Overview of ACS SASSI NQA V4.3 Application to Seismic SSI Analysis of Safety-Related NPP Buildings

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Part 1: Understanding Seismic SSI Effects

GP Technologies, Rochester, New York

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Purpose of This Presentation:

Present an overview of the seismic SSI effects on the NPP structures in the light of the recent US practice trends based on ASCE 4-16 and 43-19 standards and USNRC SRP 3.7.1 and 3.7.2. regulatory guidance.

Illustrate key SSI modeling issues showing relevant case studies.

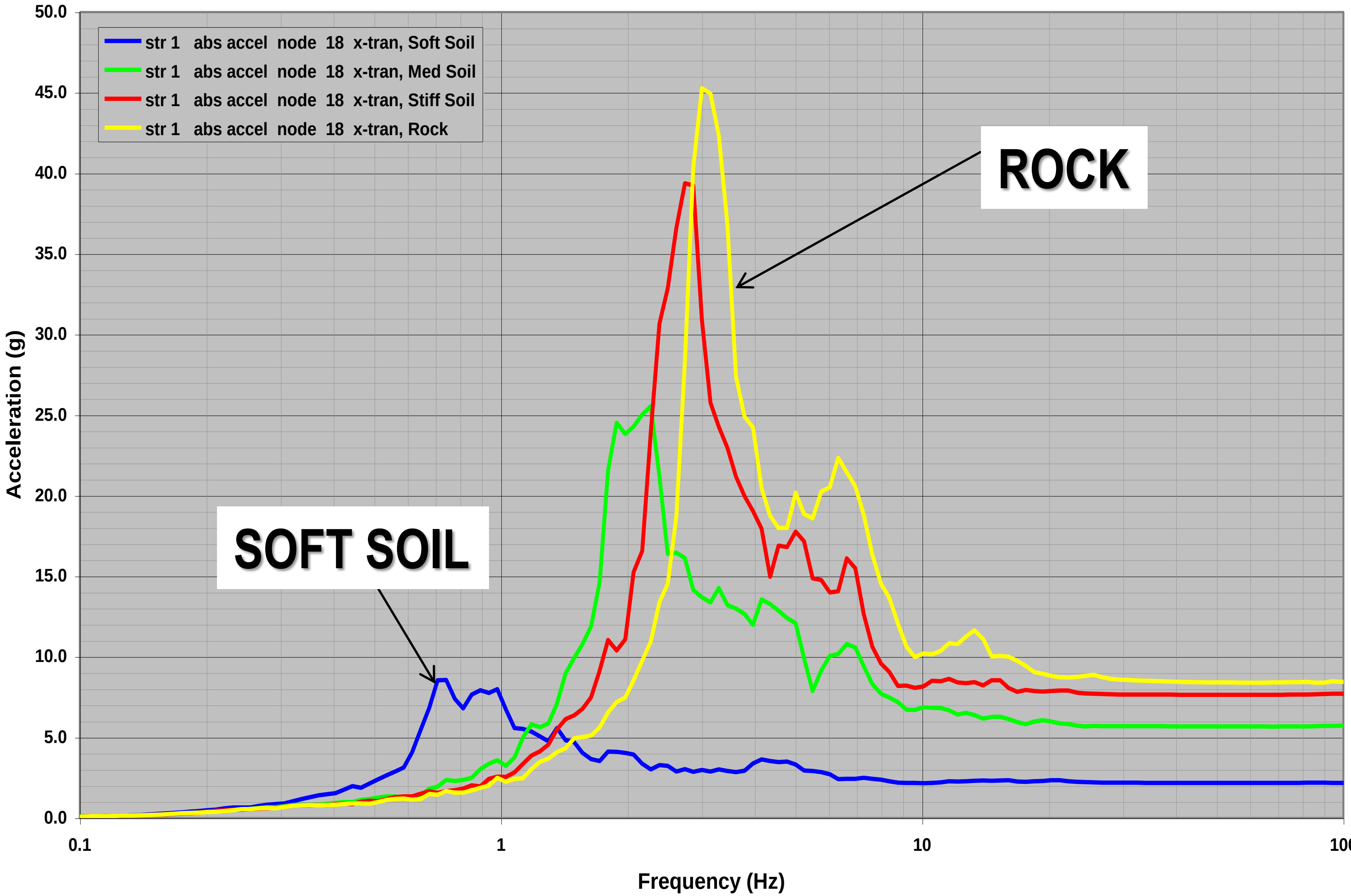
Part 1Presentation Content

1. Why is seismic SSI analysis is so important for NPP design?
2. Past and Present Seismic SSI Analysis
3. Seismic Motion Component Phasing and Spatial Variations
4. Seismic SSSI Effects on ISRS and Soil Pressures
5. Other SSI Modeling Aspects Not Addressed in this Overview
6. Seismic SSI and SSSI Sensitivity Studies for Coherent and Incoherent Motions
7. Key US NRC regulatory requirements for seismic SSI analysis, including those applicable to DES/SMR.

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

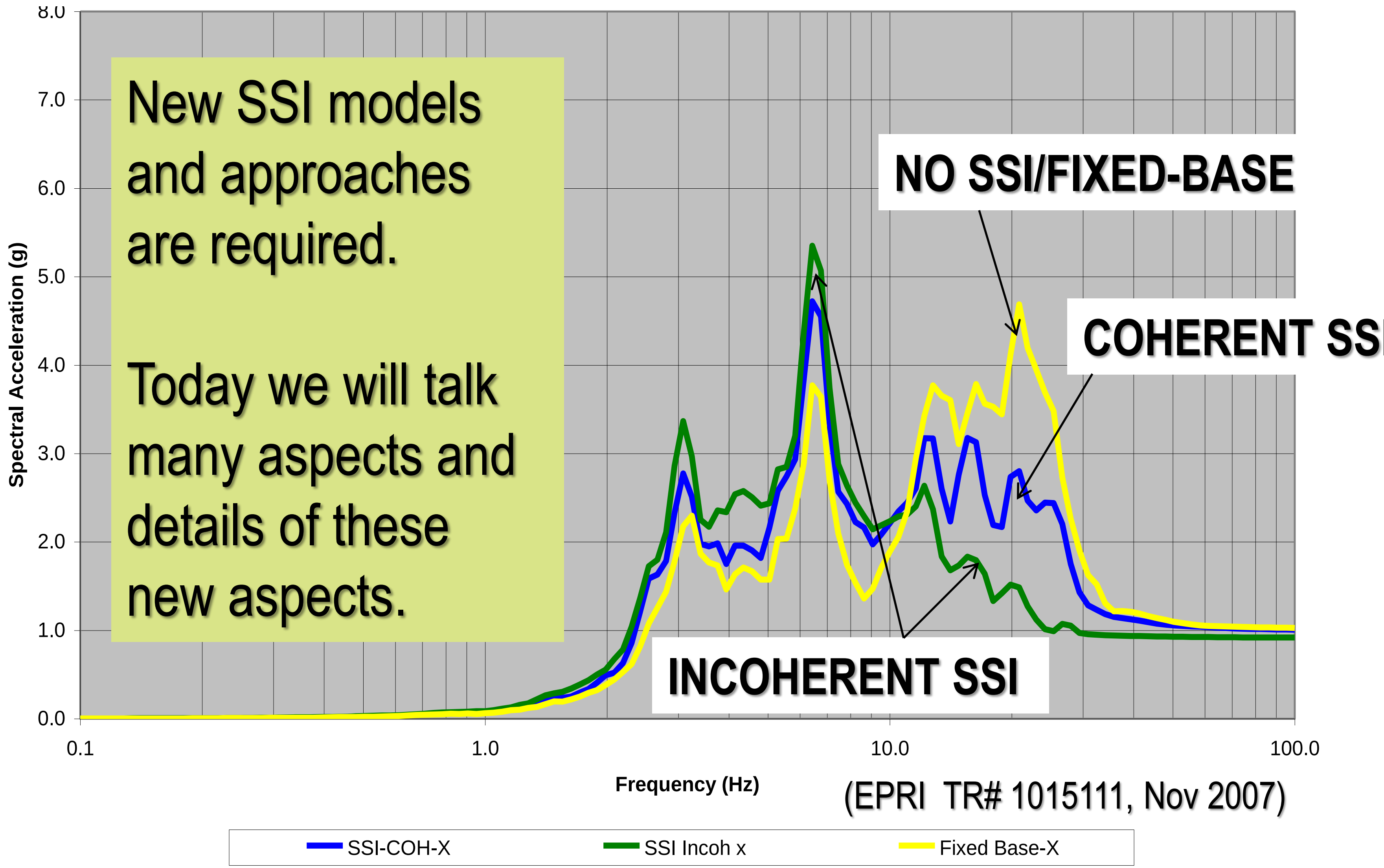
SSI Effects for Nuclear Structures on Soil Sites

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



New SSI models and approaches are required.

Today we will talk many aspects and details of these new aspects.

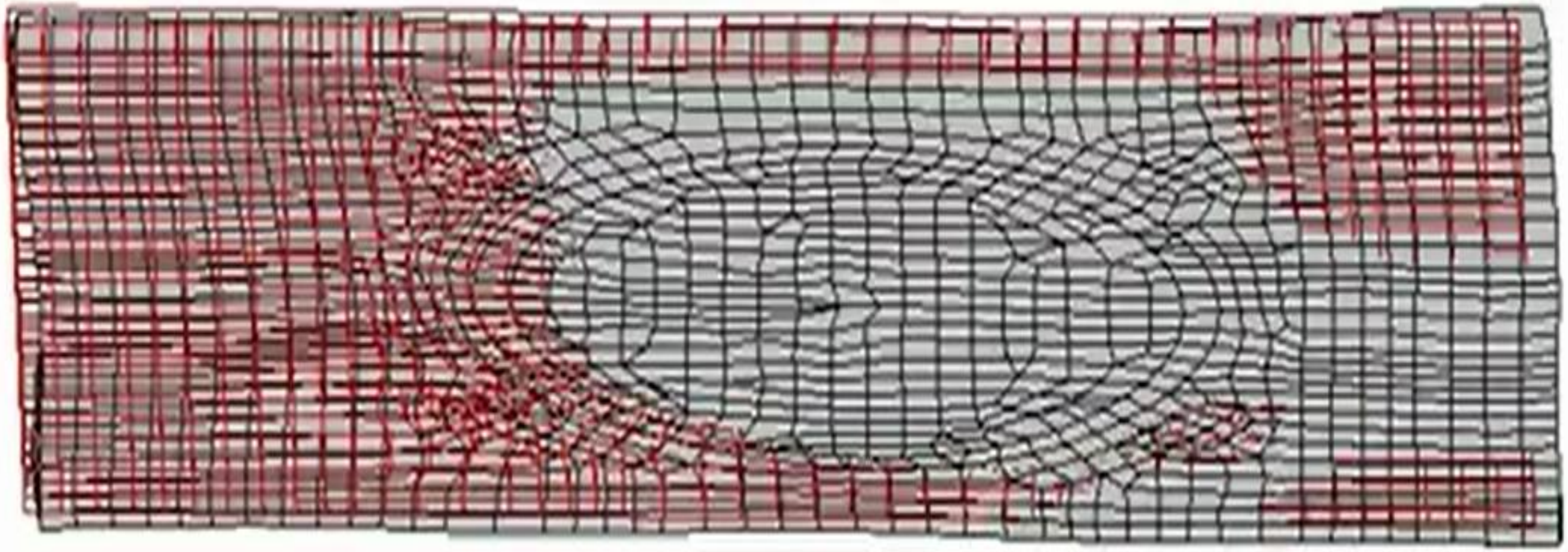
(EPRI TR# 1015111, Nov 2007)

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

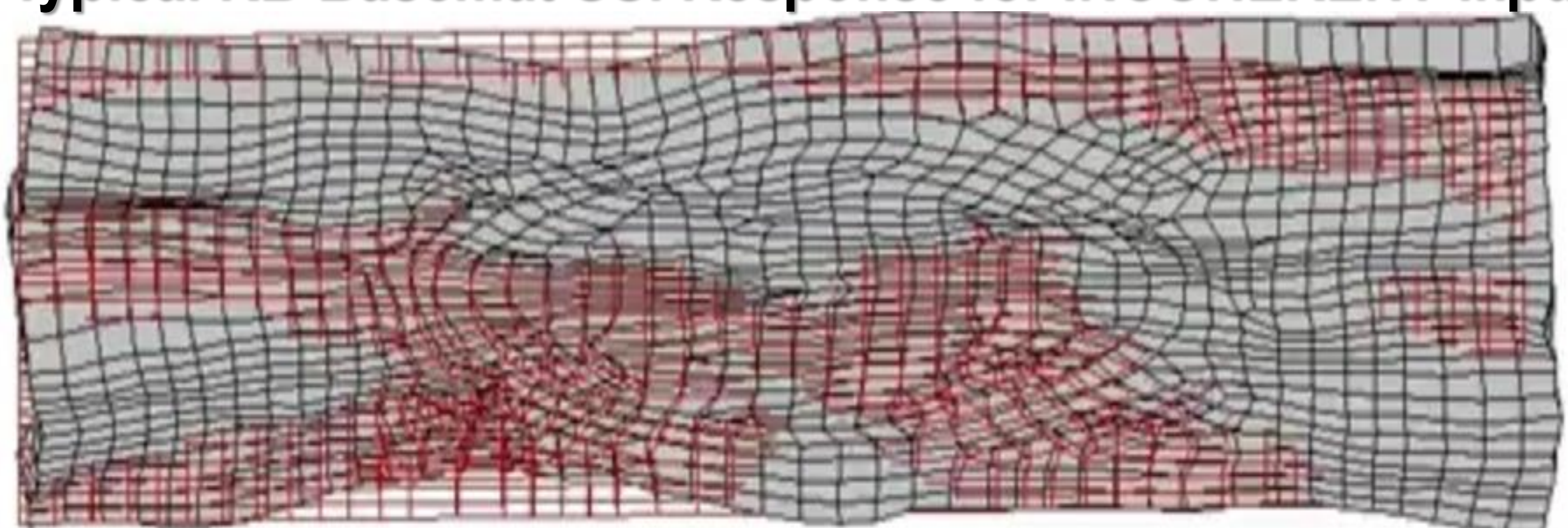
ASCE 4-16 standard states that *"for all sites that have a soil shear-wave velocity of less than 8000 fps or 2430 m/s at a shear-strain of 0.0001 %* or smaller regardless of the frequency content of the free-field motion."

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

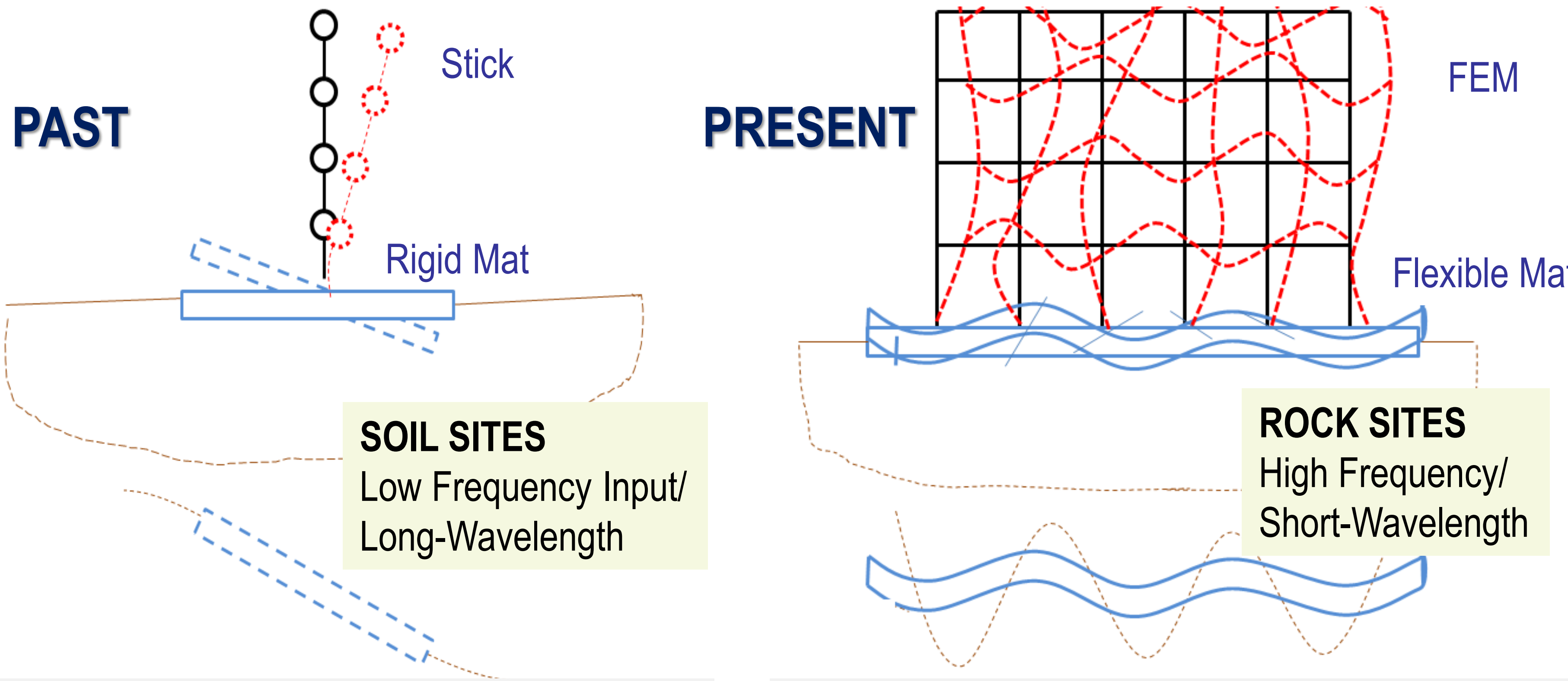


Remarks on Why SSI Effects are Important

- 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, may increase the foundation deformation, especially if the motion spatial variation is included.
- Motion incoherency reduces high-frequency ISRS amplitudes, but 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 wall and basemat bending moments, and the differential input motions at the piping/equipment supports.

2. Past and Present Seismic SSI Analysis

Past vs. Present Seismic SSI Analysis Concept

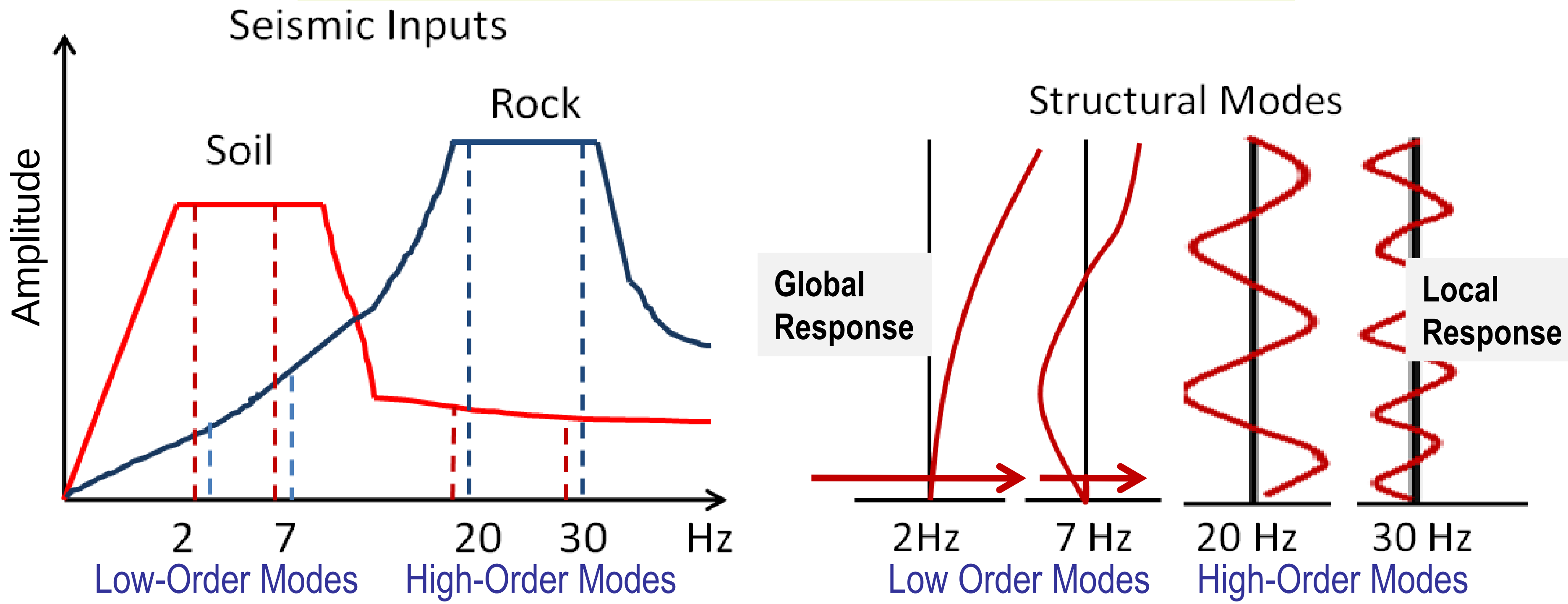


PAST EXPERIENCE:
- Low Frequency Inputs (Long-Wavelength)
- Soil Sites
- Stick Models with Rigid Mats
-Input Soil Motion as Rigid Body Motion (Coherent, 1D Propagation of S and P Waves)
Is sufficiently accurate? No…..

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.

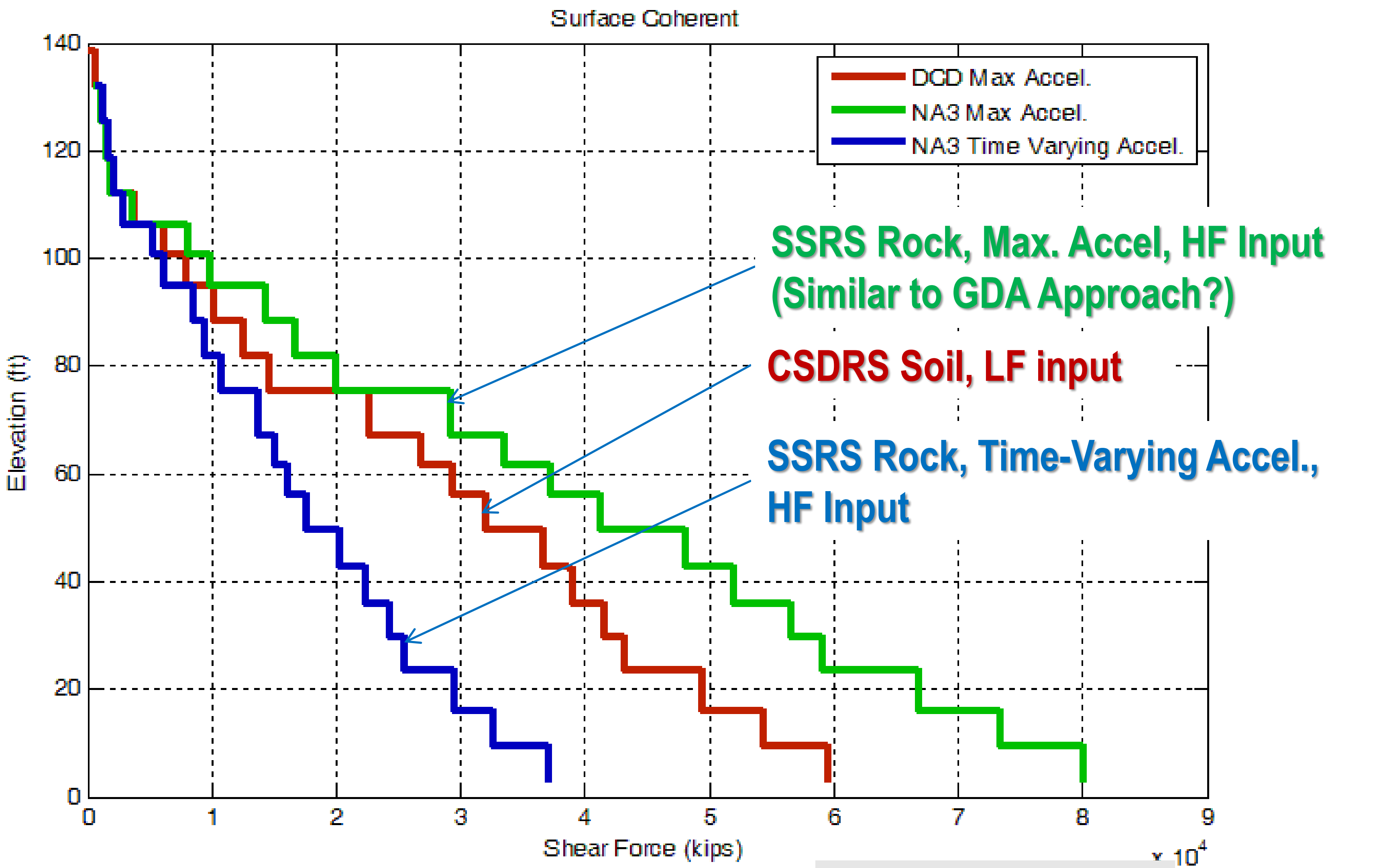
Seismic Inputs With Different Frequency Content



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)

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

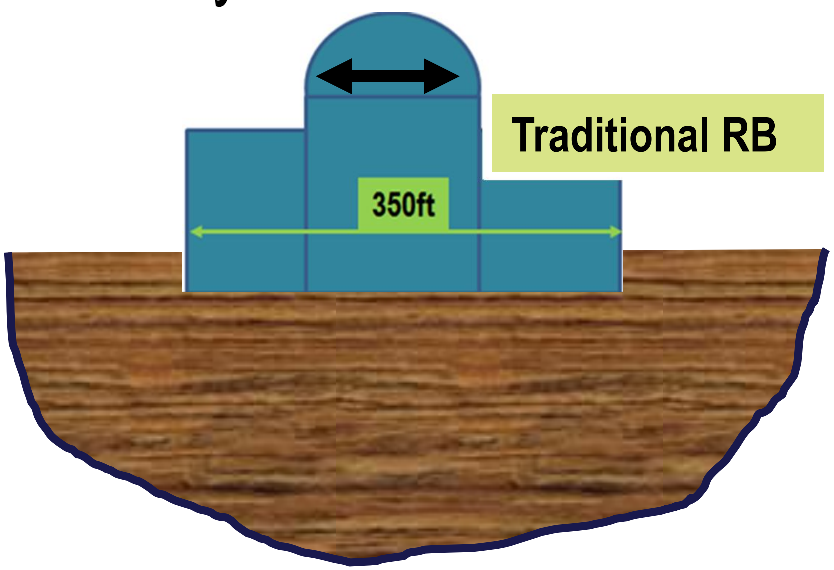
The use of maximum structural acceleration (ZPA) distribution is inappropriate for the high-frequency inputs.

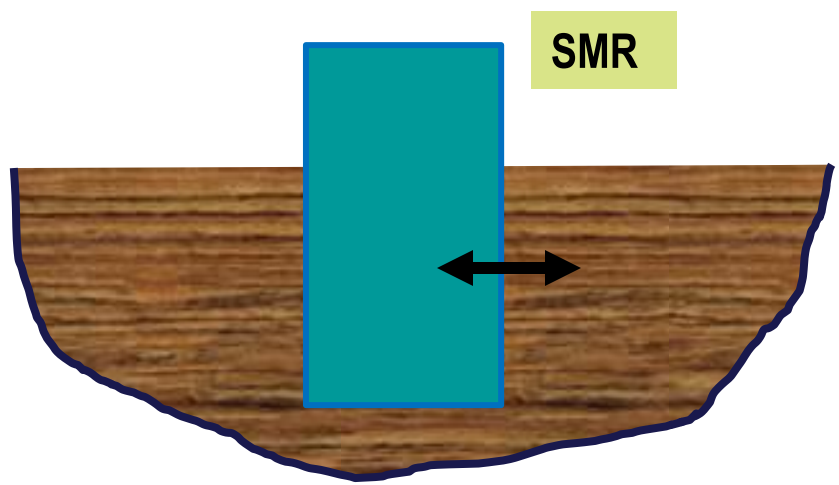
- Global shear forces are grossly overestimated. Local effects, including out-of-plane wall and floor vibration high-frequency modes, are underestimated.

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

What is particular to SSI Analysis of DES/SMR?

- Kinematic SSI or wave scattering effects are much larger for DES and SMR (up to 140ft embedment) than for the typical traditional NI structures with shallow embedment (up to 40ft embedment) that are dominated by Inertial SSI effects.
- Seismic SSI responses of SMR should be more sensitive to the variations in soil properties and seismic wave propagation in the vicinity of the DES or SMR structures.



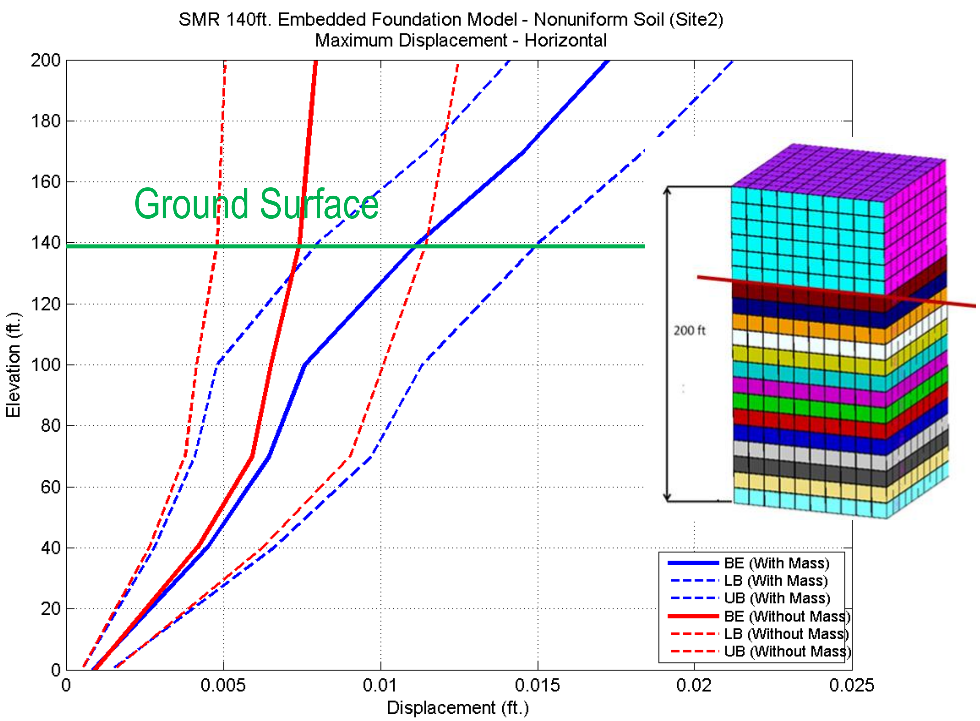


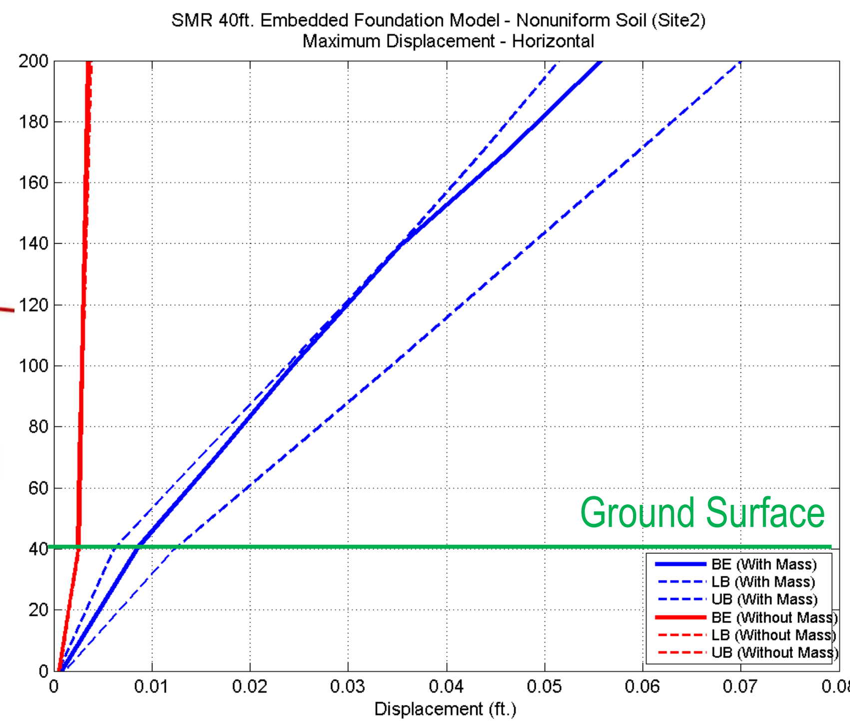
Effects of Kinematic SSI for Embedded SMR

140 ft Embedment

40 ft Embedment

Overall Displacement wrt Basemat Center





REMARKS:

- For 140 ft embedment kinematic SSI is dominant, 80-90% below surface, and about 50% above surface
- For 40 ft embedment the kinematic SSI much less significant, only 20-30% below surface and less than 10 % above surface.

3. Seismic Motion Component Phasing and Spatial Variations

A. Seismic Motion Component Phasing

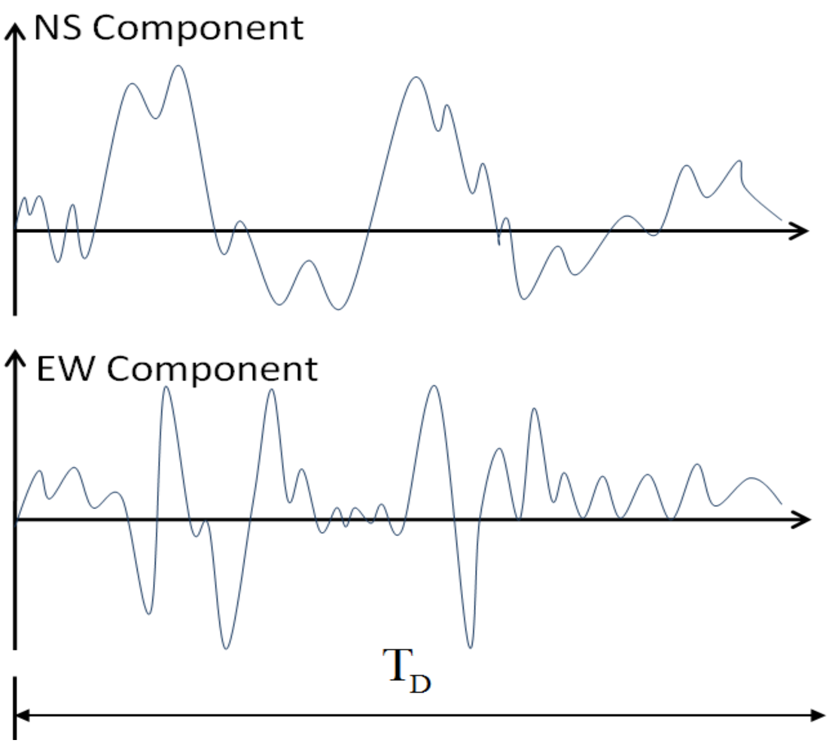
B. Spatial Variation in Vertical and Horizontal Directions

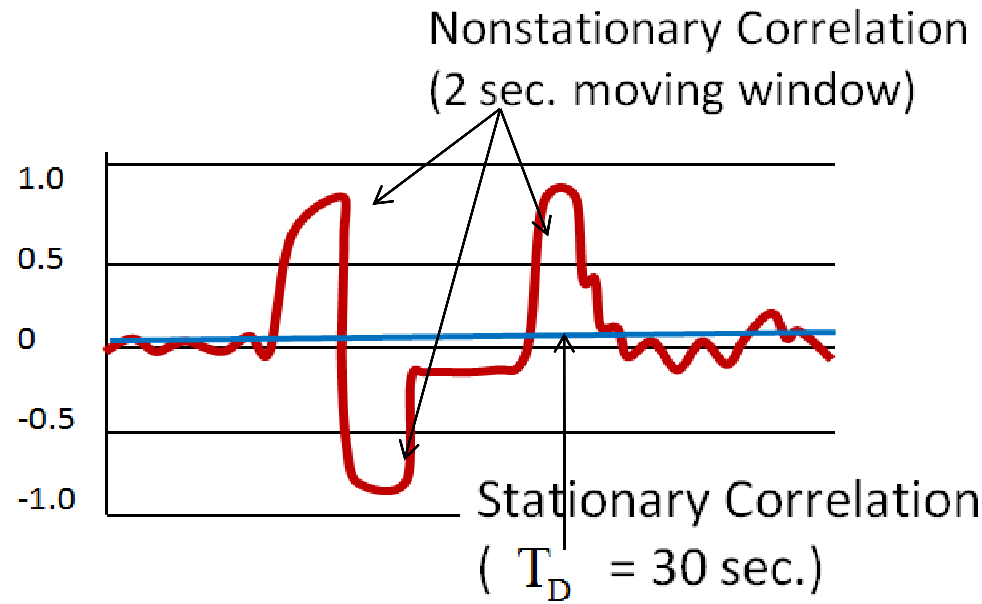
A. Seismic Motion Component Phasing (Local)

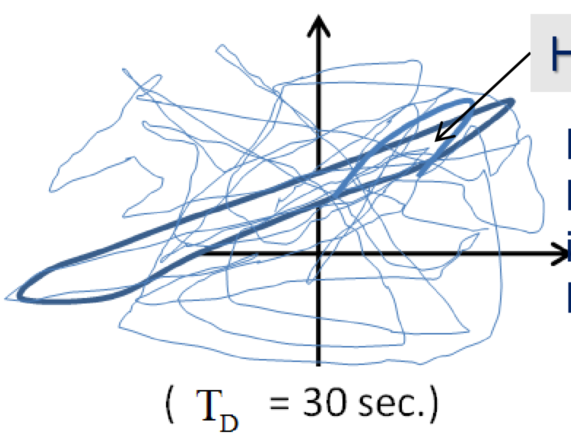
Current practice:

- 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



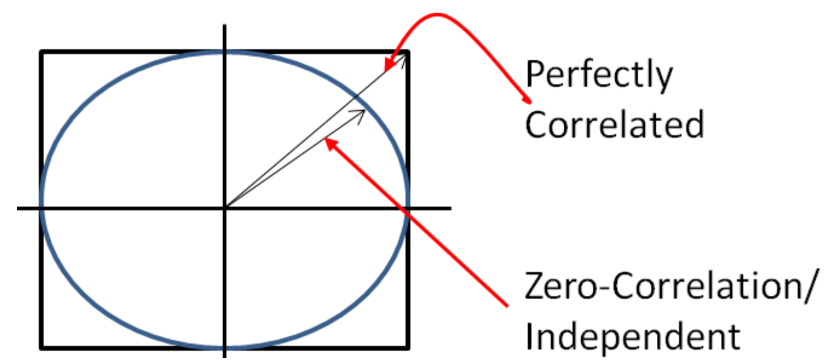




High Correlation!

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

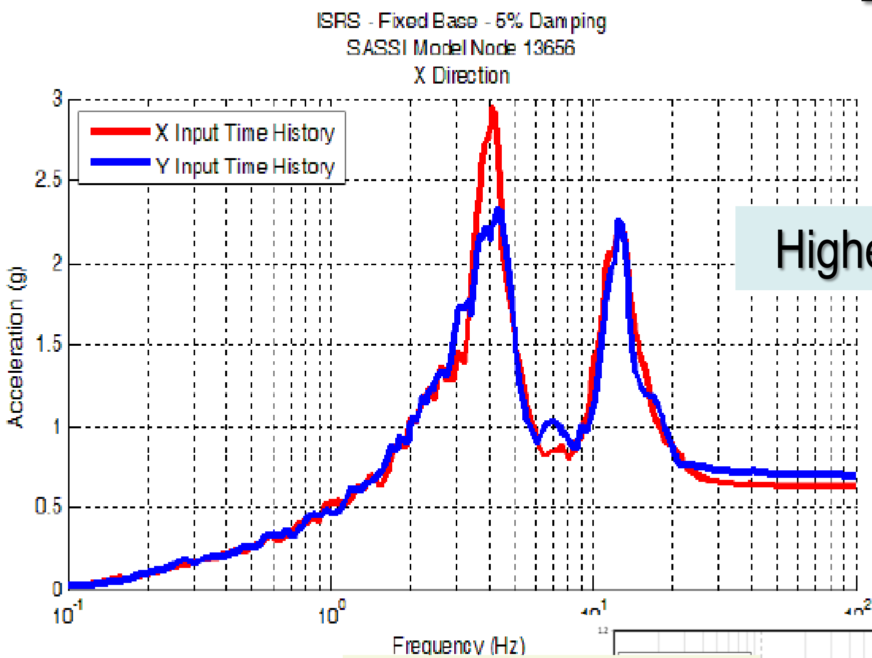
CORNER COLUMN PROBLEM



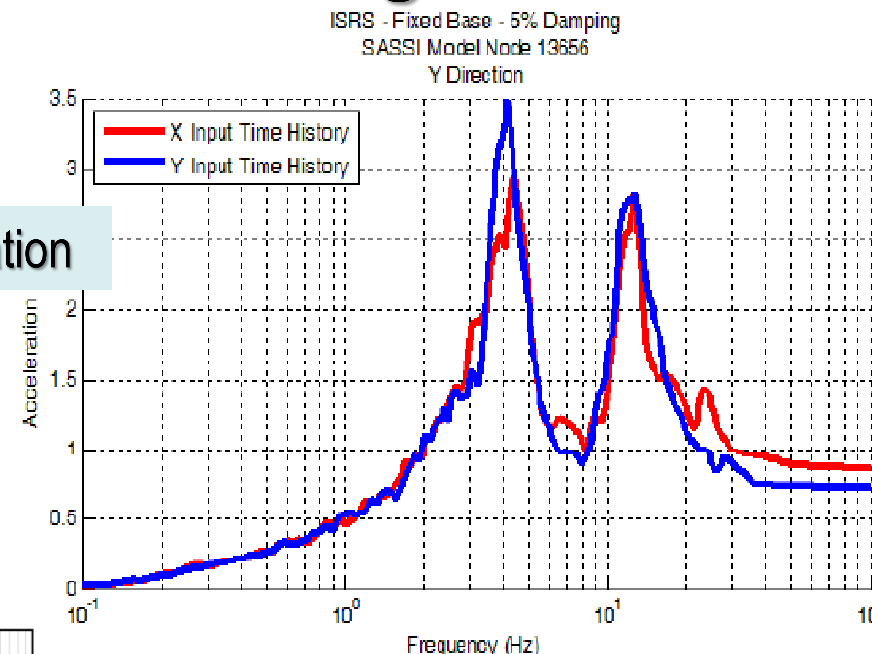
(Agnastopoulos, 1981, Der Kiureghian, 1984)

(SRSS rule neglects correlation effects)

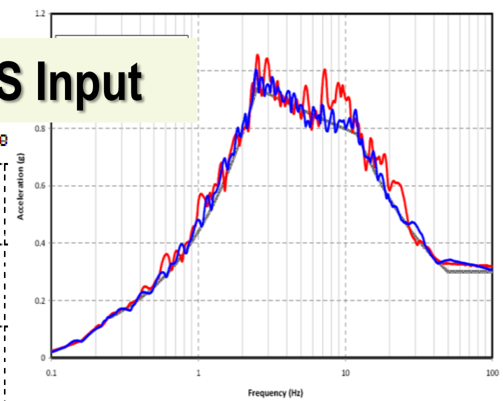
Within Motion Component Phasing Effects

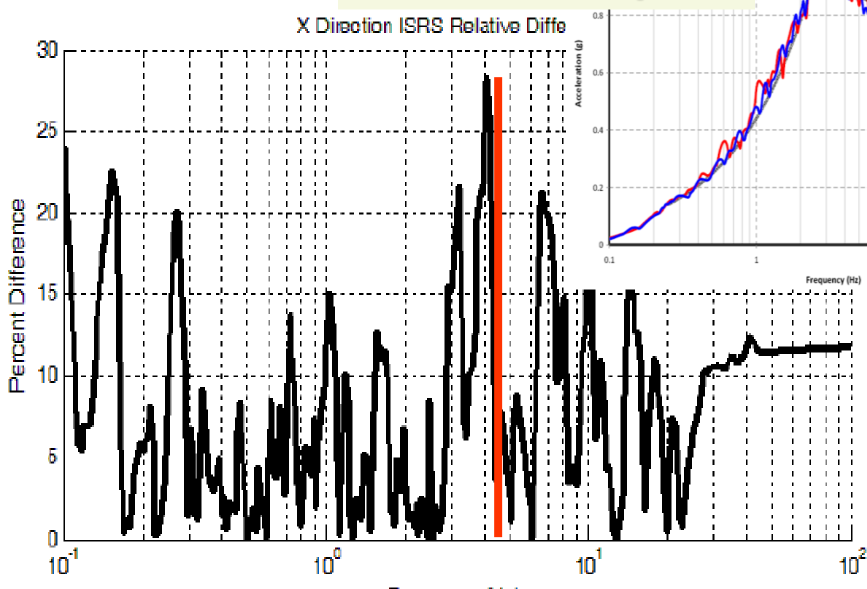


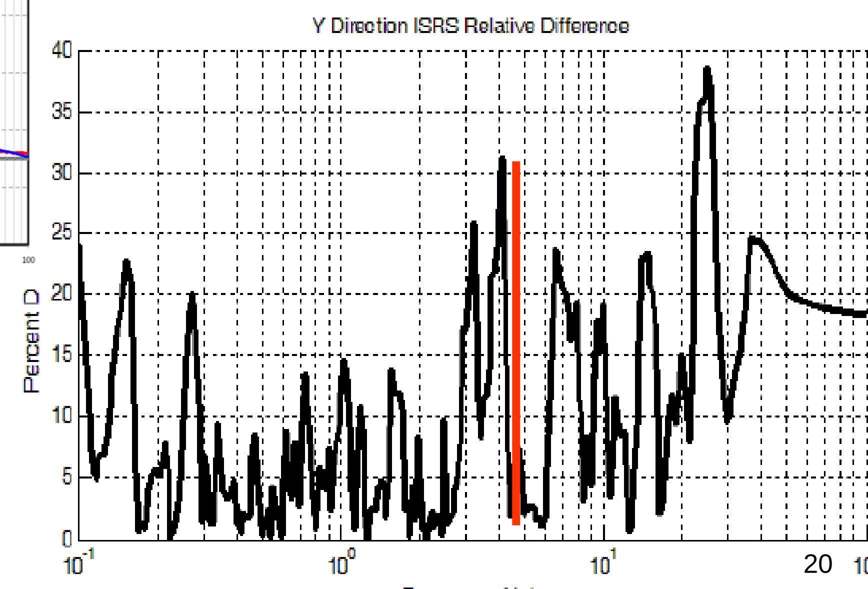
Higher Elevation



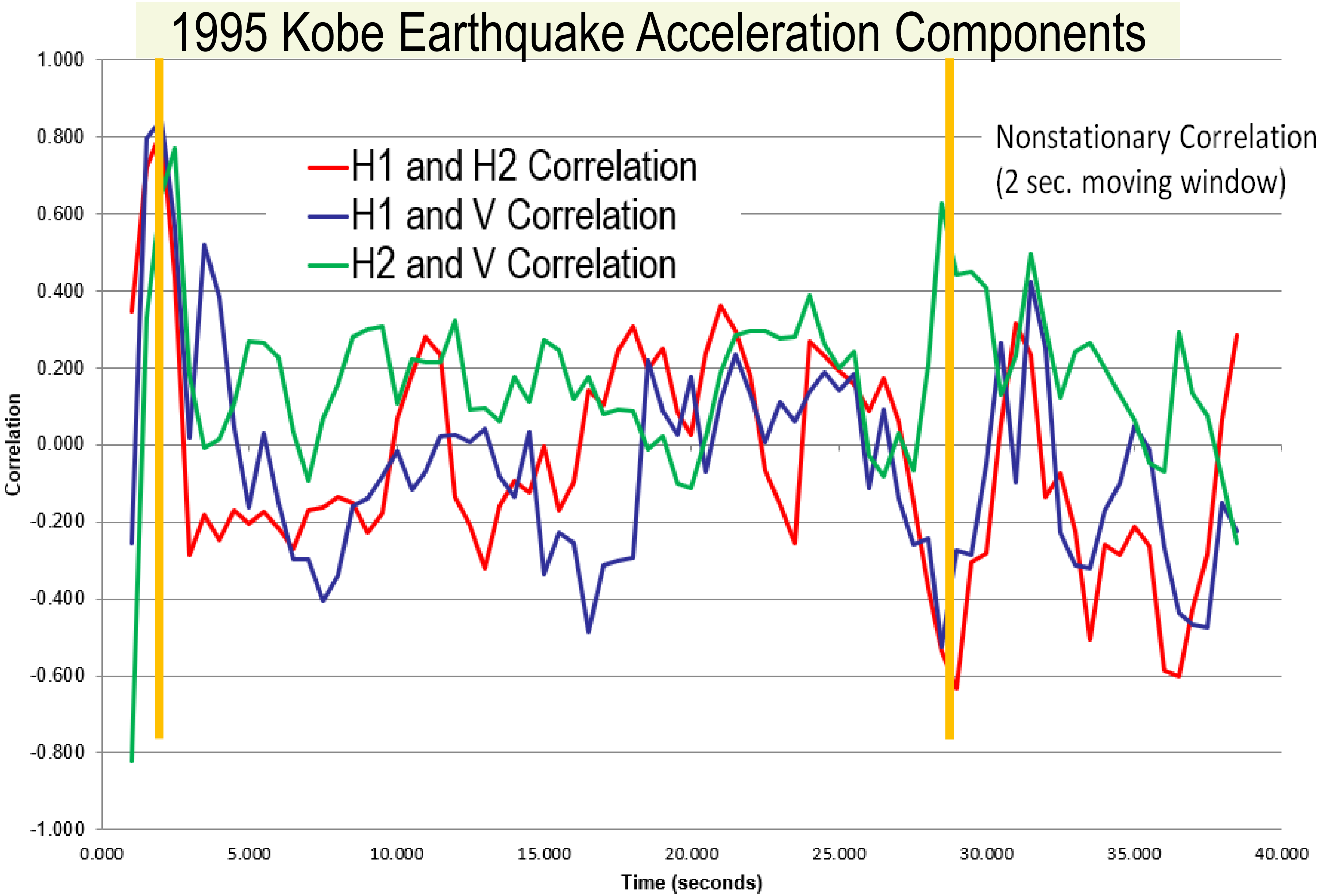
Same GRS Input



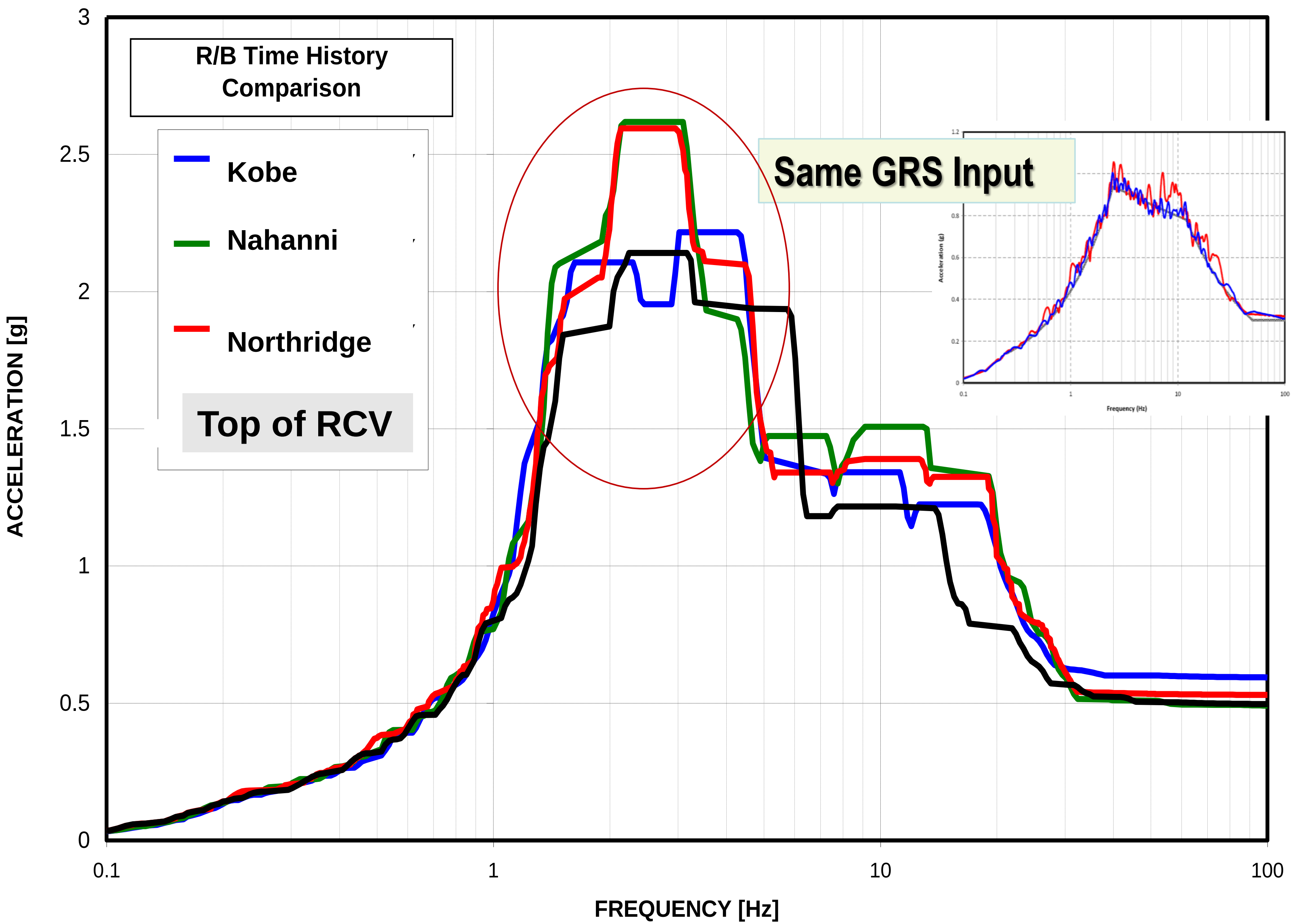




Between Motion Component Phasing Effects



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.

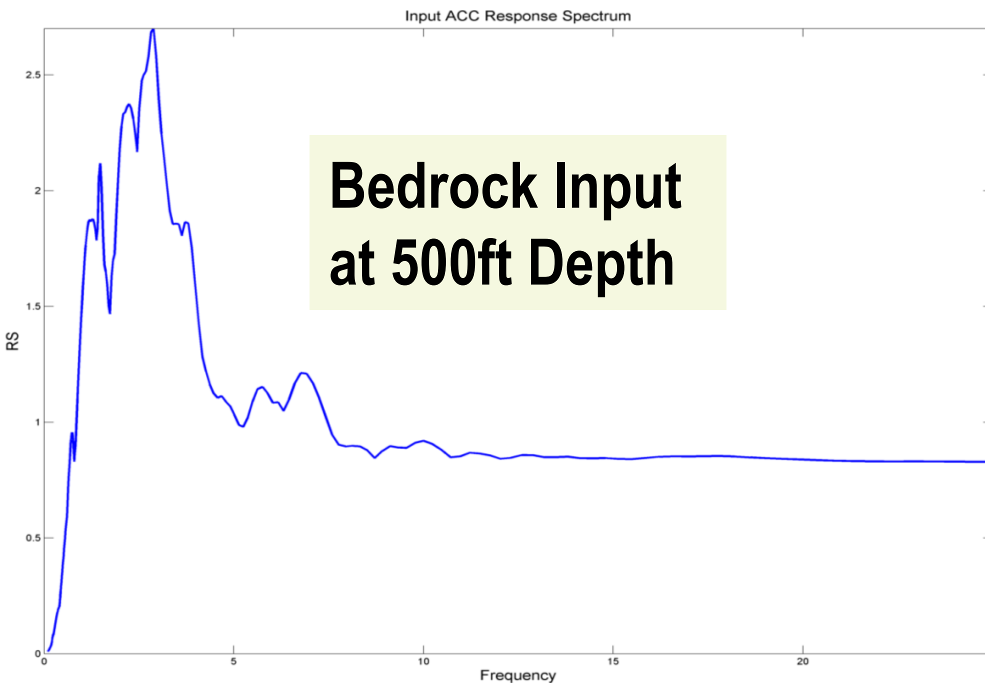
B. Seismic Motion Spatial Variation (Global)

B1. Soil Motion Variation with Depth

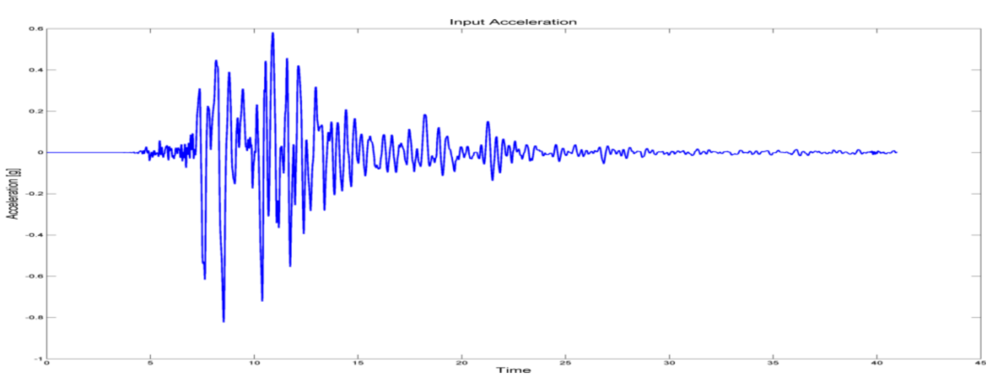
Current practice:

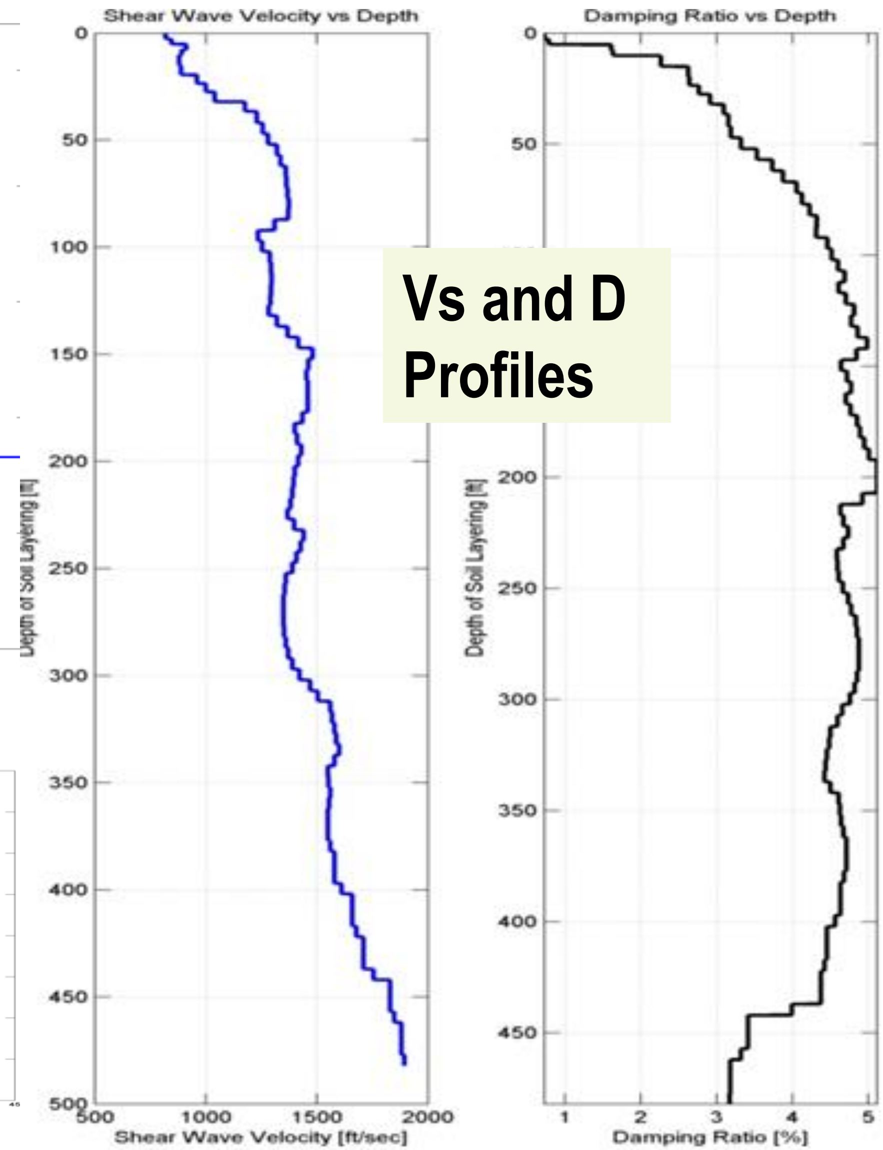
- Seismic motion varies largely with depth, especially for soil sites.
- Wave composition is based on the vertically propagating S and B body waves assuming 1D soil deposit models
- Nonlinear hysteretic behavior of the soil layers affects the seismic wave propagation.
- Equivalent-linear soil models (SHAKE) are acceptable for performing the site response analysis.

Site Response for A Typical Soil Site



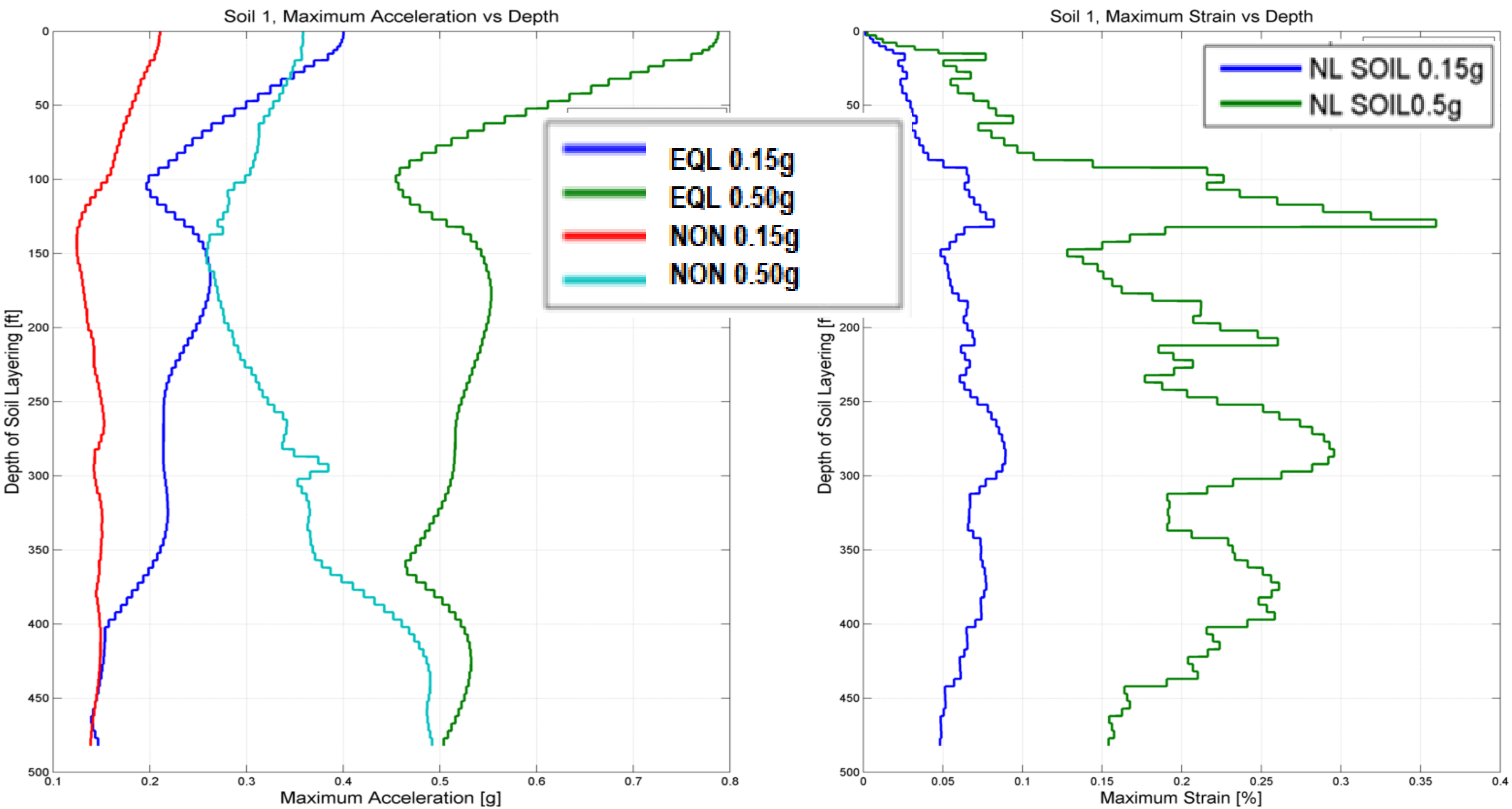
Bedrock Input at 500ft Depth



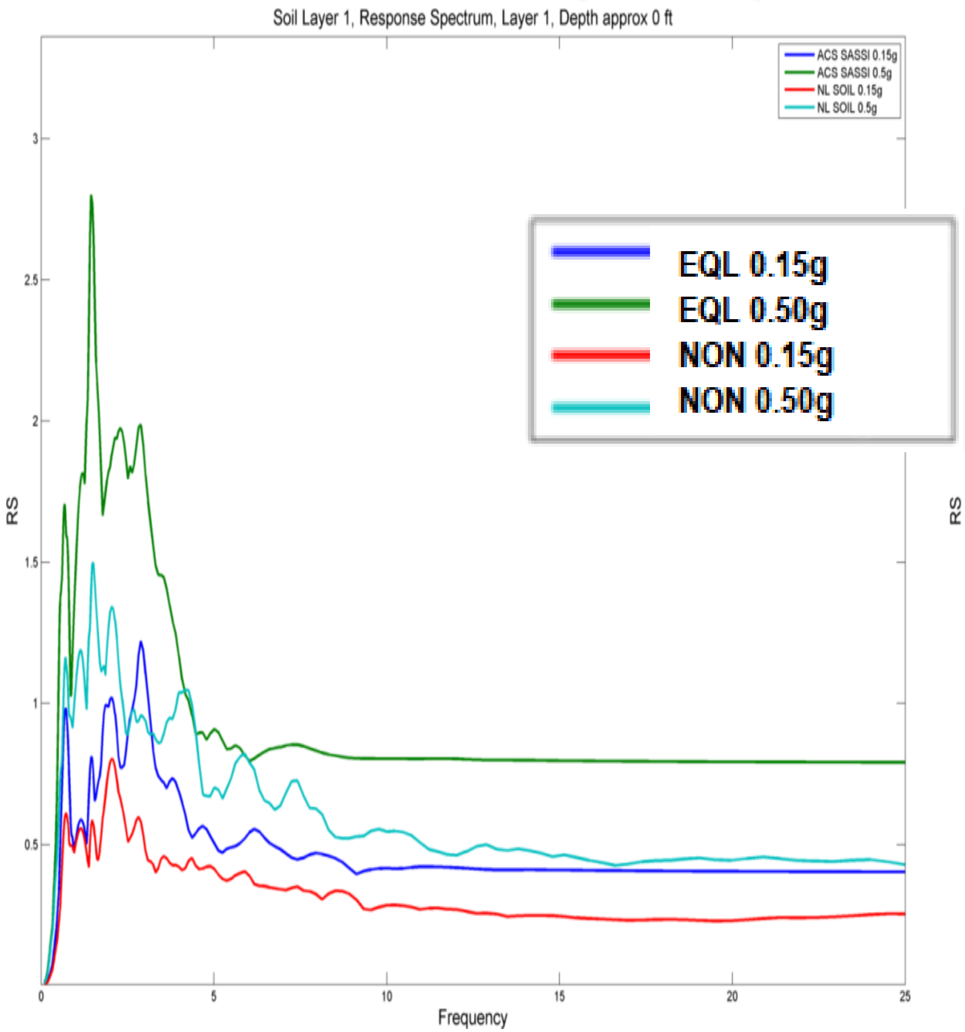


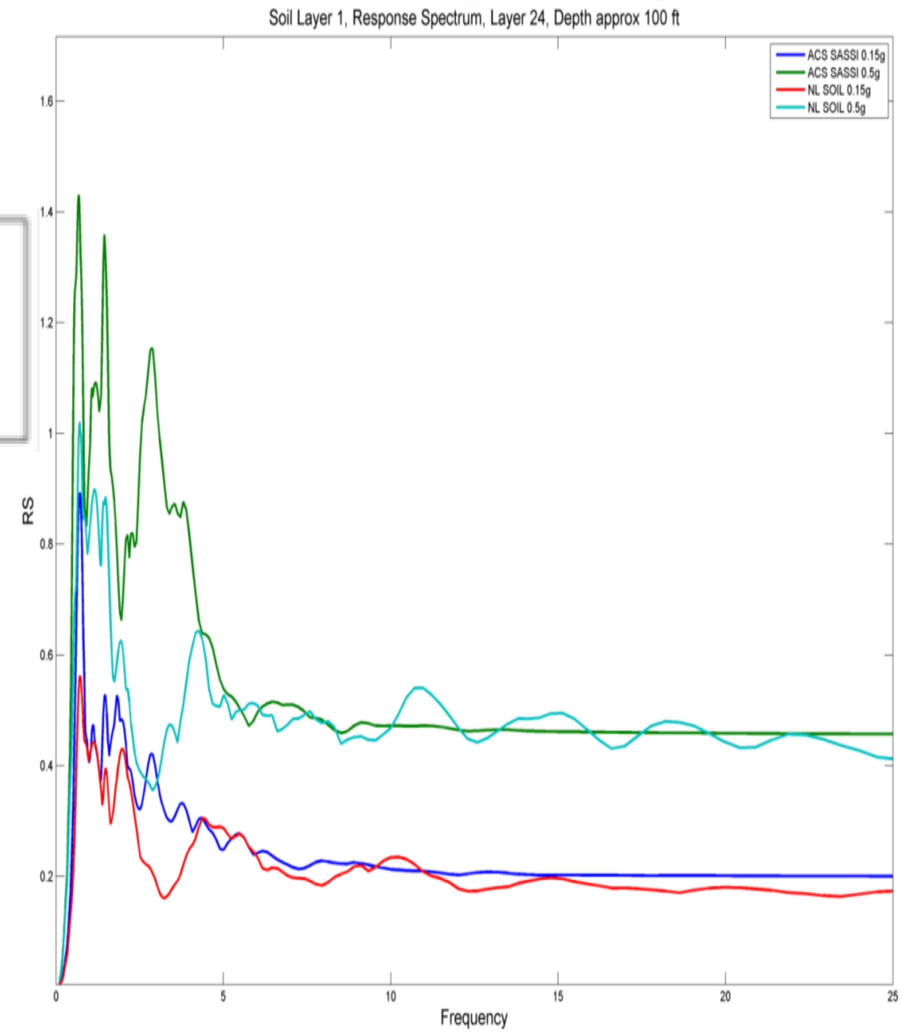
Vs and D Profiles

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)

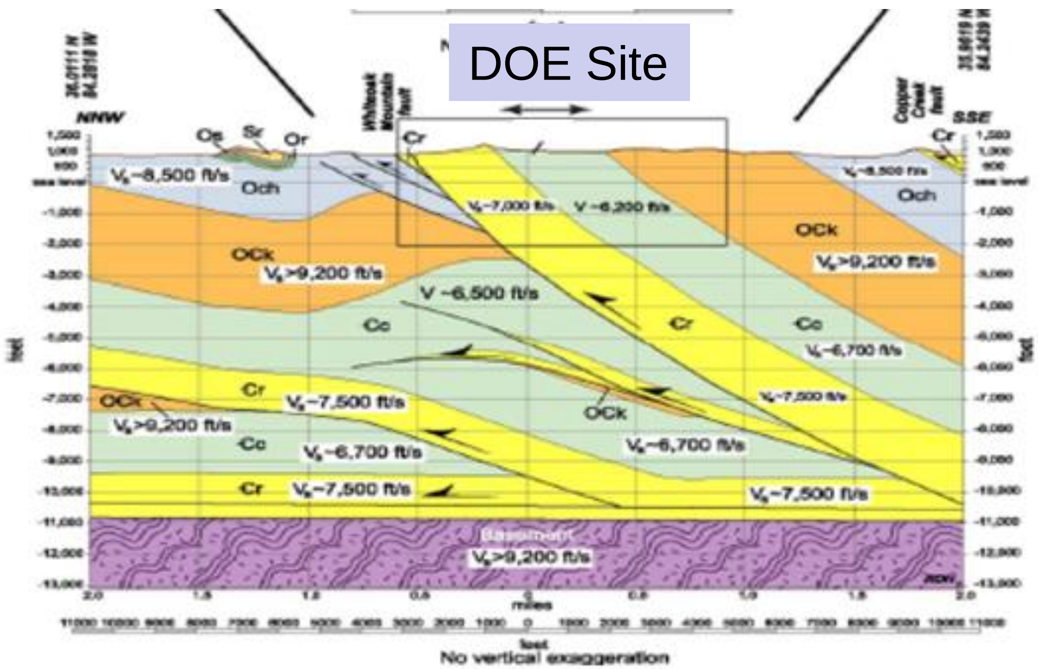


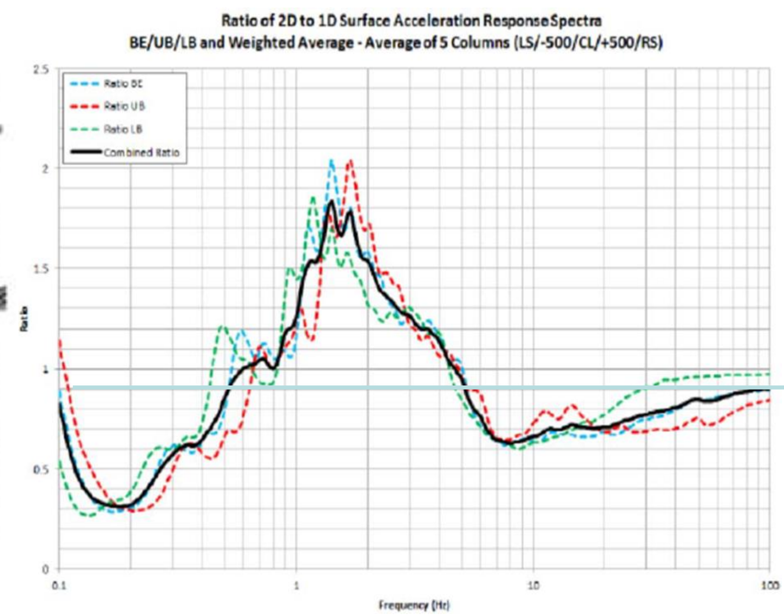


NPP Sites with Inclined Soil Layering and Waves

1-Dimensional SRA is commonly used for NPP projects as specified in the regulatory guidelines and design standards, e.g. RG1.208 and ASCE 4-16.

1-Dimensional SRA may not capture all aspects of wave propagation at a site, which may potentially result in a bias with respect to the true site amplification. This soil modelling uncertainty needs to be evaluated in site amplification estimates. *The 2-Dimensional soil models are useful for these situations.*





Anderson, 2018 DOE/NRC NPH Meeting

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.

- For more general NPP sites in US, 2D site response analysis results do not indicate that they are highly sensitive to slowly varying soil layer properties in the horizontal direction and the presence of slightly inclined SV and P waves, and Rayleigh waves produced by the soil layer property variations in horizontal direction.

Inclined SV-P and High-Order Rayleigh Waves for DES/SMR in Nonuniform Soils

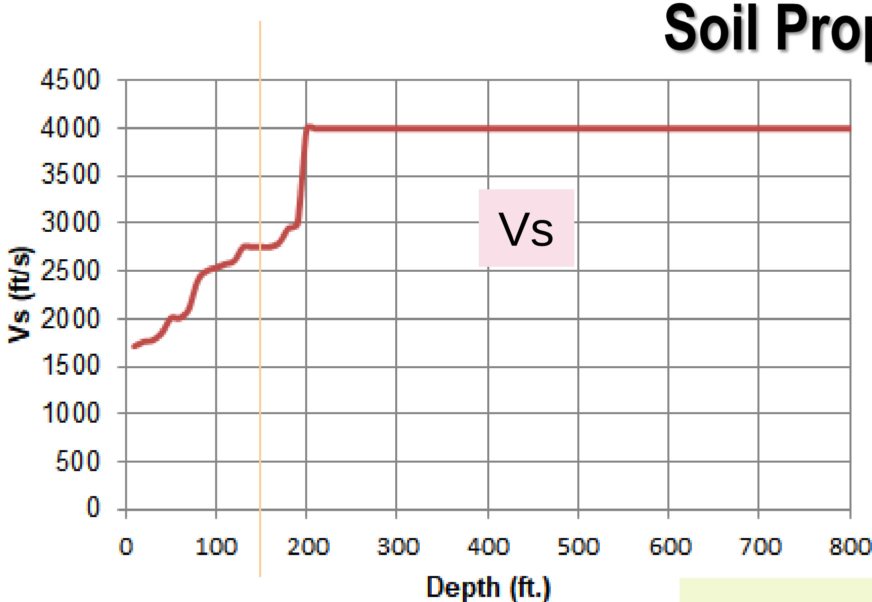
"*While most of these higher modes can be neglected, since they decay rapidly in the direction of propagation, others may decay less rapidly than the fundamental mode. This phenomenon occurs only at relatively high frequency on sites with a marked increase in stiffness with depth; say a sand profile over rock.*"

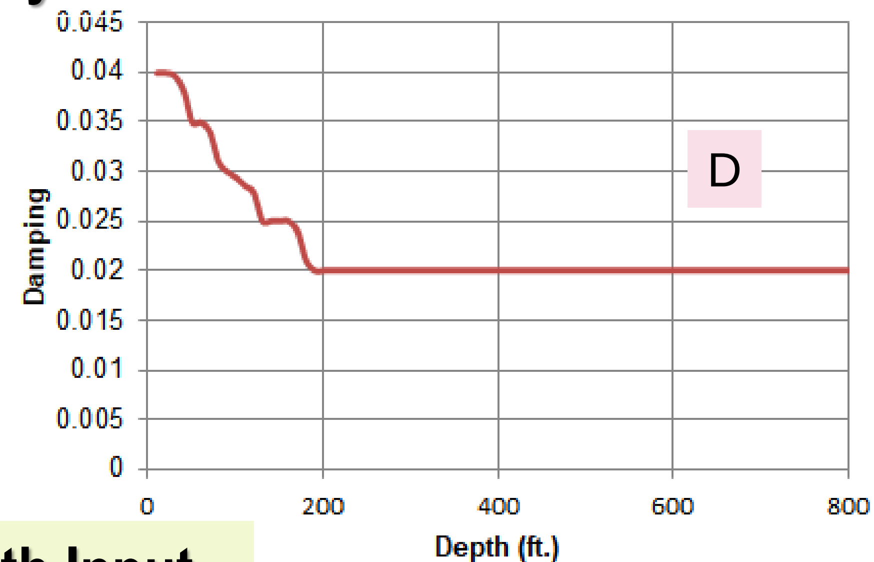
"*There is in fact evidence to suggest that most of the energy approaching the ground surface results from body waves inclined within about 30 degree of the vertical. These includes the effects of the high-order surface wave modes.*"

Seed and Lysmer, Report to LLNL under SSMRP Phase I, UCRL 15272, 1980)

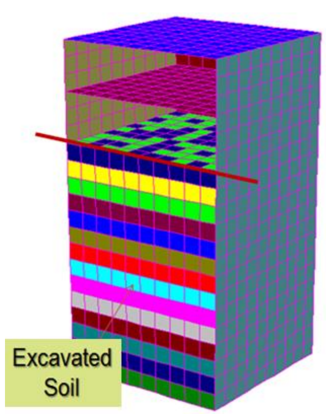
Soil Layering with Gradual Increase in Stiffness

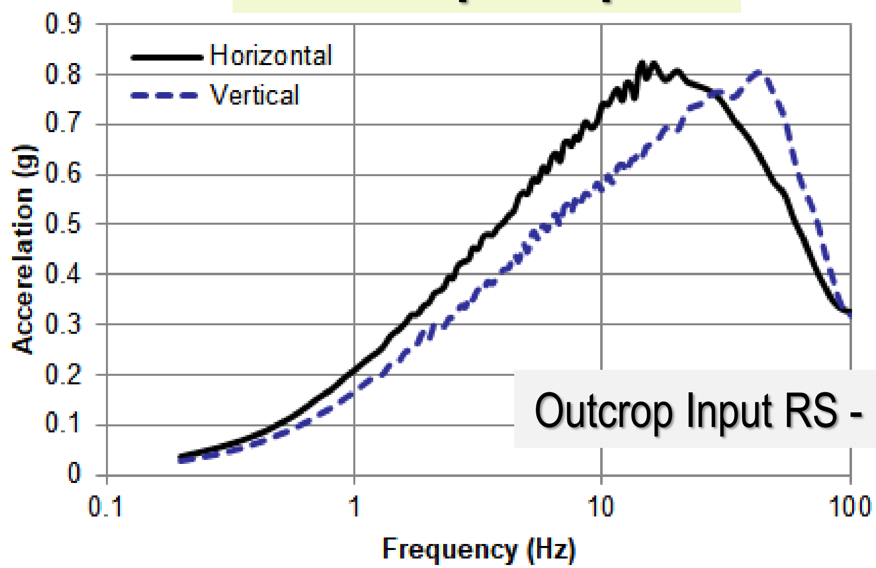
Soil Property Profiles





200ft Depth Input

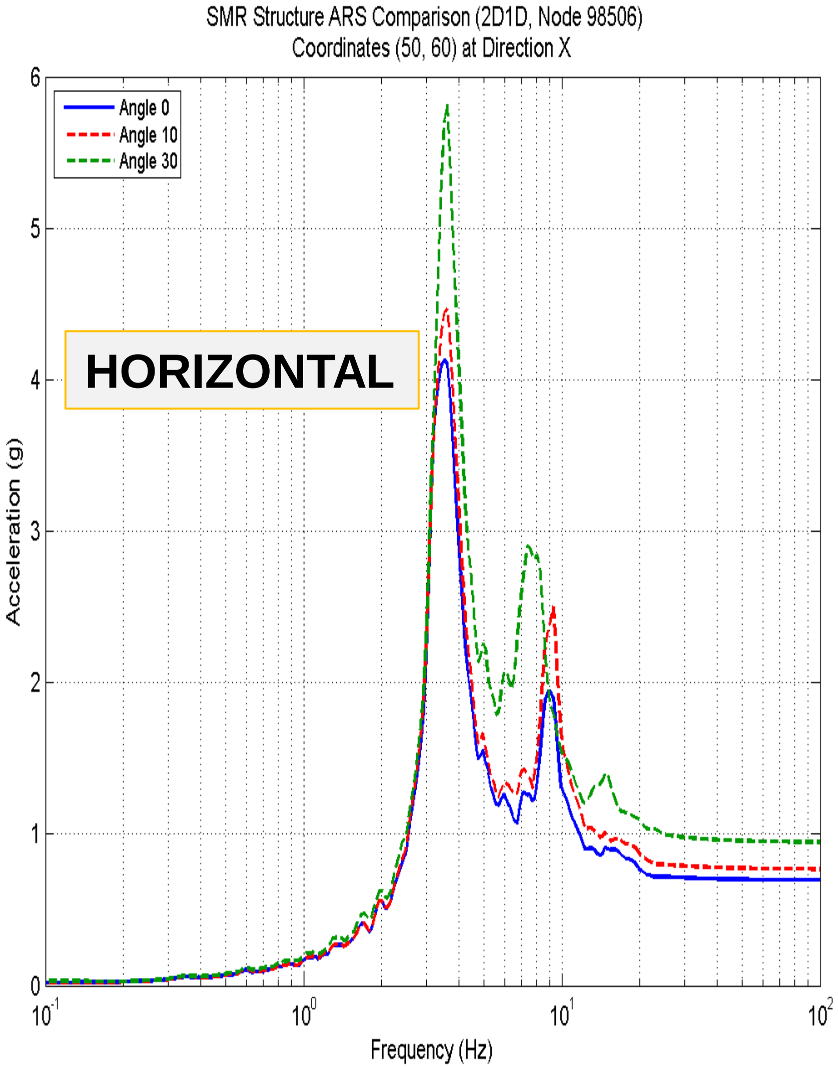


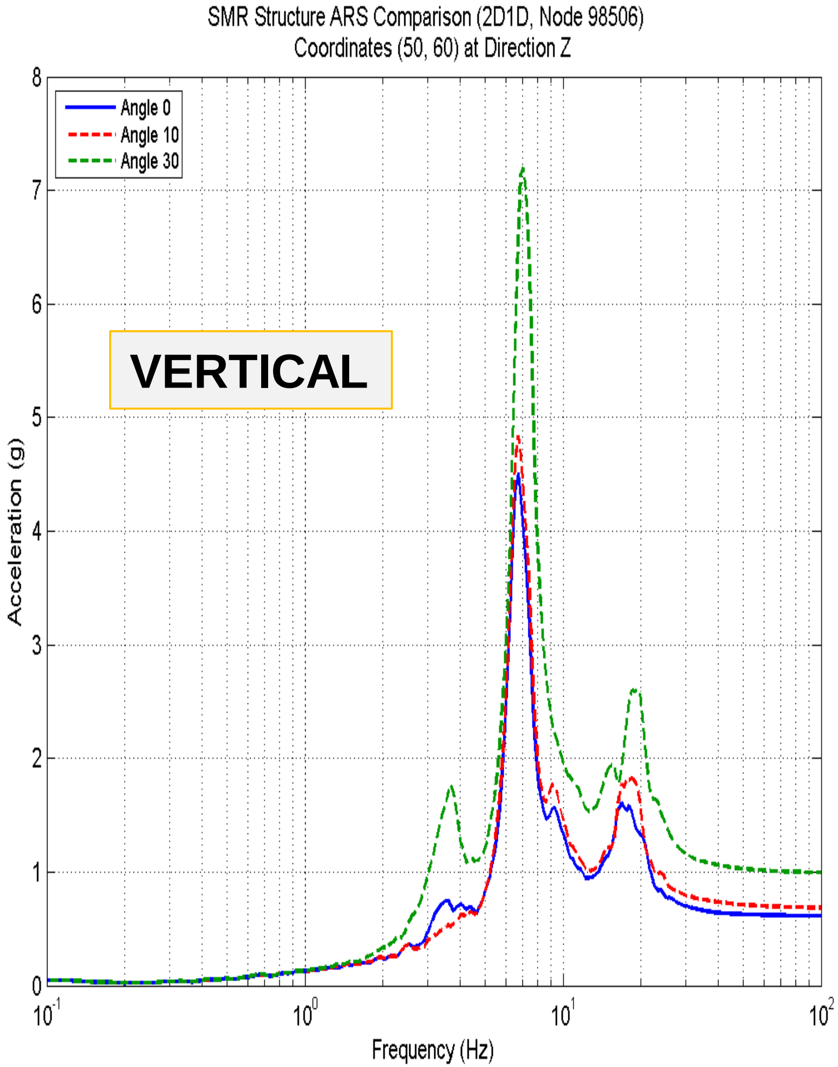


Outcrop Input RS - Mid to High Frequency

SV-P Waves with 0, 10 and 30 Inclination Angles

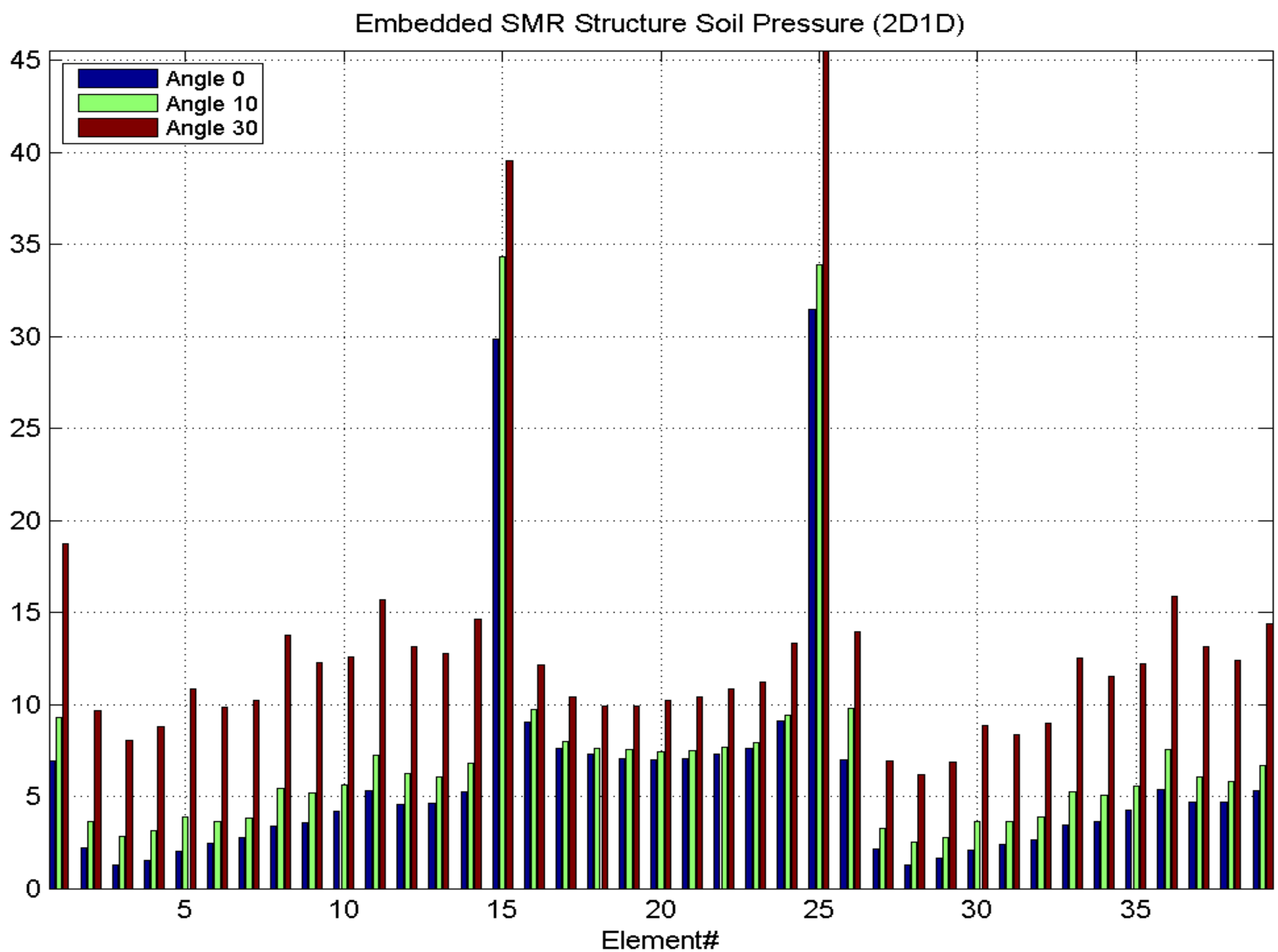
2D1D SMR ISRS at Top Edge





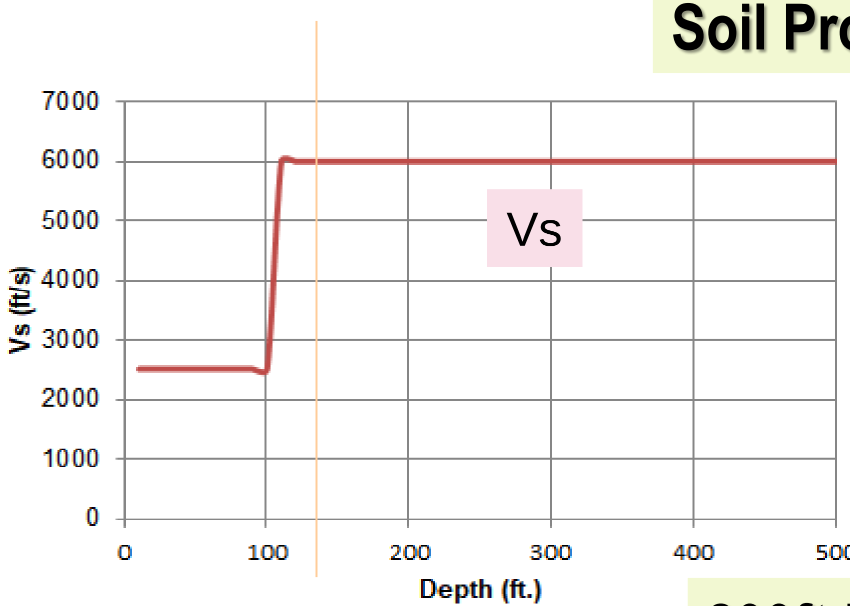
SV-P Waves with 0, 10 and 30 Inclination Angles

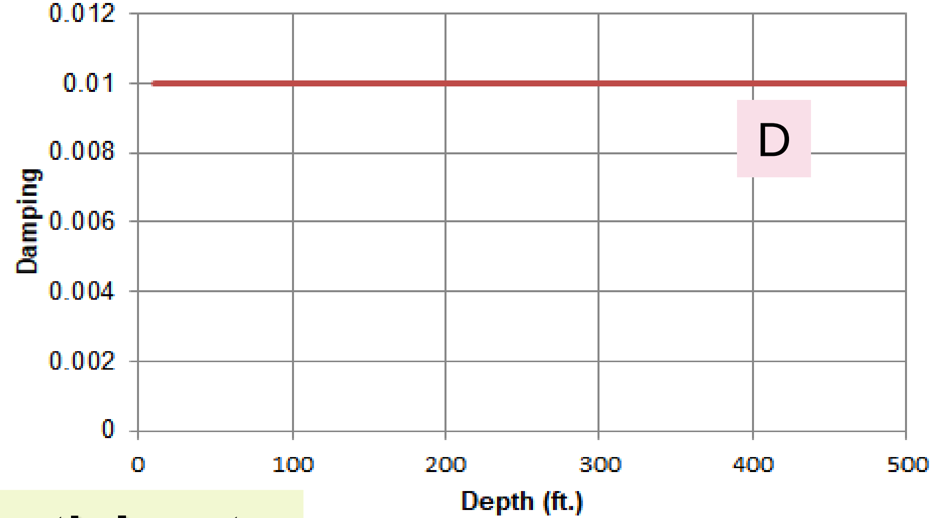
2D1D SMR Maximum Seismic Soil Pressures



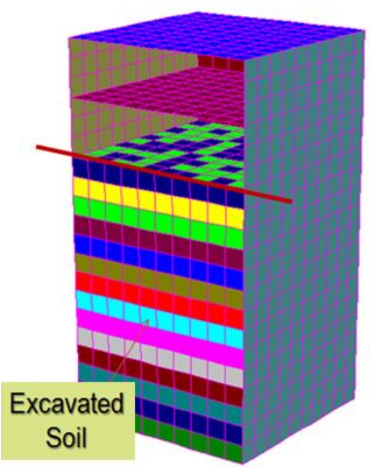
Soil Layering with Step Increase in Stiffness

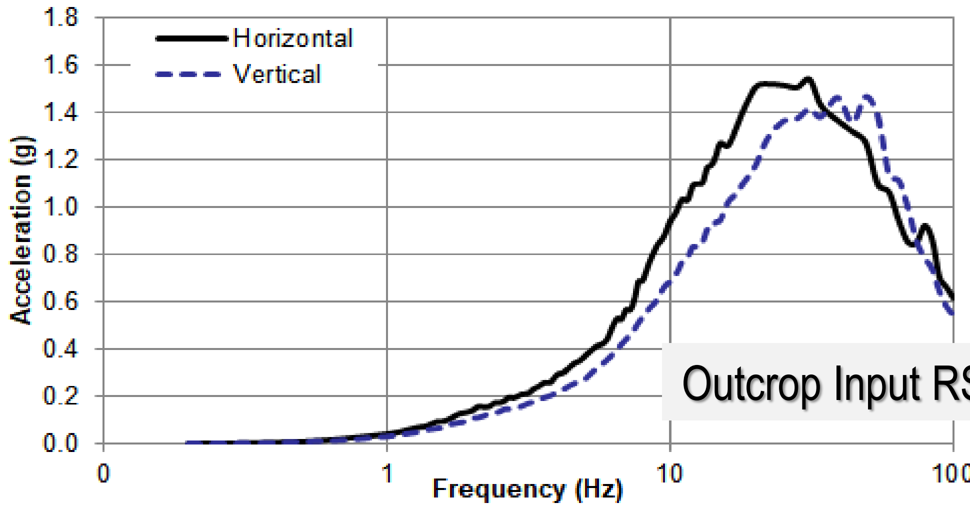
Soil Property Profiles





200ft Depth Input

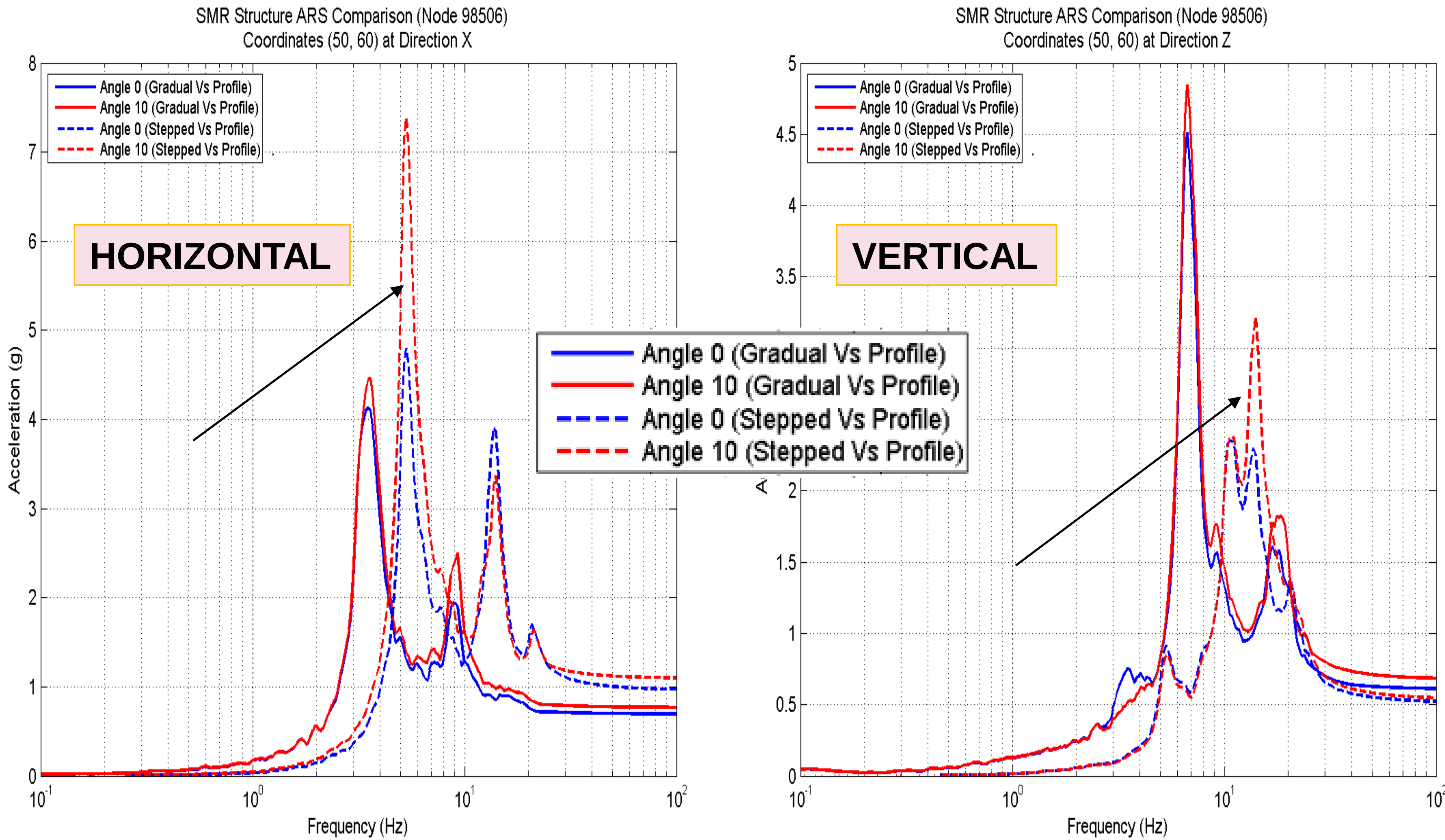




Outcrop Input RS – Very High Frequency

SV-P Waves with 0 &10 Degree Inclination Angles

3D SMR Model ISRS at Top Edge



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

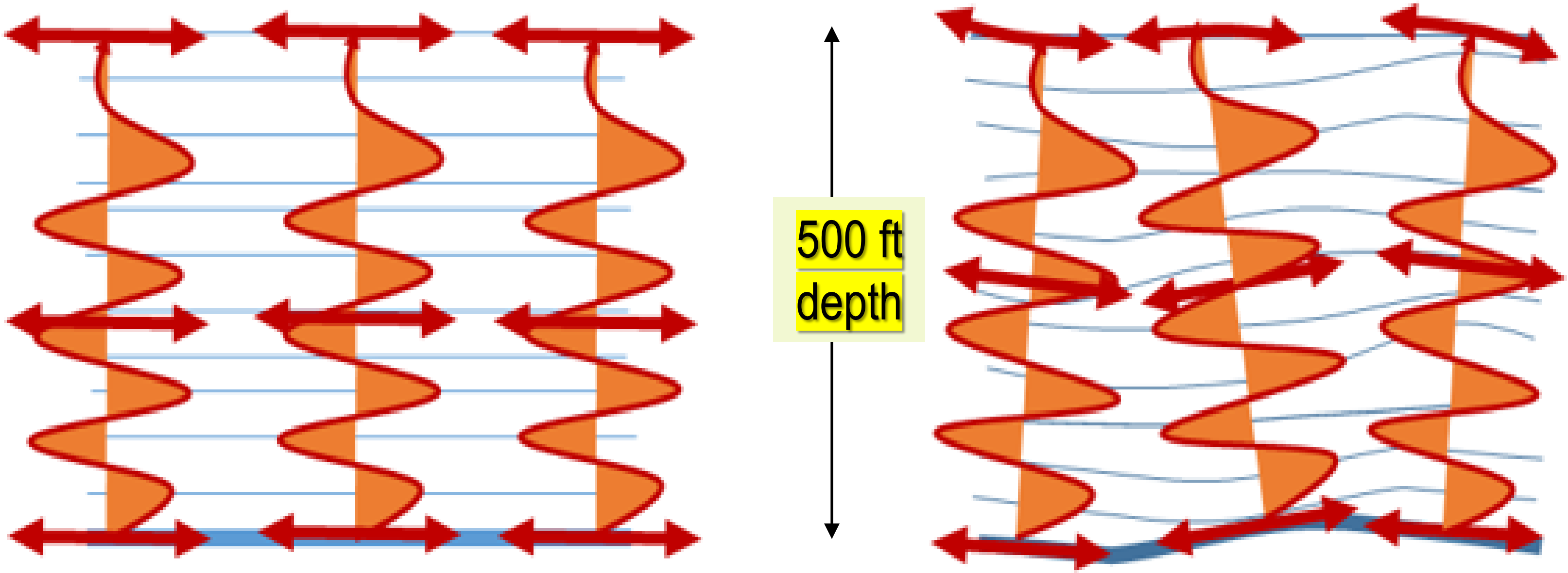
- Motion incoherency is not required for soil sites

- 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

COHERENT | **INCOHERENT**



IDEALISTIC MOTION
(1D DETERMINISTIC WAVE MODEL)

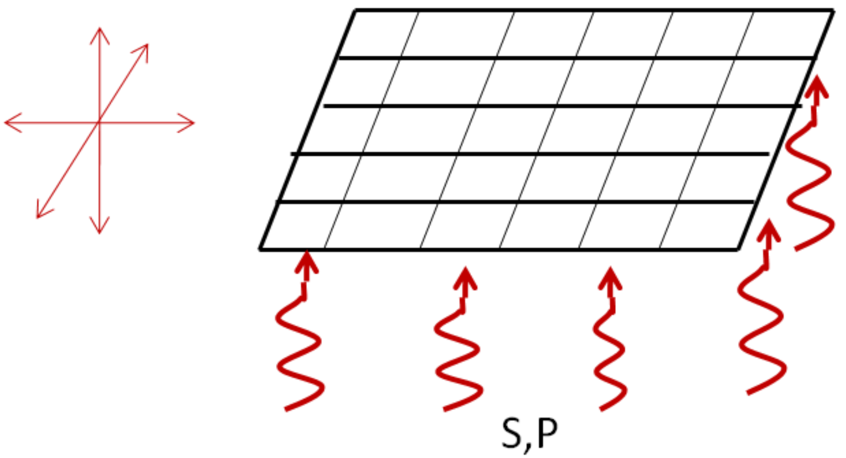
Assume vertically propagating S and P Waves in horizontal soil layering

REALISTIC MOTION
(3D RANDOM WAVE MODEL)

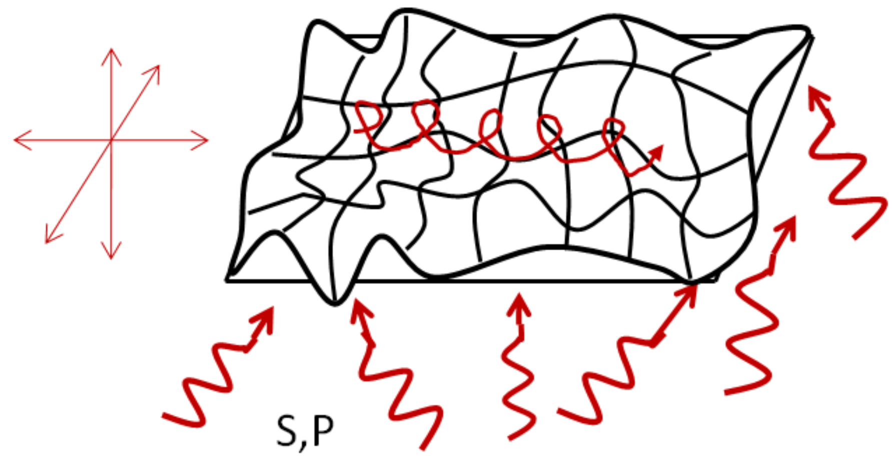
Based on stochastic models developed from real record dense array databases

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

Factors Influencing Motion Incoherency

Spatial incoherency is caused by the complex wave propagation random pattern at the site. The main cause of incoherency observed over distances of tens of meters is caused by wave scattering in the top 500 m of the soil/rock deposit (Abrahamson, 2007)

Influential Factors:

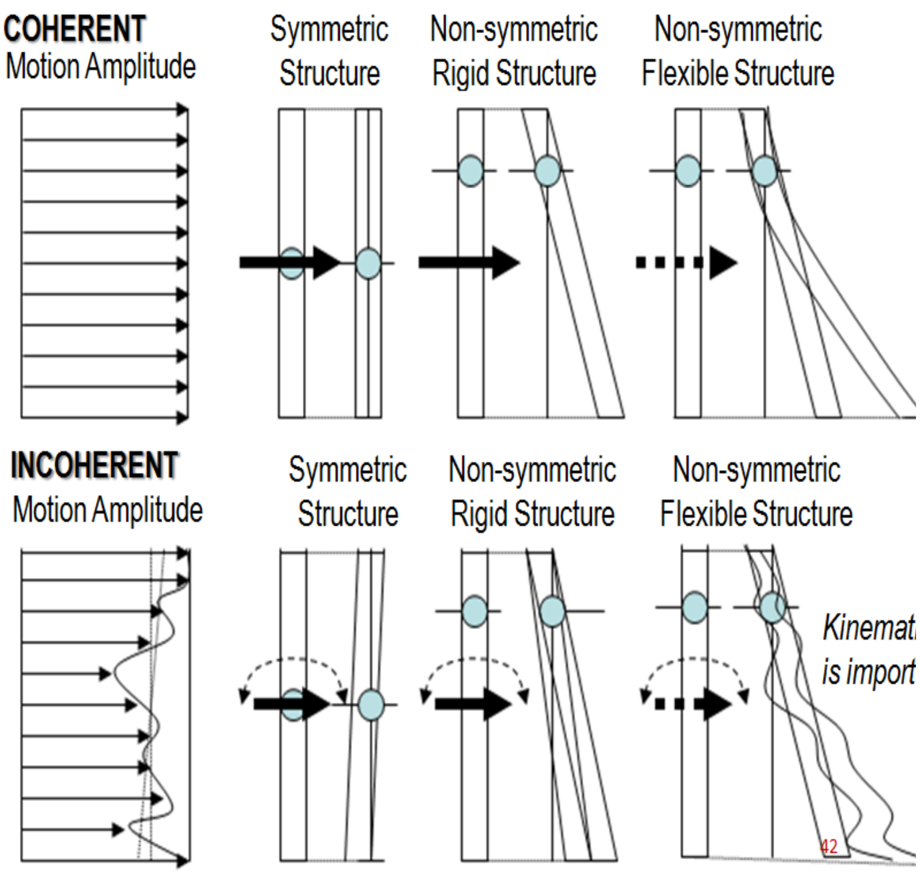
- Soil profile stiffness variation in horizontal directions increases incoherency
- Soil layer inclination, local discontinuities, faults increase incoherency
- Topography features in vicinity could significantly increase incoherency
- Earthquake magnitude is less influential especially for single point source
- For short distances near faults, the multiple wave paths from different parts of fault rupture may drastically increase the spatial variations, both the motion incoherency and wave passage effects
- Focal mechanism and directivity apparently affect less incoherency

Modeling Parameters:

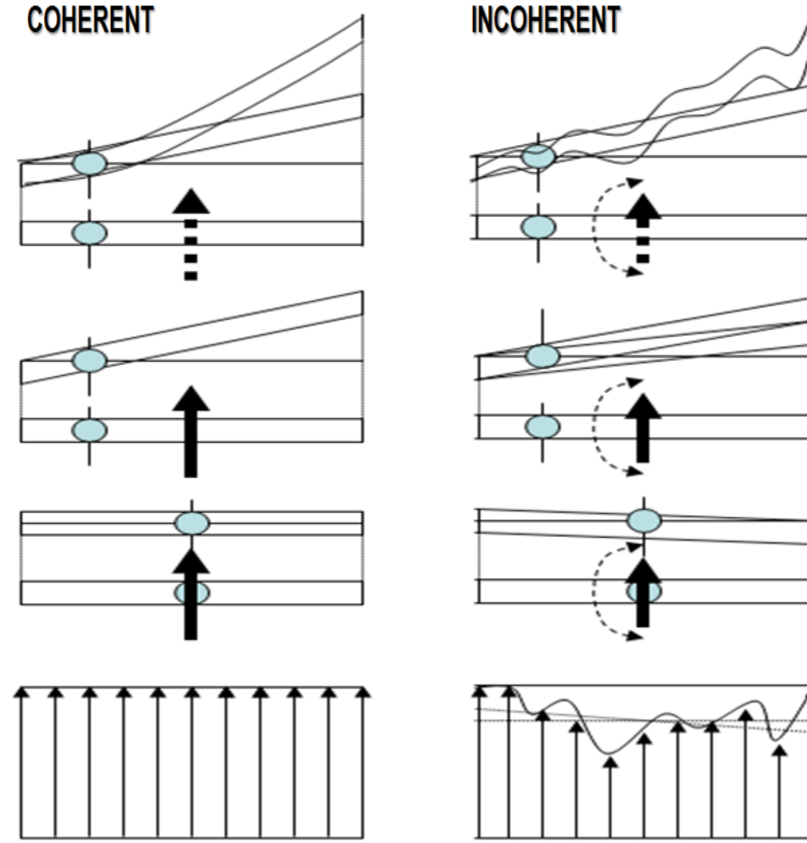
The main parameters for capturing the motion incoherency is its dependence on relative distances between locations and frequency. The latter is stronger.

Motion Incoherency Differential Motions Produce Larger Kinematic SSI Effects

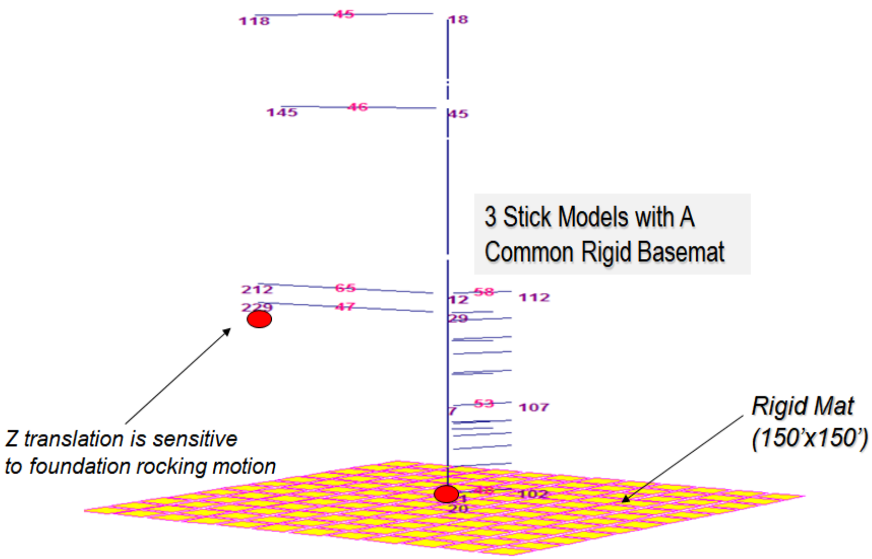
HORIZONTAL



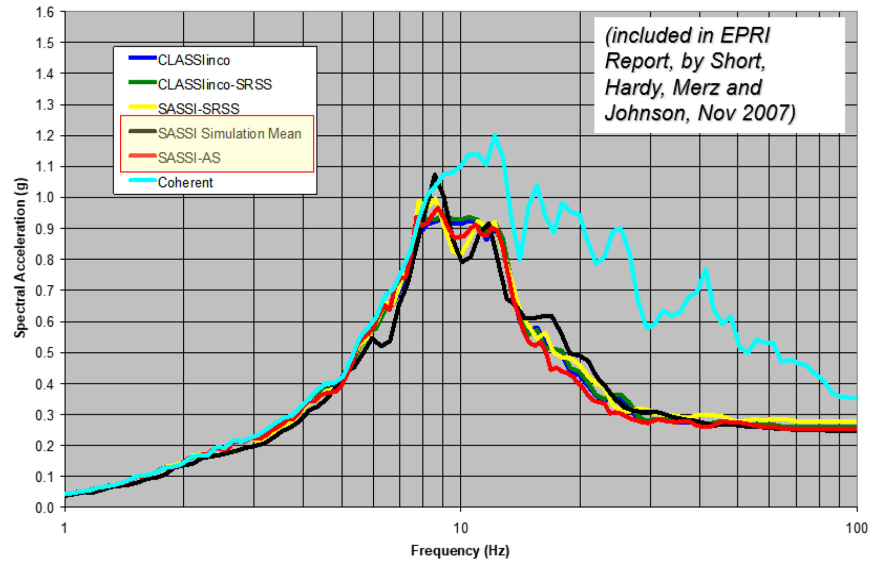
VERTICAL



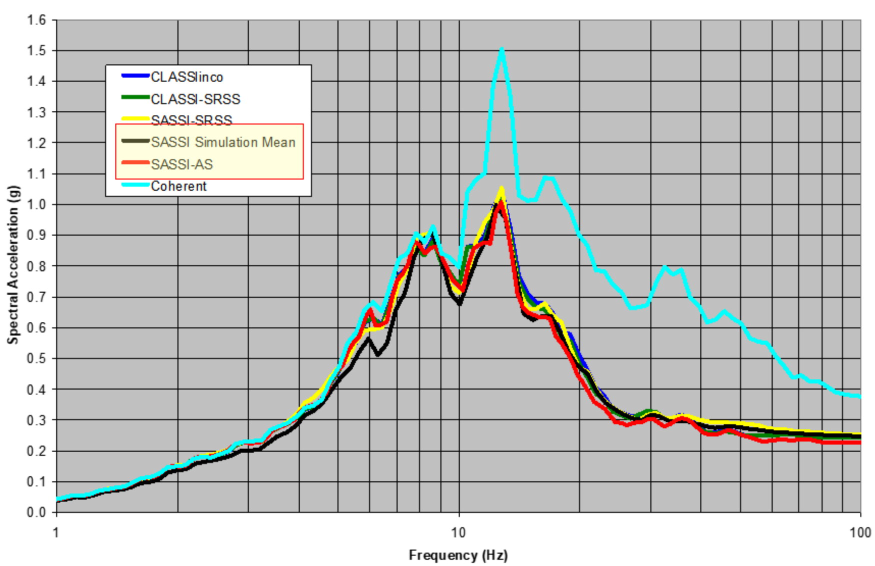
2007 EPRI Validation Study for AP1000 NI Stick Model (Surface Stick with Rigid Basemat on Rock Site)



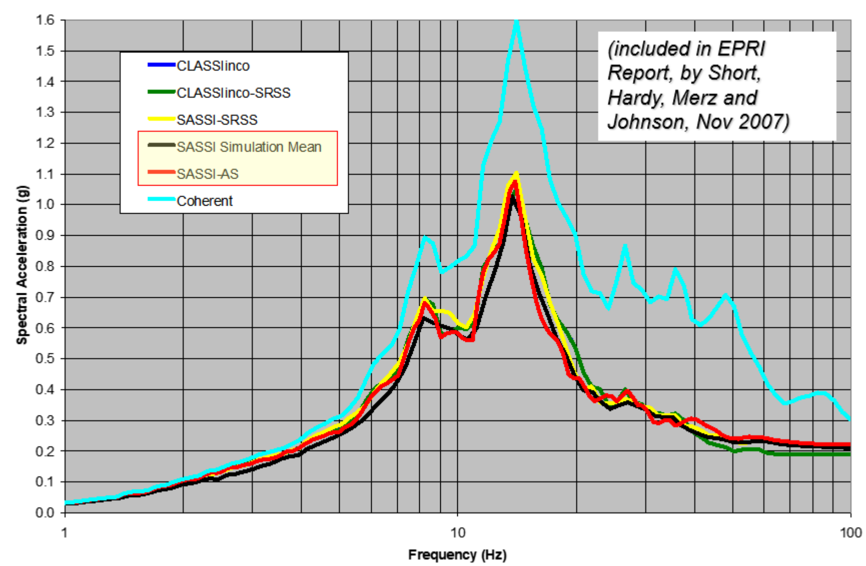
Fdn-x incoherent response due to combined input



Fdn-y incoherent response due to combined input

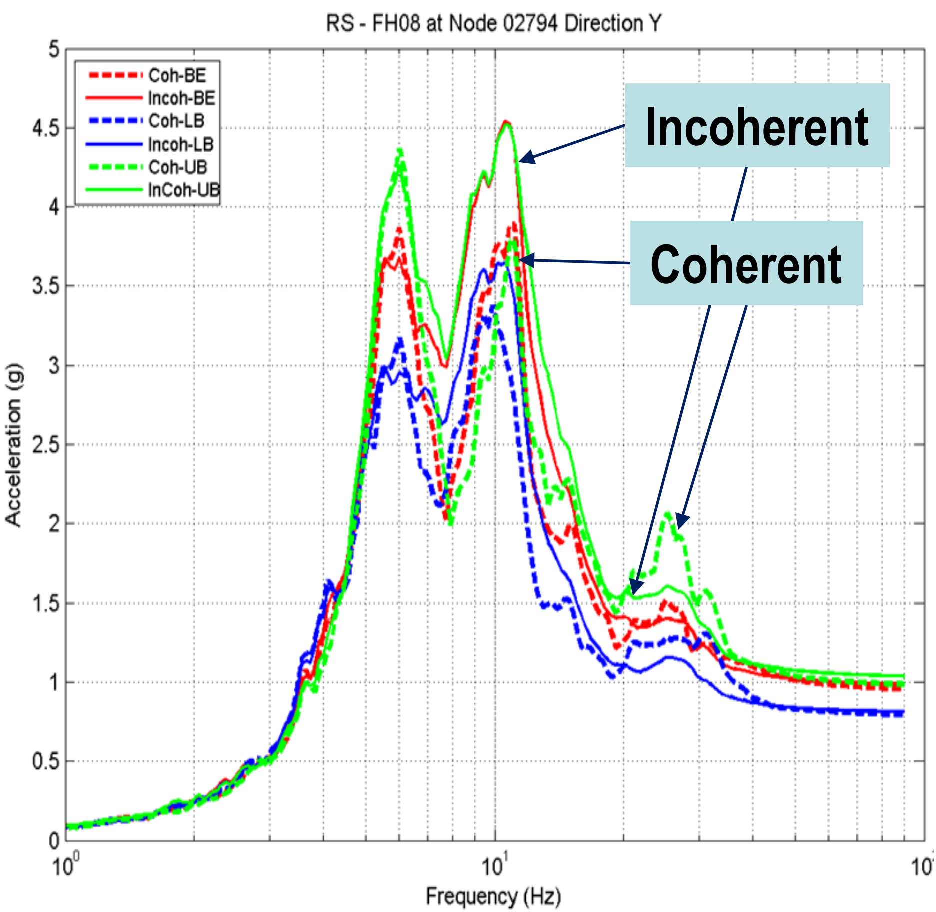


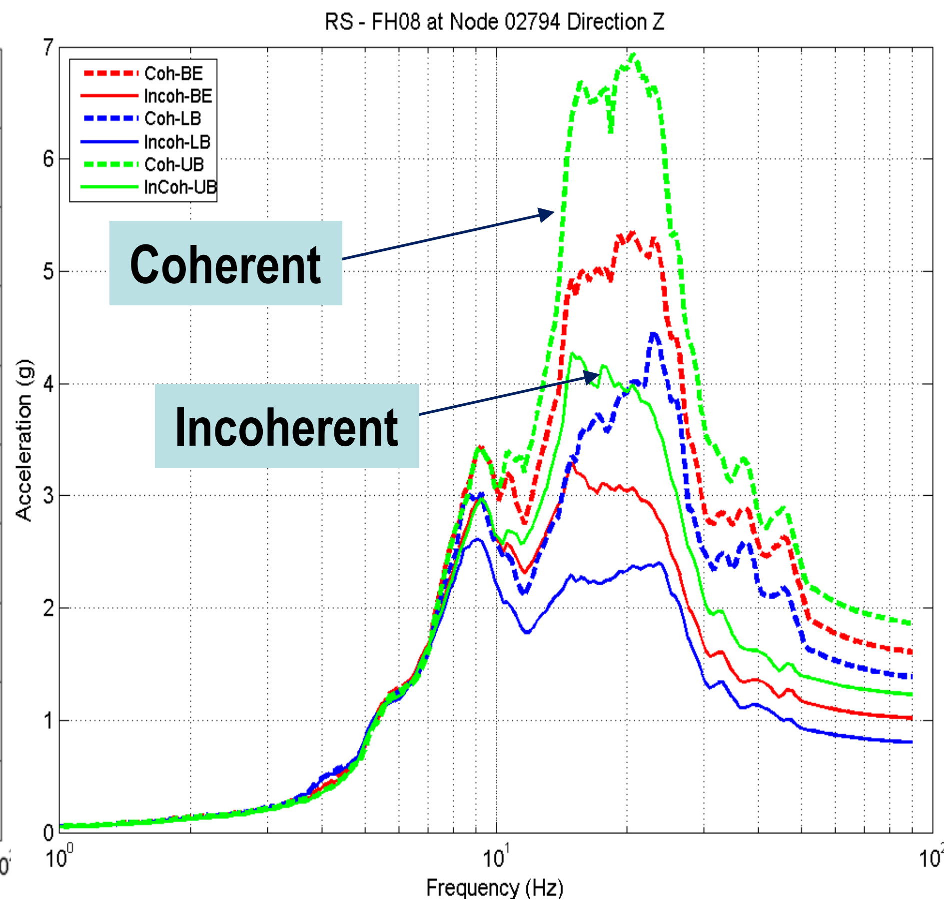
Fdn-z incoherent response due to combined input



Coherent vs. Incoherent SSI Analysis Results

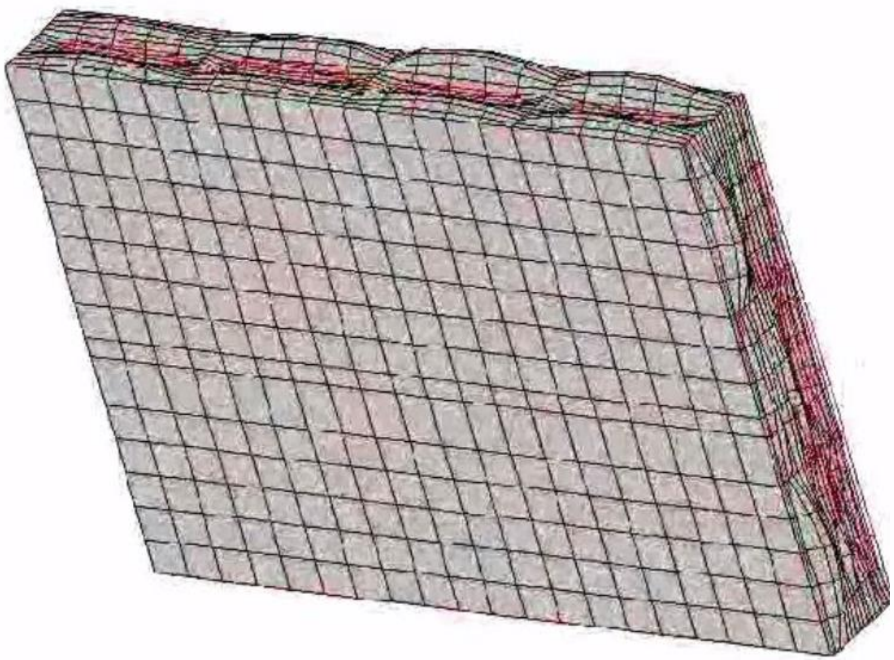
RB Complex Top-Corner ISRS in Transverse (left) and Vertical (right) Directions for LB, BE and US Soils





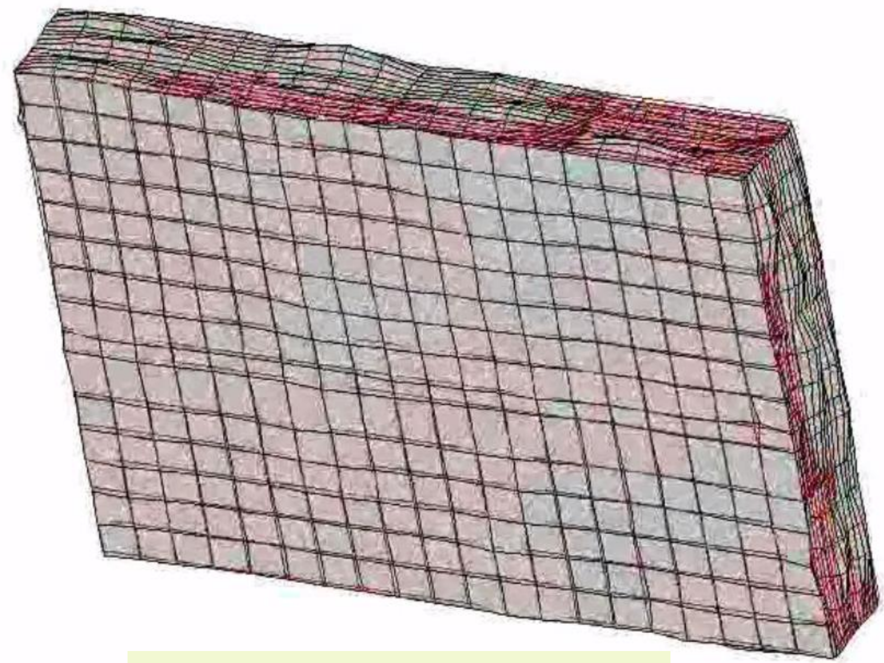
3D Wave Propagation or Motion Incoherency Effects on Baseslab Bending

Coherent SSI Motion



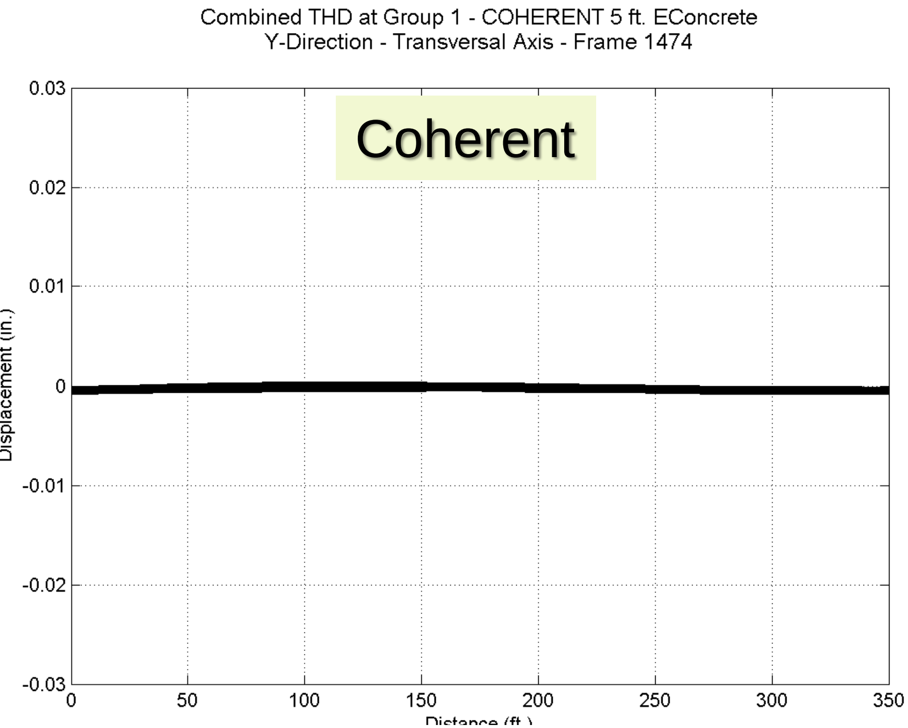
soil moves as rigid plane under foundation!

Incoherent SSI Motion



soil moves as 3D elastic waves under foundation!

Motion Incoherency Effects on Basemat Bending



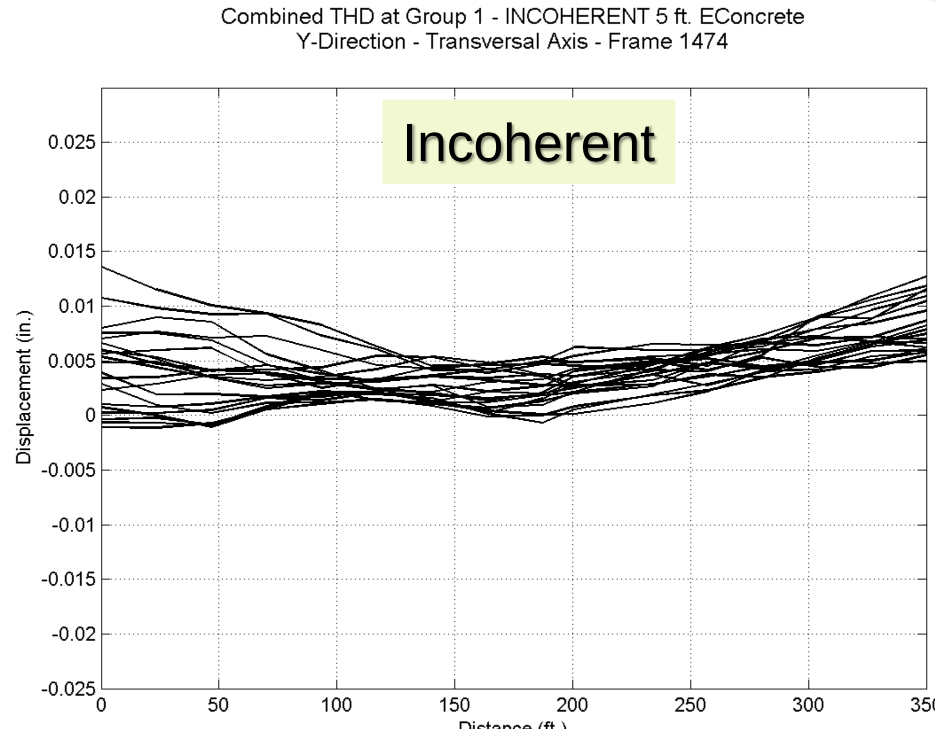


Table 1: Baseslab Bending Moments for A Soil Deposit with Vs = 3,300 ft/s

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)

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

4. Seismic SSSI Effects on ISRS and Soil Pressures

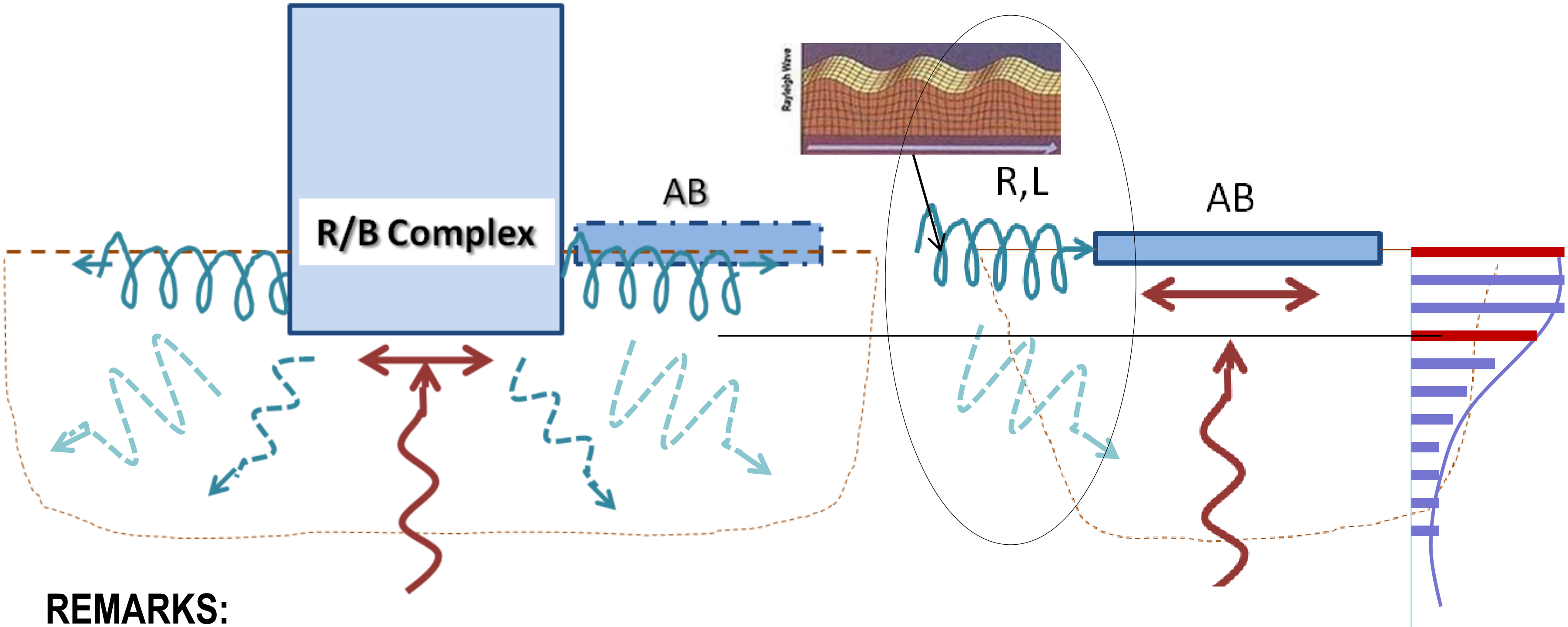
Seismic SSSI Effects

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

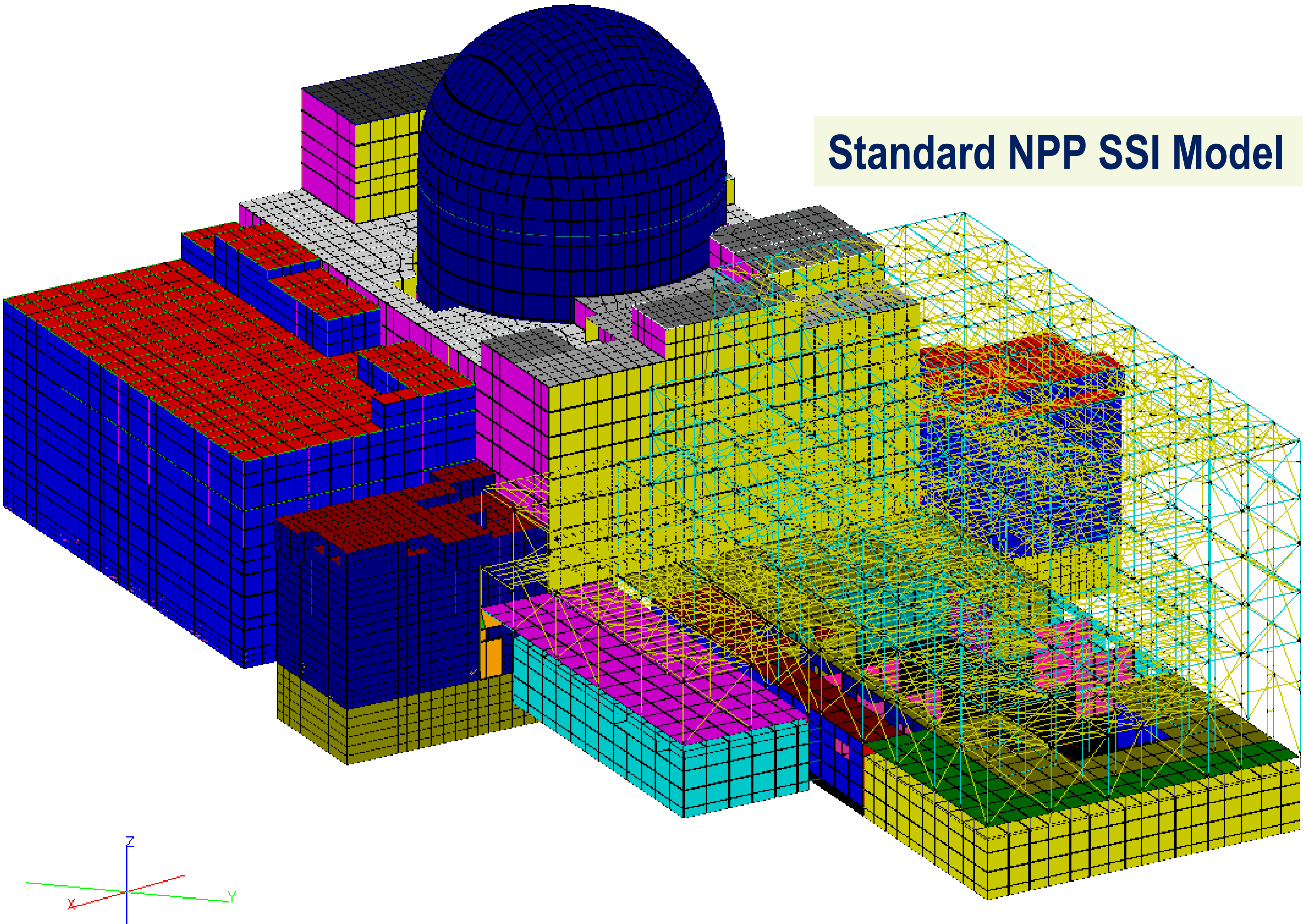
R/B Complex – AB Interaction	SSSI Effects on AB



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;

SSSI Model Includes Multiple Nuclear Structures



5. Other Important SSI Modeling Aspects. (Need Use of Advanced Options)

Concrete Cracking and Nonlinear Structure Behavior Under DBE and BDBE Inputs

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.

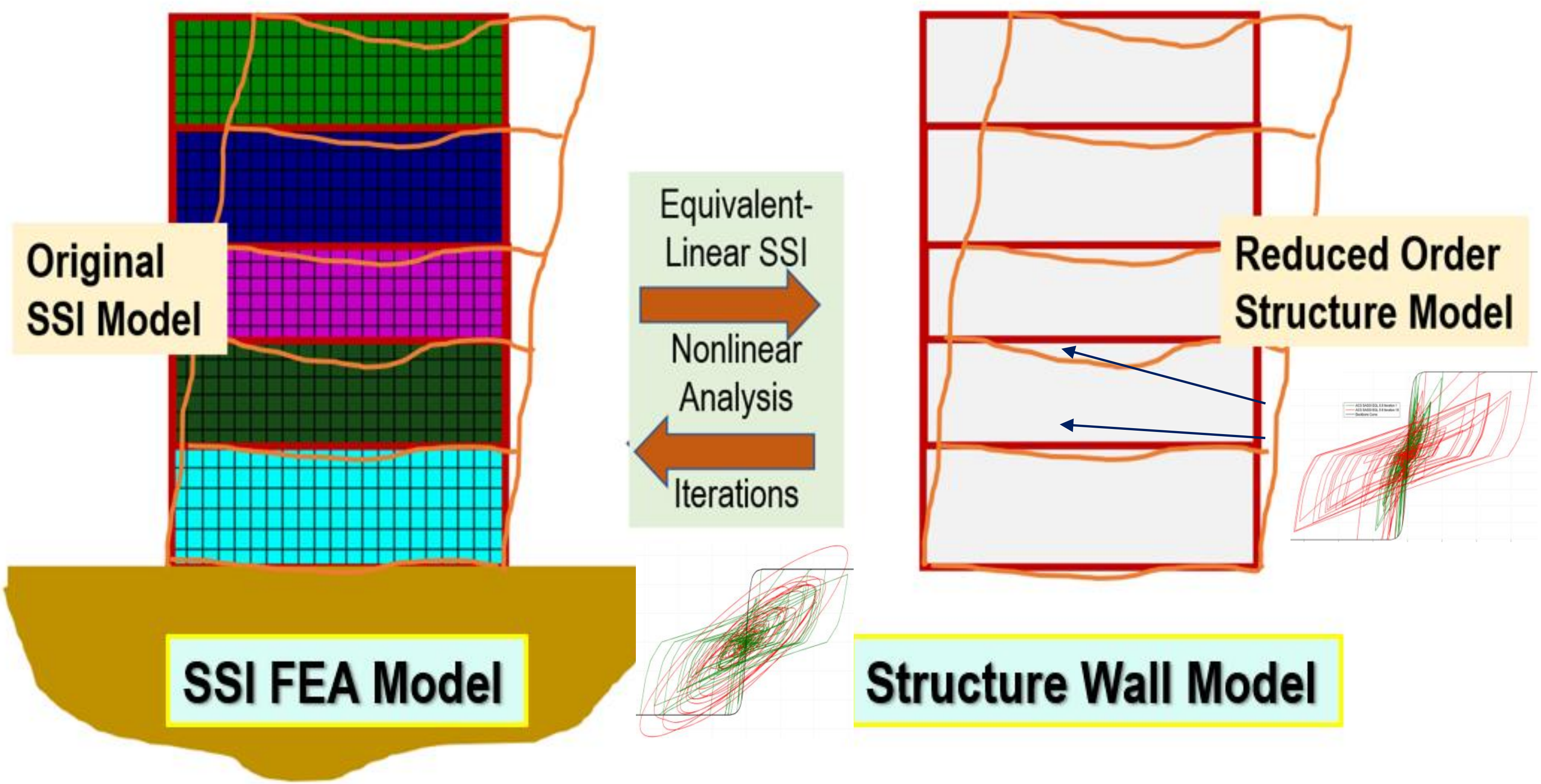
- The equivalent-linear models are numerically efficient and reasonable accurate for practical engineering analysis purposes. The computed equivalent damping shall not be above ASCE 4 accepted upper bound values without justification.

ACS SASSI Option NON is applicable.

Nonlinear Structure SSI Analysis Using A Hybrid Frequency-Time Domain Approach

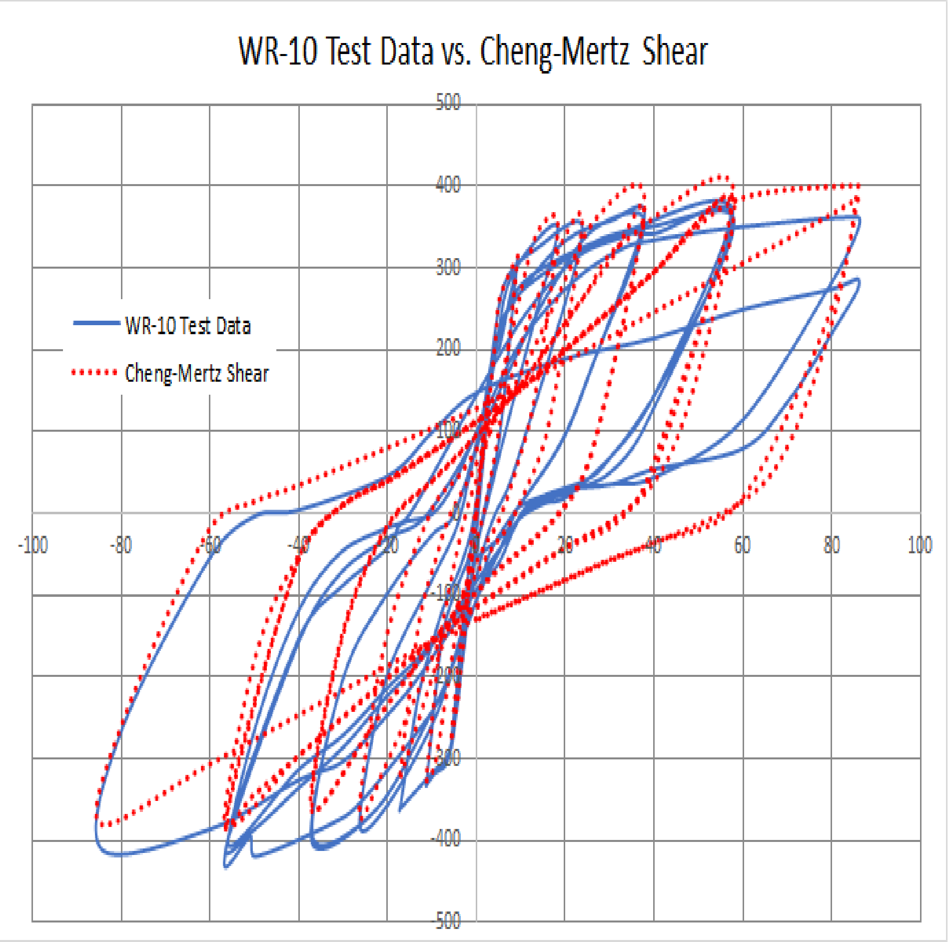
Linearized SSI Analysis
(Complex Frequency Domain)

Nonlinear Structure Analysis
(Time Domain)

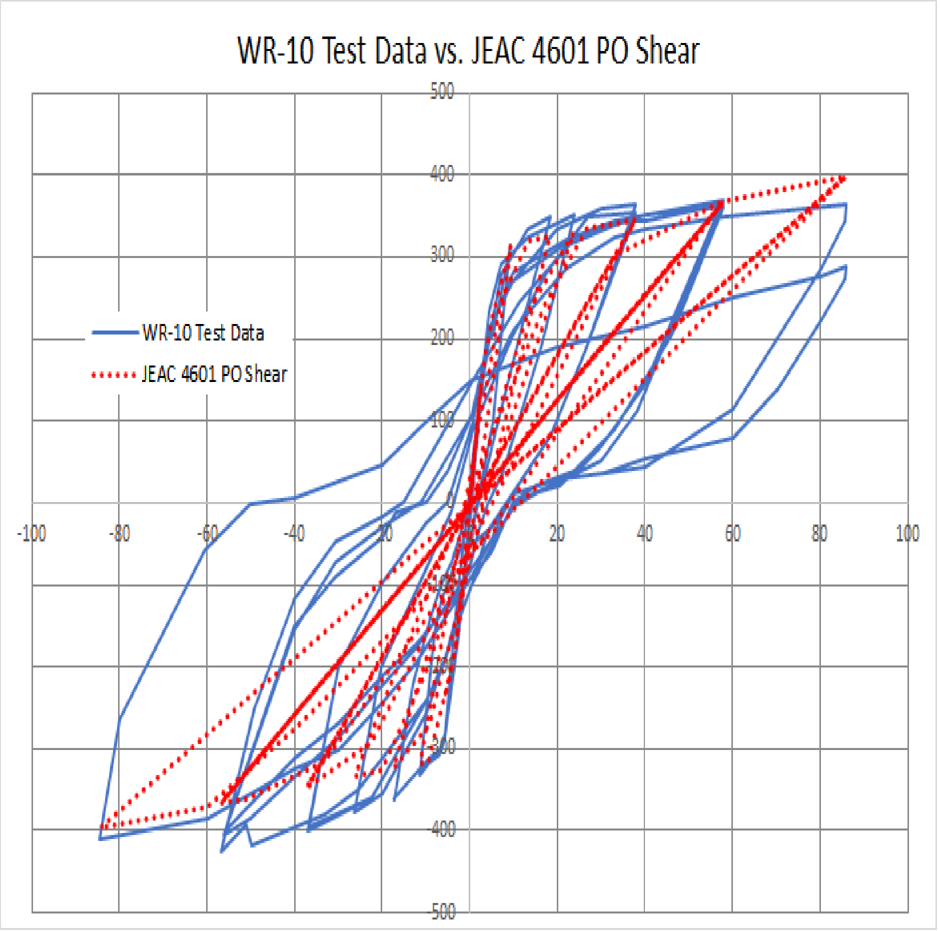


ACS SASSI Option NON Hysteretic Models Against Experimental Wall Test Data (Hayan University)

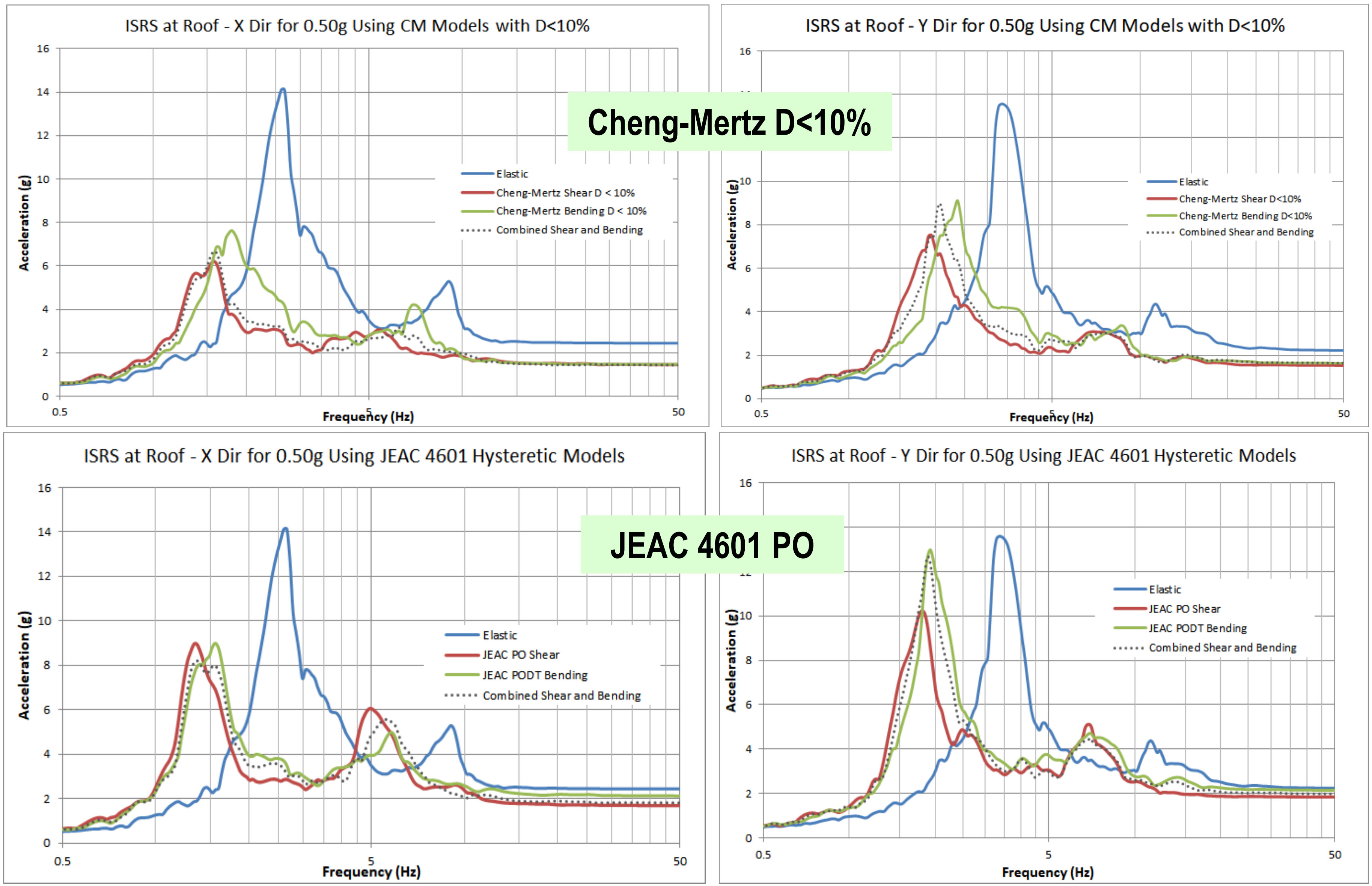
ASCE 4/43, Cheng-Mertz (CM, Model 1)



JEAC 4601, Point Oriented (PO, Model 5)



ISRS for ASCE 4 CM D<10% vs. JEAC 4601 PO for 0.50g



Foundation-Soil Separation Effects on Seismic Soil Pressure

Current practice remarks:

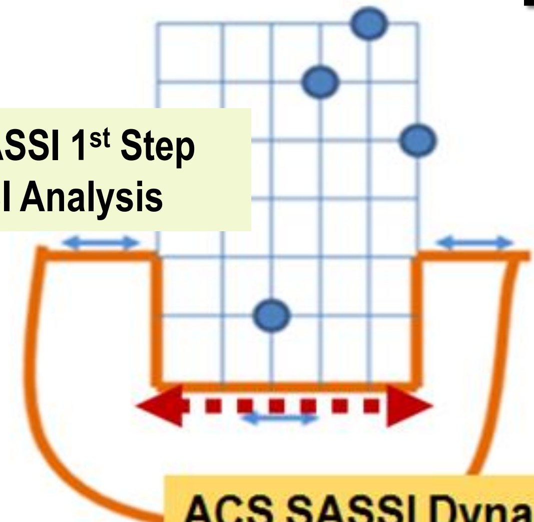
- *True nonlinear time-domain dynamic analyses* in 2D and 3D for investigating nonlinear soil and soil interface behavior are numerically sensitive to the interface modeling parameters, impractical due to huge computational resources and time involved, plus more importantly need much costlier input definition and very careful expert verification and interpretation of results.

- *Multistep nonlinear SSI 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. It permits rapid sensitivity studies on the soil and soil interface modeling, or other nonlinear behavior aspects in structure.

ACS SASSI Option A-AA

Multistep Nonlinear Analysis for Computing Soil Separation Effects (Option A)

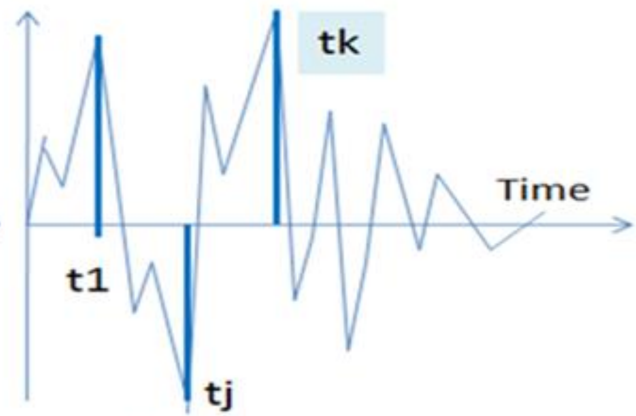
SASSI 1st Step SSI Analysis



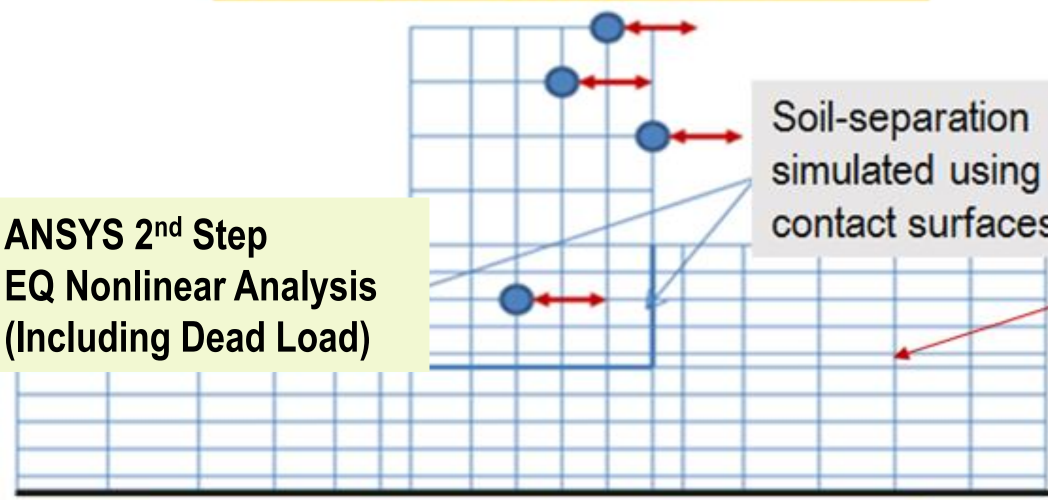
ACS SASSI Dynamic SSI Model

Use Section-Cuts To Get Base Forces/Moment Histories

Base Sliding Force/Overturning Moment History

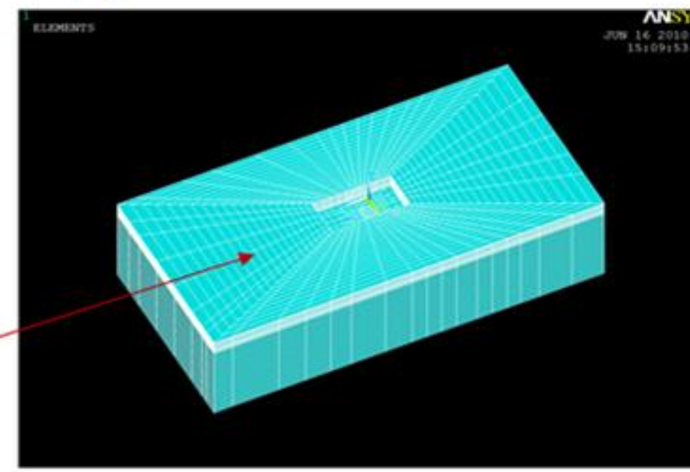


ANSYS 2nd Step EQ Nonlinear Analysis (Including Dead Load)



Soil-separation simulated using contact surfaces

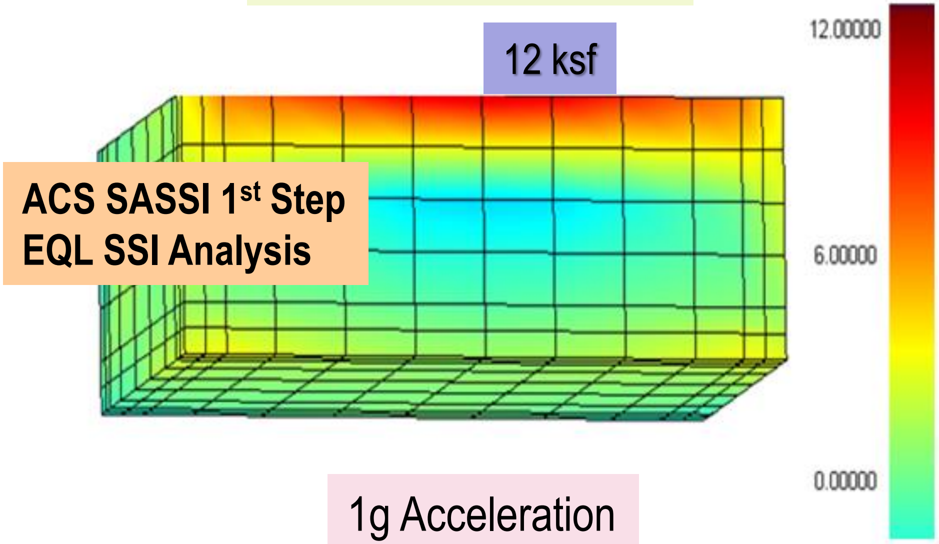
ANSYS Soil-Separation EQS Model



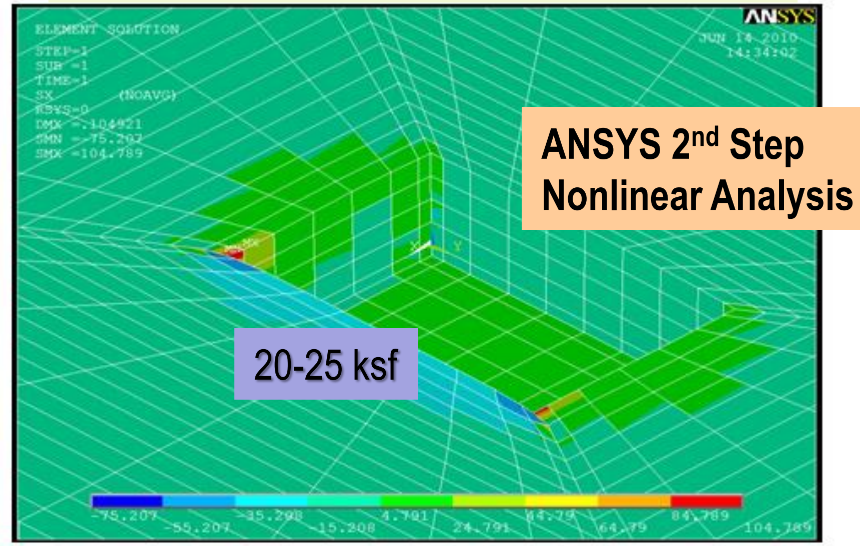
Soil Layering Static Model Automatically Generated in Option A

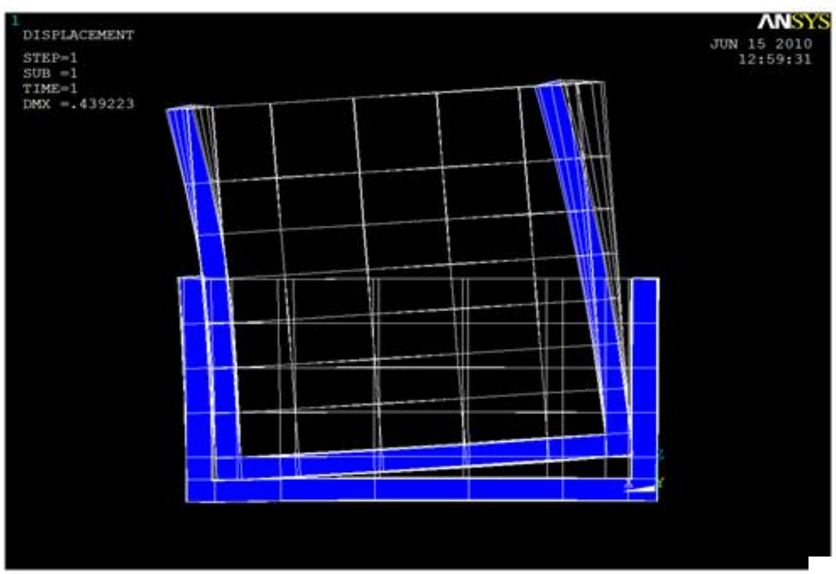
Soil Separation Example Using Option A SSI Approach

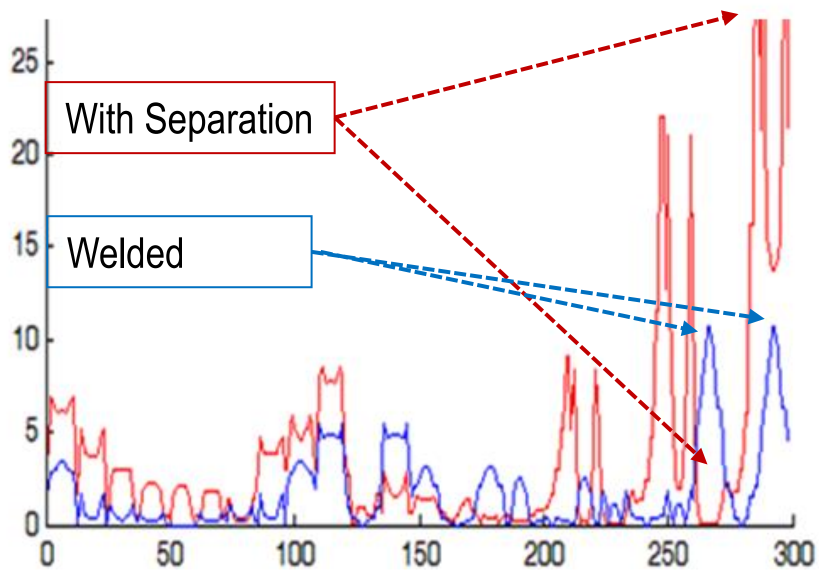
SASSI Soil Pressures



ACS SASSI Soil Pressures (Option A)







(Ghiocel and Saremi, SMiRT24 Paper 468, 2017)

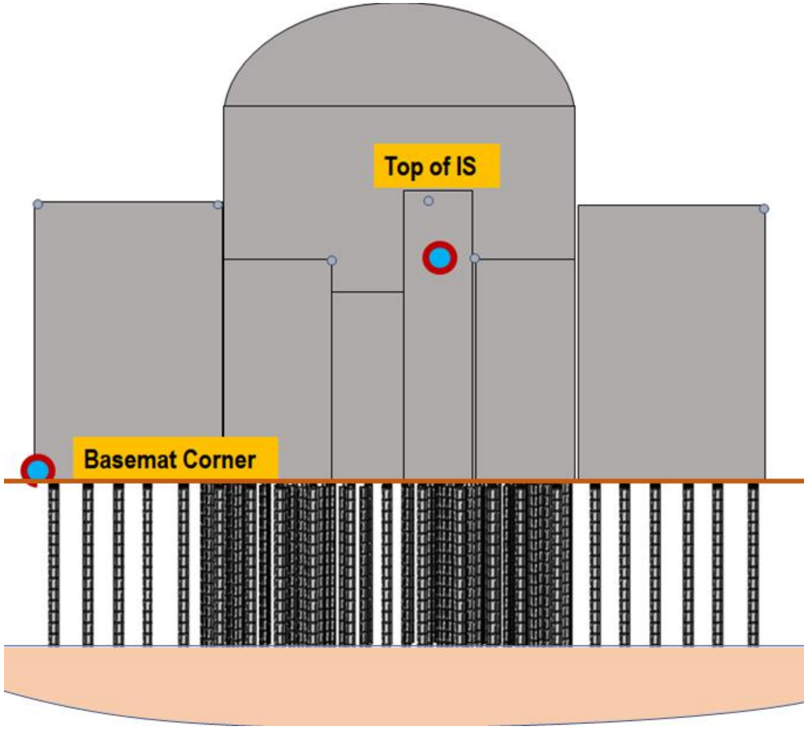
Surrounding Soil Hysteretic Behavior for DES

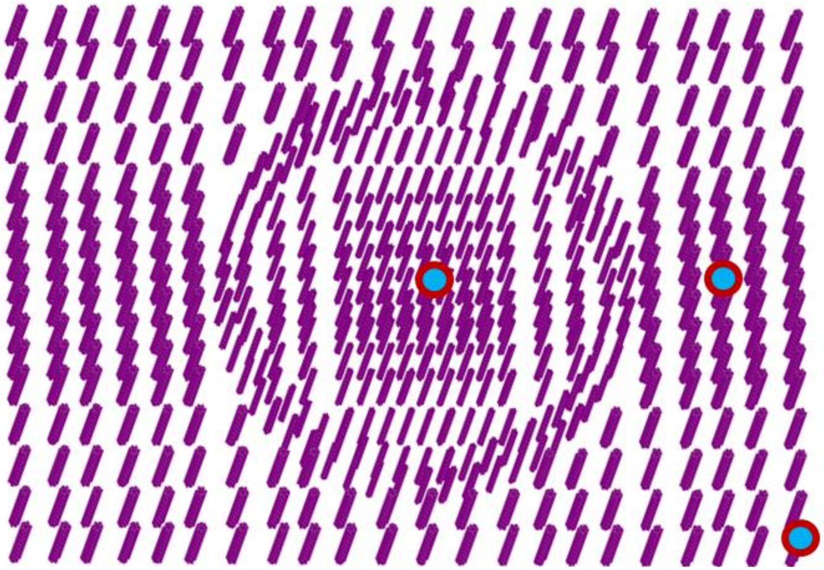
The effects of the nonlinear hysteretic soil behavior in the vicinity of deeply embedded foundations on seismic soil pressure and force and moment demands on embedded walls should be evaluated for soft soil sites.

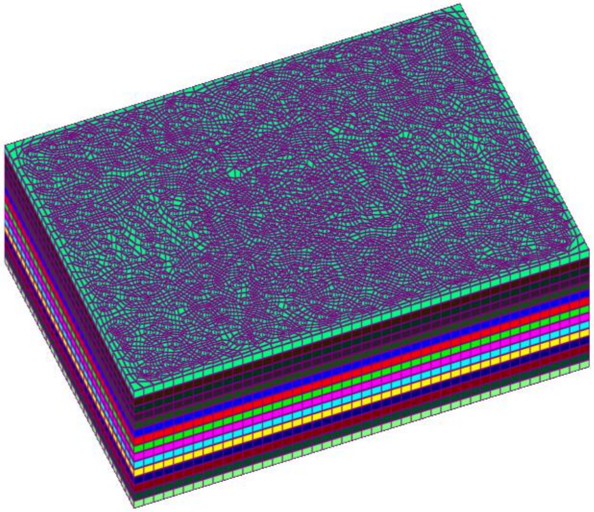
The effects of the nonlinear hysteretic soil behavior in the vicinity of foundations can be reasonably evaluated using iterative equivalent-linearization SSI analyses capable of capturing the 3D strain state in the adjacent soil.

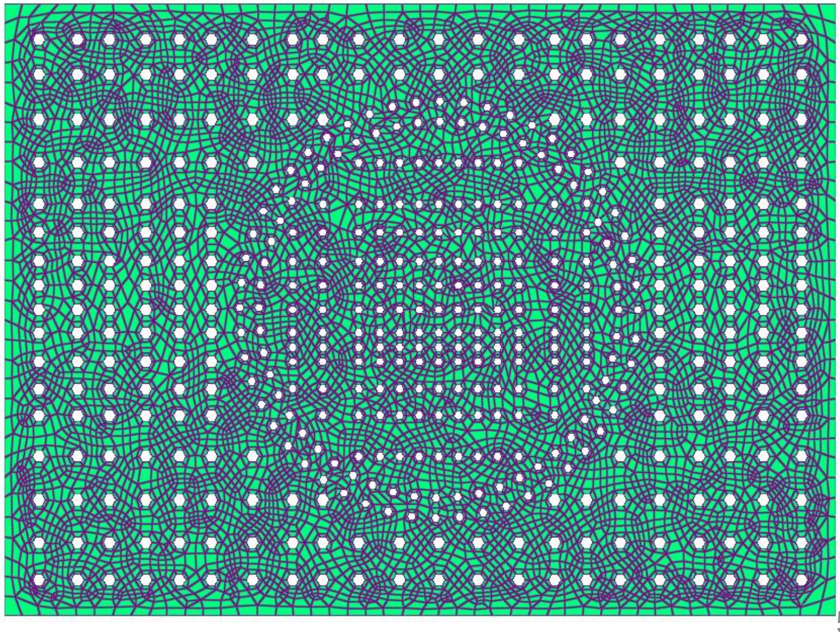
ACS SASSI NQ Main Software (Nonlinear Soil Material)

RB on Piles Including Nonlinear Soil Effects



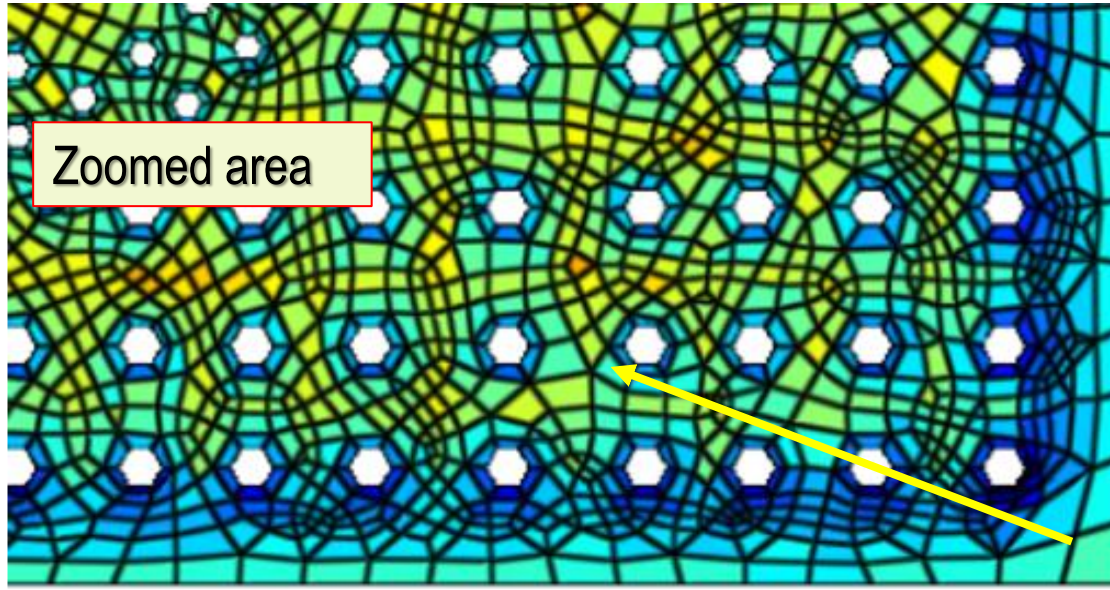




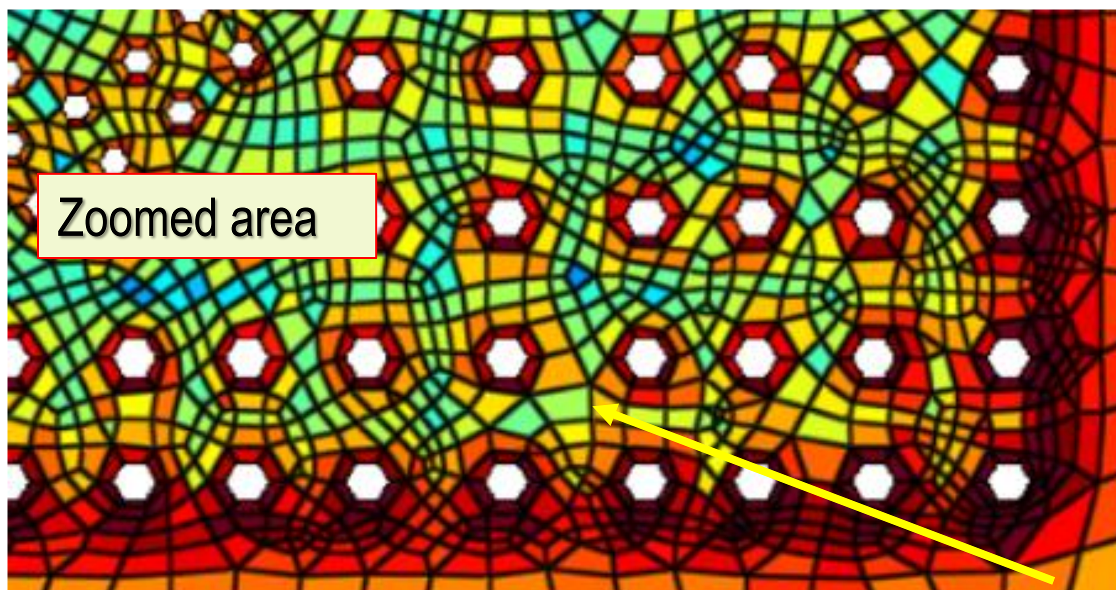


Nonlinear Soil Behavior in Vicinity of Piles

Effective Soil Shear Modulus



Effective Soil Damping

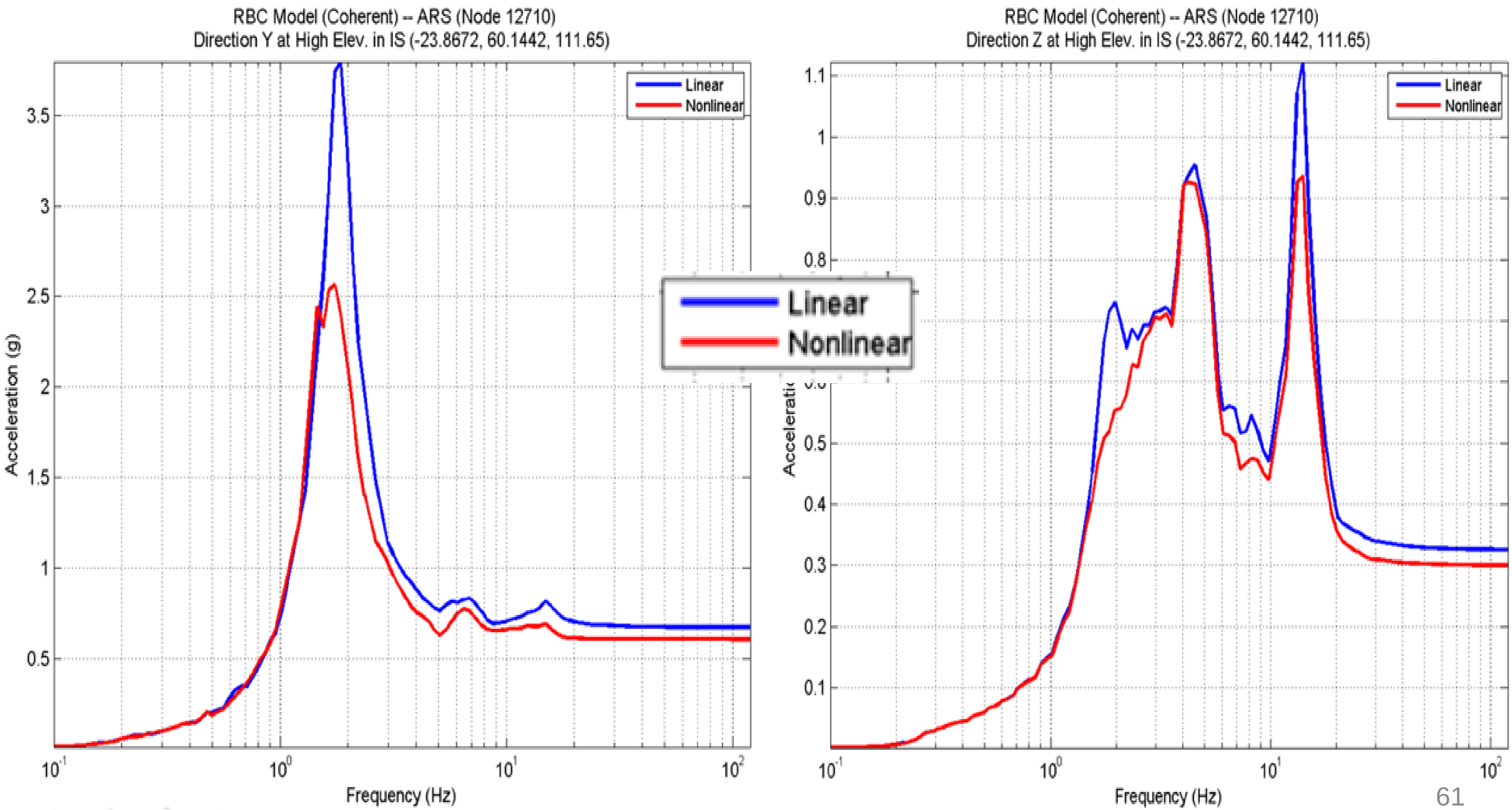


Nonlinear Soil Behavior in Vicinity of Piles.

ISRS at Top of IS

Horizontal

Vertical



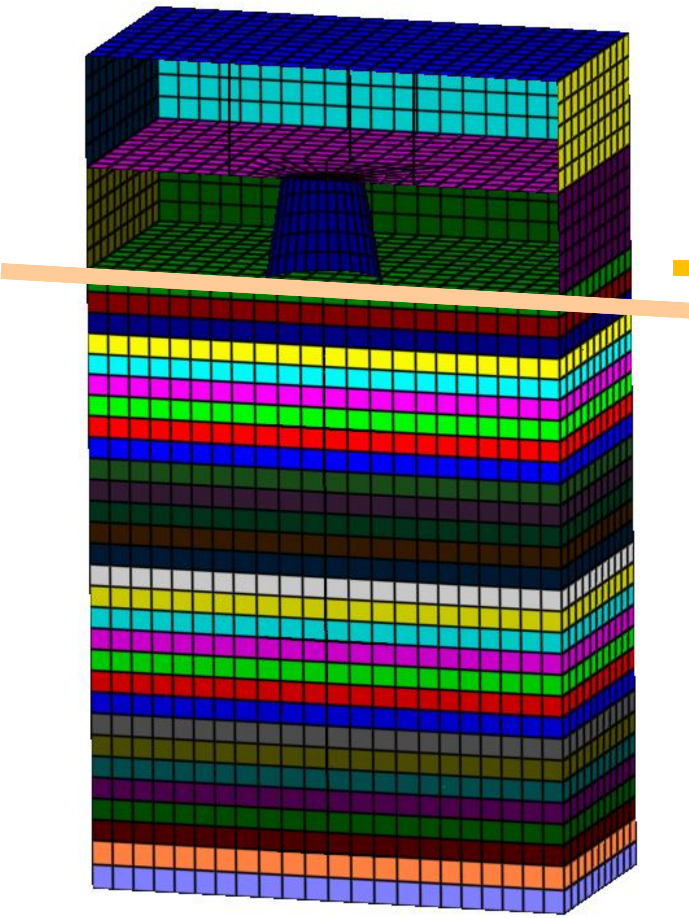
Nonlinear Embedded Wall-Soil Interface Slipping Effects for DES

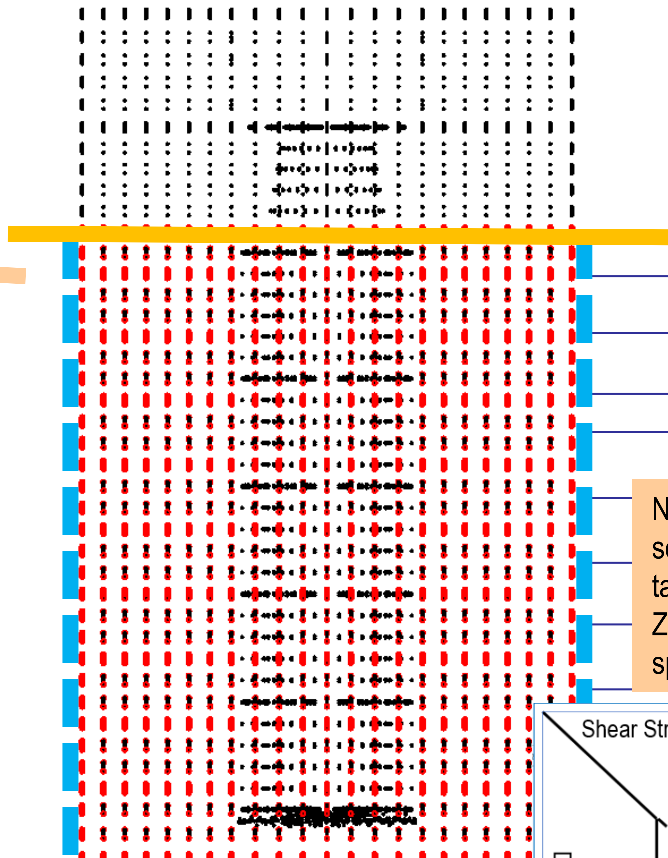
For deeply embedded structures, embedded wall-soil interface slipping conditions is bounded by two interface conditions: 1) Smooth contact surface that correspond to friction coefficients set to zero, and 2) Bonded contact surface that correspond infinite friction coefficients or no slipping.

The embedded wall slipping can be efficiently modeled on using linear or nonlinear shear springs along the embedment depth. Iterative equivalent-linear procedures can be applied for calibrating the stiffness of the wall-soil interface shear springs with the embedment depth, including the effects of both seismic and gravity loads.

ACS SASSI NQA Option NON (Nonlinear Structure & Soil Interface)

Deeply Embedded SMR Modeling with Nonlinear Structure and Nonlinear Wall-Soil Interface

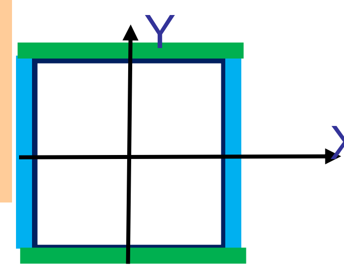


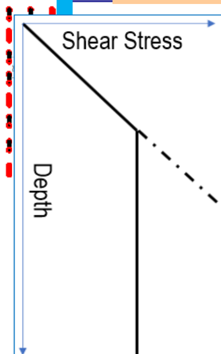


Side-soil interface modeled using nonlinear springs:

- **Nonlinear interface:** Rigid springs in normal directions X, Y and Z, and nonlinear springs in tangential directions X, Y and Z. Friction forces vary with depth.

Nonlinear side-soil springs in tangential Y and Z directions springs





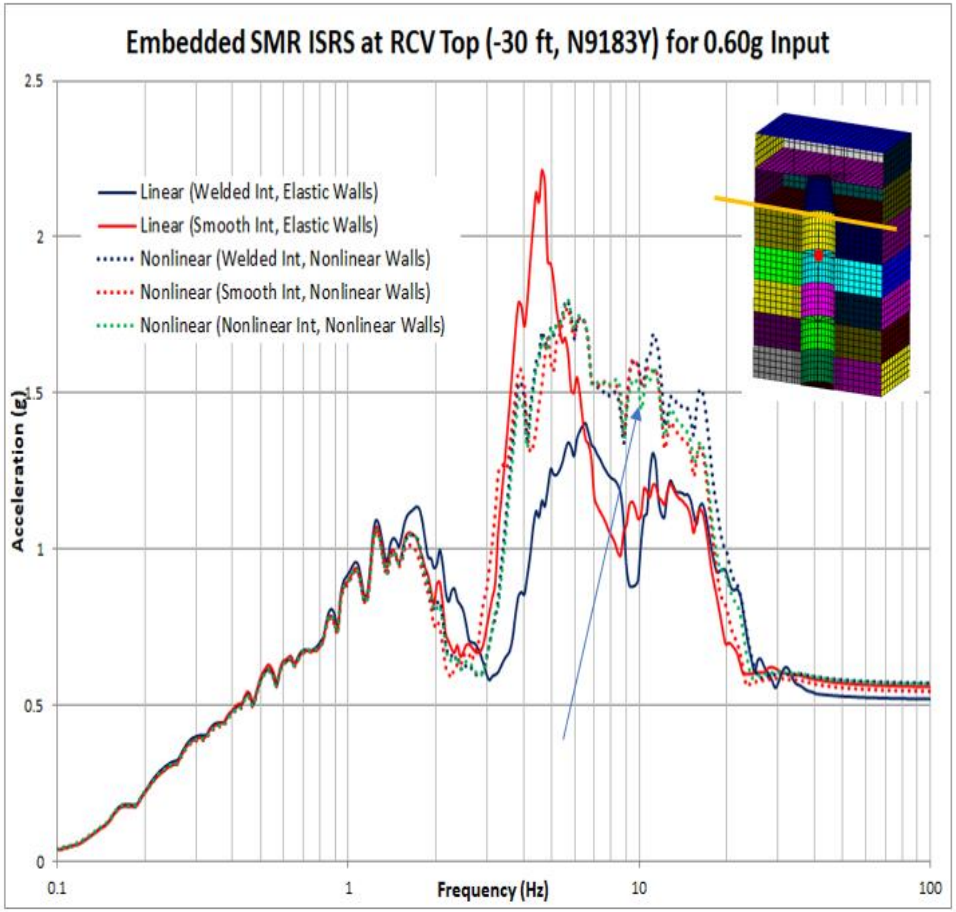
Nonlinear side-soil springs in tangential X and Z directions springs

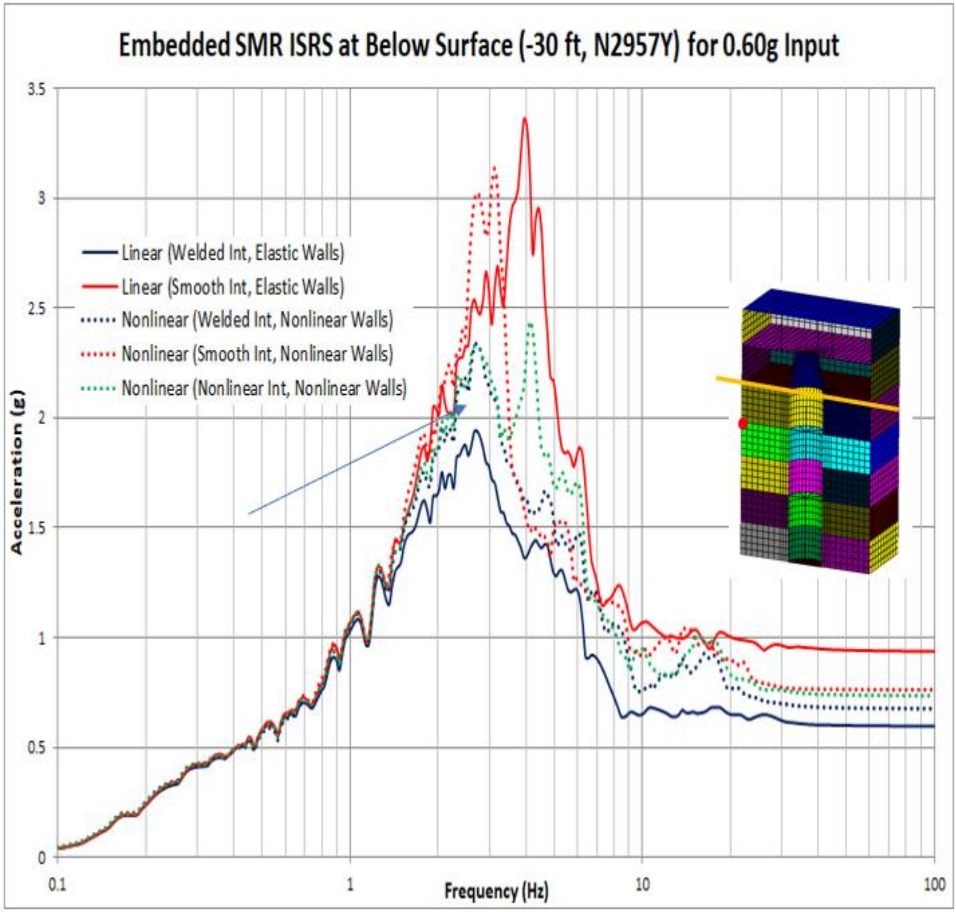
Nonlinear Structure & Wall-Soil Interface Effects on SMR ISRS At Top of RCV Level

-30ft Depth

Linear/Nonlinear Tangential Springs
Linear/Nonlinear Walls

-30ft Depth





Foundation Uplift Effects for Structures Under Severe Earthquakes

The uplift SSI analysis capability is based on the recommendations of the *Japanese JEAC 4061-2015 standard* Section 3.5.5.4 and Appendix 3.6 entitled “Foundation Uplift Nonlinearity”.

The JEAC 4601-2015 standard recommends two nonlinear uplift approaches applicable based on the basemat uplift severity:

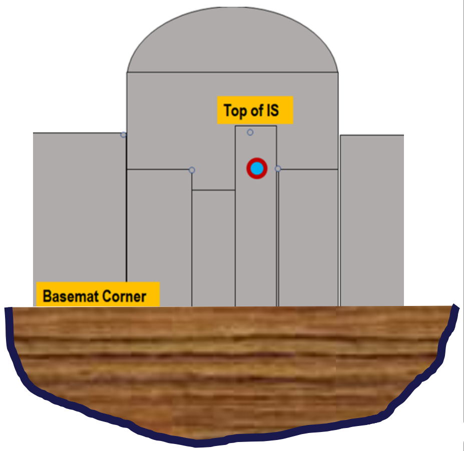
1) *Simplified nonlinear uplift approach* (Method 1) applicable if the basemat surface contact ratio is in the 65%-75% range, and

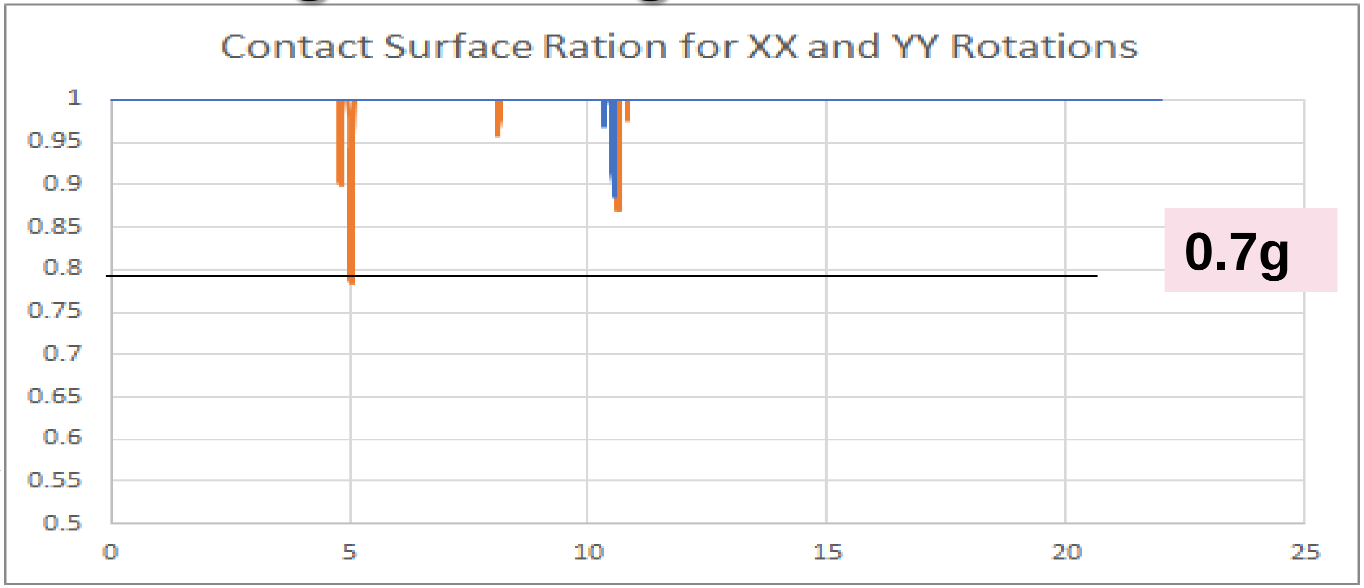
2) *Refined nonlinear uplift approach* (Method 2) applicable if the surface contact ratio is in the 50%-65% range.

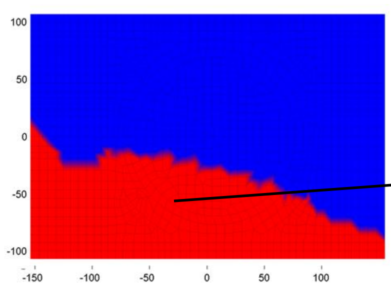
Need to redesign foundation solution if contact ratio less than 50%

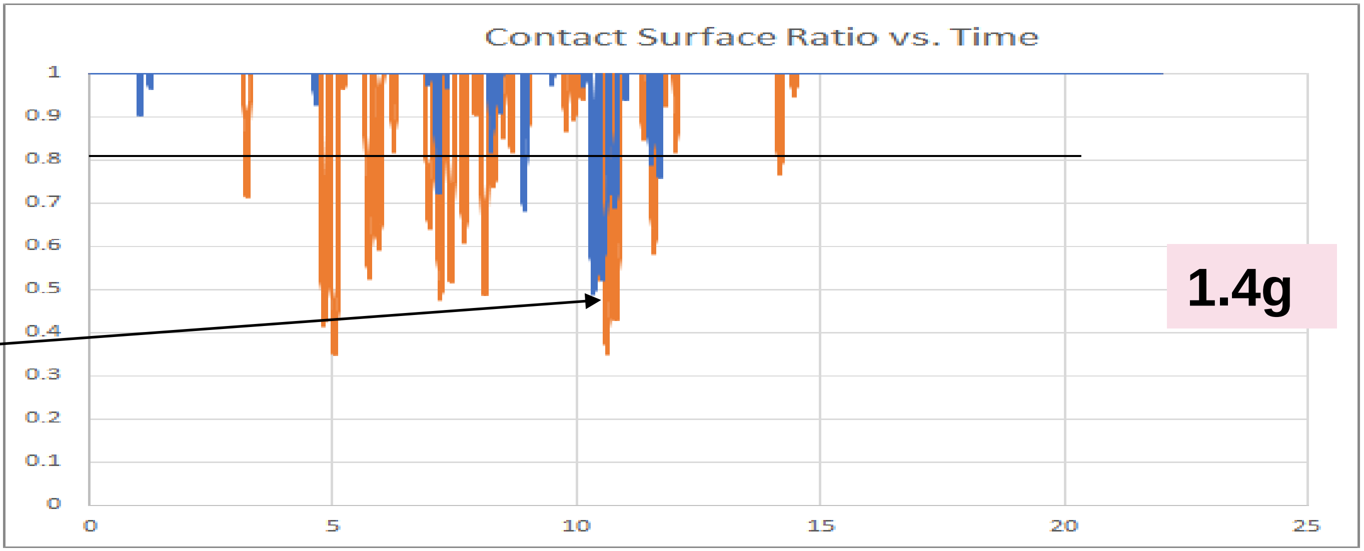
ACS SASSI NQA Option UPLIFT

RB Contact Area Ratios for X (L) and Y (T) Directions for 0.7g and 1.4g Seismic Motions



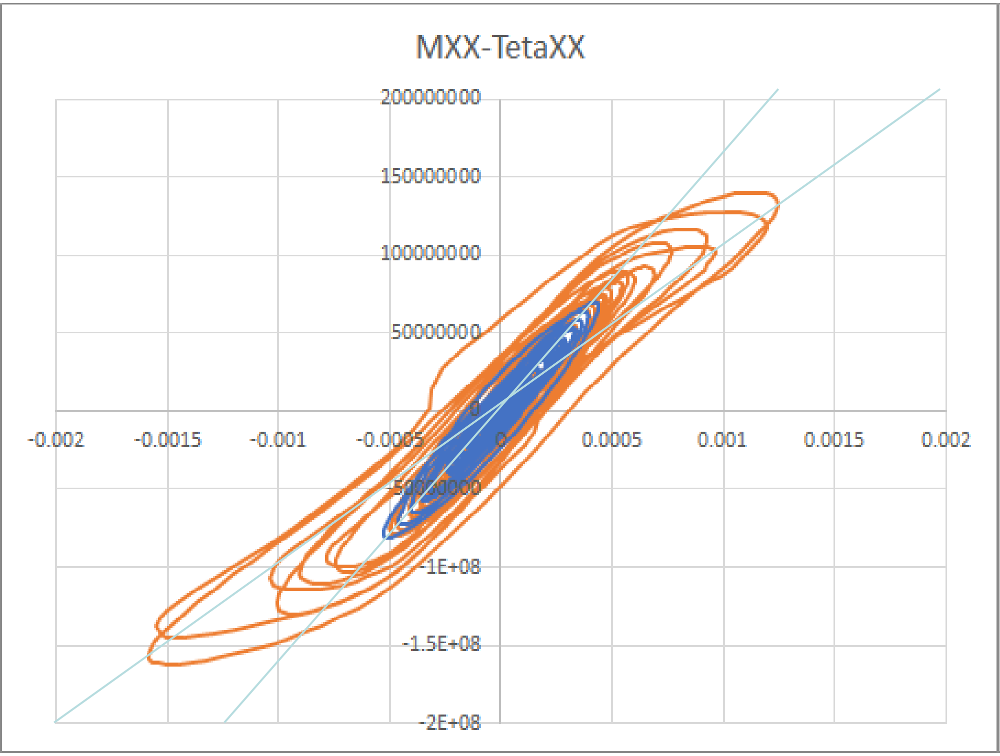




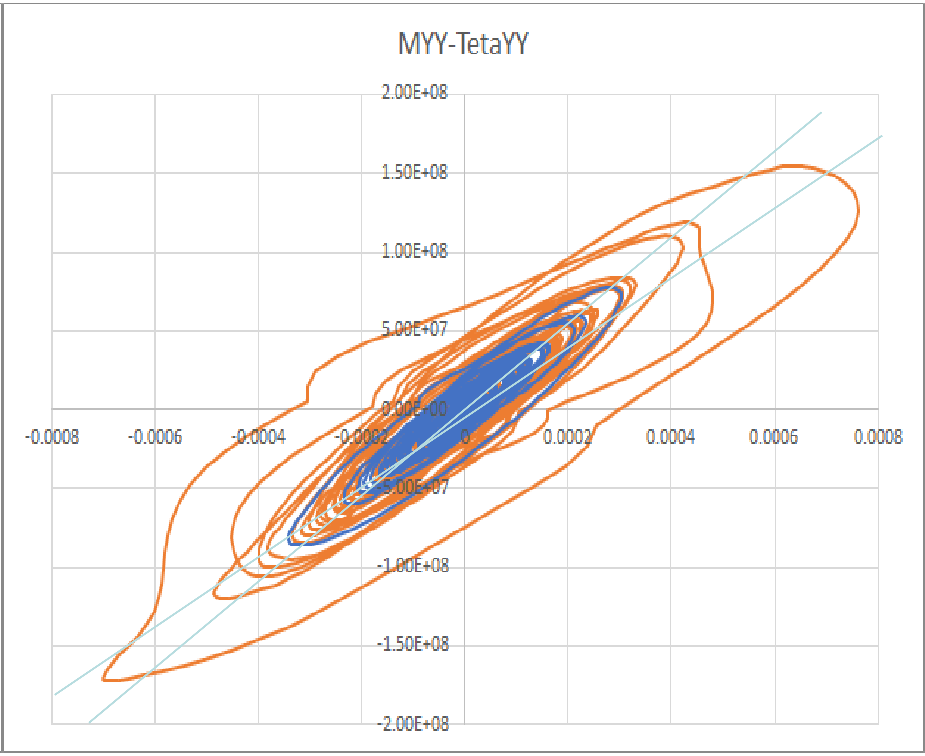


M-Teta Hysteretic Loops Showing Stiffness Reductions for 0.7g and 1.4g Seismic Inputs

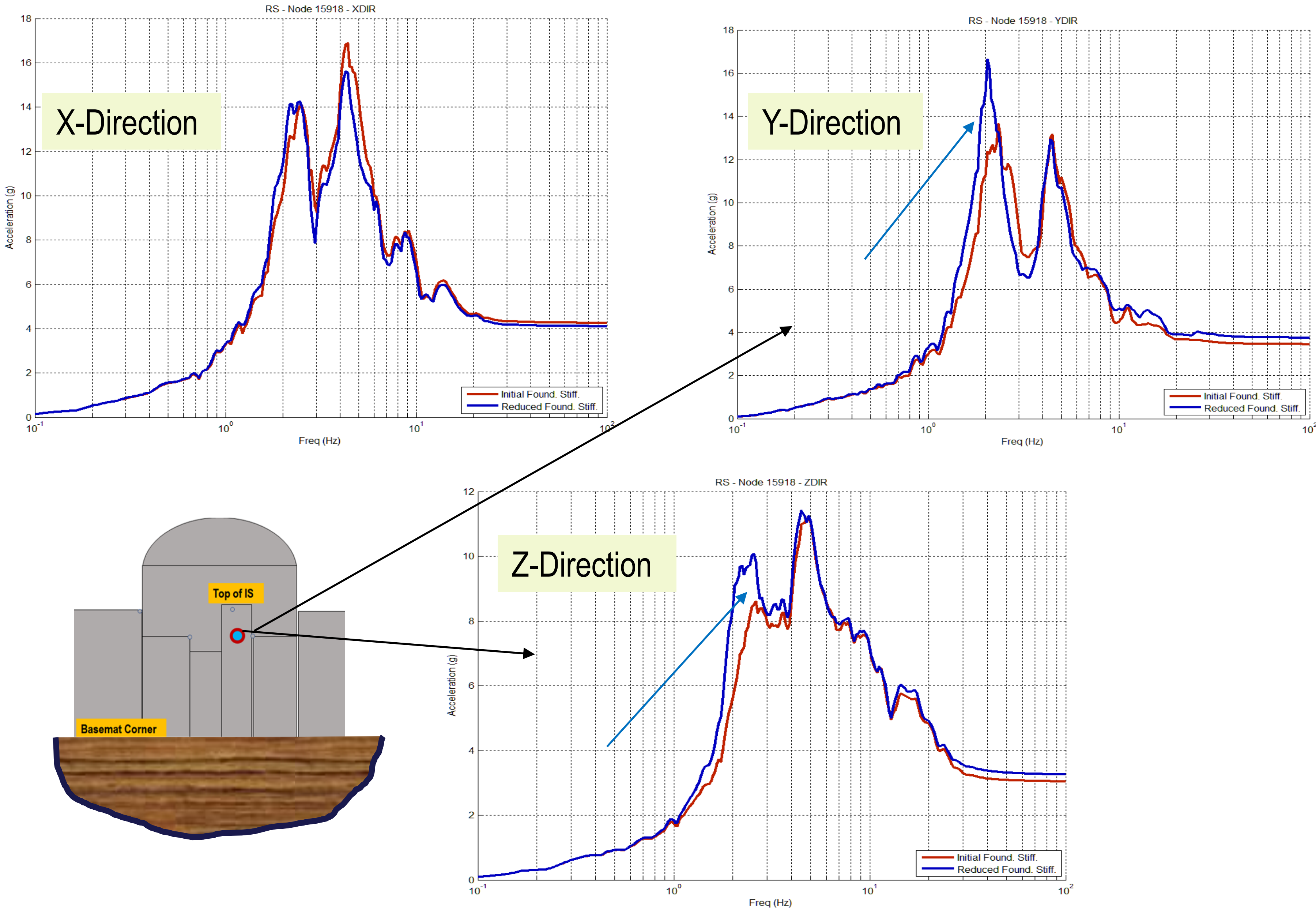
Y-Direction (T)



X-Direction (L)



Initial vs. Iterated ISRS for X, Y, Z for 3DFEM



Probabilistic SRA and SSI Per ASCE 4-16

Current practice:

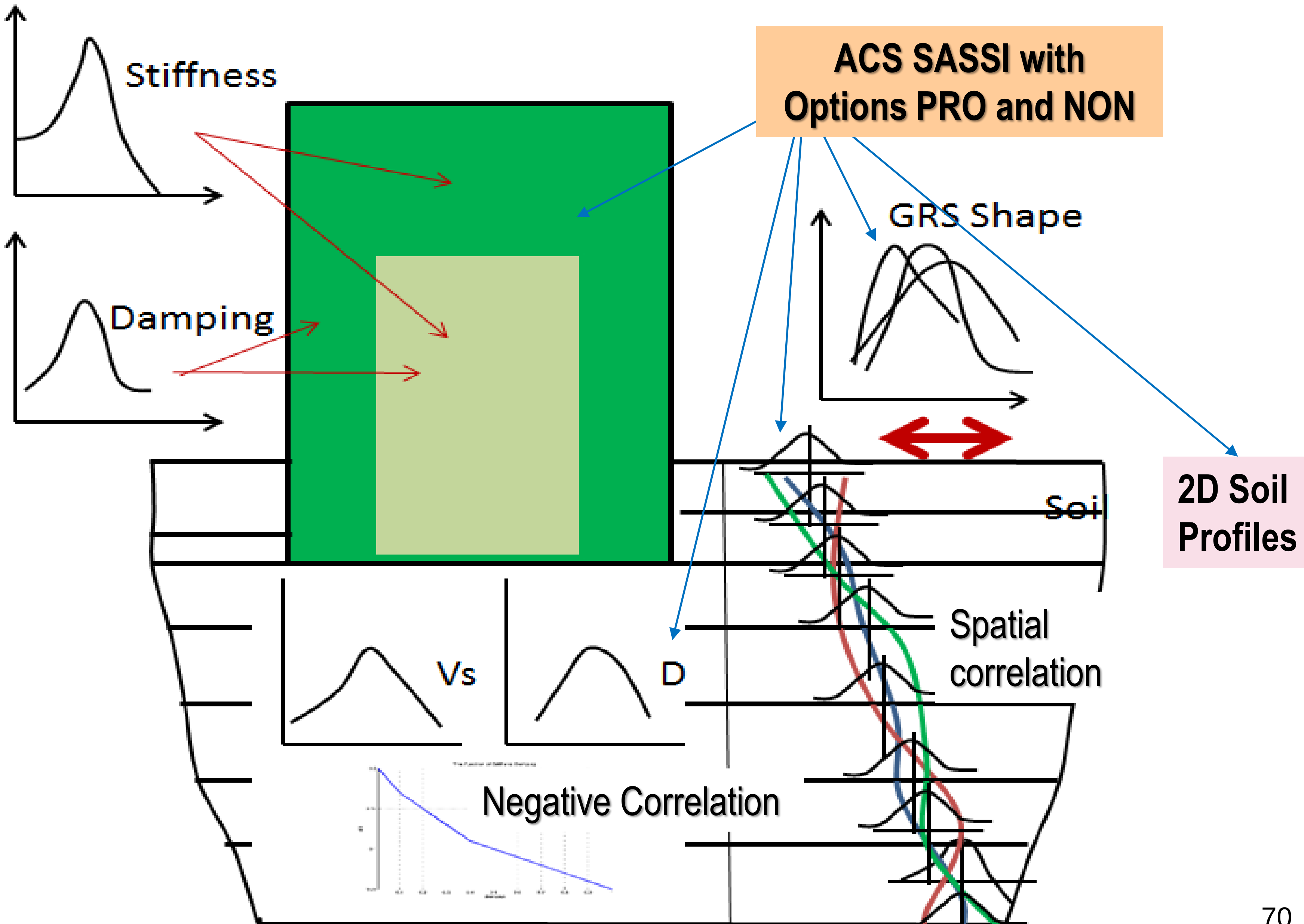
- The recent ASCE 4-16 standard provides a unique set of engineering guidance for modeling SSI uncertainties using physics-based probabilistic SSI models.

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

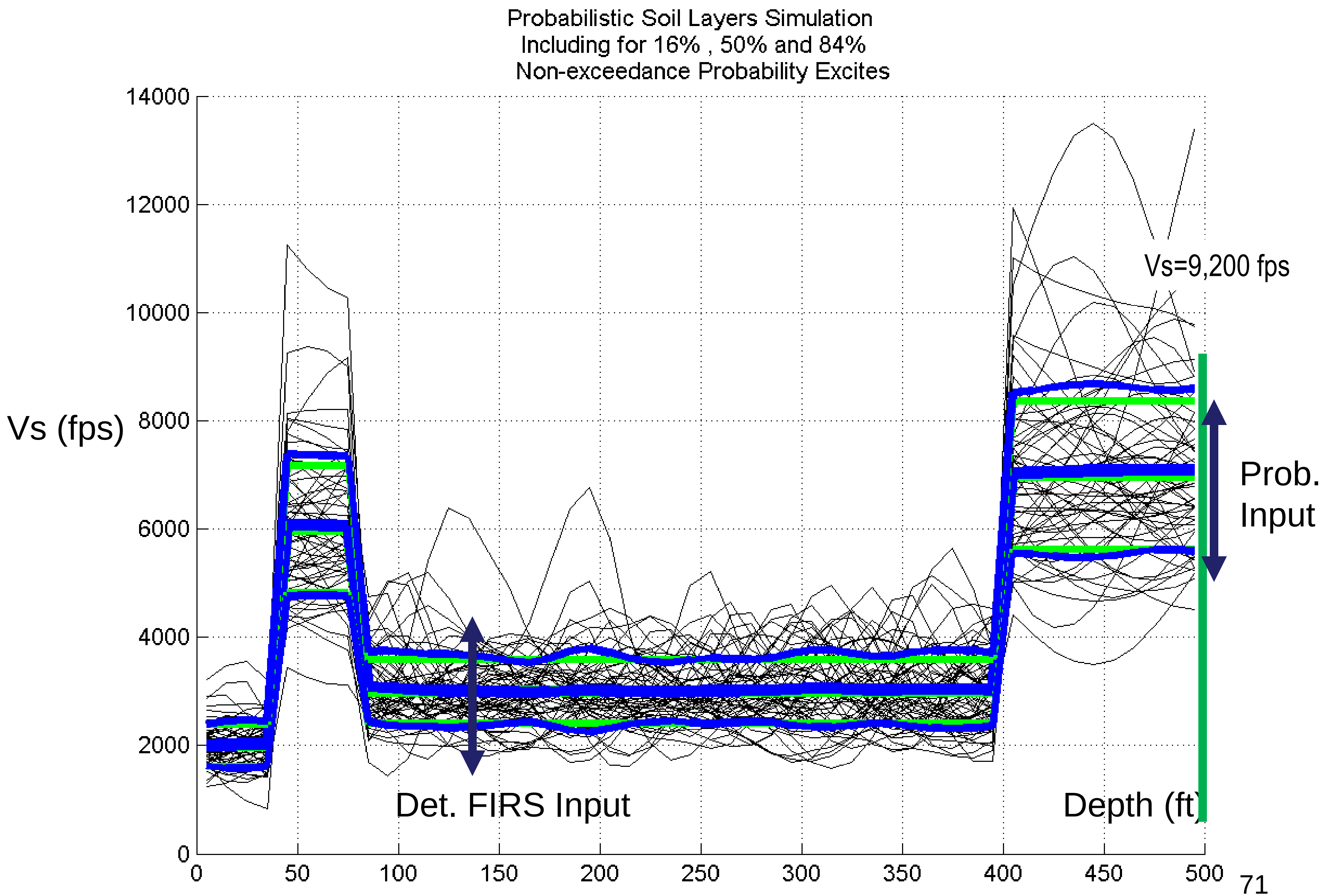
- The ASCE 4-16 based probabilistic SSI analysis provides a solid basis for improving the *design-basis* SSI analysis for DBE and the fragility calculations for BDBE.

ACS SASSI Option PRO (could be combined with Option NON)

ASCE 4-16 Probabilistic SSI Simulation Concept

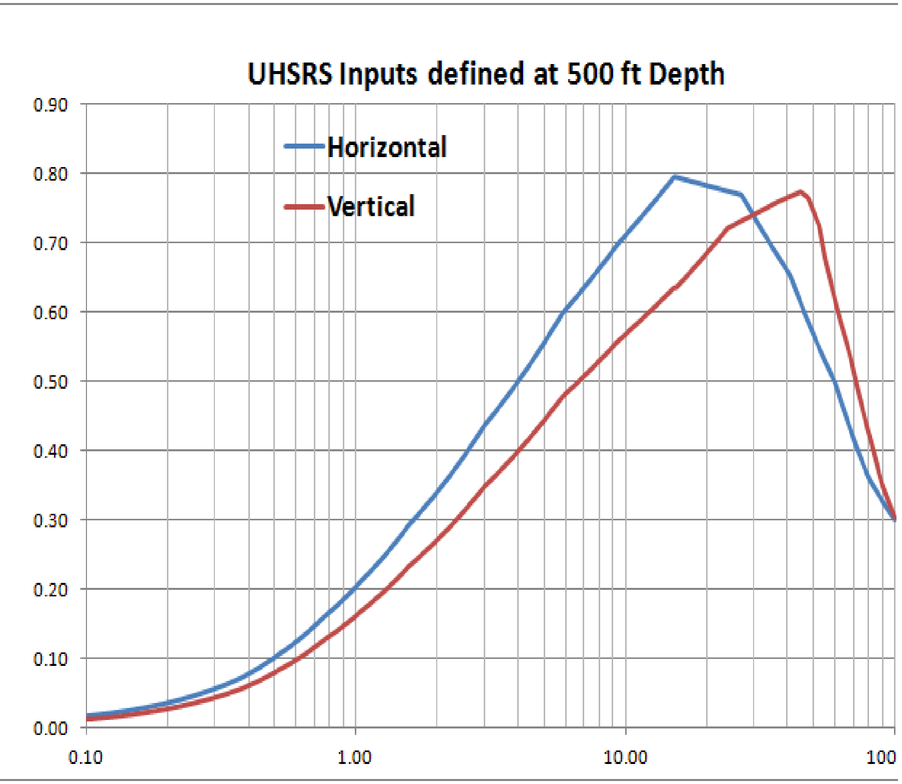


Probabilistic and Deterministic Soil Profiles

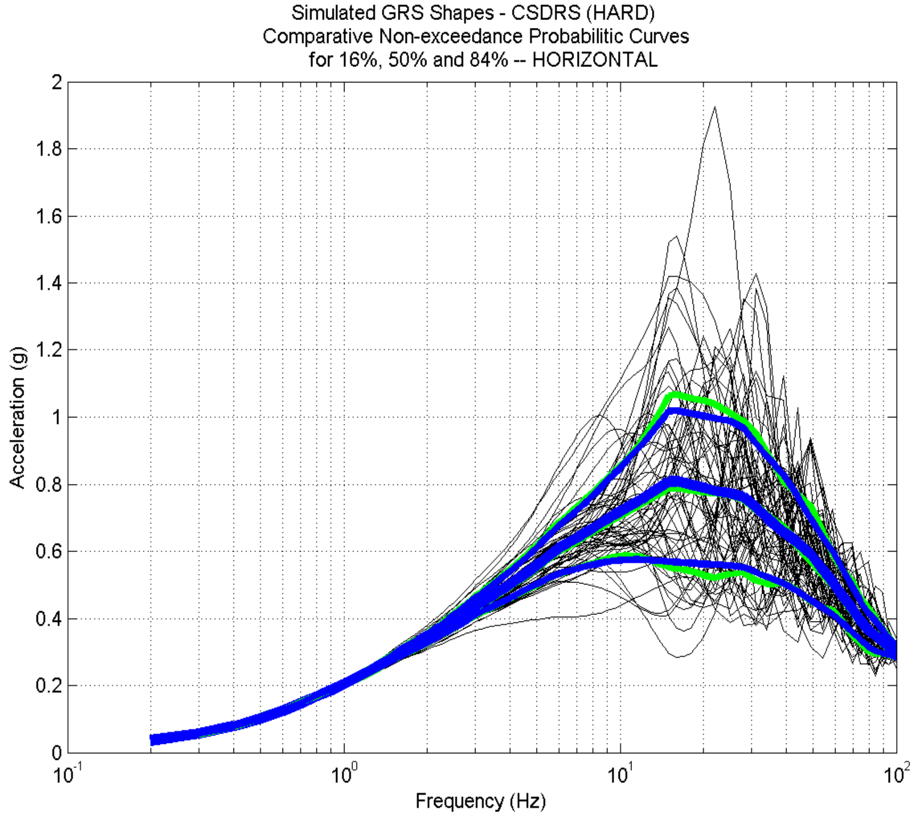


UHSRS Seismic Input Defined at the Baserock (with Vs= 9,200 fps) Situated at 500 ft Depth

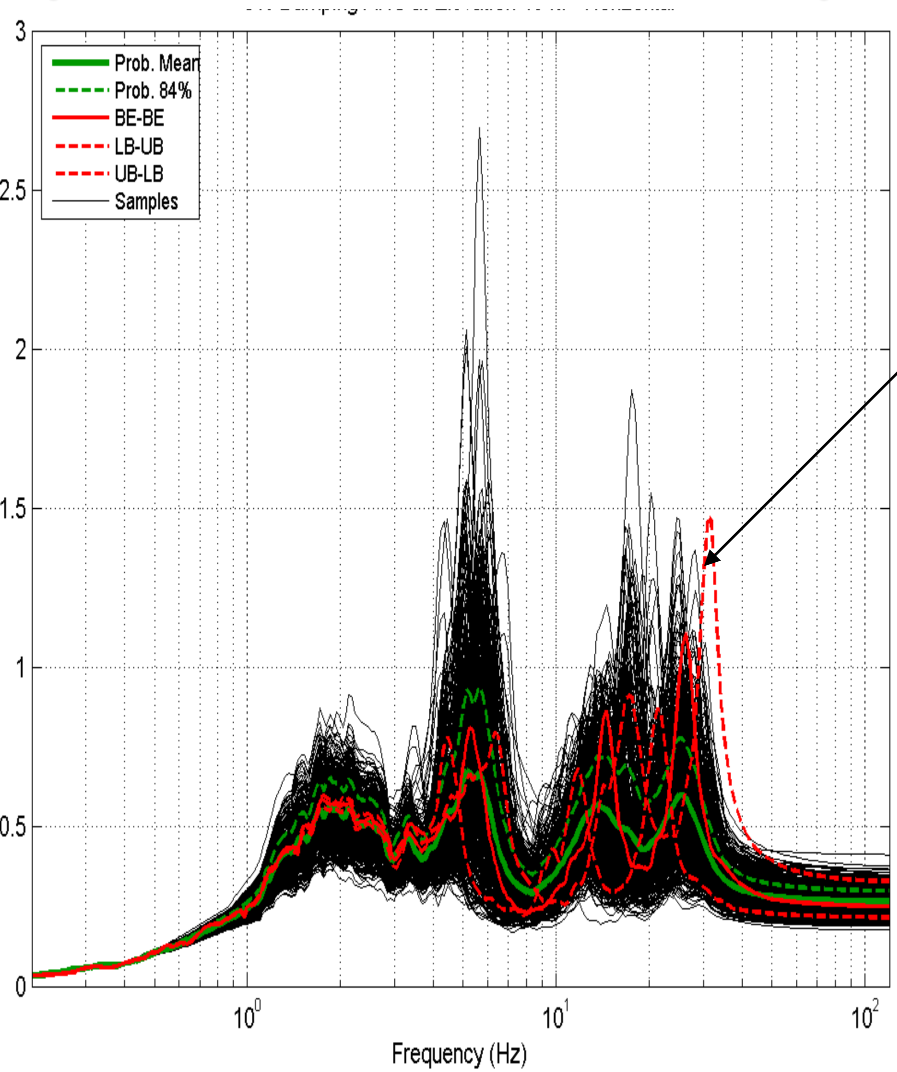
Deterministic (Mean) Spectra



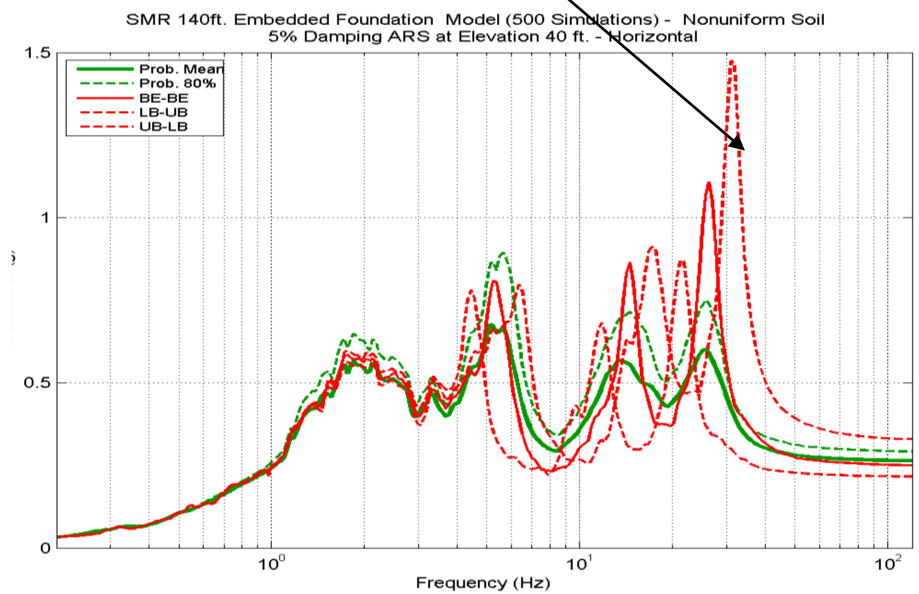
Probabilistic (Simulated) Spectra



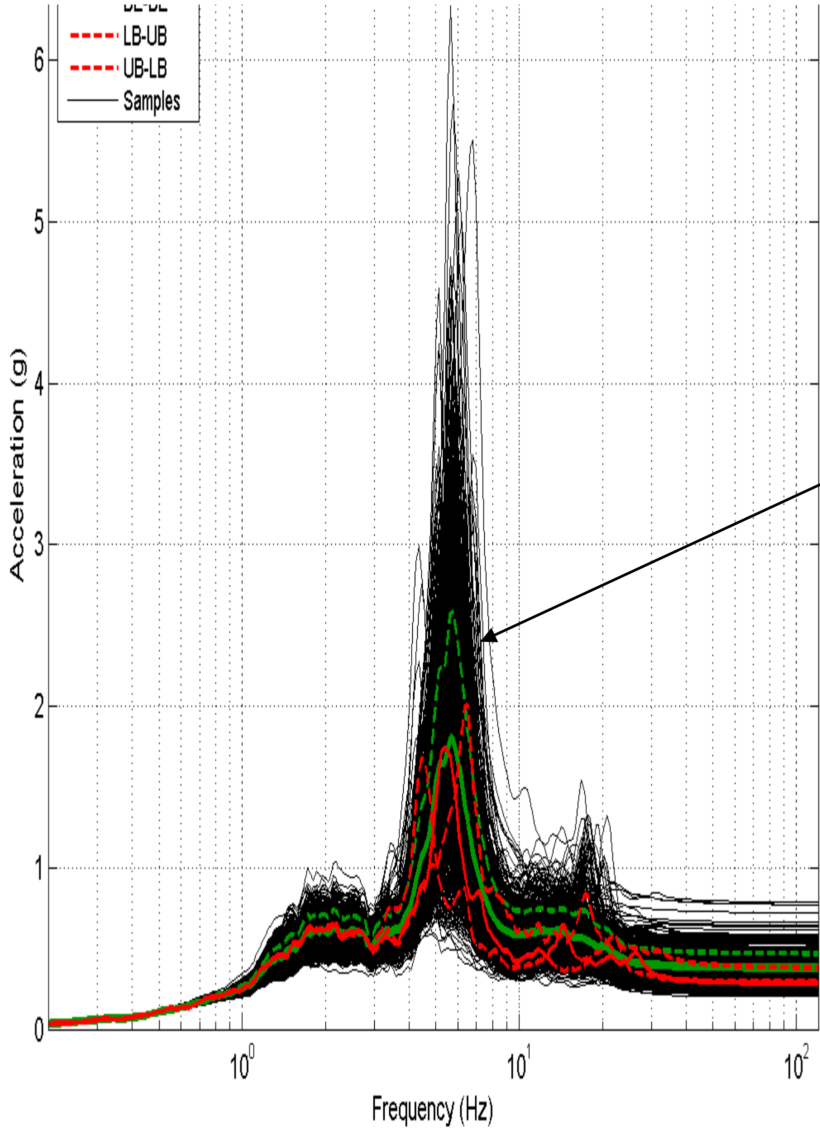
Deterministic (for LB, BE, UB) vs. Probabilistic ISRS (for Mean and 80% NEP) at Elevation 40 ft (-100 ft Depth)



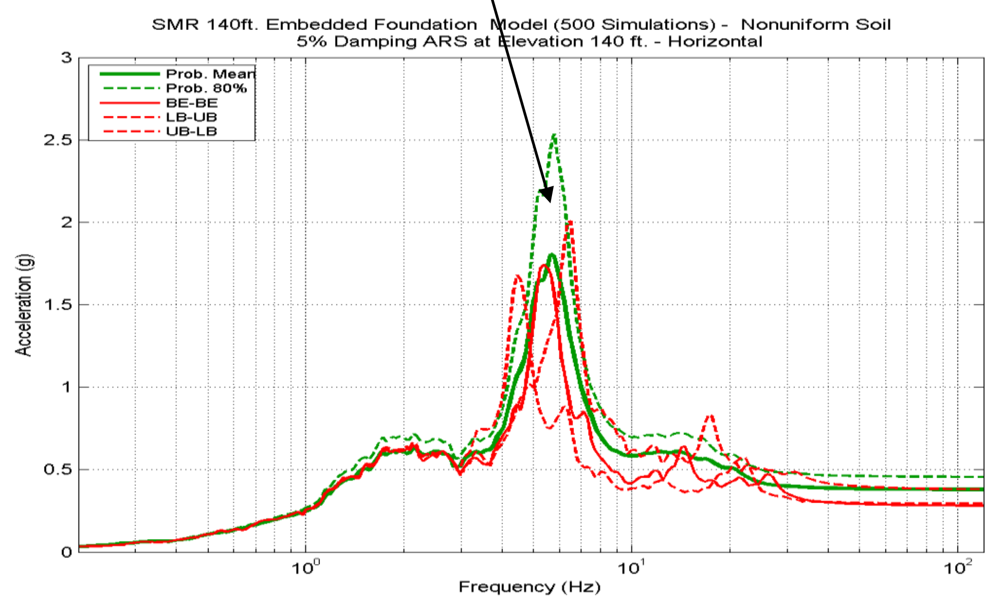
Elevation 40 ft
Horizontal



Deterministic (for LB, BE, UB) vs. Probabilistic ISRS (for Mean and 80% NEP) at Elevation 140 ft (Surface)



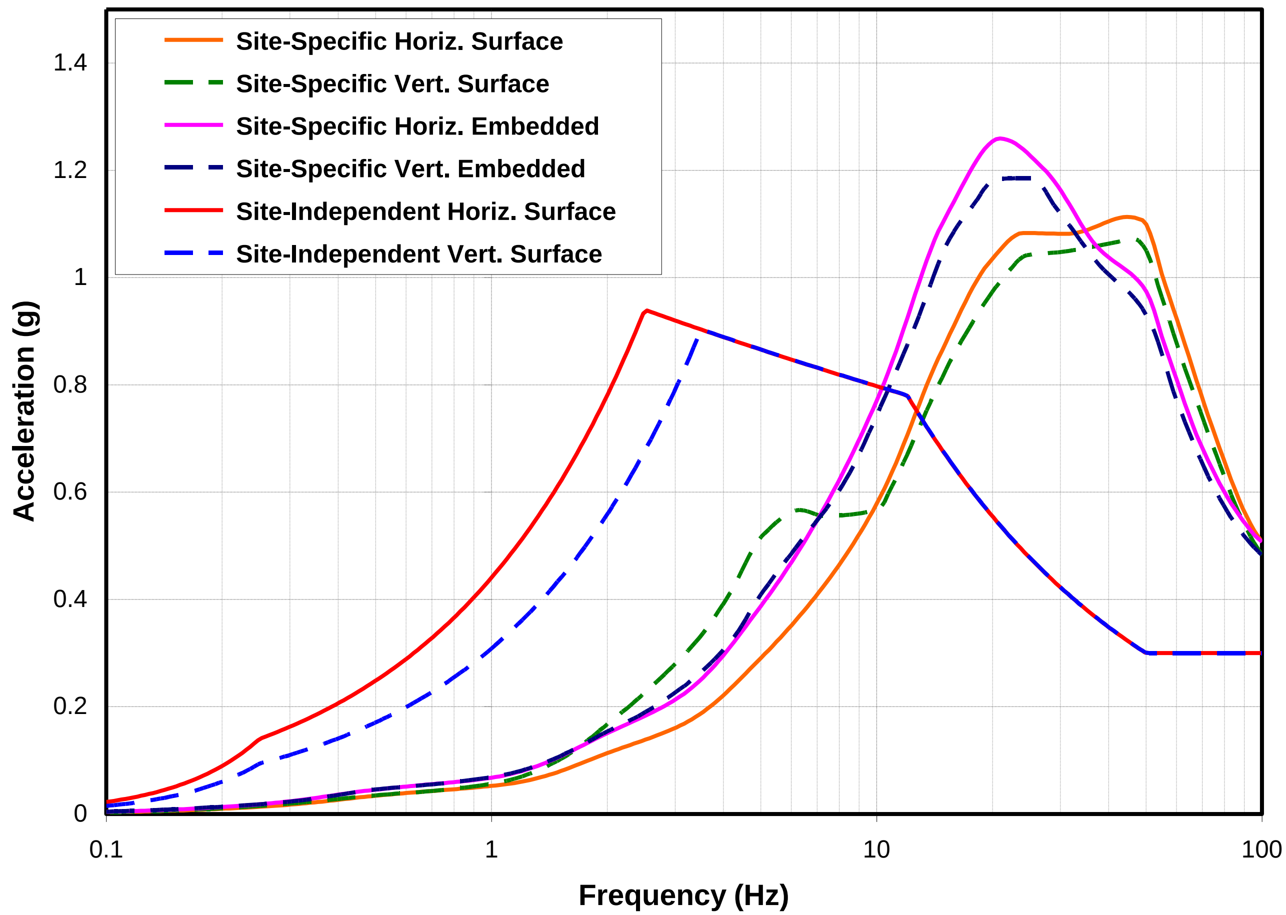
Elevation 140 ft
Horizontal



6. Seismic SSI and SSSI Sensitivity Studies for Coherent and Incoherent Motions

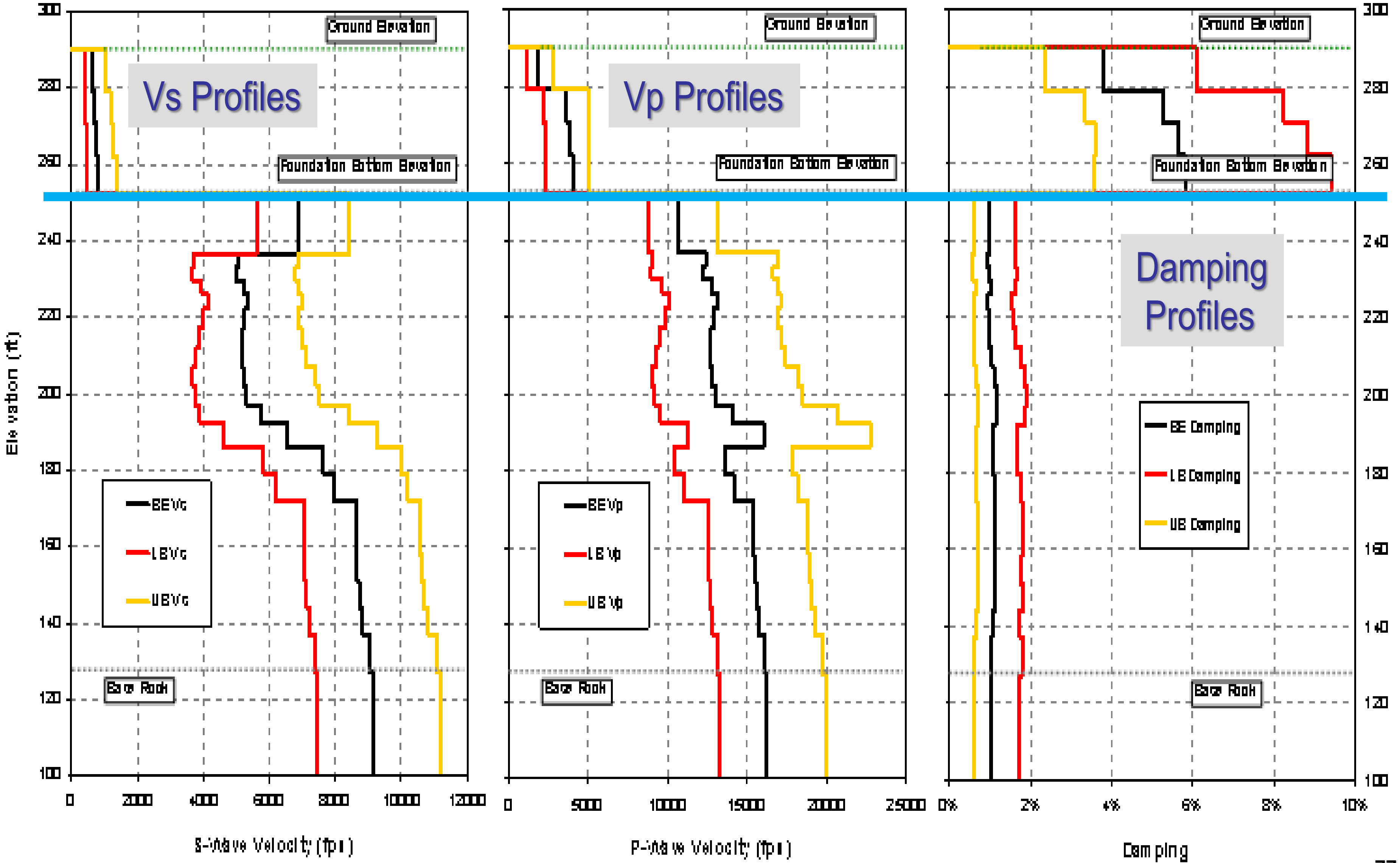
Case 1: Seismic Incoherent SSI Response of RB Complex Structure

Site-Independent (Soil) and Site-Specific HF (Rock) Seismic Ground Motion Inputs



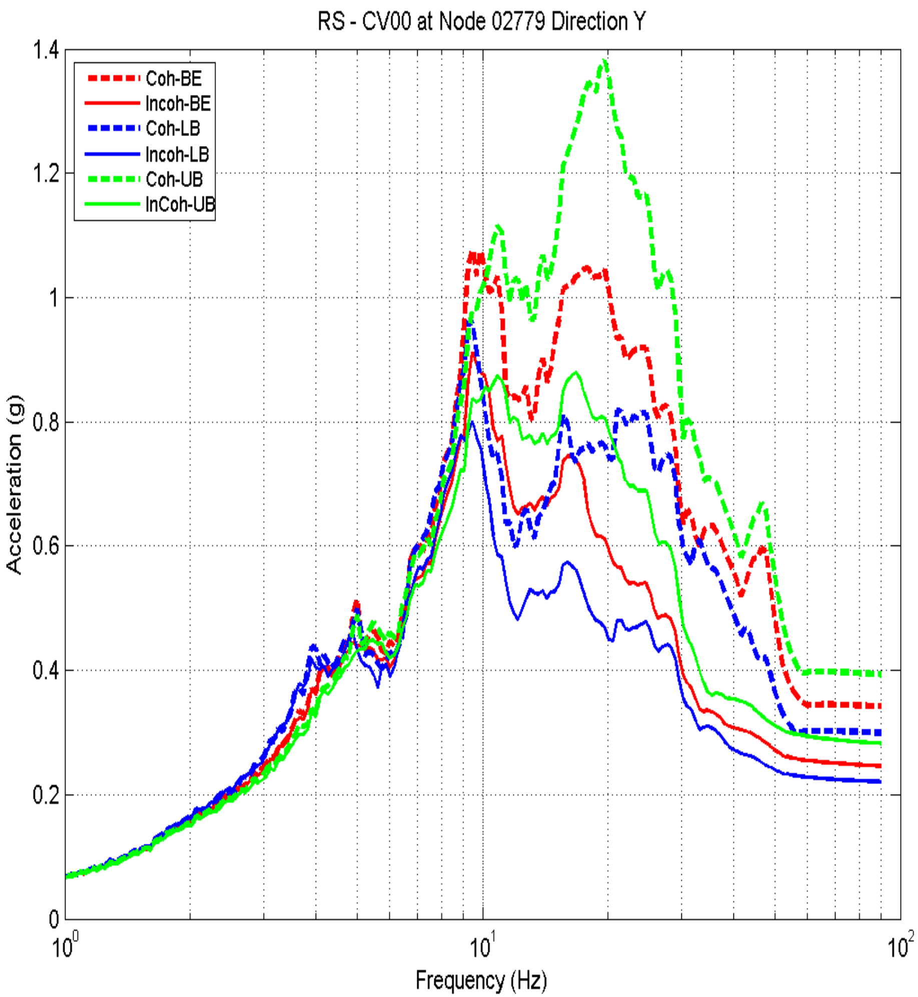
(Ghiocel et. al, OECD/NEA, 2010)

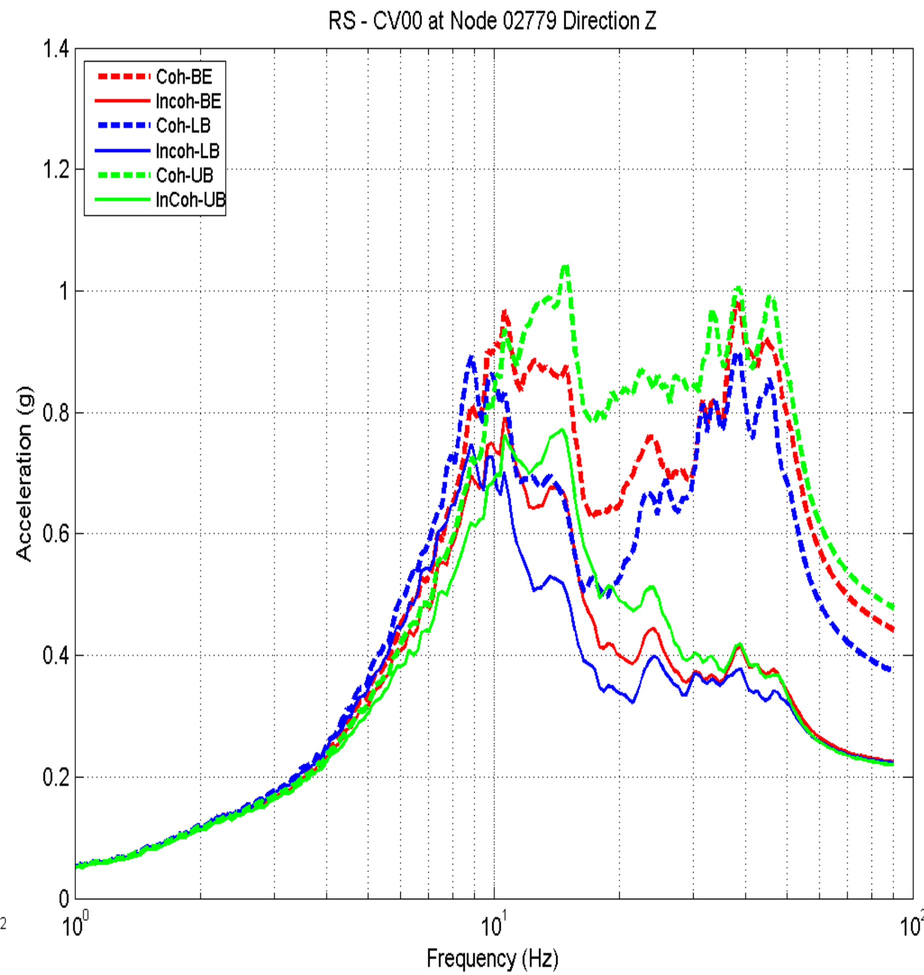
Best-Estimate (BE), Lower Bound (LB) and Upper Bound (UB) Soil Profiles



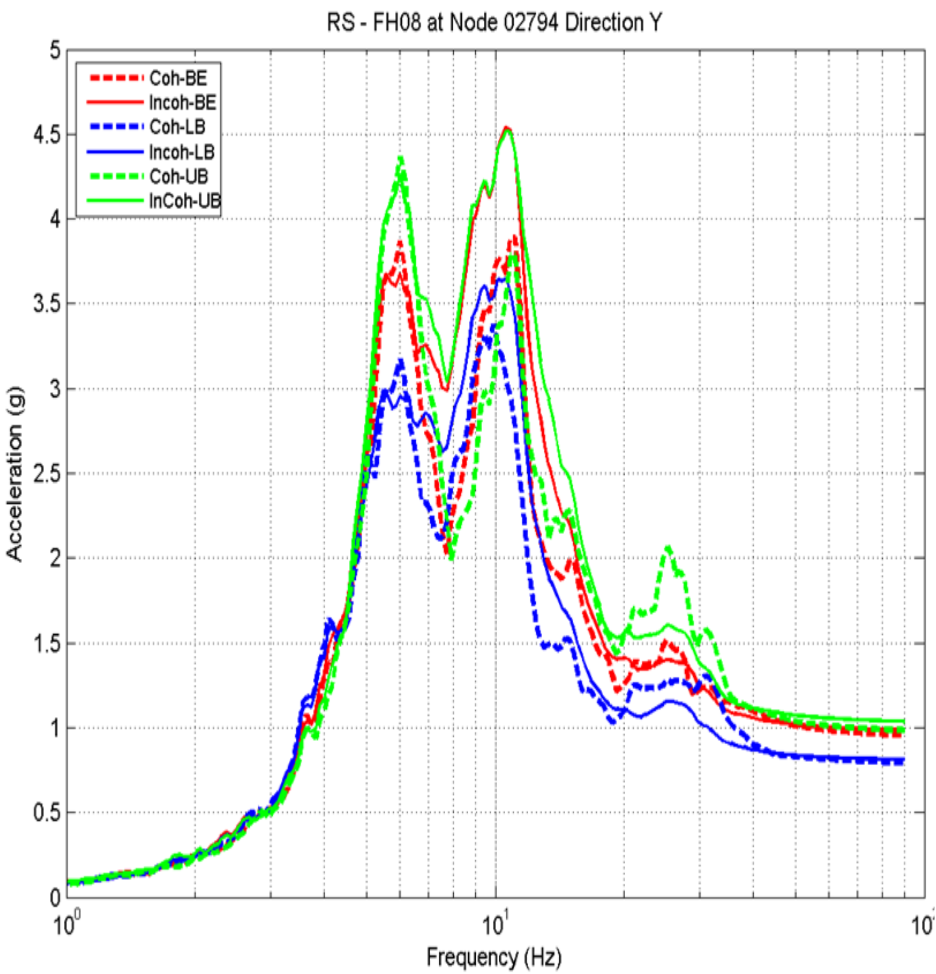
77

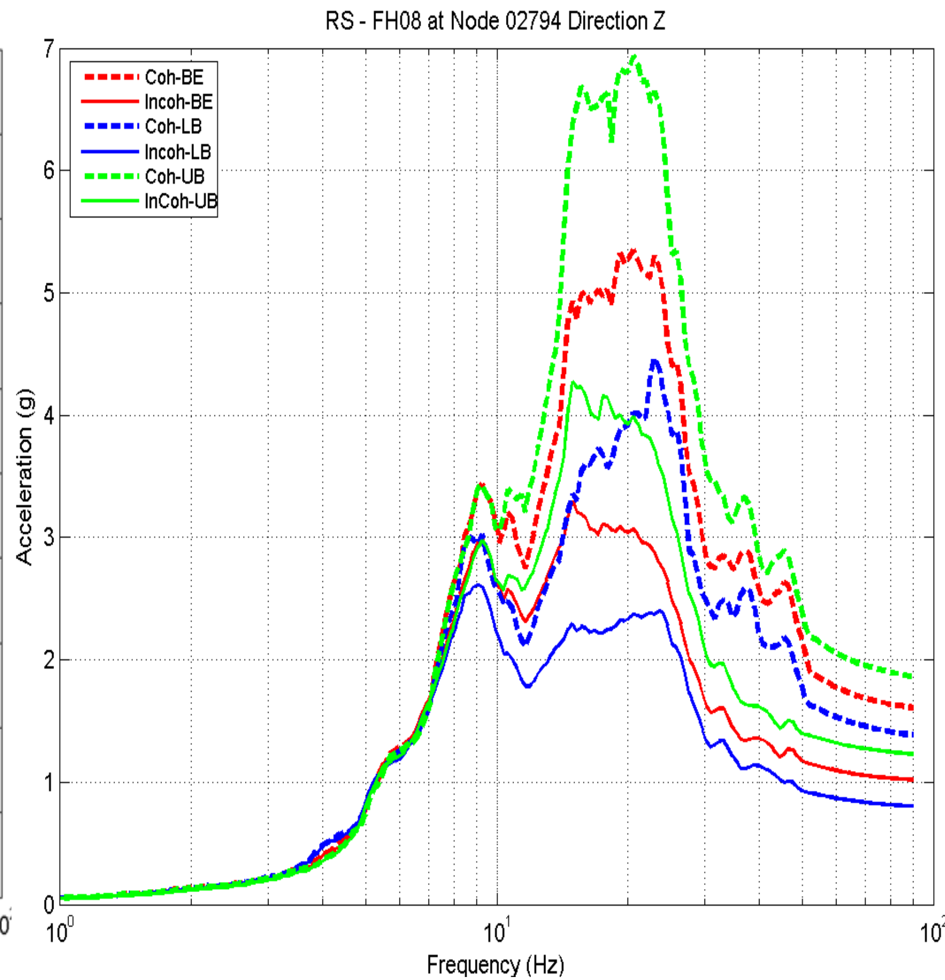
Coherent vs. Incoherent SSI Analysis Results. 5% Damp ISRS at RB Base-Center in Y and Z-Dir



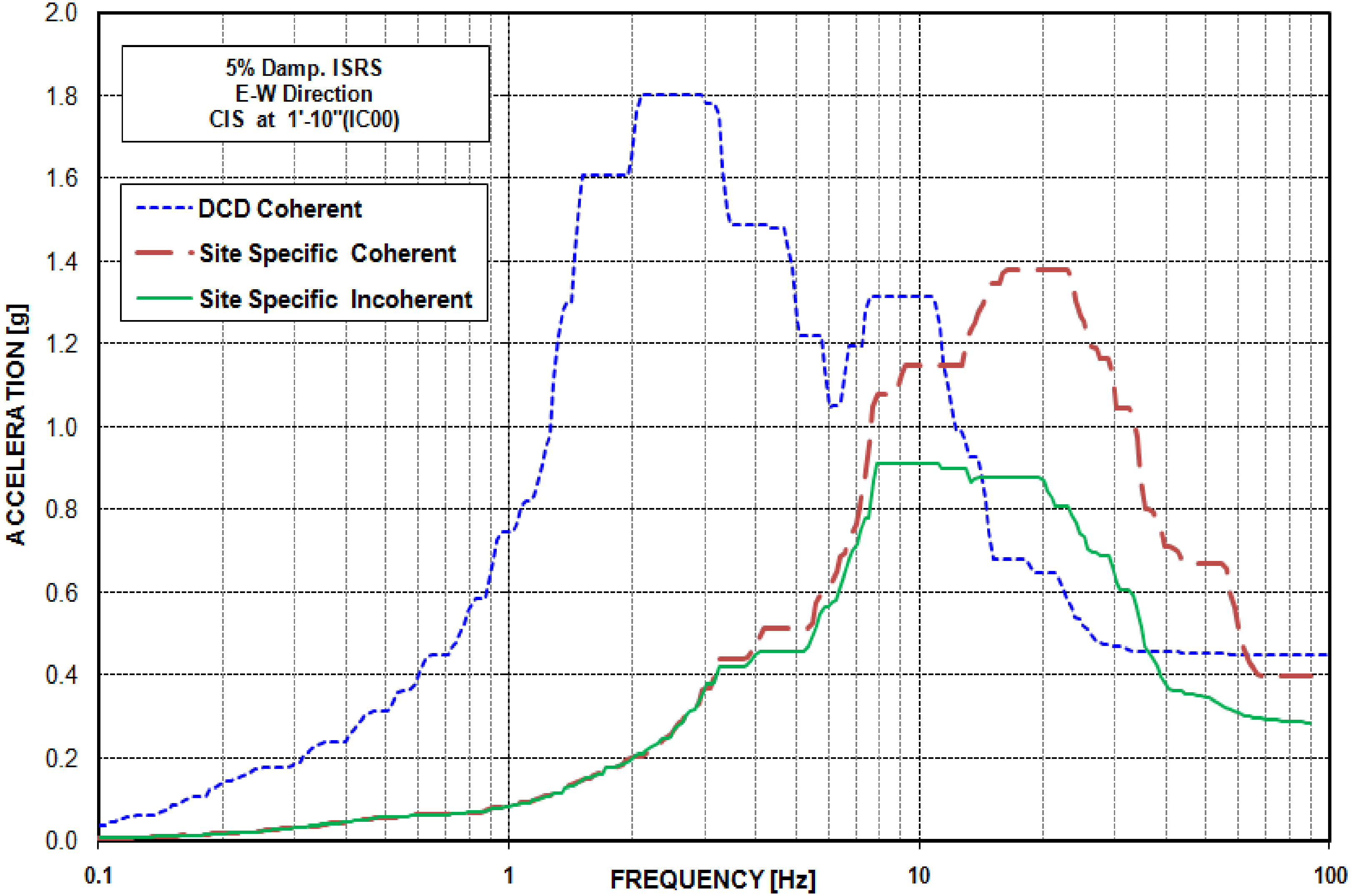


Coherent vs. Incoherent SSI Analysis Results. ISRS Plots at RB Top-Edge in Y and Z-Dir

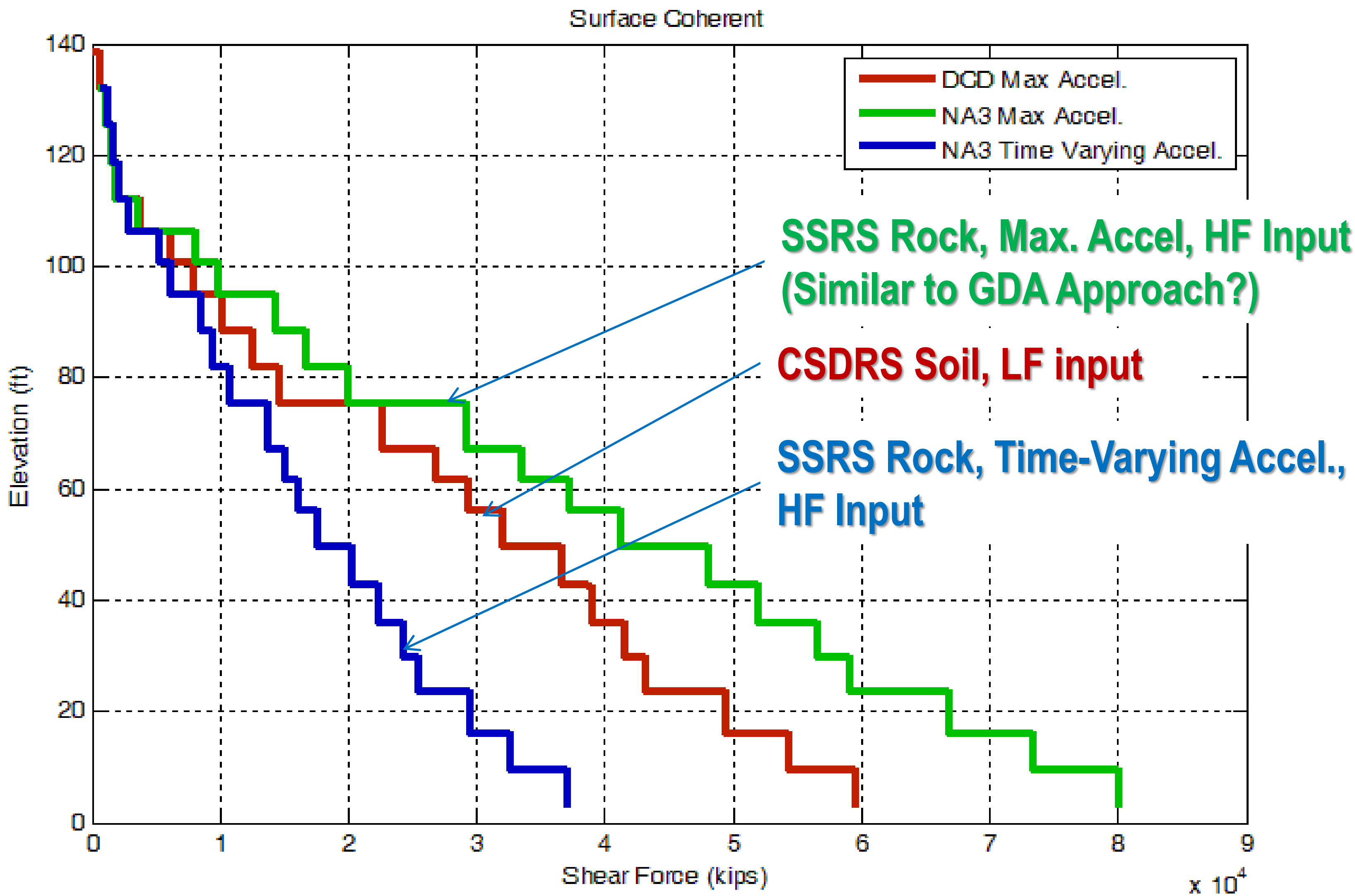




Site-Independent vs. Site-Specific Coherent and Incoherent Final ISRS Results at CIS Base in Y-Dir



Soil Sites vs. Rock Sites Structural Forces. Maximum IS Shear Force in Y Direction

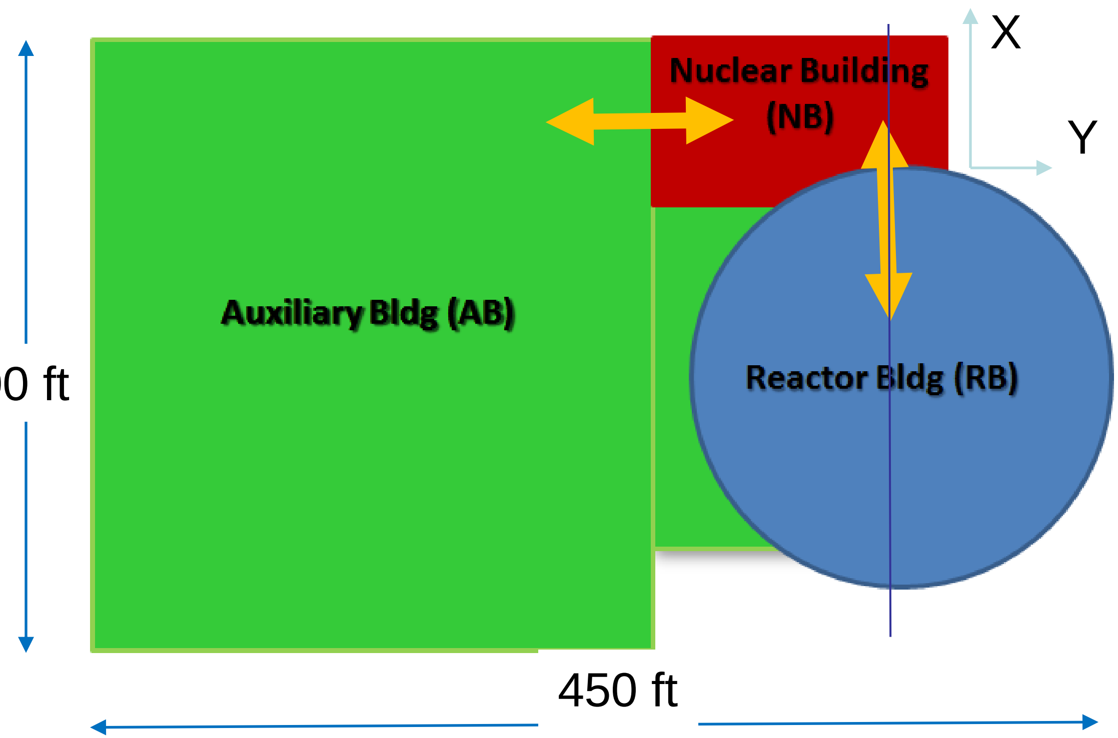


Conclusions

1) The use of maximum structural acceleration (ZPA) distribution is inappropriate for the site-specific high-frequency input. Shear forces are grossly overestimated. About 2-3 times larger than should be.
2) Need to use for computing seismic loads, the time-varying acceleration distribution (not maximum acceleration). Envelope results at the end.

Case 2: Incoherent vs. Coherent Seismic SSSI

Typical NPP SSSI Model



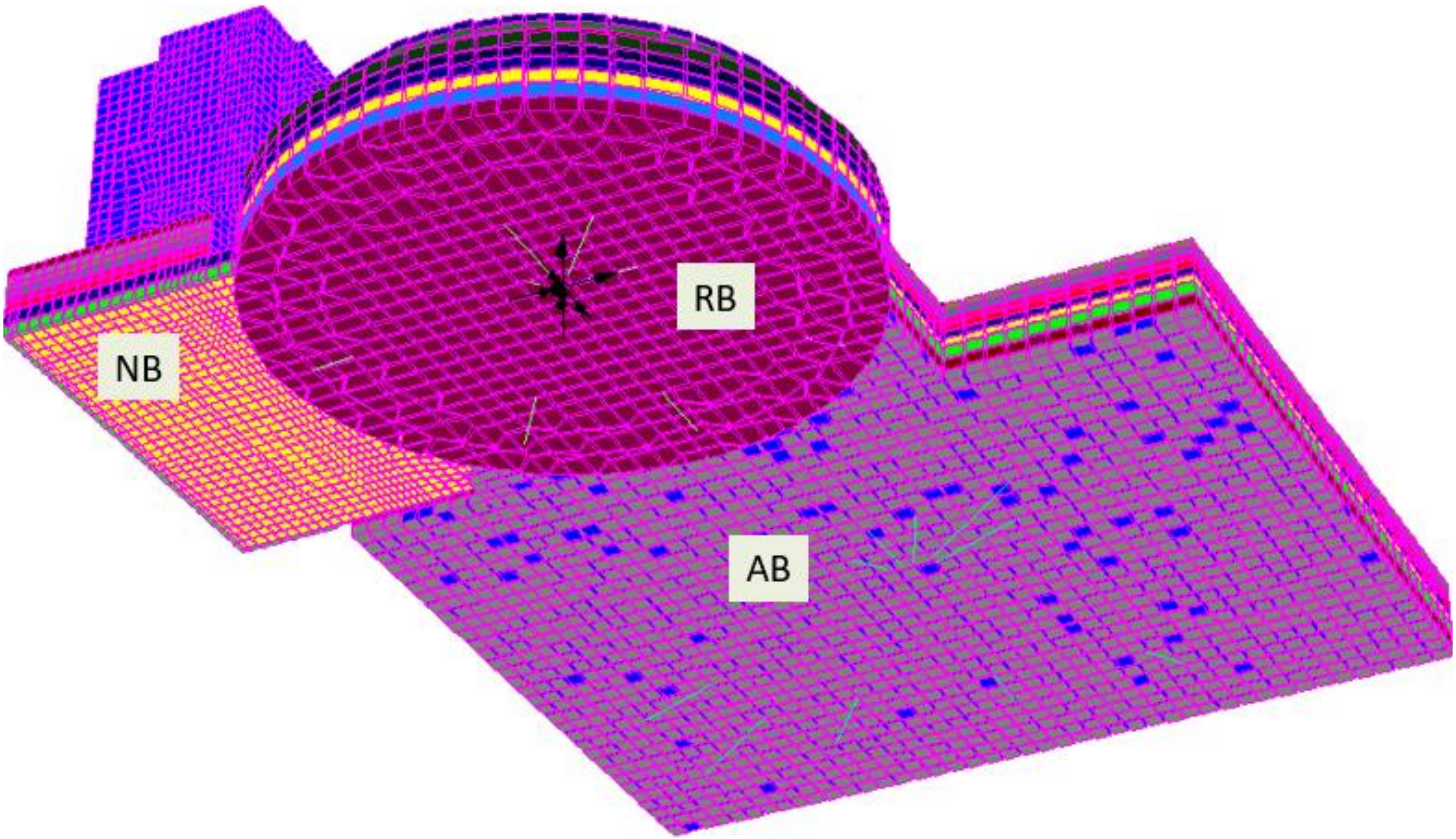
Compute relative displacements between NB and RB buildings:

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

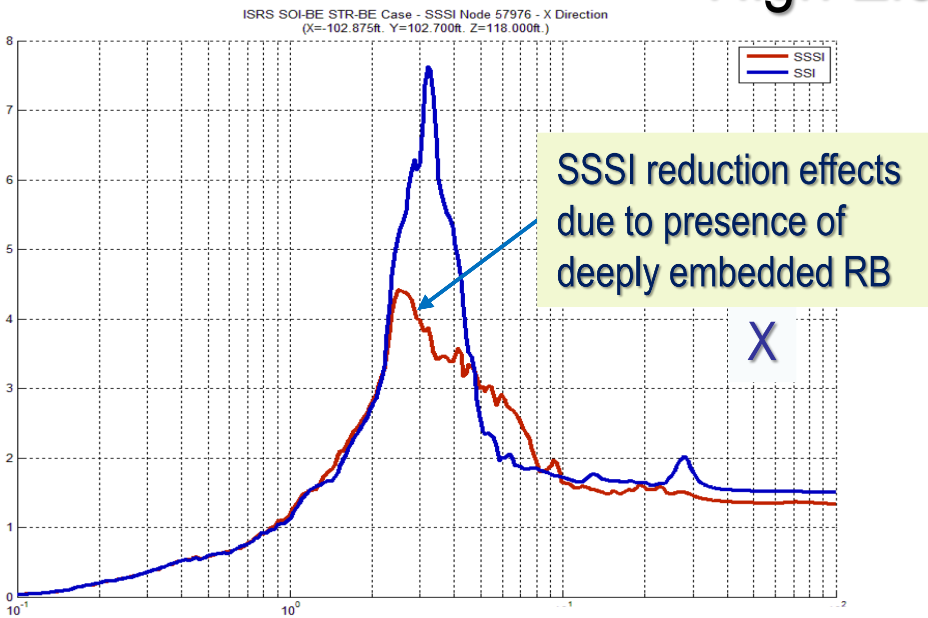
Soil site with Vs from 800fps to 1800fps at 600ft depth

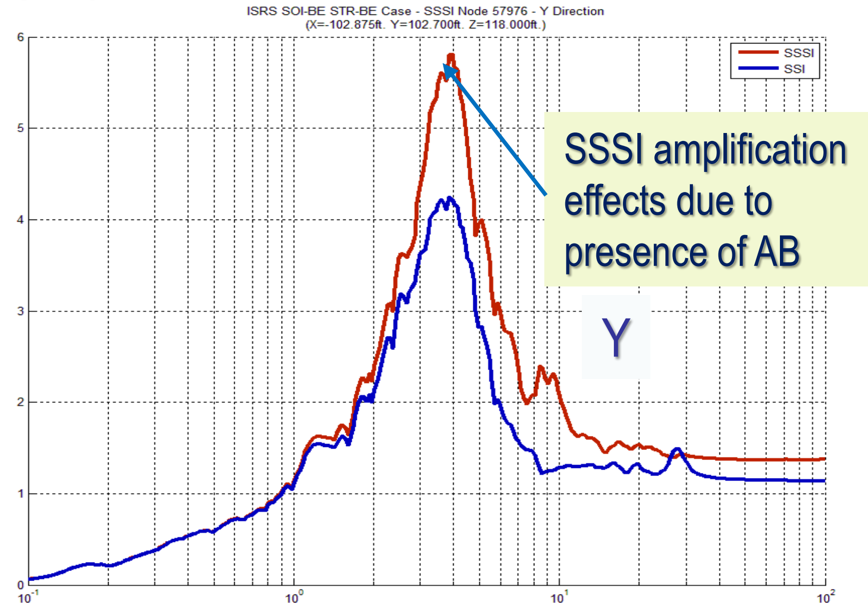
SSSI Model with Multiple Structures Having Different Foundation Levels

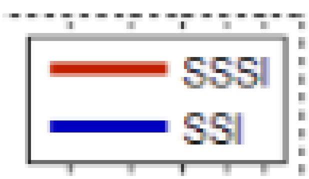


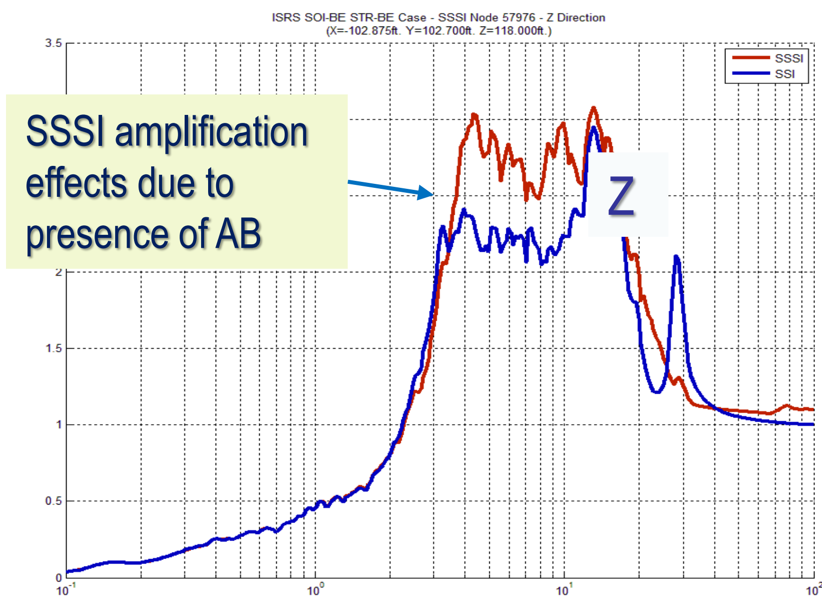
Seismic SSSI Effects on the NB ISRS

High Elevation

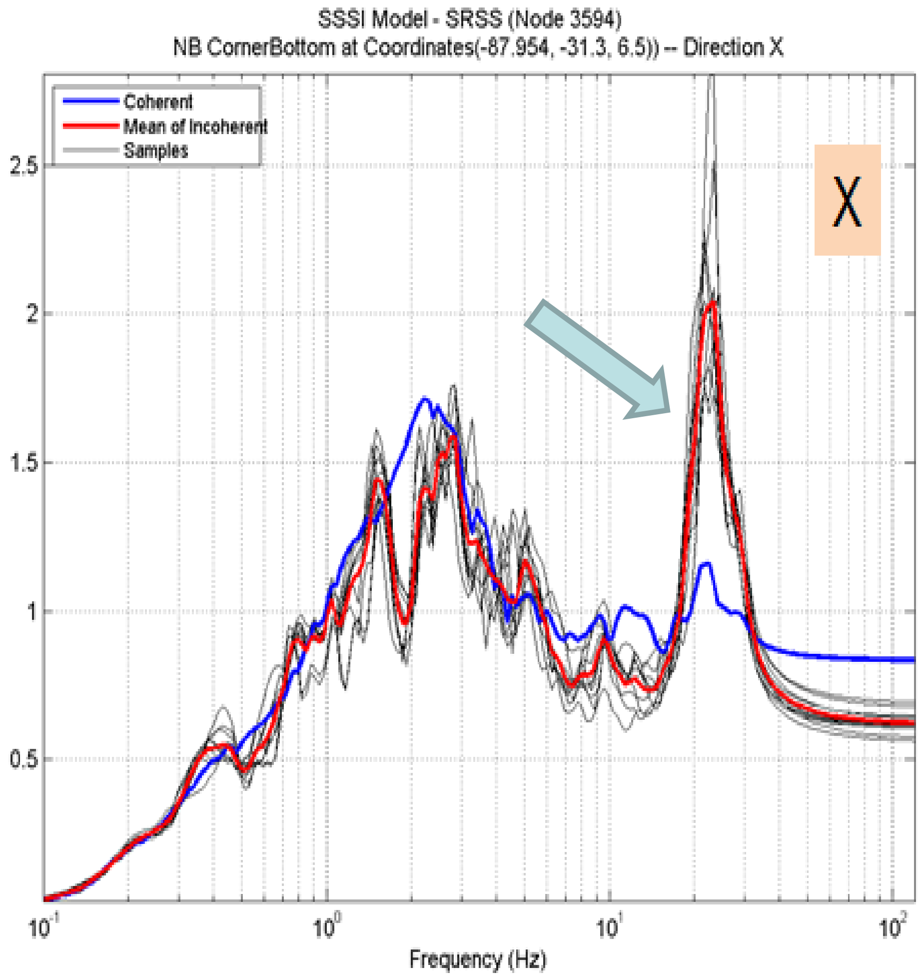


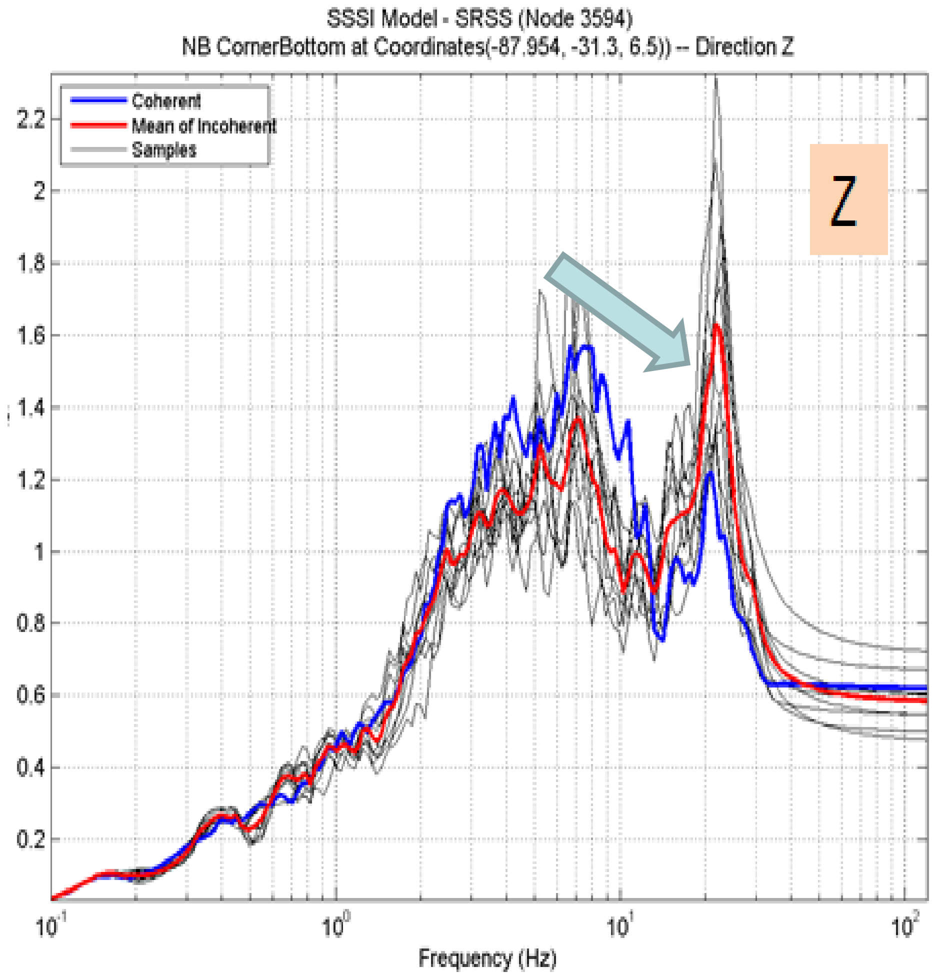






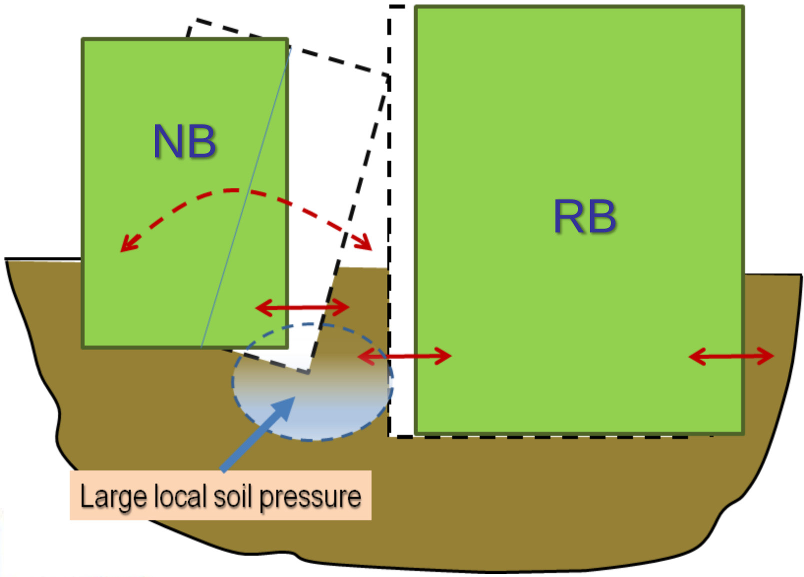
Incoherent SSSI Effects on NB ISRS at Basemat





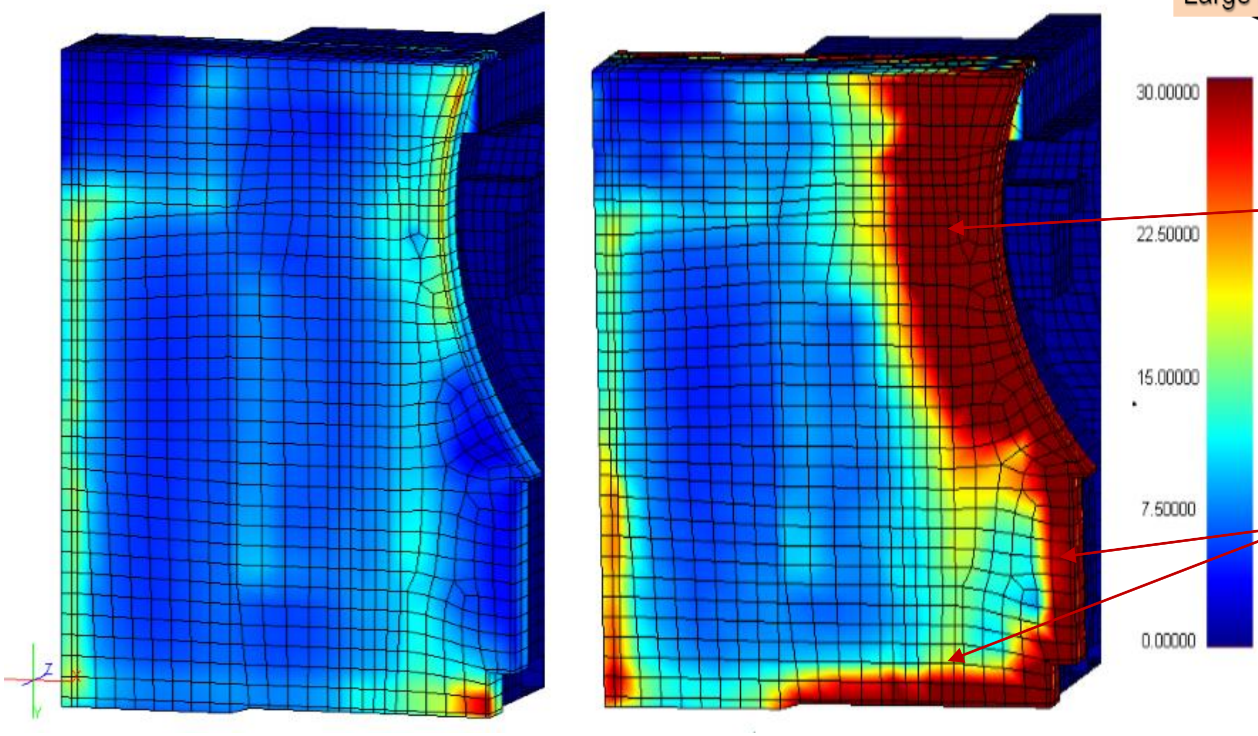
Seismic SSSI Effects on NB Basemat Pressures

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

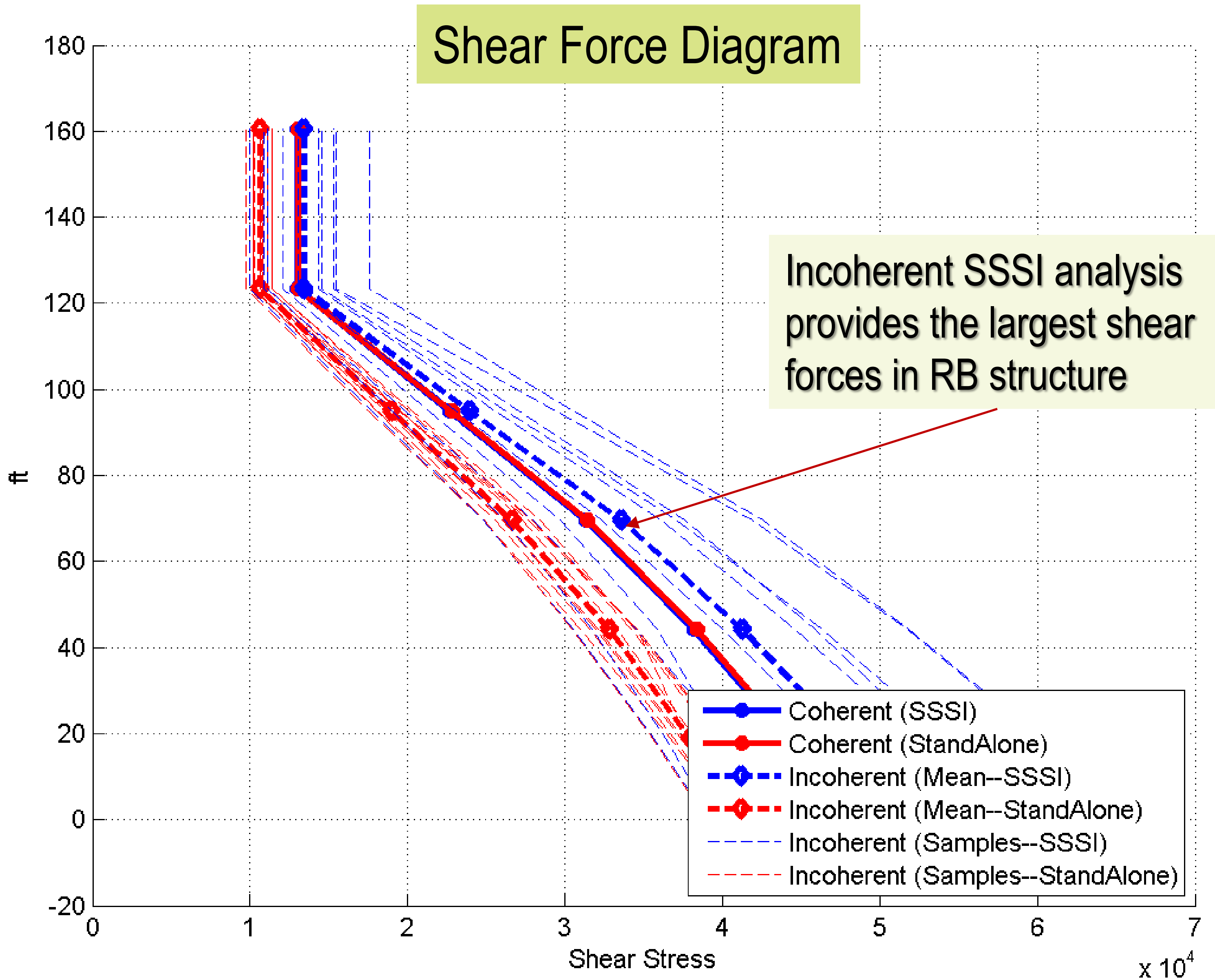


SSI Pressures

SSSI Pressures

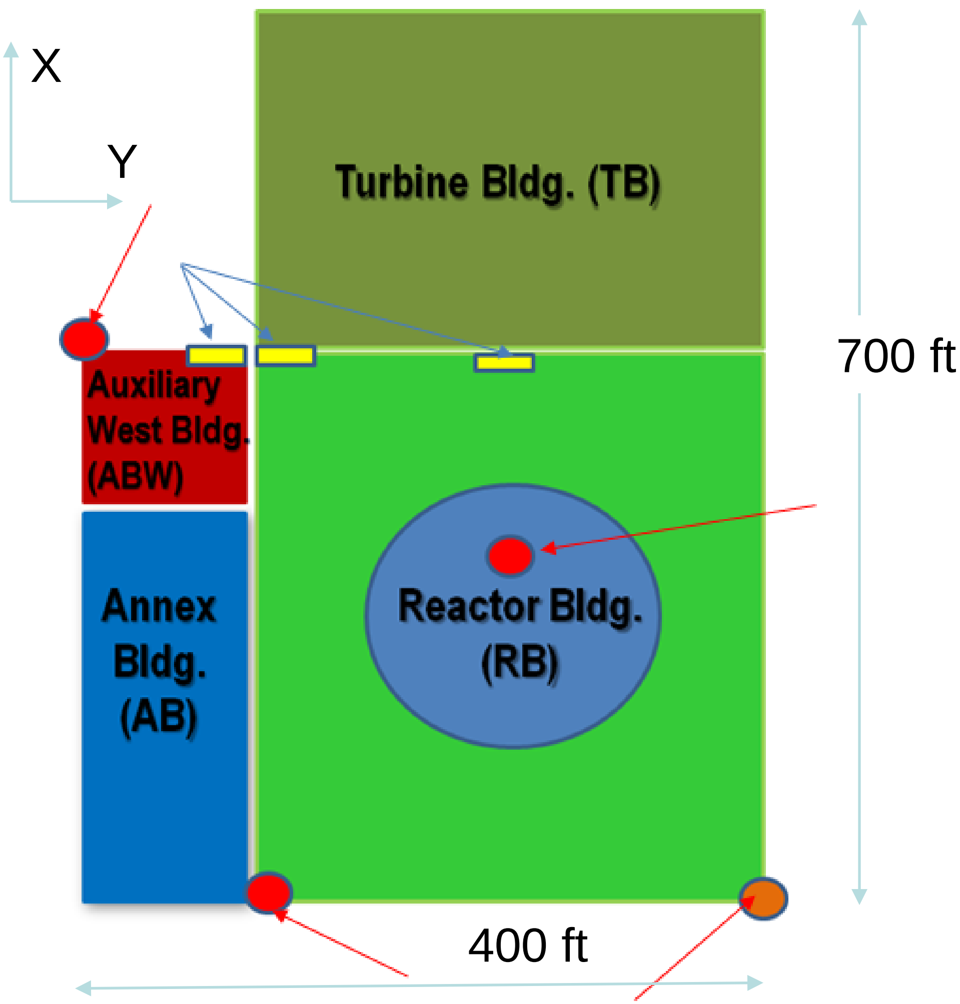


Seismic SSSI Effects on Shear Forces in RB

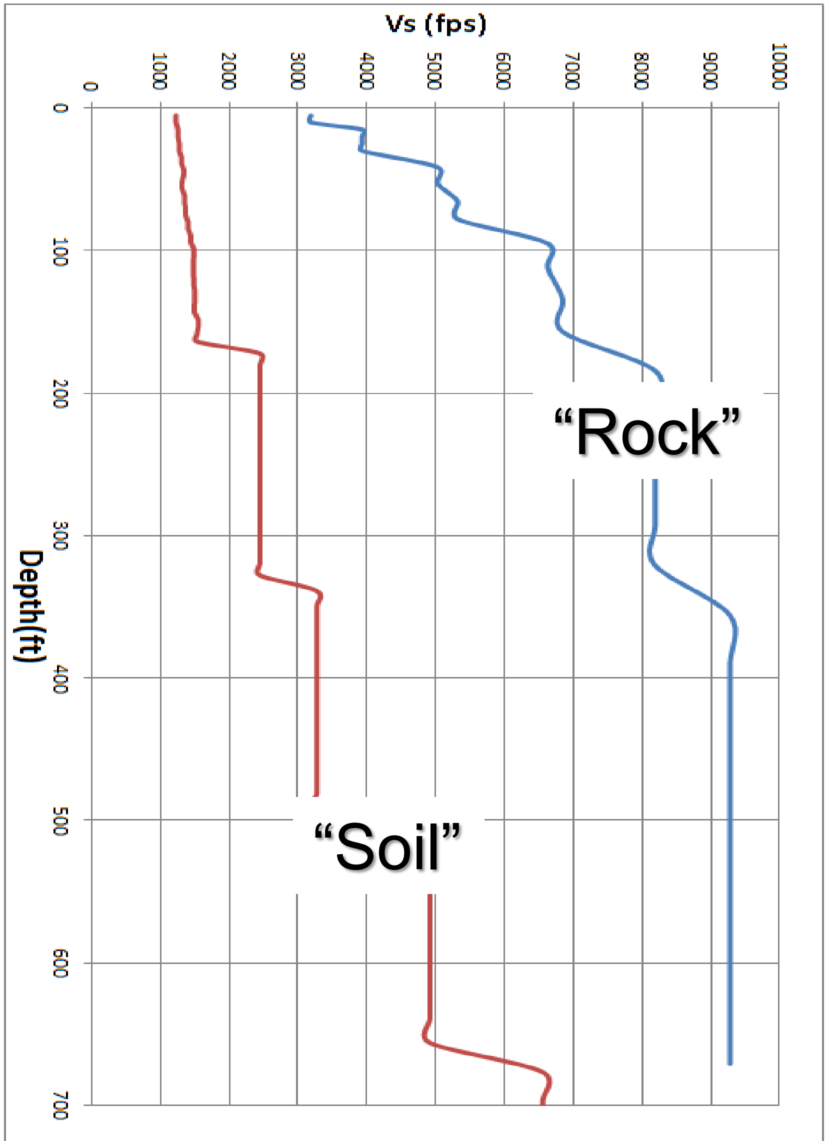


Case 3: Incoherent vs. Coherent Seismic SSSI Effects

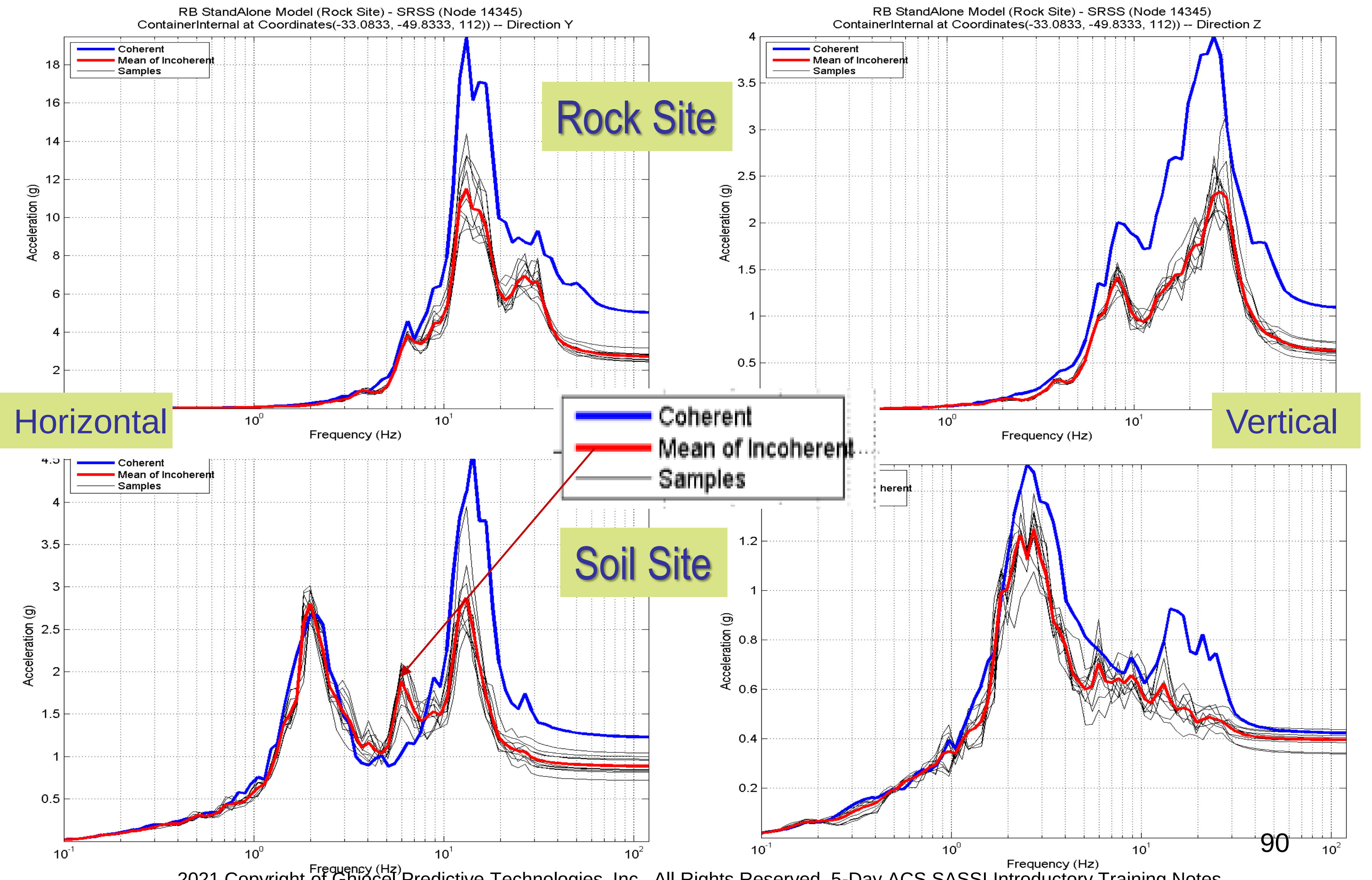
Typical NPP SSSI Model



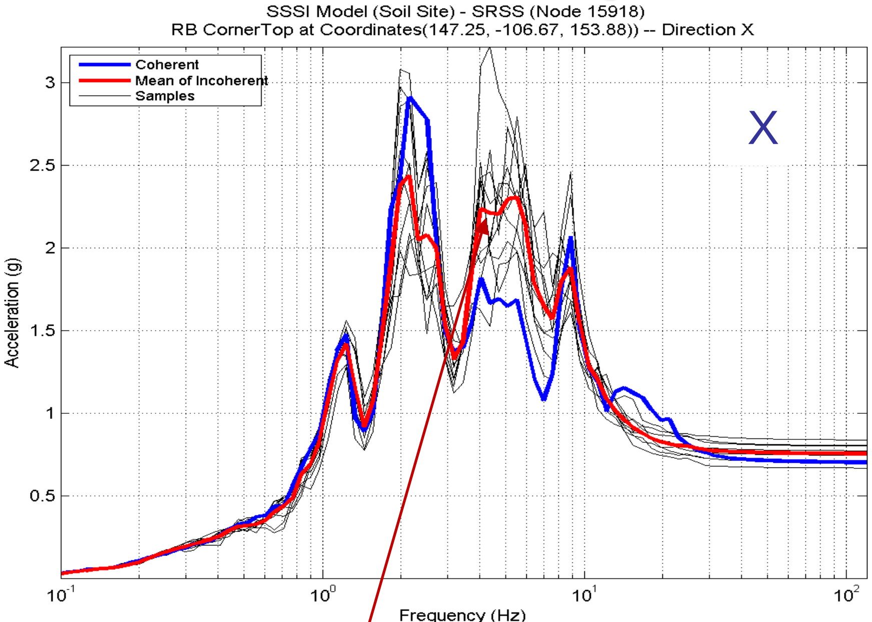
Soil Profiles

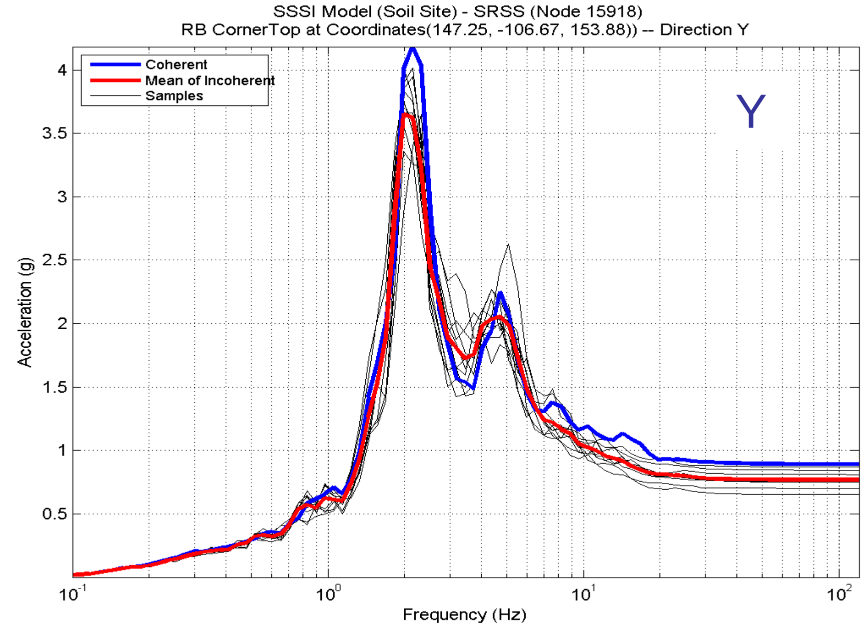


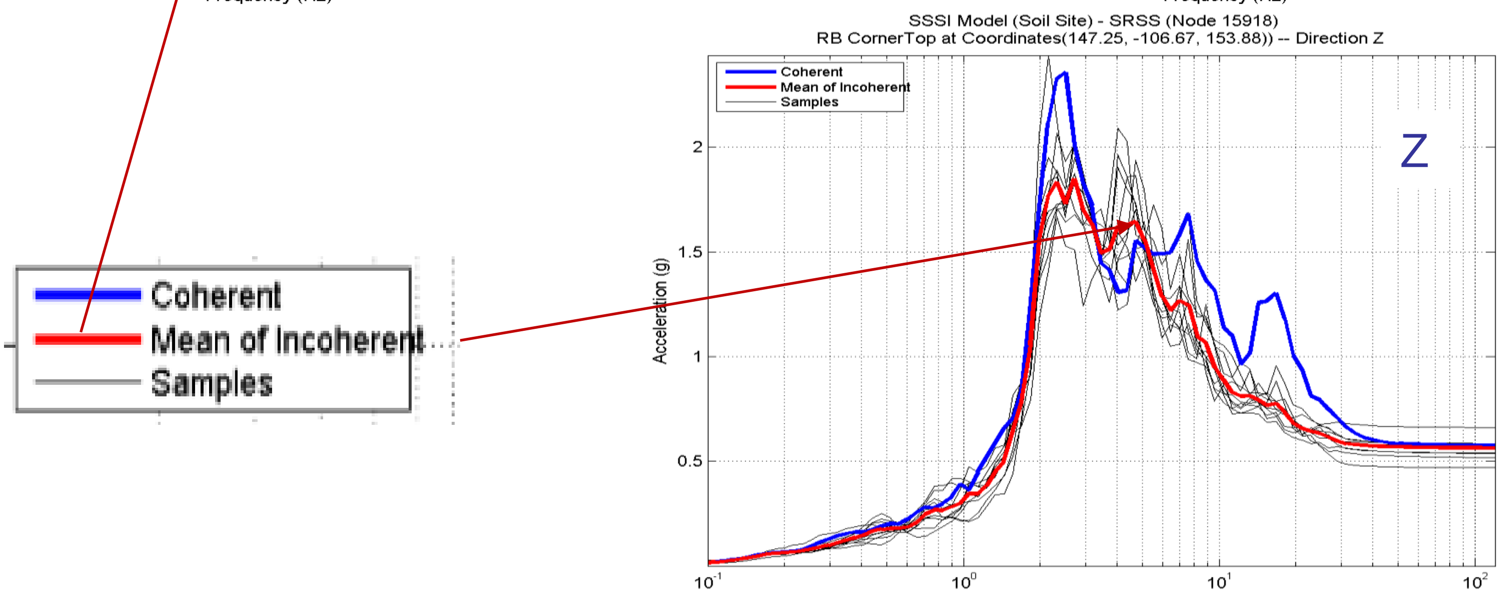
RB Complex Coherent vs. Incoherent SSSI Effects on ISRS on Top of Internal Structure – Y and Z Directions



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



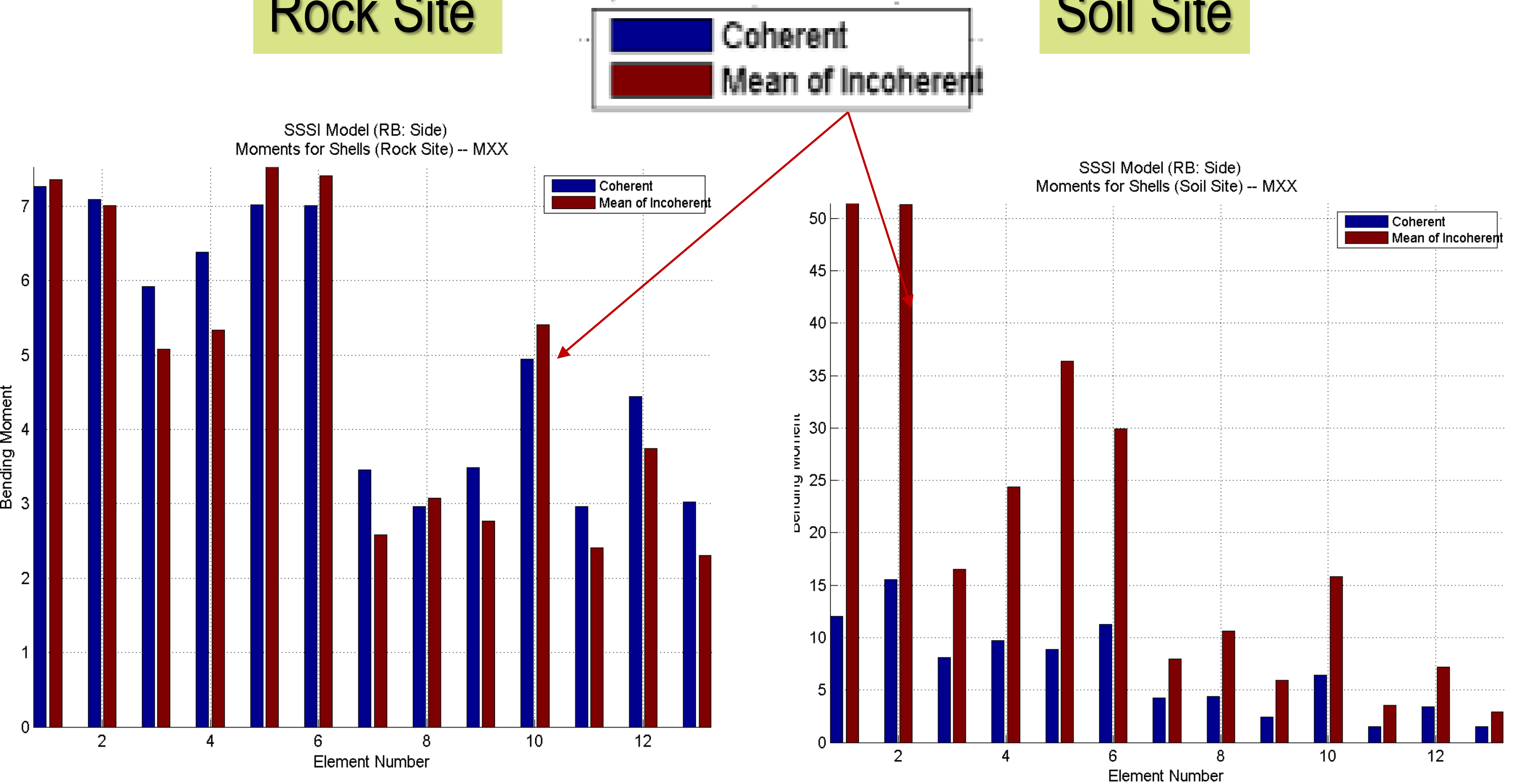




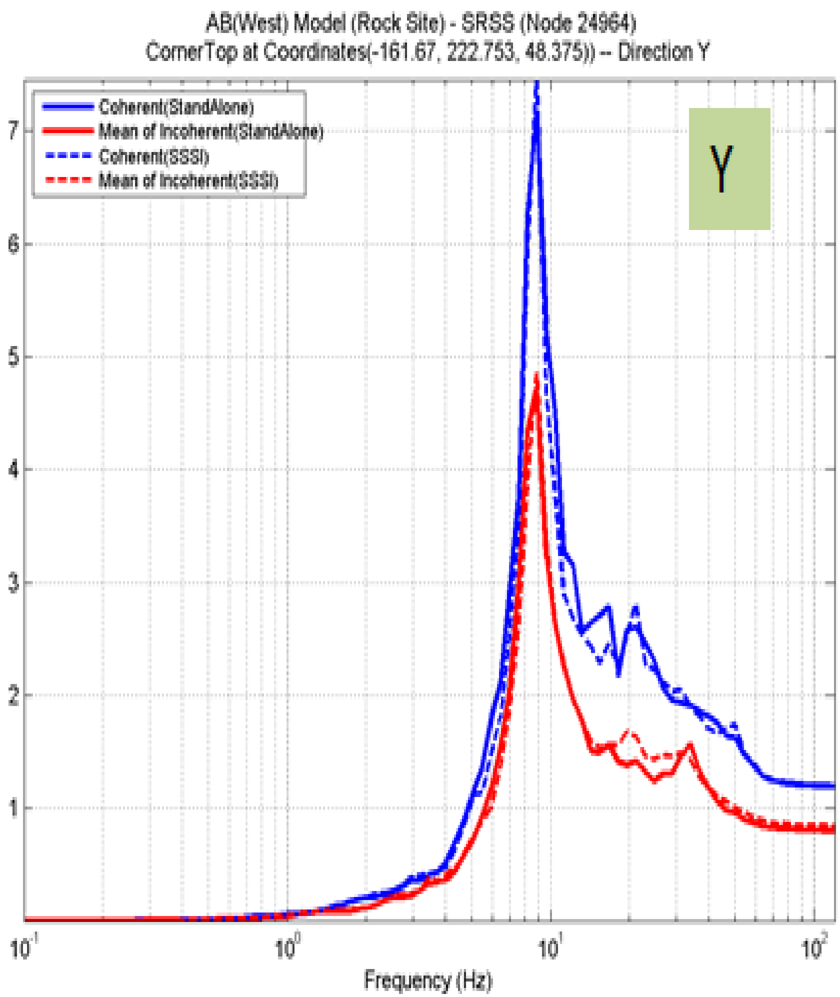
Coherent vs. Incoherent SSSI Effects for Bending Moments in Corner Wall Near AB Bldg.

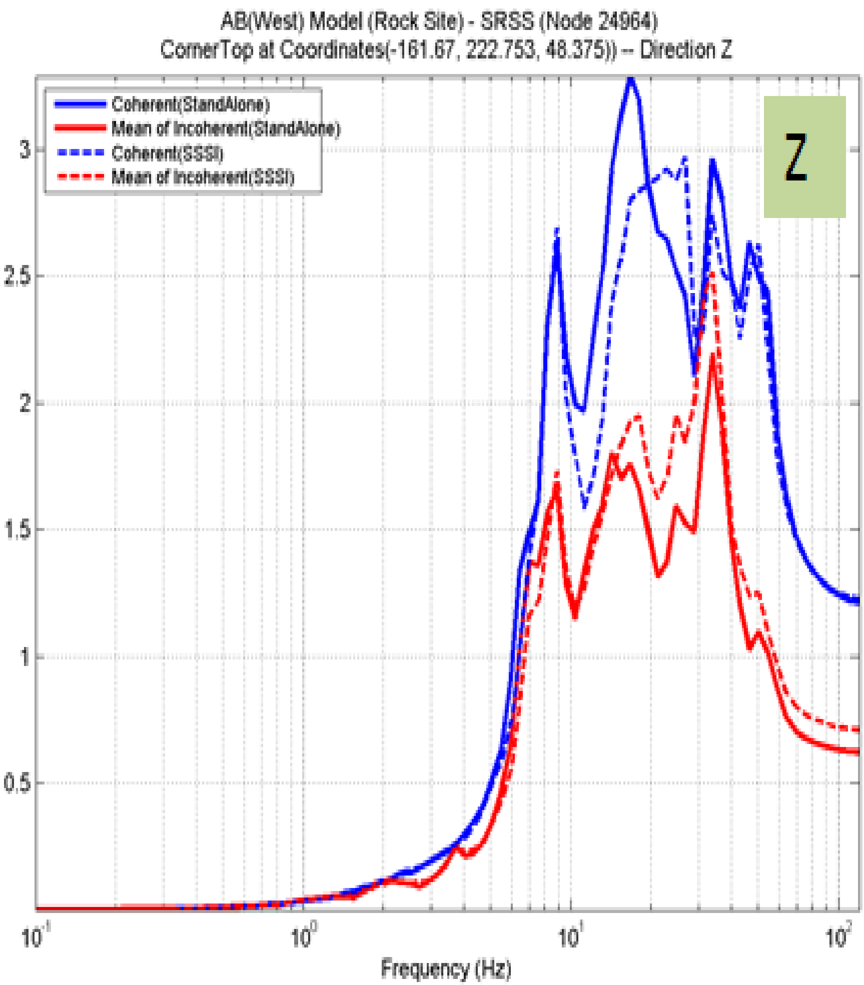
Rock Site

Soil Site



Coherent vs. Incoherent ABW ISRS at Top Corner Near RB Complex For Rock Site



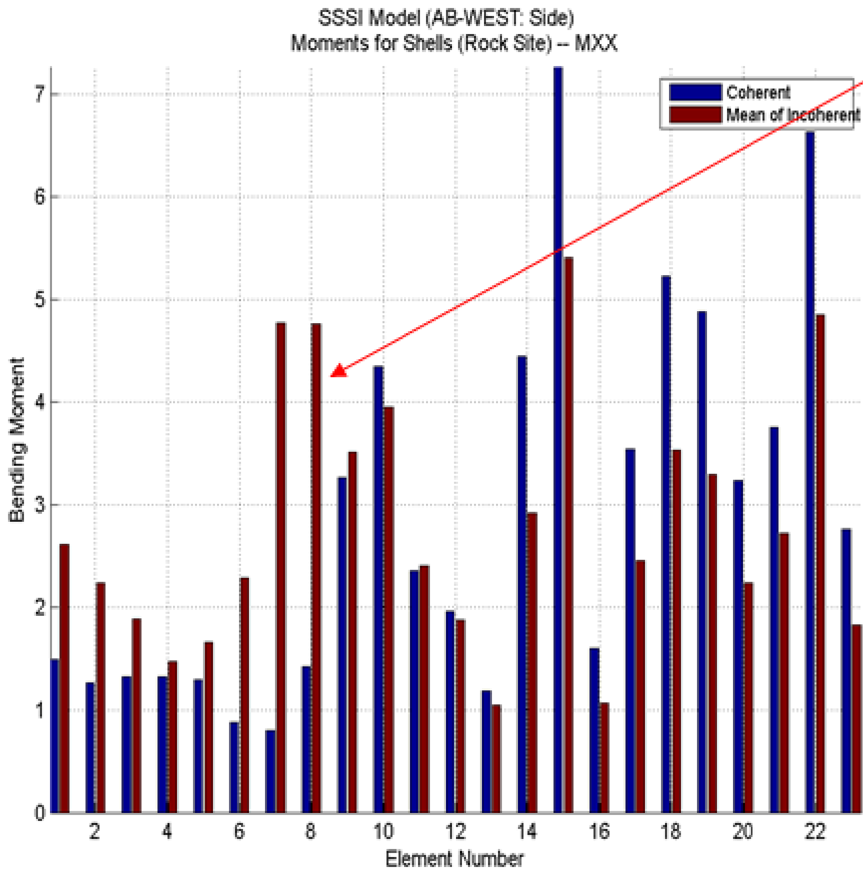


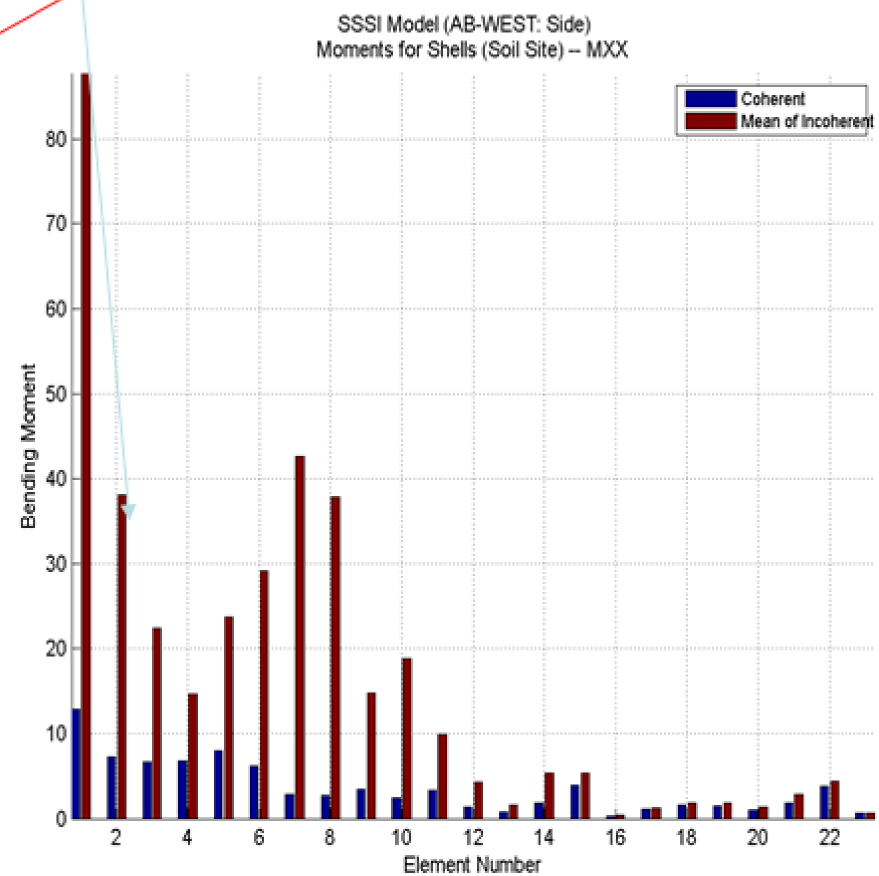
Coherent and Incoherent ABW Wall Bending Near RB Complex for Rock Site and Soil Sites

Rock Site

Coherent
Mean of Incoherent

Soil Site





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. Key US NRC regulatory requirements for seismic SSI analysis, applicable to SMRs.

USNRC DSRS for DES/SMR Design (SRP 3.7.2)

Soil-Structure Interaction *(page 2):* Foundation input response spectra (FIRS) which is the ground motion response spectra at the foundation level are defined in the free field (i.e., without the presence of structures) as described in DSRS Section 3.7.1, DC/COL-ISG-01, “Interim Staff Guidance on Seismic Issues Associated with High Frequency Ground Motion in Design Certification and Combined License Applications,” and DC/COL-ISG-017, “Interim Staff Guidance on Ensuring Hazard-Consistent Seismic Input for Site Response and Soil Structure Interaction Analyses.”

For a deeply embedded structure, performance-based response spectra (PBRS) are also defined in the free field at the ground surface and appropriate intermediate depth(s) to ensure the adequacy of the soil columns used in the deterministic SSI analysis and to determine the potential magnitude of kinematic interaction effects on the structure over the depth of the facility.

Seismic Input

The FIRS and PBRS determined at the foundation level, surface, and intermediate depth(s) should be developed in a consistent manner. They are probabilistically determined performance-based spectra generated using the soil column corresponding to the building. The properties of the soil columns usually consist of 60 or more randomized sets of properties similar to those used in the probabilistic seismic hazard analysis (PSHA) process.

For sites with soil layers near the surface that will be completely excavated to expose competent material and replaced with extended compacted backfill layers, the FIRS and PBRS are determined by considering the effect of the backfill layers in the site profiles.

FIRS at the foundation and PBRS at intermediate levels should also be developed as free field outcrop motions, not as in-column motions.

Competent material is generally considered to be in situ material having a minimum shear wave velocity of 1,000 fps.

As applicable, the USNRC staff reviews the modeling methods (including technical bases) used in the seismic system analysis to account for SSI.

The factors to be considered in accepting a particular modeling method include (1) the extent of embedment, (2) the layering of the soil/rock strata, and (3) the boundary of the soil-structure model.

All SSI analyses should recognize the uncertainties prevalent throughout the phenomenon and include consideration of the following:

A. The random nature of the soil and rock configuration and material characteristics.
B. Uncertainty in soil constitutive modeling (soil stiffness, damping, etc.).
C. Nonlinear soil behavior.
D. Coupling between the structures and soil.
E. Lack of lateral uniformity in the site soil profile that is usually assumed to be uniformly layered in all horizontal directions in SSI analyses.
F. Effects of the flexibility of soil/rock.

G. Effects of the flexibility of basemat, sidewalls, and interior structures.
H. The effect of pore water on structural responses, including the effects of variability of ground water level with time.
I. Effects of potential separation or loss of contact between the structure (embedded portion of the structure and foundation mat) and the soil during the earthquake.
J. For deeply embedded or fully buried structures,
(1) the effect of deep embedment on the relative significance of kinematic interaction,
(2) the extent to which nonvertically propagating shear waves may be more important for deeply embedded structures than for those with shallow embedment depth,
(3) the impact of deep embedment on the accuracy of sidewall impedance functions calculated with standard methods,
(4) the effect of nonlinear behavior (e.g., separation of structure and soil, and soil material properties) on wall pressure and SSI calculations, and
(5) the variation of V/H (vertical to horizontal) spectral ratios of ground motion over the depth of the facility.

K. If incoherence effects to reduce high-frequency motions are included in the SSI response, the evaluation needs to include consideration of the potential variation of the Coherency Function described in DC/COL-ISG-01 with depth.

Motion Incoherency - USNRC 3.7.1 Rev 4 Page 15

vii. Perform an SSI analysis using the site-specific FIRS and an advanced seismic analytical technique (e.g., method that considers the effects of incoherent ground motion). When such analytical methods are utilized, the detailed technical justification shall be reviewed on a case-by-case basis. Further discussion on consideration of the effects of incoherent ground motion is provided in subsection II.4.C (under the heading Input Ground Motion, Specific Guidelines for SSI Analysis) in SRP Section 3.7.2. The in-structure responses in terms of floor response spectra, building member forces, and deformations at key locations in the structure shall be obtained. The key locations for calculating the in-structure responses, proposed by the licensee, need to be evaluated to ensure that they are sufficient to represent the various locations throughout the building. Locations should include responses at peripheral locations to detect rocking and torsion, and should include responses to check overturning, torsional, and sliding stability of the structures. The

Motion Incoherency - USNRC 3.7.2 Rev 4 Page 21

There are advanced analytical methods currently being applied in the nuclear industry to develop seismic responses to high frequency ground motion inputs, incorporating the effect of ground motion incoherency. These methods might be used when a site acceptability determination is performed, as discussed in subsection II.4 of SRP Section 3.7.1. The phenomenon of ground motion incoherency in the free field has been investigated and characterized in terms of coherency functions, based on recorded earthquake data collected from dense array field tests. The ground motion incoherency effect on structural response is considered by incorporating coherency functions in analytical methods for SSI analyses. SSI analyses based on analytical methods that consider ground motion incoherency generally reduce structural response in high frequencies, compared to the response based on the traditional assumption of ground motion coherency. If the effect of incoherent ground motion is used to reduce the high frequency response, the potential effects of incoherent ground motion in increasing overturning and torsional responses need to be considered.

The NRC issued Interim Staff Guidance (DC/COL-ISG-01) on May 19, 2008, describing methods acceptable to the staff for evaluating high frequency ground motion input. It includes guidance for conducting analyses that incorporate incoherent ground motion.

Because of the complexity of such analyses, and the lack of both an experience data base and test data, the implementation of the analytical methods described in DC/COL-ISG-01, for considering incoherent ground motion, is subject to staff review on a case-by-case basis. Applicants are expected to present comparisons between calculated coherent and incoherent seismic demands. Based on the staff's current experience, the following maximum reductions in the amplitude of spectral accelerations are acceptable for the ISRS:

0 to 10 Hz – 0% reduction
30 Hz and above – 30% reduction
10 to 30 Hz – reduction based on linear variation between 0% at 10 Hz and 30% at 30 Hz

Motion Incoherency - USNRC 3.7.2 Rev 4 Page 22

The maximum ISRS reduction limits are applied to the calculated incoherent ISRS results only where the reduction limits are exceeded by the calculated reductions. Where the reduction limits are not exceeded, the calculated incoherent ISRS results are to be used, including where the incoherent results exceed the coherent results. The corresponding adjusted incoherent ISRS results are to be included in the ISRS comparison plots described above.

Larger ISRS reductions than specified above may be acceptable to the staff, if there is sufficient technical information supporting the larger reductions. The staff reviews and accepts the technical justifications for larger reductions on a case-by-case basis.

For structural loads, which are predominantly controlled by seismic input up to 10 Hz, the maximum acceptable reduction, due to the effects of incoherent ground motion, is 10 percent. If the structural loads increase due to the effects of incoherent ground motion, then the higher incoherent structural loads are to be used for structural design.

It is noted that the effects of incoherent ground motion may be considered at the DC application stage in a generic evaluation of high-frequency ground motion input. In such a case, a COL applicant would confirm that the site-specific high-frequency ground motion input and the underlying site profile are encompassed by the generic evaluation. When referencing a certified design, a COL applicant may also conduct site-specific SSI analysis that considers incoherency effects to reduce the high-frequency response. In this case, the site-specific in-structure responses should be enveloped by the responses obtained from the analysis of the CSDRS; further guidance can be found in SRP 3.7.1 II.4.

End of Part 1 Presentation.
Thank You!