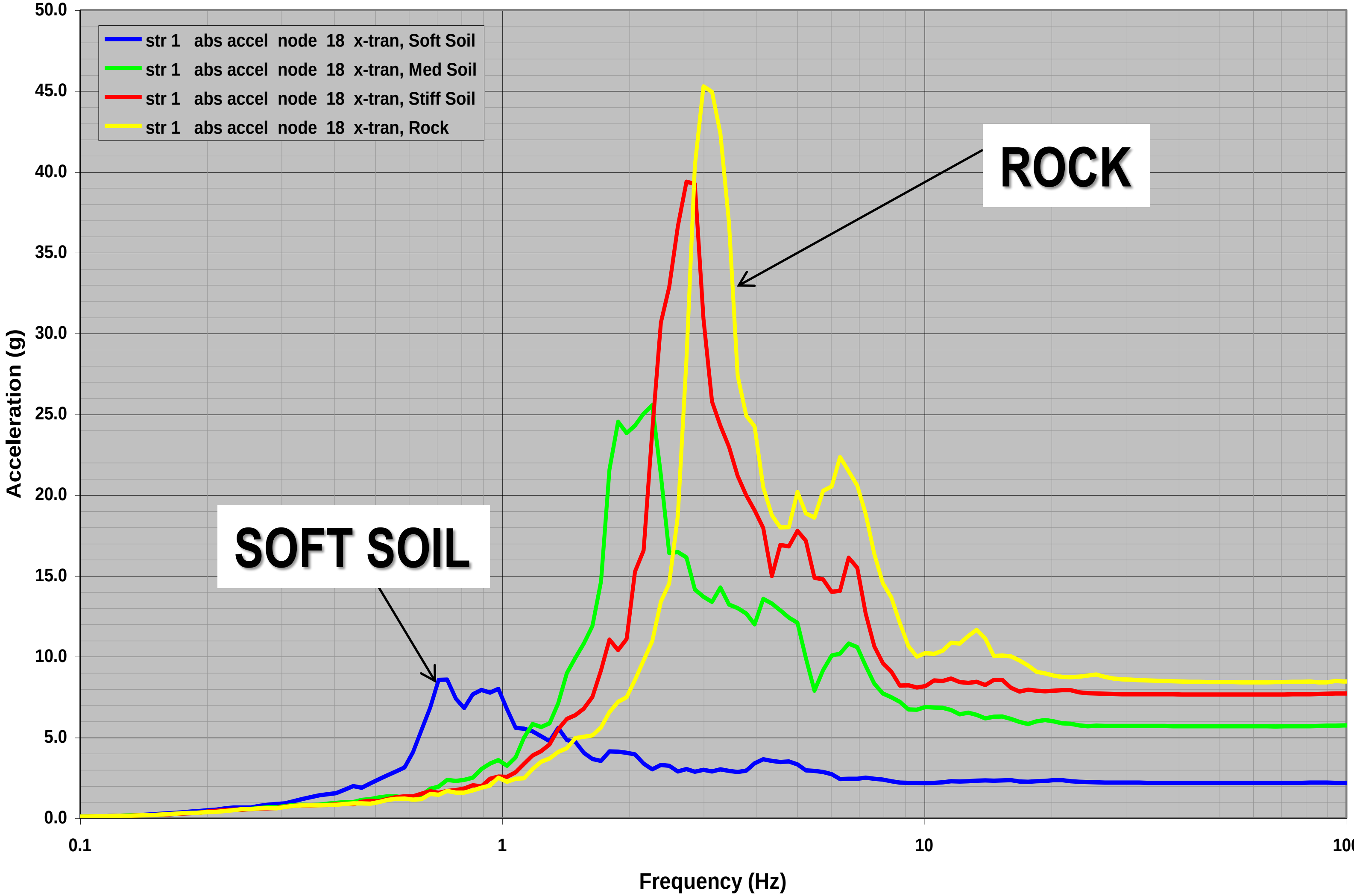
Content:

1. Why is seismic SSI analysis so important for NPP design?
2. Basic Seismic SSI Analysis Methods and Models
3. Past and Present Seismic SSI Analysis
4. Seismic SSI Motion Phasing and Spatial Variations
5. Seismic SSSI Effects on ISRS and Soil Pressures
6. Case Studies for Evaluation of Seismic SSI and SSSI Effects
7. Other Important SSI Modeling Aspects Not Addressed in This Overview
8. Concluding Remarks

1. Why is seismic SSI analysis so important for NPP design?

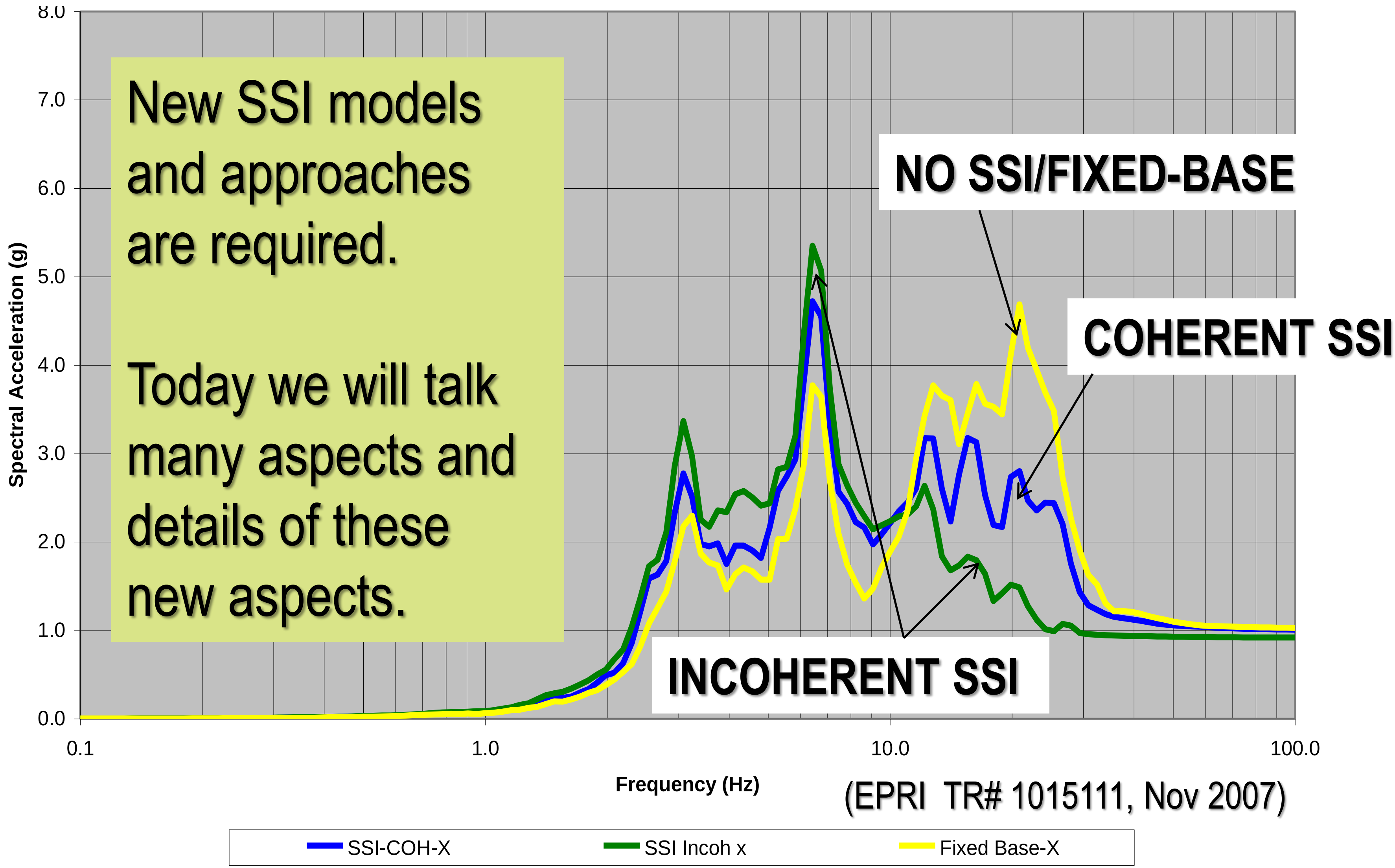
SSI Effects for Nuclear Structures on Soil Sites

EPRI AP1000 Stick 5% Damping ISRS at Top of SCV



SSI Effects on Nuclear Structures on Rock Sites

EPRI AP1000 Stick 5% Damping ISRS at Top of SCV



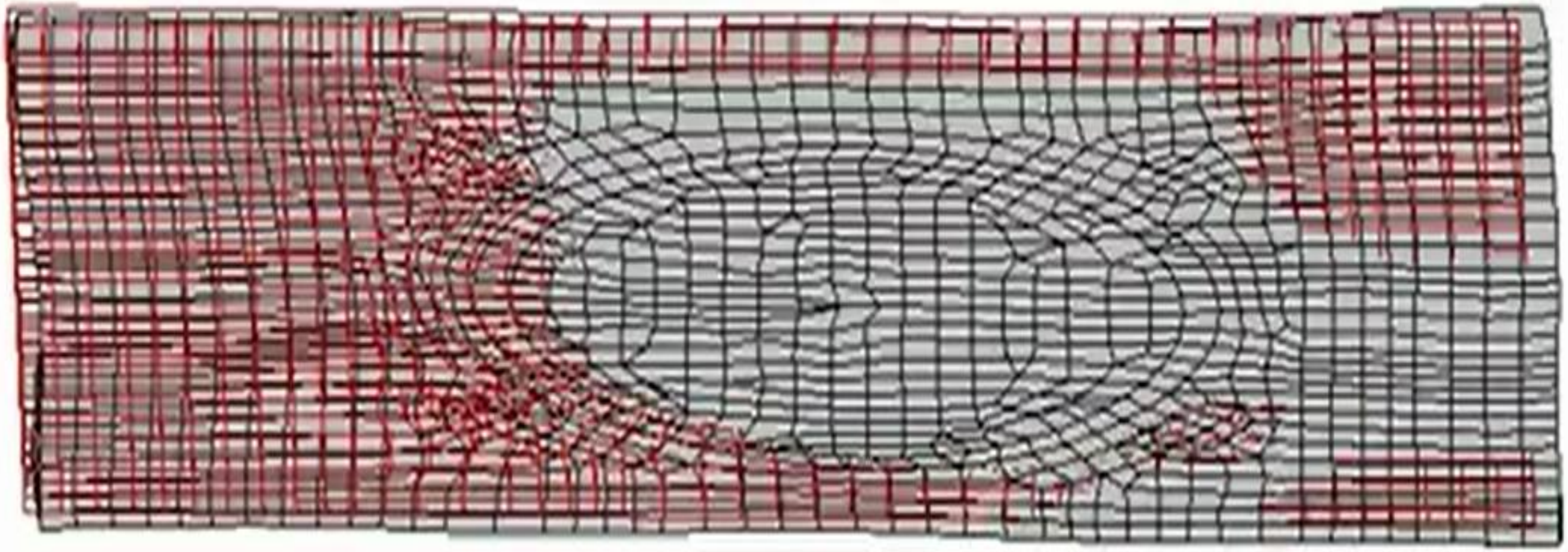
(EPRI TR# 1015111, Nov 2007)

ASCE 4-16 Standard Requirements for Considering SSI Analysis of NPP Structures

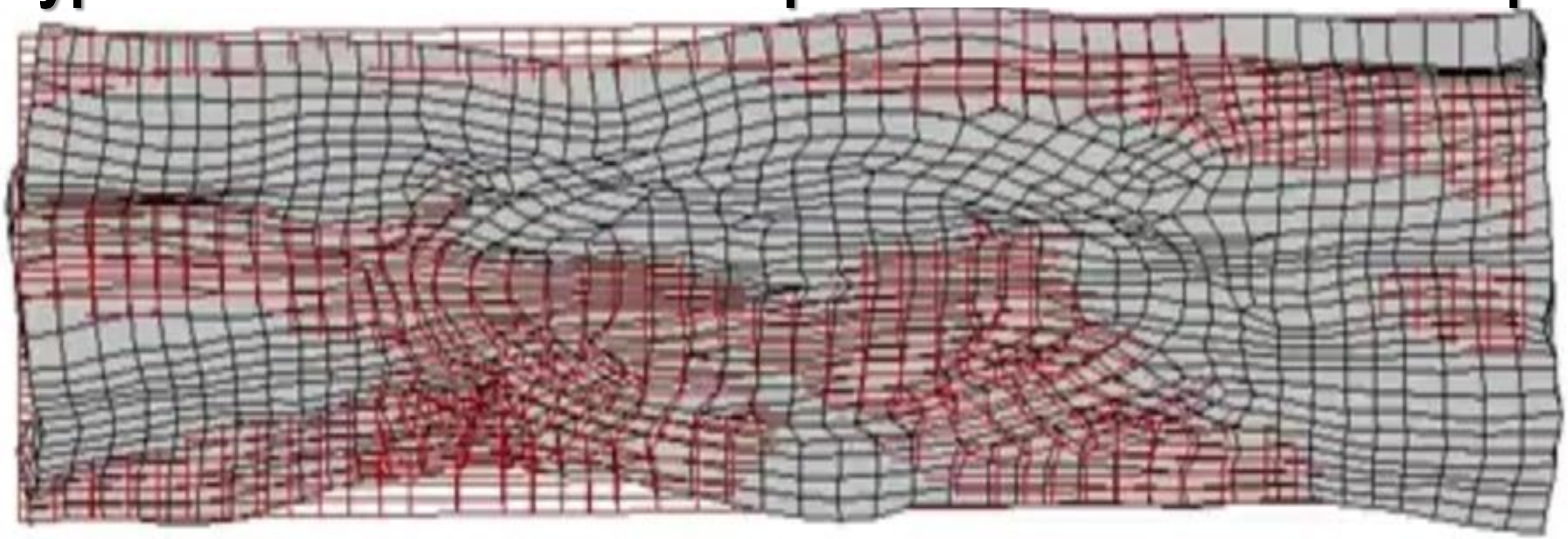
ASCE 4-16 standard states that *"for all sites that have a soil shear-wave velocity of less than 8000 fps or 2430 m/s at a shear-strain of 0.0001 %* or smaller regardless of the frequency content of the free-field motion."

Also, "*When ground motion incoherency effects are considered, SSI analysis shall be performed regardless of the stiffness of the supporting soil or rock below the foundation*."

Typical RB Basemat SSI Response for COHERENT Inputs



Typical RB Basemat SSI Response for INCOHERENT Inputs



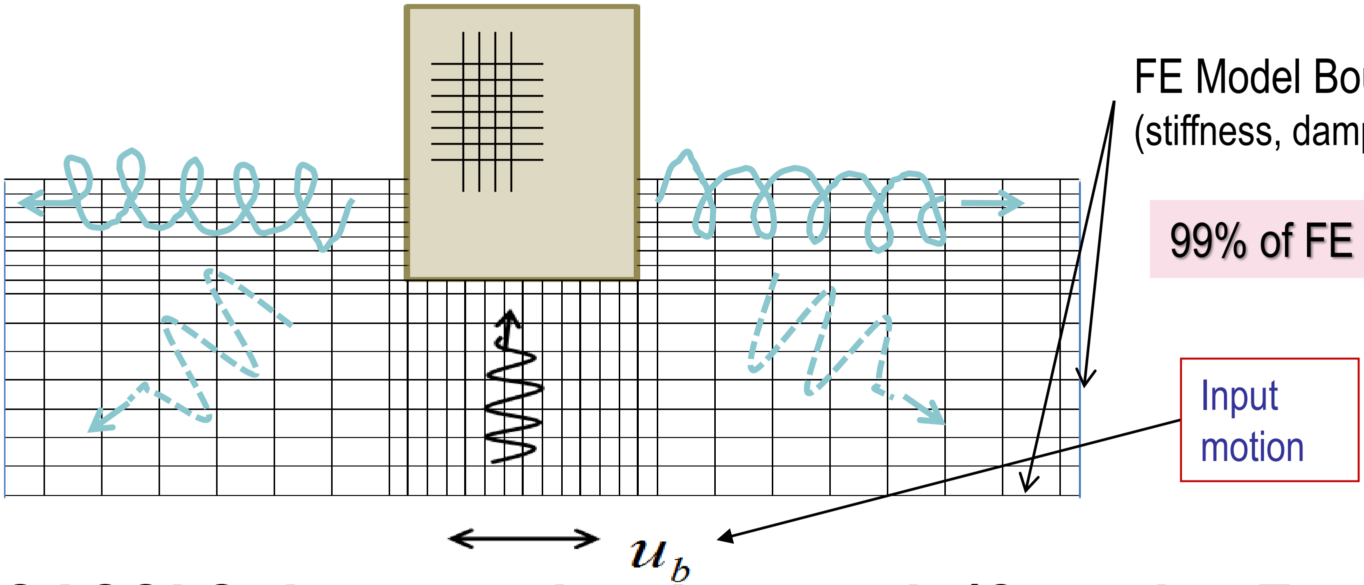
Remarks on Why SSI Effects are Important

- Seismic SSI effects affect largely both the ISRS amplitudes and the maximum structural forces in nuclear structures
- Seismic SSI effects reduce the structure accelerations and inertial forces, but increase the foundation deformation, especially if the motion spatial variation is included.
- Motion incoherency reduces the high-frequency ISRS amplitudes, but still could increase ISRS for narrow bands in the mid-frequency range (torsional modes).
- Differential soil motions due to incoherency (3D random wave propagation) could increase the foundation bending moments, and possibly the differential motions at the piping/equipment supports.

2. Basic Seismic SSI Analysis Models and Methods

Direct SSI Approach vs. SASSI Approach

Direct Approach (Time-Domain)

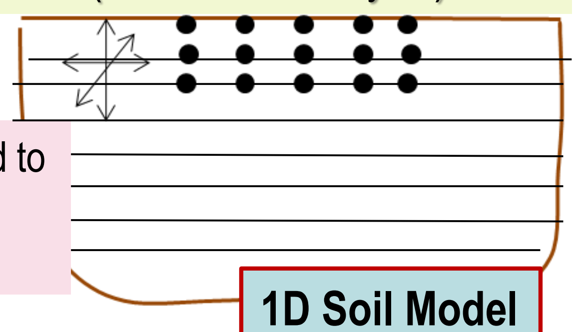


SASSI Substructuring Approach (Complex Frequency)

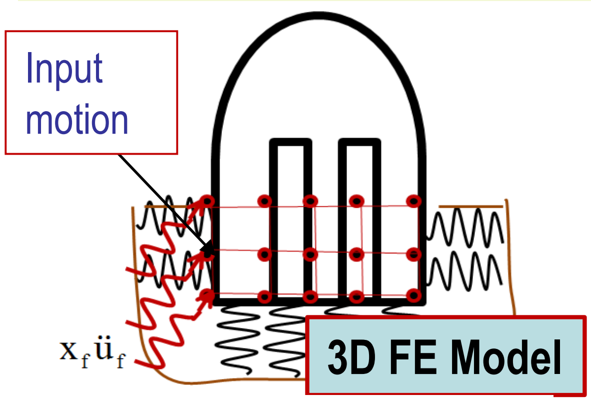
Structural dynamic analysis step includes *3D Structure FEM* and *Excavated Soil FEM*

Only *1D soil layering model* is used to compute the input motions and the soil impedance for SSI analysis.

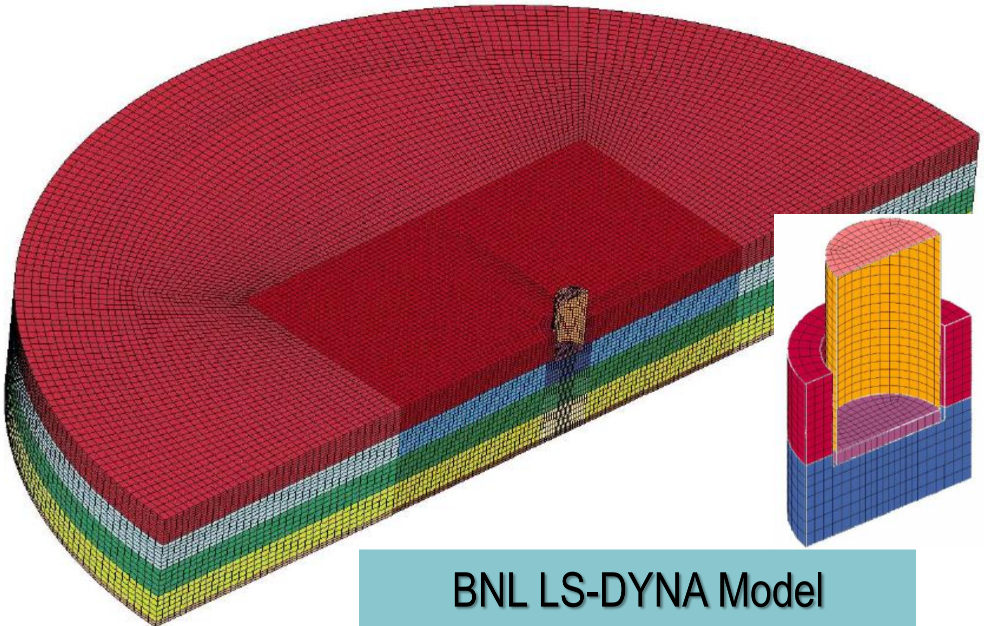
1D Soil Layering FE Model
w/o Excavated Soil
(Free Field Analysis)



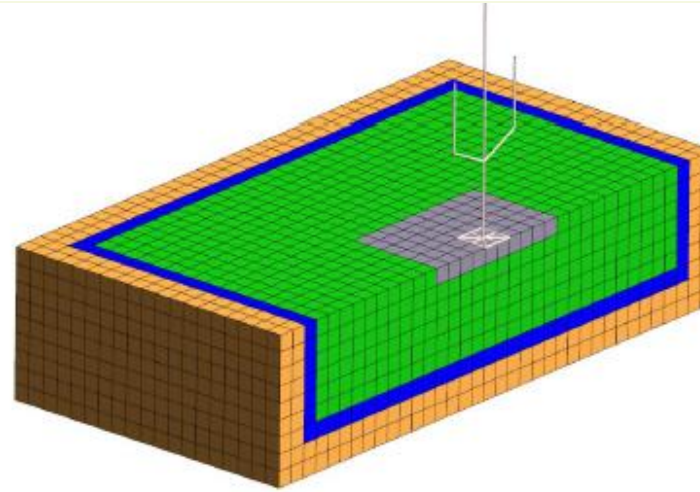
3D Structure w/ Excavated Soil
FE Model (SSI Analysis)



Direct SSI Approach and SASSI Approach Models

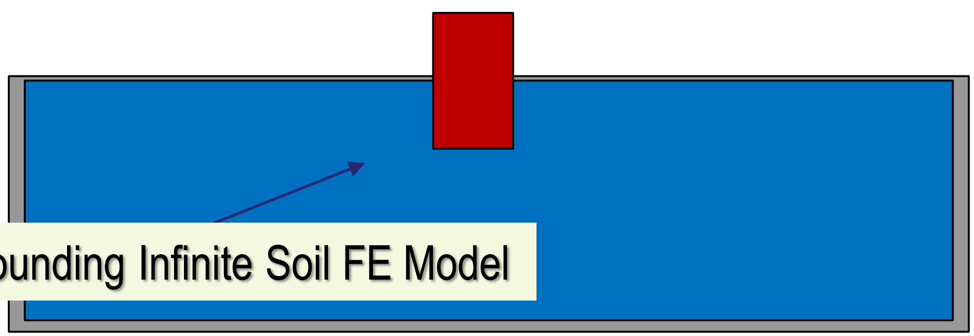


BNL LS-DYNA Model
Xu et al., 2006



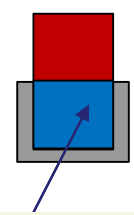
E-SSI Model
Neboja et al., 2015

Direct SSI Approach Model



Surrounding Infinite Soil FE Model

SASSI Approach Model

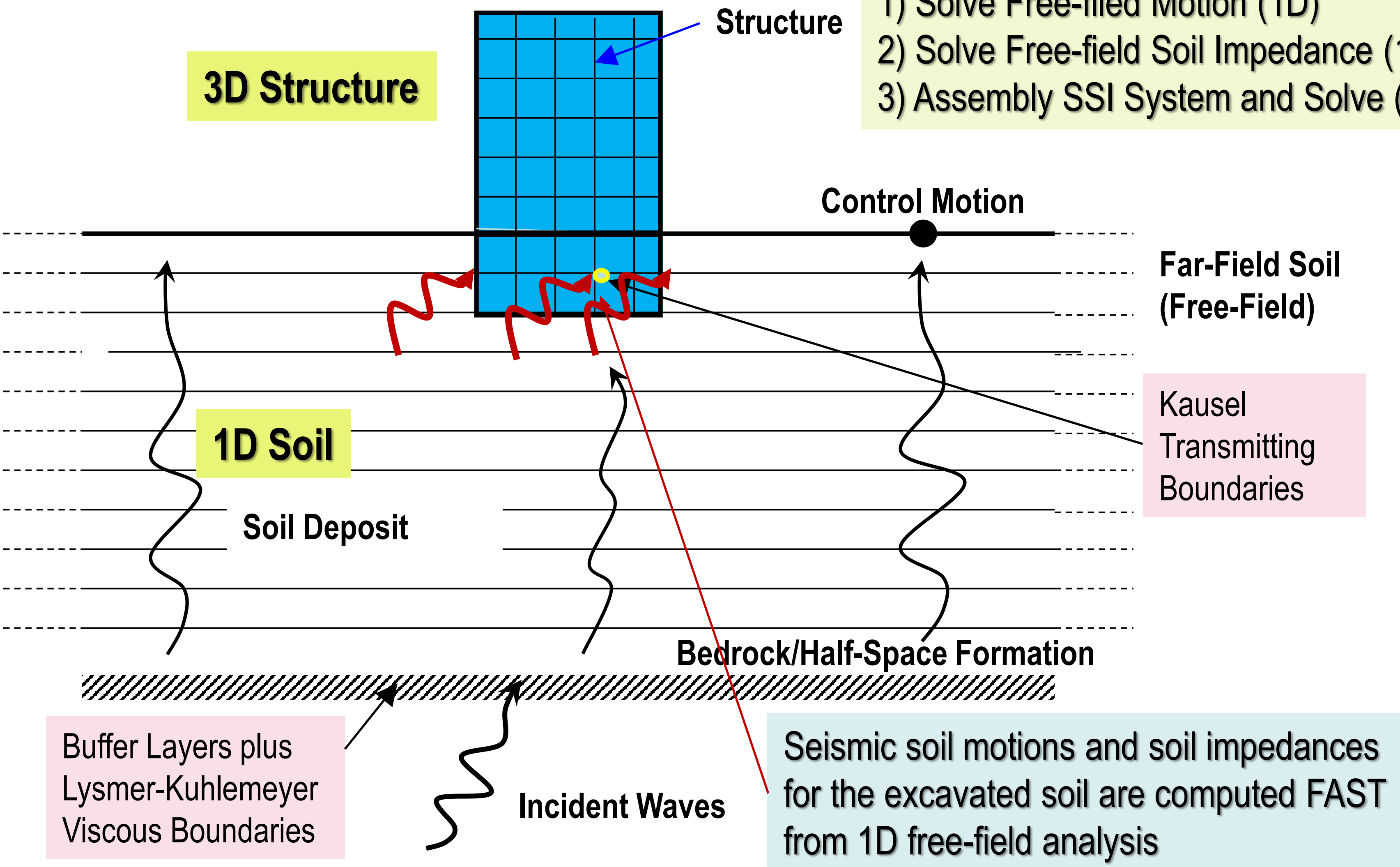


Excavated Soil FE Model
Plus Soil Impedances

SASSI Substructuring Uses 3D1D SSI Models

Computational Aspects:

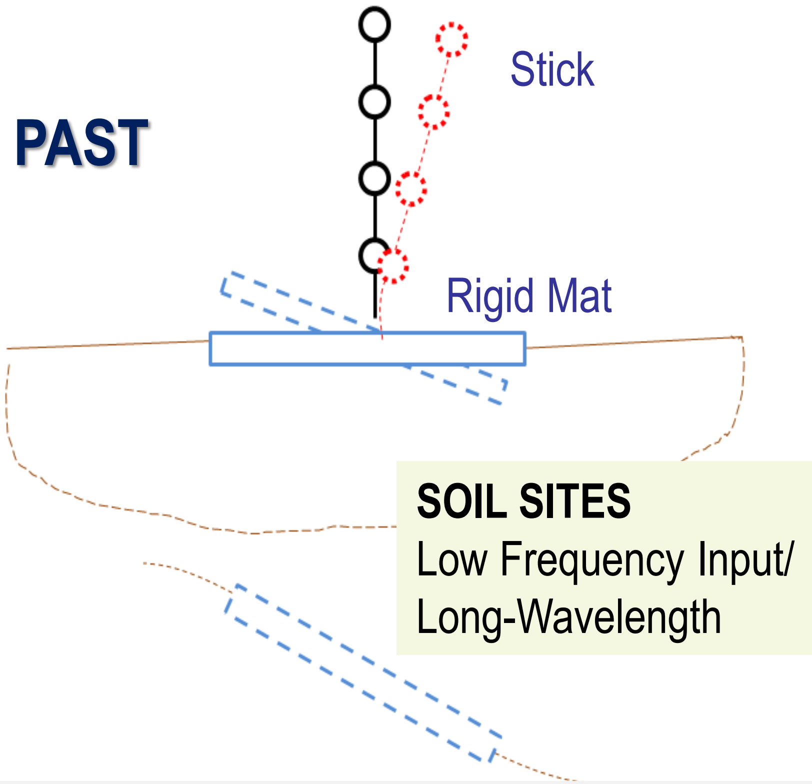
1) Solve Free-filed Motion (1D)
2) Solve Free-field Soil Impedance (1D)
3) Assembly SSI System and Solve (3D)



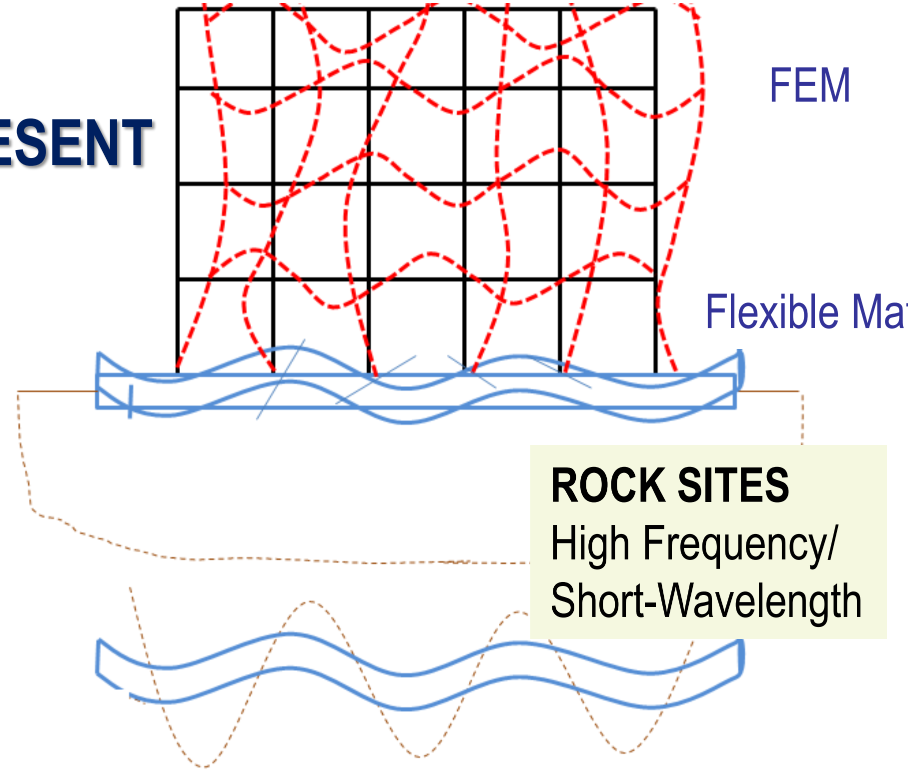
3. Past and Present Seismic SSI Analysis

Past vs. Present Seismic SSI Analysis Concept

PAST



PRESENT

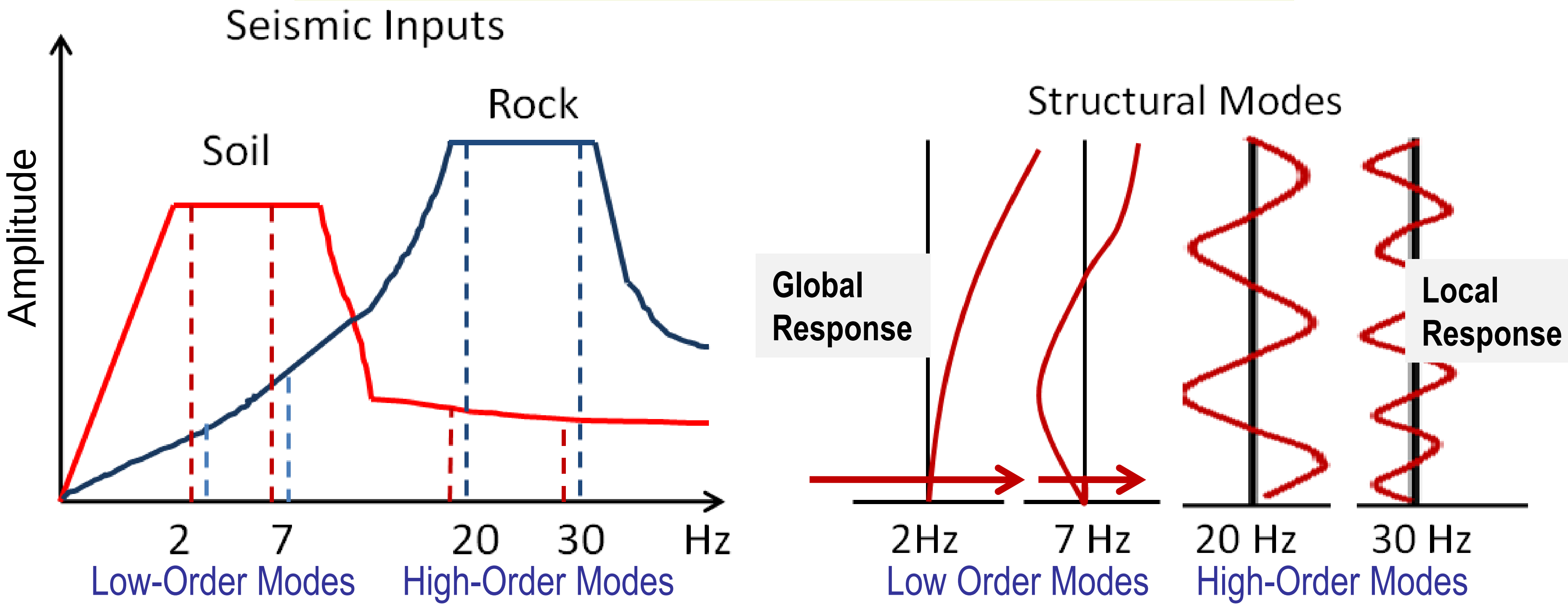


PAST EXPERIENCE:
- Low Frequency Inputs (Long-Wavelength)
- Soil Sites
- Stick Models with Rigid Mats
-Input Soil Motion as Rigid Body Motion (Coherent, 1D Propagation of S and P Waves)
Is sufficiently accurate? No…..

PRESENT EXPERIENCE:
- Low and High Frequency Inputs (Long-and Short Wavelengths)
- Soil and Rock Sites
- Finite Element Models, Stick for Preliminary
- Input Soil Motions as Rigid Body (Coherent) and Elastic Body Wave Motion (Incoherent, 3D Waves)

Past Soil Site SSI to Present Rock Site SSI.

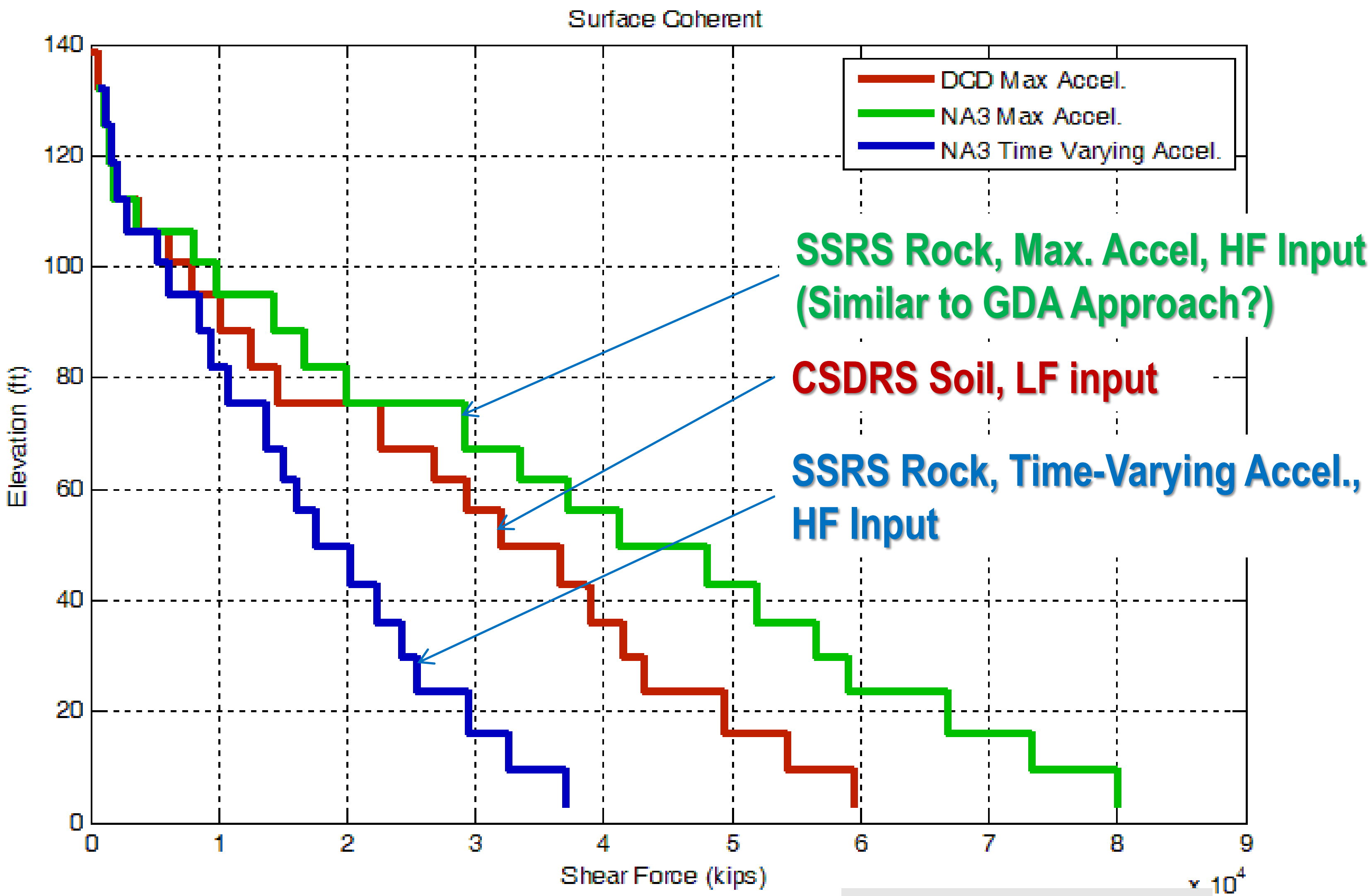
Seismic Inputs With Different Frequency Content



REMARKS:

- If DCD (baseline design) uses only LF inputs, the SSI evaluation for HF inputs will show many ISRS outliers in the HF range.
- *Global* structural forces are much larger for LF inputs than HF inputs. However, for the high-frequency *local* wall vibration responses, i.e. the o-p moments and forces, the HF might be much larger...

Failure of Equivalent Static Method for High-Frequency. RB Complex IS Shear Force Comparisons



(Ghiocel et al., 2010)

Few Remarks for Computing Seismic Demands and ISRS for High-Frequency SSI Problems

The use of maximum structural acceleration (ZPA) distribution is inappropriate for the high-frequency inputs.

- Global shear forces are grossly overestimated. Local effects coming from the high-frequency modes are underestimated.

- For computing seismic loads need to use the time-varying acceleration distribution for all time steps, not only the maximum acceleration values. Envelope results at the end.

4. Seismic SSI Motion Component Phasing and Spatial Variations

A. Seismic Motion Component Phasing

B. Spatial Variation in Vertical and Horizontal Directions

A. Seismic Motion Component Phasing

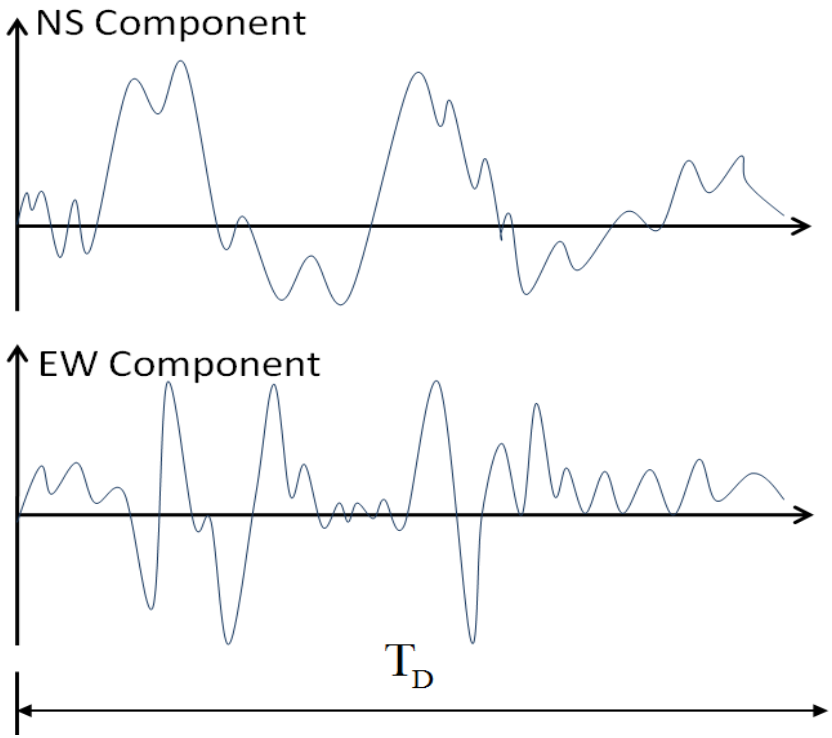
Current practice:

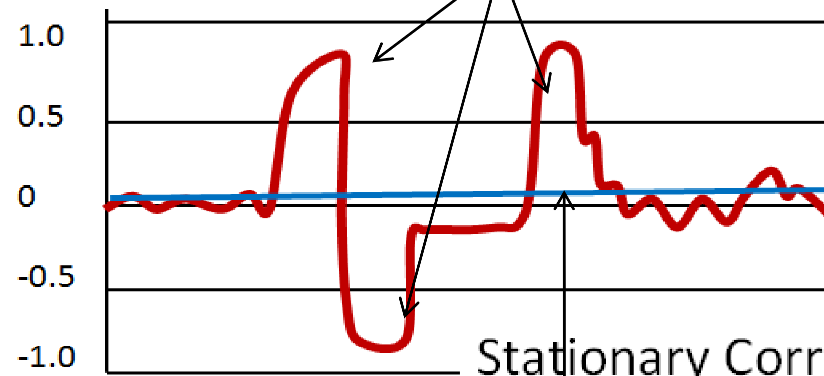
- Seismic motion components are uncorrelated over the entire duration of the intense part of the motion

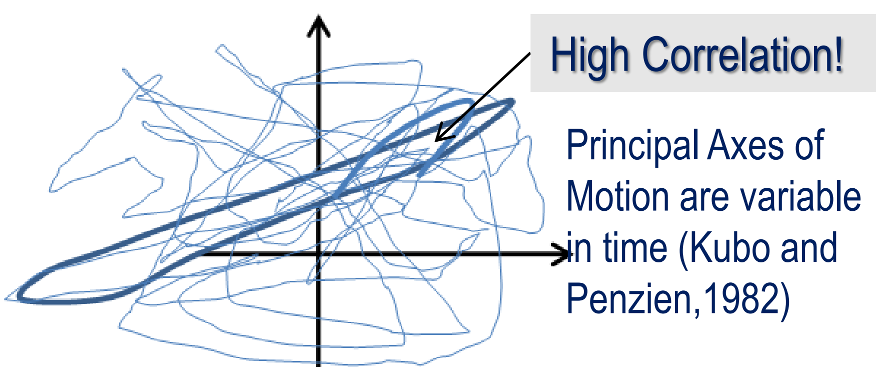
- To avoid including artificial phasing effects in the numerically generated spectrum compatible acceleration motion components, the use of the “seed” records is recommended.

- To eliminate the seismic motion random phasing effects (within component and between components), a number of five sets of acceleration inputs are recommended.

A. Seismic Motion Component Phasing Effects

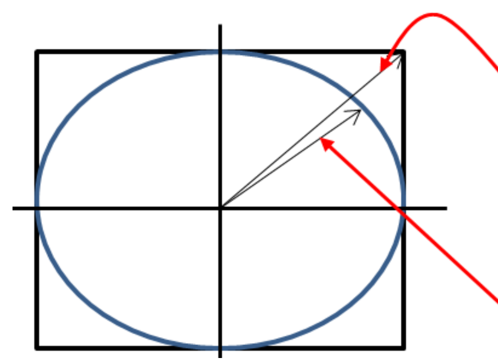






Principal Axes of Motion are variable in time (Kubo and Penzien,1982)

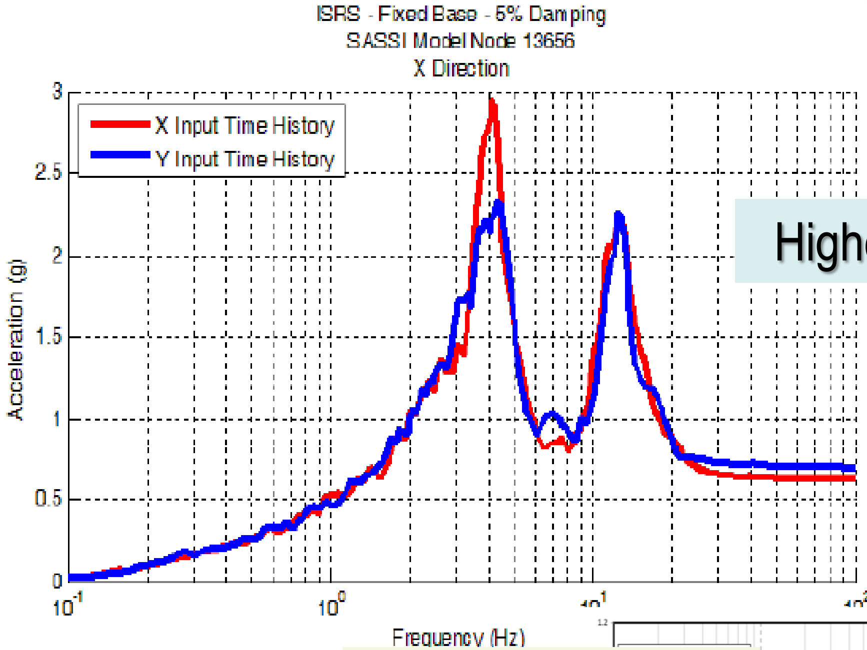
CORNER COLUMN PROBLEM



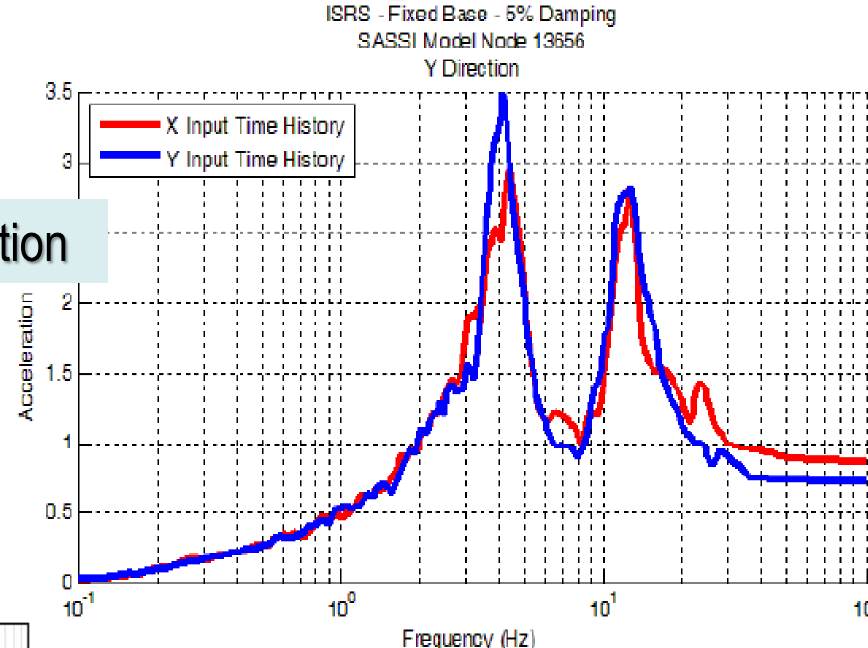
(Agnastopoulos, 1981, Der Kiureghian, 1984)

(SRSS rule neglects correlation effects)

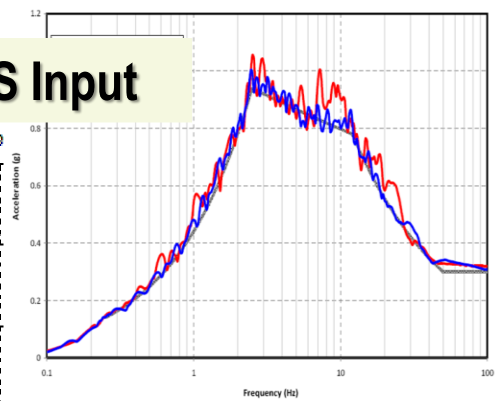
Within Motion Component Phasing Effects

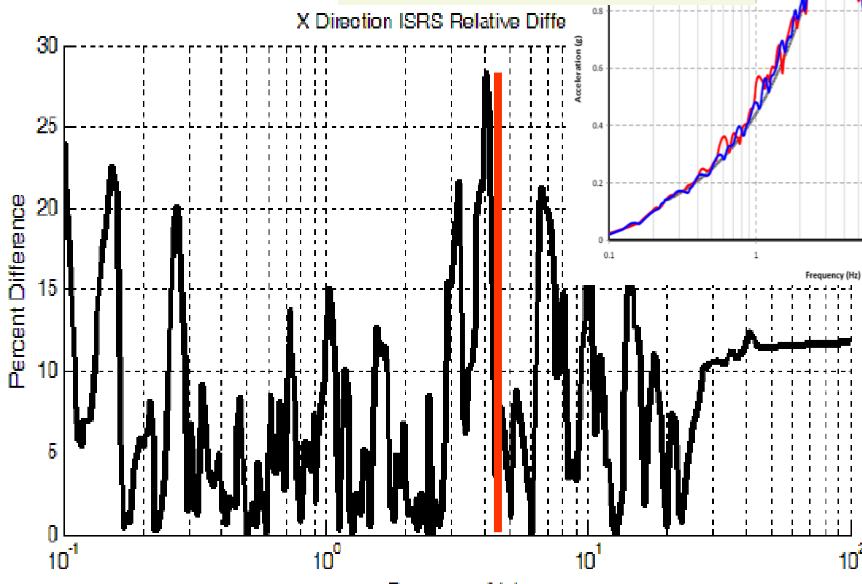


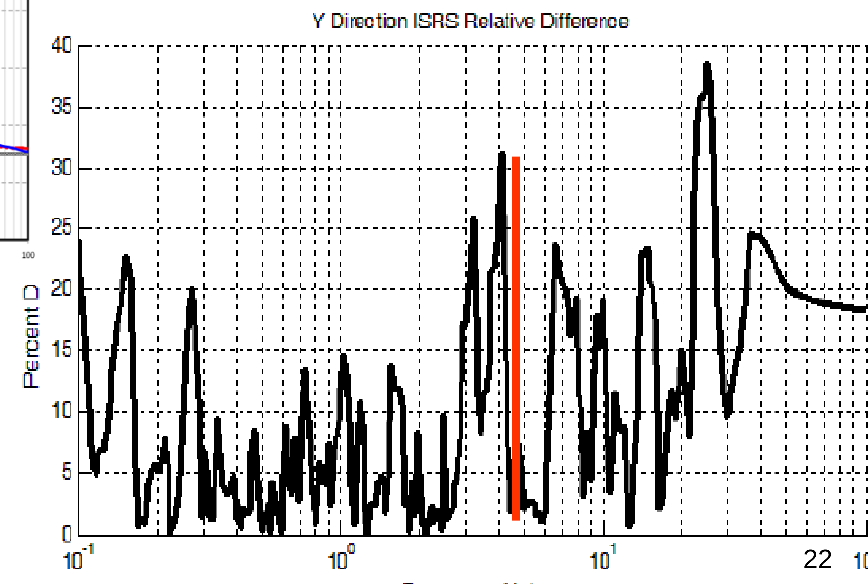
Higher Elevation



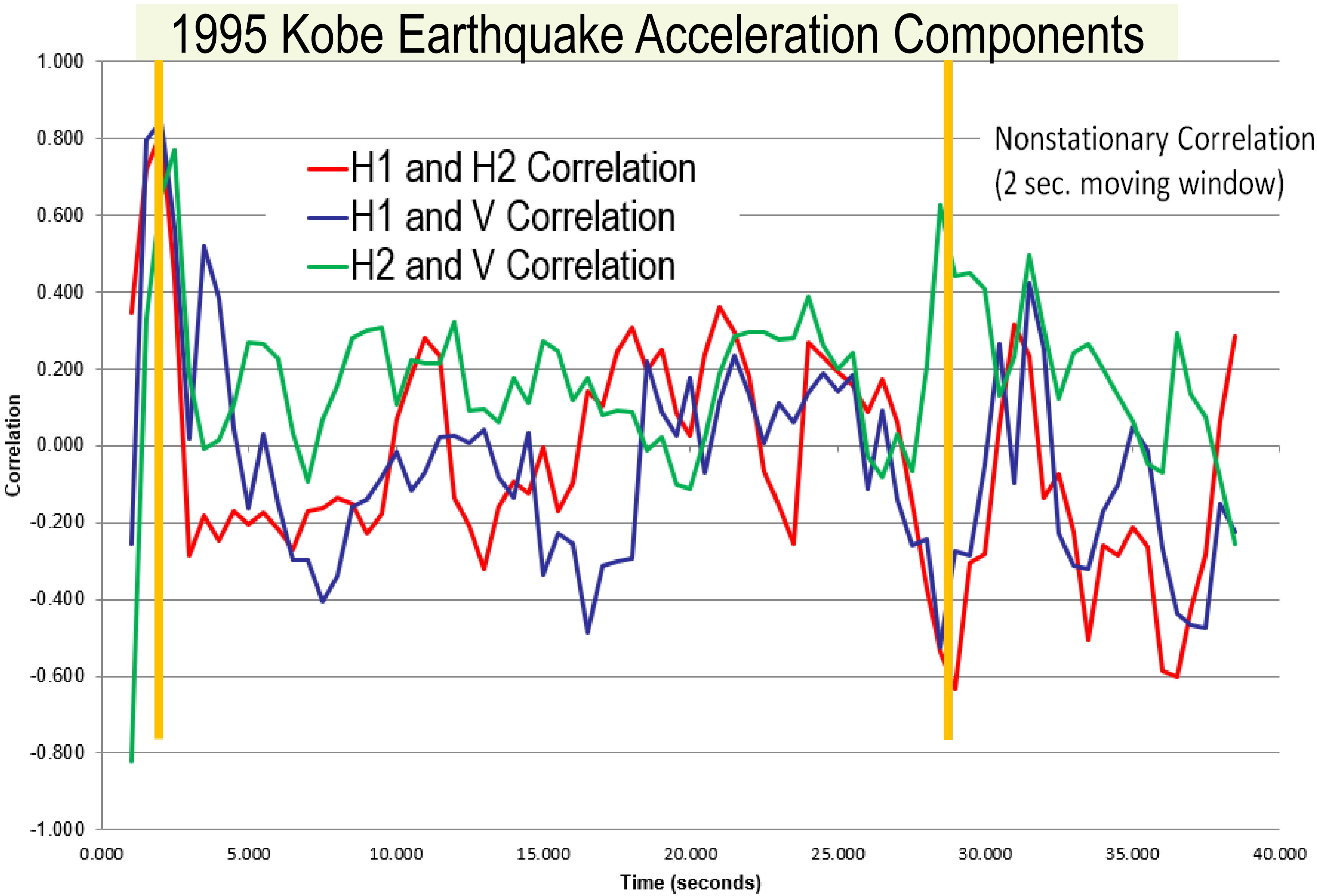
Same GRS Input



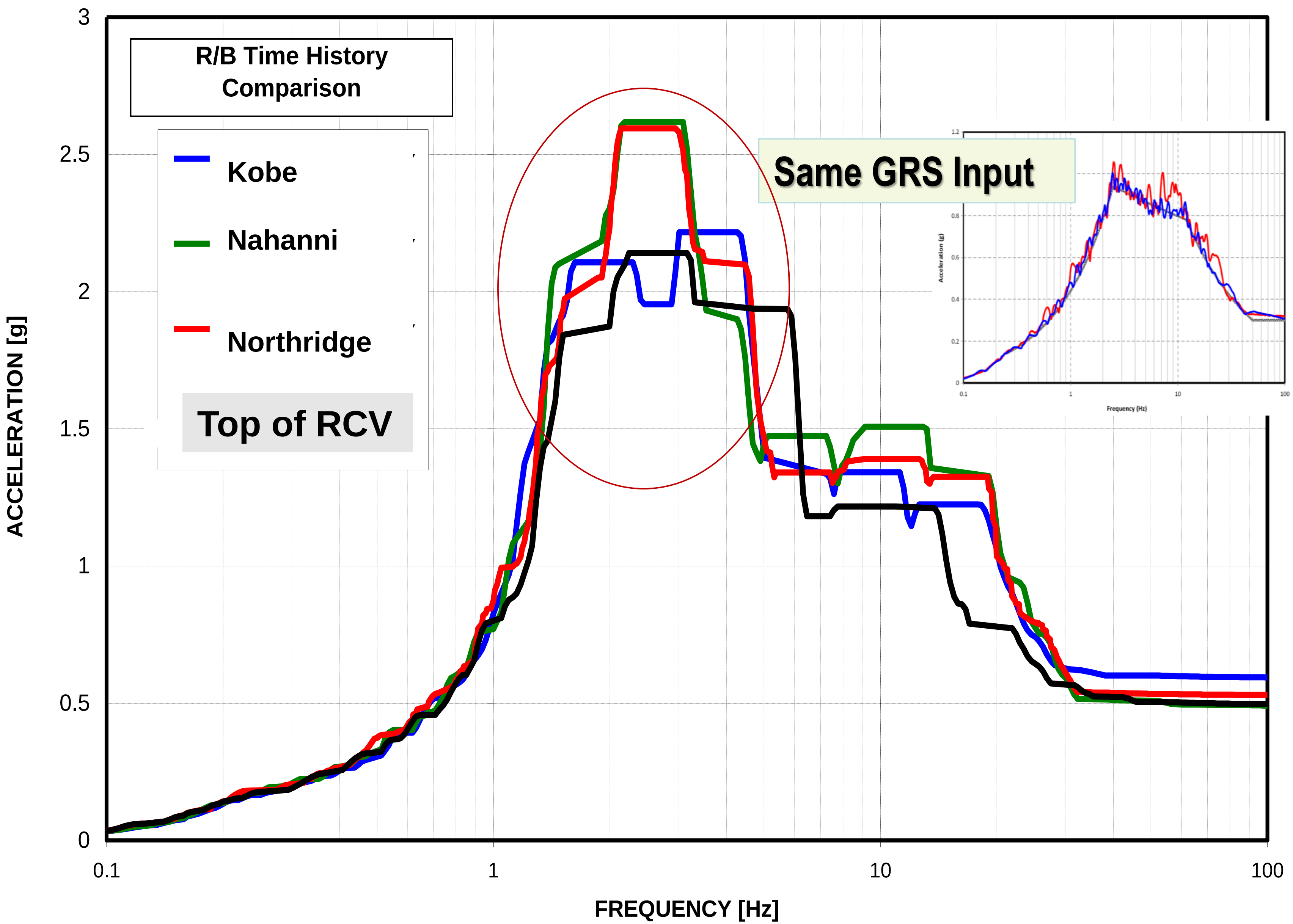




Between Motion Component Phasing Effects



Seismic Input Phasing Effects on RCV ISRS



Remarks Seismic Motion Component Phasing

- The use of five sets of inputs is an important requirement to avoid the motion component random phasing effects

- The motion phasing SSI effects are more significant for the refined FE models that have many closely-spaced vibration modes than for simple stick models as used in the past.

- The largest motion component phasing effects was noted on the contact soil pressure area.

ANIMATION 1

B. Seismic Motion Spatial Variation

B1. Soil Motion Variation with Depth

B2. Soil Motion Variation in Horizontal Plane

B1. Soil Motion Variation with Depth

Current practice:

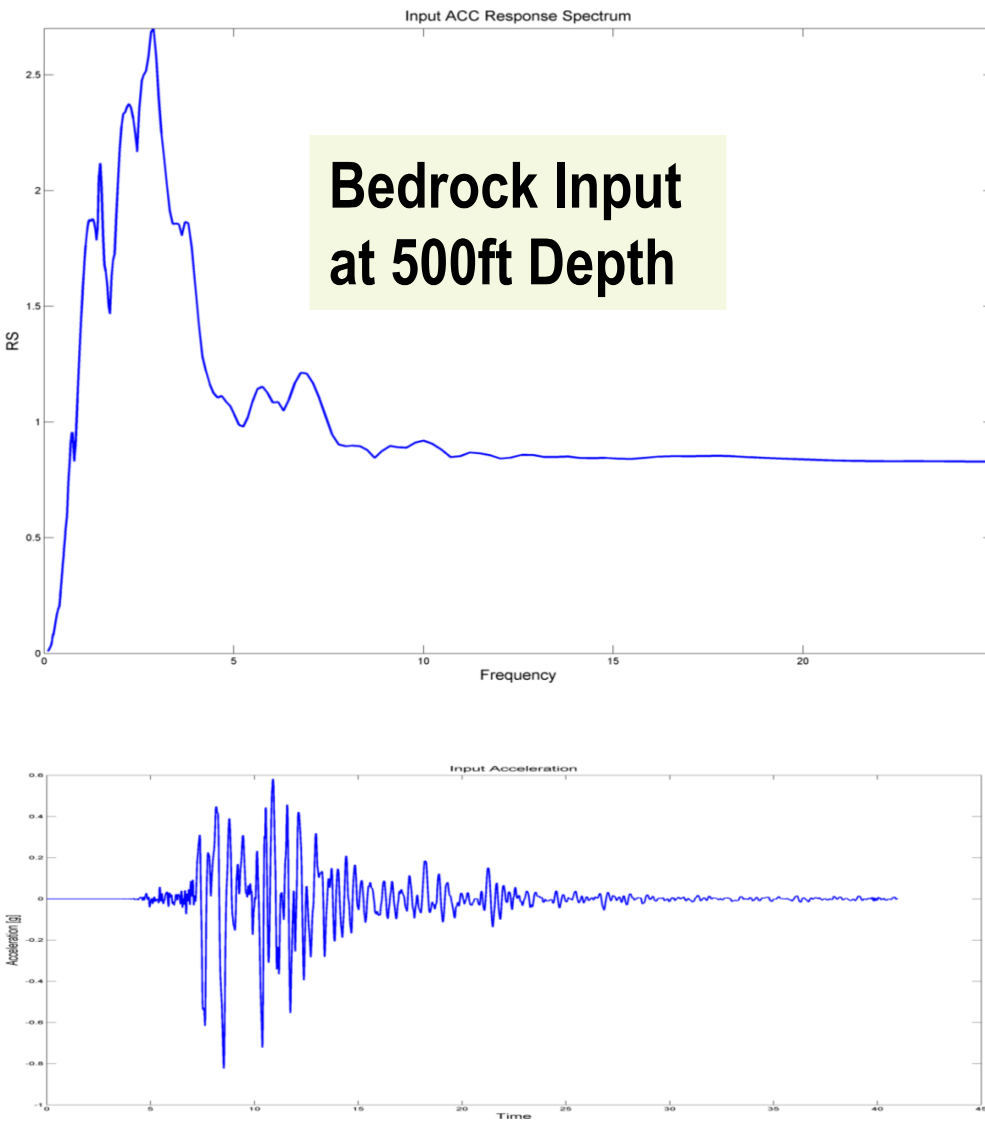
- Seismic motion varies largely with depth, especially for soil sites.

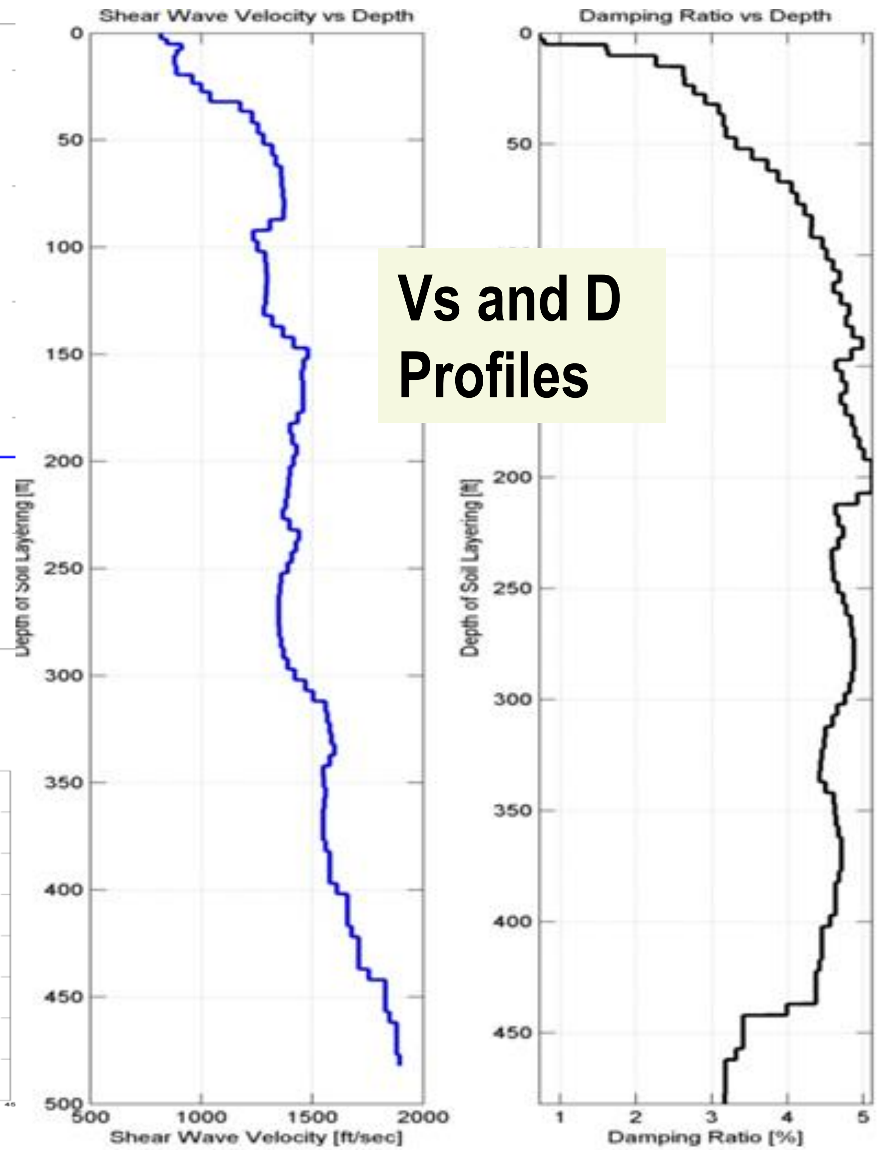
- Wave composition is based on the vertically propagating S and B body waves assuming 1D soil deposit models

- Nonlinear hysteretic behavior of the soil layers affects the seismic wave propagation.

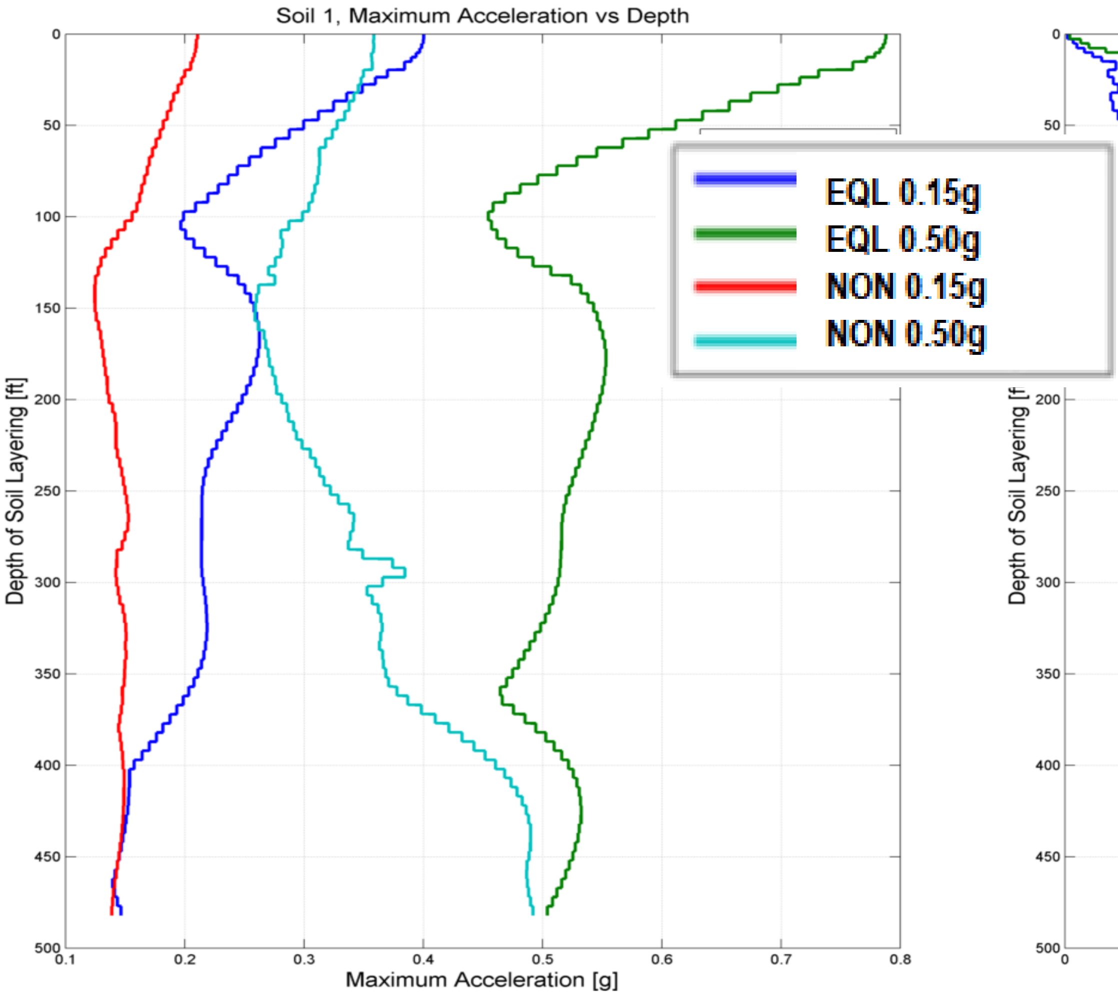
- Equivalent-linear soil models (SHAKE) are acceptable for performing the site response analysis.

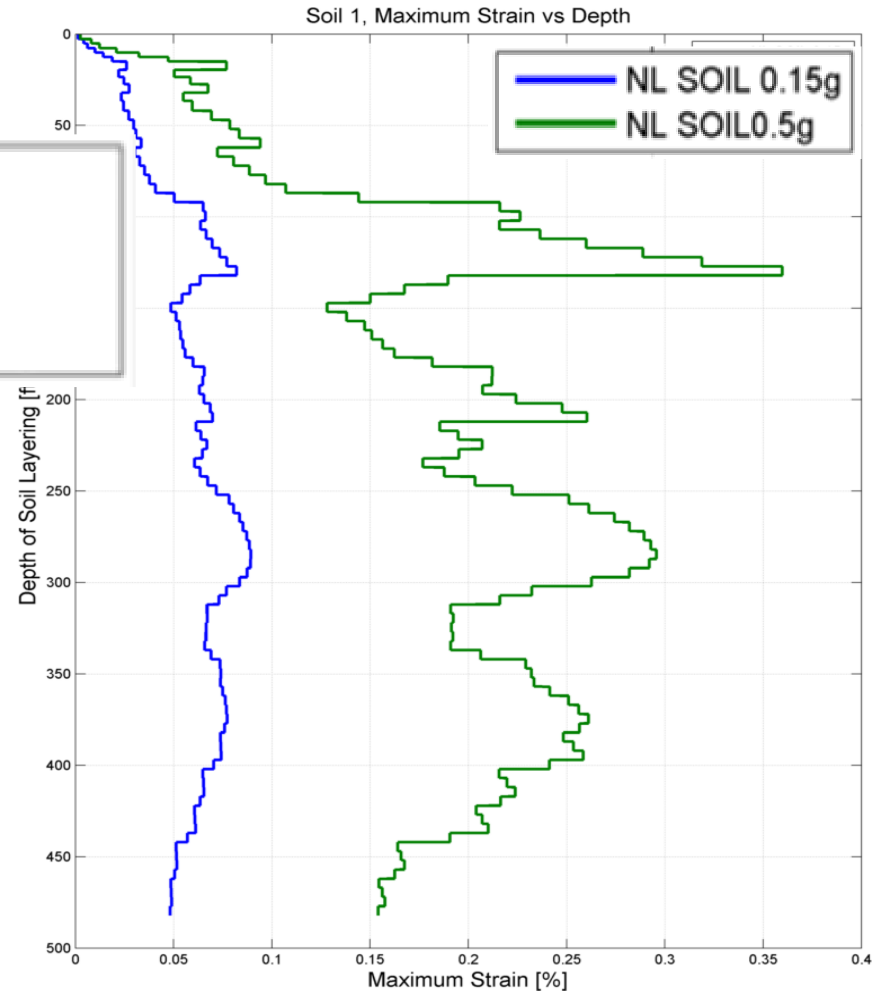
Site Response for A Typical Soil Site



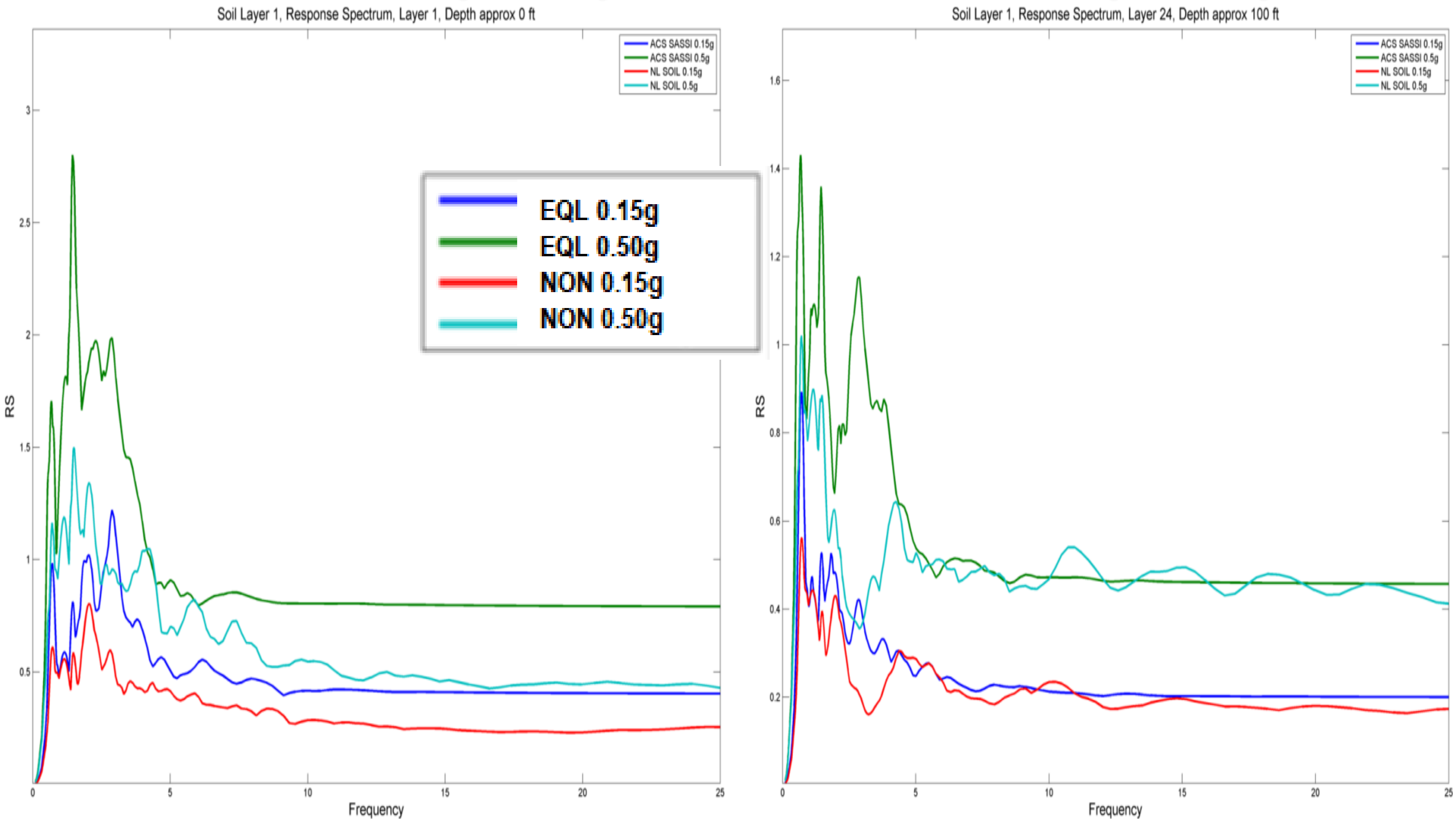


Maximum Acceleration and Shear Strain For 0.15g and 0.50g Scaled Inputs Using SHAKE (EQL) and DEEPSOIL (NON)

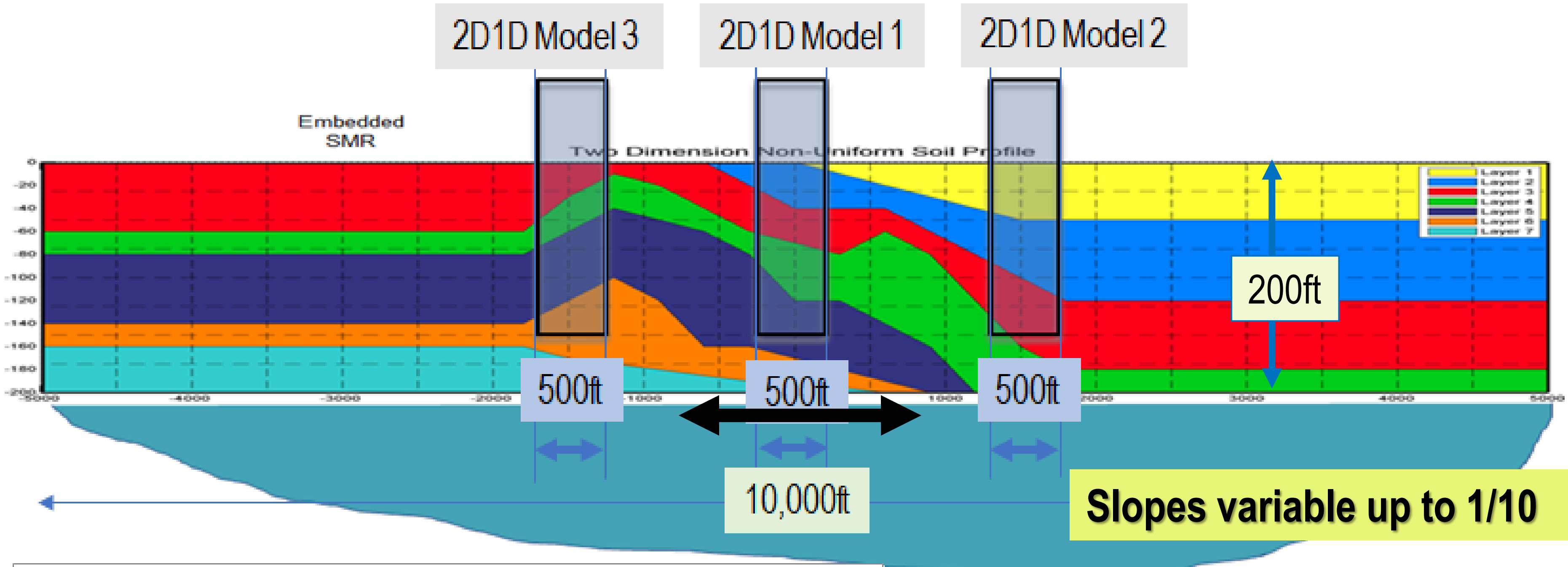


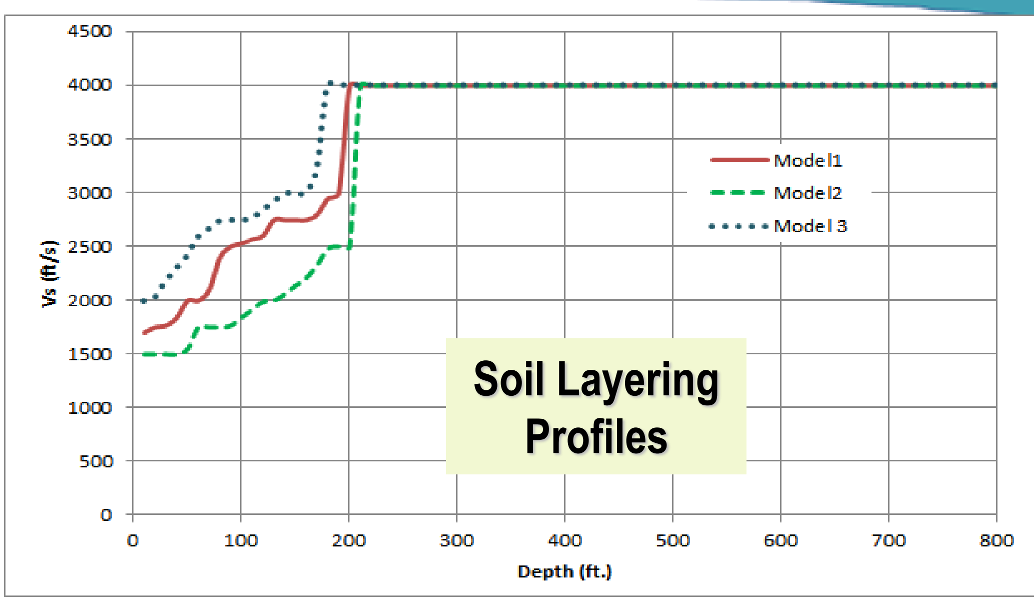


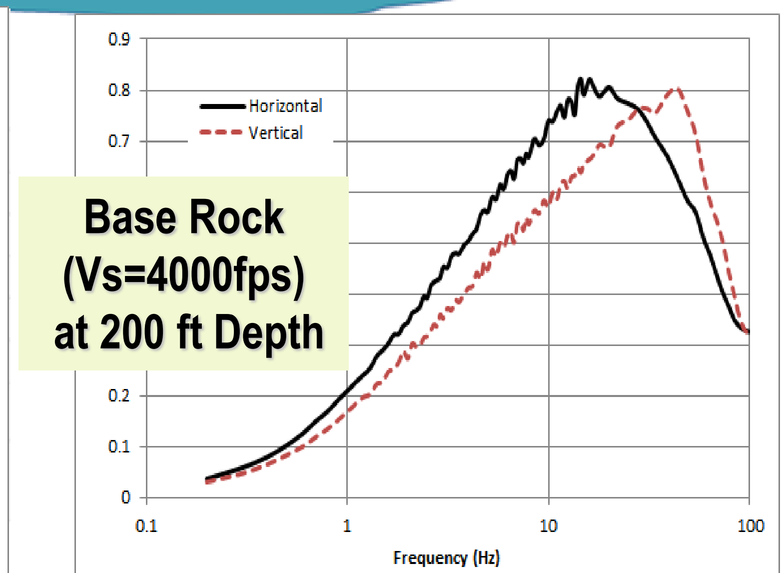
Computed Soil Motion RS at Surface and 100ft Depth For 0.15g and 0.50g Scaled Inputs Using SHAKE (EQL) and DEEPSOIL (NON)



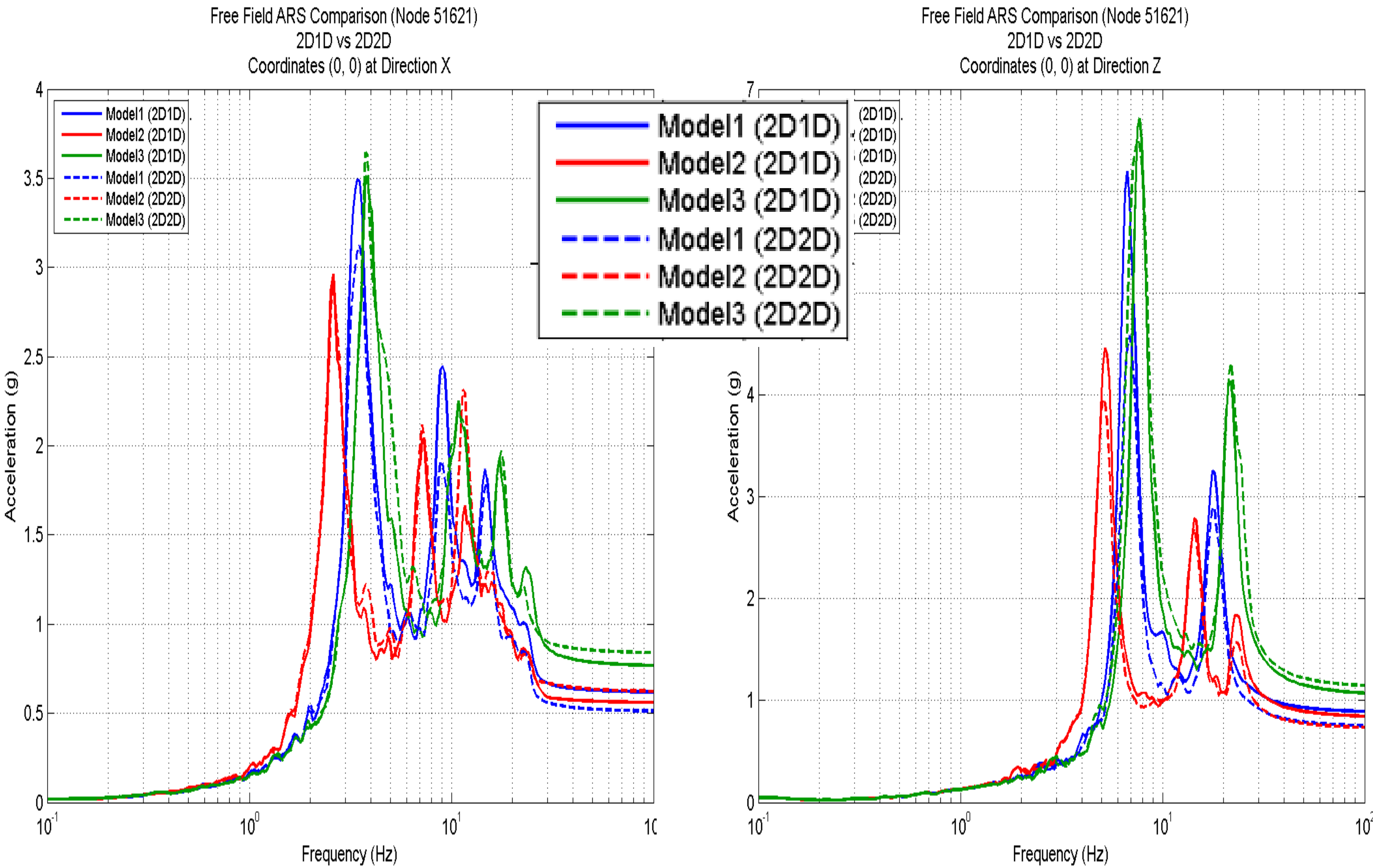
1D vs. 2D Soil Model Effects on Wave Propagation



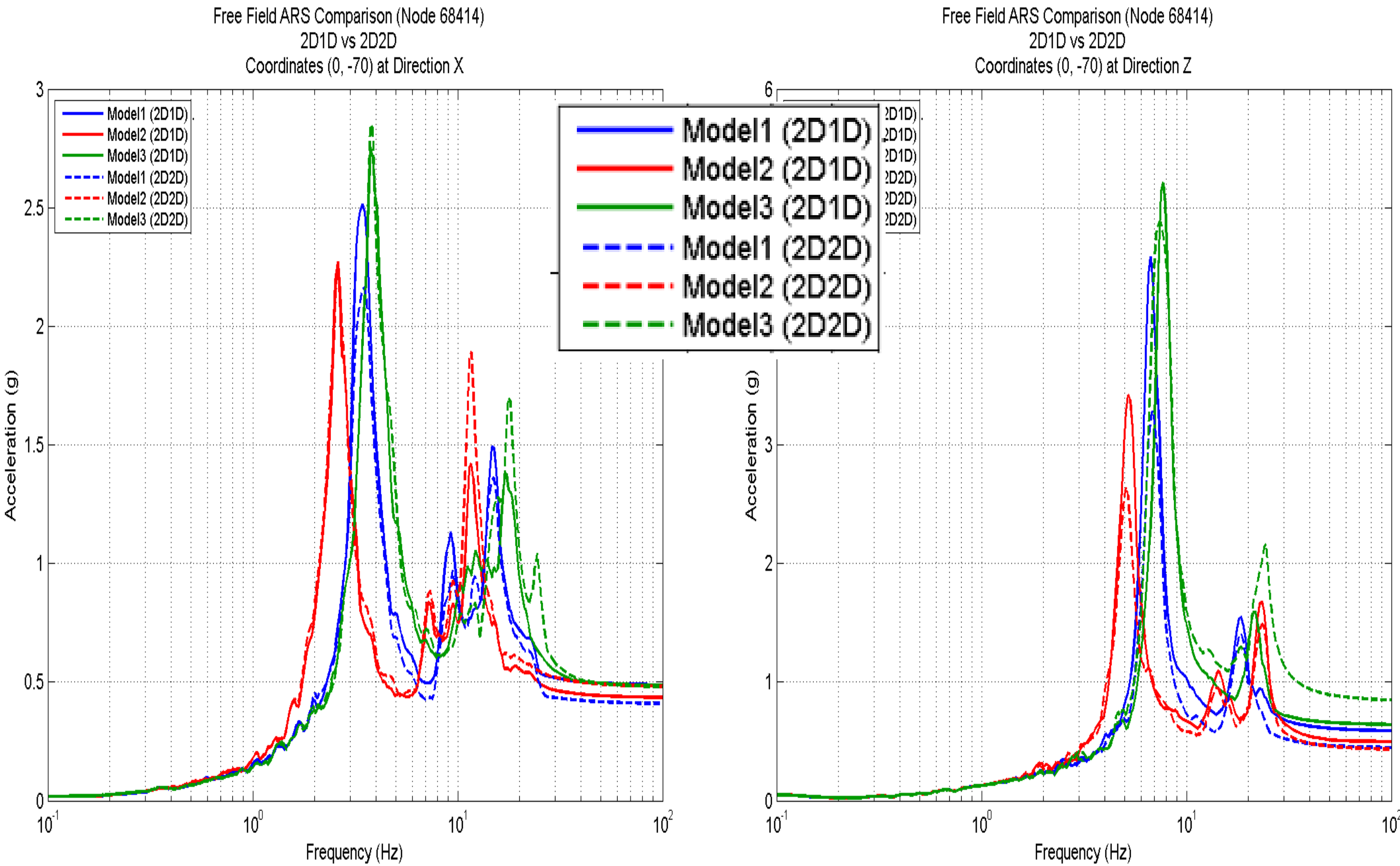




1D vs. 2D Soil Model Effects on Surface Motion



1D vs. 2D Soil Model Effects on -70ft Depth Motion



ANIMATION 2

Remarks on Seismic Motion Variation with Depth

- For typical soil sites and upward seismic S wave propagation, the equivalent-linear hysteretic soil model (SHAKE) provides usually conservative ground motions in comparison with nonlinear time domain (DEEPSOIL). Sometimes, this is not fully true, especially for certain soil depths and higher frequency components.

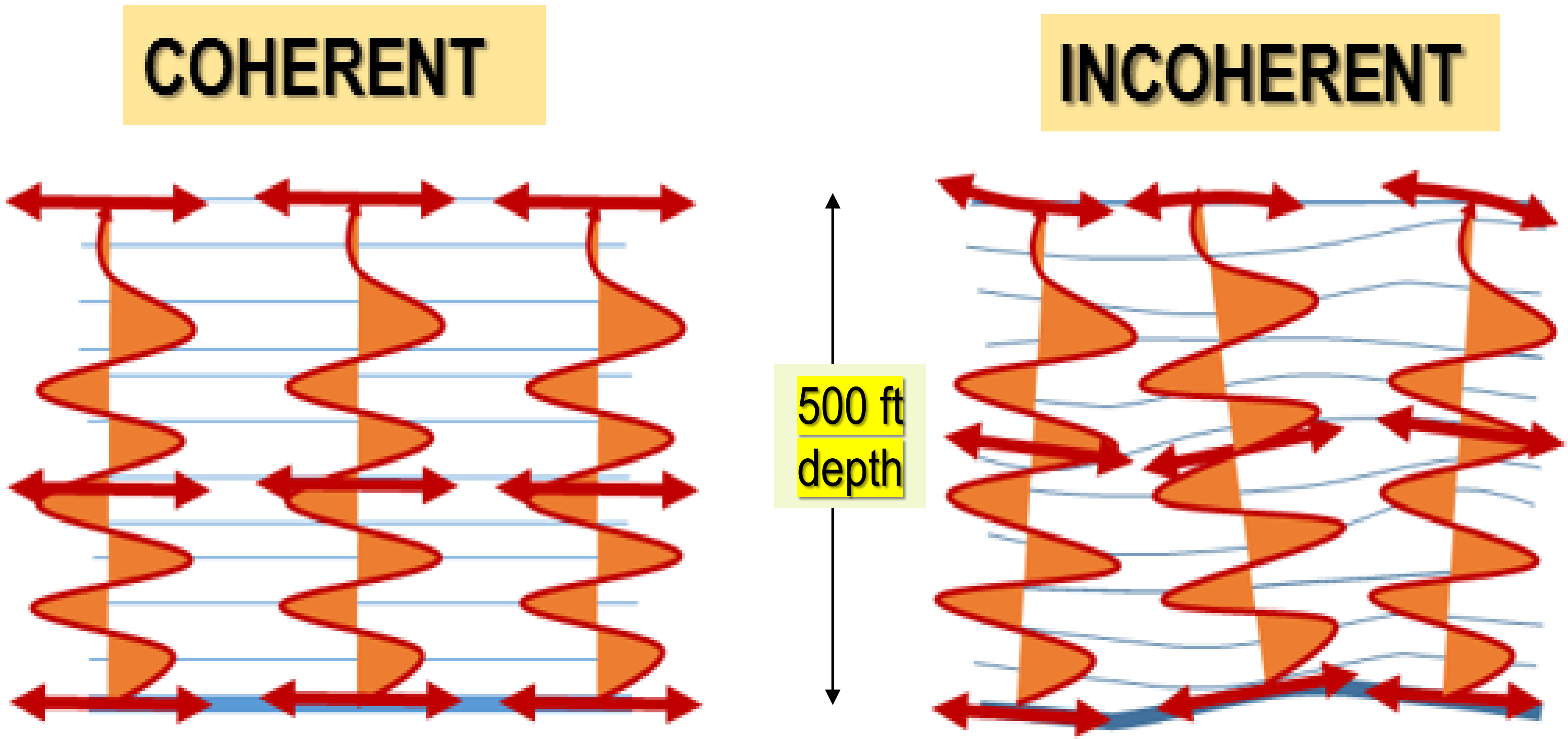
- Based on a limited number of 2D site response analyses, we noted that the site response appears to be not highly sensitive to slowly varying soil layer properties in the horizontal direction and presence of slightly inclined SV and P waves, and Rayleigh waves produced by the soil layer property variations in horizontal direction.

B2. Seismic Motion Variation in Horizontal Plane

Current practice:

- Seismic motion can be coherent motion (1D deterministic wave propagation) or incoherent motion (3D random wave propagation).
- Incoherent motions are allowed for the seismic SSI analysis for the rock sites which have very high-frequency inputs
- Motion incoherency is defined based on the 2007 Abrahamson coherence functions
- Motion incoherency is not required for soil sites
- Strict lower-bound limits are imposed to incoherent ISRS and structural response reductions vs. the coherent responses.
- Motion incoherency can amplify some SSI responses

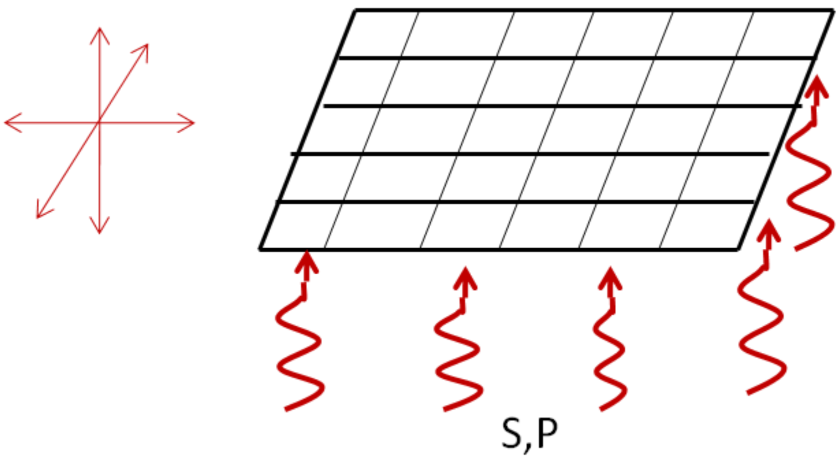
Coherent (1D) vs. Incoherent (3D) Seismic Motion



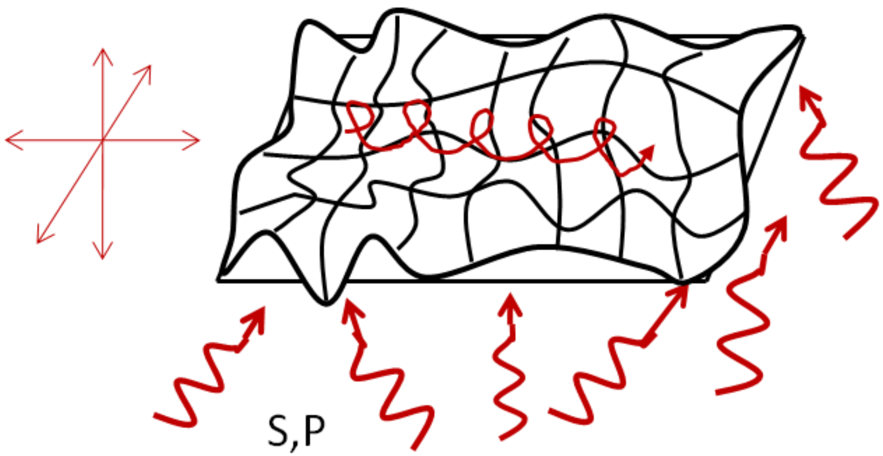
IDEALISTIC MOTION (1D DETERMINISTIC WAVE MODEL)	REALISTIC MOTION (3D RANDOM WAVE MODEL)
Assume vertically propagating S and P Waves in horizontal soil layering	Based on stochastic models developed from real record dense array databases

Coherent (1D) vs. Incoherent (3D) Seismic Motion

3D *Rigid* Body Soil Motion (Idealized)



3D Random Wave Field Soil Motion (Realistic)



1 D Wave Propagation Model (Coherent)

Vertically Propagating S and P waves (1D)

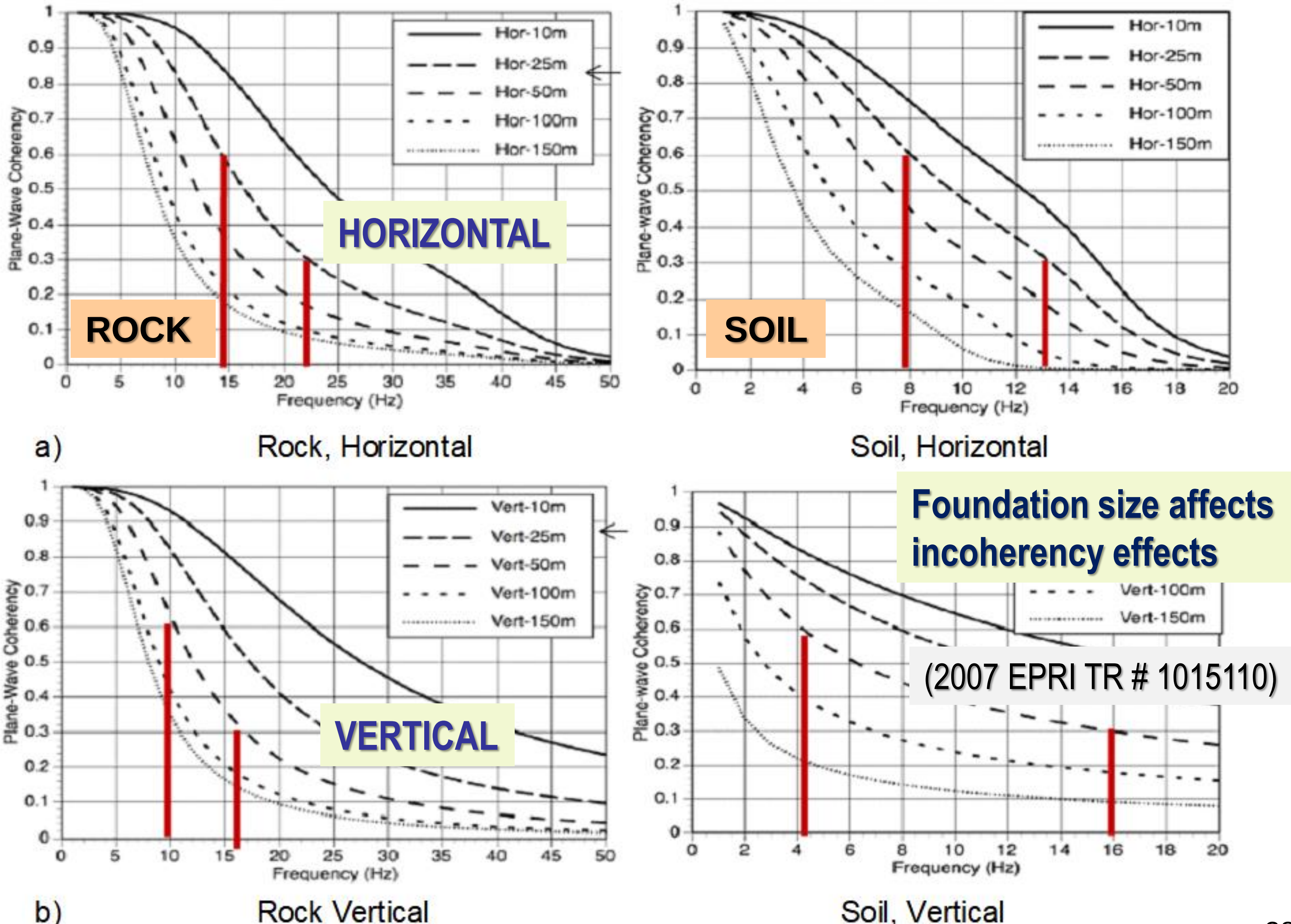
- No other waves types included
- No soil heterogeneity ncluded
- *Rigid body soil motions*, even for very large-size foundations

3D Wave Propagation Model (Incoherent).

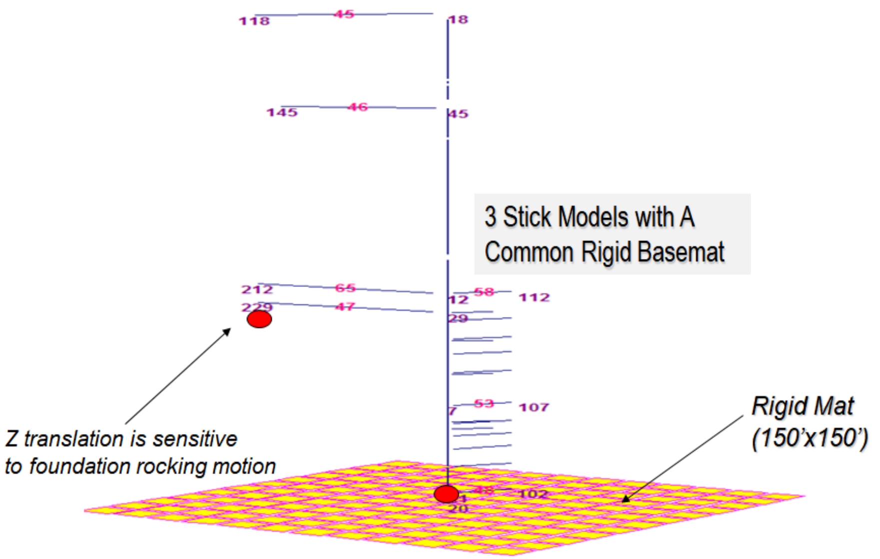
Based on the statistical models derived from various dense-array record databases (as the Abrahamson's plane wave coherency models)

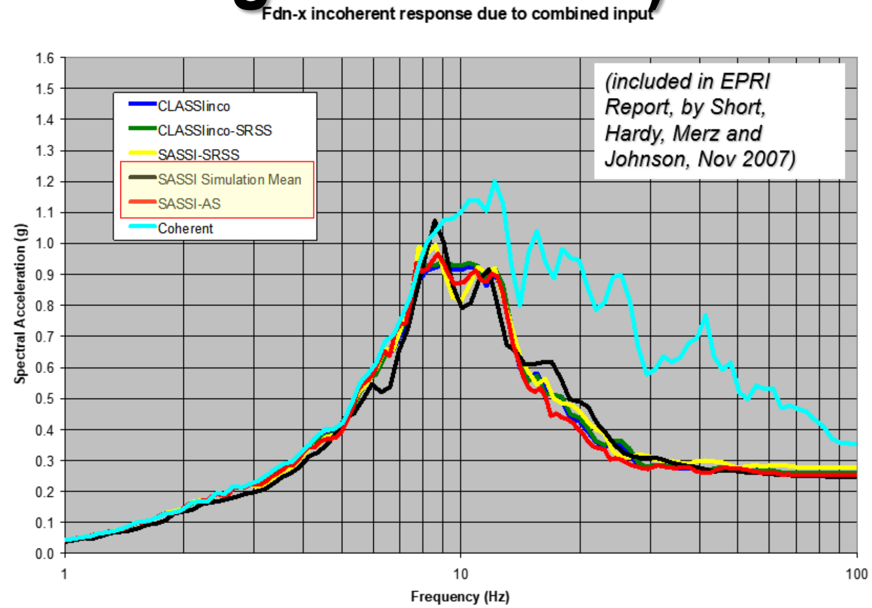
- Includes real field records information, including implicitly motion field heterogeneity, random arrivals of different wave types under random incident angles

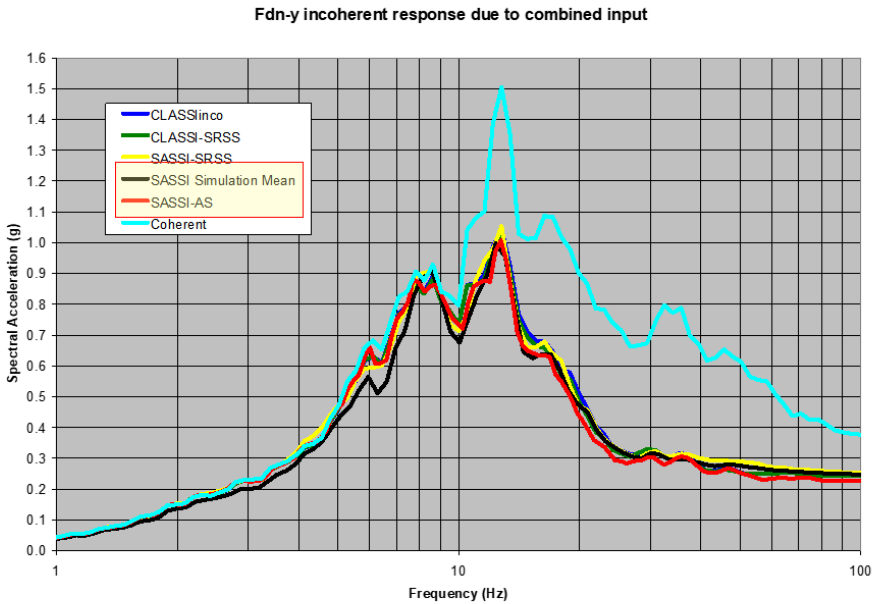
"Generic" Abrahamson Plane-Wave Coherence Functions

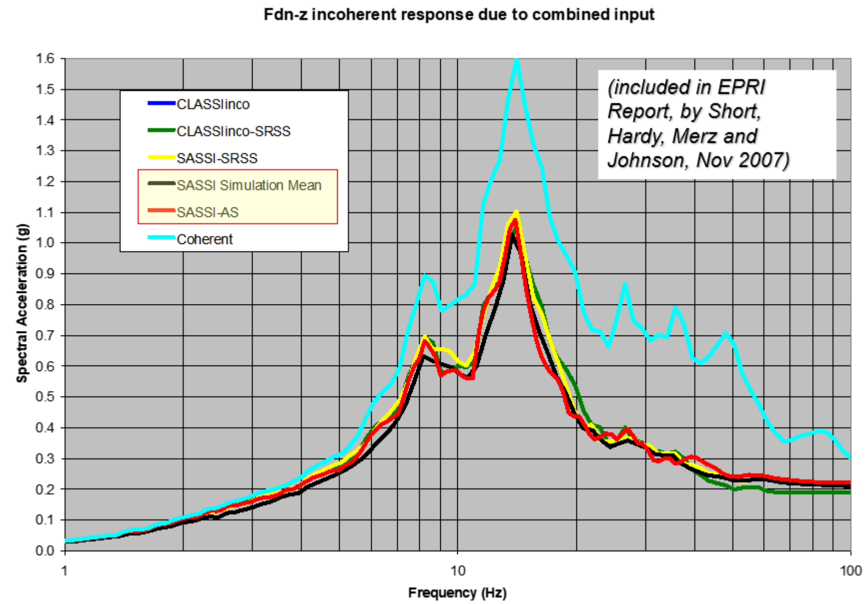


2007 EPRI Validation Study for AP1000 NI Stick Model (Surface Stick Model with Rigid Basemat)

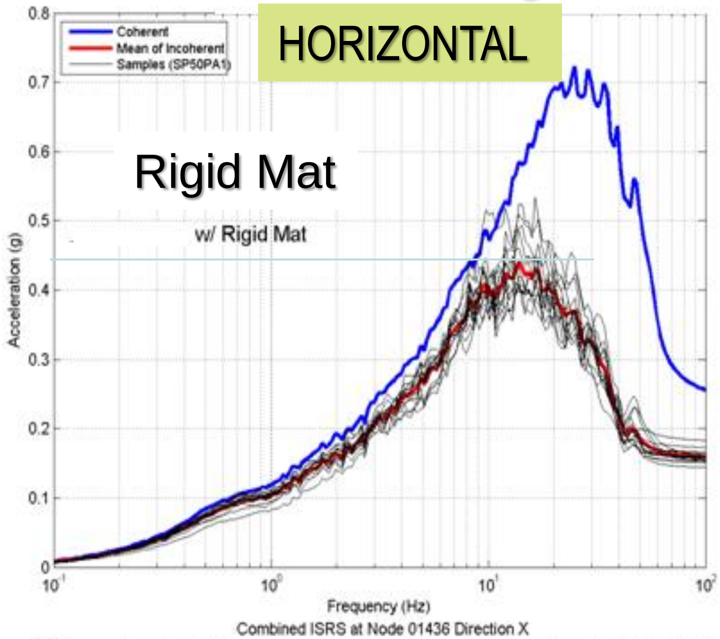


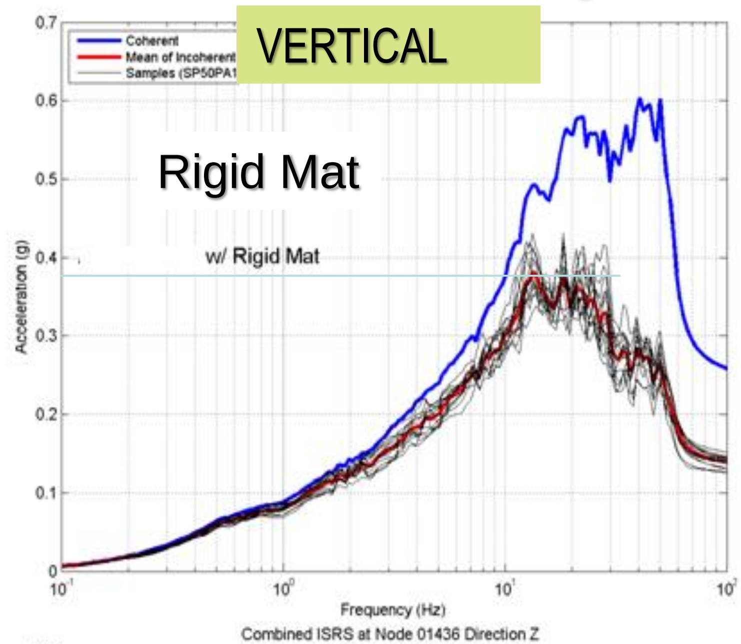




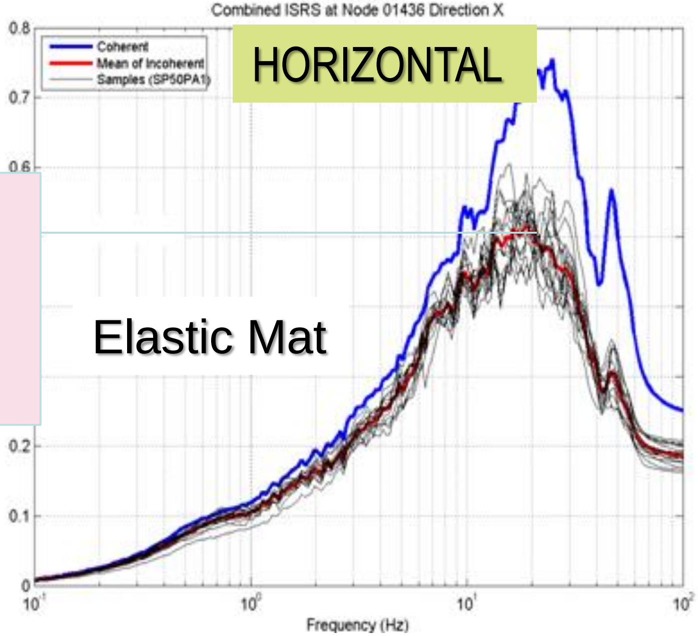


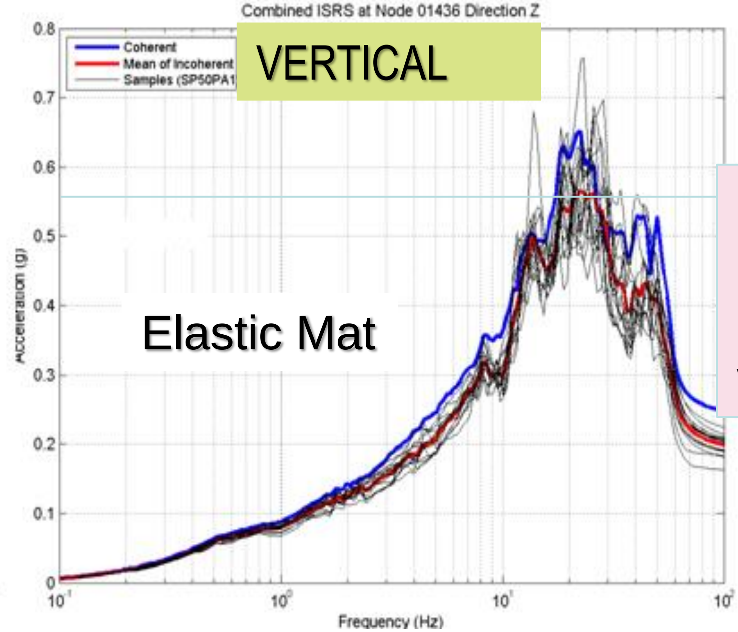
Basemat Flexibility Effects on RB Complex ISRS





Elastic is 20% up for horizontal

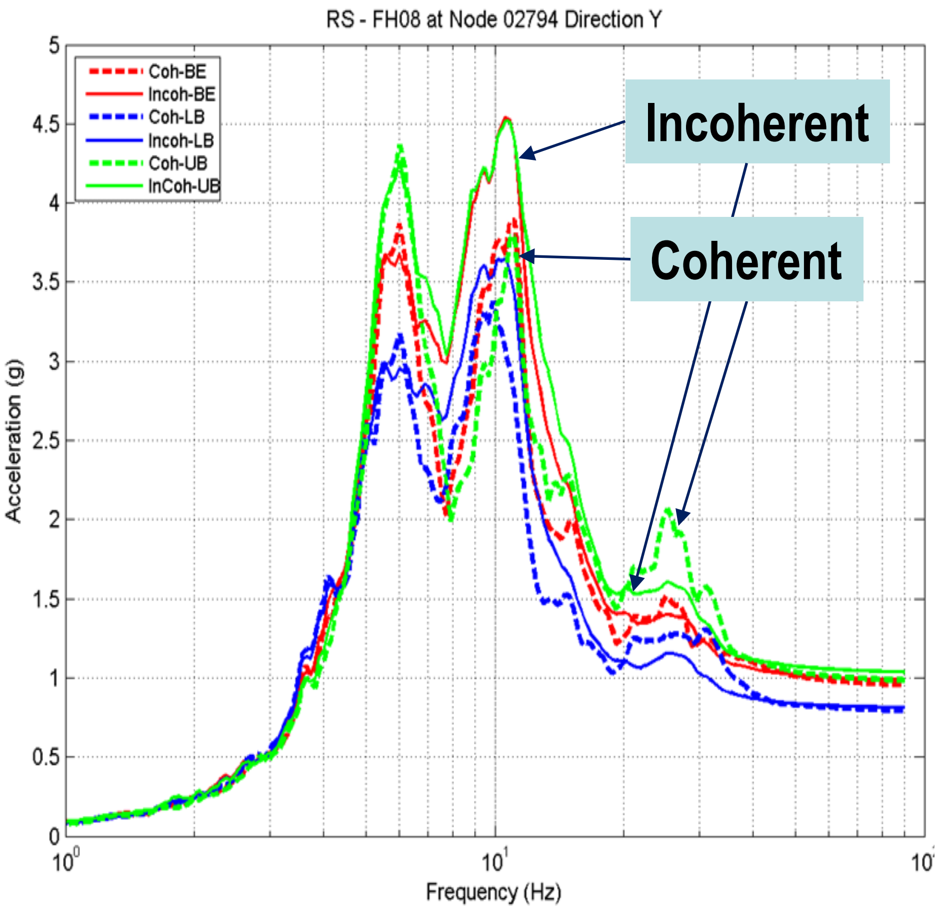


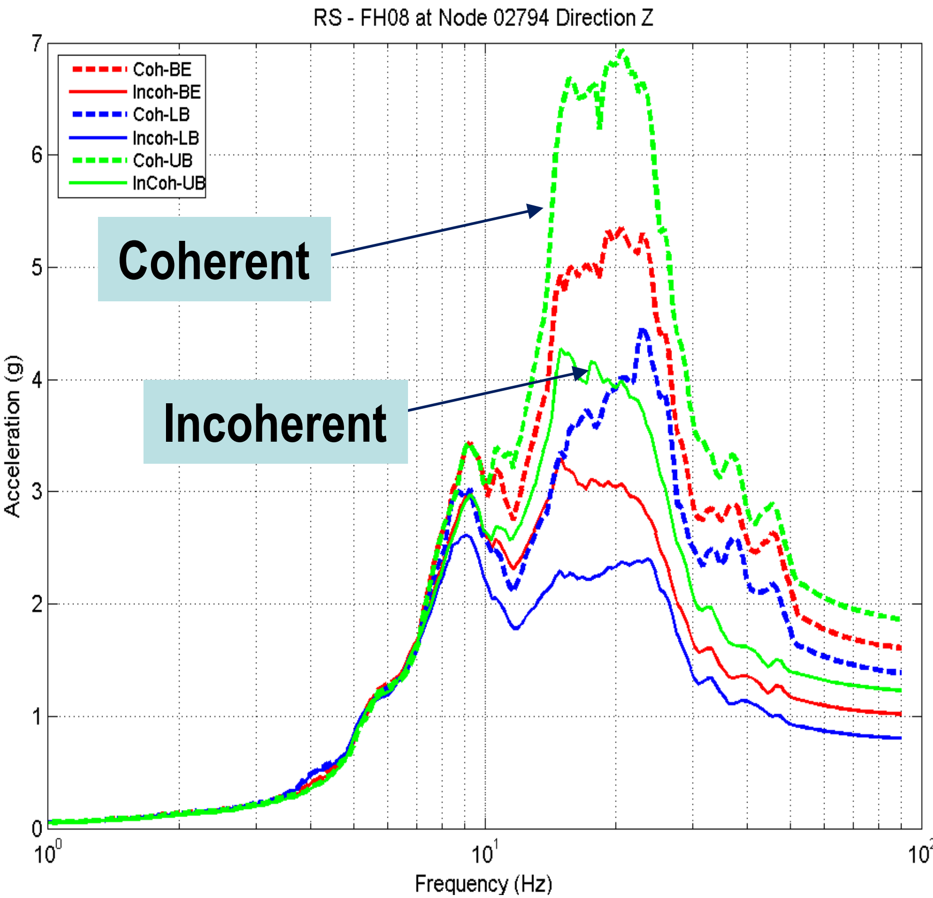


Elastic is 65% (!) up for vertical

Coherent vs. Incoherent SSI Analysis Results

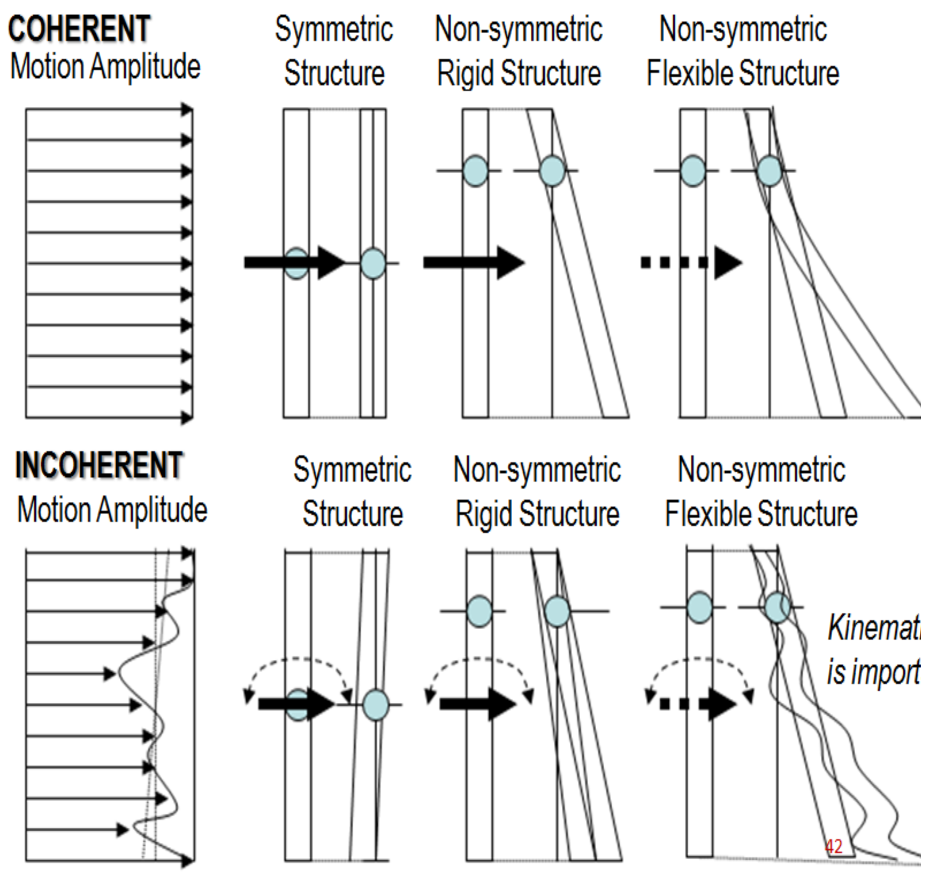
RB Complex Top-Corner ISRS in Transverse (left) and Vertical (right) Directions for LB, BE and US Soils



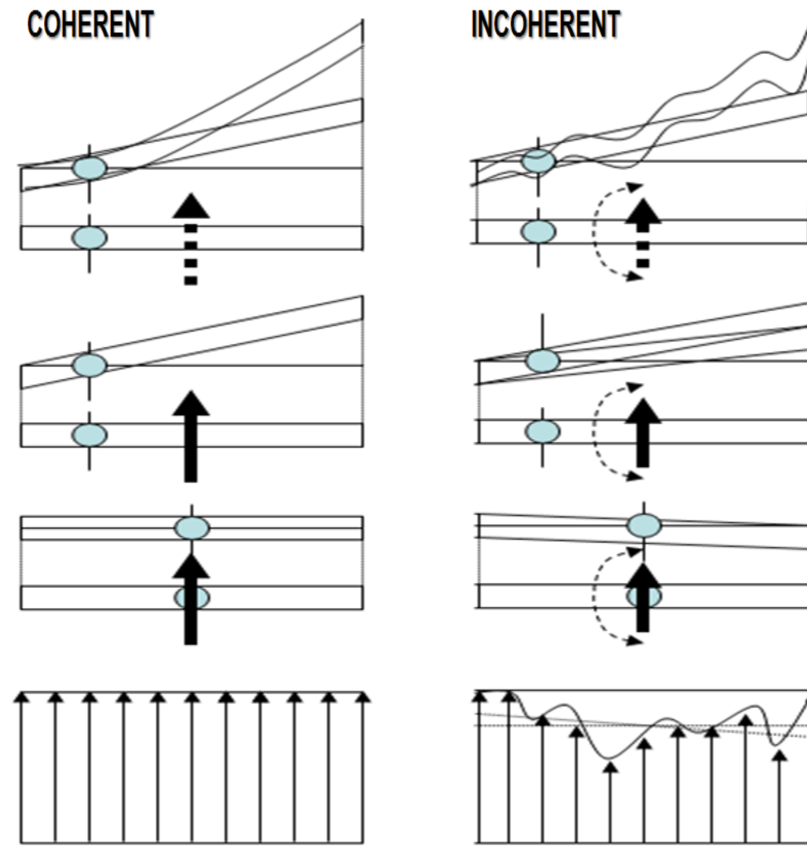


Motion Incoherency Differential Motions Produce Larger Kinematic SSI Effects

HORIZONTAL



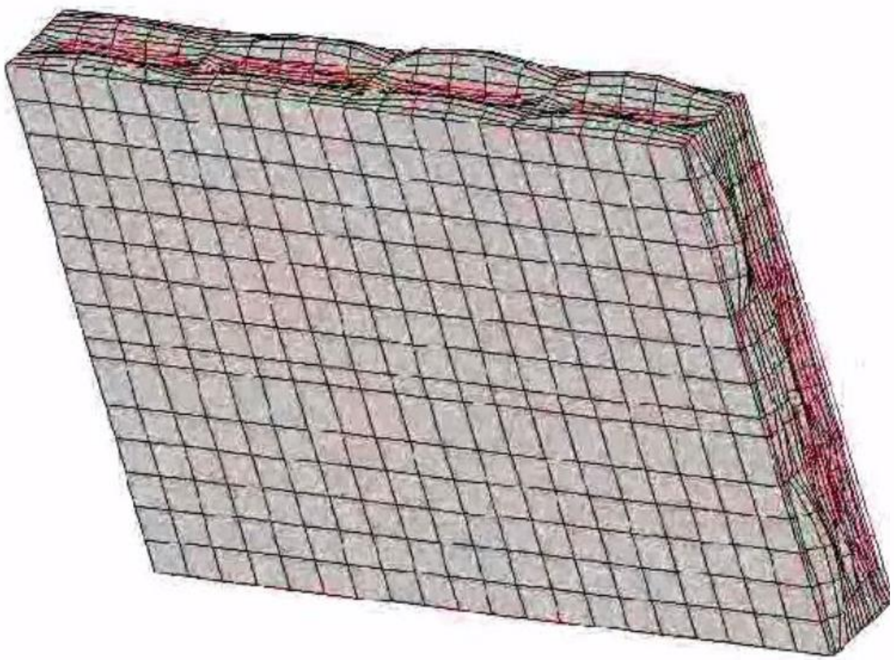
VERTICAL

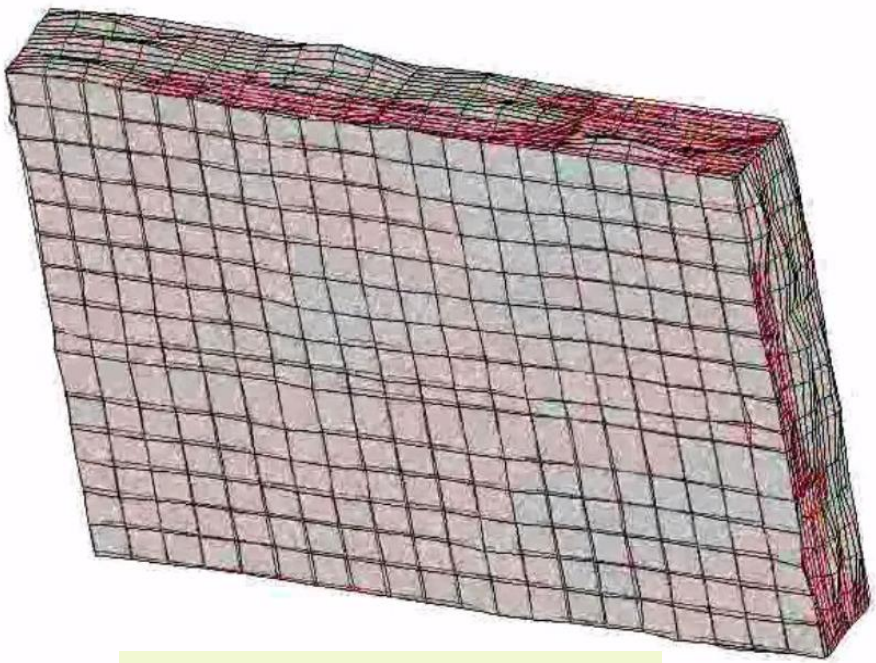


3D Wave Propagation or Motion Incoherency Effects on Baseslab Bending

Coherent SSI Motion

Incoherent SSI Motion



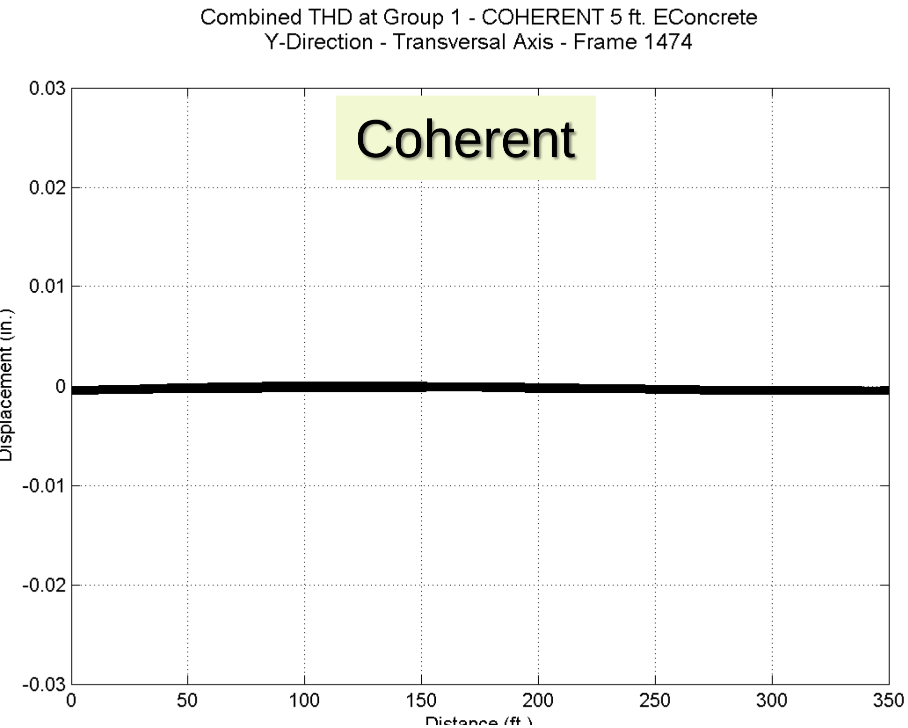


soil moves as rigid plane under foundation!

soil moves as 3D waves under foundation!

ANIMATION 3

Motion Incoherency Effects on Basemat Bending



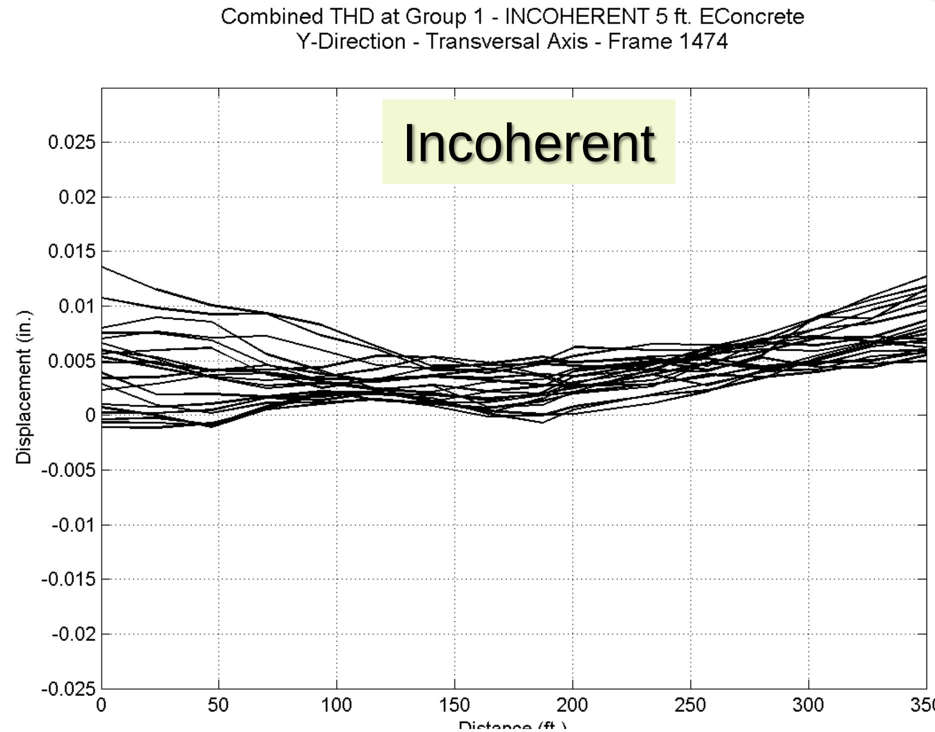


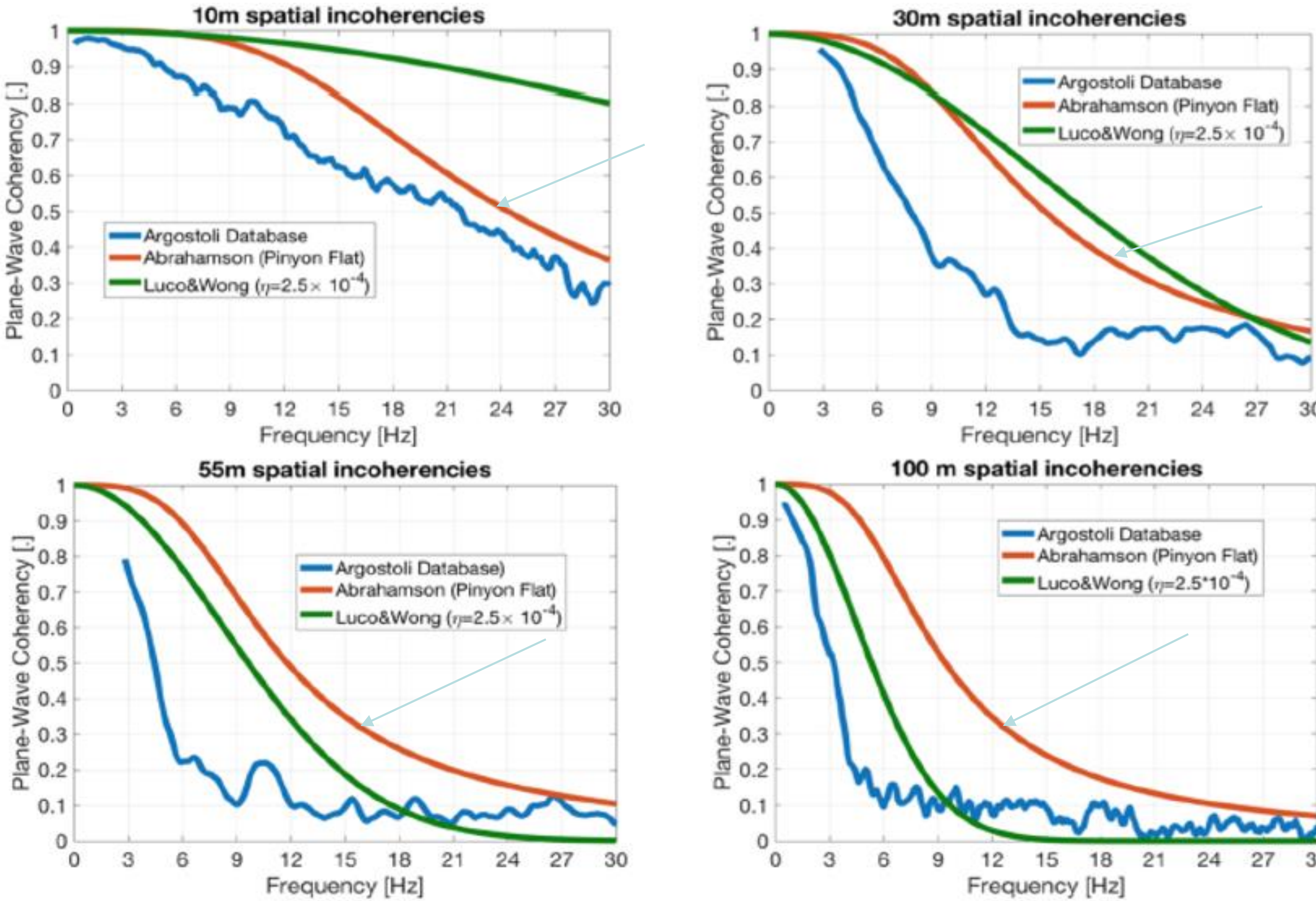
Table 1: Baseslab Bending Moments for A Soil Deposit with Vs = 3,300 ft/s

Zone #	Coherent MXX	Incoherent MXX	Ratio Inc./Coh MXX	Coherent MYY	Incoherent MYY	Ratio Inc./Coh MYY
1	10.293	15.196	1.476	9.567	14.812	1.548
2	8.345	19.986	2.395	7.197	14.901	2.070
3	10.291	13.499	1.312	9.695	15.475	1.596
4	7.404	14.859	2.007	8.386	17.199	2.051
5	7.360	14.618	1.986	7.124	14.879	2.089
6	7.370	17.503	2.375	8.354	14.293	1.711

Remark: Incoherent bending moments are 130%-240% of coherent bending moments.

(Ghiocel, DOE NPH Meeting, 2014)

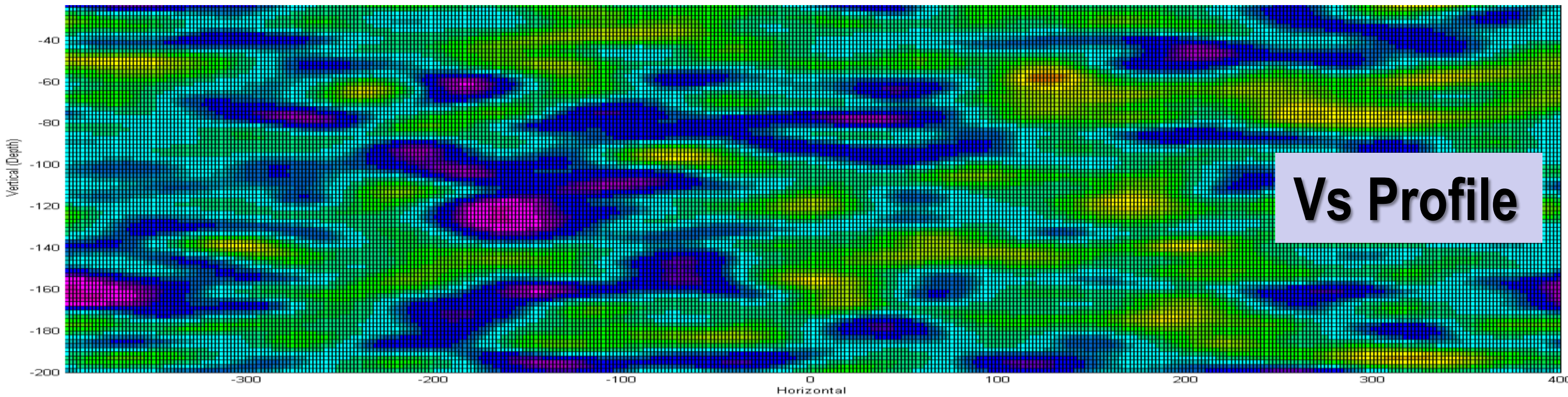
“Site-Specific” Plane-Wave Coherence Functions

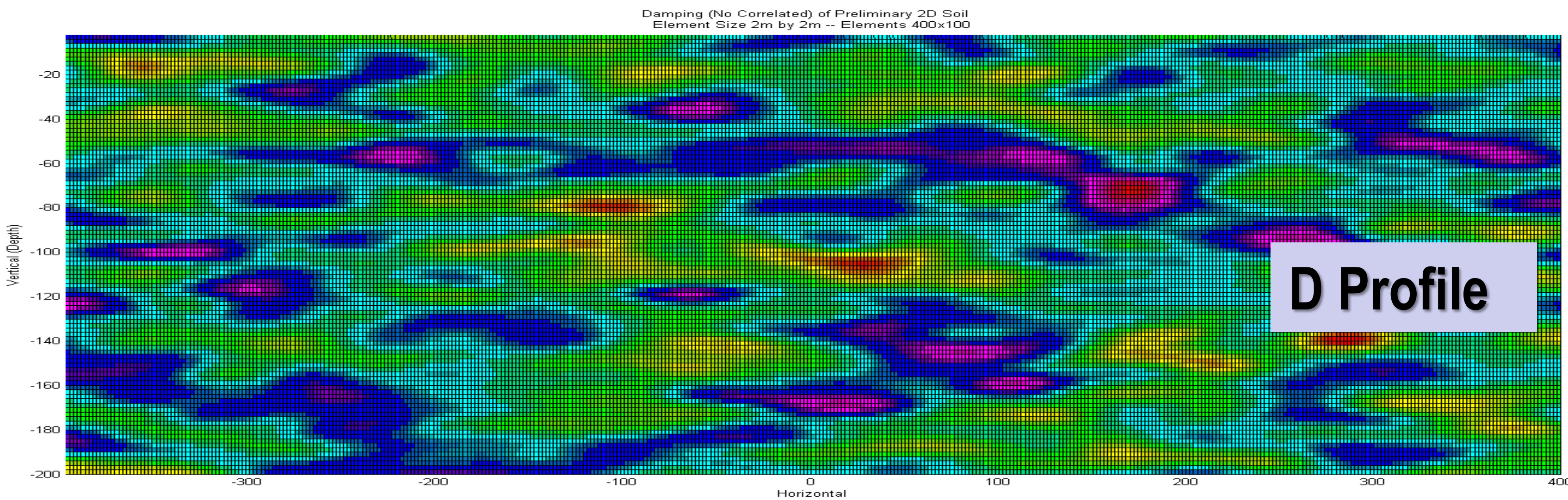


Site-Specific Coherence Functions for Argostoli Site (after Svay et al., 2016, EDF Seminar)

2D Soil Model Probabilistic Simulations for "EDF Digital Site" (Vs = 818m/s)

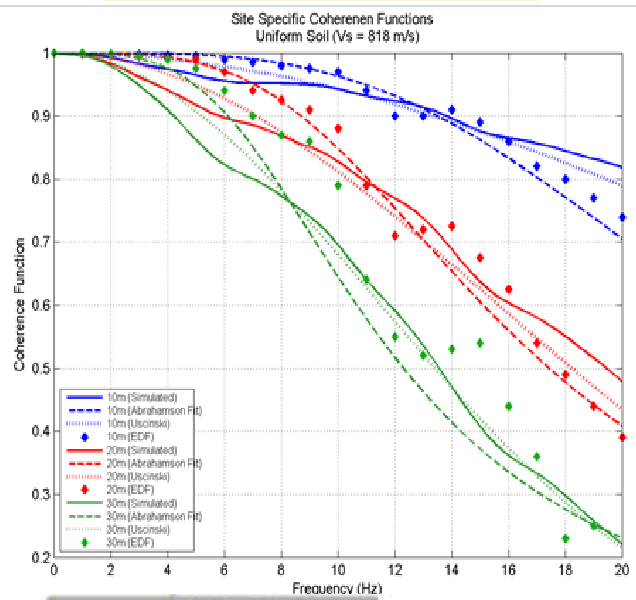
Vs and D Simulated Profiles for Correlation Lengths of 60m x 10m

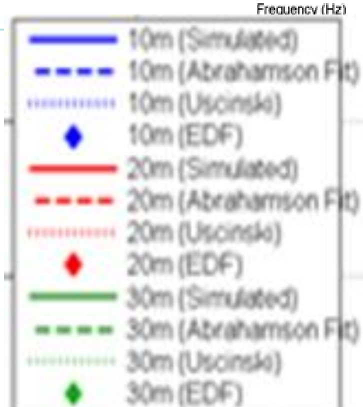


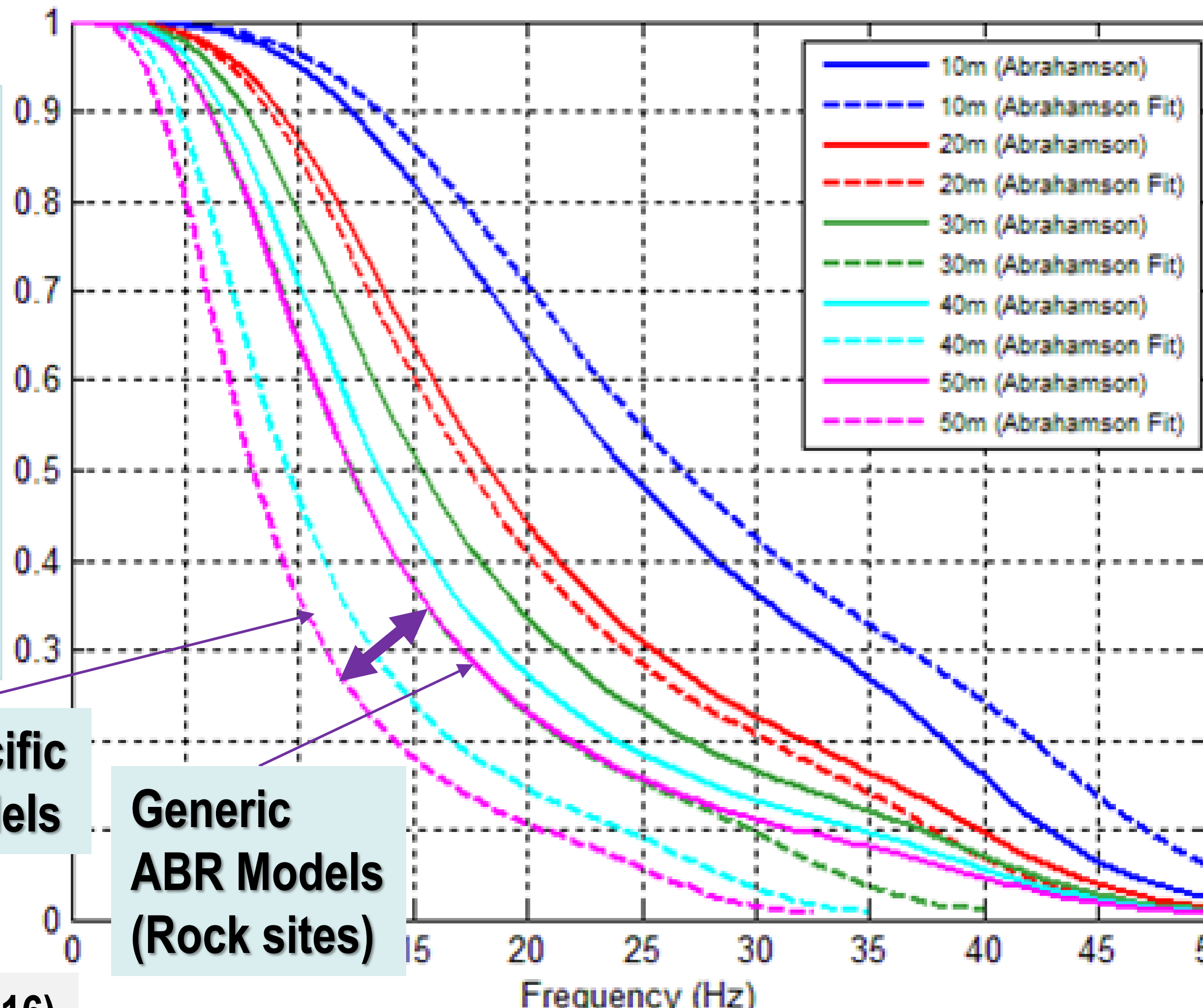


Site-Specific Coherence Functions Computed for "*EDF Digital Site*" with An Uniform Soil with Vs=818m/s

Comparative Results For EDF Digital Site







Site-Specific ABR Models

Generic ABR Models (Rock sites)

(Zentner, 2016)

Remarks on Seismic Motion Incoherency Effects

- Seismic incoherent motions are more realistic seismic motion inputs being based on a 3D random wave propagation field data.
- In principle motion incoherency exists for both rock and soil sites.
- Motion incoherency could amplify the bending moments in the foundation walls and basemat.
- For soil sites, incoherency could amplify some structure torsional responses in the 2-10 Hz range, especially for structures that have poor seismic design layouts with significant mass eccentricities.
- Abrahamson generic coherence function models might not be fully accurate for some site-specific conditions

5. Seismic SSSI Effects on ISRS and Soil Pressures

Seismic SSSI Effects

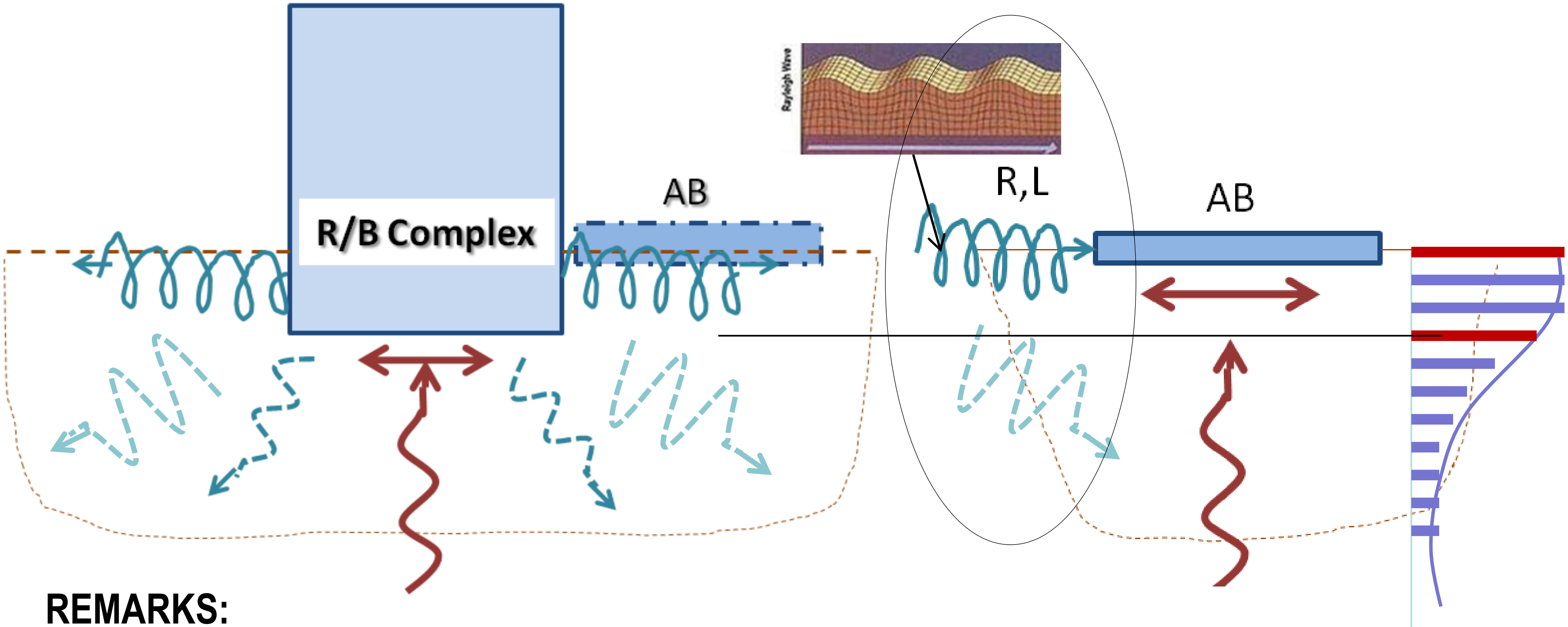
Current practice:

- SSSI effects could impact significantly on the local SSI responses, especially on the seismic soil pressures
- SSSI effects are larger for soil sites than rock sites, and for buildings which are very close than with a larger separation.
- Seismic SSSI effects are larger for the neighbor buildings with multiple level foundations
- No mandatory requirements are implemented for evaluation of the SSSI effects on ISRS

Seismic SSSI Effects Could Affect Largely ISRS and Soil Pressures

R/B Complex – AB Interaction

SSSI Effects on AB

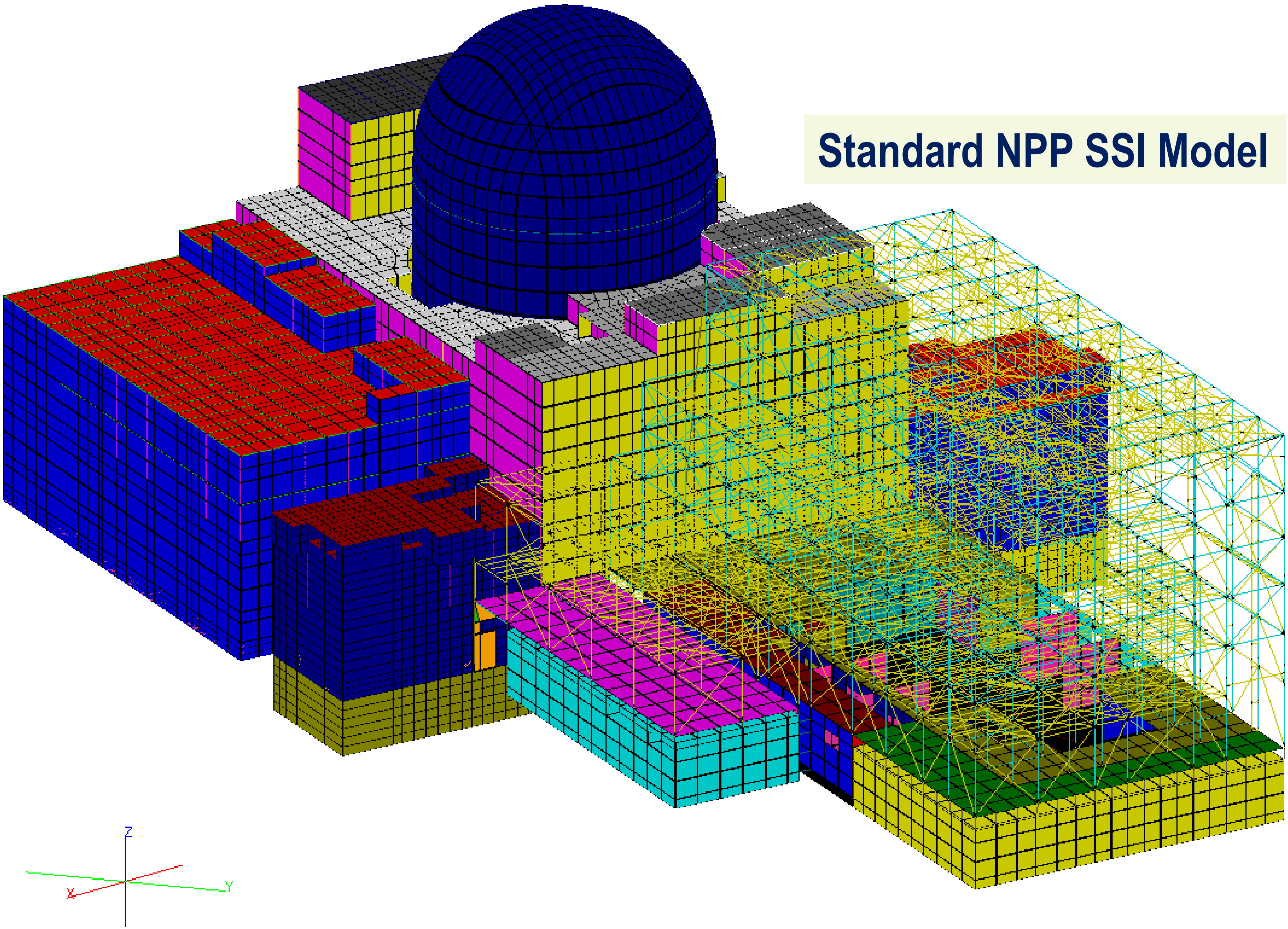


REMARKS:

- The SSSI effects could be significant. Both i) wave scattering and ii) inertial coupling effects could play significant roles. Effects show more significant in the ISRS and soil pressures.
- Foundation levels and sizes affects the SSSI phenomena
- Light surface structures in vicinity of large embedded nuclear islands (NI) could be affected seriously by wave scattering effects;

ANIMATION 4

SSSI Model Includes Multiple Nuclear Structures



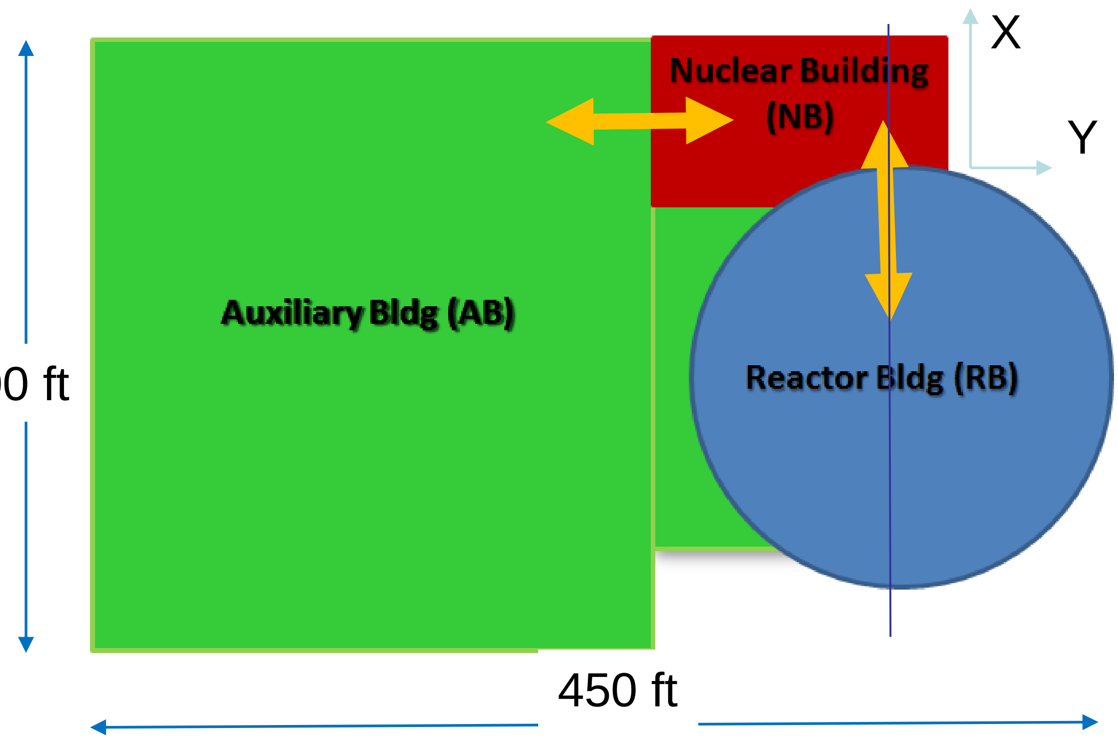
6. Seismic SSI and SSSI Case Studies.

Case 1: Incoherent vs. Coherent Seismic SSSI

Typical NPP SSSI Model

Compute relative displacements between NB and RB buildings:

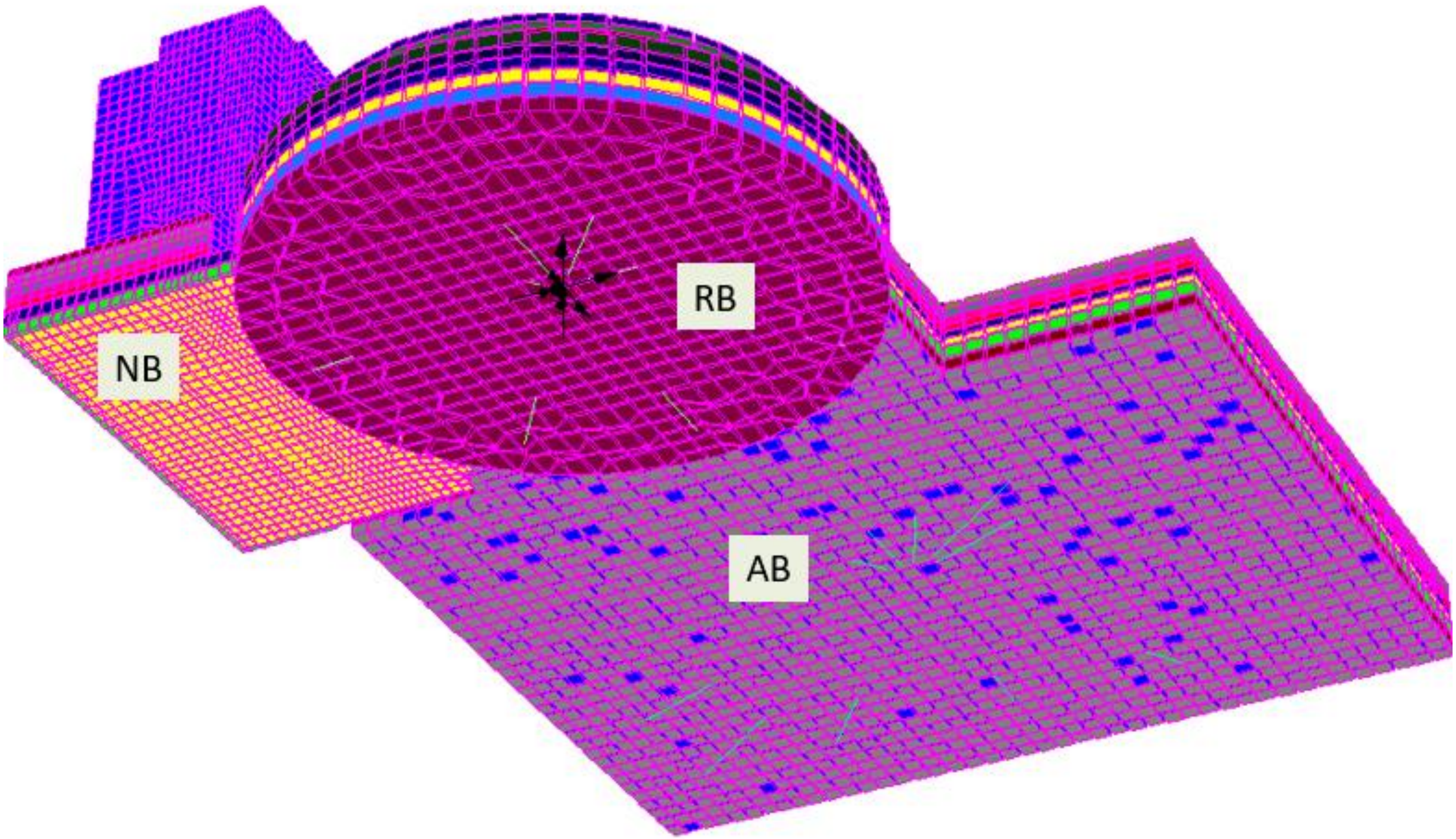
Differential motion amplitude is twice larger for incoherent input



	Coordinates			Absolute Difference of Displacements Coherent			Incoherent-Sample1		
Node Number Model	X	Y	Z	X	Y	Z	X	Y	Z
49678RB	-75.615	27	30						
49760I	-76.67	26.922	30	0.061357	0.020896	0.148144	0.13164	0.03274	0.1385
14966RB	-72.881	33.75	30						
32740I	-73.941	33.611	30	0.060101	0.022399	0.128837	0.12595	0.03474	0.10894

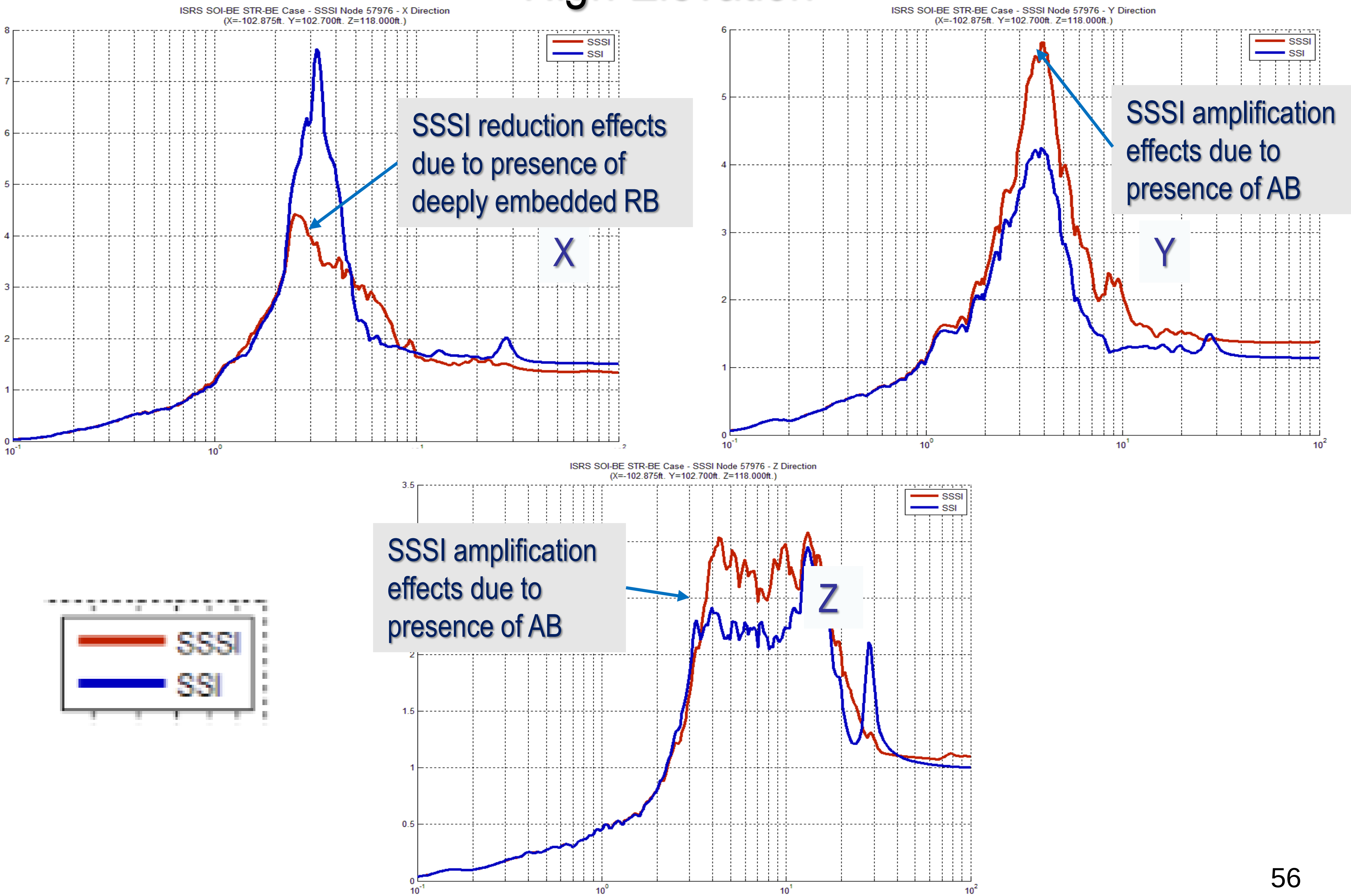
Soil site with Vs from 800fps to 1800fps at 600ft depth

SSSI Model with Multiple Structures Having Different Foundation Levels



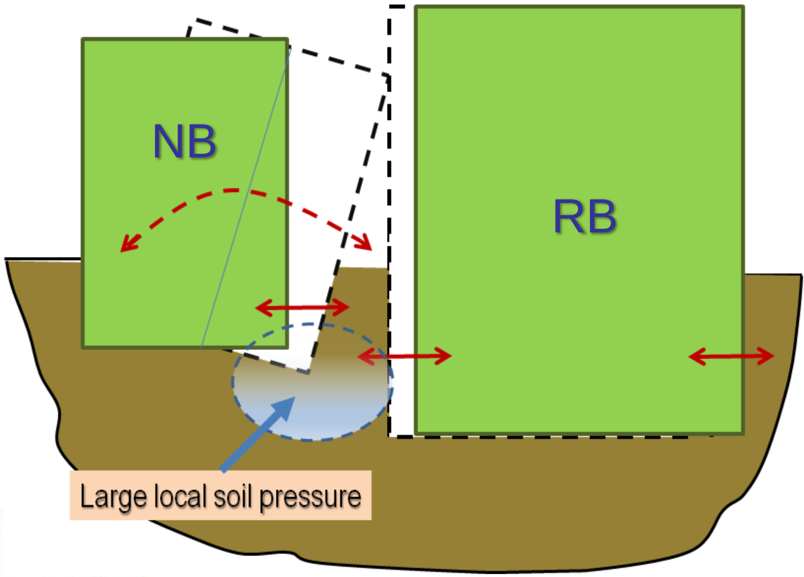
Seismic SSSI Effects on the NB ISRS

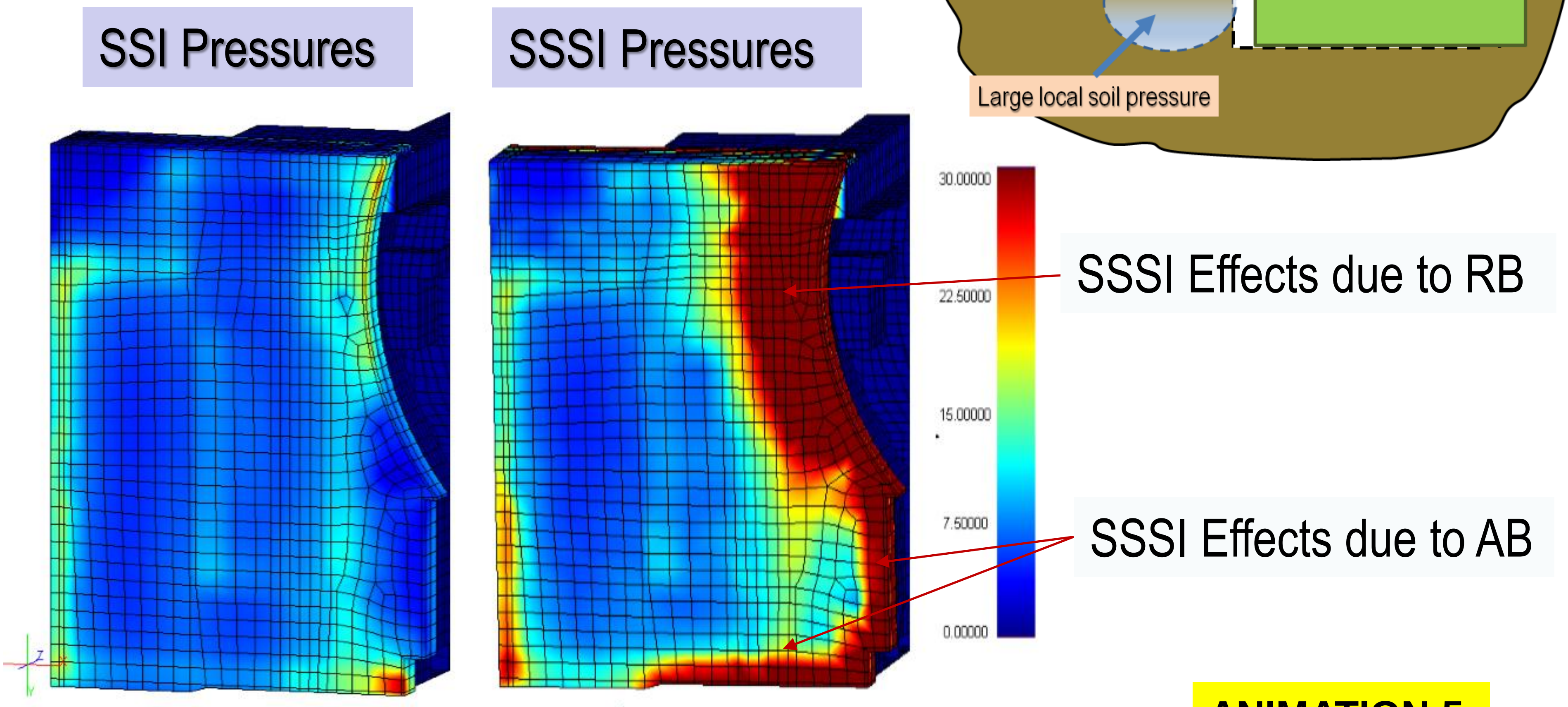
High Elevation



Seismic SSSI Effects on NB Basemat Pressures

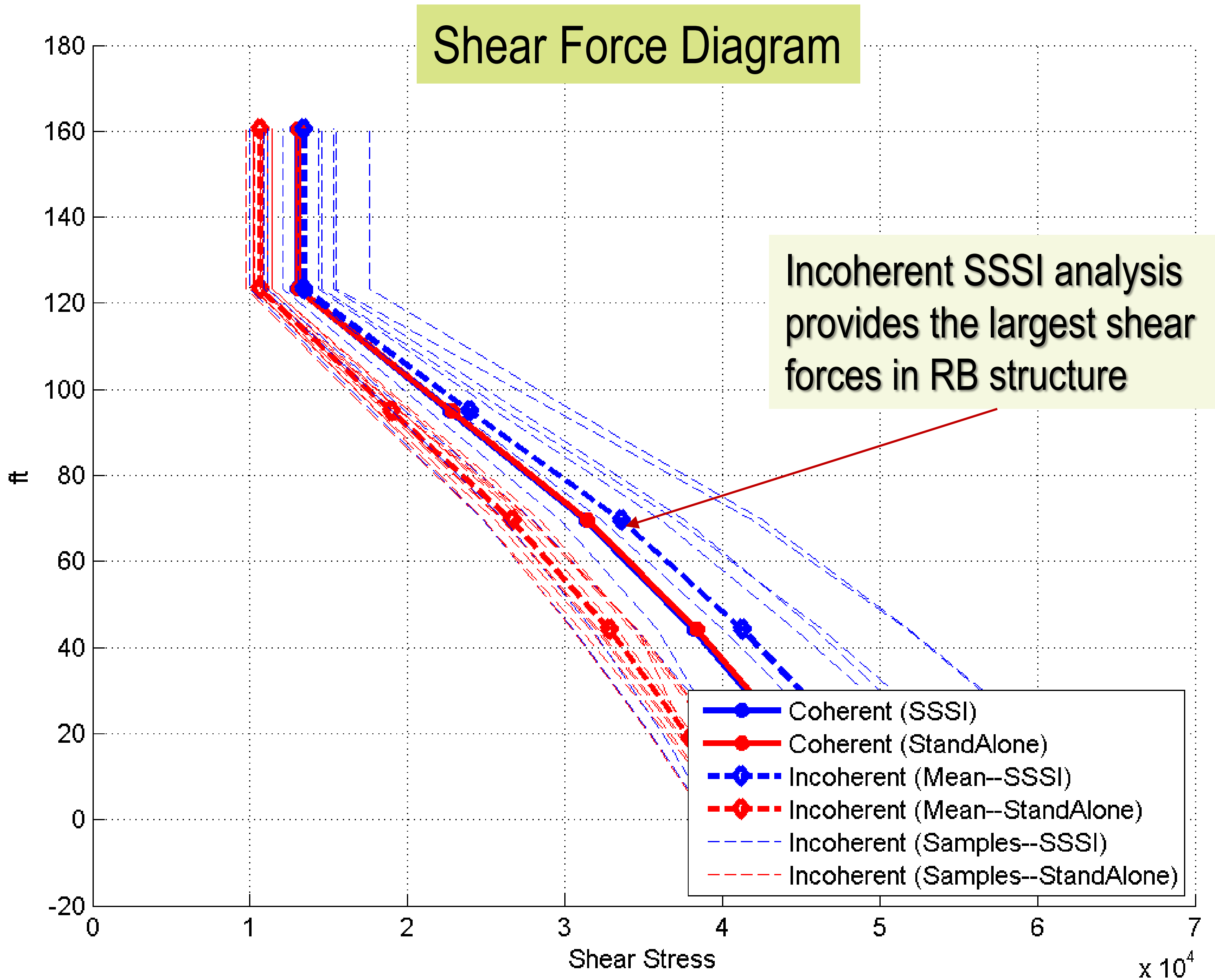
SSSI Effects may increase severely seismic pressures on foundation walls and basemat. Suggestion to include local nonlinear soil behavior (only 2-3 iterations)





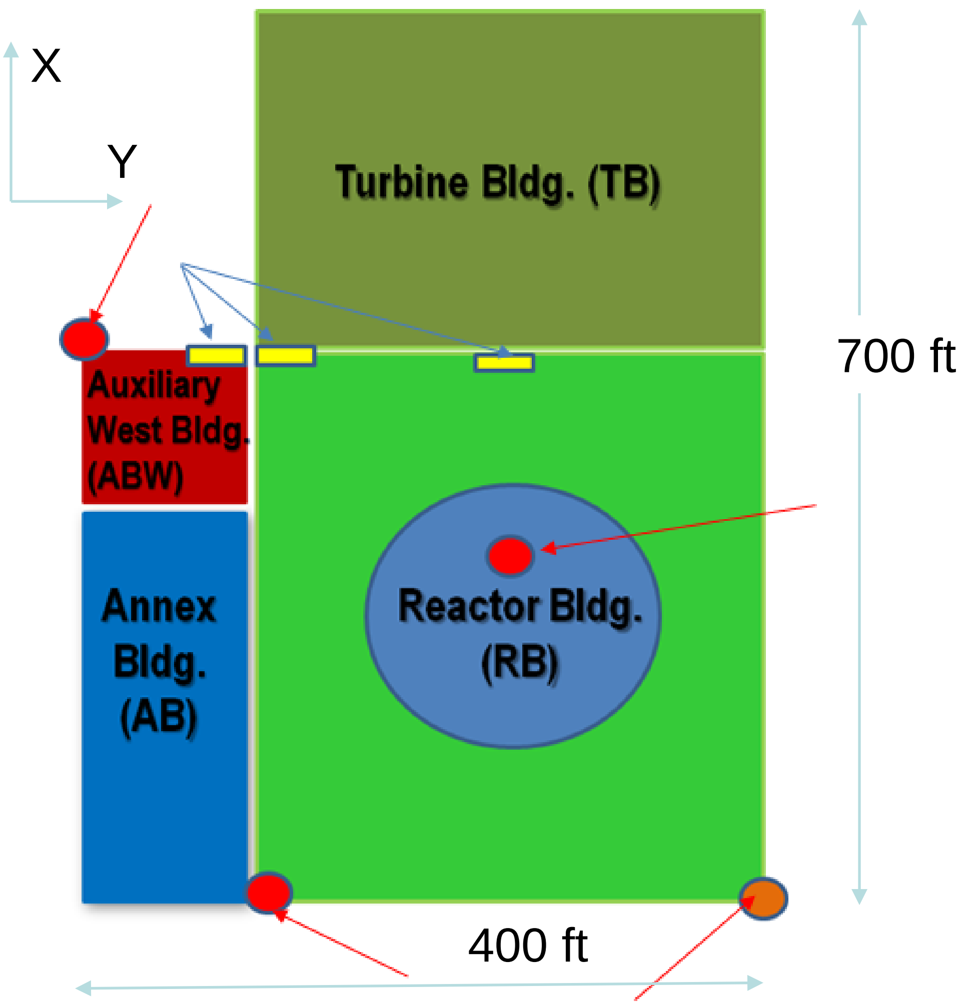
ANIMATION 5

Seismic SSSI Effects on Shear Forces in RB

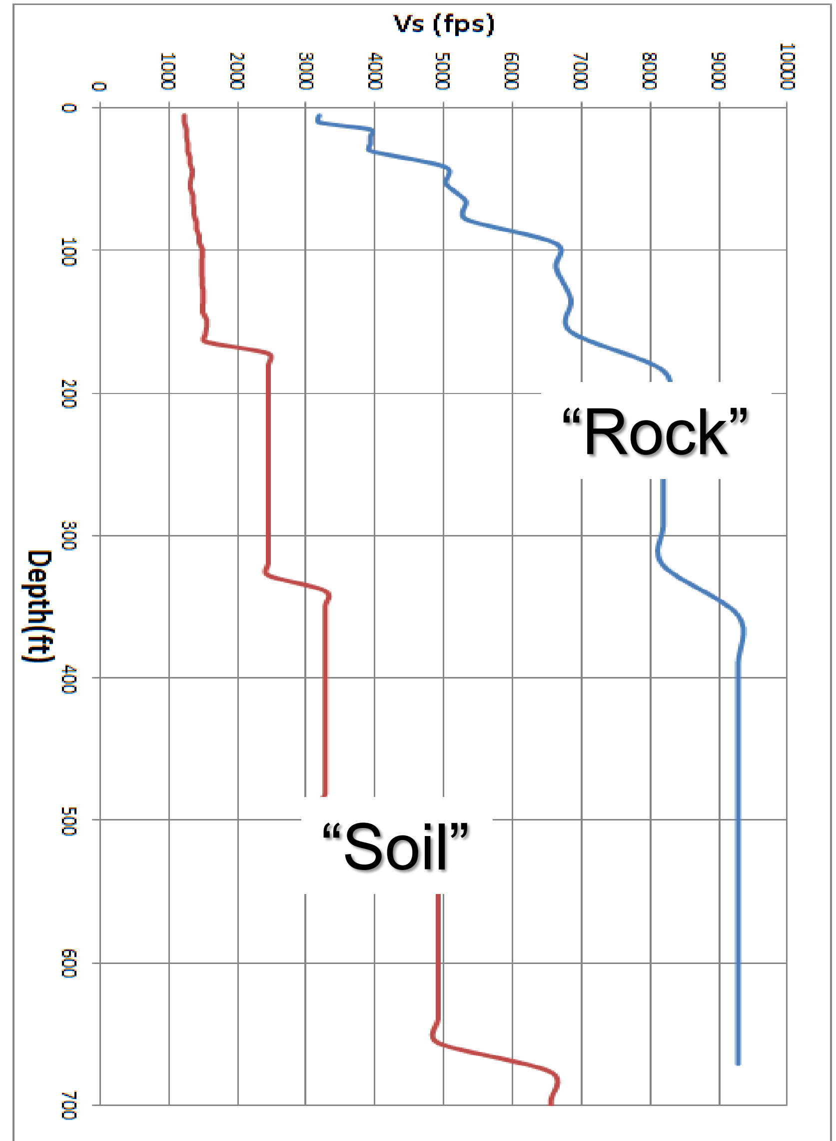


Case 2: Incoherent vs. Coherent Seismic SSSI Effects

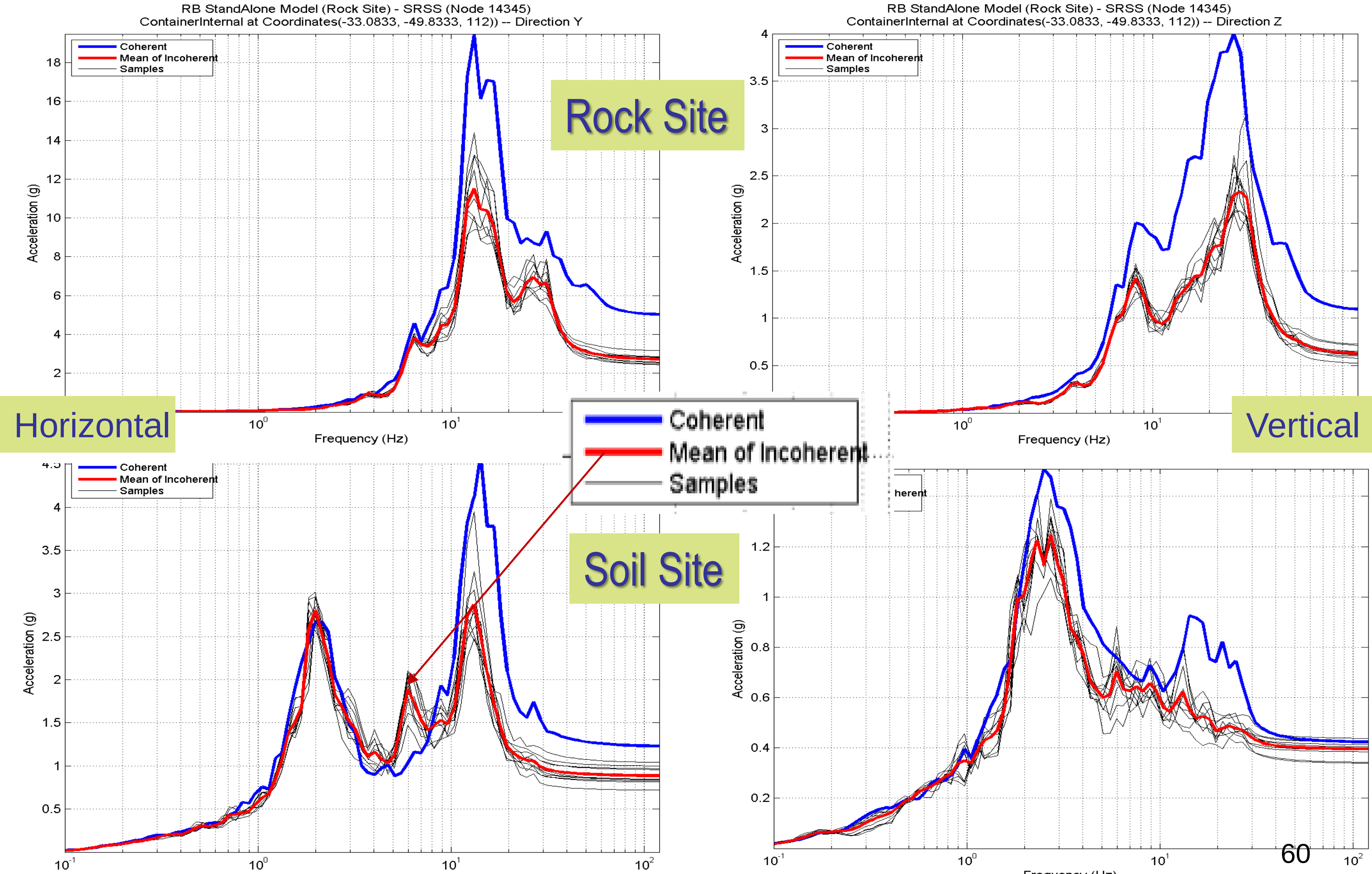
Typical NPP SSSI Model



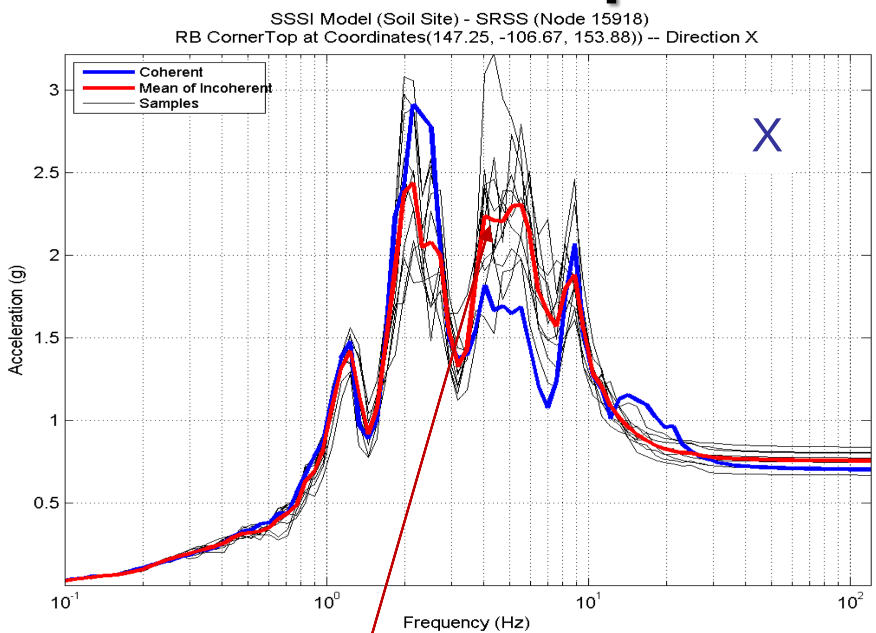
Soil Profiles

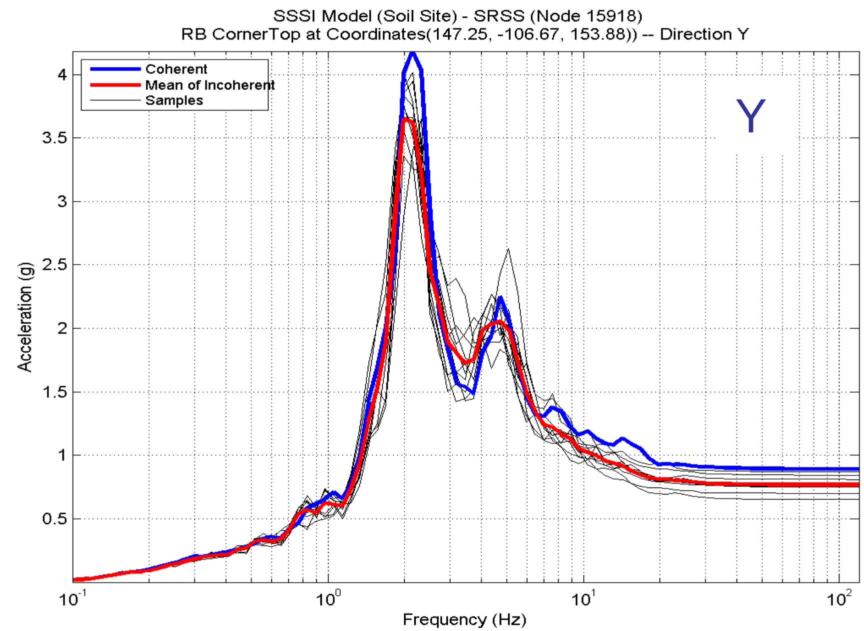


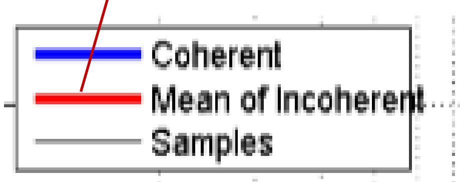
RB Complex Coherent vs. Incoherent SSSI Effects on ISRS on Top of Internal Structure – Y and Z Directions

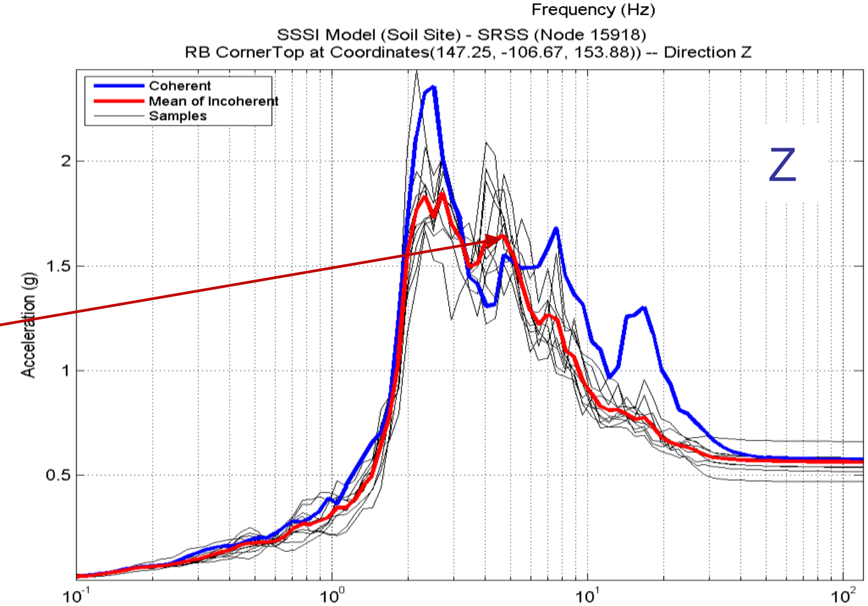


RB Complex Coherent vs. Incoherent SSSI Effects on ISRS at Top Corner Near AWB for Soil Site





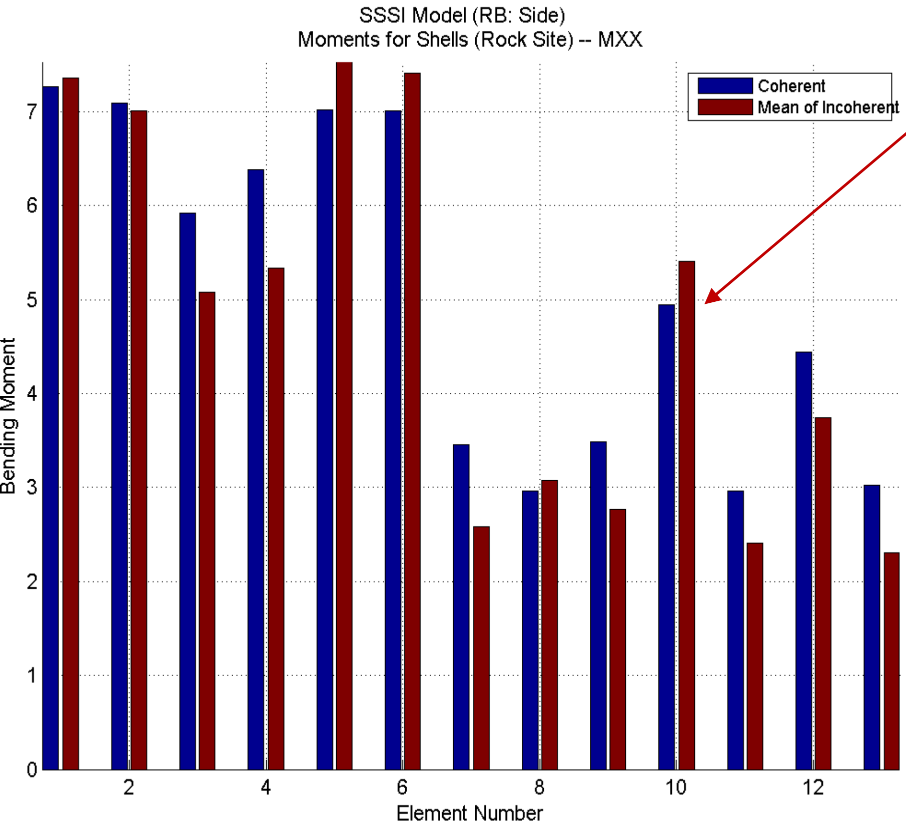


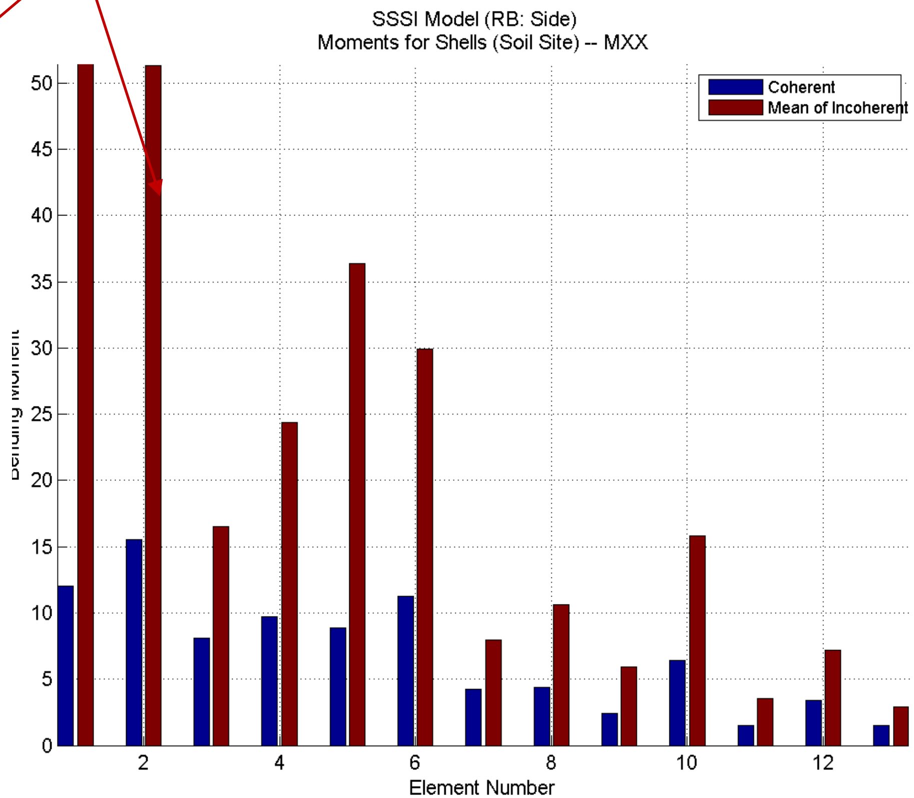


Coherent vs. Incoherent SSSI Effects for Bending Moments in Corner Wall Near AB Bldg.

Rock Site

Soil Site





ANIMATION 6

Remarks on Seismic SSSI Effects

- Seismic SSSI effects could affect largely the soil pressures and ISRS; Need to include mandatory requirement in the ASCE 4-20 standard
- Structural forces are affected less by SSSI effects
- Motion incoherency could increase the SSSI effects for soil sites. New aspect.

7. Other Important SSI Modeling Aspects Not Addressed in this Overview

Other Important SSI Modeling Aspects Not Addressed in This Presentation

Concrete cracking and nonlinear structure behavior

Current practice remarks:

- Iterative equivalent-linear hysteretic models are usually reasonable for the material nonlinear behavior. For the concrete cracking, the ASCE 4-16 Section C3.3.2 recommends at a minimum a two-step equivalent-linearization procedure.

- The equivalent-linear models are numerically efficient and reasonable accurate for practical engineering analysis purposes.

Foundation sliding and uplift effects

Current practice remarks:

- Nonlinear dynamic analyses in 2D and 3D for investigating sliding and uplift analyses are numerically sensitive to the interface modeling parameters and hugely computational demanding, plus need very careful expert verification and interpretation of results.

- Multistep nonlinear analyses are based on the linearized overall SSI response in 1st step to get the input BCs for the nonlinear contact structure analysis in 2nd step. Similar to the ASCE 4-16 recommendations for the base-isolated structures. It permits rapid sensitivity studies on the interface modeling and other nonlinear local aspects in structure.

Including SSI Modeling Uncertainties

Current practice remarks:

- The recent ASCE 4-16 standard provides an unique set of engineering guidance for modeling SSI uncertainties using physics-based probabilistic SSI models.

- *Probabilistic SSI analysis is a superior engineering approach, if correctly implemented by the analyst*. Need experts and analyst training.

- The ASCE 4-16 based probabilistic SSI analysis provides a solid basis for improving the design-basis SSI analysis and the fragility calculations in next future.

- Need for research projects to fully understand in all details the differences between probabilistic and deterministic SSI results.

7. Concluding Remarks

Concluding Remarks

Current US practice provides a advanced, robust and practical approach for the seismic SSI analysis that ensures the safety of NPPs subjected to earthquakes.

A specific engineering need that should attract more attention in future is to better understand the effects of the motion incoherency on the SSI and SSSI responses for both the rock and soil sites.