Recent Advances in Seismic Soil-Structure Interaction (SSI) Analysis for NPP Structures; Application of ACS SASSI

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Company Expertise
(http://www.ghiocel-tech.com):

KEY EXPERTISE AREAS:

GP Technologies, Inc. is a small business corporation that is *highly specialized in computational mechanics, uncertainty modeling and risk prediction for large-scale complex engineering applications*. GP Technologies has accumulated unique extensive experience in the area of computational stochastic mechanics, statistical modeling and structural risk prediction. Joint research projects for DOD with Cornell, CWRU, Vanderbilt, Virginia Tech, etc.

Most of the GP Technologies innovative research projects are related to engineering projects on the *application of advanced computational mechanics modeling, with emphasis on stochastic mechanics, to structural analysis, seismic SSI, random vibrations, and state-of-the-art reliability prediction tools* for Government and high-tech corporations in *aerospace, automotive and nuclear energy industries. List of clients provided on our website.*

RESEARCH PROJECTS:
For USAF on jet engine vibration, US Army on ground vehicle reliability, OSD on airframe fatigue reliability, DNFSB and US NRC on seismic SSI analysis methodology for nuclear facilities.

COMMERCIAL PROJECTS:
Various clients. At present focus on nuclear energy applications for seismic analysis. Unique software and consulting for major nuclear corporations including Westinghouse for AP1000 and SMRs, Toshiba for AP1000S and ABWR, Mitsubishi Heavy Industries for APWR, Hitachi-GE for ABWR, KEPCO for APR1400, AECL/Candu Energy for ACR1000 and CANDU 6, AREVA/MHI for ATMEA1. Consulting for Government, DNFSB/DOE and NRC.

TECHNICAL STAFF: A core of high expertise and experienced consultants, plus highly skilled and specialized technical staff in structural mechanics, with advanced academic degrees in engineering, particularly in solid mechanics, computer science and statistics. Available technical staff personnel 10 specialists including affiliates and consultants.

NUCLEAR CUSTOMERS:

The ACS SASSI NQA software is used by key nuclear technology companies, in addition to KEPCO-EC for APR1400, including Westinghouse Co. for AP1000 NPP, Mitsubishi Heavy Industry for US-APWR NPP, Toshiba Co. for AP1000S and ABWR NPP, Hitachi-GE for US-ABWR, CANDU Energy (formerly AECL) for ACR1000 and CANDU 6 NPP and PBMR Ltd. for the Koeberg NPP. The ACS SASSI NQA software is also used by US Nuclear Regulatory Commission (US NRC) and International Atomic Energy Agency (IAEA) agencies for performing confirmatory seismic SSI analyses for various NPPs in US or other worldwide places. Used also by US DNFSB for independent reviews and US DOE for YM project.

ACS SASSI is used by many nuclear structural design and consulting corporations including URS, B&V, Paul Rizzo & Associates, MCEER, etc. in US, B&H in Switzerland, SMP and MMB Baudynamic in Germany, EnergoProjekt in Checz Republic, Areva in Germany, Shimizu, Obayashi and Taisei in Japan, KEPCO, KAERI, KAIST in Korea, Eletronuclear in Brasil, etc. AECOM Asia in Hong-Kong, NCREE in Taiwan, etc.. Also, in universities, as UCLA, North-Eastern Boston University, CWRU, Chiba, Nagoya, Akita, Shinshu, Patras, etc.

In China, the ACS SASSI NQA software was used over a numbers of years by CNPE, SNPDRI in Beijing, and by SNERDI in Shanghai and Guangdong Power Energy Design Institute (GEDI) in Guangzhou.

Purpose of This Presentation:

To present an overview on seismic soil-structure interaction (SSI) effects on nuclear facility structures based on the ACS SASSI application to a variety of SSI problems.

-This presentation is made from a personal perspective based on my involvement with the ASCE04 Standard committee for seismic analysis of NPP structures – to be completed by 2013! This includes new concepts for site-specific seismic SSI analyses.

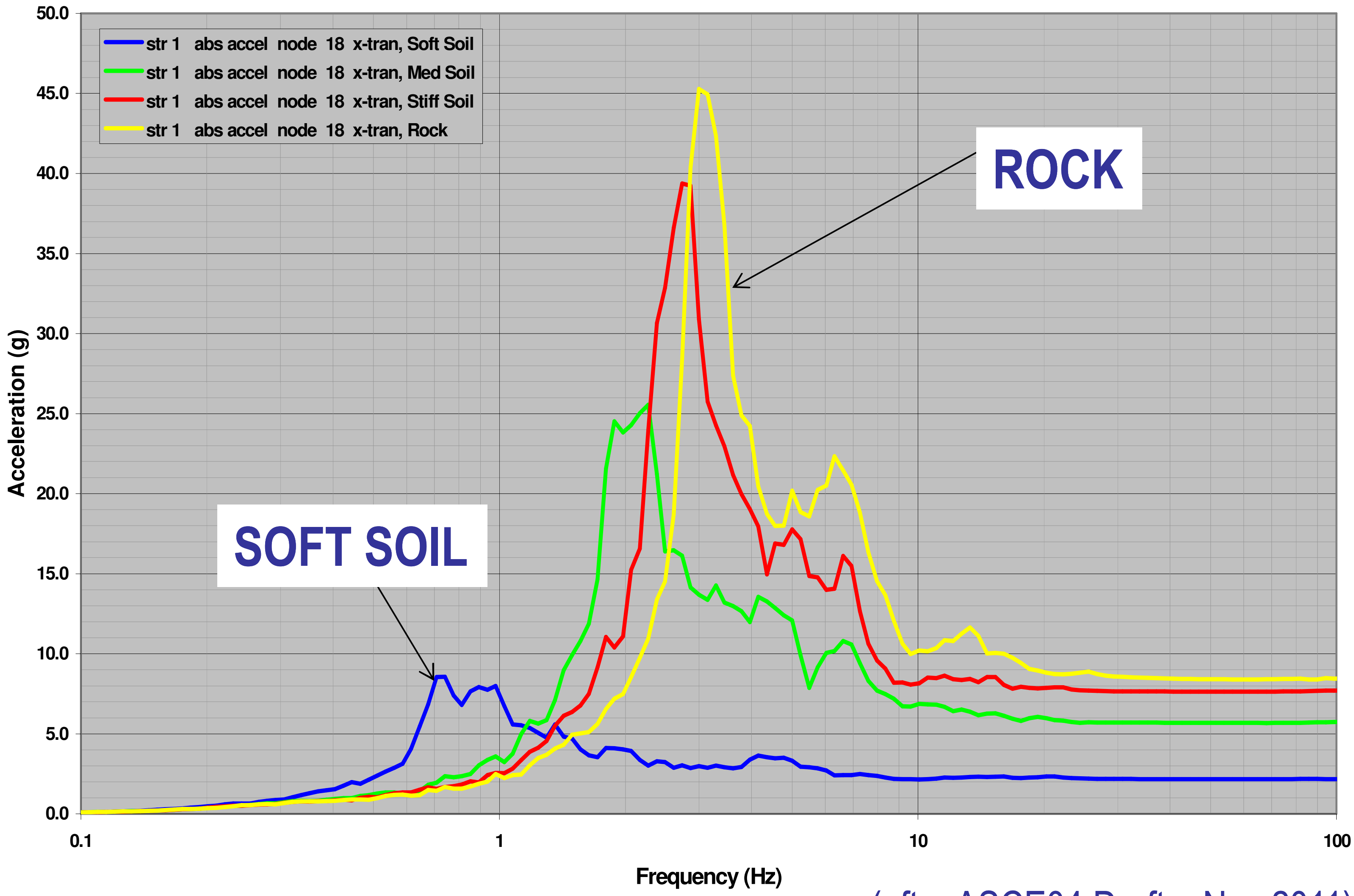
- Highlight key insights and new SSI methodologies and requirements

SSI effects are of paramount importance for seismic analysis of massive, concrete structures, with or without embedment.

Both the inertial effects due to accelerations and the kinematic effects due to soil deformation under incident and scattered waves should be considered.

SSI Effects on Nuclear Structures

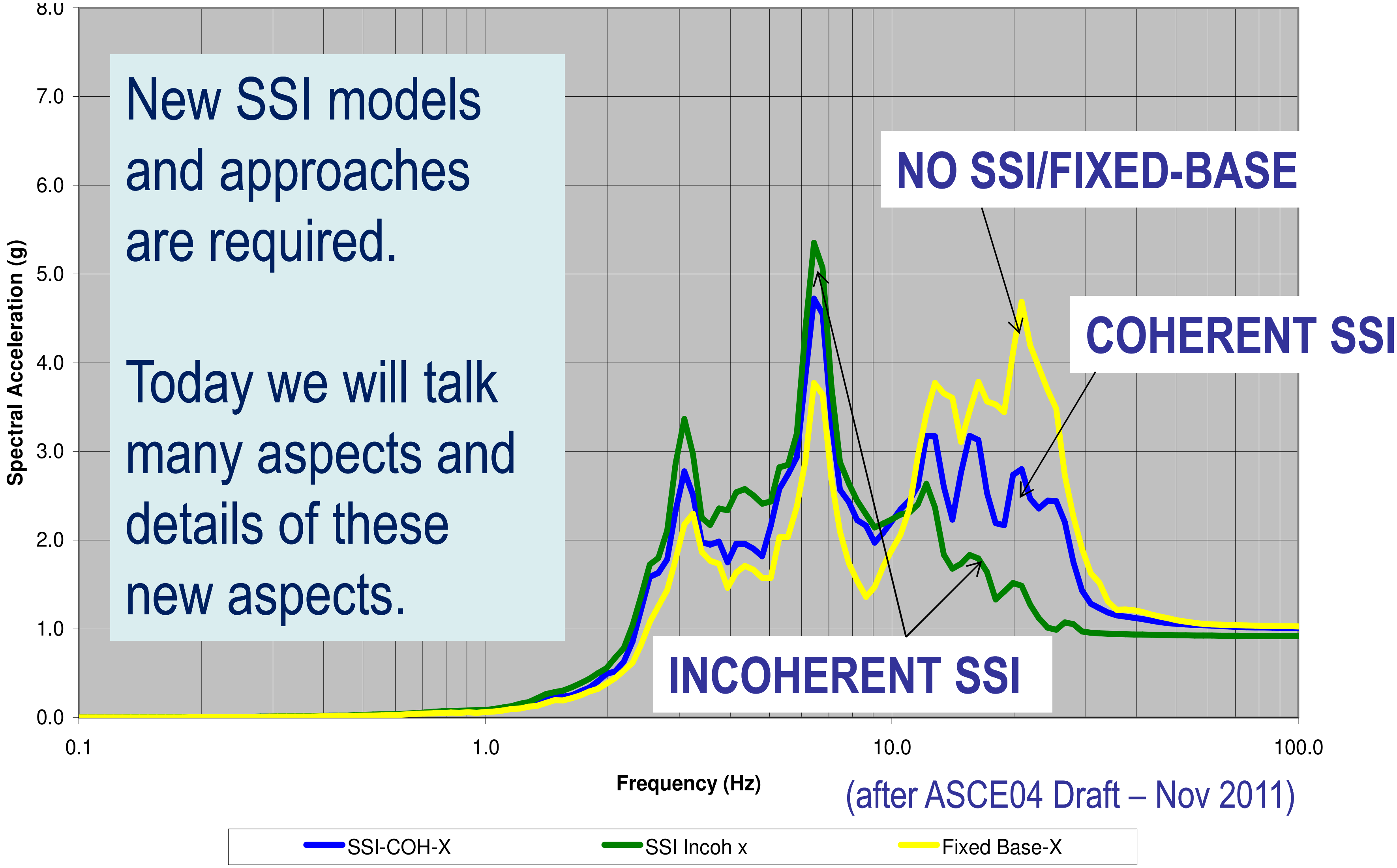
EPRI AP1000 Stick 5% Damping ISRS at Top of SCV



(after ASCE04 Draft – Nov 2011)

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.

(after ASCE04 Draft – Nov 2011)

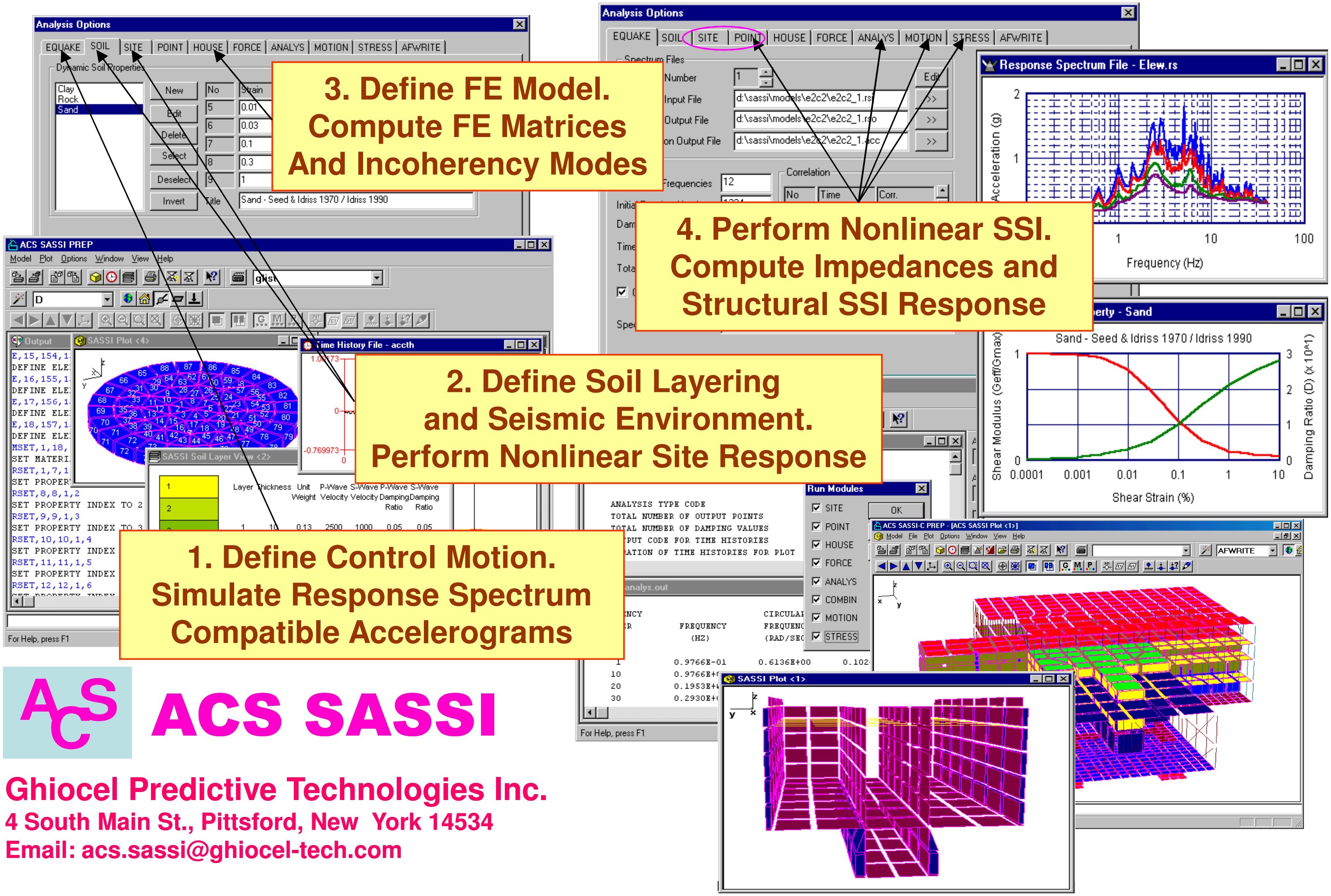
ACS SASSI NQA Software for Seismic SSI

The ACS SASSI software is a *specialized seismic soil-structure interaction (SSI) analysis computer code with unique engineering capabilities, that combines stochastic 3D seismic wave modeling and simulation with finite element computations.* To access the ACS SASSI page for more information, please click http://www.ghiocel-tech.com/engineeringTools.html# and, then, select "ACS SASSI" under the "Software Package" option.

Developed under the nuclear QA program of GP Technologies, Inc. Includes an active NQA maintenance service including tech support and bug and error reporting under 10CFR Part21.

ACS SASSI approaches includes *all* the SSI approaches validated by EPRI (2007 EPRI TR# 1015111) and accepted by US NRC (ISG-01, May, 2008).

An Advanced Computational Software for Dynamic Soil-Structure Interaction Analysis on Personal Computers



ACS SASSI

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SSI Analysis Inputs and Outputs

Inputs:

1. Seismic Input: Control Motion, Local Correlation and Spatial Coherency
2. Vibration: External Force Time Histories
3. Soil Layering: Geometry and Dynamic Properties (Geff, Deff) per Layer
4. Baserock: Depth & Dynamic Properties (G,D)
5. Structure: Structural Configuration - FE Modeling, Nodal Masses, Springs

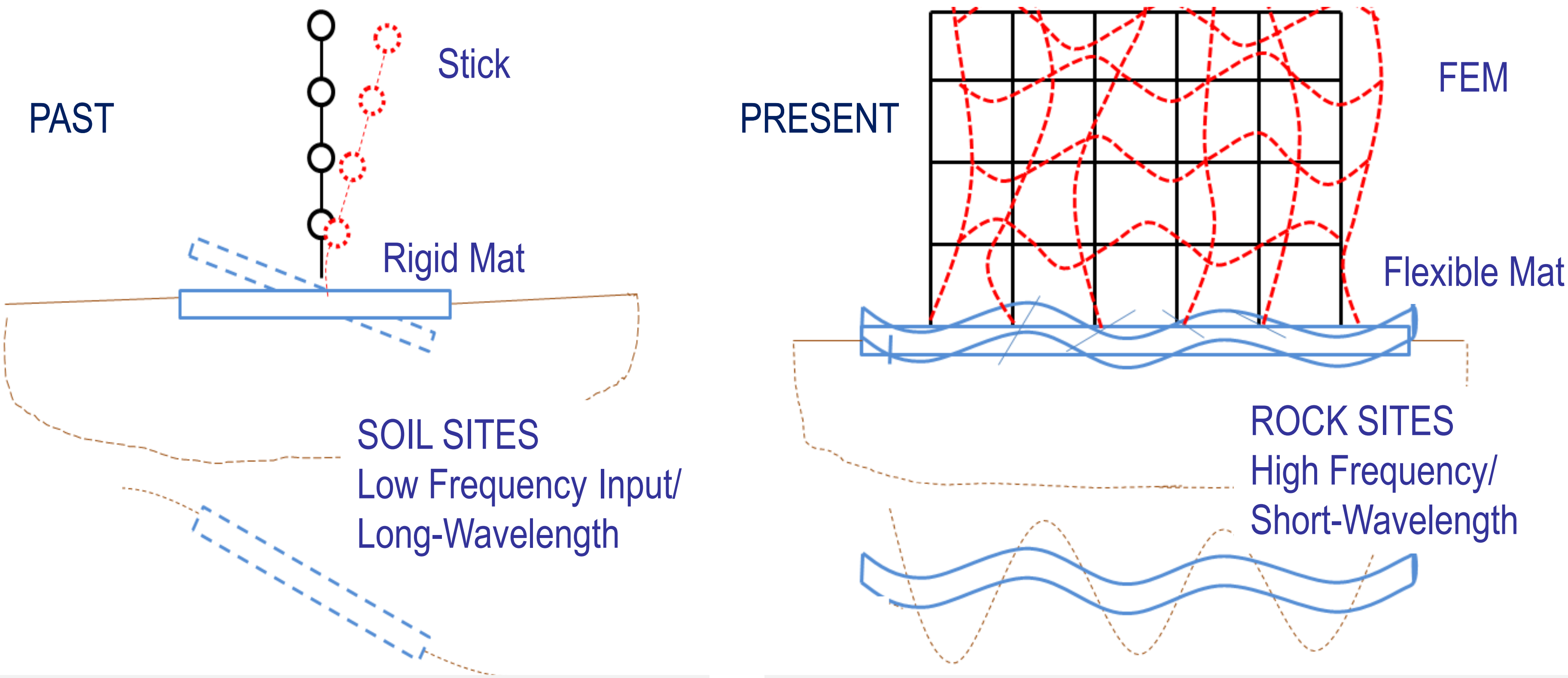
Outputs:

1. Seismic Free-Field Soil Motions and Linearized Dynamic Soil Properties
2. SSI Response Transfer Functions for Accelerations, Displacements and Element Stresses/Forces/Moments
3. Structural Acceleration and Displacement Motions and In-Structure Response Spectra (ISRS)
4. Structural Stresses/Strains for Shells/Solids & Forces/Moments for Beams and Springs

Application Areas Involving Dynamic SSI Analysis

• Civil, industrial, nuclear or hazardous facility buildings with complex arbitrary 3D geometry foundations and complex seismic or external load environments
• Underground multilevel buried structures, waste storage tanks, tunnels
• Large-size industrial under spatially varying seismic waves
• Embedded, buried structures of hazardous facilities under seismic or dynamic loads
• SSI for Concrete and earth dams, embankment, large-span concrete bridges
• Retaining structures and walls, including effects of seismic soil pressures from surface and body wave propagation, including Rayleigh waves.
• Concrete massive deep foundations, including caissons, piers
• Tunnels, subway stations and buried storage facilities
• Multiple interacting neighboring constructions
• Underground lifelines, pipelines under surface waves
• Dynamics from rotating machinery or fast moving loads, as vehicles, trains

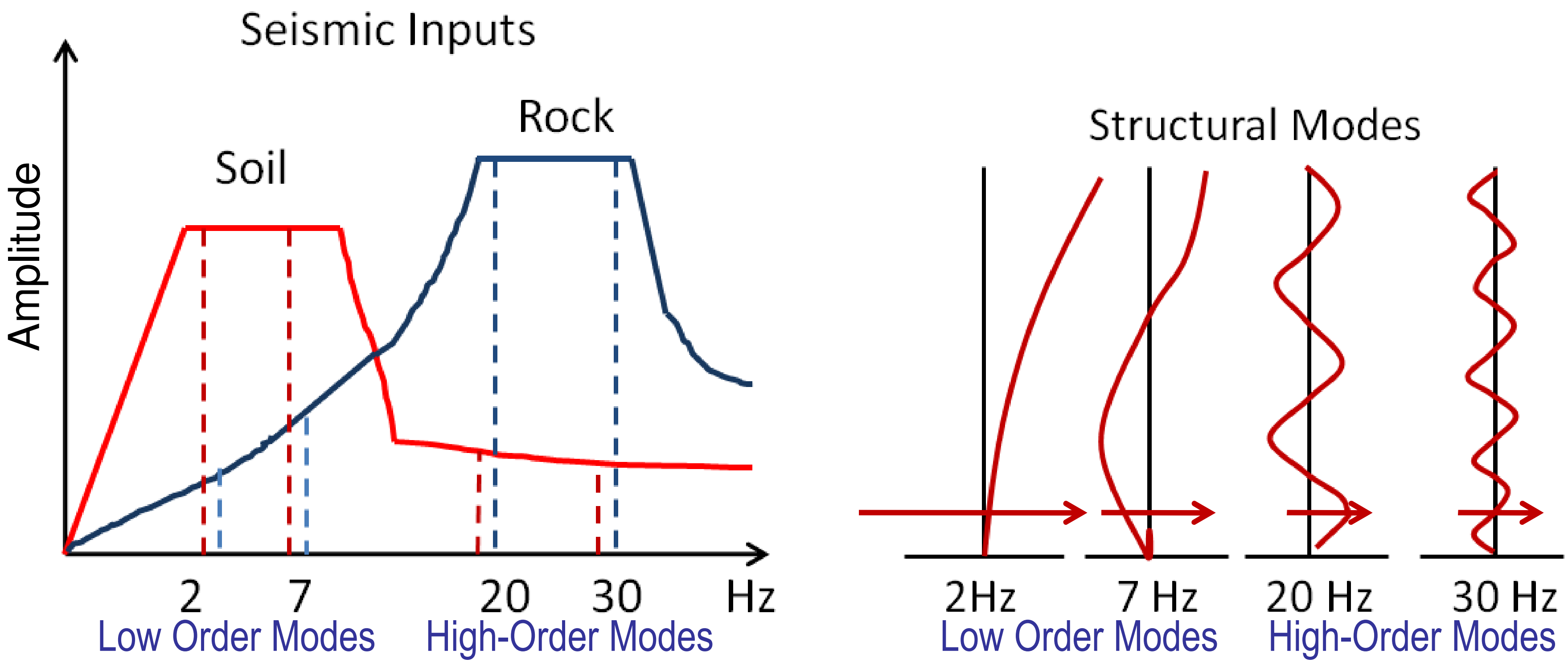
Past and Present Engineering Applications



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)

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)

Seismic Input:
Low-Frequency (LF) vs. High-Frequency (HF) Inputs



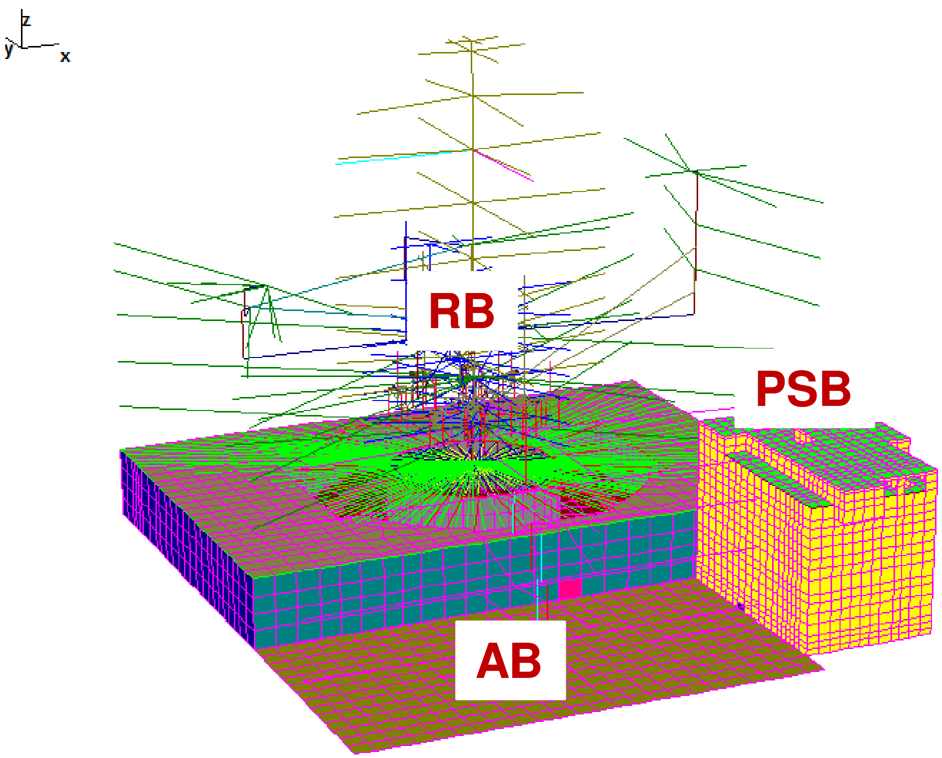
REMARKS:

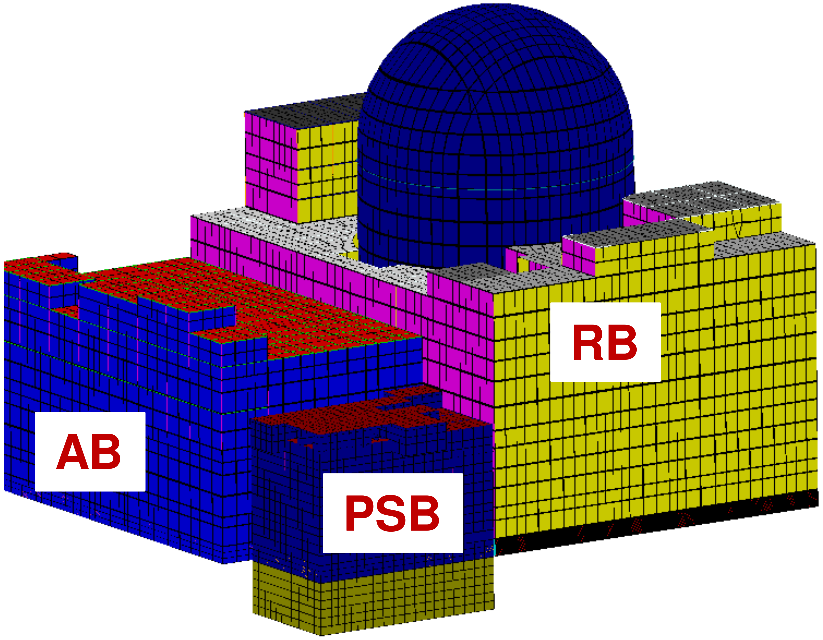
- Structural forces are much lower for LF inputs than HF inputs; EQ static methods based on ZPA values fail to be consistent with the dynamics…
- ISRS will have very different shapes

ANIMATIONS

Seismic SSSI Effects Using Stick & FE Models

Stick Model - Past ⟶ **Stick Model - Present**

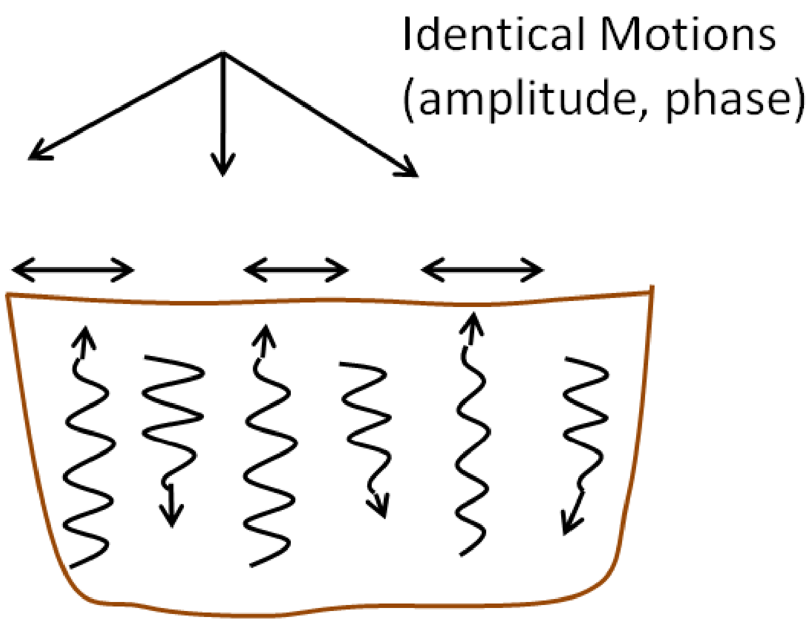




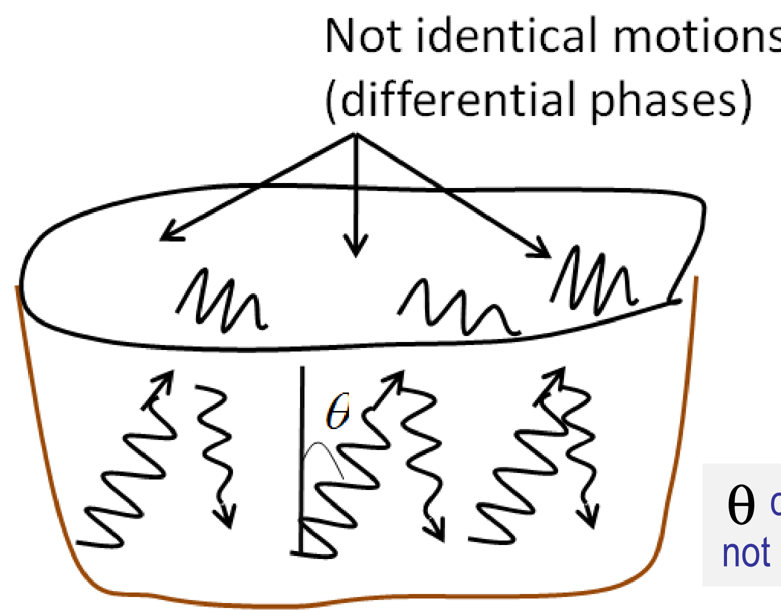
ACS SASSI V230 Baseline ⟶ ACS SASSI V230 Fast-Solver (FS)

Wave Propagation Physics-Based Models

1D Wave Propagation (Idealized)



3D Wave Propagation (Realistic)



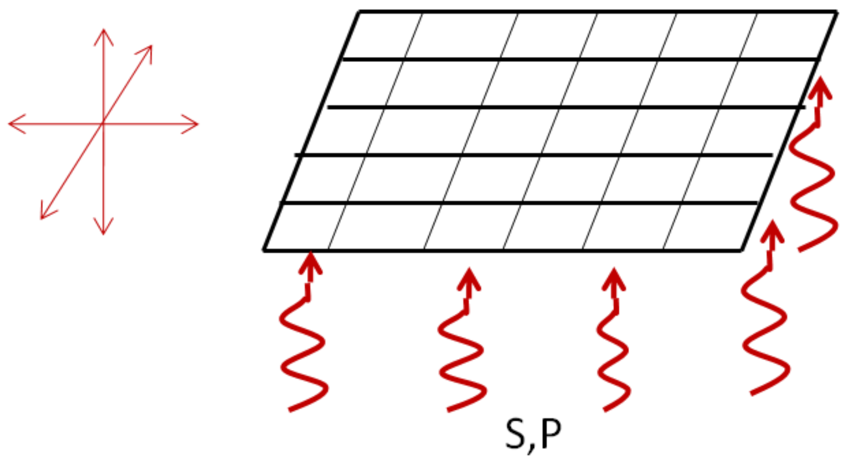
θ constant not realistic!

1D WAVE PROPAGATION MODEL:
- Simple Assumption: Vertically Propagating S and P body waves
- Simplicity. Less accurate than 3D waves
- Robustness to speculative assumptions
- Rigid body motion of the soil surface is not realistic!

3D WAVE PROPAGATION MODEL:
- Complex Assumptions on wave composition, S and P wave orientations; model parameters should be assumed random quantities.
- Sophisticated stochastic models. Case-by-case for each site! Validation!
- Sensitive to speculative assumptions!!!
- 3D wave motion of soil surface is realistic!

Wave Propagation Models: Coherent vs. Incoherent

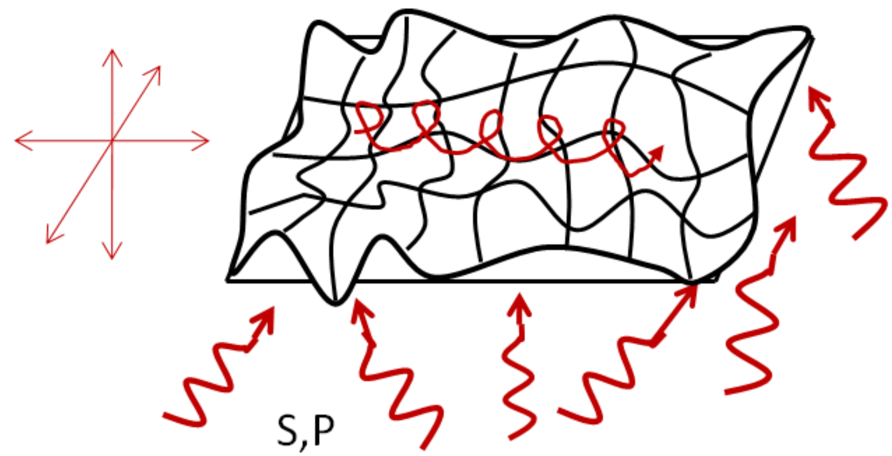
3D Rigid Body Soil Motion (Idealized)



1 D Wave Propagation Analytical Model (Coherent)

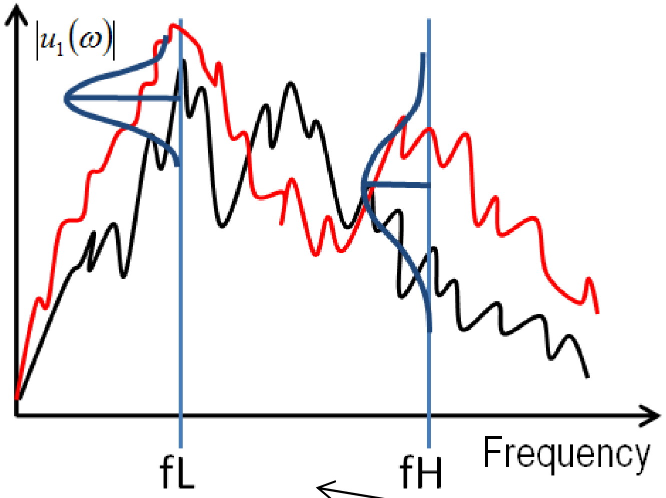
Vertically Propagating S and P waves (1D)
- No other waves types included
- No heterogeneity random orientation and arrivals included
- Results in a rigid body soil motion, even for large-size foundations

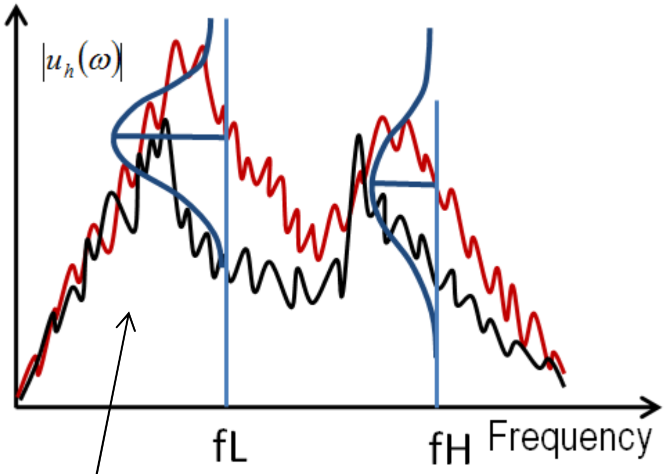
3D Random Wave Field Soil Motion (Realistic)

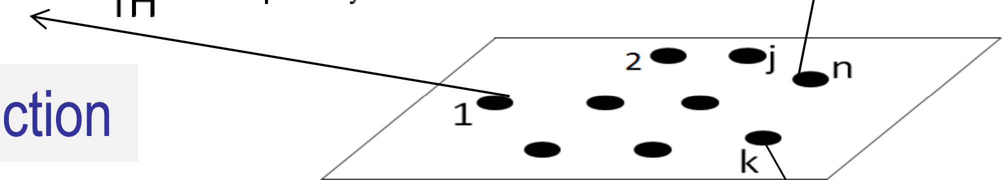


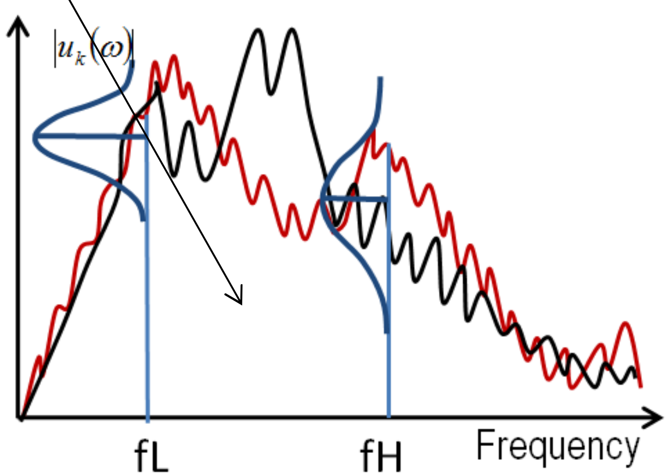
3D Wave Propagation Data-Based Model (Incoherent – Database-Driven Adjusted Coherent)
Amplitude of vertically propagating S and P wave motions are adjusted based on the statistical models derived from various field dense-arrays record databases (plane wave coherency models, plus wave passage – Abrahamson's models)
- Includes real field records information, including implicitly motion field heterogeneity, random arrivals of different wave types under random incident angles

3D Stochastic Wave Model: Incoherent Motion Field









Coherent Function

$$\Gamma_{Uj,Uk}(\omega)=\frac{S_{Uj,Uk}(\omega)}{[S_{Uj,Uj}(\omega)S_{Uk,Uk}(\omega)]^{1/2}}$$

$$\Gamma_{U\,Ui,Uk}(\omega)=\Gamma_{L\,Ui,Uk}(\omega)\exp[i\omega(X_{D,i}-X_{D,k})/V_D]$$

$$\gamma_{ij}(\omega)=\frac{E\left[|u_i(\omega)||u_j(\omega)|\right]}{E\left[|u_i(\omega)|\right]^{1/2}E\left[|u_j(\omega)|\right]^{1/2}}\exp\left(i\omega\frac{\Delta_{ij}}{V_a}\right)$$

2007 Abrahamson Coherence for Hard-Rock and Soil Sites

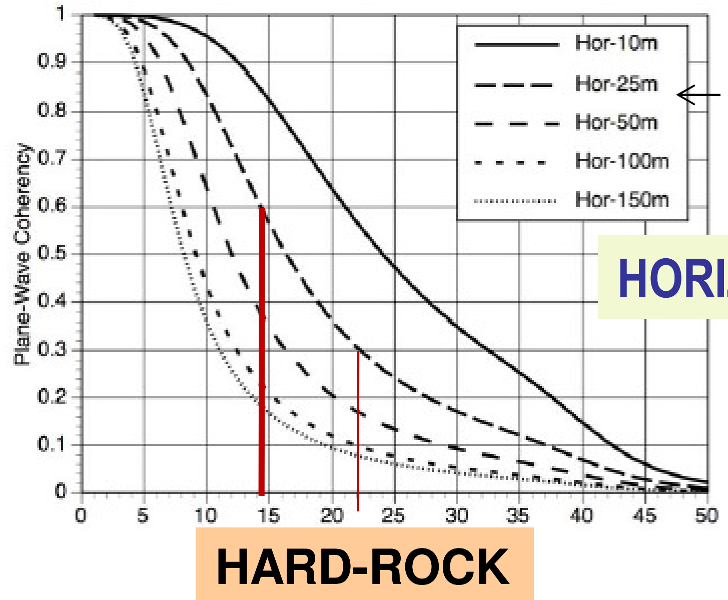


Figure 6-1
Plane-Wave Coherency for the Horizontal Component

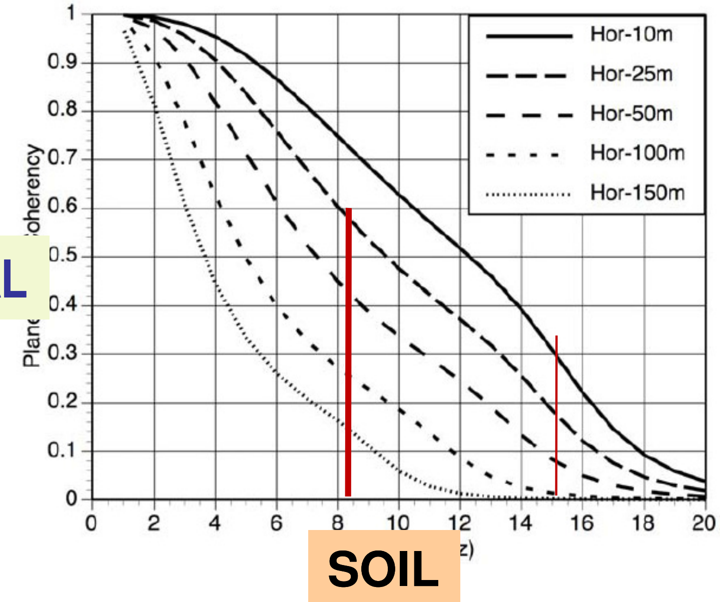


Figure 7-1
Plane-Wave Coherency for the Horizontal Component for Soil Sites

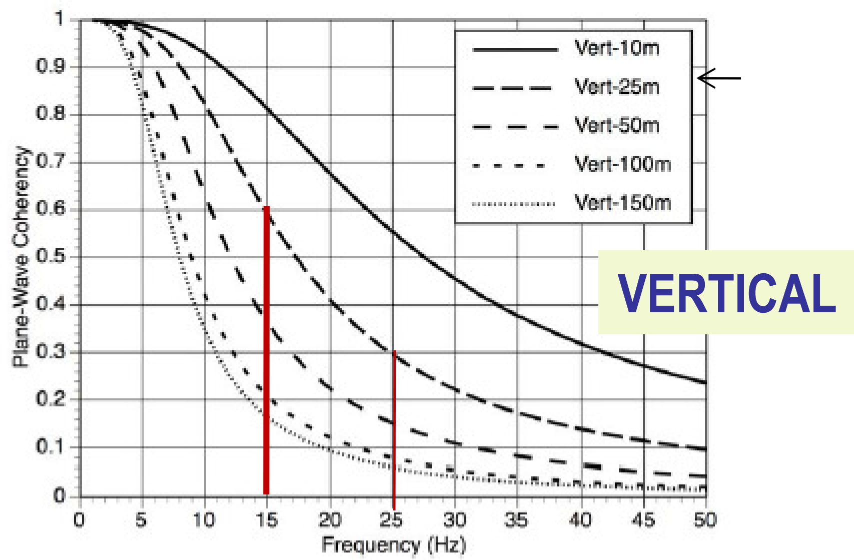


Figure 6-2
Plane-Wave Coherency for the Vertical Component

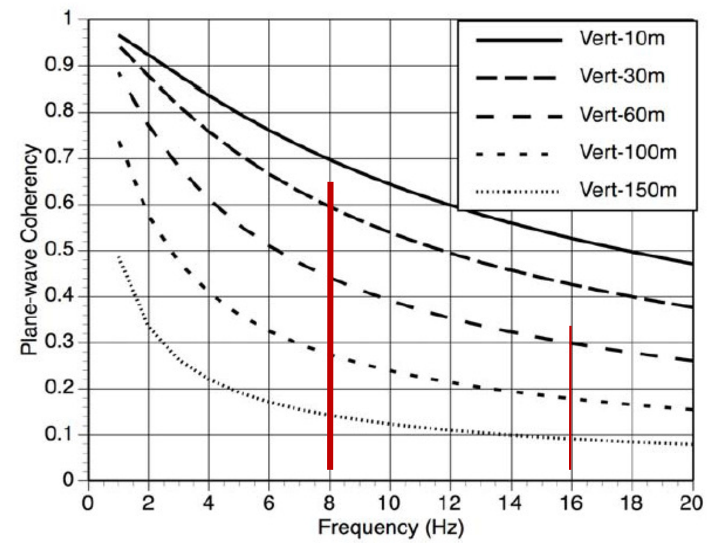
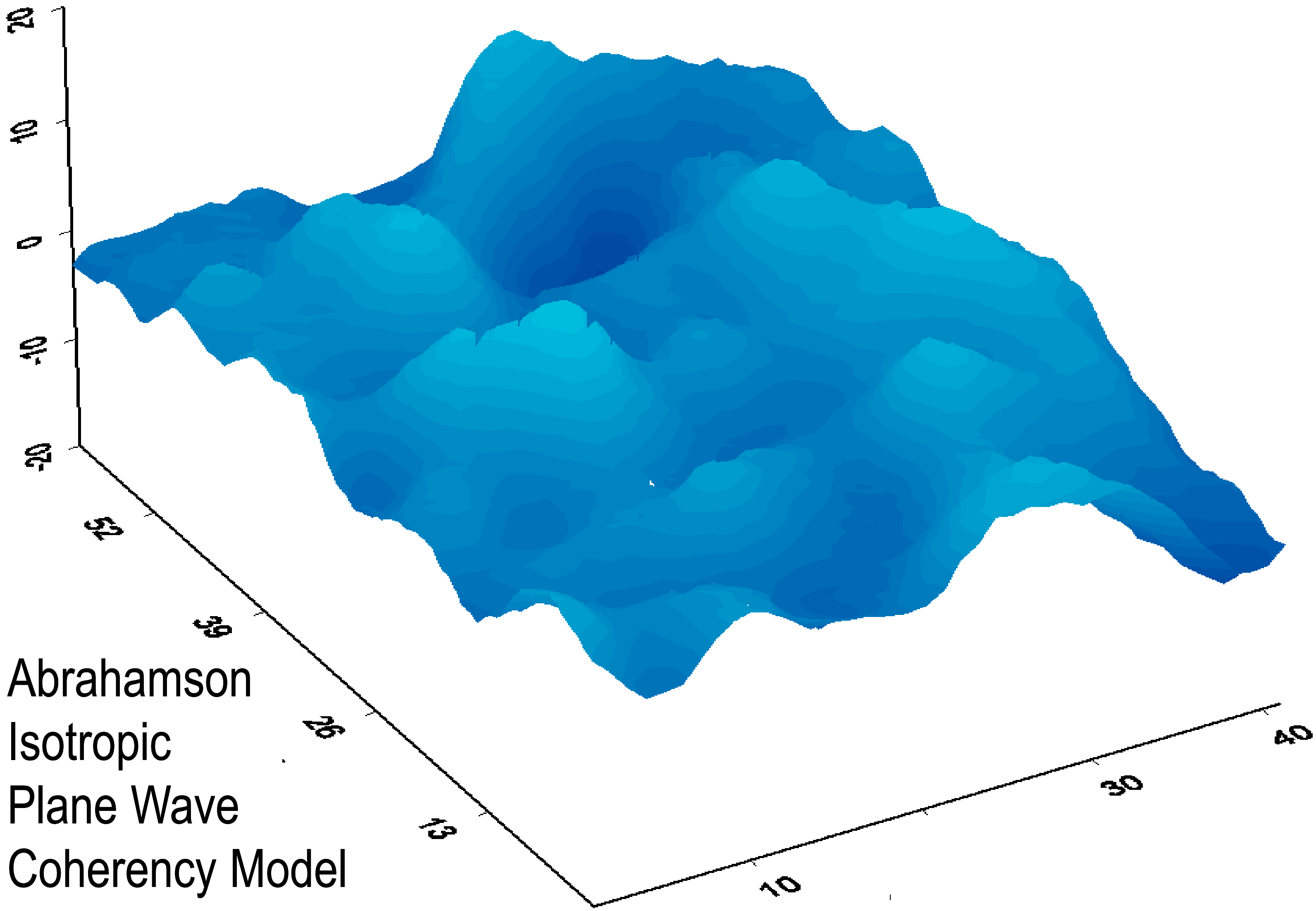


Figure 7-2
Plane-Wave Coherency for the Vertical Component for Soil Sites

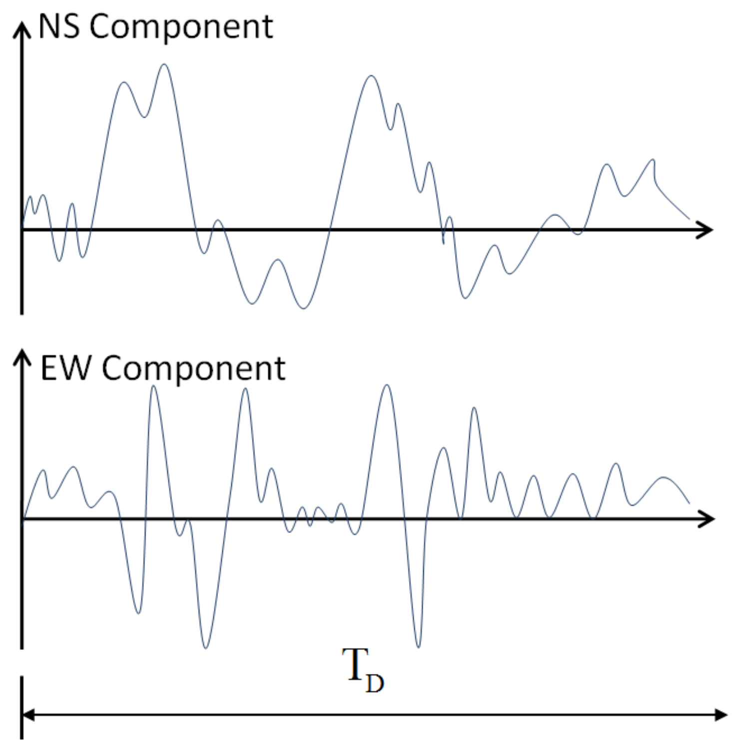
(EPRI TR # 1015110, December 2007)

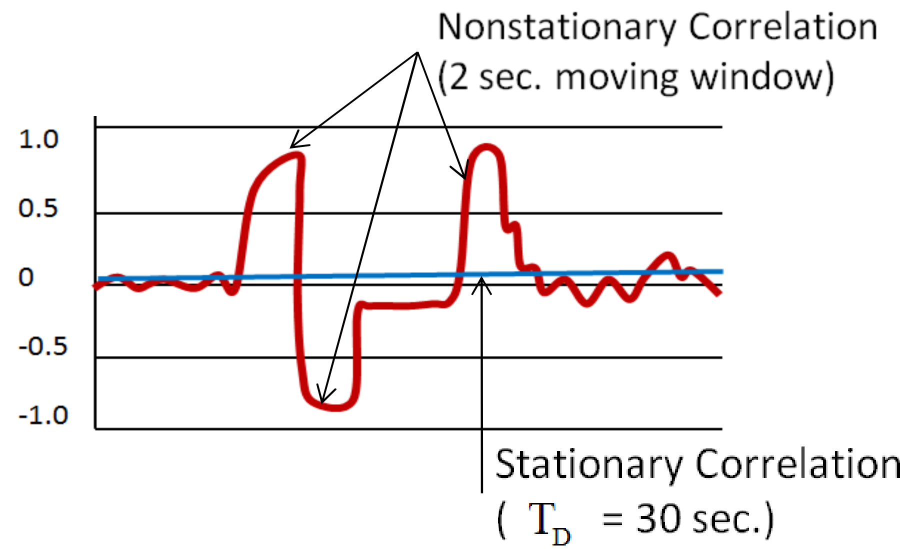
Simulated Incoherent Motion Amplitude at 10 Hz

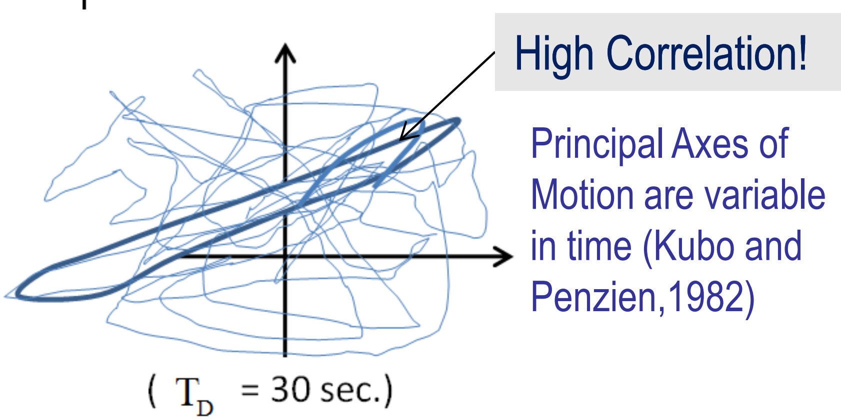


Abrahamson
Isotropic
Plane Wave
Coherency Model

Seismic Input Directionality (Including 3D Direction Variations)

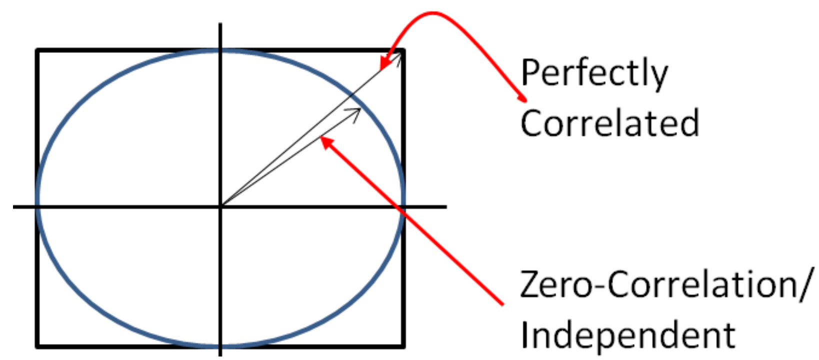






Principal Axes of Motion are variable in time (Kubo and Penzien,1982)

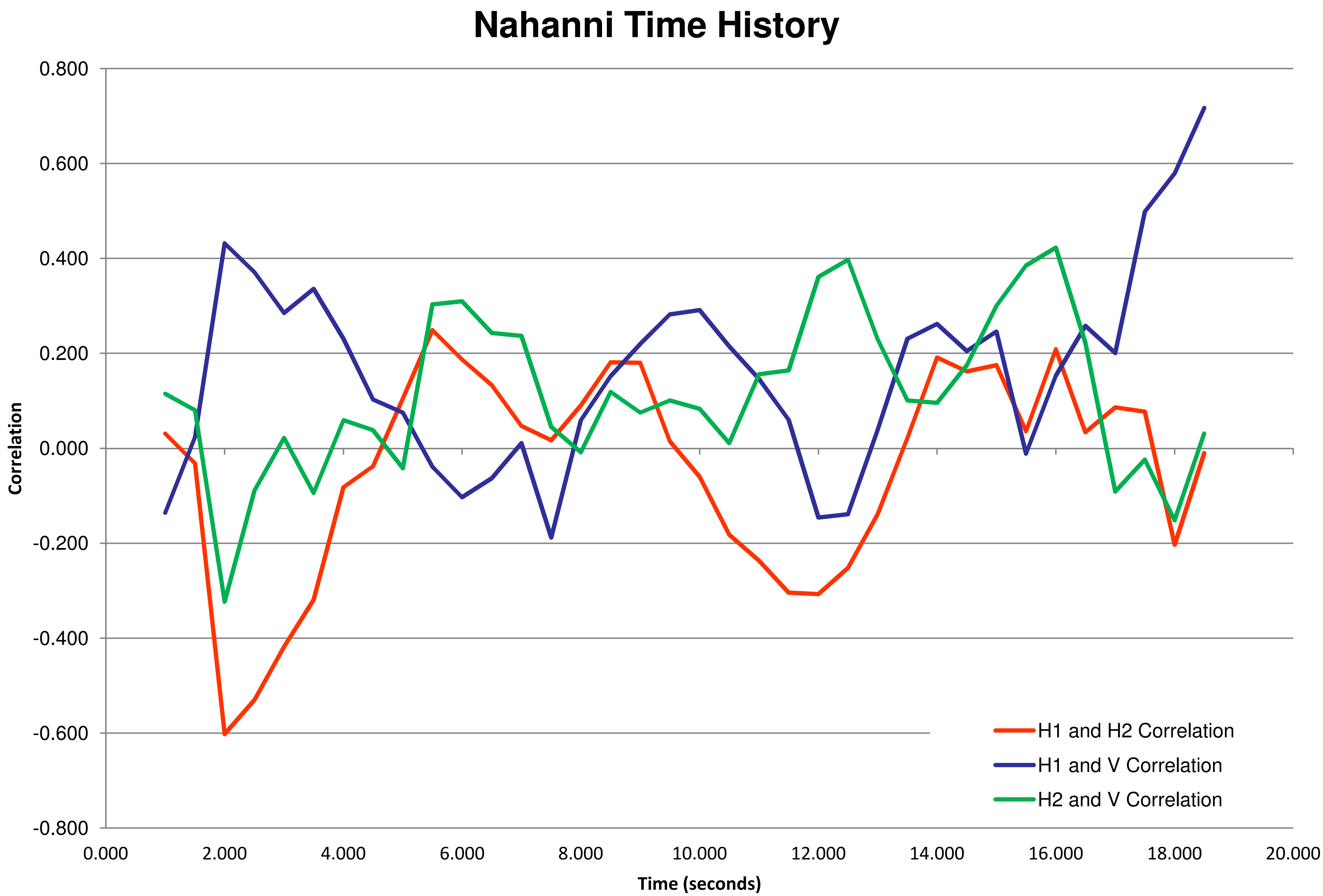
CORNER COLUMN PROBLEM



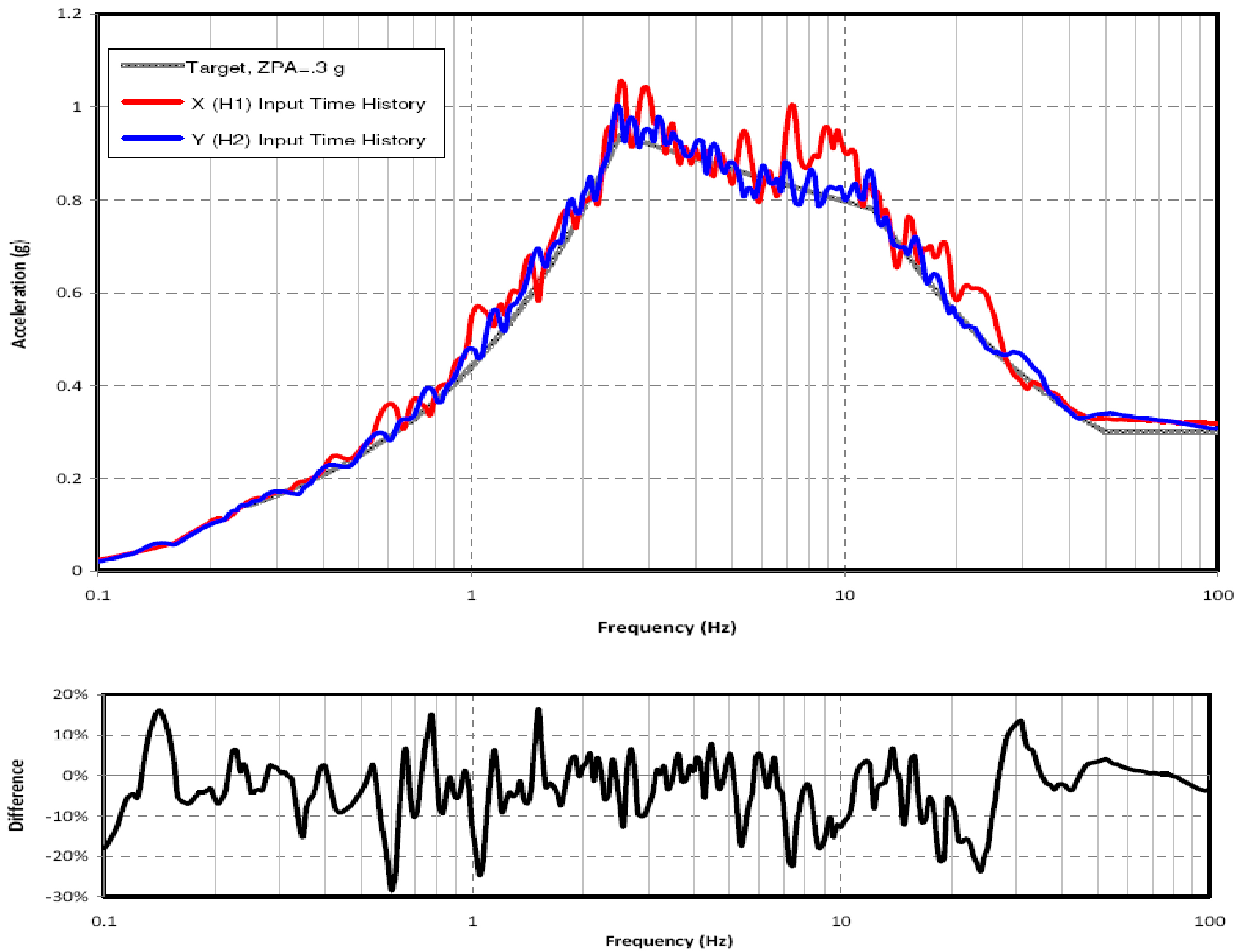
(Agnastopoulos, 1981, Der Kiureghian, 1984)

(SRSS rule neglects correlation effects)

Input Motion Phasing (Non Stationary Correlation)



Input Motions



Differences in 5% ABS of CSDRS Compatible Input Ground Motion

Input Motion Phasing Effects

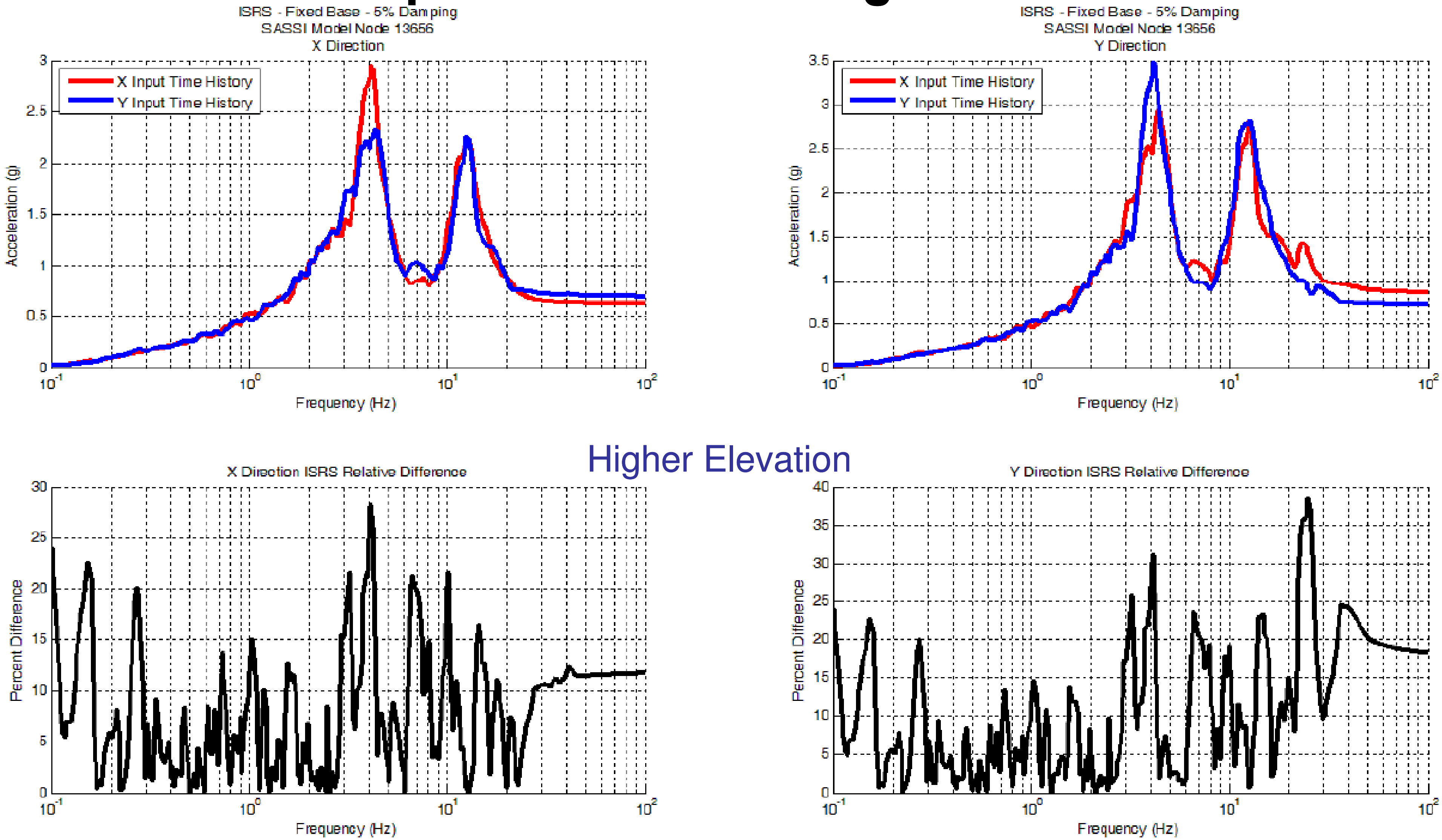
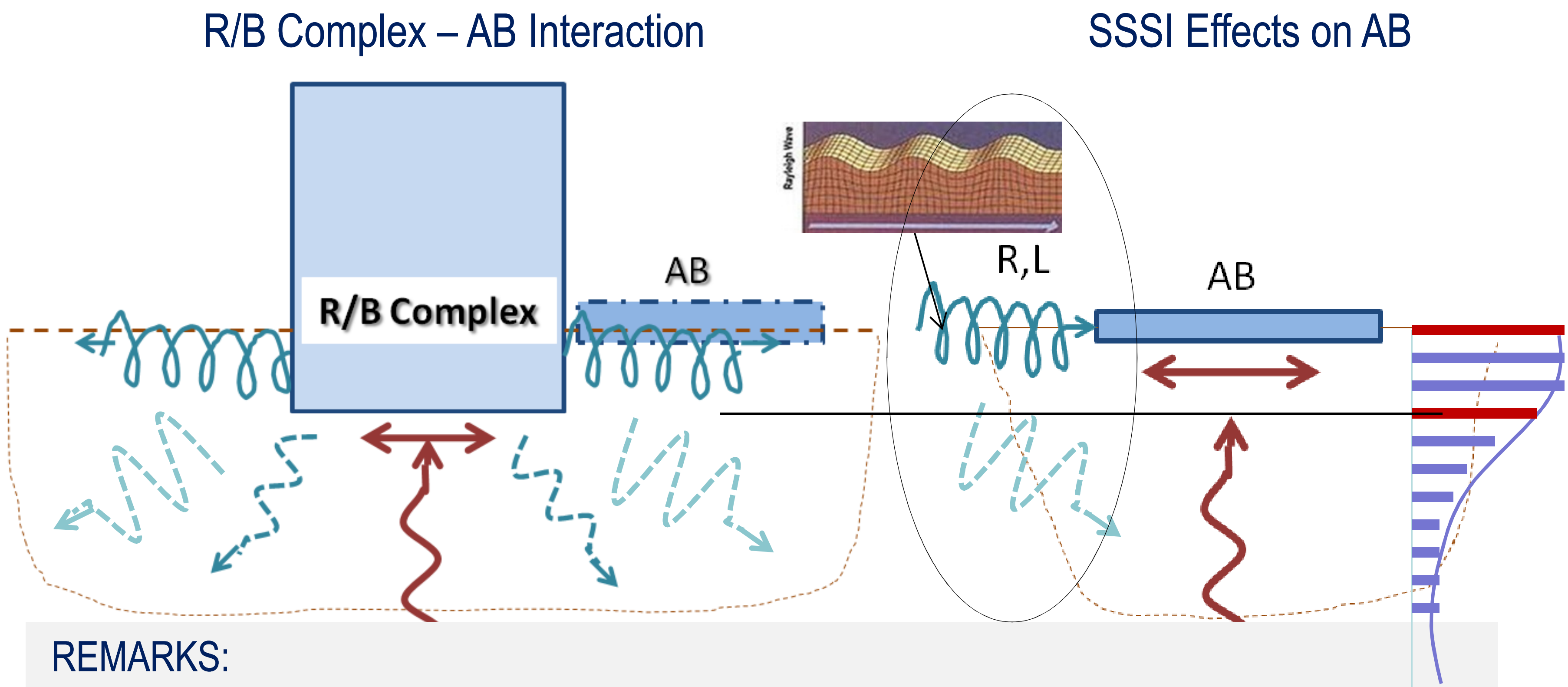


Figure 5c Differences in the 5% Damping ARS Calculated using different horizontal input acceleration time histories

Use 5 seismic inputs – Voted recently for ASCE04 Draft 2011!

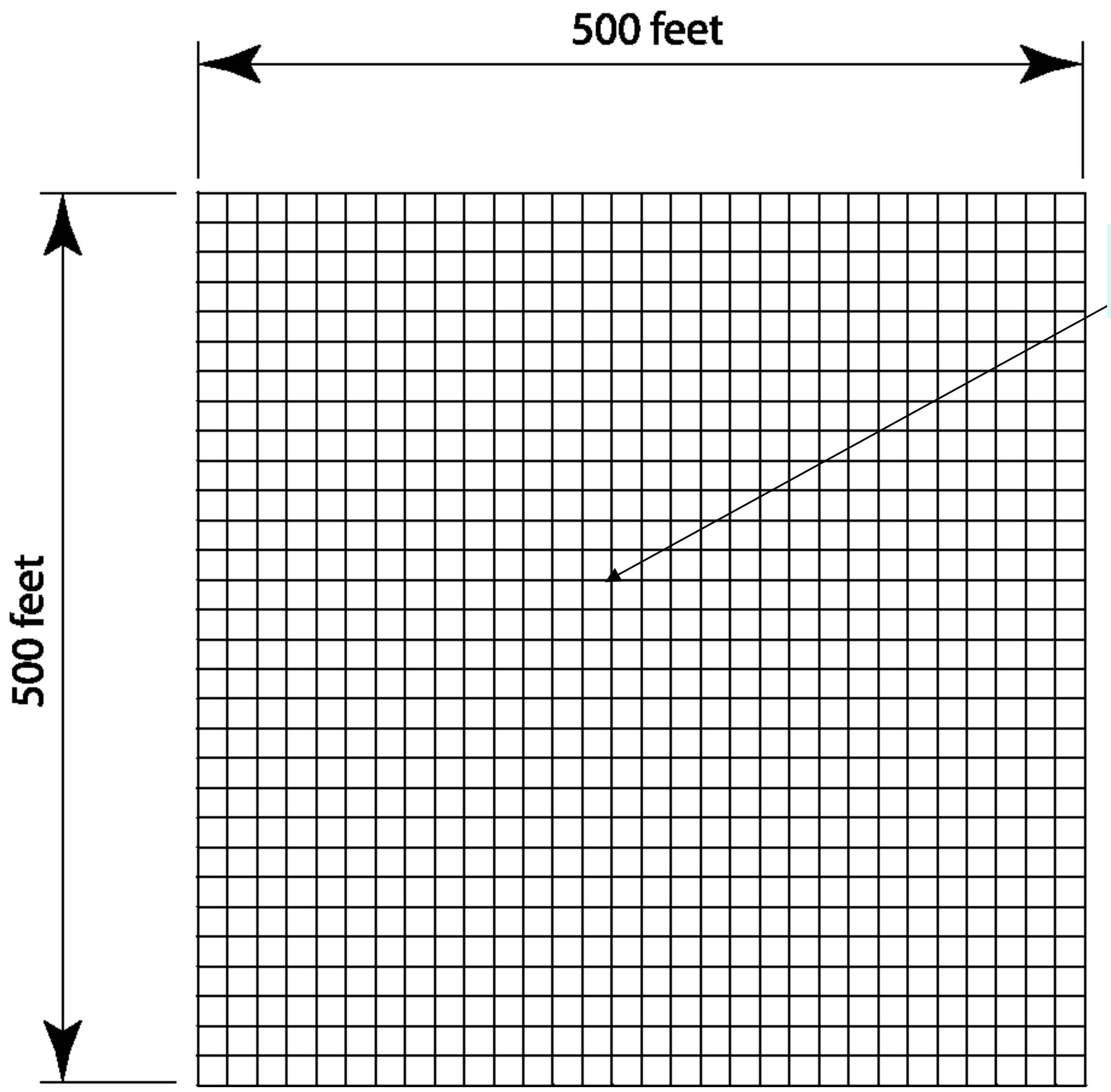
Seismic Structure-Soil-Structure Interaction (SSSI) Effects



REMARKS:

- The SSSI effects could be very significant. Both i) wave scattering and ii) inertial coupling could play significant roles. Effects show in ISRS. Usually less significant in structural forces
- Foundation levels and sizes affects the SSSI phenomena
- Light surface structures in vicinity of embedded nuclear islands (NI) could be affected seriously by wave scattering effects; these include the soil motion variation with depth, and the surface waves, oblique S and P body waves radiated from NI foundation

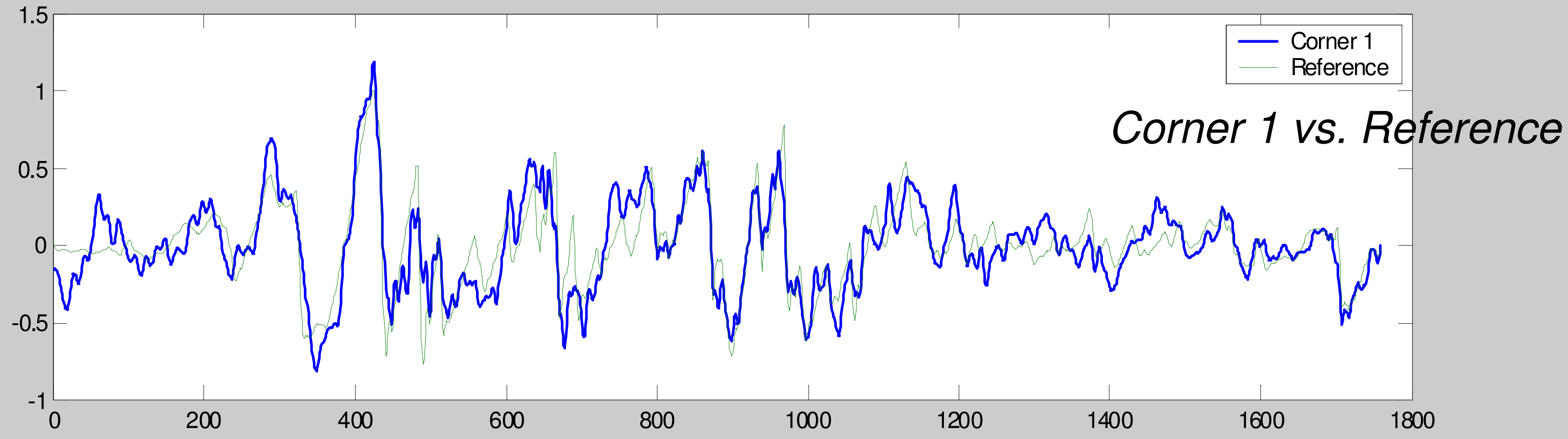
Incoherent Free-Field Motion

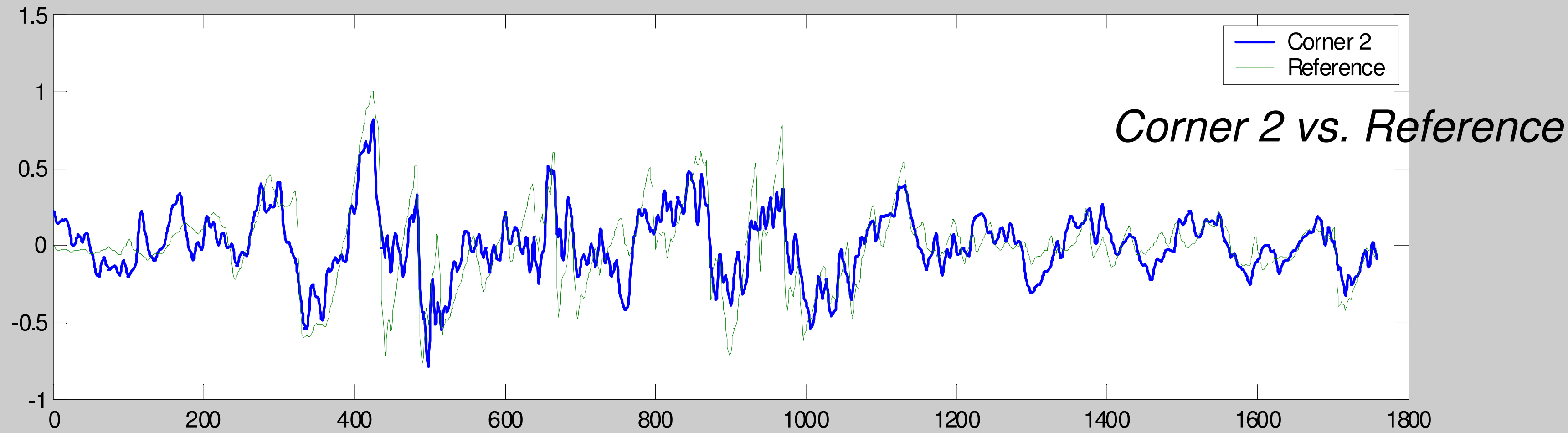


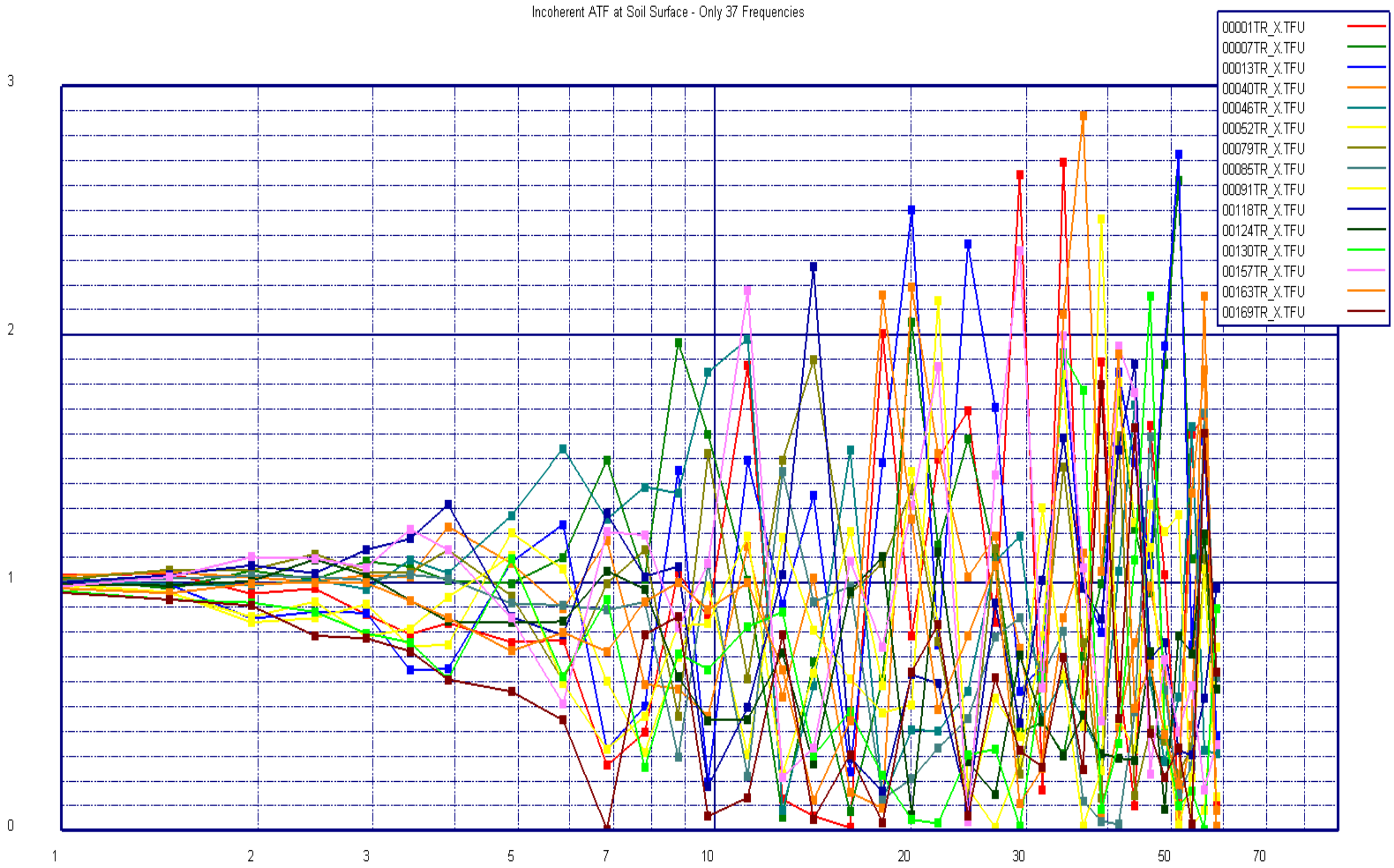
Dimension: 500ftx500ft

Mesh: 31 x 31 nodes

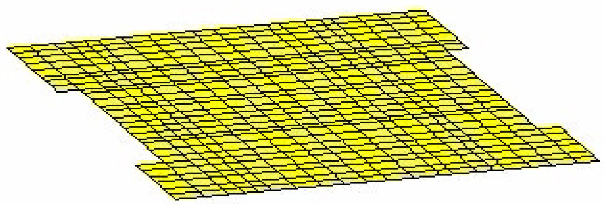
Ground Motion at Two Points Separate by 700 ft (two corners on the grid, for γ=0.15)

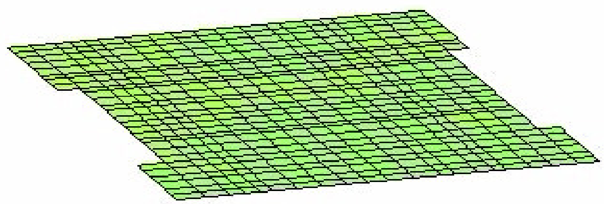





Incoherent ATF at Soil Surface - Only 37 Frequencies
00001TR_X.TFU
00007TR_X.TFU
00013TR_X.TFU
00040TR_X.TFU
00046TR_X.TFU
00052TR_X.TFU
00079TR_X.TFU
00085TR_X.TFU
00091TR_X.TFU
00118TR_X.TFU
00124TR_X.TFU
00130TR_X.TFU
00157TR_X.TFU
00163TR_X.TFU
00169TR_X.TFU
3
2
1
0
1
2
3
5
7
10
20
30
50
70

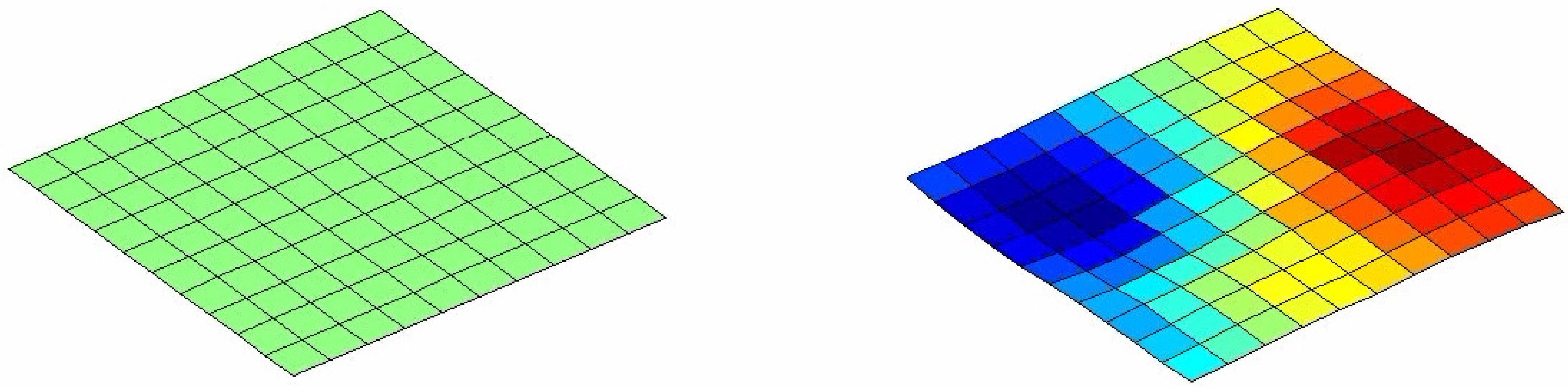
Seismic Free-Field Incoherent Motion Simulation (3-Directional Motion at Foundation-Soil Interface)





ANIMATIONS

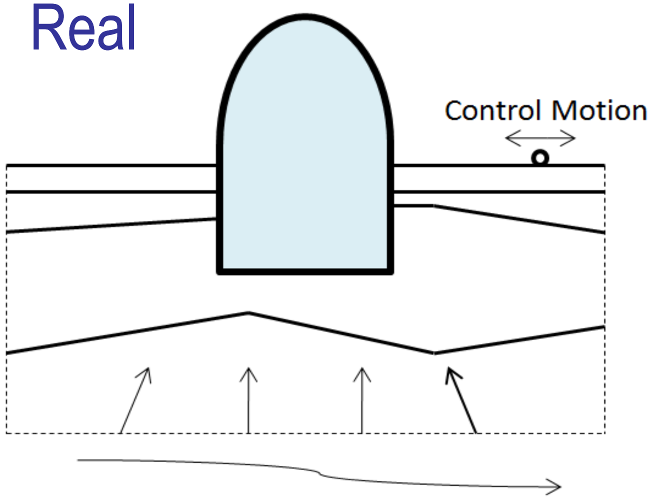
Seismic Free-Field Incoherent Motion Simulation (Vertical Shaking Direction)



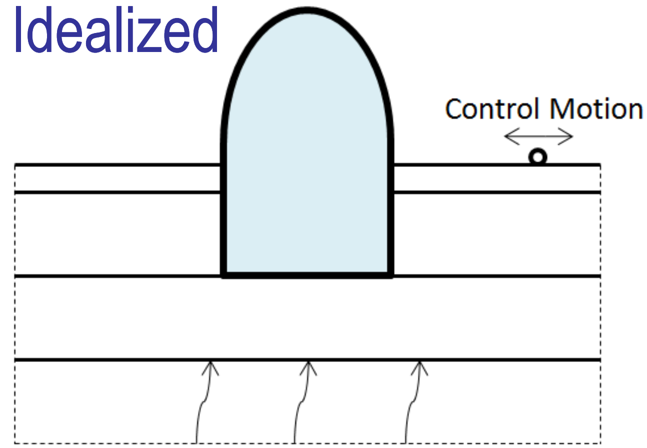
ANIMATIONS

SSI Analysis Methods

Real



Idealized

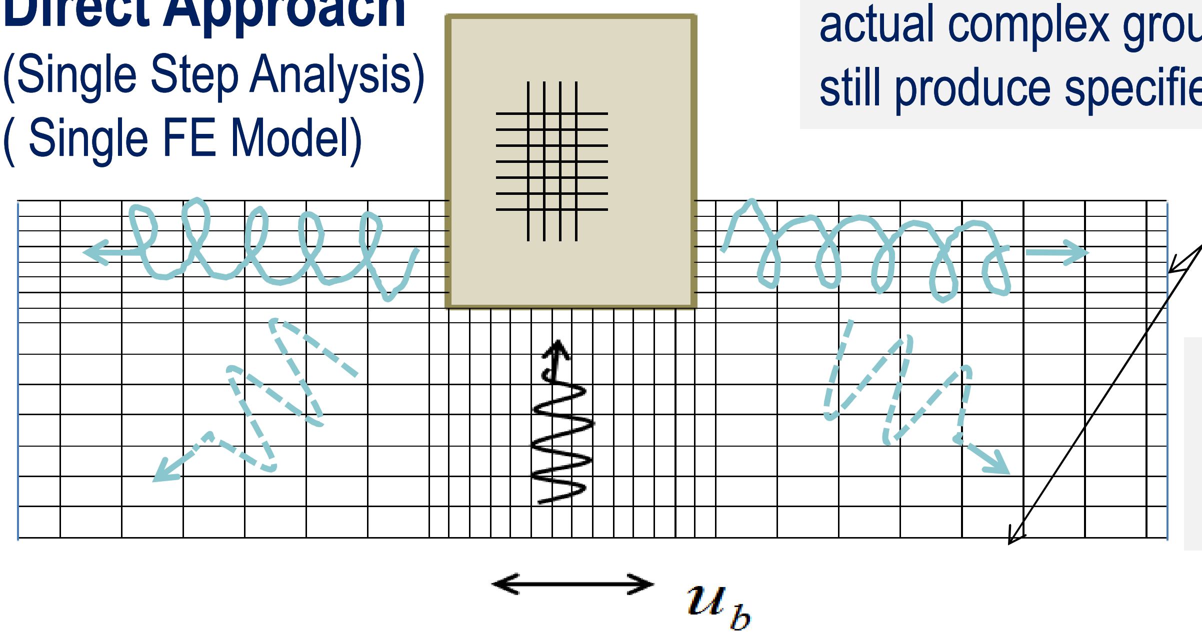


Vertical wave propagation is used to replace actual complex ground motion pattern, but still produce specified motion at control point.

Direct Approach

(Single Step Analysis)

(Single FE Model)



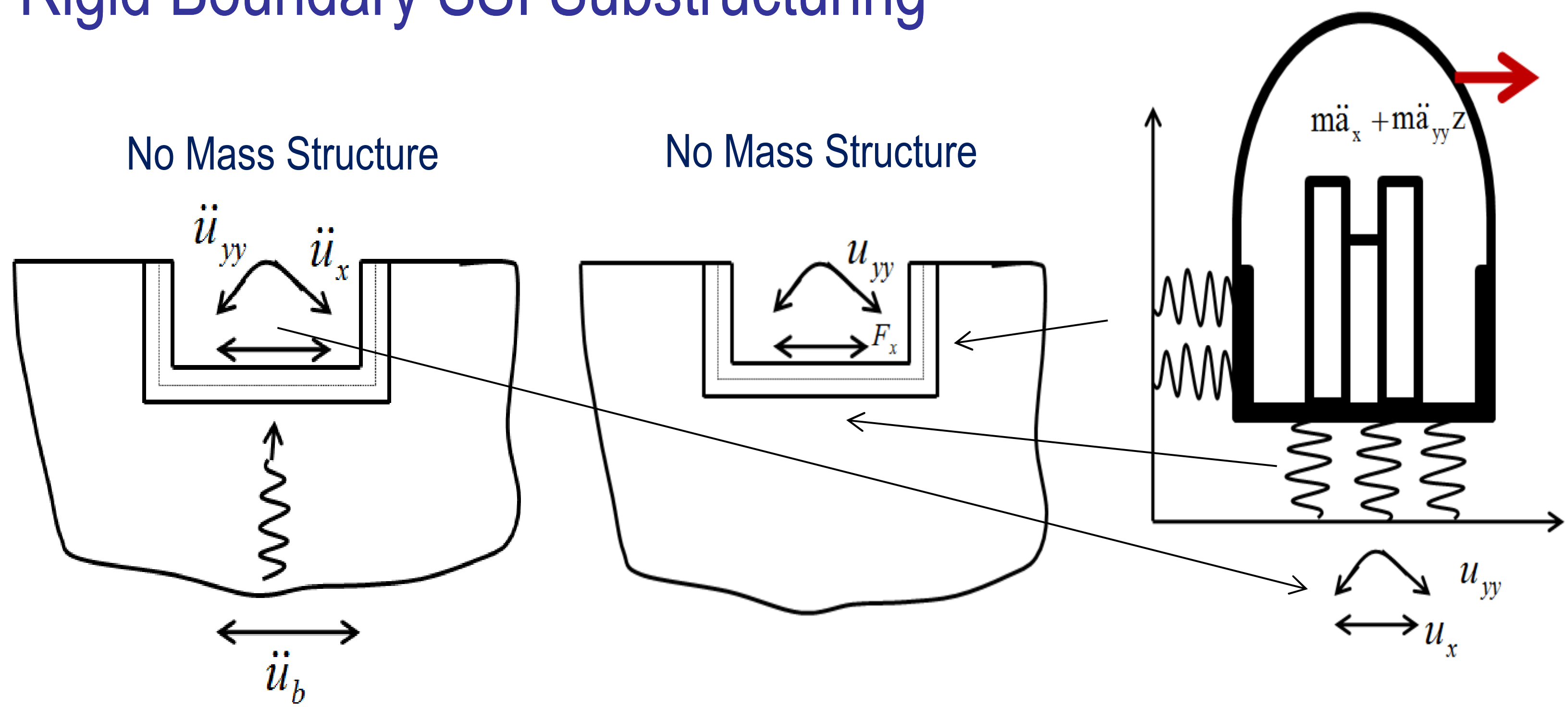
Conventional BCs

(stiffness, damping, soil motion)

Enormous amount of solid elements; 90% of FE elements are in soil media

Linearized SSI Analysis Using Complex Frequency Domain Substructuring

Rigid Boundary SSI Substructuring



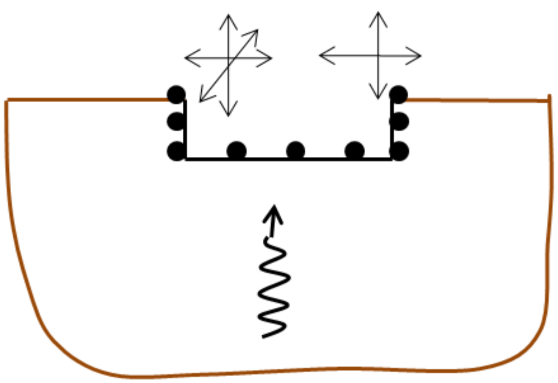
a) Wave Scattering Problem (Kinematic SSI, Wave Pb)

b) Impedance Problem (External Force Pb)

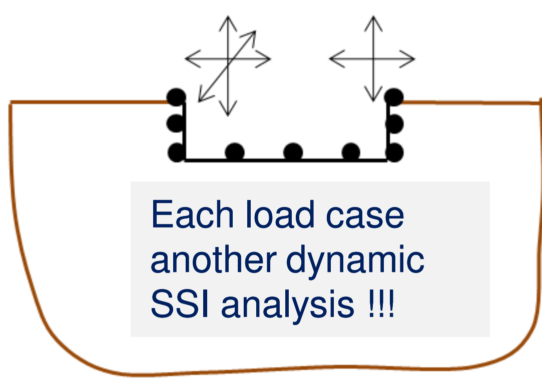
c) Structural Dynamic Analysis (Inertial SSI, External Force Pb)

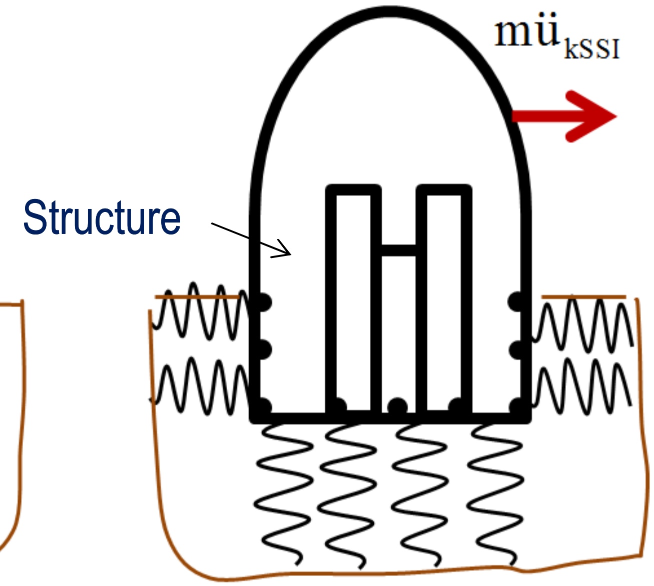
Flexible Boundary SSI Substructuring

No Mass Structure



No Mass Structure

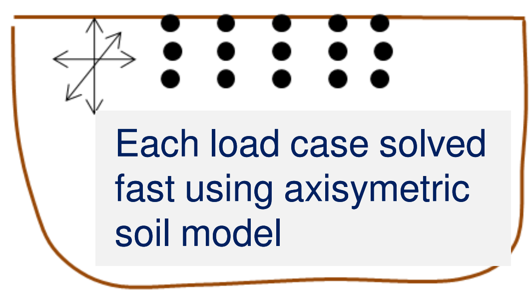


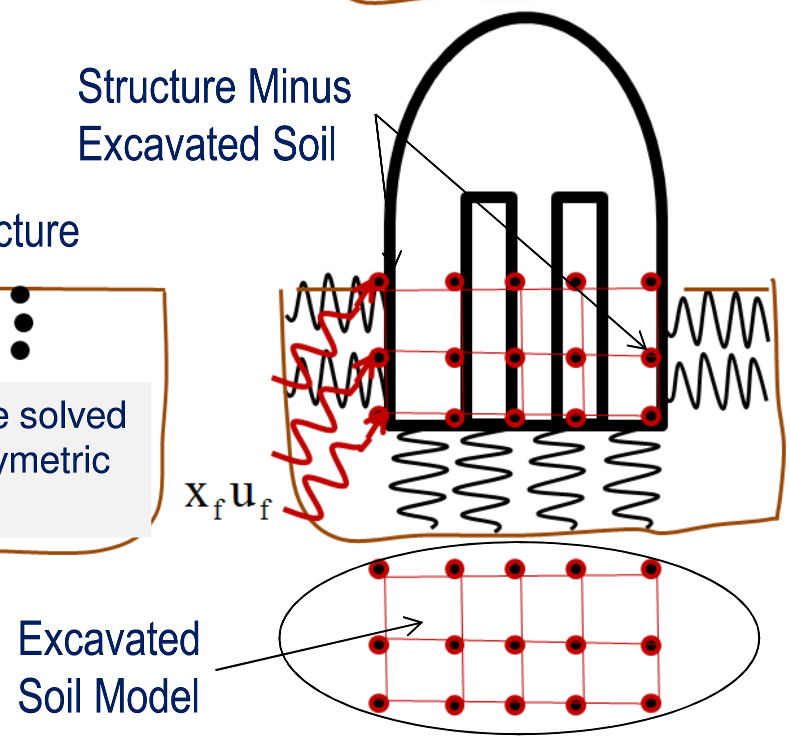


Flexible Volume SSI Substructuring

- No wave scattering analysis.
- Impedance Problem is trivial; reduced to a free-field problem.
- Structural dynamic problem slightly more complex since includes a coupled excavated soil
- Multiple SSSI effects could be analyzed without including FE soil elements! Otherwise impossible…

No Mass Structure

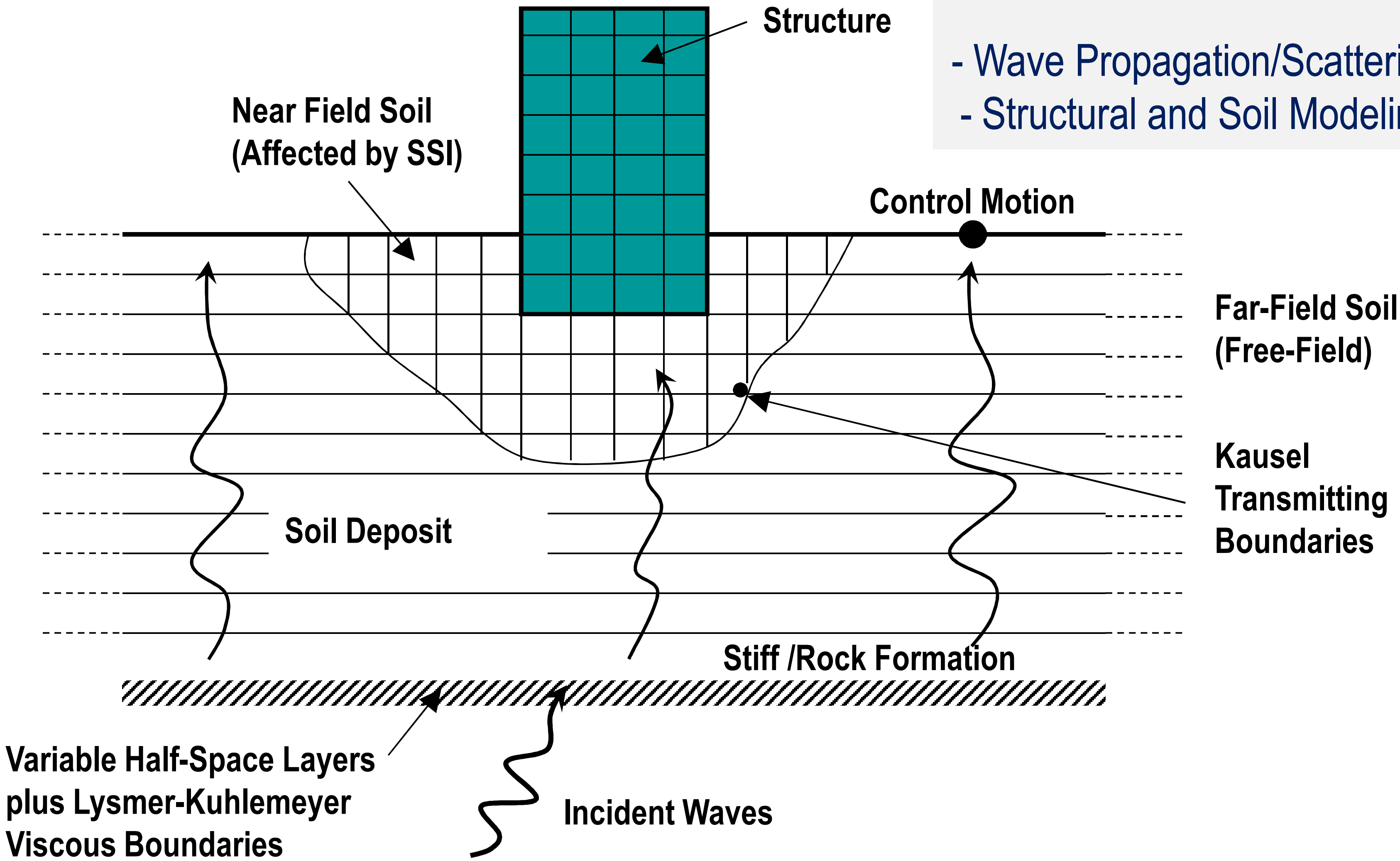




Seismic SSI Analysis Problem

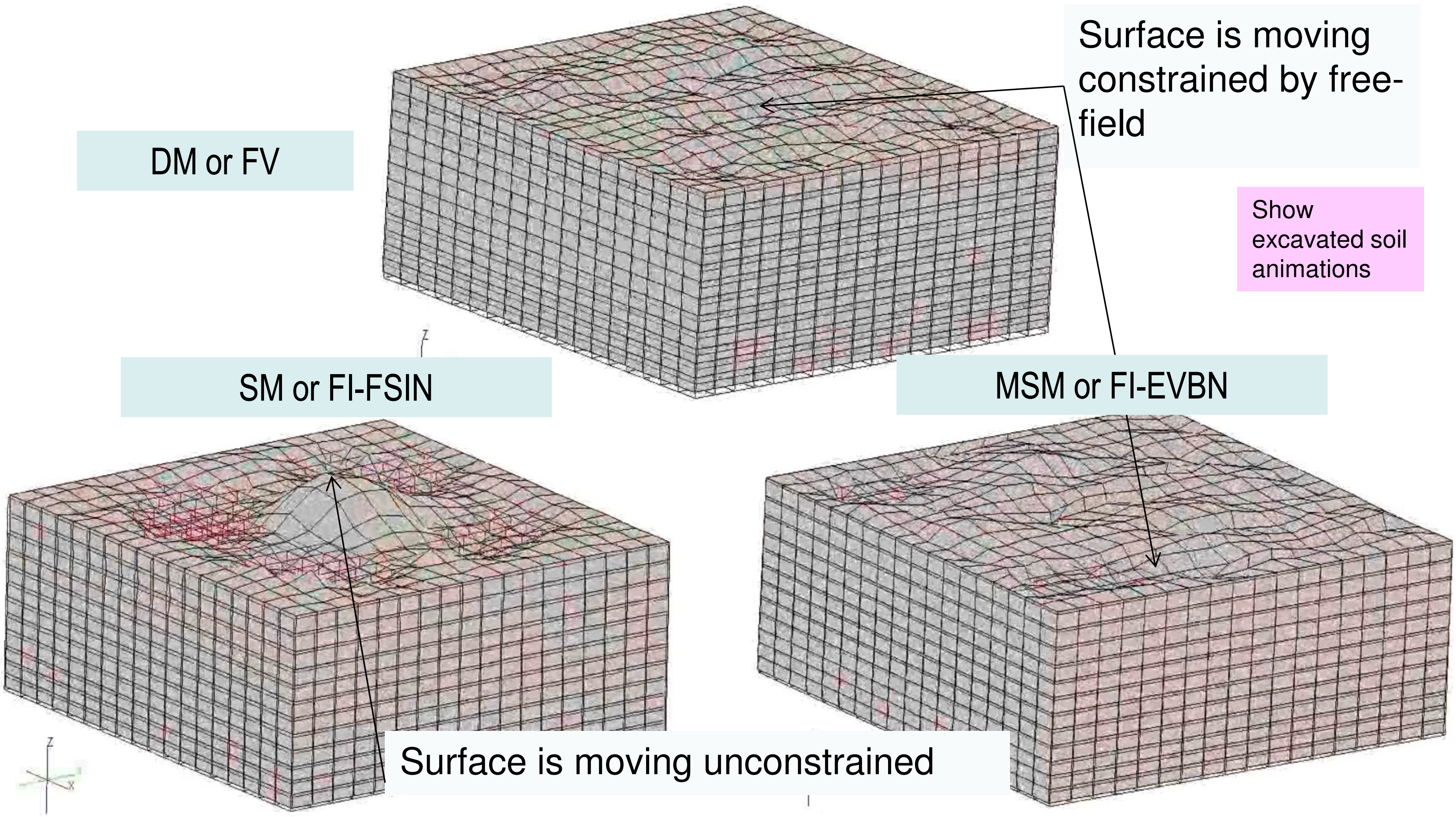
Seismic SSI Analysis Aspects:

- Wave Propagation/Scattering
- Structural and Soil Modeling

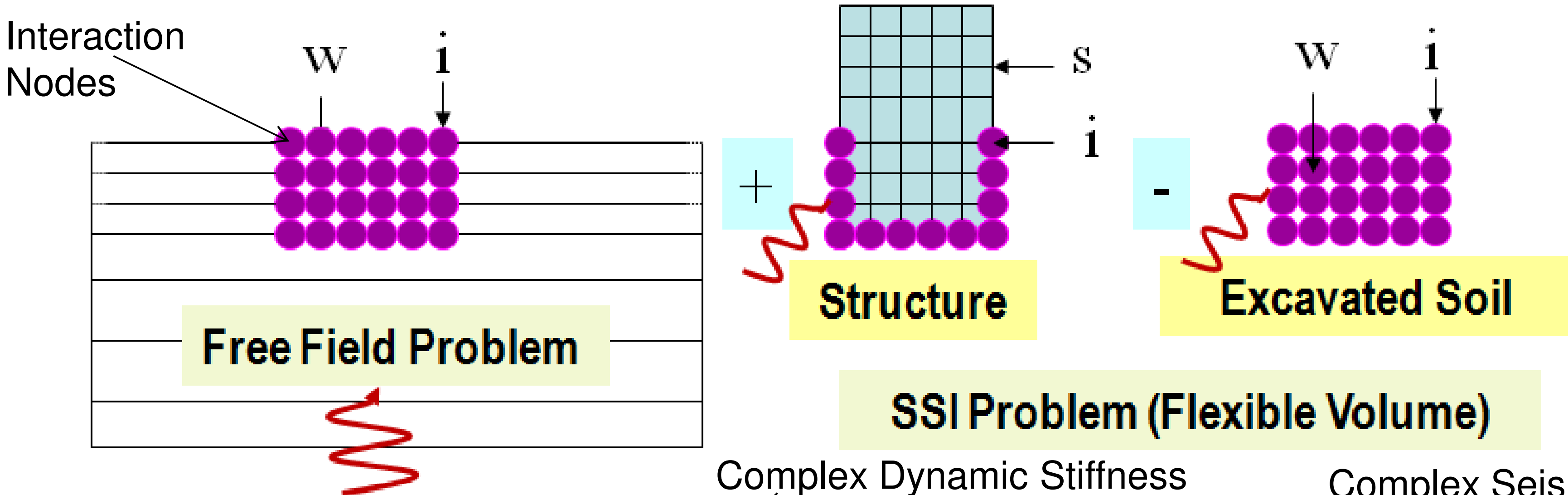


Excavated Soil Vibration

Effects of Ground Surface Constraints on Scattered Surface Waves



Flexible Volume Methods in ACS SASSI (FV or DM)



Complex Frequency Domain Formulation:

Complex Dynamic Stiffness

Complex Seismic Load Vector

$$\mathbf{C}(\omega)\mathbf{U}(\omega) = \mathbf{Q}(\omega)$$

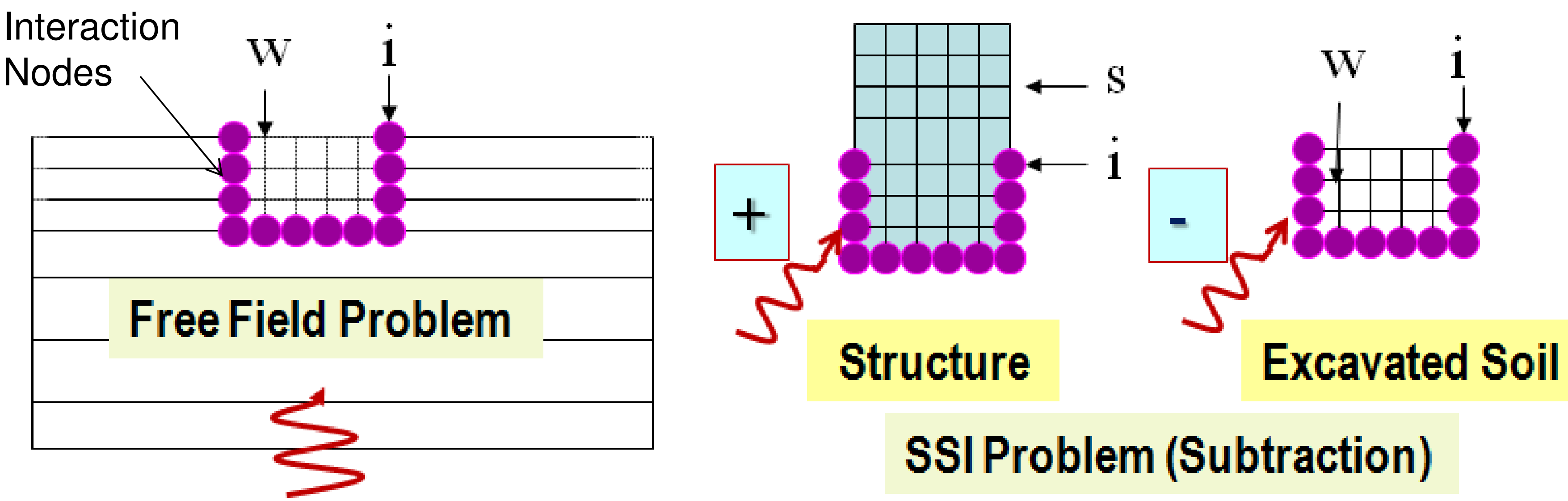
Complex Absolute Displacements

Complex Soil Impedance Terms

$$\begin{bmatrix} \mathbf{C}^{s}_{ii} - \mathbf{C}^{e}_{ii} + \mathbf{X}_{ii} & -\mathbf{C}^{e}_{iw} + \mathbf{X}_{iw} & \mathbf{C}^{s}_{is} \\ -\mathbf{C}^{e}_{wi} + \mathbf{X}_{wi} & -\mathbf{C}^{e}_{ww} + \mathbf{X}_{ww} & \mathbf{0} \\ \mathbf{C}^{s}_{si} & \mathbf{0} & \mathbf{C}^{s}_{ss} \end{bmatrix} \begin{Bmatrix} \mathbf{U}_{i} \\ \mathbf{U}_{w} \\ \mathbf{U}_{s} \end{Bmatrix} = \begin{Bmatrix} \mathbf{X}_{ii}\mathbf{U}'_{i} + \mathbf{X}_{iw}\mathbf{U}'_{w} \\ \mathbf{X}_{wi}\mathbf{U}'_{i} + \mathbf{X}_{ww}\mathbf{U}'_{w} \\ \mathbf{0} \end{Bmatrix}$$

REMARK: All Excavated Soil nodes are interaction nodes (include exact equations of motion)

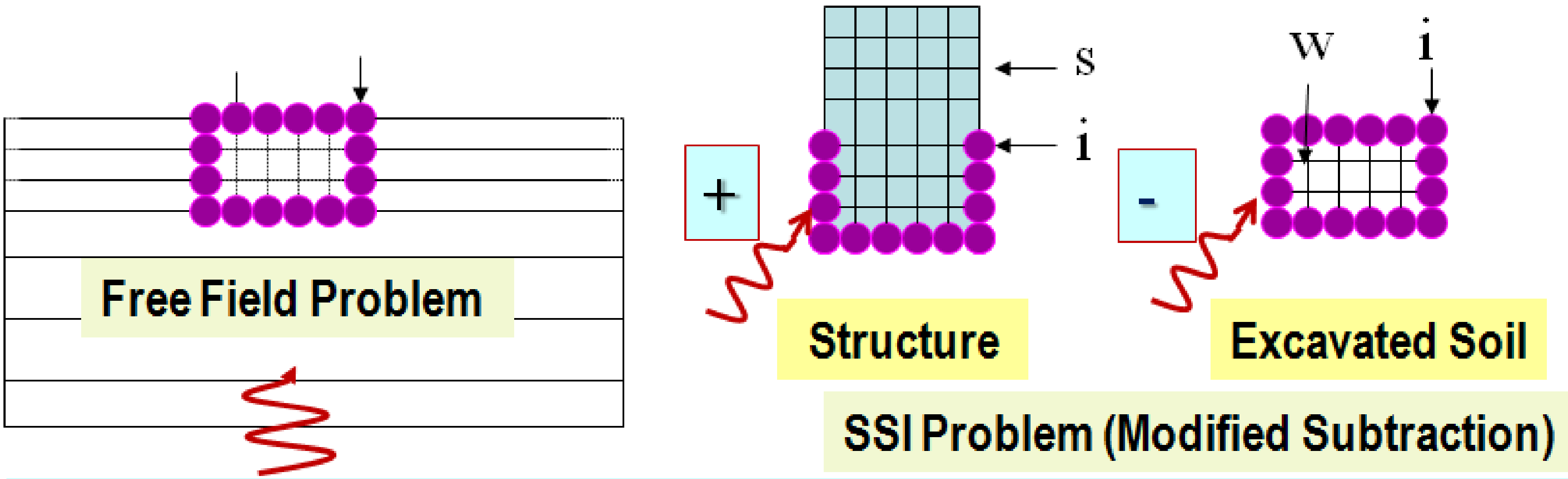
Flexible Volume Methods in ACS SASSI (FI-FSIN or SM)



$$\begin{bmatrix} C^{s}_{ii} - C^{e}_{ii} + X_{ii} & -C^{e}_{iw} \cancel{+ X_{iw}} & C^{s}_{is} \\ -C^{e}_{wi} \cancel{+ X_{wi}} & -C^{e}_{ww} \cancel{+ X_{ww}} & 0 \\ C^{s}_{si} & 0 & C^{s}_{ss} \end{bmatrix} \begin{Bmatrix} U_{i} \\ U_{w} \\ U_{s} \end{Bmatrix} = \begin{Bmatrix} X_{ii} U'_{i} + X_{iw} U'_{w} \\ X_{wi} U'_{i} + X_{ww} U'_{w} \\ 0 \end{Bmatrix}$$

REMARK: Only foundation soil interface nodes are interaction nodes. Equations at the non-interaction nodes, at ground surface and internal nodes are not exact. Simplification is acceptable only at low frequency.

Flexible Volume Methods in ACS SASSI (FI-EVBN or MSM)

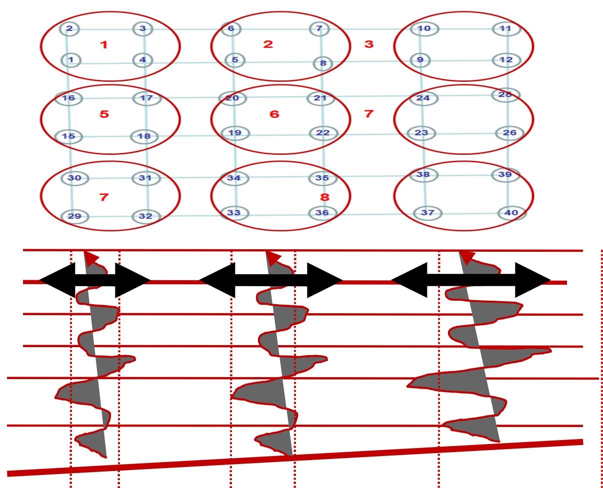


$$\begin{bmatrix} C^s_{ii} - C^e_{ii} + X_{ii} & -C^e_{iw} + X_{iw} & C^s_{is} \\ -C^e_{wi} + X_{wi} & -C^e_{ww} + X_{ww} & 0 \\ C^s_{si} & 0 & C^s_{ss} \end{bmatrix} \begin{Bmatrix} U_i \\ U_w \\ U_s \end{Bmatrix} = \begin{Bmatrix} X_{ii} U'_i + X_{iw} U'_w \\ X_{wi} U'_i + X_{ww} U'_w \\ 0 \end{Bmatrix}$$

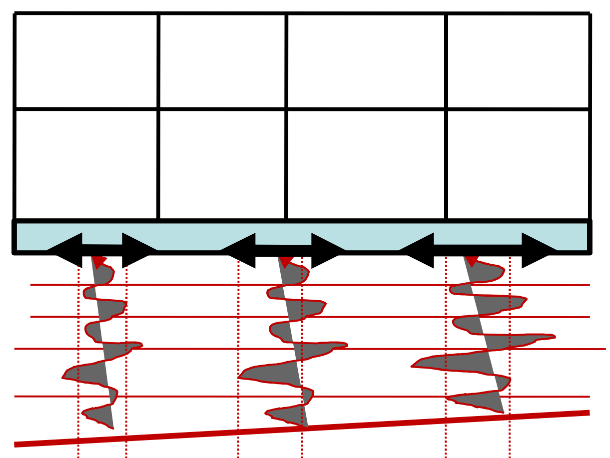
REMARK: All the Excavation Soil outer surface nodes are interaction nodes. Equations at the non-interaction nodes (internal nodes) are approximate. The approximation is acceptable in the frequency range of interest, as shown by all DOE studies performed.

Nonuniform Seismic Input Motion in Horizontal Plane

Multiple Soil Column Response Analyses



Non-Uniform Excitation and Soil Stiffness

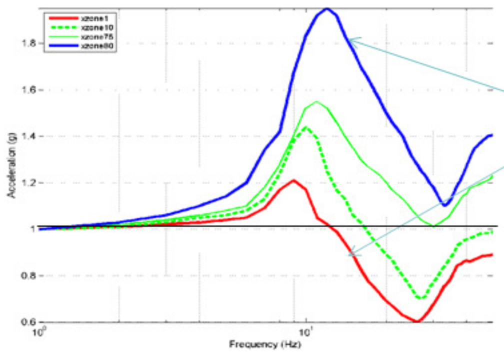


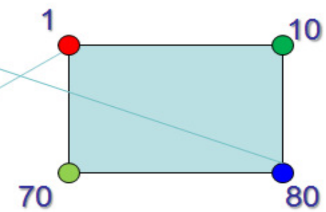
ACS SASSI Version 2.3.0 has the capability to consider deterministic spatial variation patterns for differential input motions in the horizontal plane. Currently, we are testing a new capability that includes nonuniform soil layering and nonuniform motion amplitude in horizontal plane.

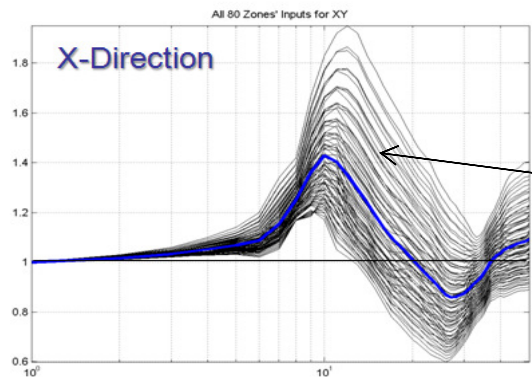
These deterministic spatial variation effects can be combined with the effects of motion incoherency and wave passage to create more realistic seismic inputs for SSI analysis of NPP structures, especially for those that have large foundation sizes.

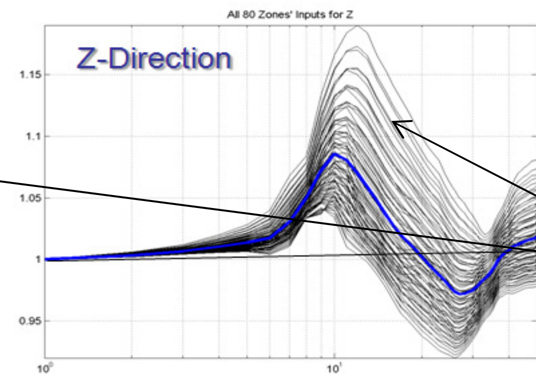
Nonuniform Seismic Input Motion in Horizontal Plane

Multiple borehole soil column models

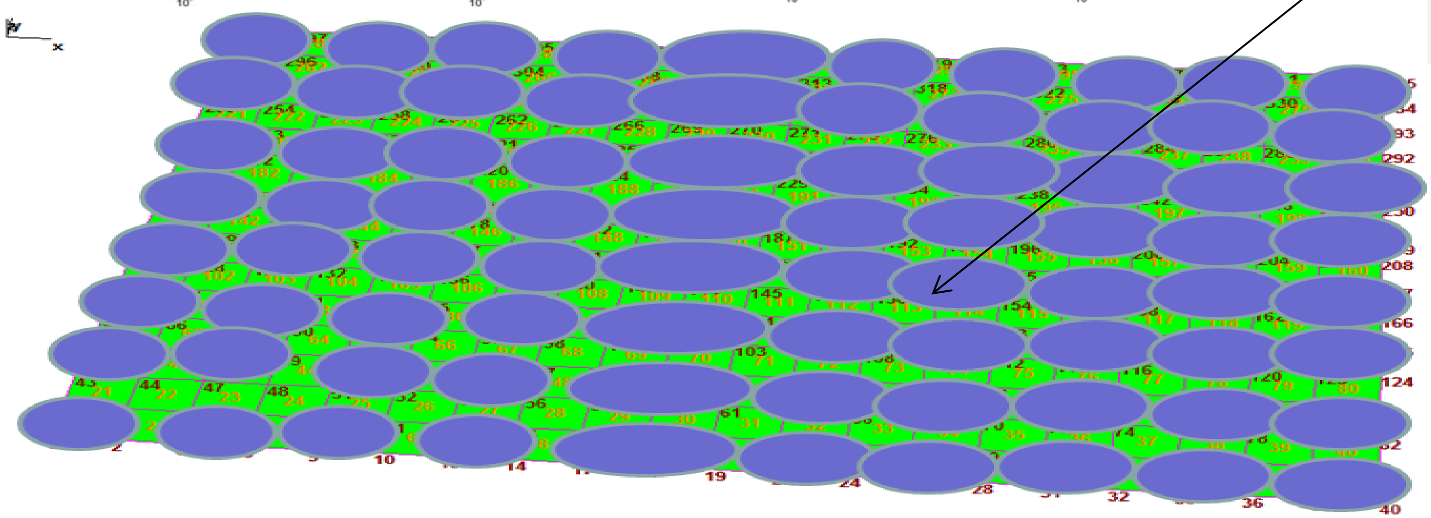








Each zone has different inputs that can be different for X, Y and Z directions

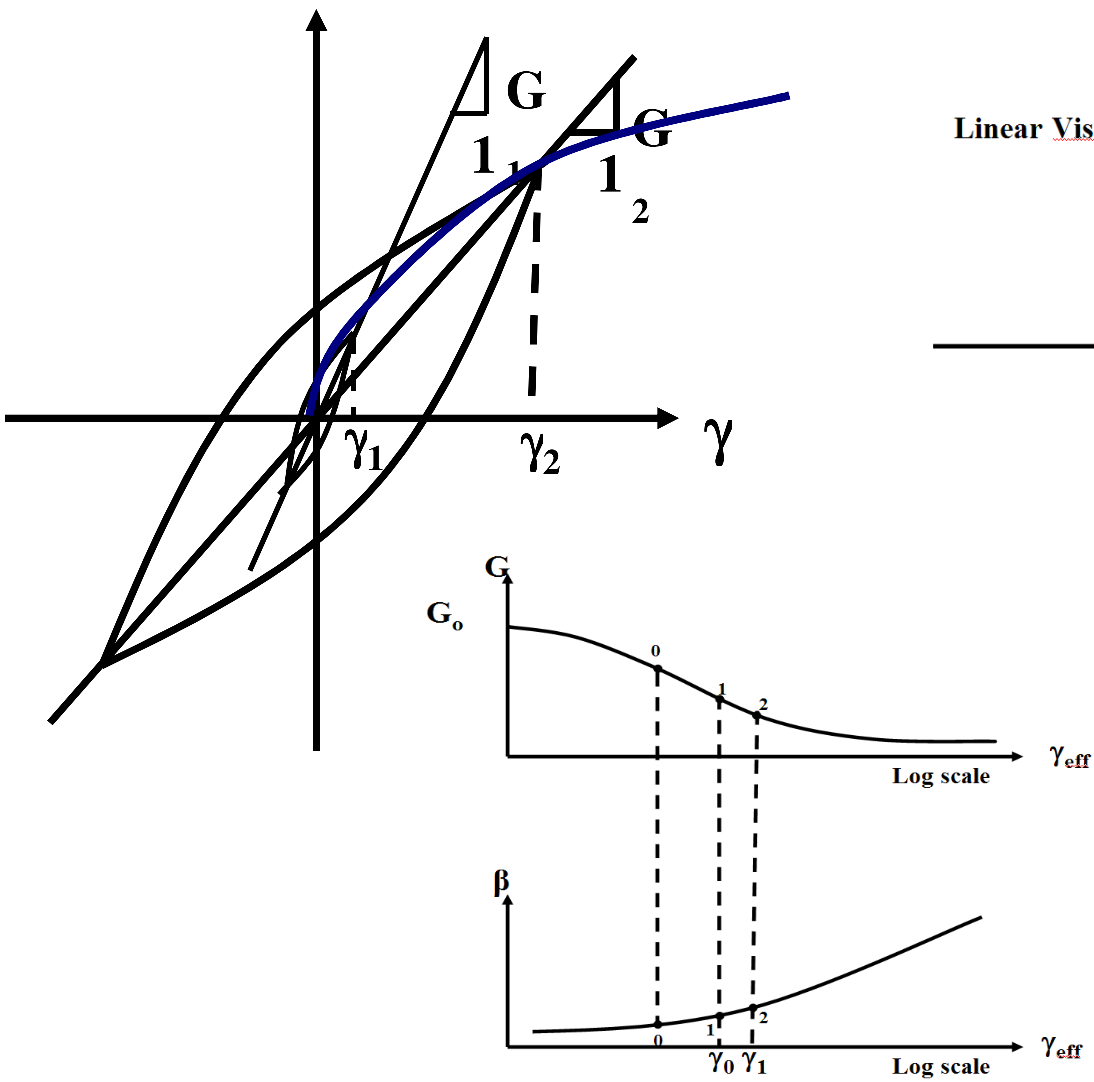


Equivalent-Linear Model for Soil Hysteretic Behavior

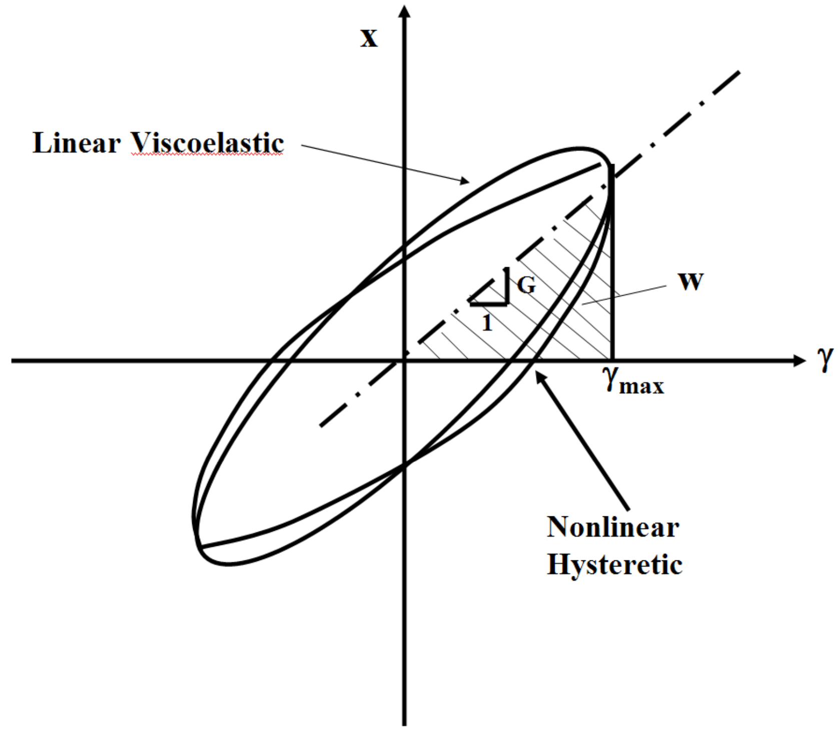
1. The nonlinear properties of the soil are approximated by equivalent linear properties consisting of the shear modulus and damping ratio for the soil which are compatible with the effective shear-strain amplitudes in soil
2. The effects of nonlinear soil behavior include two components:
   (i) The primary nonlinearity due to seismic wave propagation in free-field
   (ii) The secondary nonlinearity due to soil-structure interaction effects.
3. A SSI linear analysis which is performed with estimated soil properties provides approximate values of the effective strain amplitude developed in each soil layer. These are used as an initial estimate for soil properties within an iterative process. The iterative process is continued until compatibility is obtained between soil properties and strain amplitudes. The SSI results of the last iteration reanalysis is assumed to represent the nonlinear response. Could be significant for seismic soil pressure distribution.

Seed-Idriss Equivalent Linear Iterative Method

Shear Modulus Variation



Viscous Damping Variation

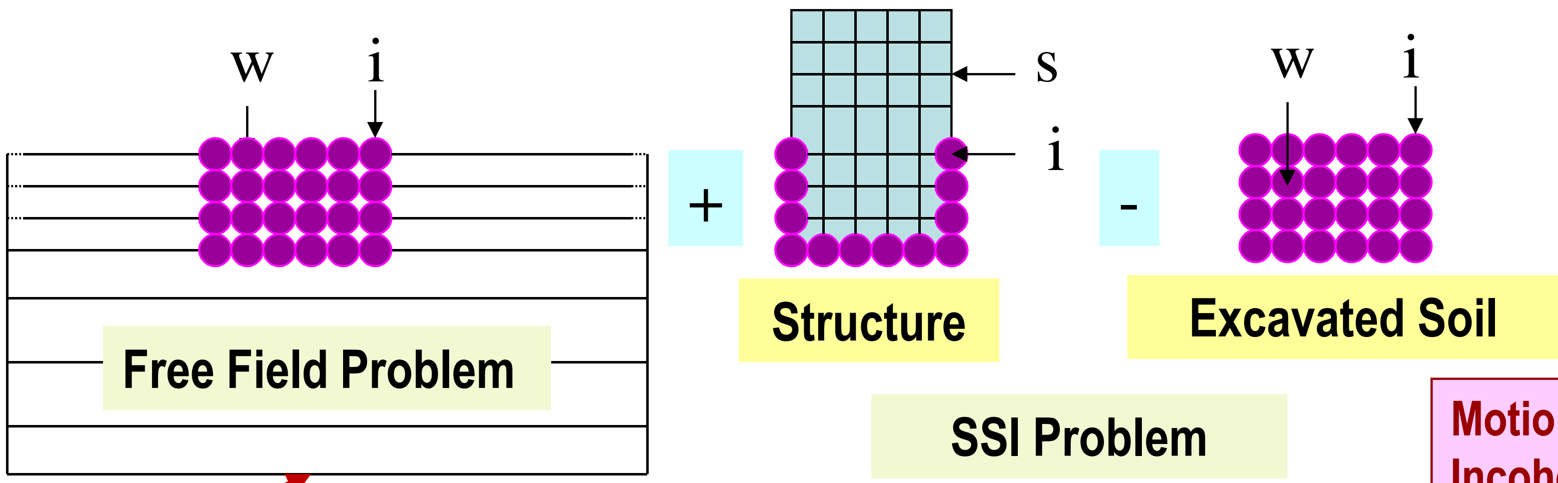


Δw = Area of hysteretic loop

β = critical damping ratio

$$\beta = \frac{1}{4\pi} = \frac{\Delta w}{w}$$

Incoherent SSI Analysis in ACS SASSI



Motion Incoherency affects free-field motion at interaction nodes

Flexible Volume Method (using all excavated volume nodes)

$$\begin{bmatrix} C^s_{ii} - C^e_{ii} + X_{ii} & -C^e_{iw} - X_{iw} & C^s_{is} \\ -C^e_{wi} + X_{wi} & -C^e_{ww} + X_{ww} & 0 \\ C^s_{si} & 0 & C^s_{ss} \end{bmatrix} \begin{Bmatrix} U_i \\ U_w \\ U_s \end{Bmatrix} = \begin{Bmatrix} X_{ii}U'_i + X_{iw}U'_w \\ X_{wi}U'_i + X_{ww}U'_w \\ 0 \end{Bmatrix}$$

Flexible Interface Methods (using excavation volume outer surface nodes)

$$\begin{bmatrix} C^e_{ii} - C^e_{ii} + X_{ii} & -C^e_{iw} & C^s_{is} \\ -C^e_{wi} & -C^e_{ww} & 0 \\ C^s_{si} & 0 & C^s_{ss} \end{bmatrix} \begin{Bmatrix} U_i \\ U_w \\ U_s \end{Bmatrix} = \begin{Bmatrix} X_{ii}U'_i \\ 0 \\ 0 \end{Bmatrix}$$

$$C(\omega)U(\omega) = Q(\omega)$$

where $C(\omega) = K - \omega^2 M$

Seismic SSI Analysis Using ACS SASSI

The complex frequency response is computed as follows:

- Coherent SSI response:

$$U_s(\omega) = H_s(\omega) * H_g^c(\omega) * U_{g,0}(\omega)$$

Structural transfer function given input at interaction nodes

Coherent ground transfer function at interface nodes given control motion

Complex Fourier transform of control motion

•Incoherent SSI response:

$$U_s(\omega) = H_s(\omega) * S_g^i(\omega) * H_g^c(\omega) * U_{g,0}(\omega)$$

Incoherent ground transfer function given coherent ground motion and coherency model (random spatial variation in horizontal plane)

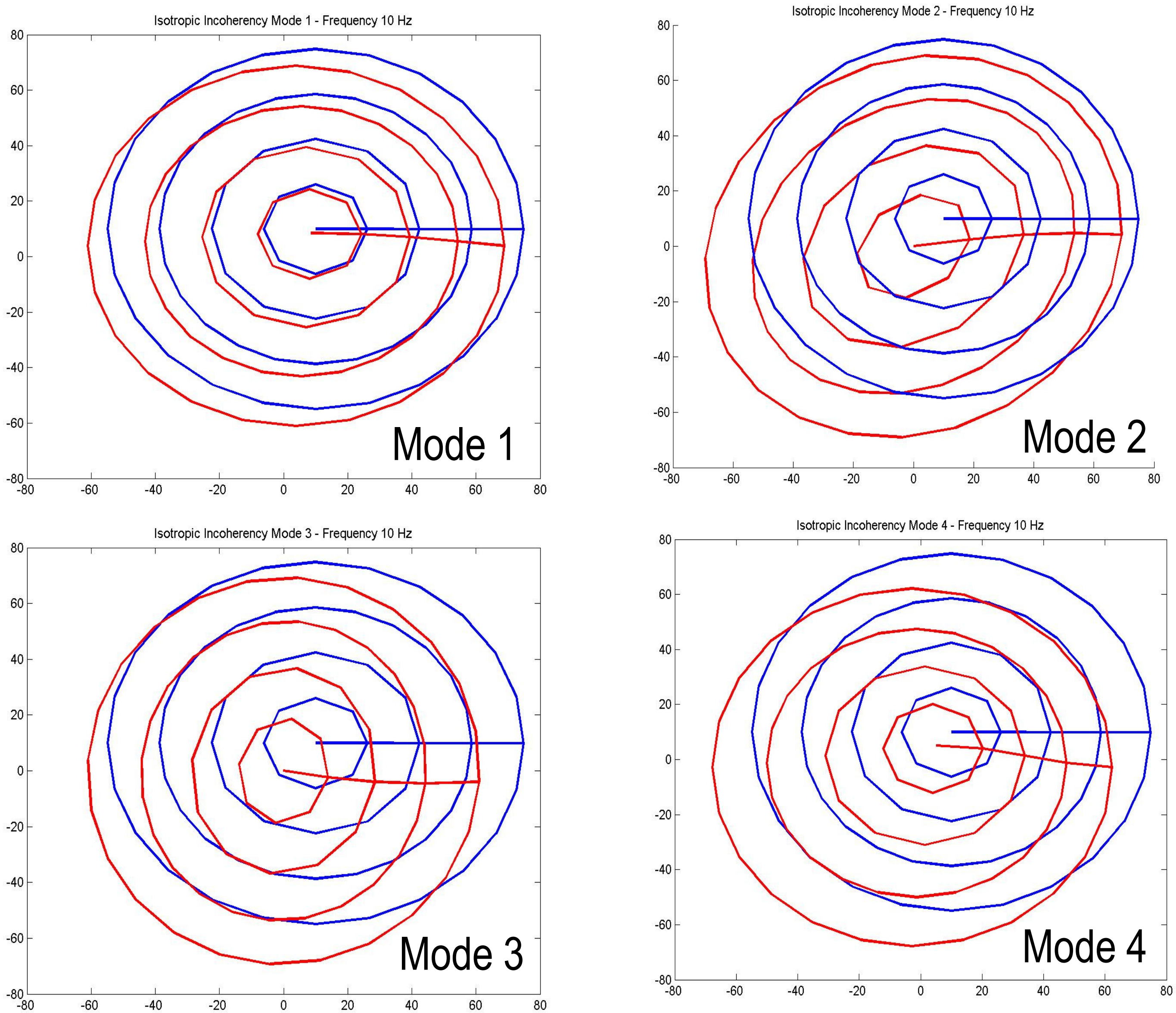
$$S_g(\omega) = [\Phi(\omega)][\lambda(\omega)]\{\eta_\theta\}$$

Complex Fourier transform of relative spatial variations of motion at interaction nodes that is stochastic by nature

Spectral factorization of coherency kernel

Random phases (stochastic part)

Motion Incoherency Modes of Basemat at 10 Hz

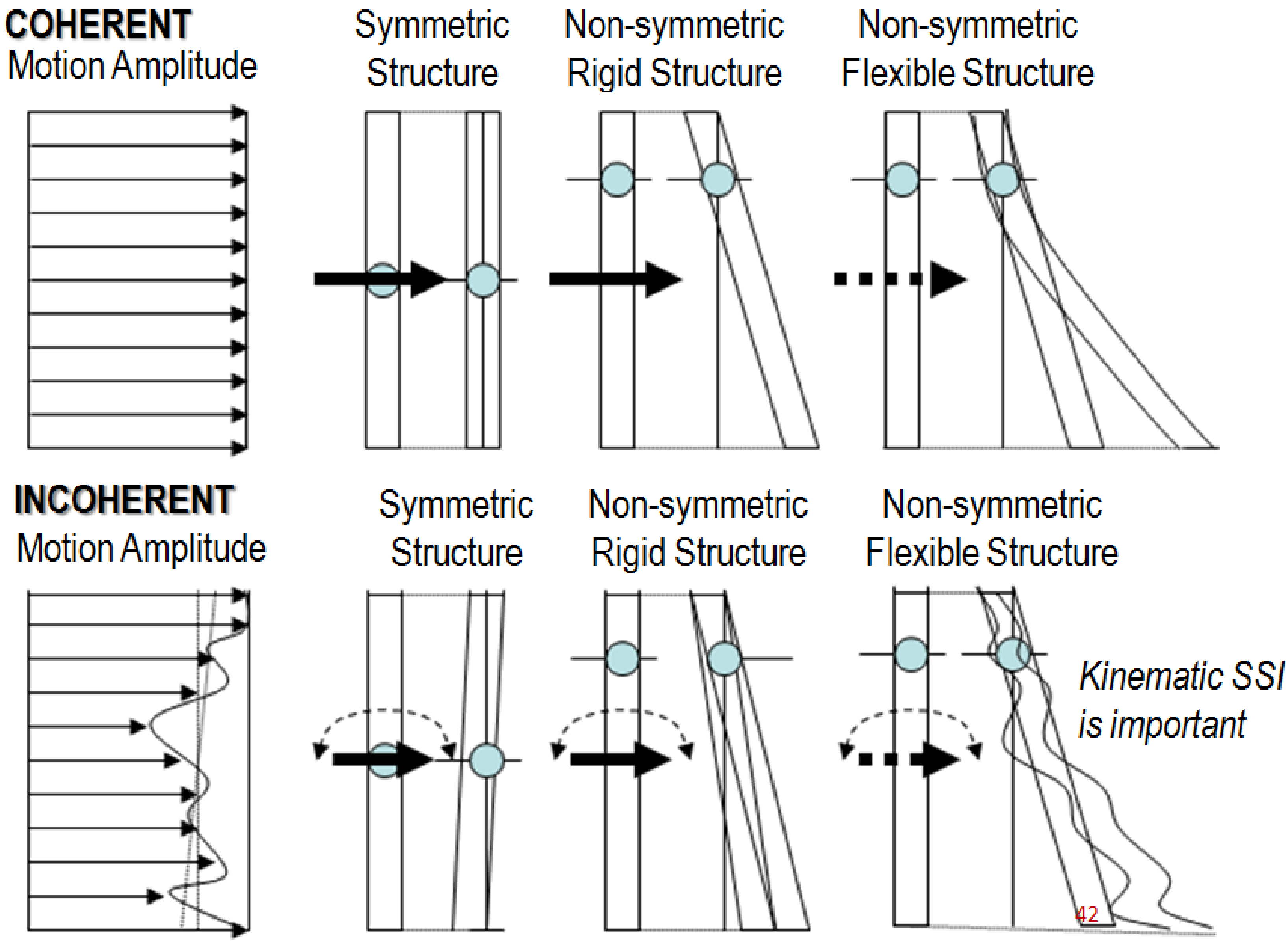


REMARKS:

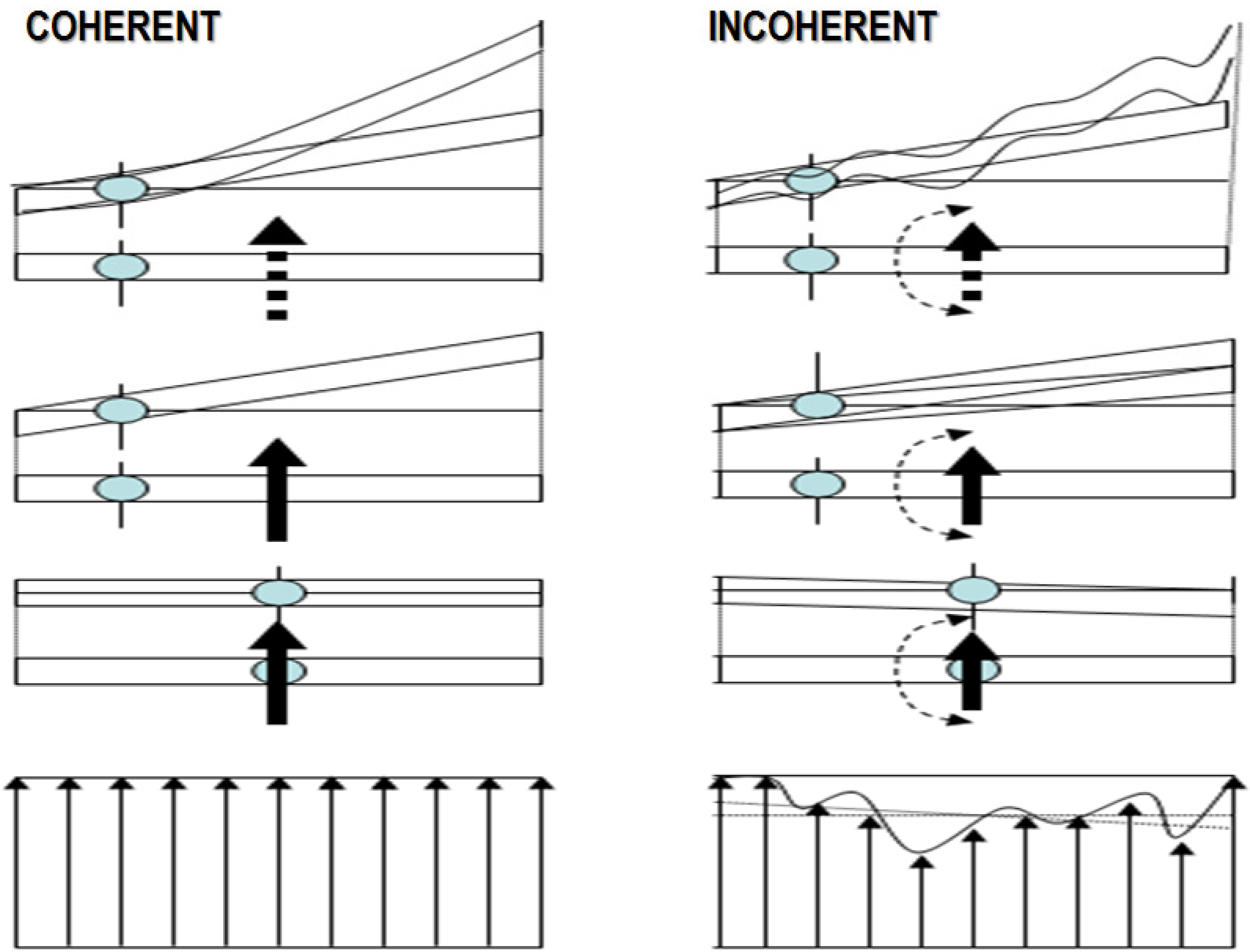
1) For low frequencies only a number of few incoherency modes are sufficient.

2) Motion incoherency modes are stochastically combined. We try to use simple mode superposition rules – single SSI run.

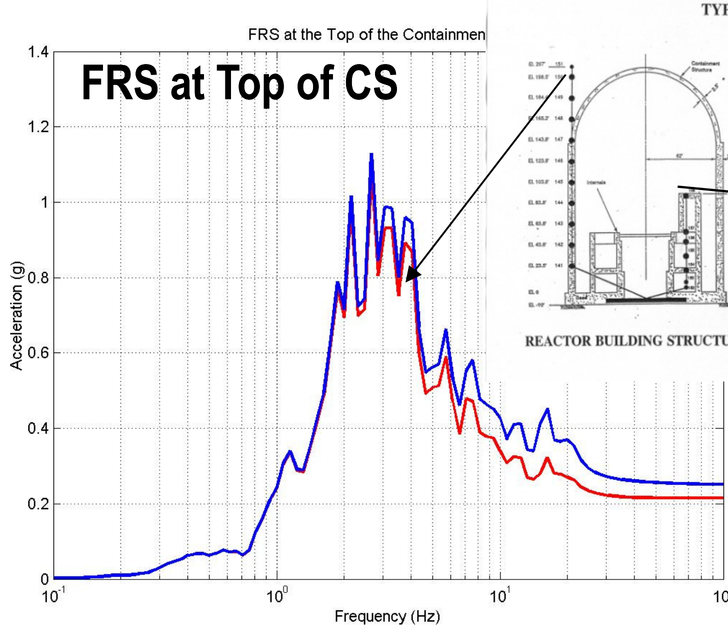
Coherent vs. Incoherent SSI Response - Horizontal

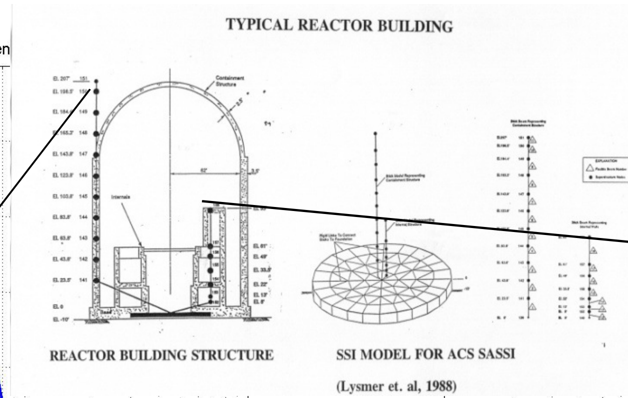


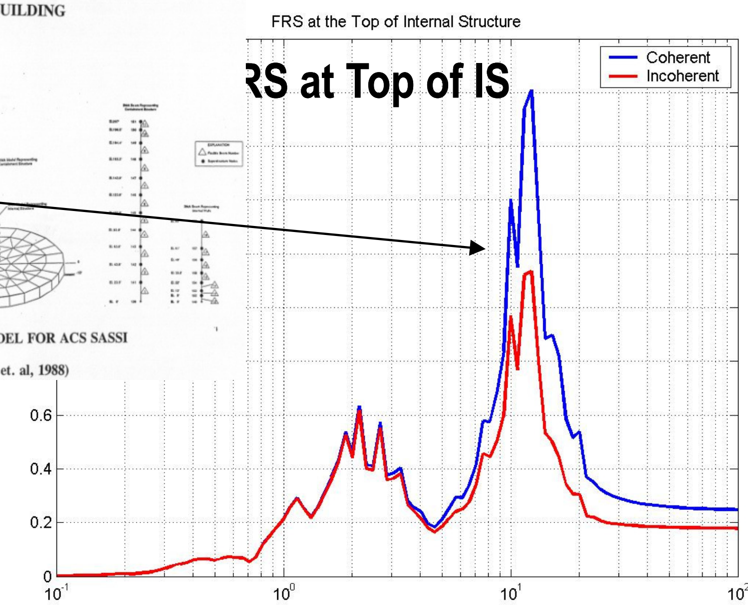
Coherent vs. Incoherent SSI Response – Vertical

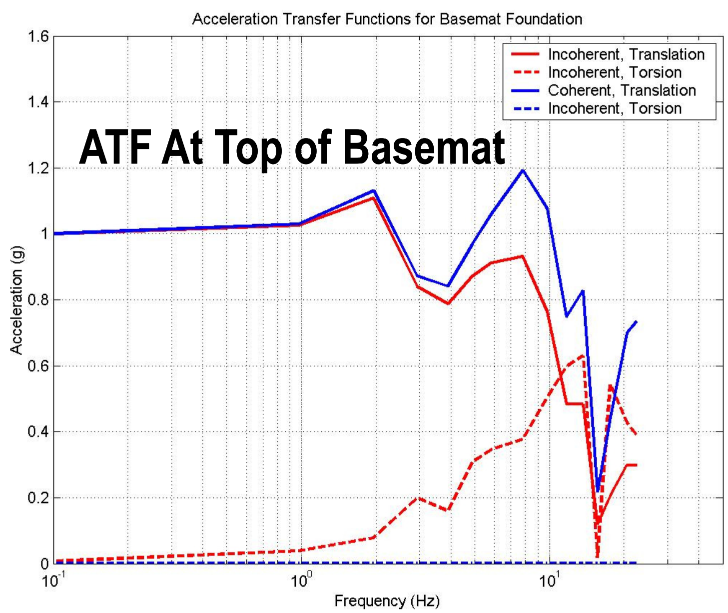


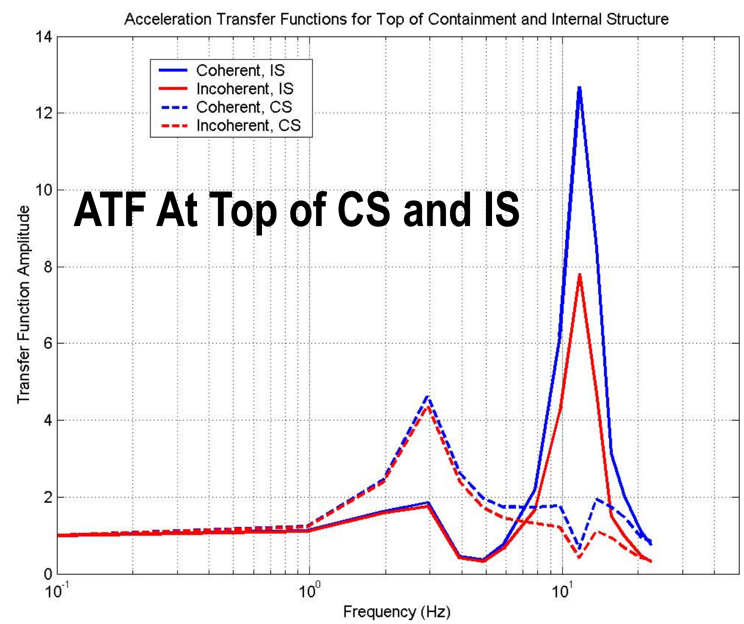
An Axisymmetric RB Structure Founded on A Soil Site



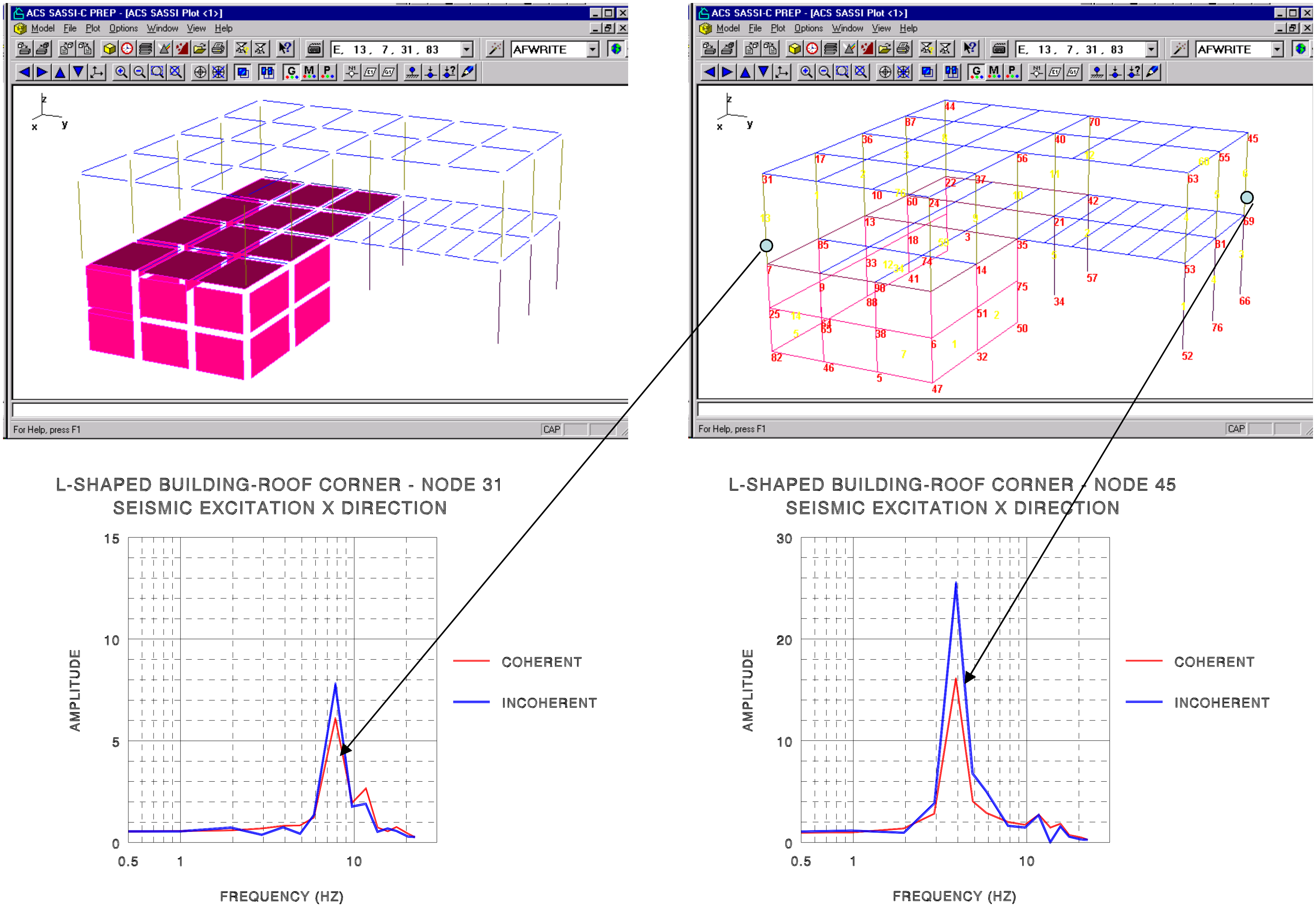








L-Shaped Composite Auxiliary Building



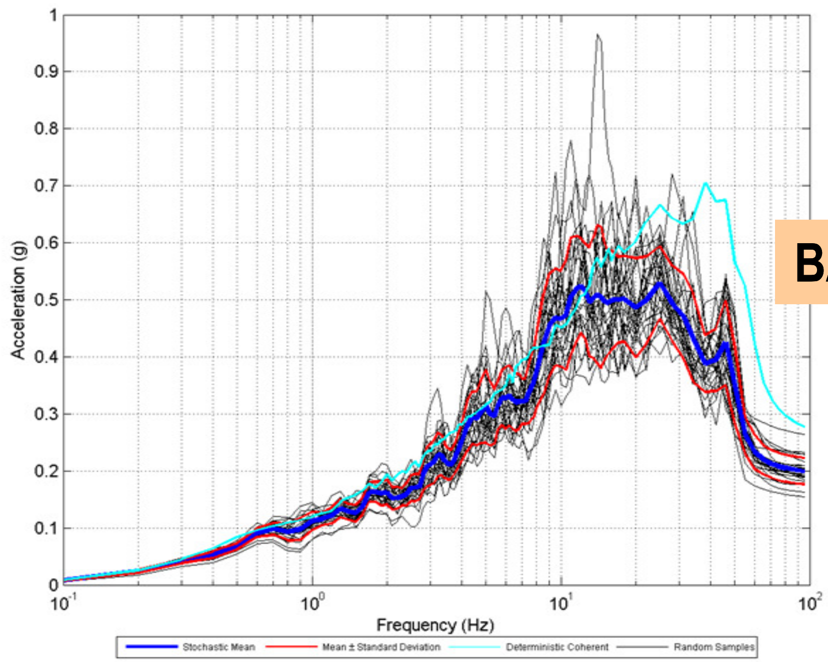
Seismic Incoherent SSI Approaches

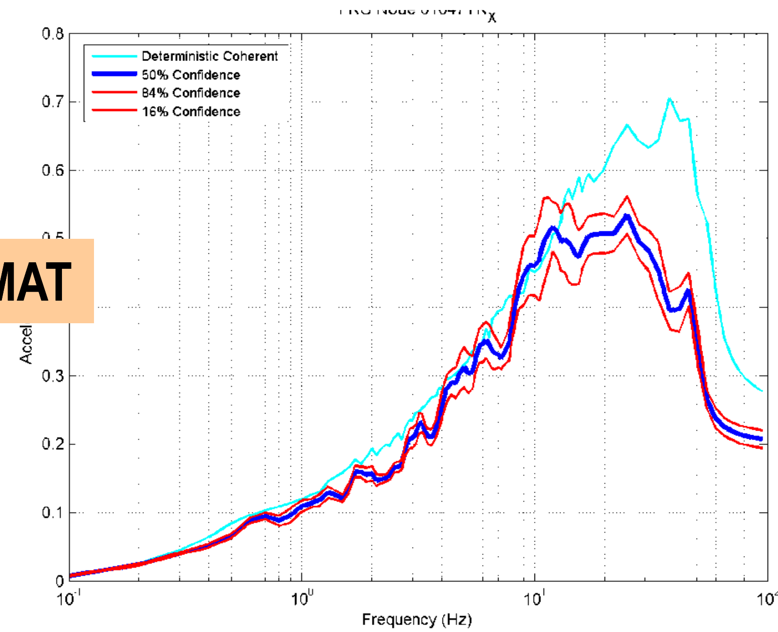
Stochastic simulation approach similar to Monte Carlo simulation used for probabilistic analyses. It is based on performing statistical SSI analyses for a set of random field realizations of the incoherent free-field motion. Respects in detail the SSI physics. Compute mean incoherent SSI responses and their scatter*. Recommended for both simple and complex SSI models with rigid or flexible foundations.*

Deterministic approximate approaches based on *simple rules* for combining the incoherency modes (AS approaches) or modal SSI responses (SRSS approaches). Approximates the mean incoherent SSI responses. *Recommended for simple stick models with rigid basemats.*

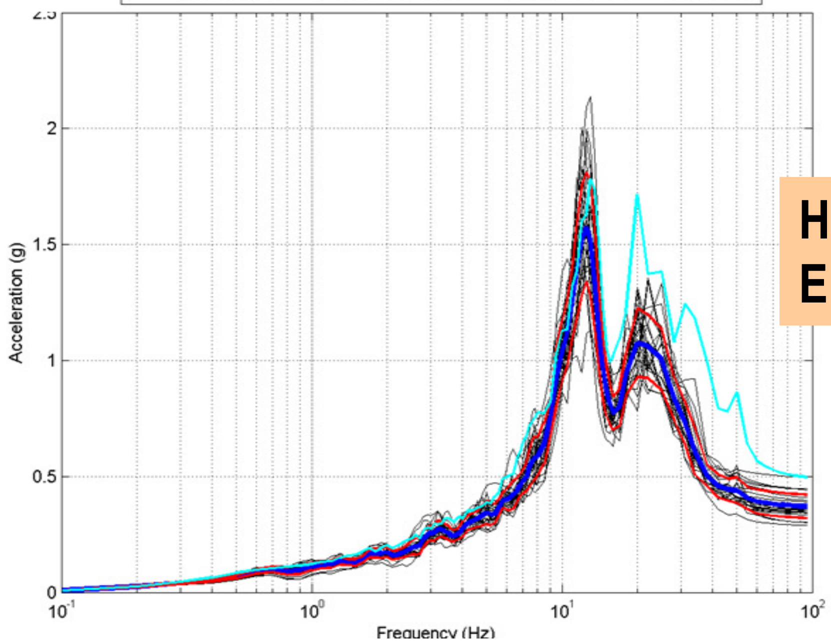
Stochastic Simulation validated by EPRI (TR# 1015111, Nov 2007) and endorsed by US NRC (ISG-01, May 2008). Reference approach for validating deterministic approaches

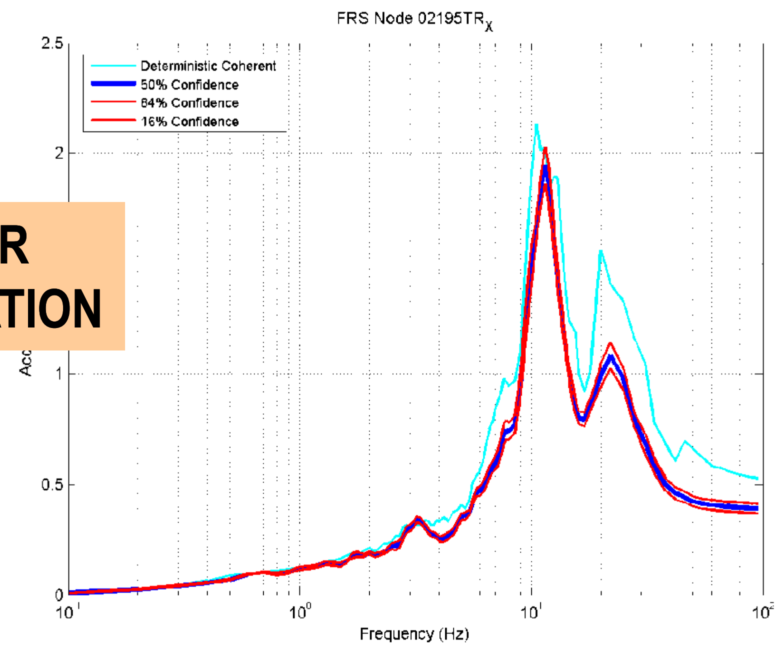
Stochastic Incoherent SSI Approach





BASEMAT





HIGHER ELEVATION

Deterministic Incoherent SSI Approaches

ACS SASSI uses simplified superposition rules for combining incoherency modes or their random SSI modal effects:

i) Linear superposition of motion incoherency modes scaled with their standard deviation to simulate the free-field motion (AS in EPRI studies) – *single* SSI analysis

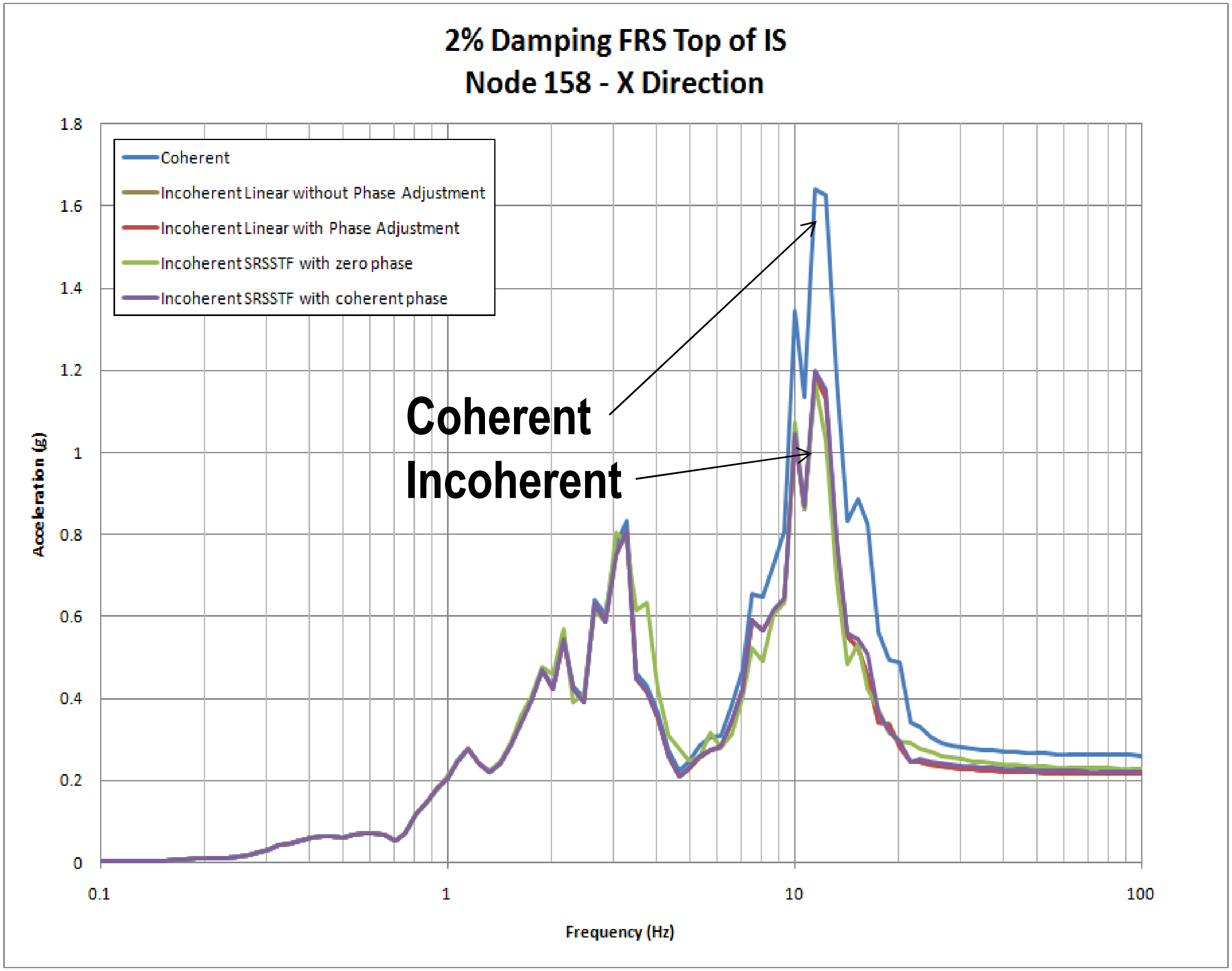
ii) Quadratic superposition of incoherency modal amplitude responses, applicable for the computed ATF or RS modal responses (SRSS in EPRI studies) – *multiple* SSI analysis

Five deterministic incoherent SSI approaches could be used:

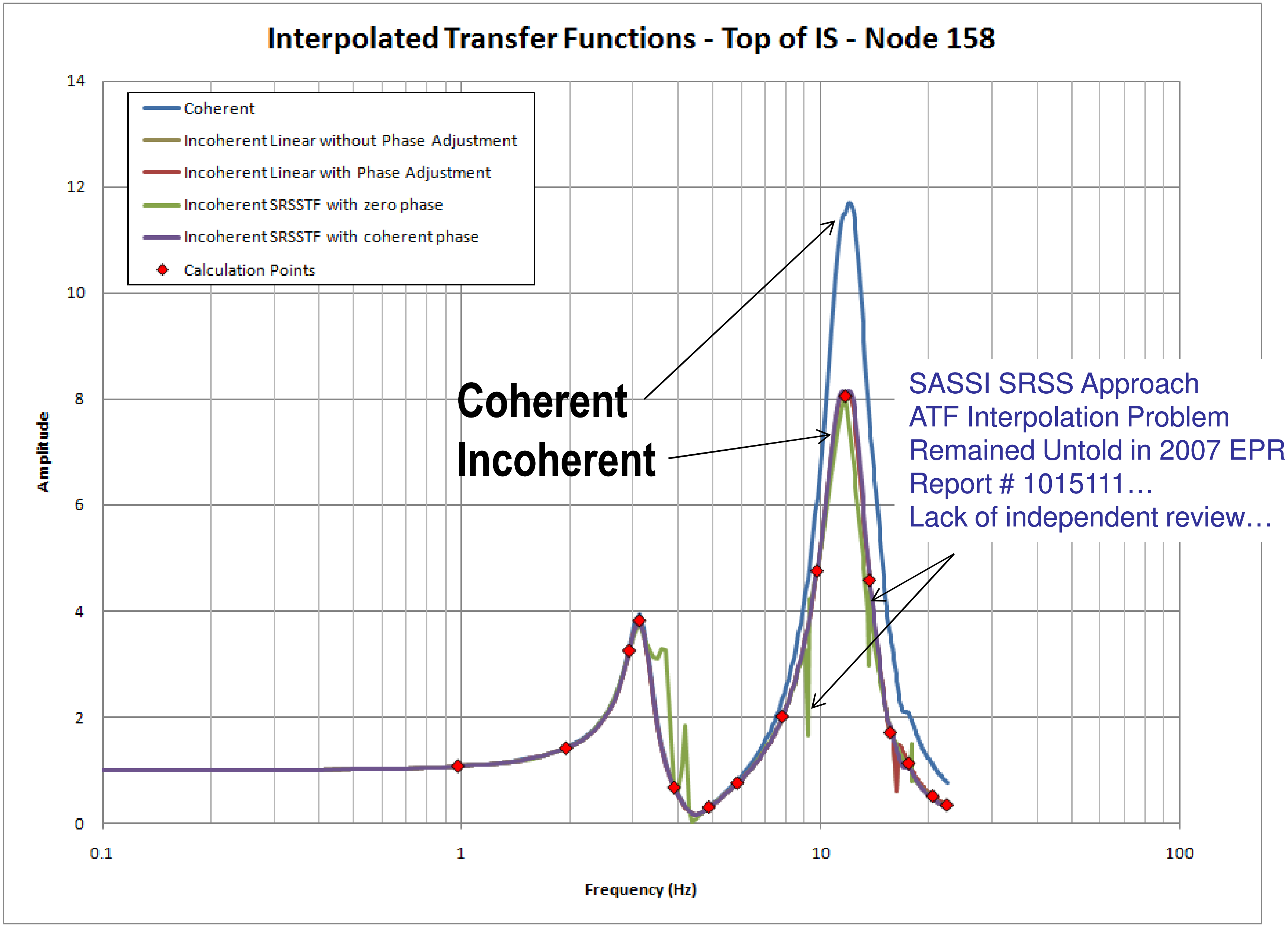
1) Linear/algebraic summation (AS) w/ phase adjustment *(EPRI TR#1015111)*
2) Linear/algebraic summation (AS) w/o phase adjustment *
3) SRSS of ATF Amplitude w/ zero-phase *(EPRI TR#1015111)*
4) SRSS of ATF Amplitude w/ non-zero phase *
5) SRSS of RS (used in 1997 EPRI TR#102631, but not validated in 2007 EPRI TR#1015111) *

* Note: Not considered in the 2006-2007 EPRI studies (EPRI TR# 1015111)

Deterministic Incoherent SSI Approaches

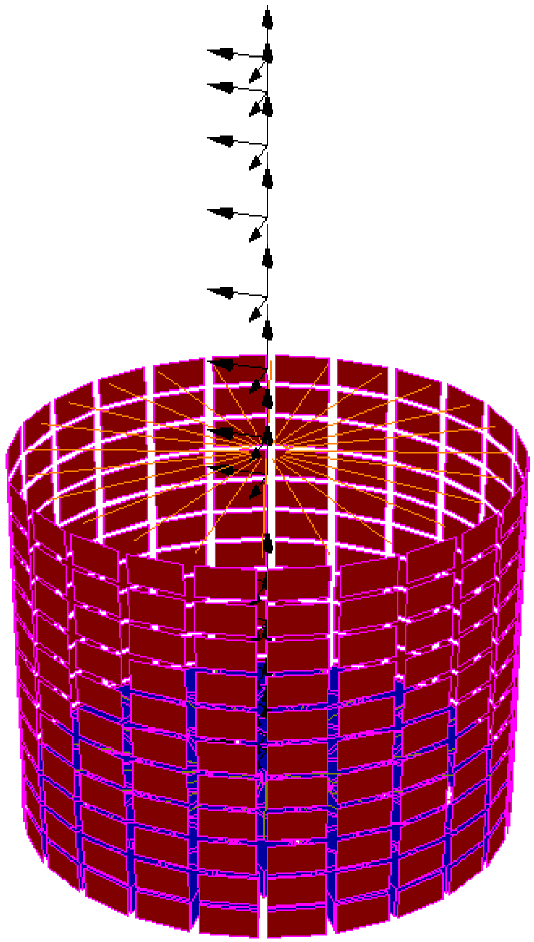


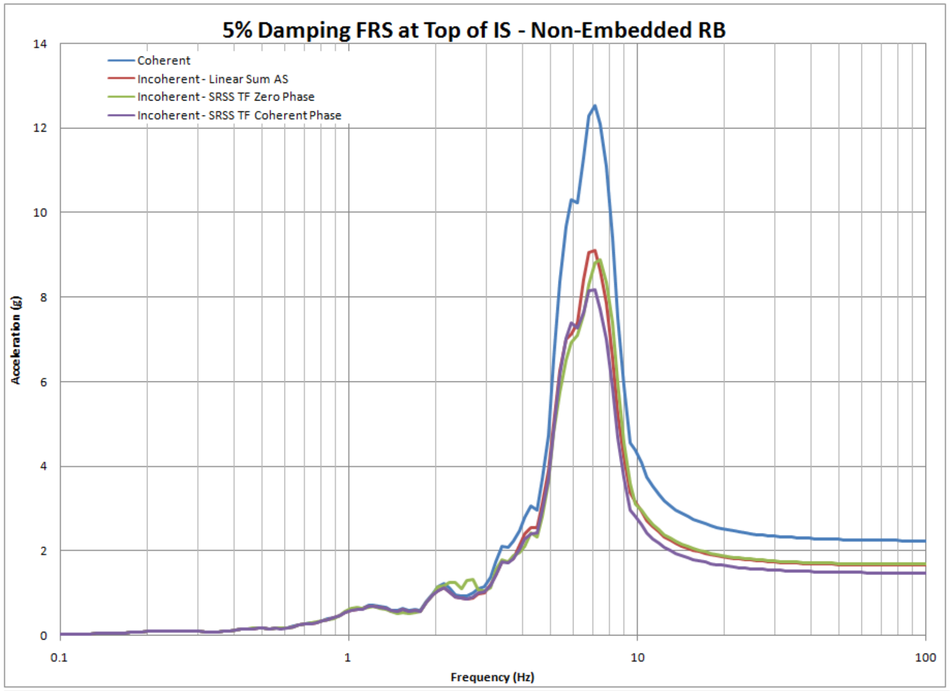
Deterministic Incoherent SSI Approaches

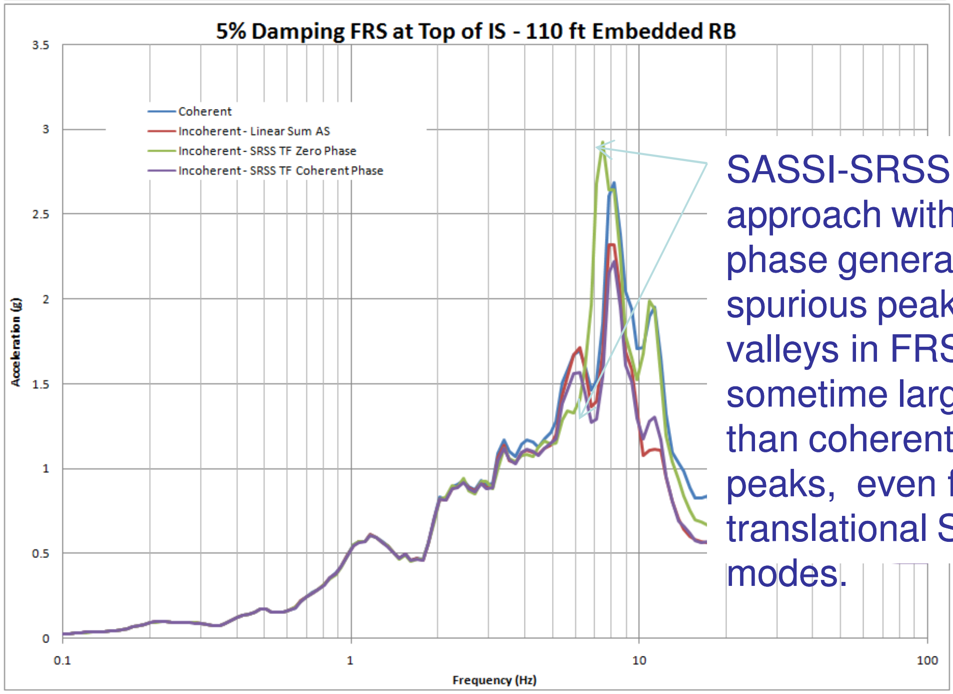


•

Deeply Embedded SSI Model Case Study

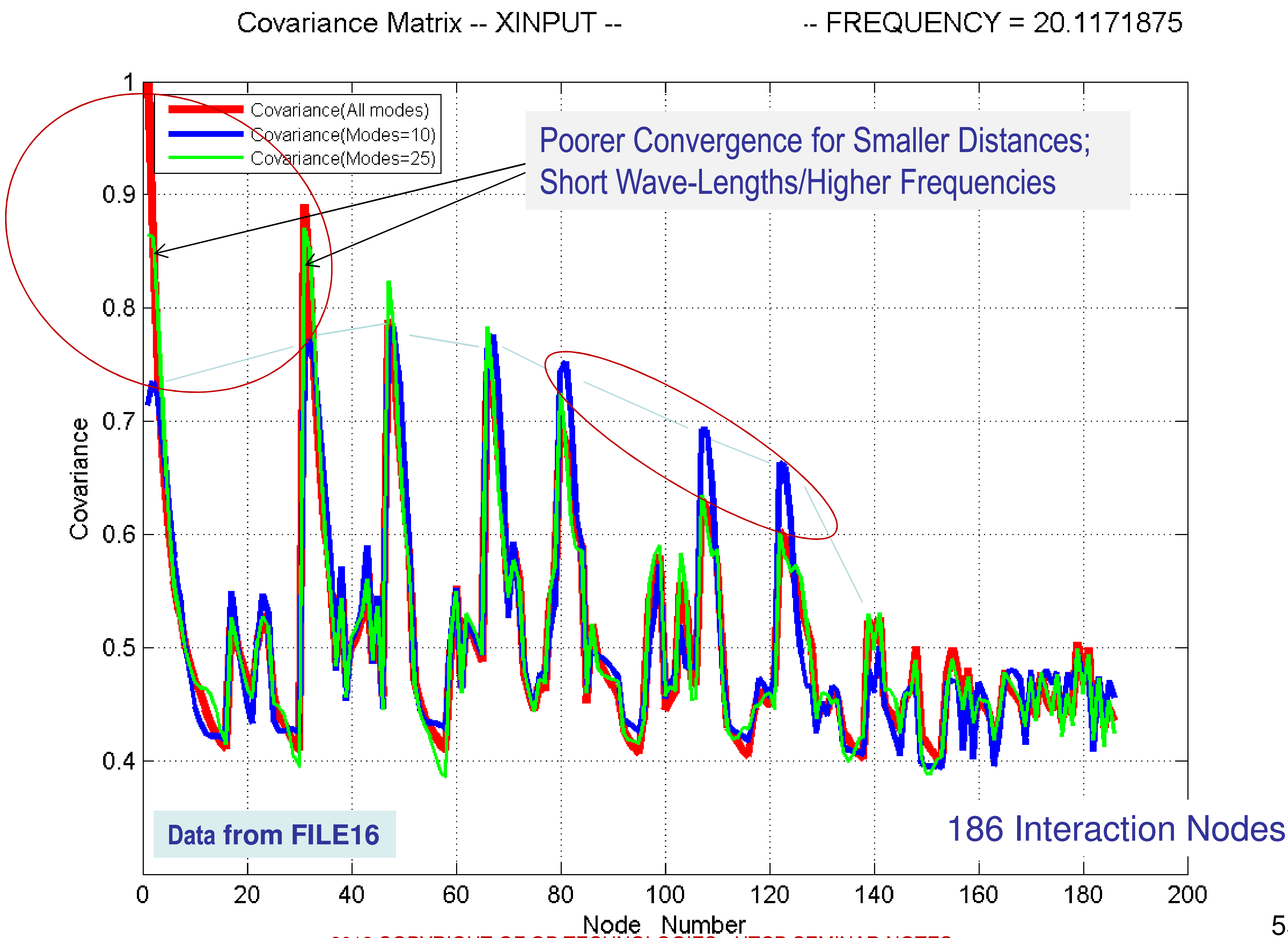






SASSI-SRSS TF approach with zero phase generates spurious peaks and valleys in FRS, sometime larger than coherent FRS peaks, even for translational SSI modes.

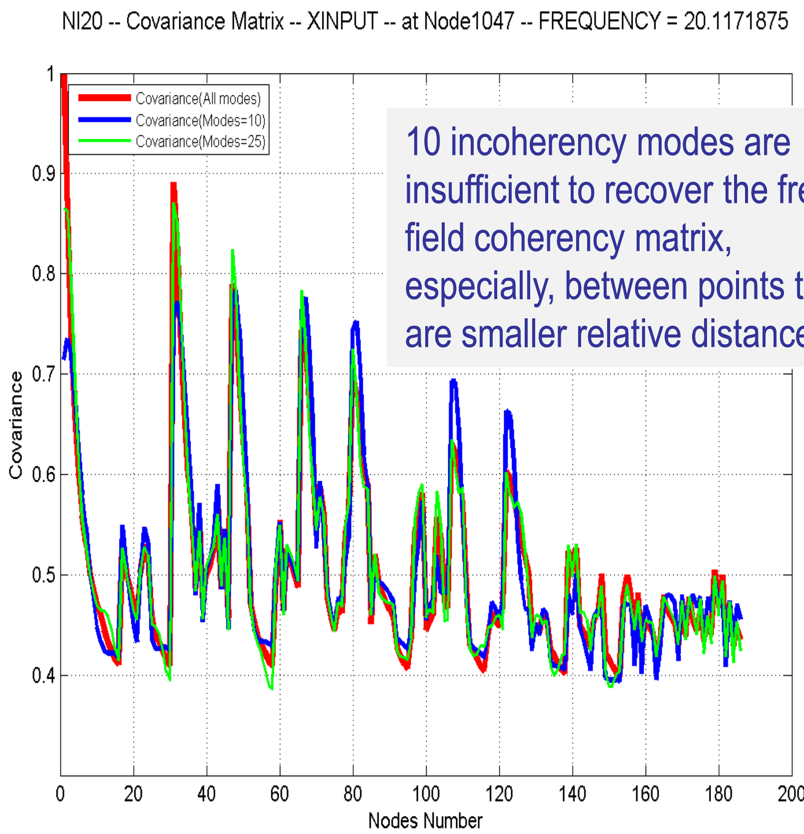
Free-Field Covariance Matrix Convergence Criterion. Selected Mat Corner Node



"Recovery" of Free-Field Coherency Matrix Input

Stochastic Simulation approach includes all the extracted coherency matrix eigenvectors (called also incoherent spatial modes) for computing incoherent SSI response.

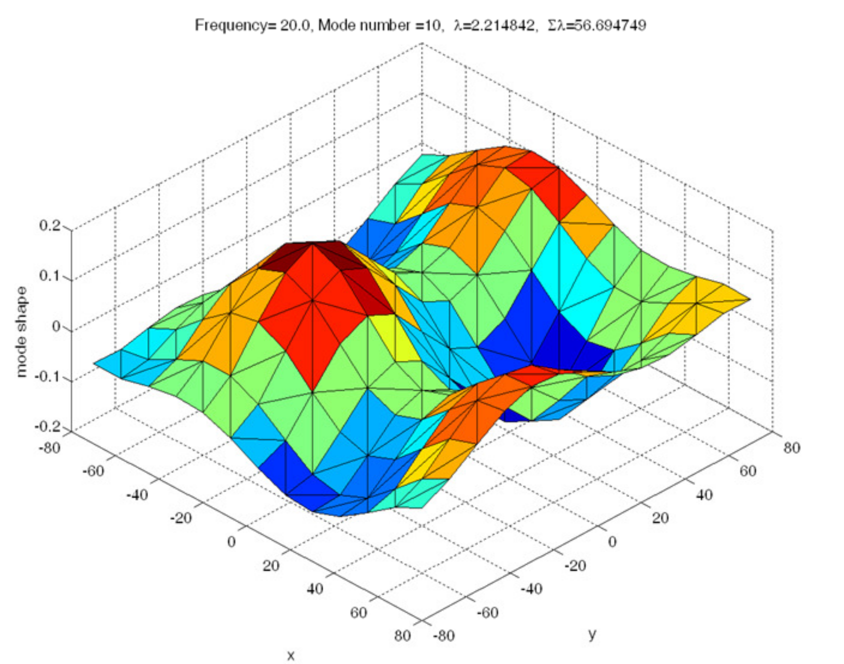
This is very important for the high frequency range were participation of higher-order incoherent spatial modes is large, especially in vertical direction and for flexible



10 incoherency modes are insufficient to recover the free-field coherency matrix, especially, between points that are smaller relative distances.

Using 10 Incoherent Spatial Modes AP1000 Stick Foundation

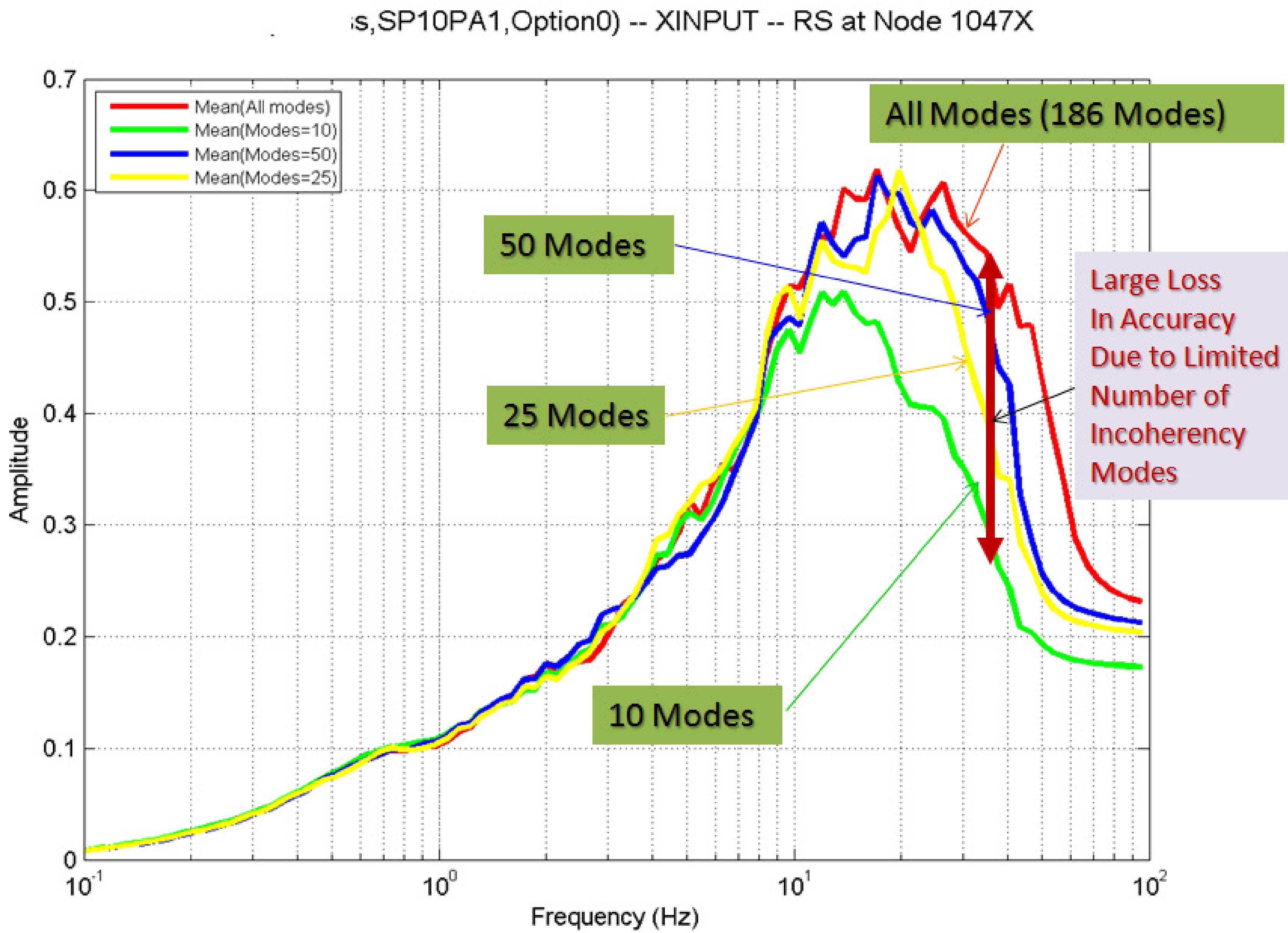
At 20.0 Hz Frequency: Cumulative Modal Variance = 33.72 % of Total Variance
At 30.0 Hz Frequency: Cumulative Modal Variance = 11.04 % of Total Variance



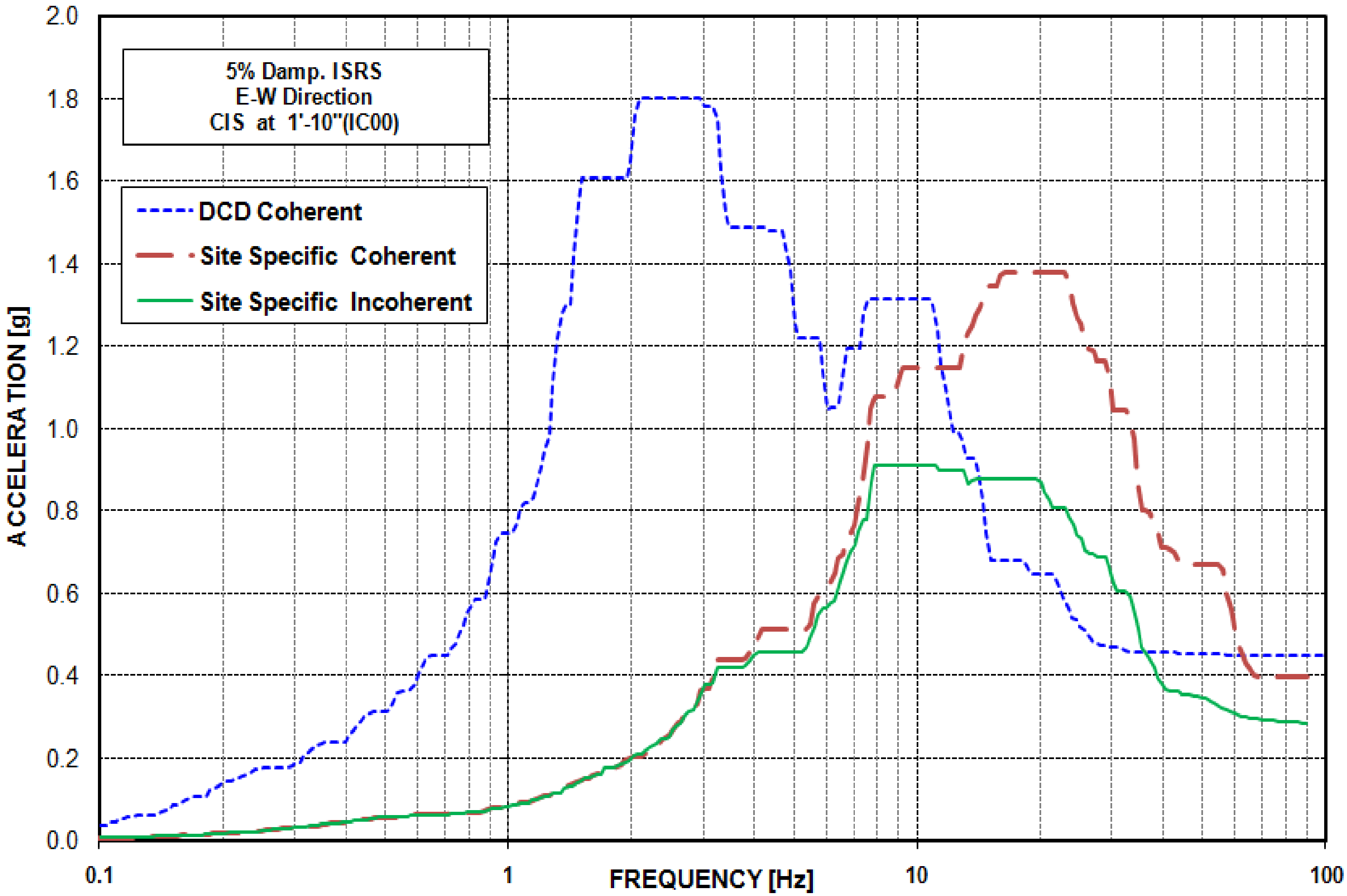
```
*** ABRAHAMSON 2007 PWI FOR SURFACE/HARD-ROCK SITES ***  NUMBER OF SPATIAL MODES  =          10

 NUMBER OF EMBED. LEVELS  =           0 (IS ZERO FOR SURFACE FOUNDATION)
APPARENT WAVE SPEED ALONG RADIAL DIRECTION    =  100000.00
RADIAL DIRECTION ANGLE WITH THE X-AXIS        =       0.00
UNLAGGED SEISMIC MOTION INCOHERENCY MODELING   =          5
=1 LUCO-WONG  1986 ANISOTROPIC MODEL
=2 ABRAHAMSON 1993 MODEL FOR ALL SITES/SURFACE
=3 ABRAHAMSON 2005 MODEL FOR ALL SITES/SURFACE
=4 ABRAHAMSON 2006 MODEL FOR ALL SITES/EMBEDMENT
=5 ABRAHAMSON 2007 MODEL FOR HARD-ROCK SITES/SURFACE
=6 ABRAHAMSON 2007 MODEL FOR SOIL SITES/SURFACE

 NUMBER OF INTERACTION NODES AT DEPTH      0.000 IS   336
 MAXIMUM NUMBER OF EMBEDDED NODES IN HORIZ. PLANE =         336
*** MOTION INCOHERENCY SIMULATION PARAMETERS ***
    SEED NUMBER FOR HORIZONTAL DIRECTION =            0
    SEED NUMBER FOR VERTICAL DIRECTION    =           0
    RANDOM PHASE ANGLE                    =    0.000000000000000E+000
*** CUMULATIVE MODAL MASS/VARIANCE(%) ***
```

Frequency =	0.098	Horizontal =	100.00%	Vertical =	100.00%
Frequency =	1.562	Horizontal =	100.00%	Vertical =	99.97%
Frequency =	3.125	Horizontal =	99.94%	Vertical =	99.75%
Frequency =	4.688	Horizontal =	99.69%	Vertical =	99.20%
Frequency =	6.250	Horizontal =	98.90%	Vertical =	98.09%
Frequency =	7.812	Horizontal =	97.01%	Vertical =	96.00%
Frequency =	9.375	Horizontal =	93.55%	Vertical =	92.59%
Frequency =	10.938	Horizontal =	88.54%	Vertical =	87.93%
Frequency =	12.500	Horizontal =	82.47%	Vertical =	82.46%
Frequency =	14.062	Horizontal =	75.90%	Vertical =	76.67%
Frequency =	15.625	Horizontal =	69.31%	Vertical =	70.92%
Frequency =	17.188	Horizontal =	63.02%	Vertical =	65.45%
Frequency =	18.750	Horizontal =	57.20%	Vertical =	60.37%
Frequency =	20.312	Horizontal =	51.92%	Vertical =	55.74%
Frequency =	21.875	Horizontal =	47.19%	Vertical =	51.55%
Frequency =	23.438	Horizontal =	42.99%	Vertical =	47.79%
Frequency =	25.000	Horizontal =	39.26%	Vertical =	44.40%
Frequency =	26.562	Horizontal =	35.96%	Vertical =	41.37%
Frequency =	28.125	Horizontal =	33.04%	Vertical =	38.65%
Frequency =	29.688	Horizontal =	30.42%	Vertical =	36.20%
Frequency =	31.250	Horizontal =	28.04%	Vertical =	34.00%
Frequency =	32.812	Horizontal =	25.81%	Vertical =	32.01%
Frequency =	34.375	Horizontal =	23.63%	Vertical =	30.21%
Frequency =	35.938	Horizontal =	21.37%	Vertical =	28.57%
Frequency =	37.500	Horizontal =	18.93%	Vertical =	27.09%
Frequency =	39.062	Horizontal =	16.31%	Vertical =	25.74%

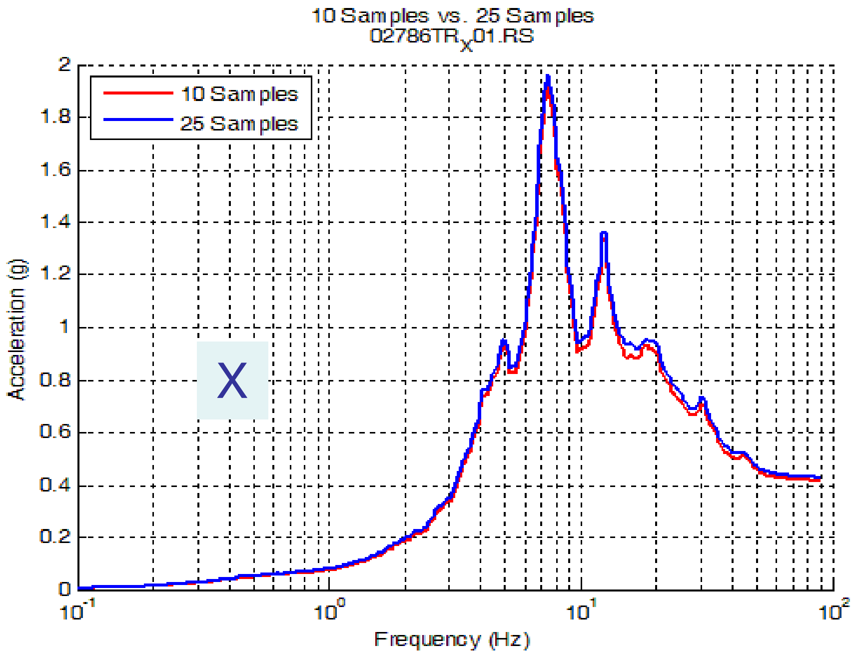
Incoherent FRS at Flexible Mat Corner. Effect of Number of Incoherence Modes

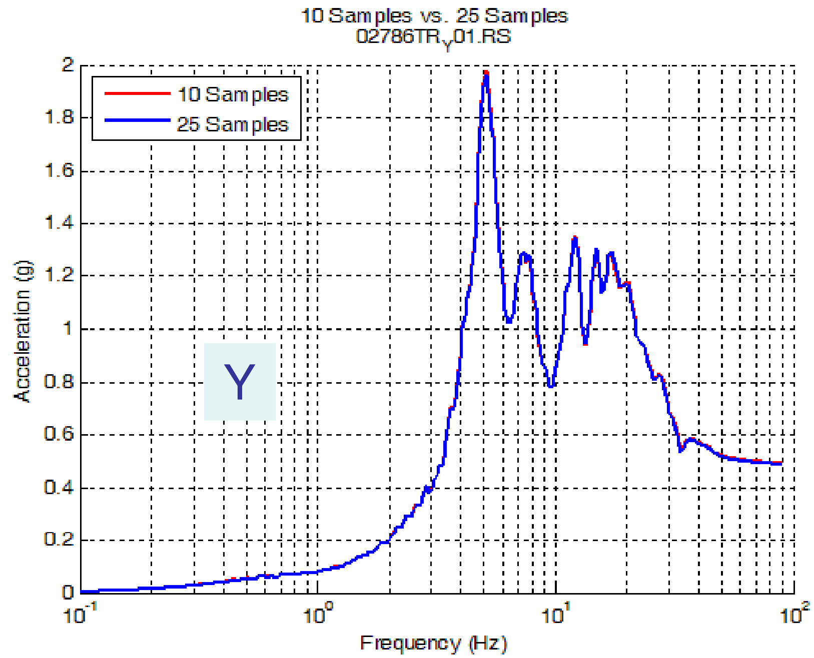


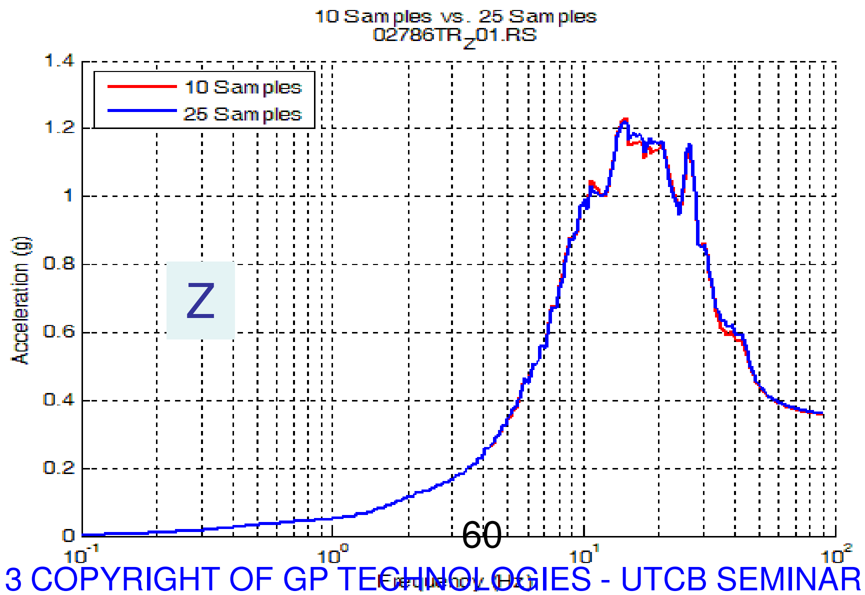
Site-Independent vs. Site-Specific Coherent and Incoherent Final ISRS Results at CIS Base in Y-Dir

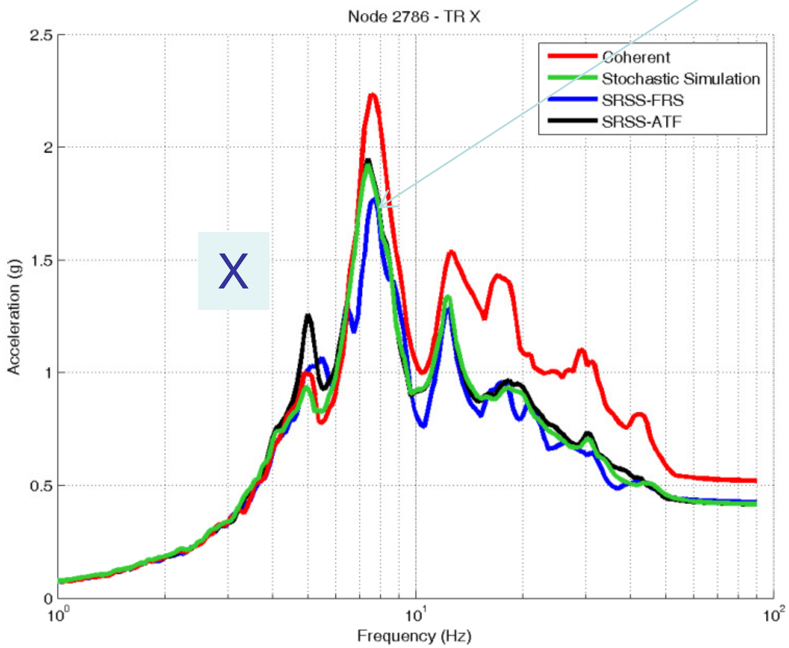


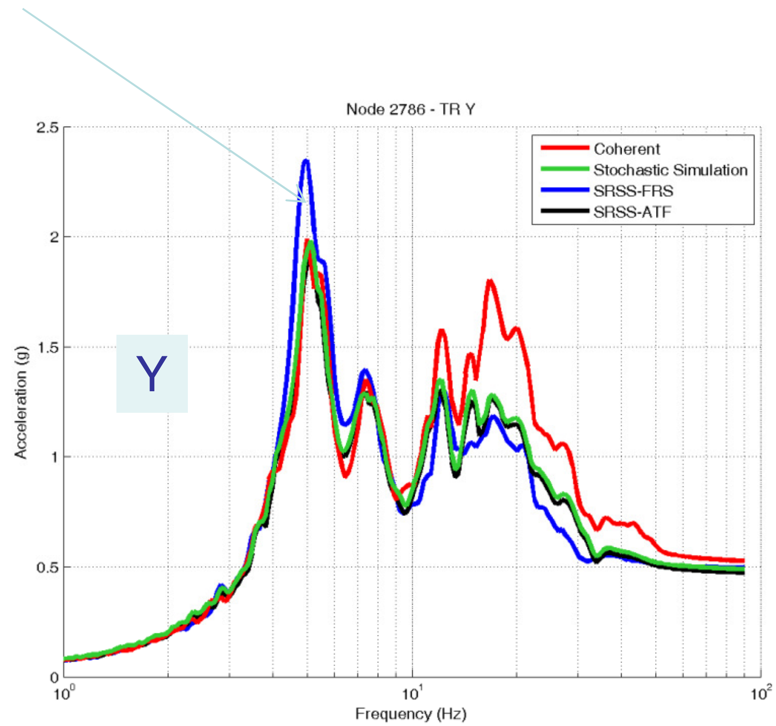
Comparison 10 vs. 25 Samples for CIS 05

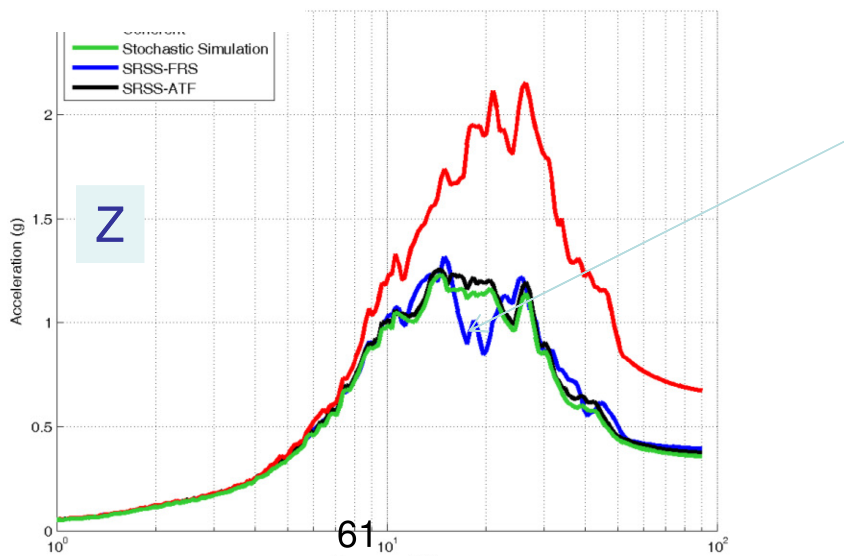


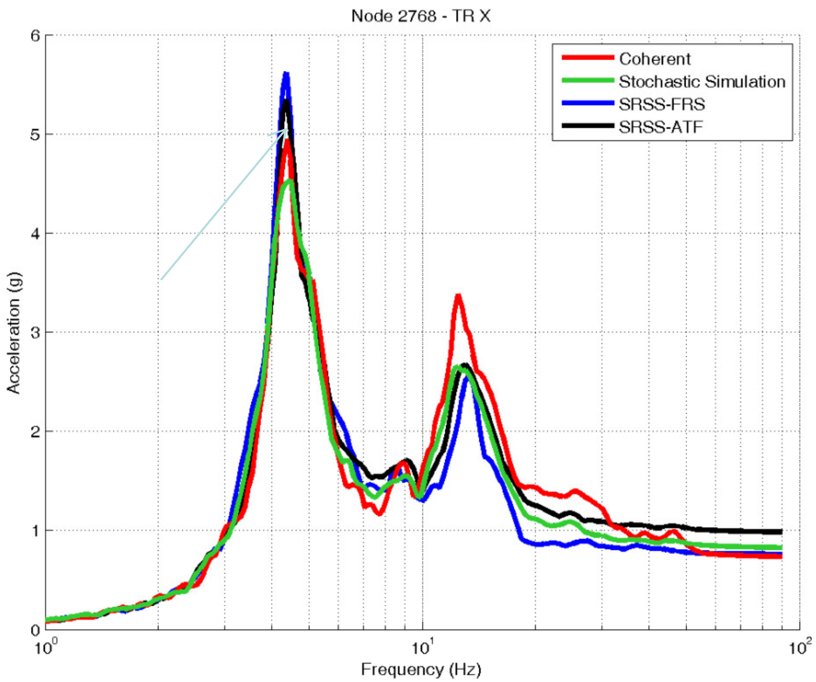


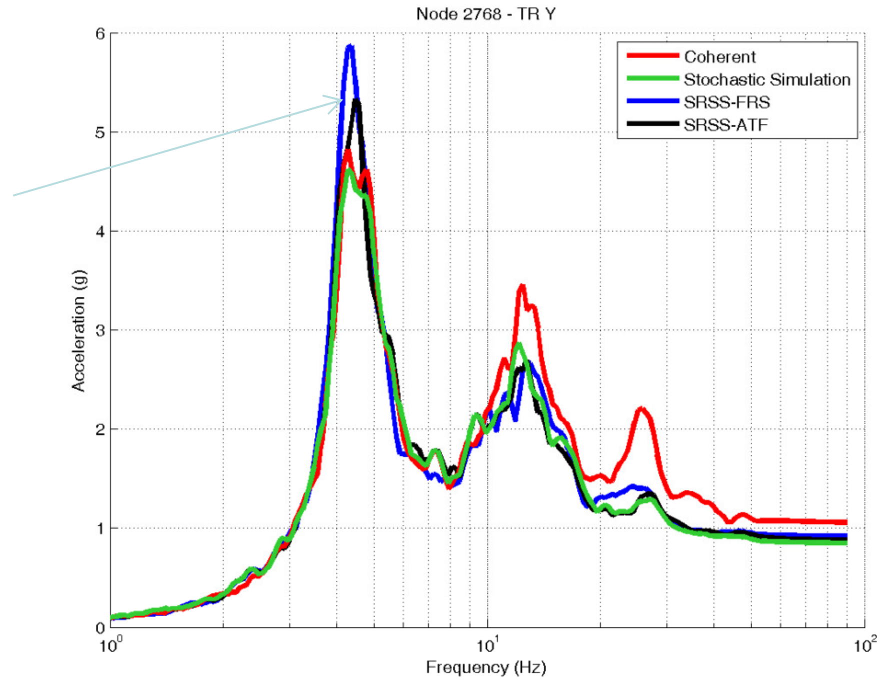


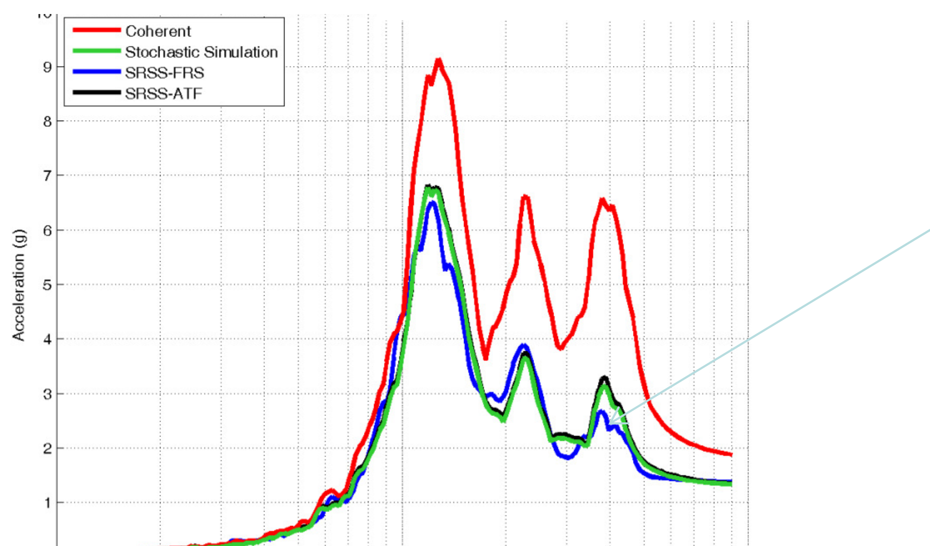

Node 2786 - TR X
Coherent
Stochastic Simulation
SRSS-FRS
SRSS-ATF
X
Acceleration (g)
Frequency (Hz)

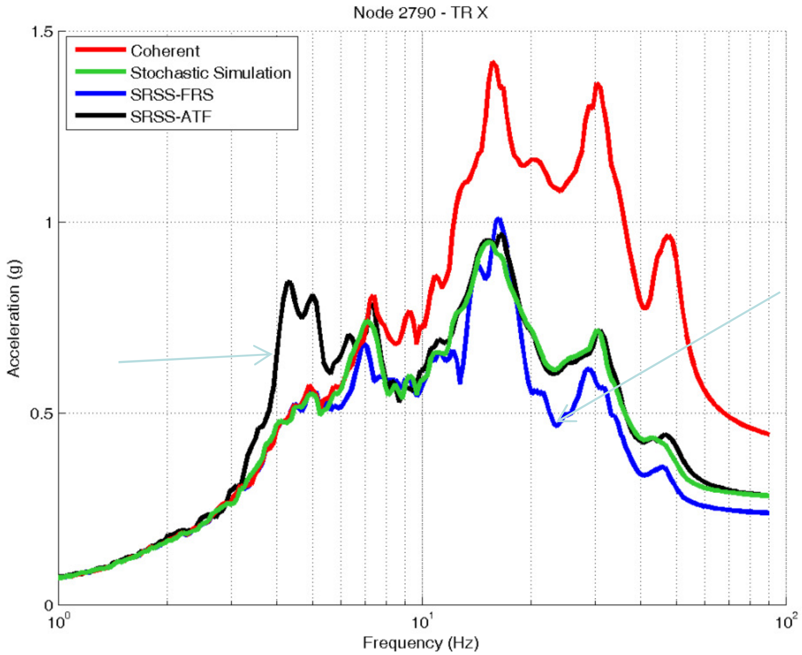

Node 2786 - TR Y
Coherent
Stochastic Simulation
SRSS-FRS
SRSS-ATF
Y
Acceleration (g)
Frequency (Hz)

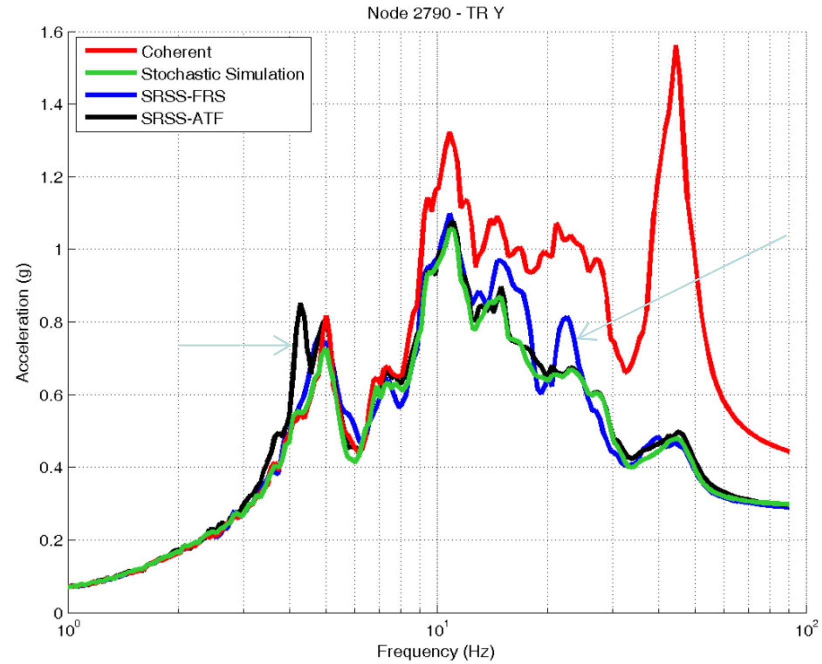

Stochastic Simulation
SRSS-FRS
SRSS-ATF
Z
Acceleration (g)

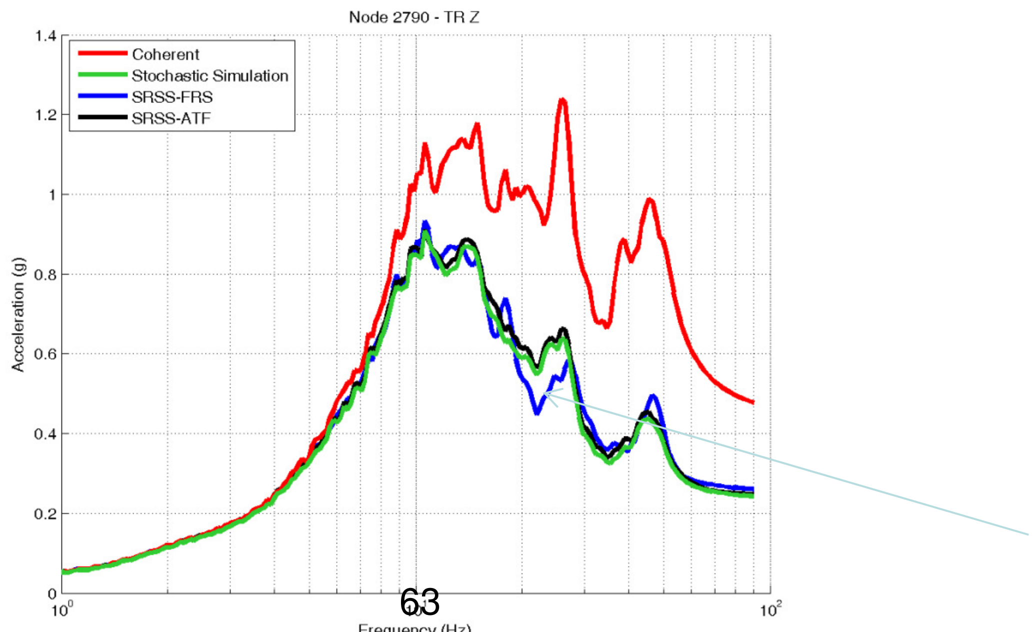

Node 2768 - TR X
Coherent
Stochastic Simulation
SRSS-FRS
SRSS-ATF
Acceleration (g)
Frequency (Hz)

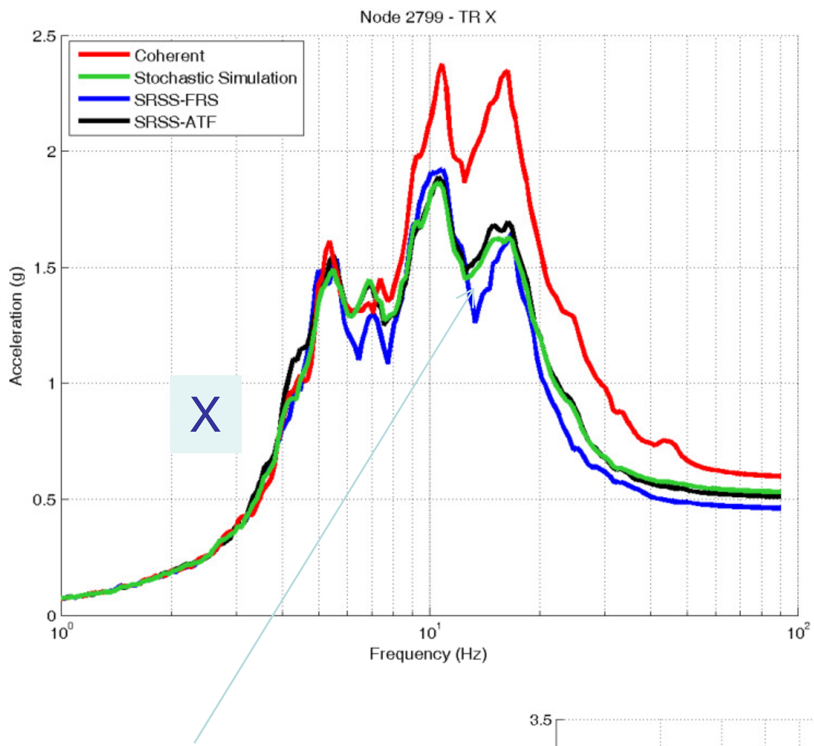

Node 2768 - TR Y
Coherent
Stochastic Simulation
SRSS-FRS
SRSS-ATF
Acceleration (g)
Frequency (Hz)

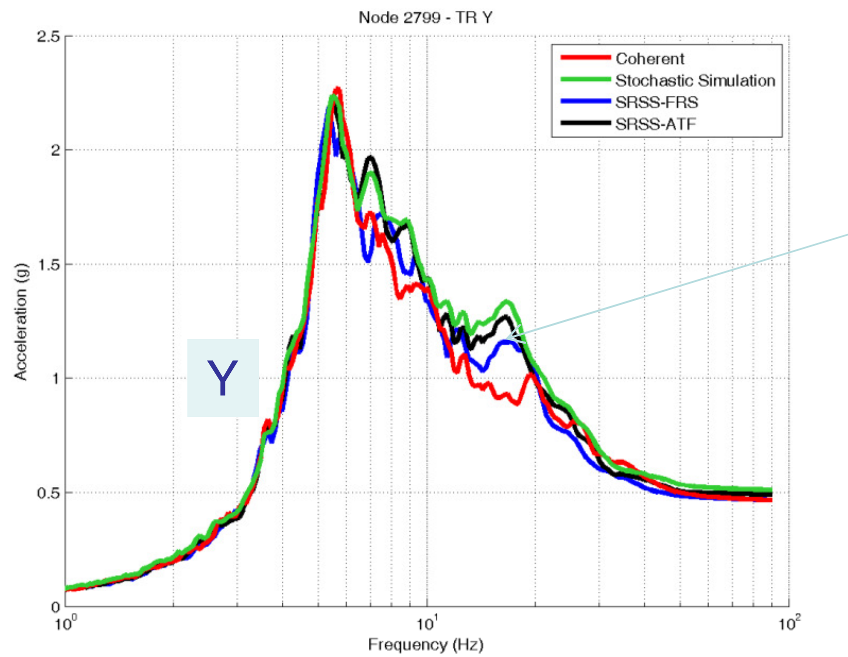

Coherent
Stochastic Simulation
SRSS-FRS
SRSS-ATF
Acceleration (g)
Frequency (Hz)

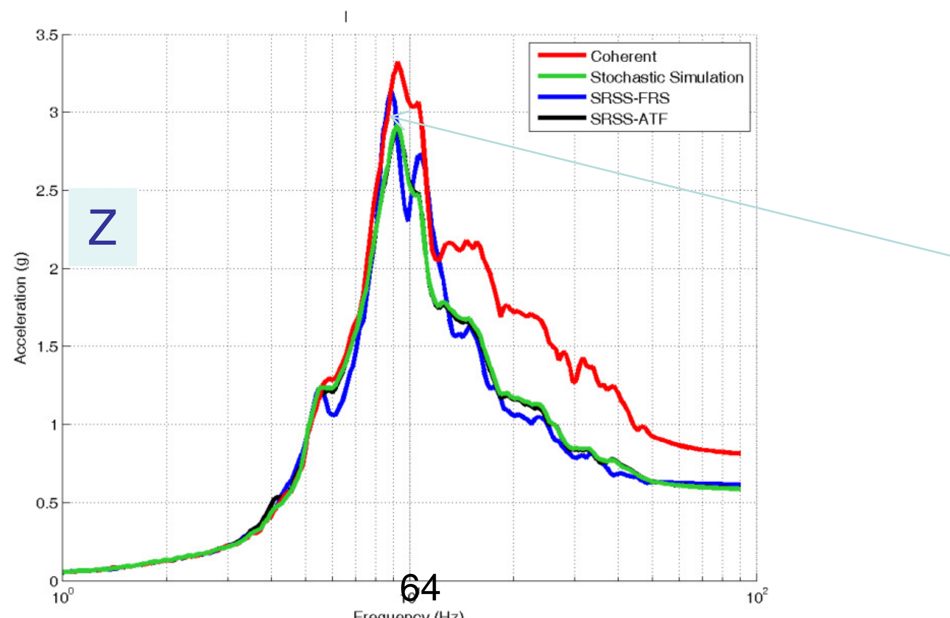

Node 2790 - TR X
Coherent
Stochastic Simulation
SRSS-FRS
SRSS-ATF
Acceleration (g)
Frequency (Hz)


Node 2790 - TR Y
Coherent
Stochastic Simulation
SRSS-FRS
SRSS-ATF
Acceleration (g)
Frequency (Hz)


Node 2790 - TR Z
Coherent
Stochastic Simulation
SRSS-FRS
SRSS-ATF
Acceleration (g)
Frequency (Hz)

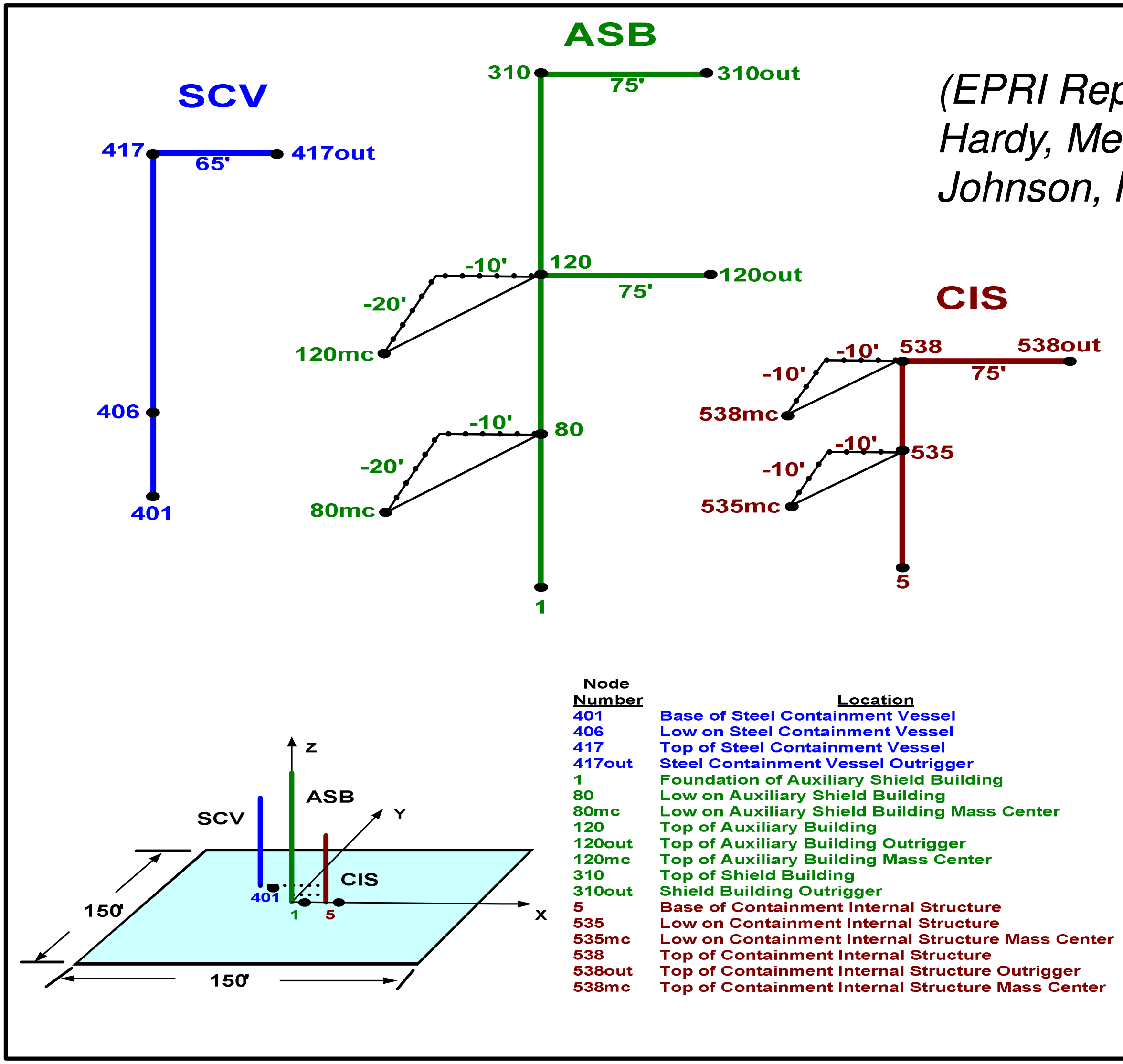

Node 2799 - TR X
Coherent
Stochastic Simulation
SRSS-FRS
SRSS-ATF
X
Acceleration (g)
Frequency (Hz)


Node 2799 - TR Y
Coherent
Stochastic Simulation
SRSS-FRS
SRSS-ATF
Y
Acceleration (g)
Frequency (Hz)


Coherent
Stochastic Simulation
SRSS-FRS
SRSS-ATF
Z
Acceleration (g)
Frequency (Hz)

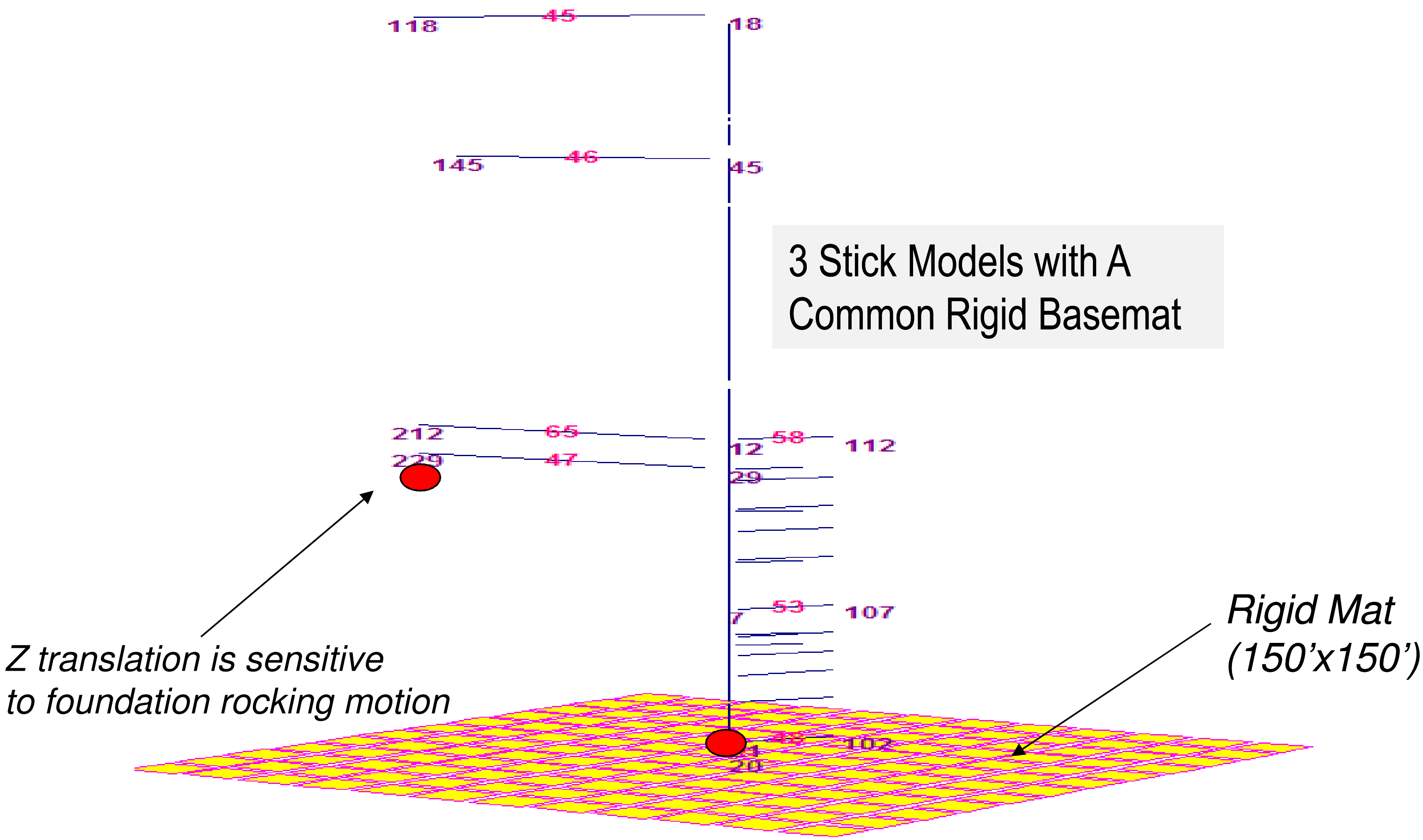
EPRI Validation of ACS SASSI for Incoherent SSI

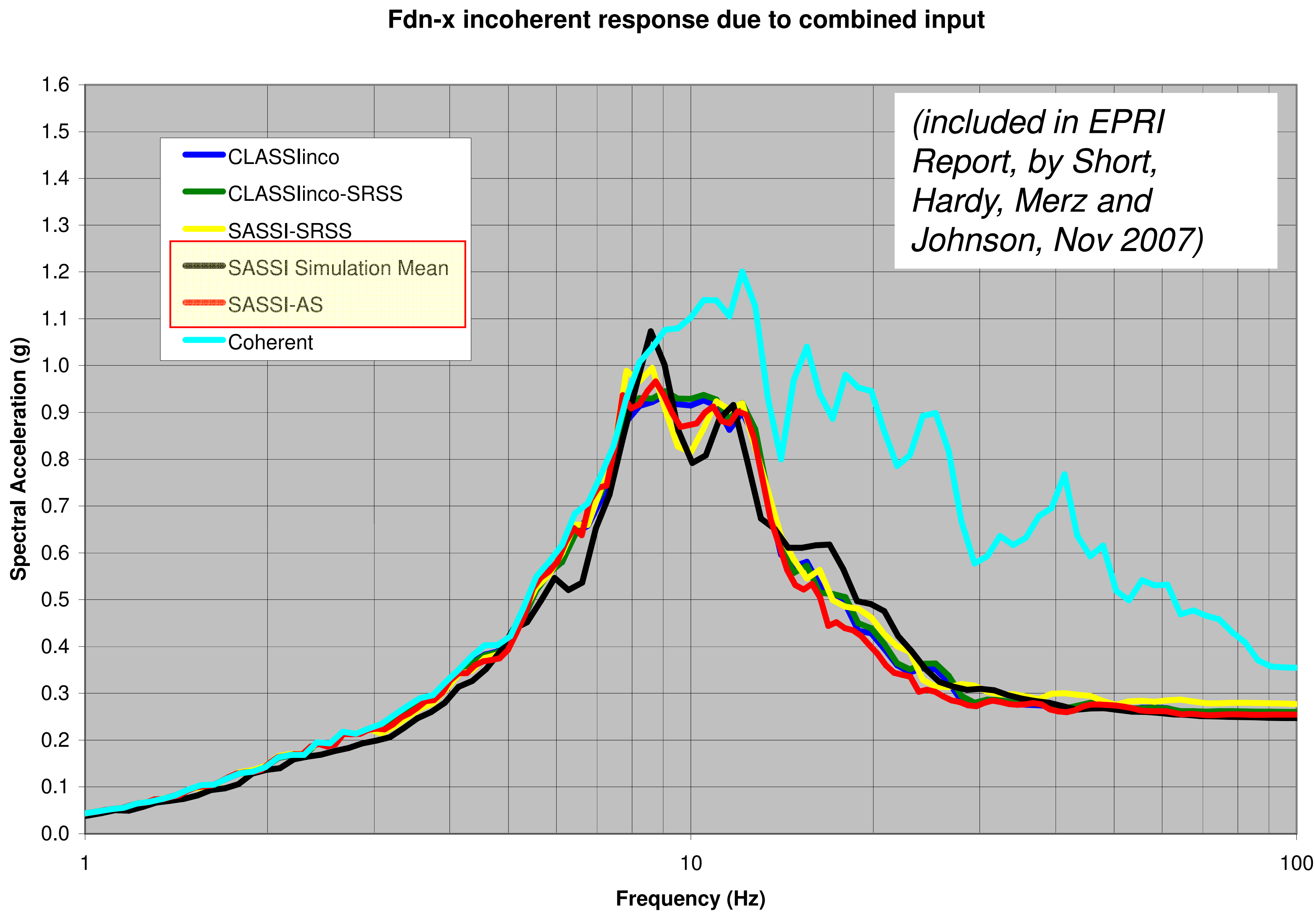
EPRI AP1000 Stick NI Model Masses (150ftx150ft)



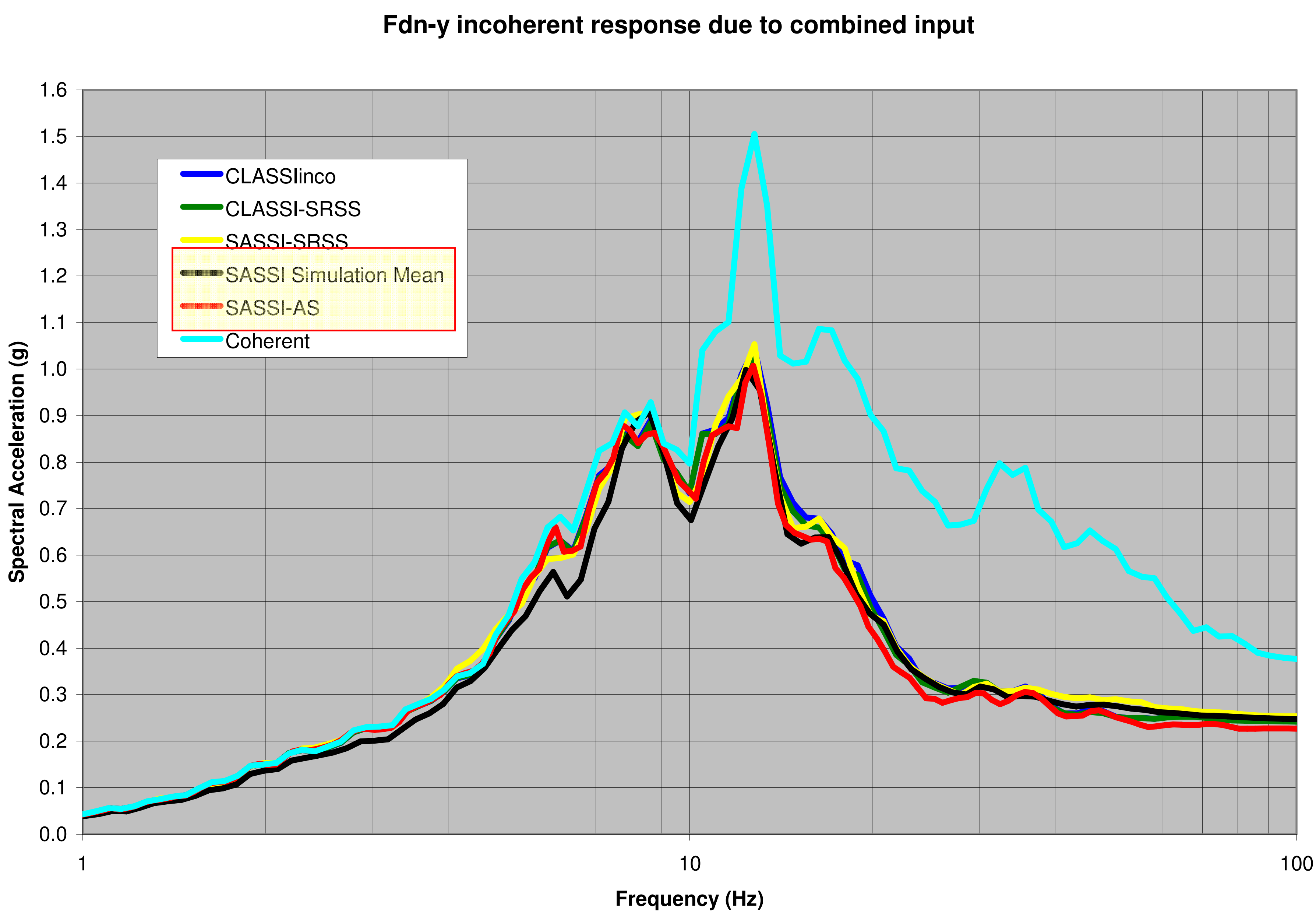
(EPRI Report, by Short, Hardy, Merz and Johnson, Nov 2007)

EPRI AP1000 Stick Model Has Increased Mass Eccentricities and Reduced Foundation Size



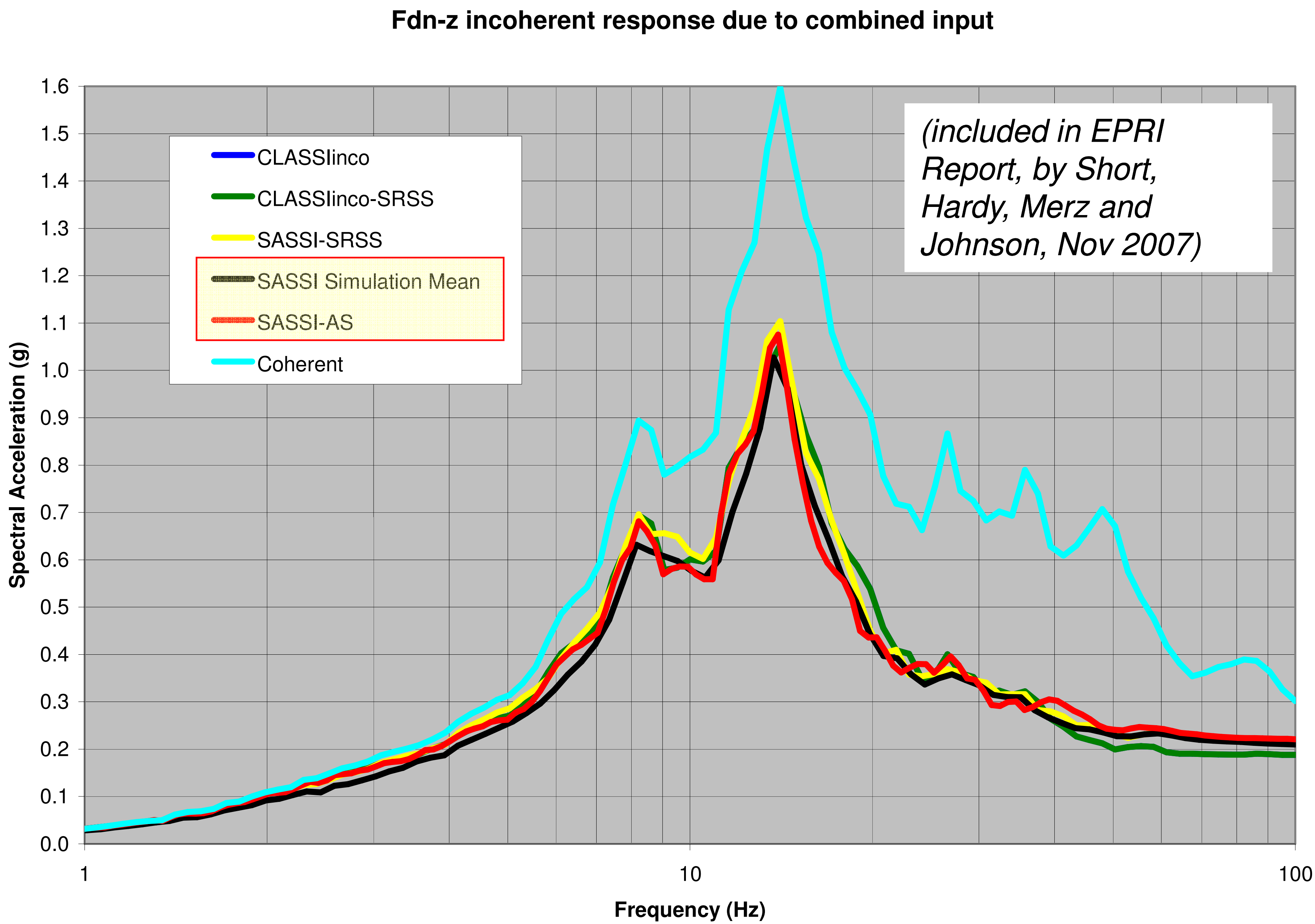


Center of Foundation (Node 1) Response Spectra – X Direction
CLASSIinco, CLASSIinco-SRSS, Bechtel SASSI-SRSS, ACS SASSI Simulation Mean and AS



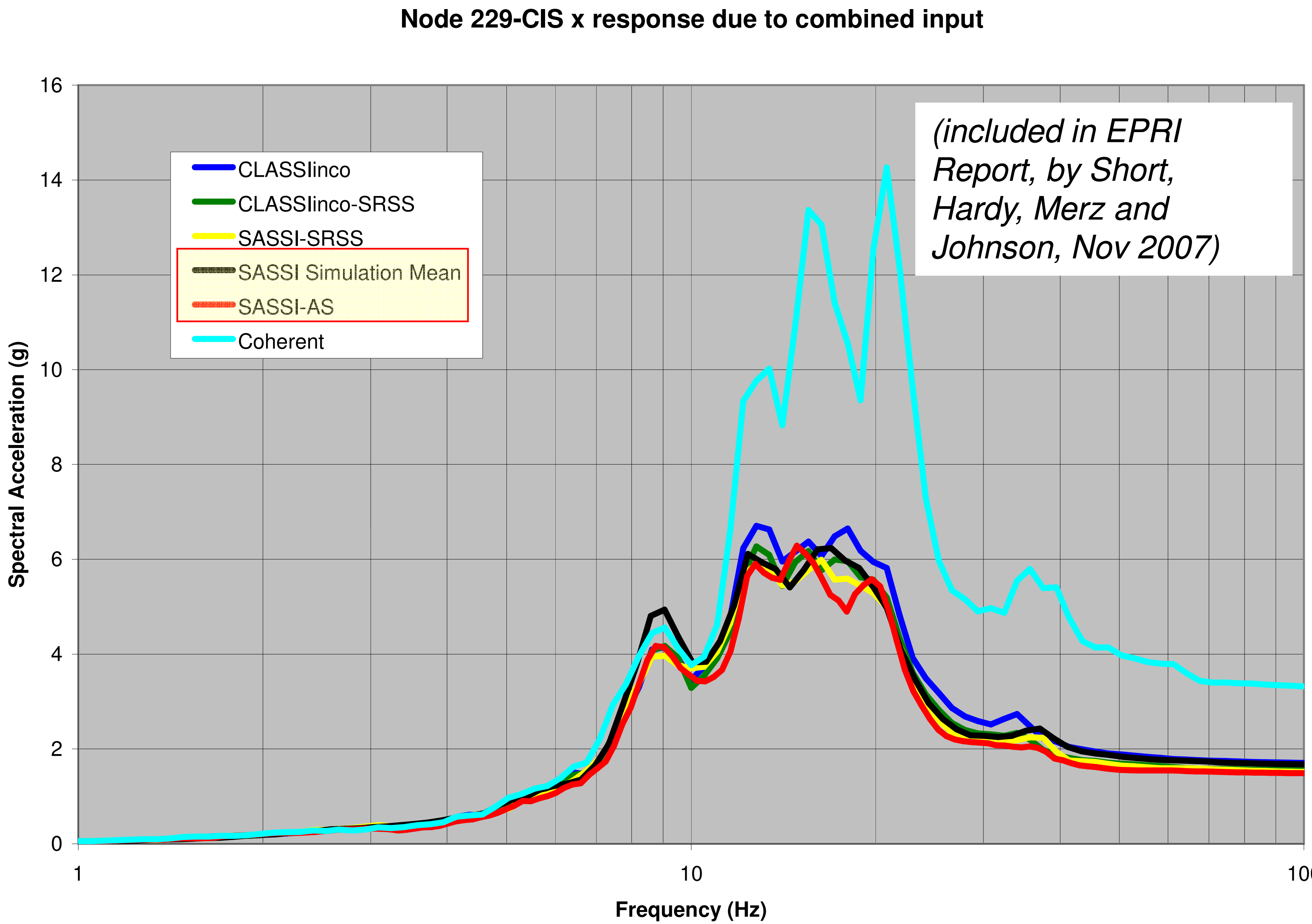
Center of Foundation (Node 1) Response Spectra – Y Direction

CLASSIinco, CLASSIinco-SRSS, Bechtel SASSI-SRSS, ACS SASSI Simulation Mean and AS

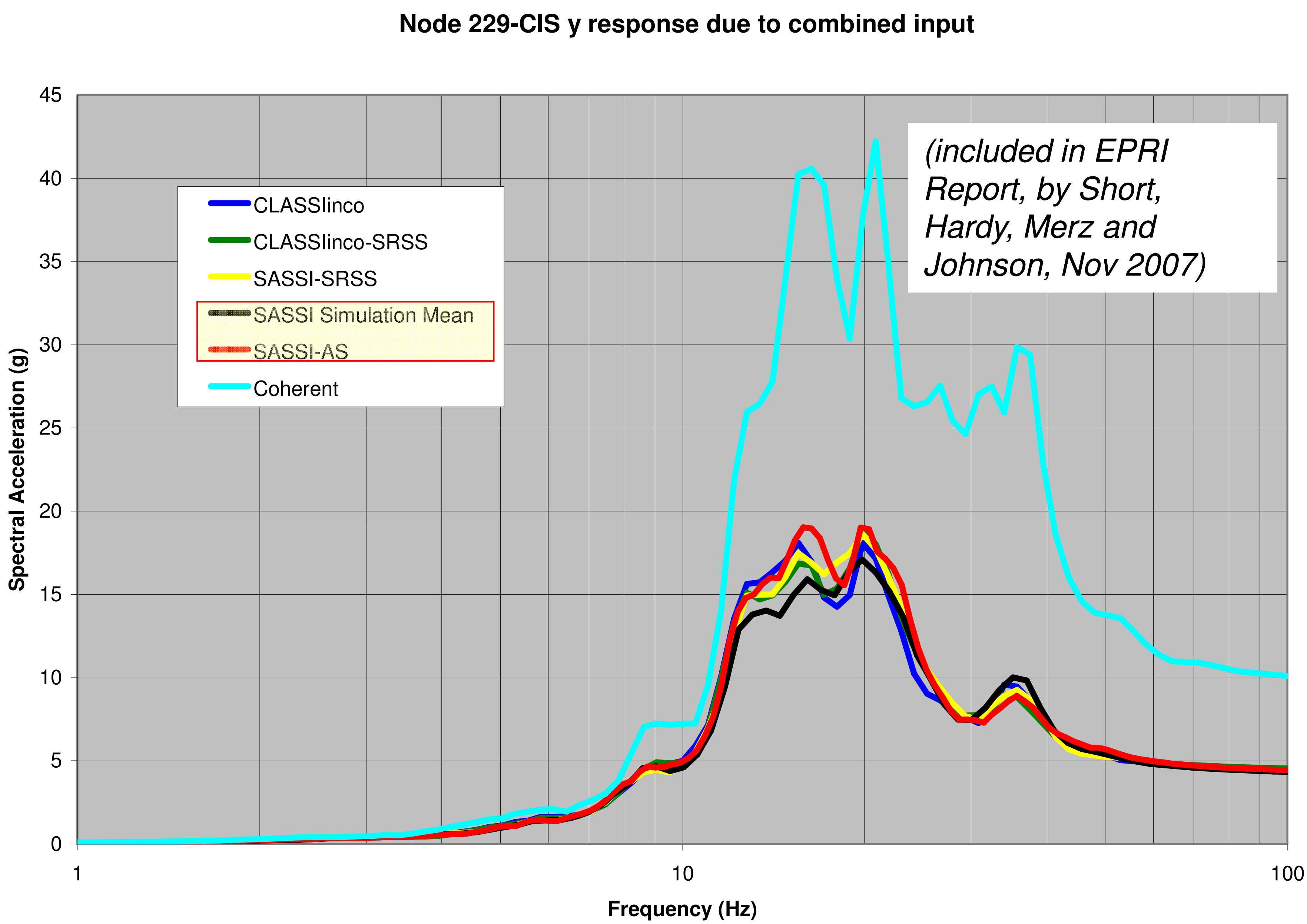


Center of Foundation (Node 1) Response Spectra – Z Direction

CLASSIinco, CLASSIinco-SRSS, Bechtel SASSI-SRSS, ACS SASSI Simulation Mean and AS

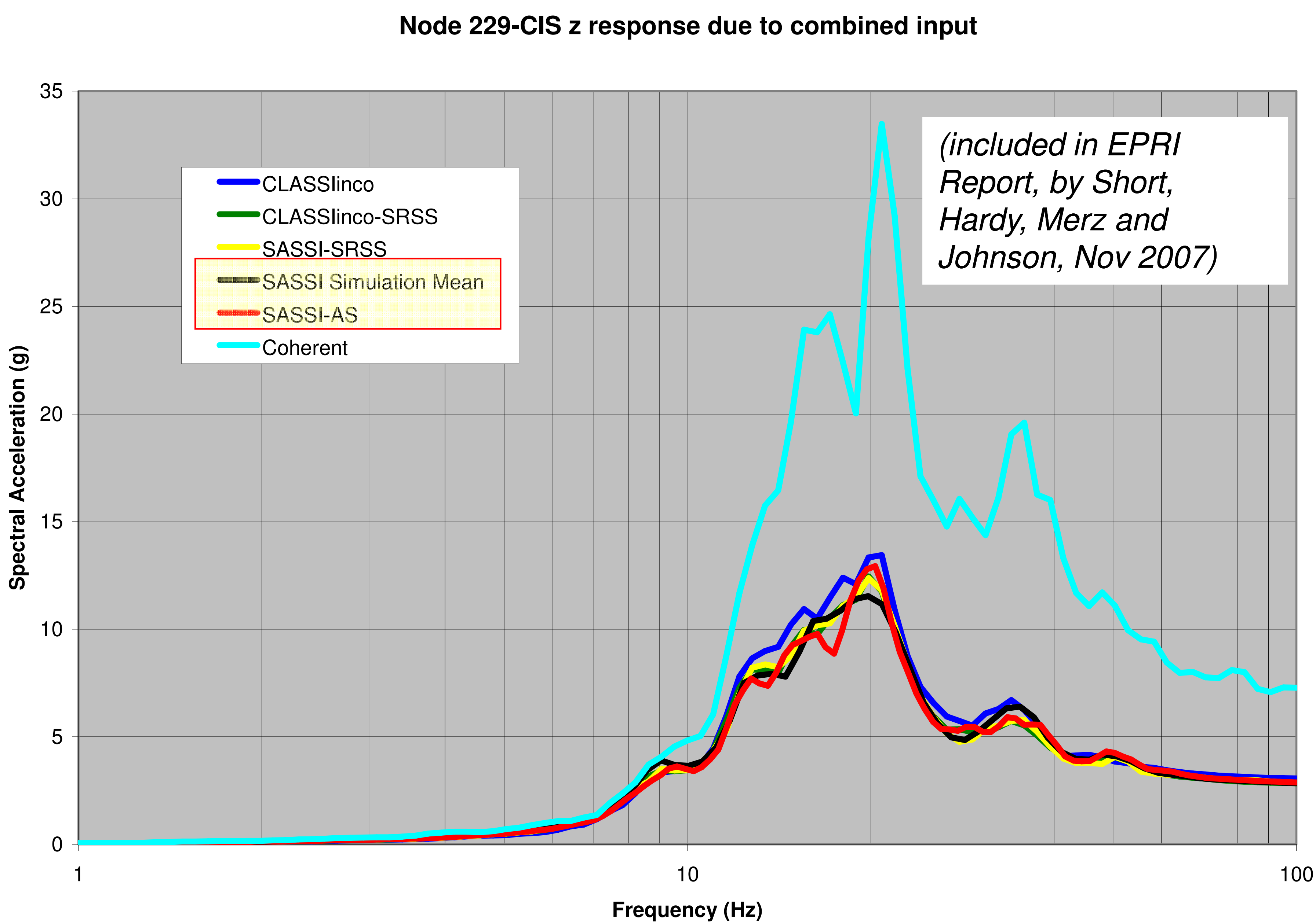


CIS Outrigger (Node 229) Response Spectra – X Direction
CLASSIinco, CLASSIinco-SRSS, Bechtel SASSI-SRSS, ACS SASSI Simulation Mean and AS



CIS Outrigger (Node 229) Response Spectra – Y Direction

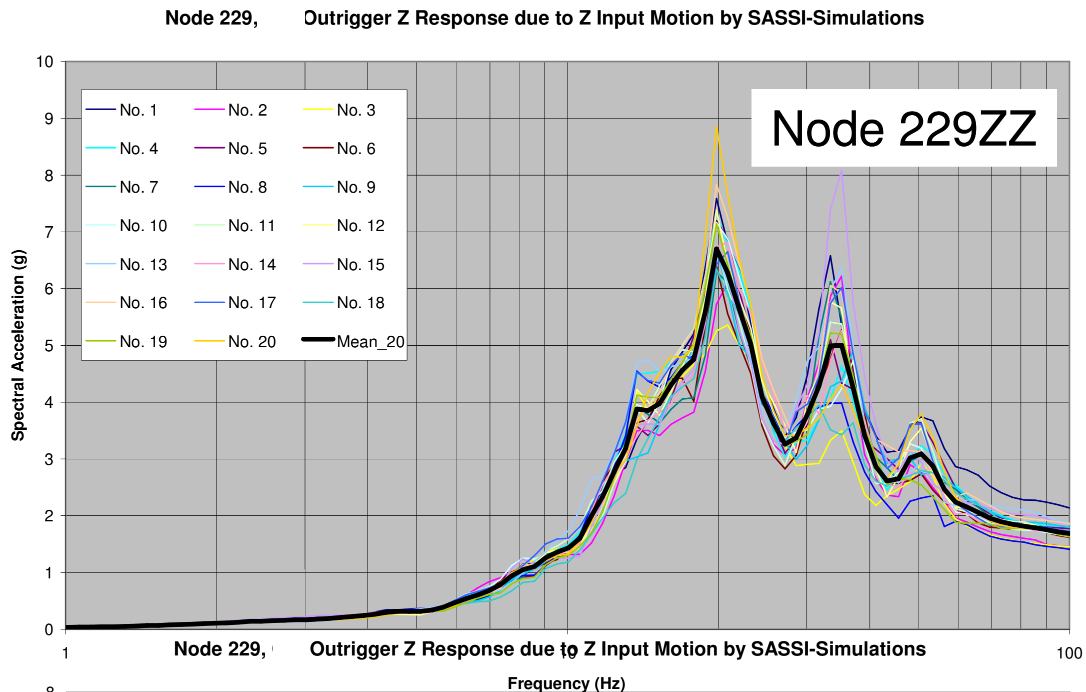
CLASSIinco, CLASSIinco-SRSS, Bechtel SASSI-SRSS, ACS SASSI Simulation Mean and AS



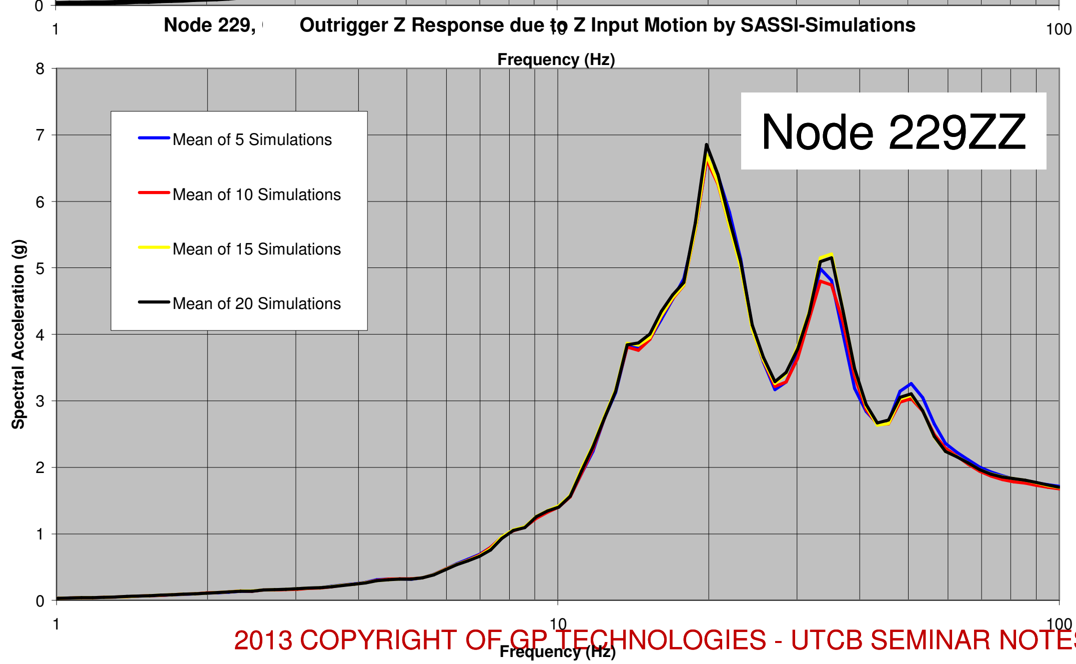
CIS Outrigger (Node 229) Response Spectra – Z Direction
CLASSlinco, CLASSlinco-SRSS, Bechtel SASSI-SRSS, ACS SASSI Simulation Mean and AS

Mean RS for 5, 10, 15 and 20 Stochastic Samples
For 3 Stick Model with Rigid Basemat (EPRI Studies, 2007)

Random FRS Samples



Mean FRS



(included in EPRI Report, Figs. 4.1 and 4.2, page 4-5, by Short, Hardy, Merz and Johnson, Sept 2007)

We also compared with results from 50 random Samples – not shown.

ANIMATIONS

EPRI Conclusions on Incoherency Effects
(EPRI Report # 1015111, Nov 30, 2007)

The qualitative effects of motion incoherency effects are:

i) for horizontal components are a reduction in excitation translation concomitantly with an increase of torsional excitation and a reduction of foundation rocking

ii) for vertical component is a reduction in excitation translation concomitantly with an increase of rocking excitation.

Benchmarked SASSI-Based Approaches:

1) Stochastic Simulation – Validated/Accurate, Final Design Calcs
2) SRSS TF Approach – Validated/Accurate, Final Design Calcs
3) AS Approach – Validated/Approximate, Preliminary Design Calcs

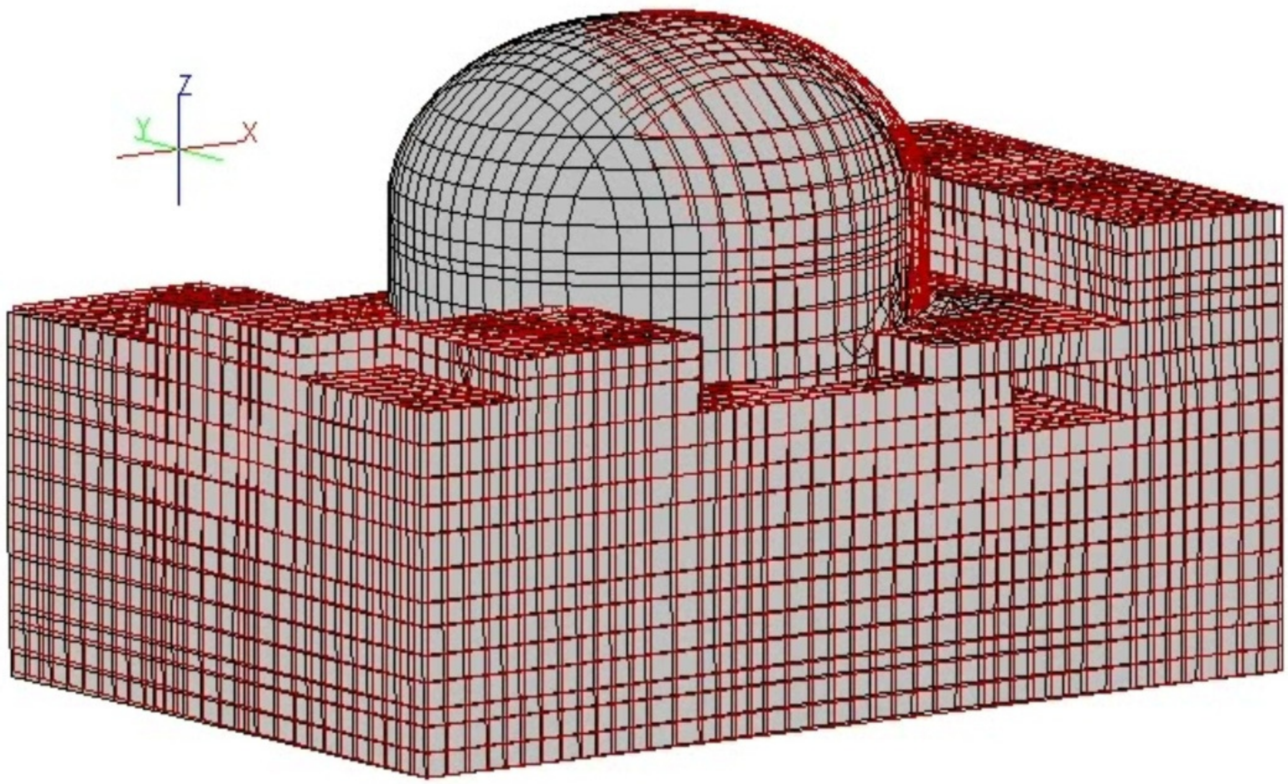
Other remarks:

- No clear guidance for flexible foundations
- No guidance is provided for the piping/equipment multiple history analysis with incoherent inputs
- No guidance is provided for evaluation of incoherent structural forces

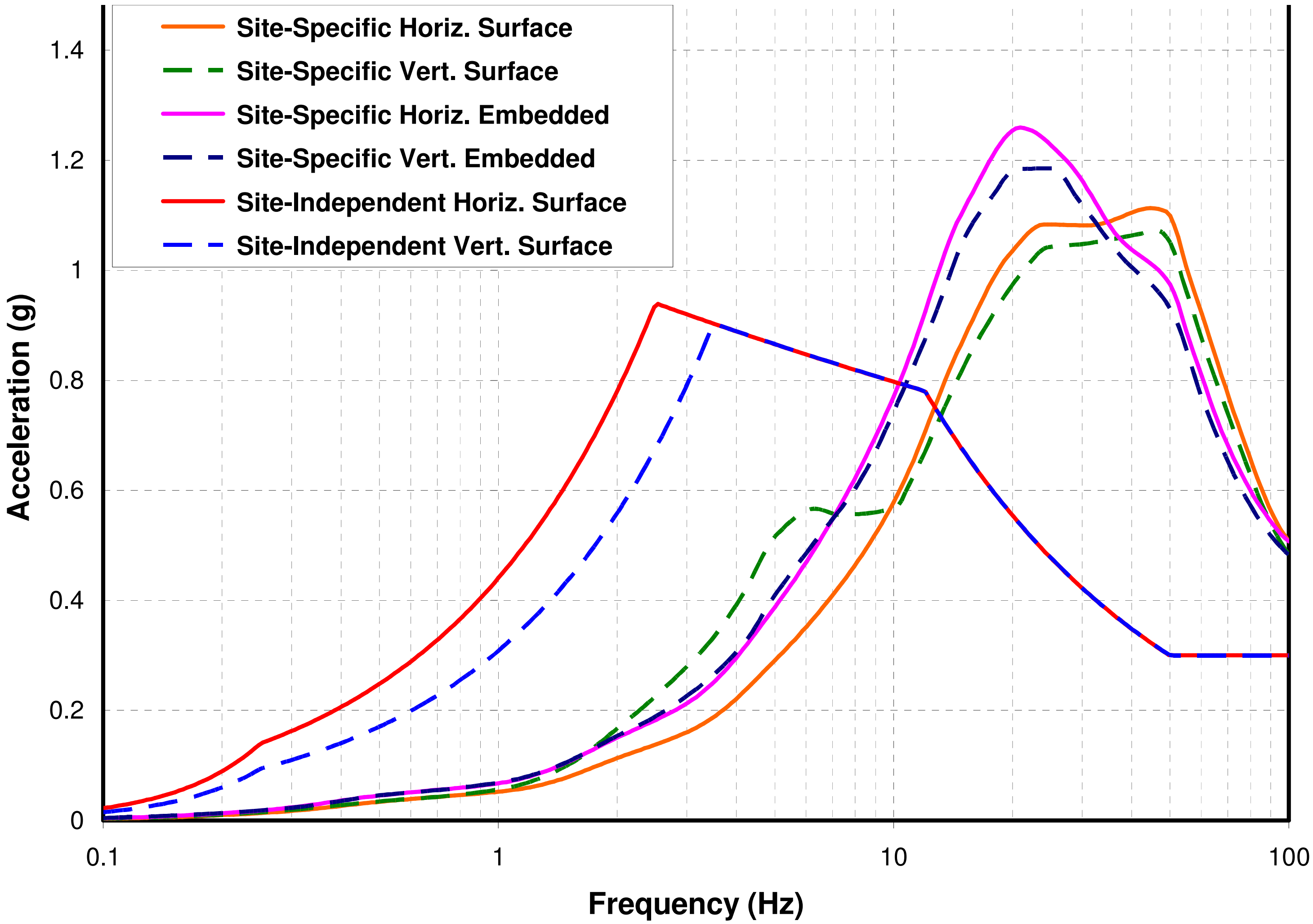
PART B: Case Studies

R/B Complex SSI Surface FE Model

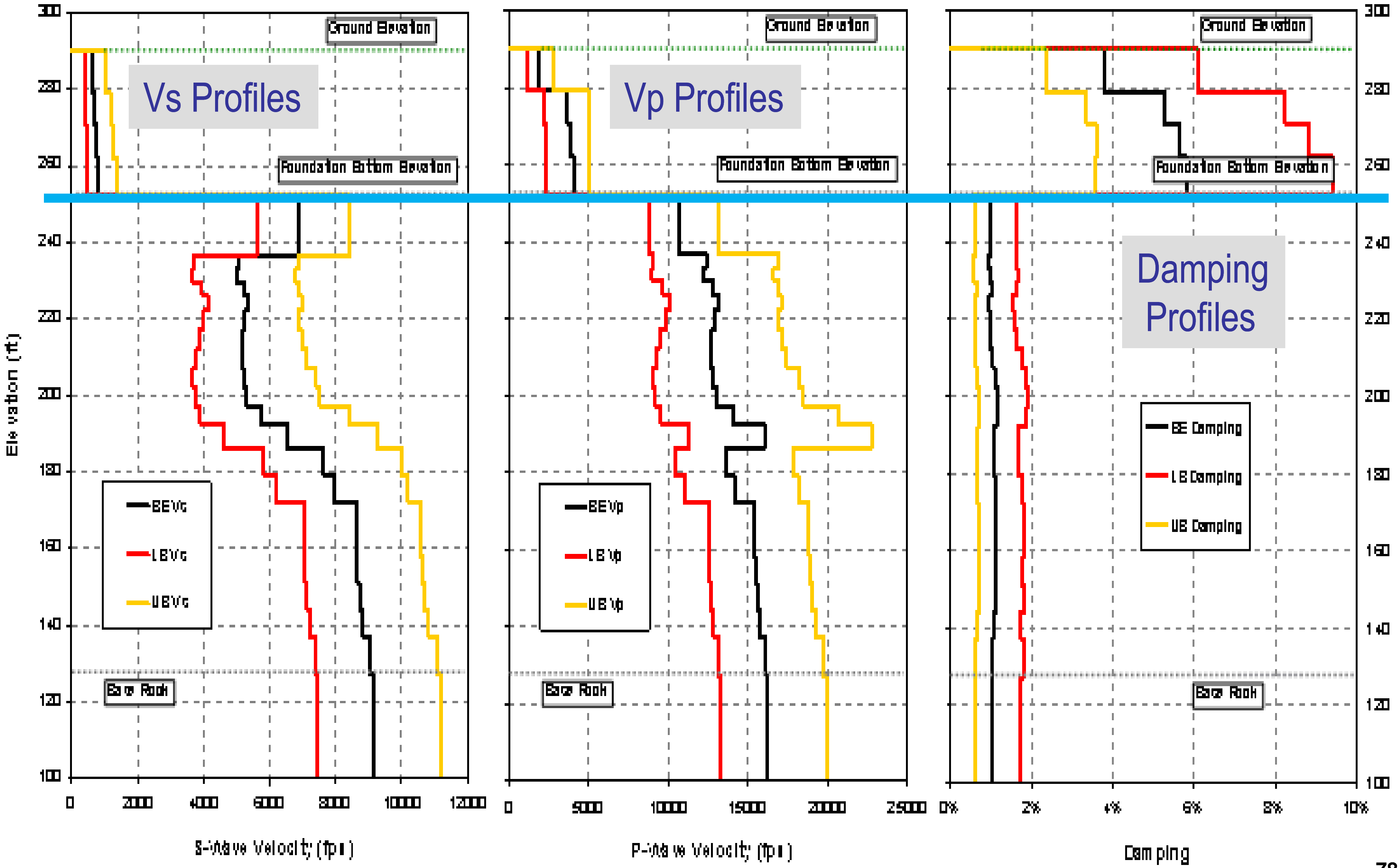
ACS SASSI Dynamic FE Model of R/B Complex



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

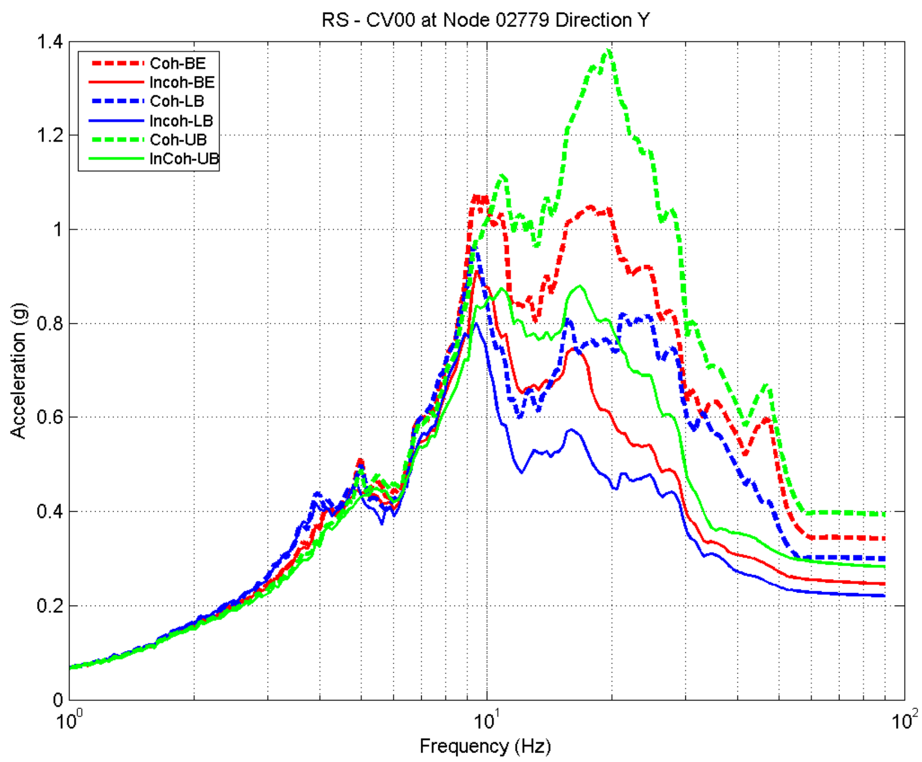


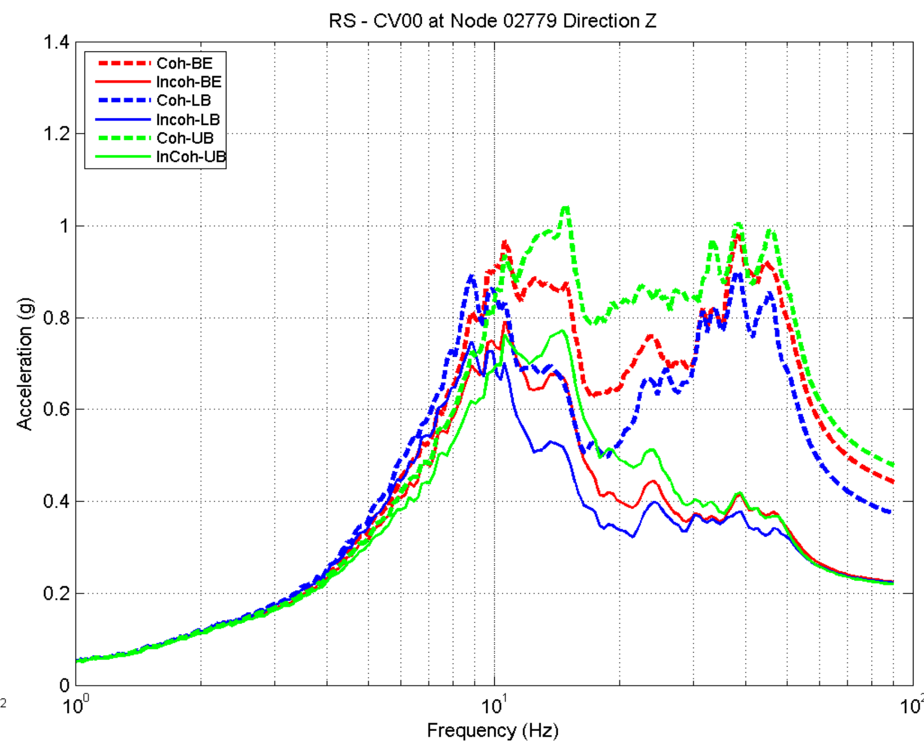
Best-Estimate (BE), Lower Bound (LB) and Upper Bound (UB) Soil Profiles



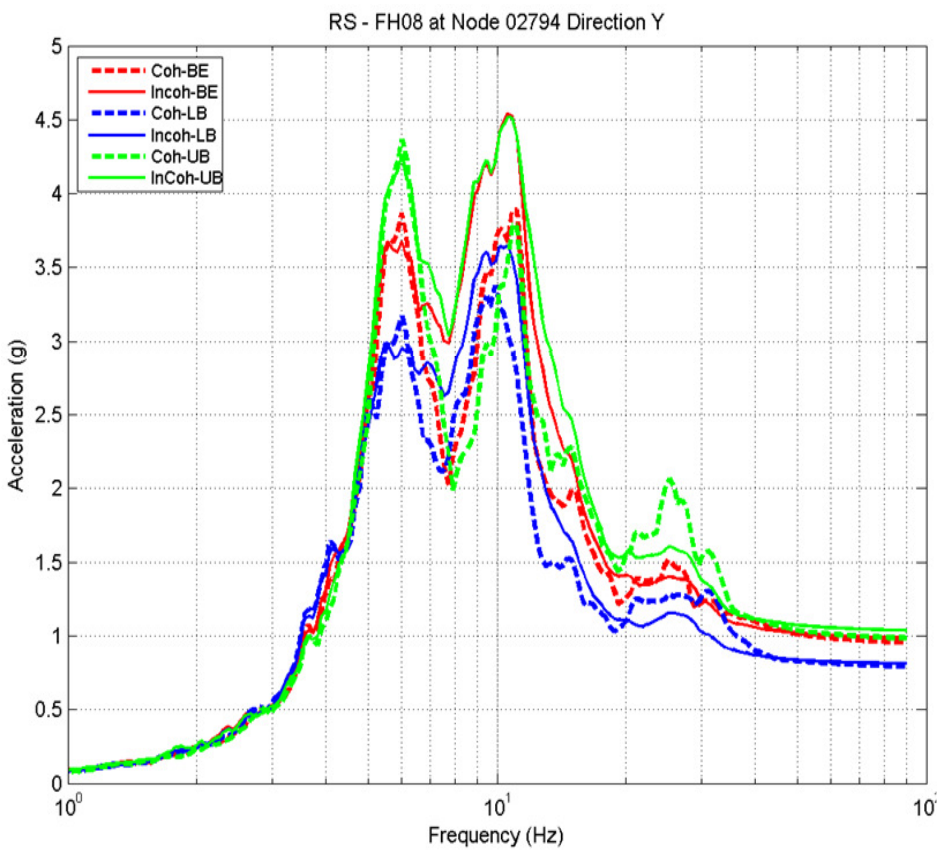
ISRS and Structural Force Results

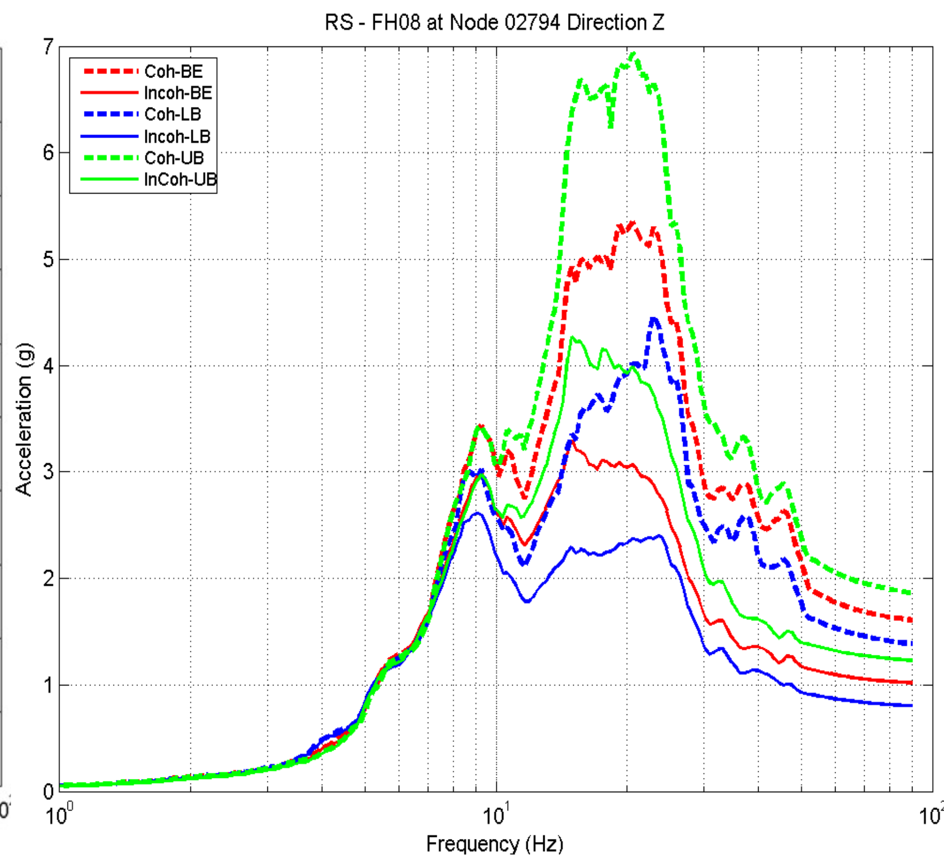
Coherent vs. Incoherent SSI Analysis Results.
5% Damp ISRS at PCCV Base-Center in Y and Z-Dir



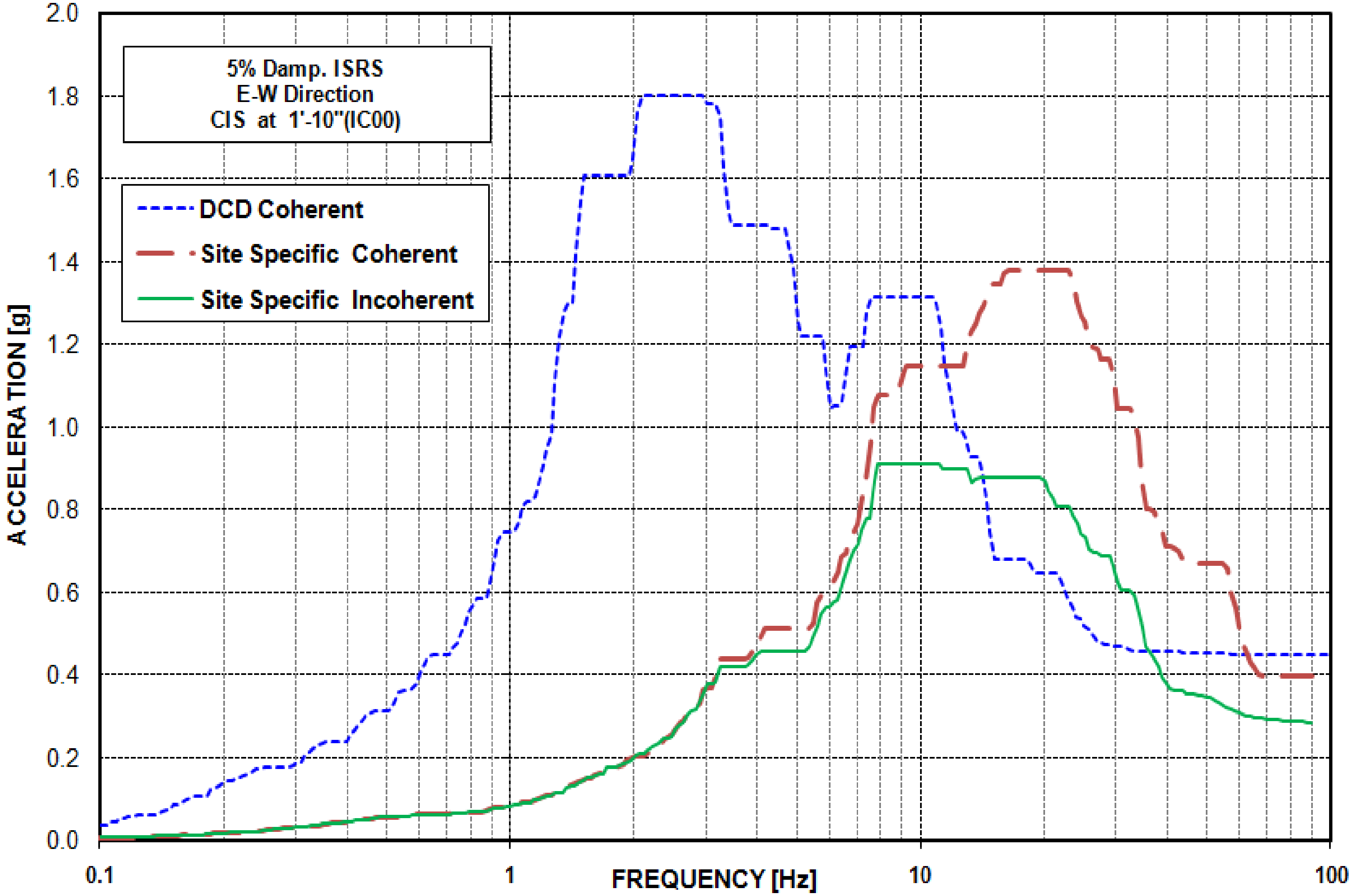


Coherent vs. Incoherent SSI Analysis Results.
5% Damp ISRS Plots at RB Top-Edge in Y and Z-Dir

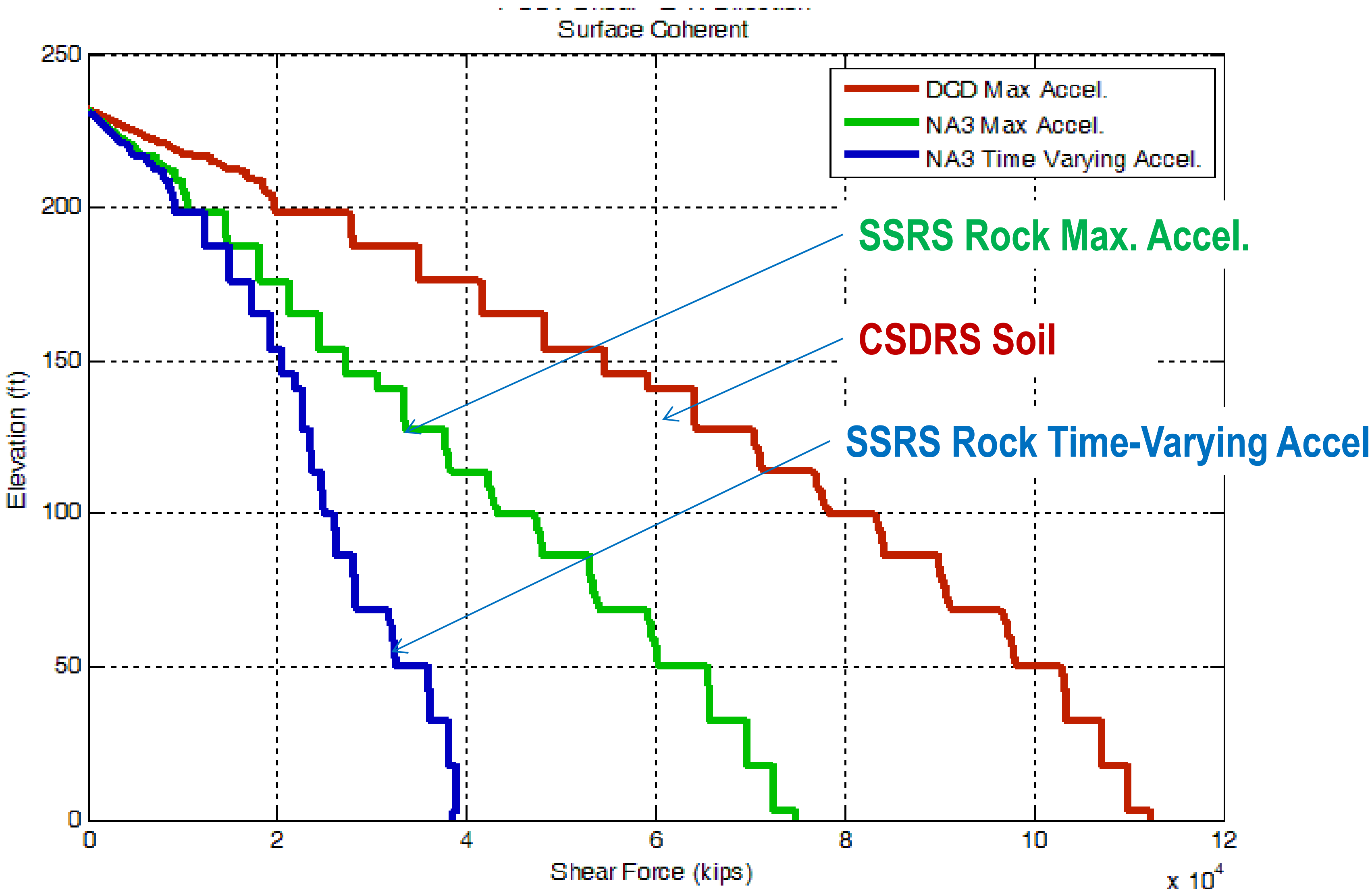




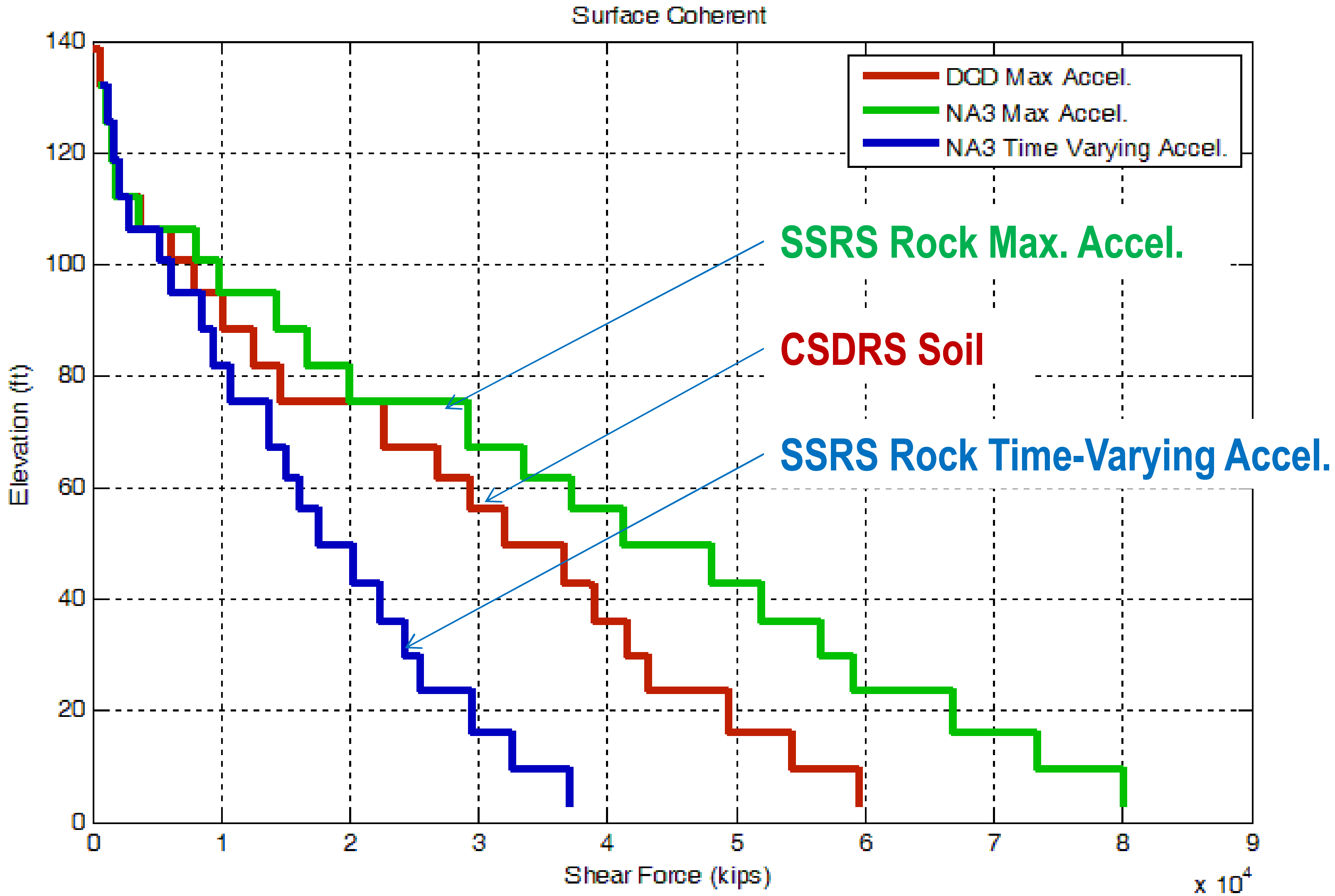
Site-Independent vs. Site-Specific Coherent and Incoherent Final ISRS Results at CIS Base in Y-Dir



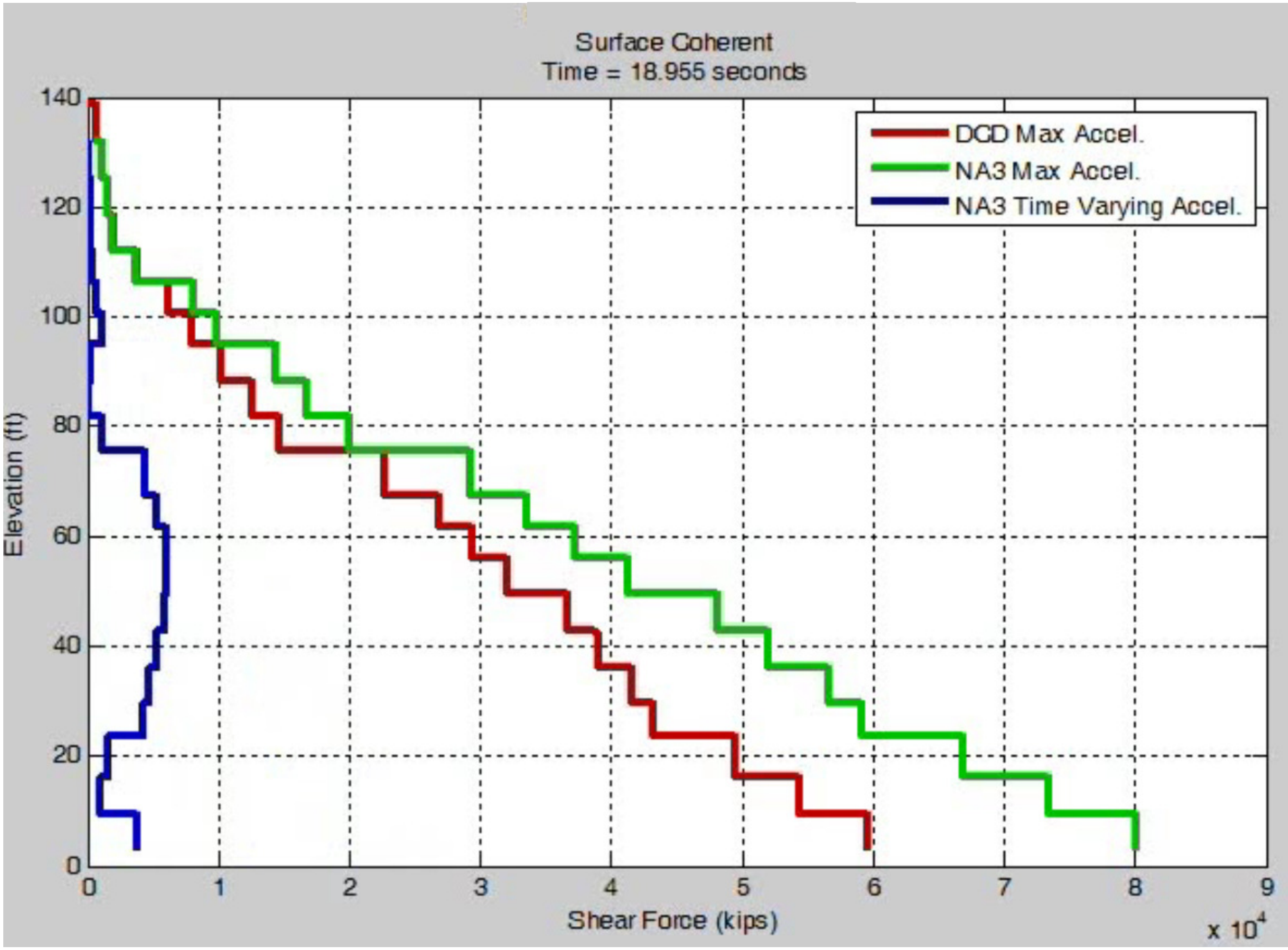
Soil Sites vs. Rock Sites Structural Forces. Maximum CS Shear Force in Y Direction



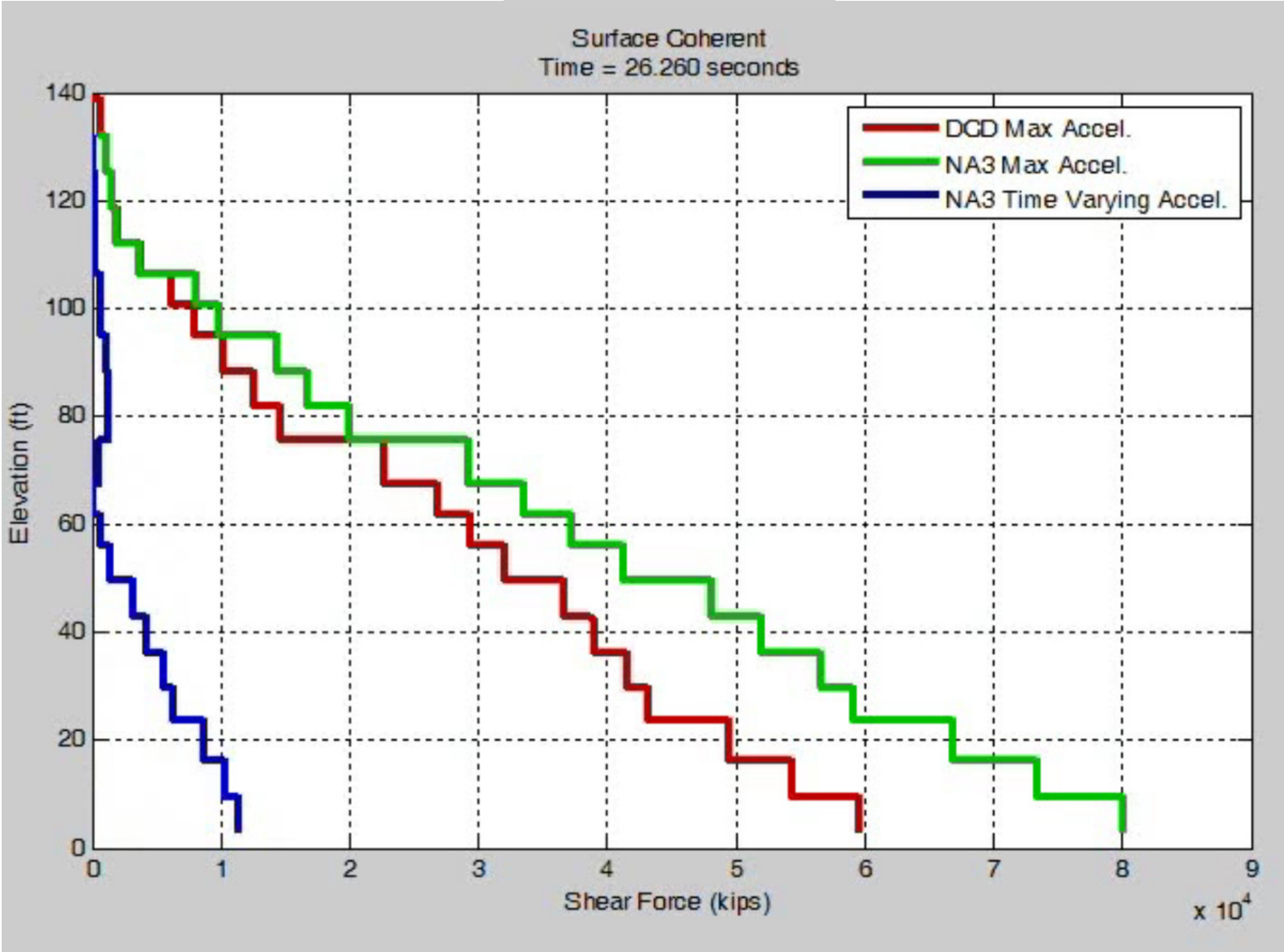
Soil Sites vs. Rock Sites Structural Forces. Maximum IS Shear Force in Y Direction



Instant IS Shear Force at 18.956 Sec.



Instant IS Shear Force at 26.260 Sec.

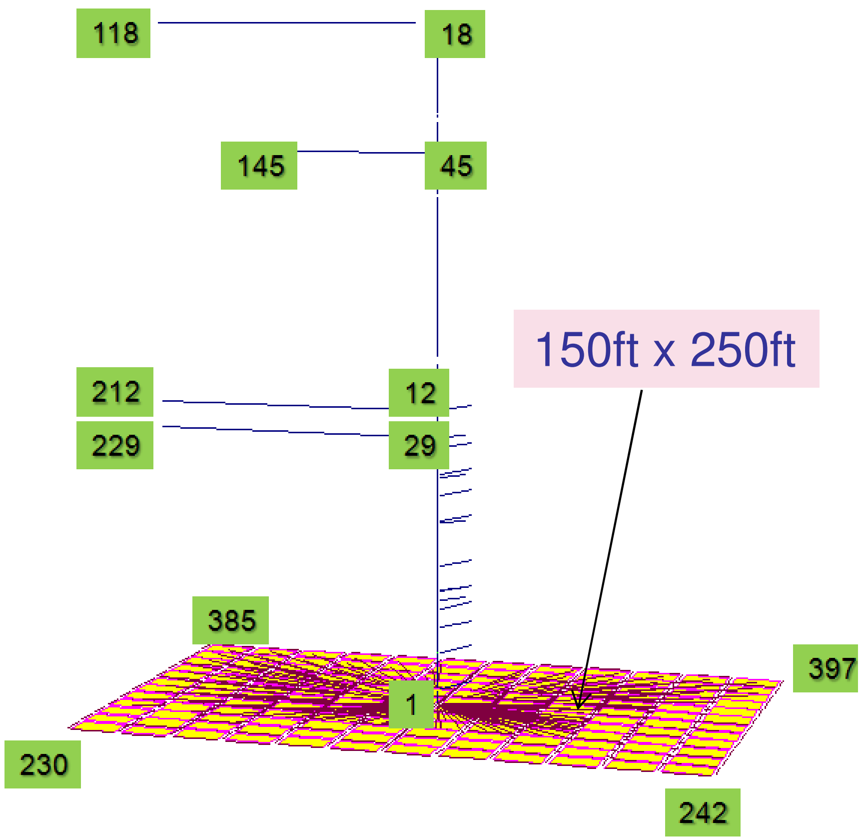


Conclusions

1) The use of maximum acceleration 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.

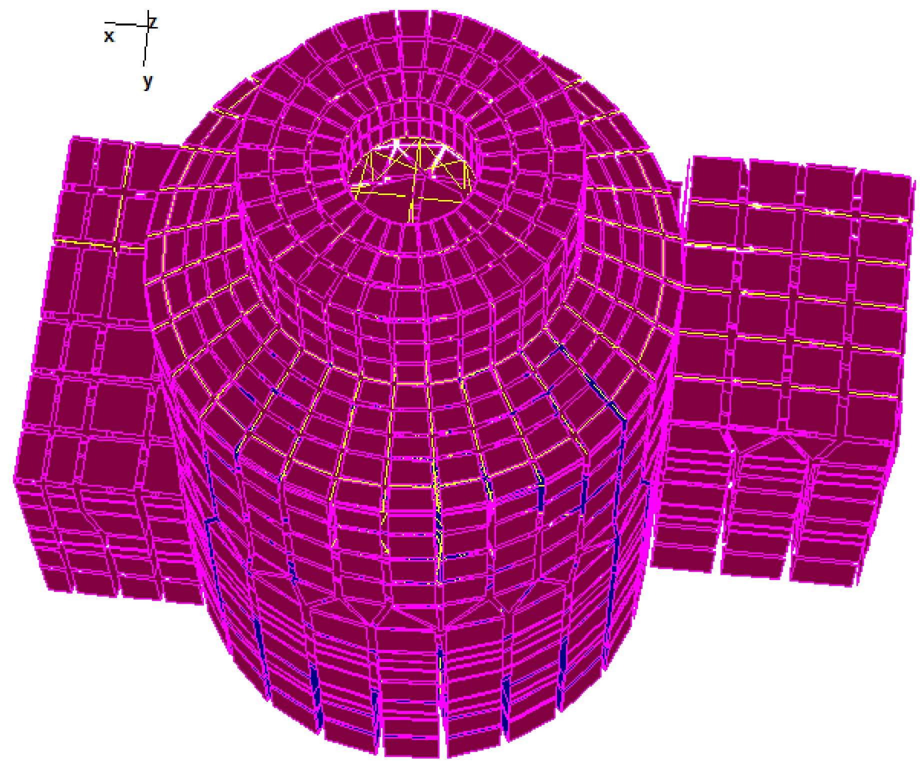
Stick with Rigid Mat vs. FE Model with Flexible Mat

Stick SSI Model



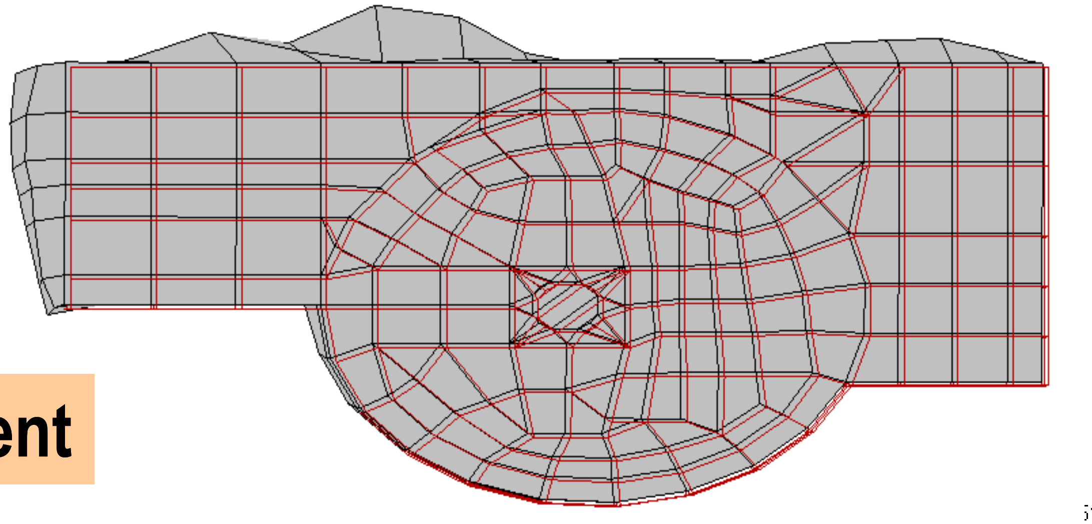
Accurate structural modeling up to 20-30 Hz

NI20 SSI Model

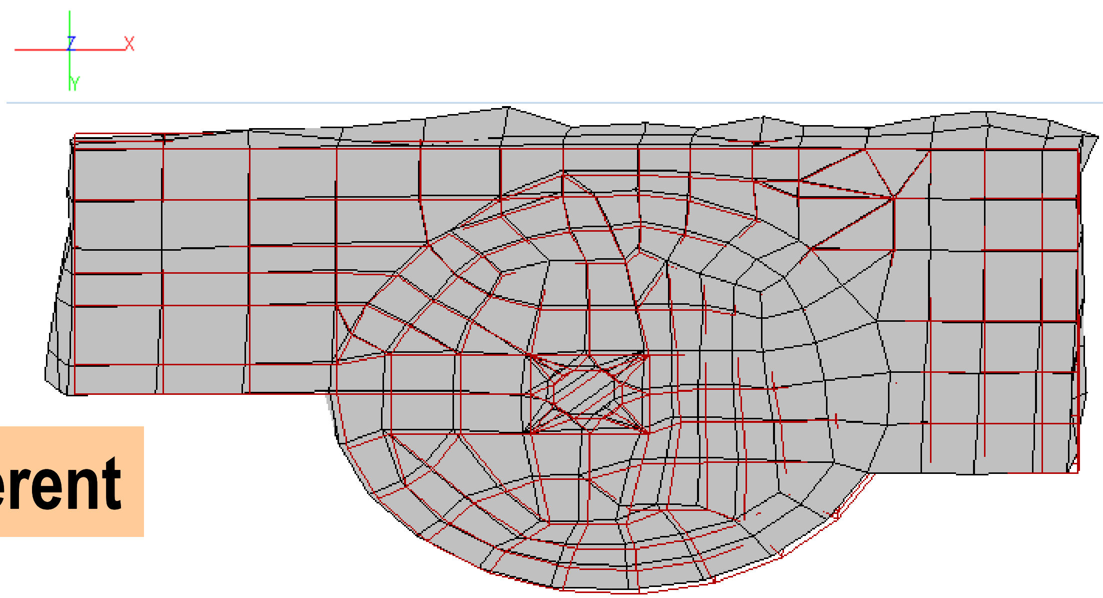


Accurate structural modeling up to 100 Hz

Coherent vs. Incoherent Basemat SSI Motion

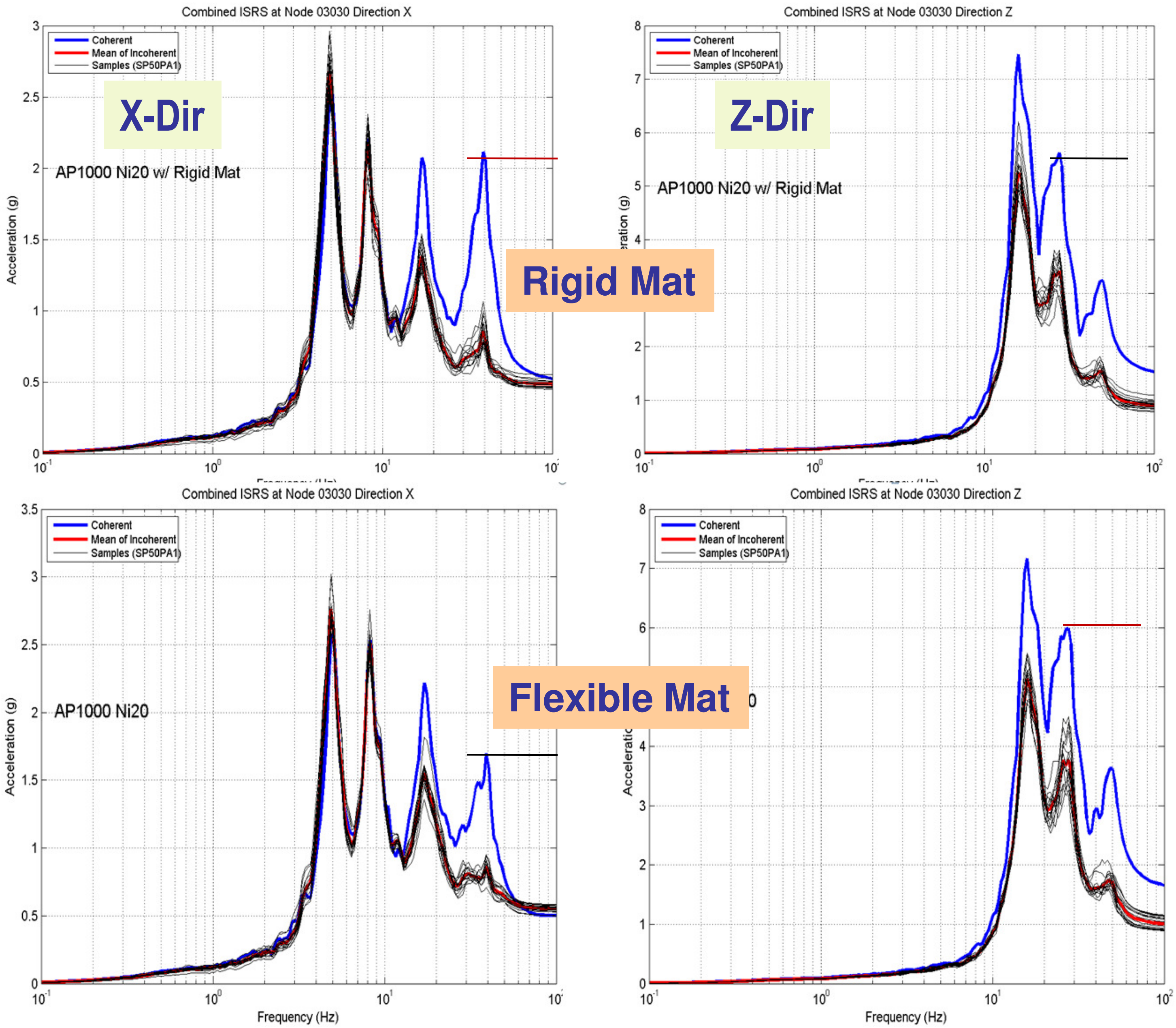


Coherent

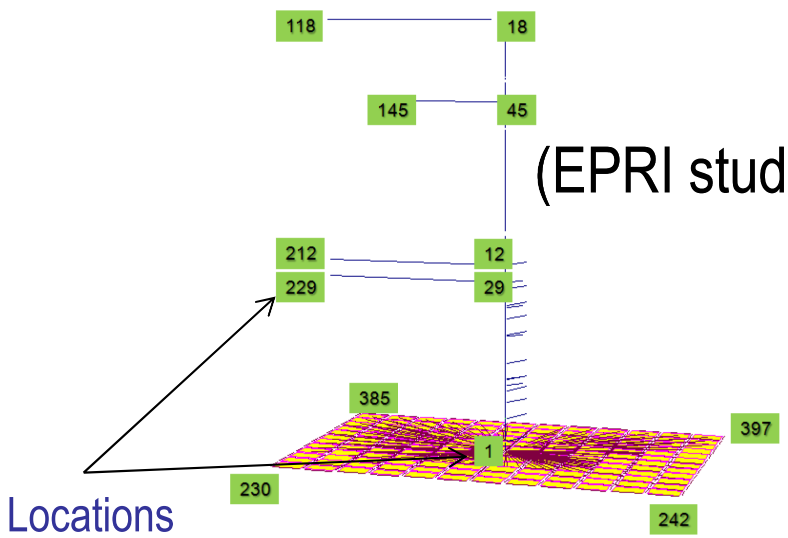


Incoherent

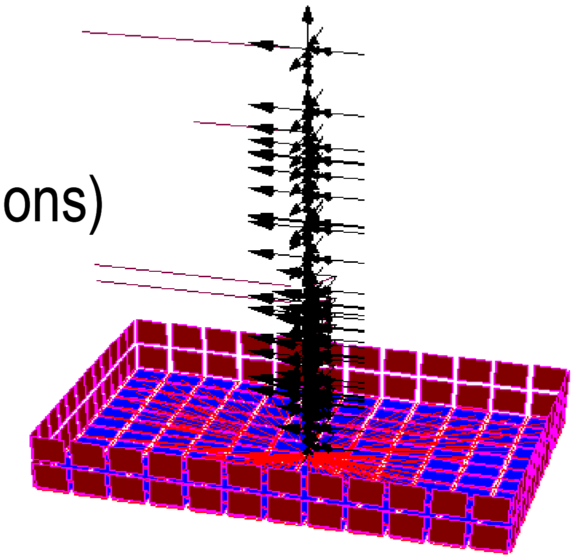
AP1000 NI20 Model Basemat Flexibility Study

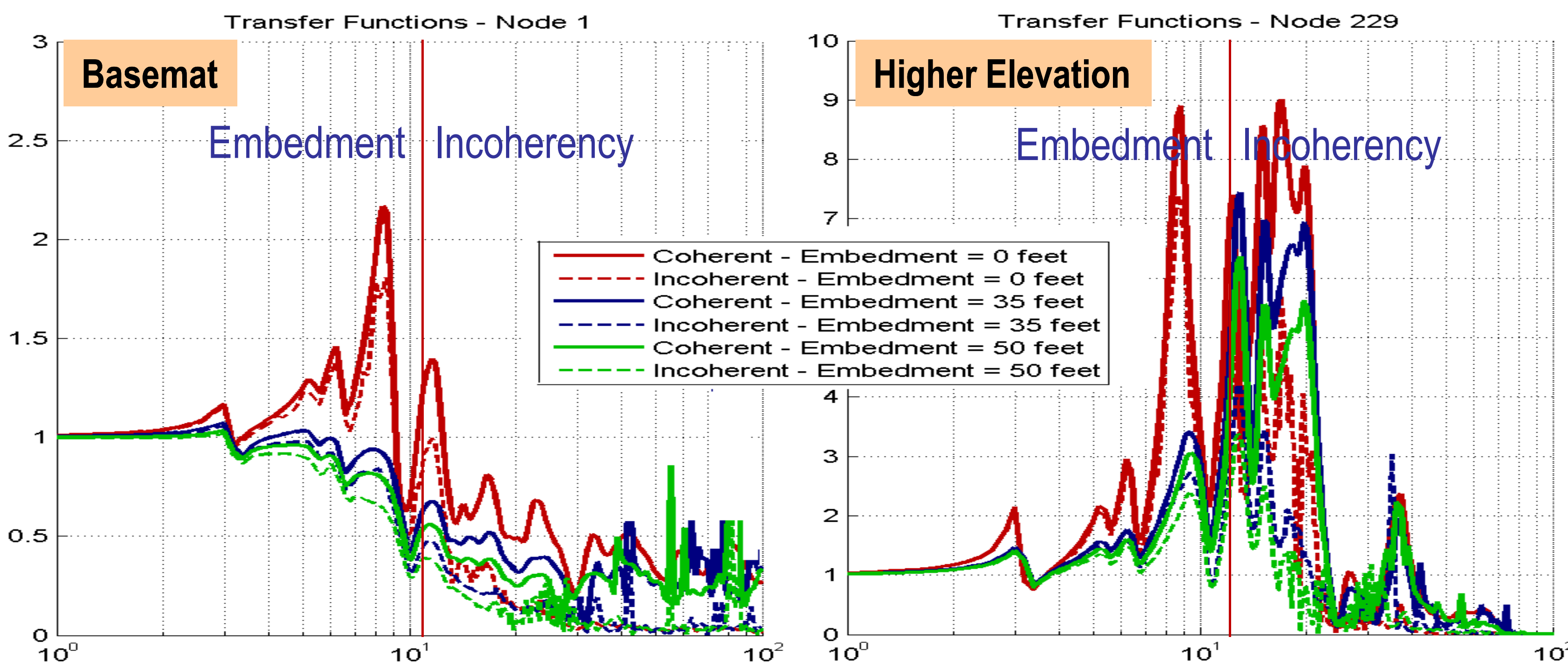


Embedded EPRI AP1000 Stick Incoherent SSI Studies



(EPRI study site conditions)

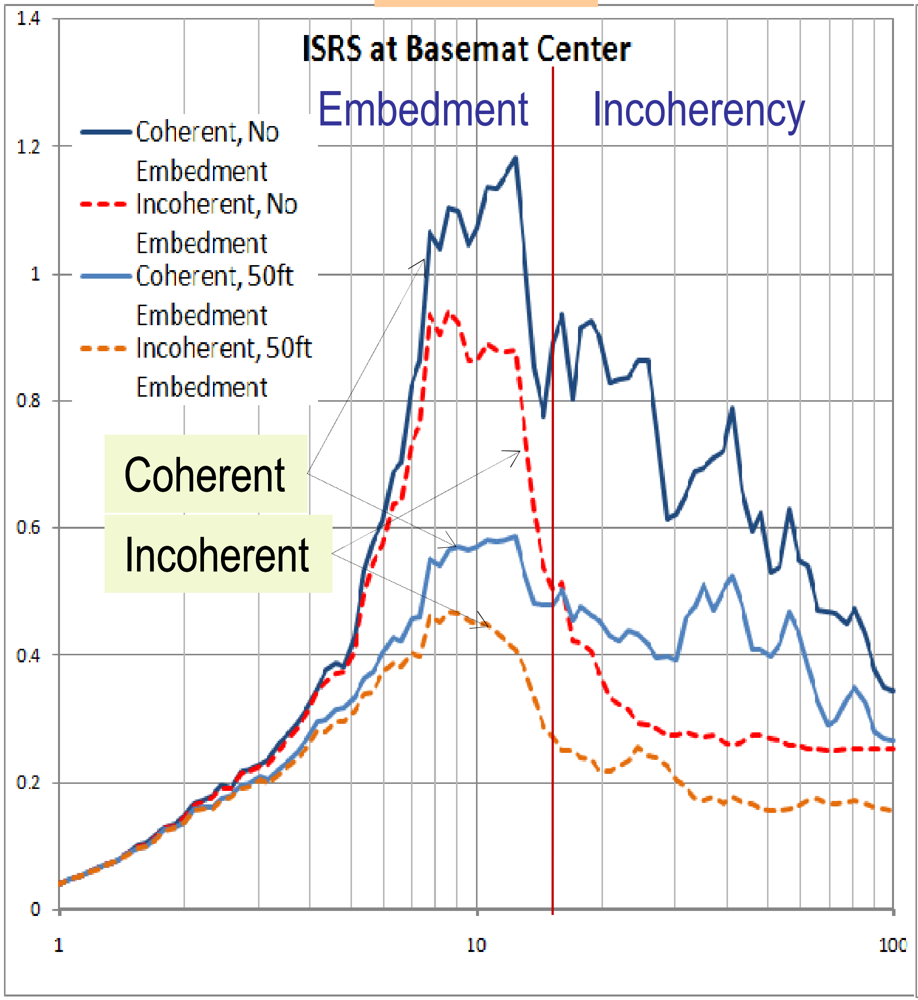




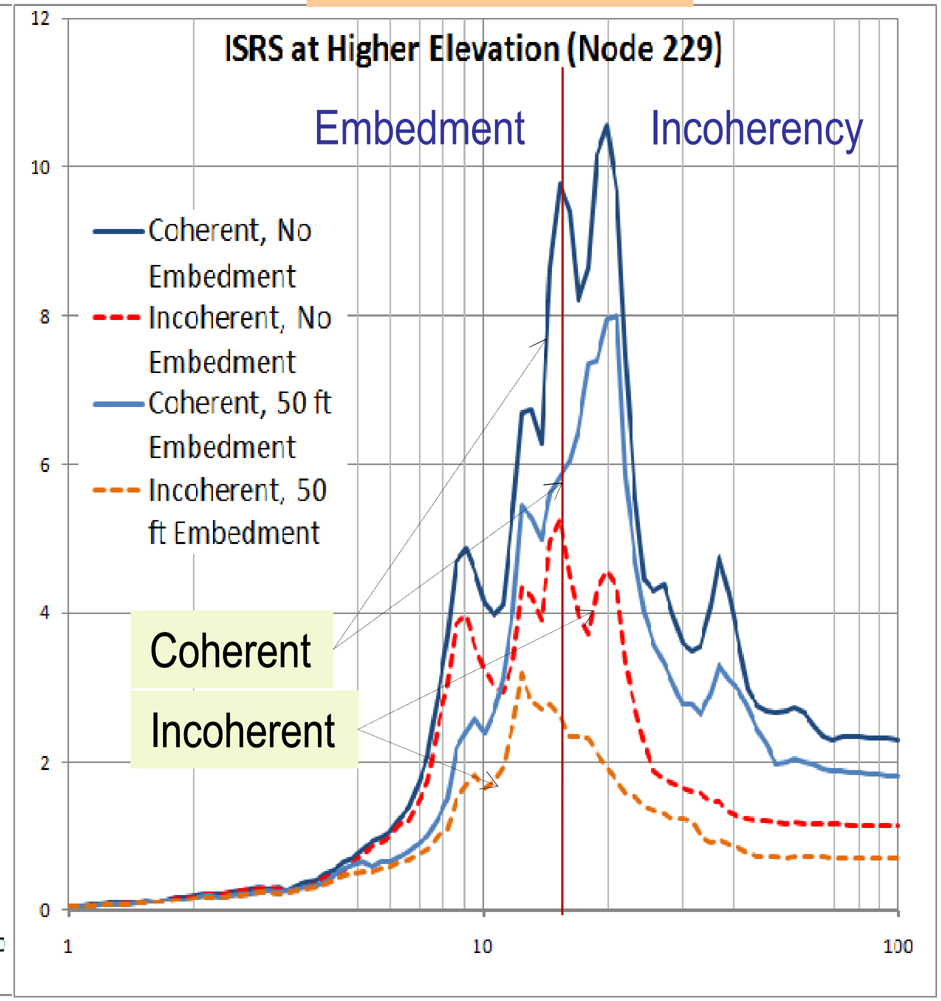
Embedded EPRI AP1000 Stick ISRS Response

(EPRI study model, input and site conditions)

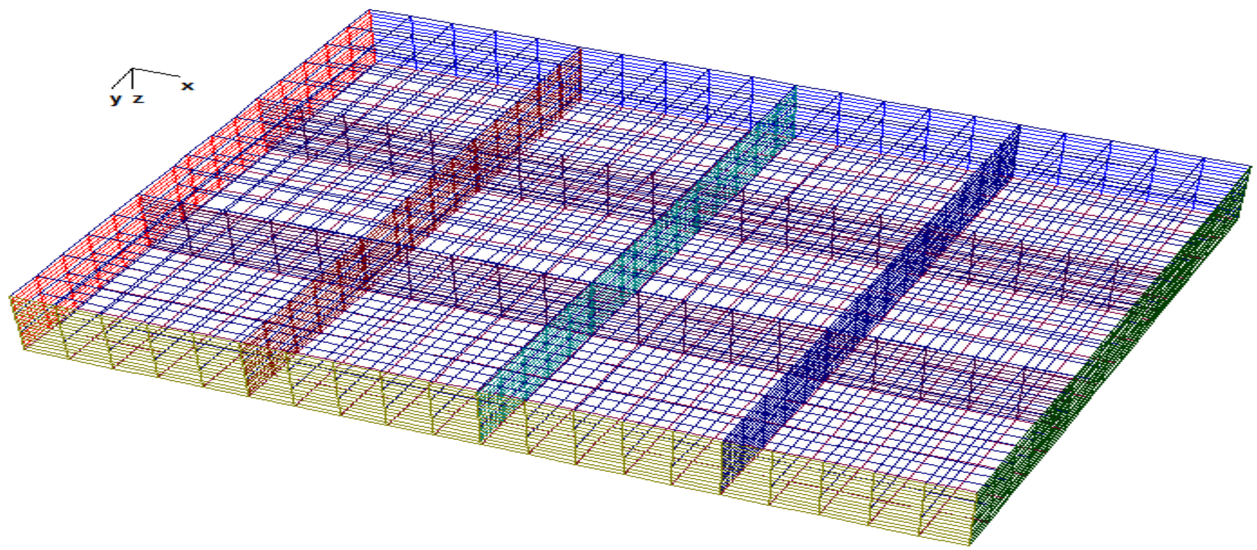
Basemat



Higher Elevation



Large-Size Shear Wall Structure

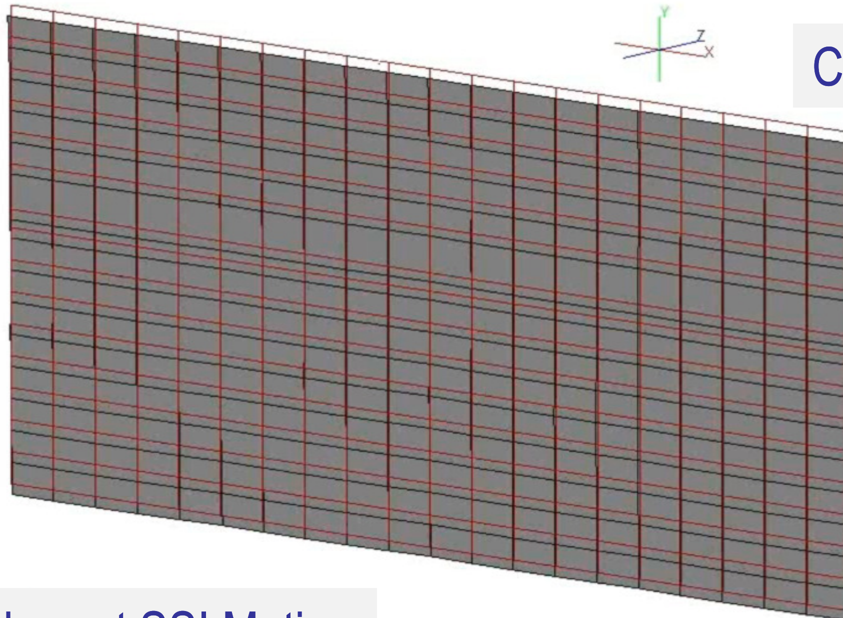


SSI Analysis Inputs:

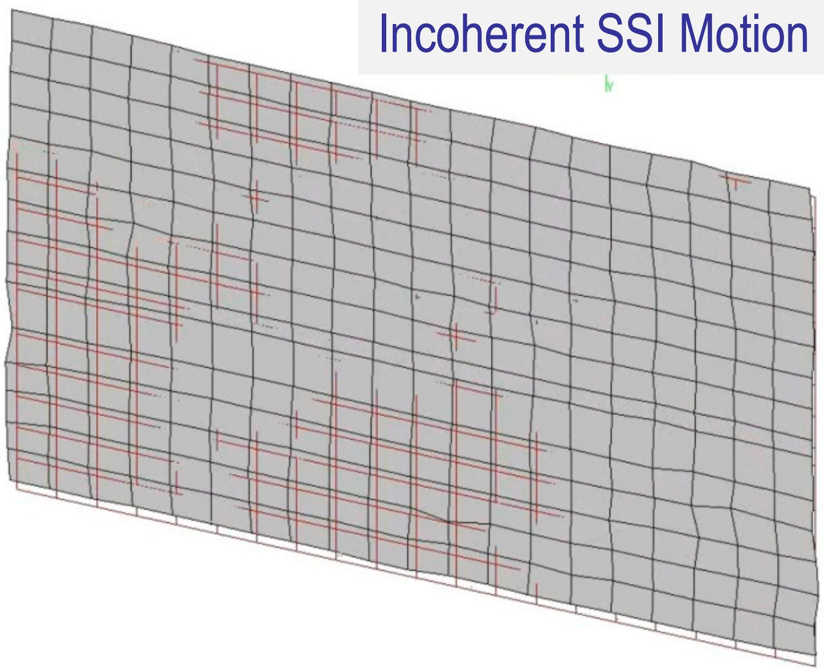
- Structure: Assumed with surface flexible foundation of 350ft x 450ft size
- Soil Deposit: Uniform soil layering with Vs of 4,500 fps
- Control Motion: HRHF Input (EPRI input, RS highest in 20-30 Hz range)
- Incoherency: 2007 Abrahamson Coherence Function for Hard-Rock
- Wave Passage: Va = 6,000 fps at 30 degree angle with X longitudinal axis

NOTE: It should be noted that at this time only the 2007 Abrahamson for hard-rock site conditions is permitted by US NRC.

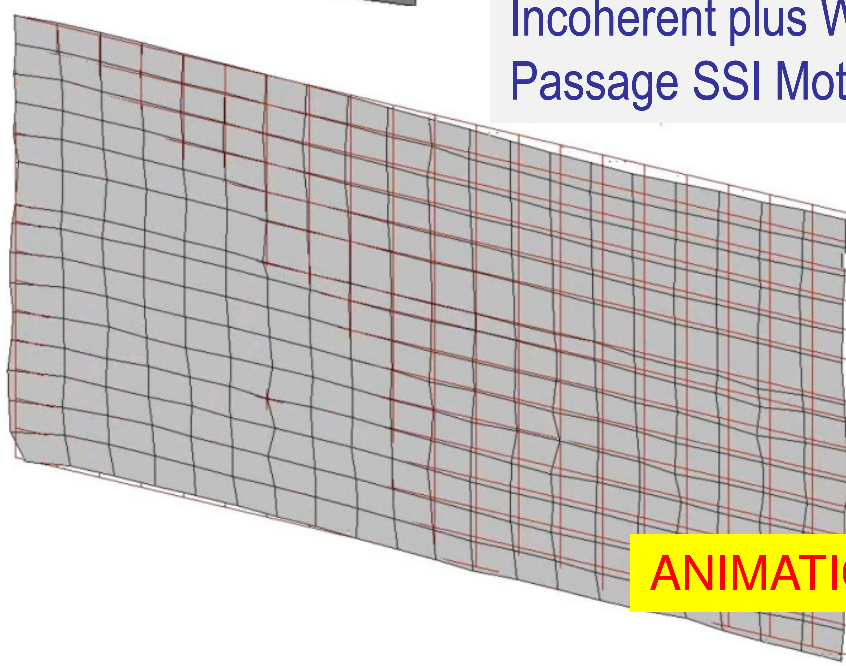
Coherent and Incoherent Basemat SSI Motion View



Coherent SSI Motion



Incoherent SSI Motion



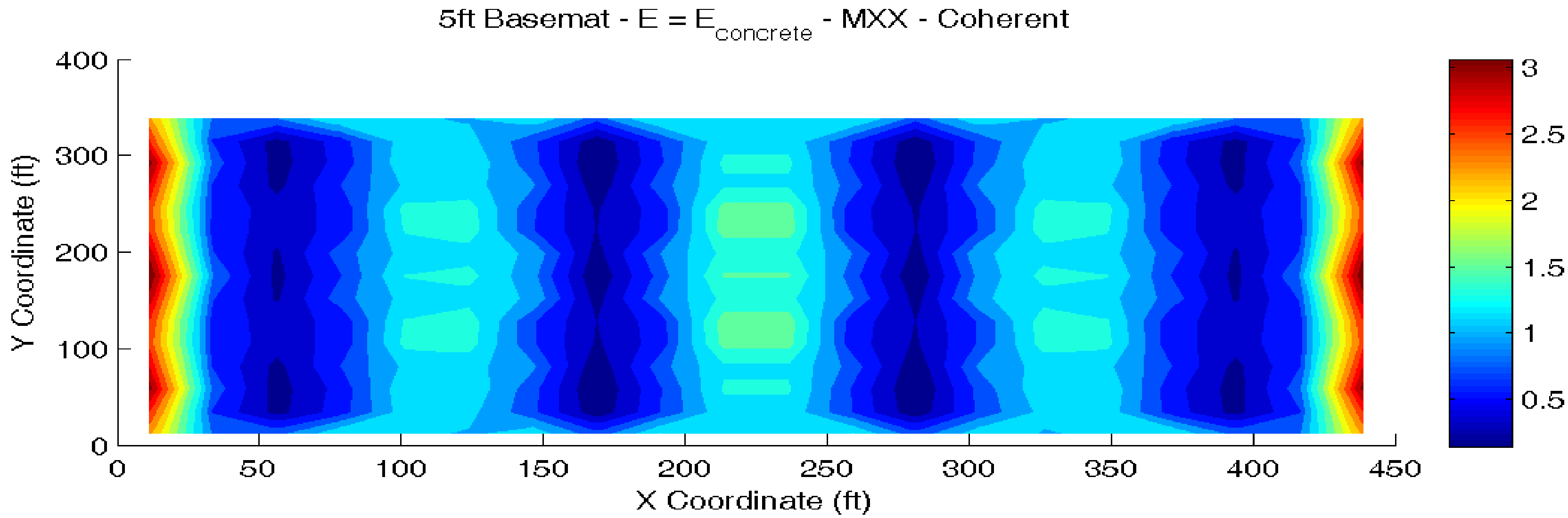
Incoherent plus Wave Passage SSI Motion

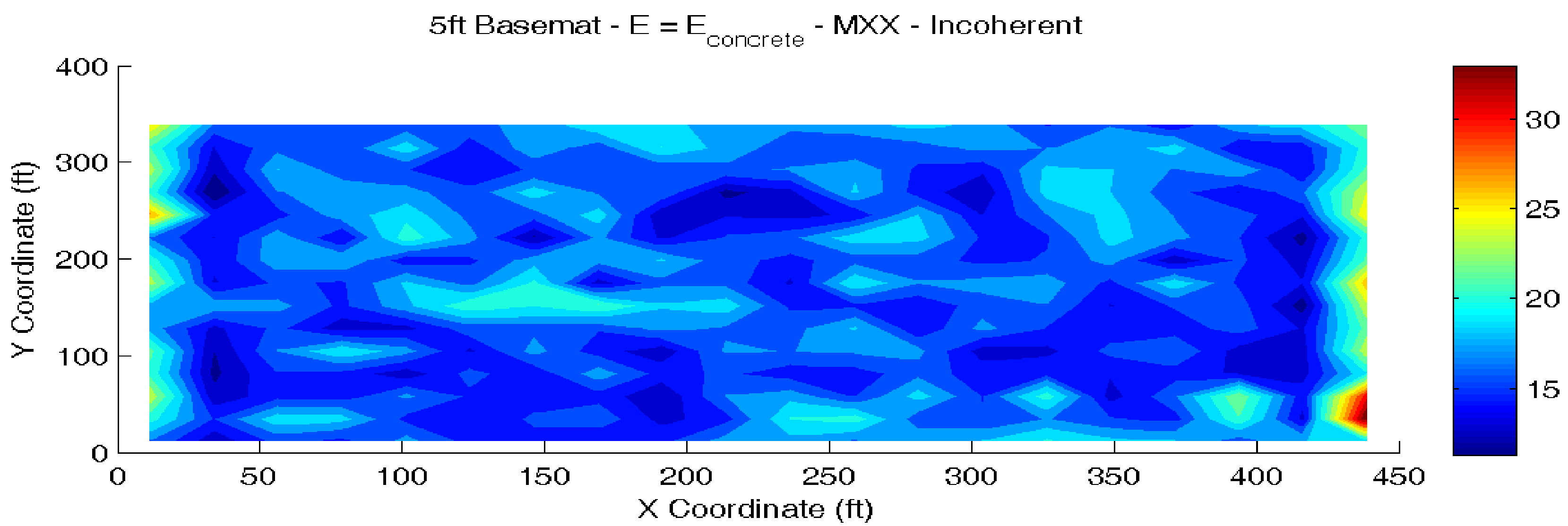
ANIMATIONS

Coherent and Incoherent Forces and Moments in External and Internal Shear Walls

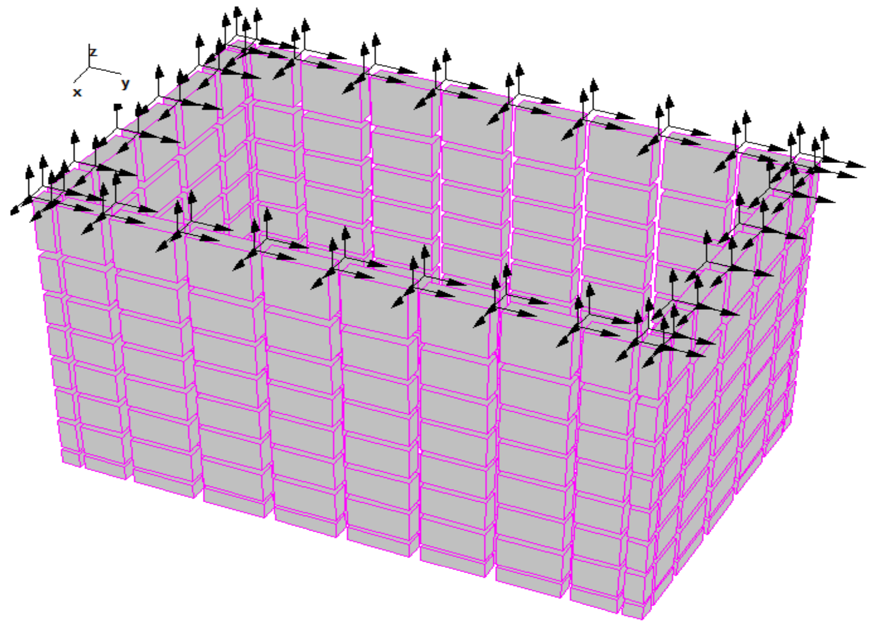
Element	Analysis	Va	Value	Axial	Shear	Moment
	coh		max	35.398	28.541	3.476
			max	26.987	24.671	3.809
external wall	incoh	Infinity	ratio	0.762	0.864	1.096
			max	40.309	31.365	4.474
		6000	ratio	1.139	1.099	1.287
	coh		max	19.313	45.618	2.874
			max	14.940	35.326	2.242
interior wall	incoh	Infinity	ratio	0.774	0.774	0.780
			max	13.807	32.663	1.811
		6000	ratio	0.715	0.716	0.630

Coherent and Incoherent Basemat SSI Response
Basemat Bending Moments, MXX





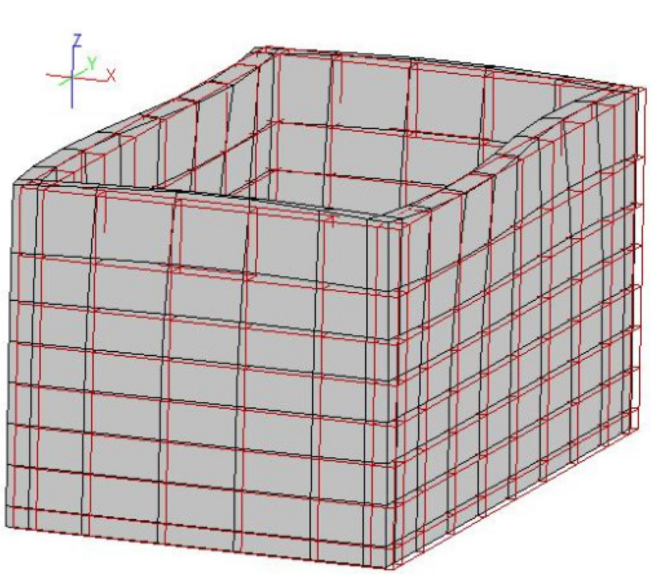
30 ft Embedded Concrete Pool Structure



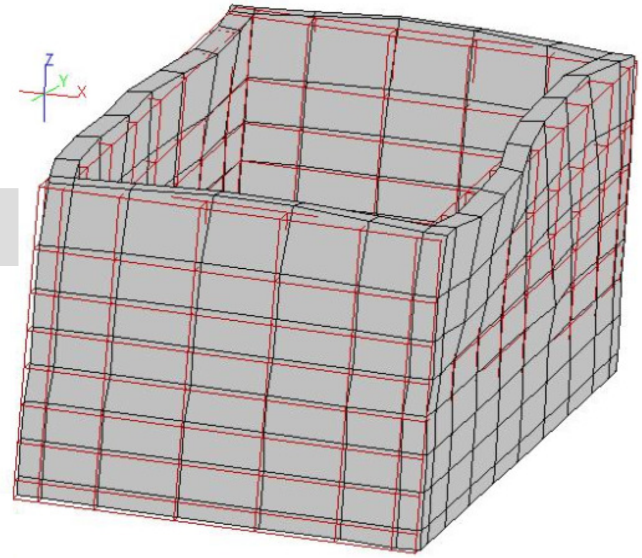
ACS SASSI SSI Analysis Inputs:

- Structure: Embedded Concrete Pool Structure of 50ft x 80ft Size
- Soil Deposit: Uniform soil layering with Vs of about 1,000fps
- Control Motion: RG 1.60 Input
- Incoherency: 2007 Abrahamson Coherence Function for Soil

Coherent and Incoherent SSI Motions and Stresses

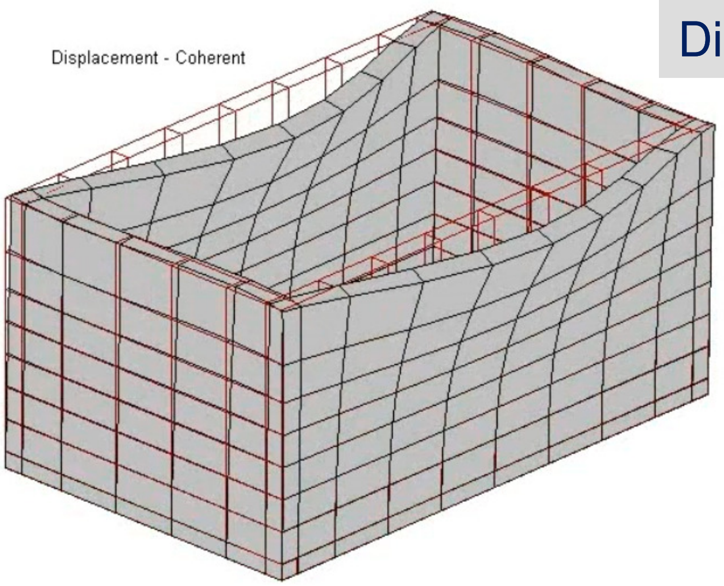


Accelerations

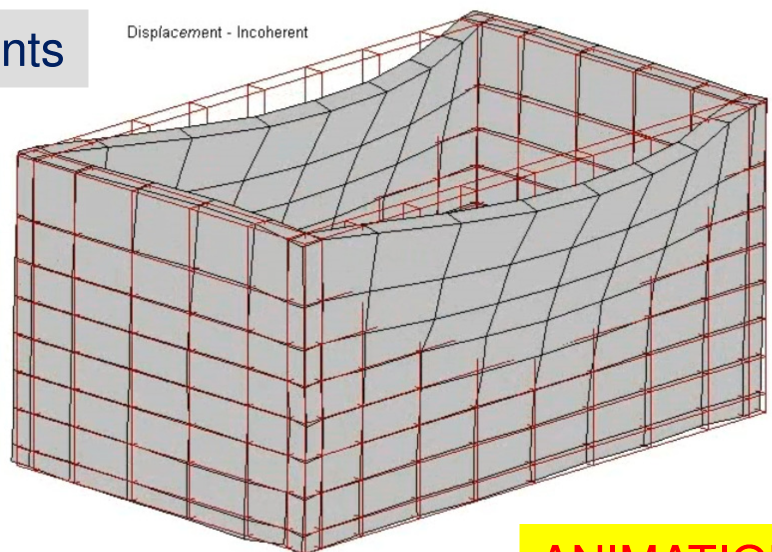


Coherent

Incoherent



Displacements

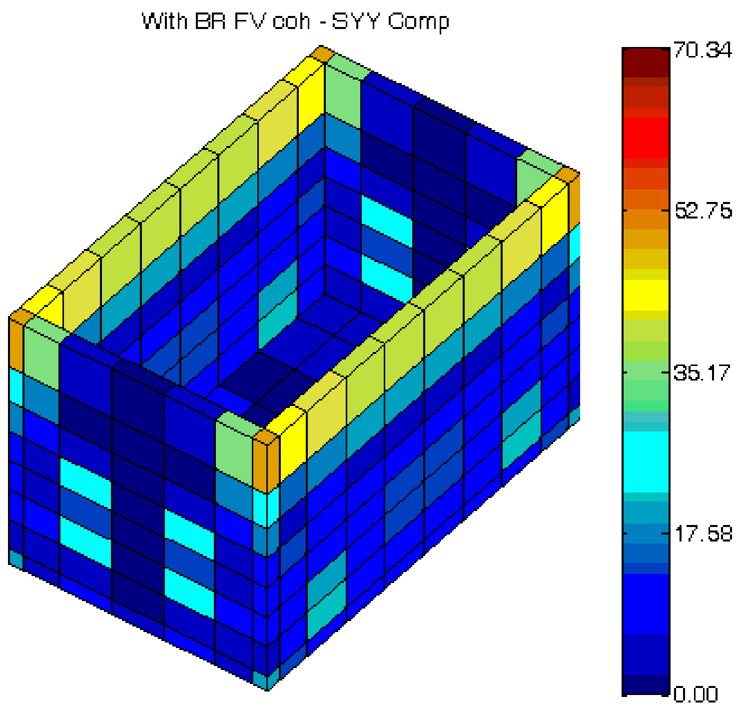


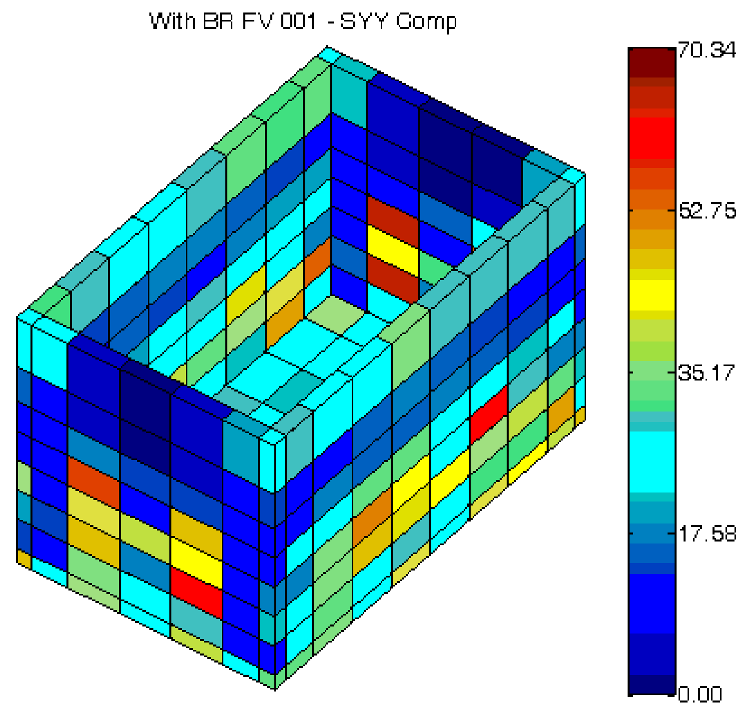
ANIMATIONS

Seismic Coherent vs. Incoherent Stresses for X-Input

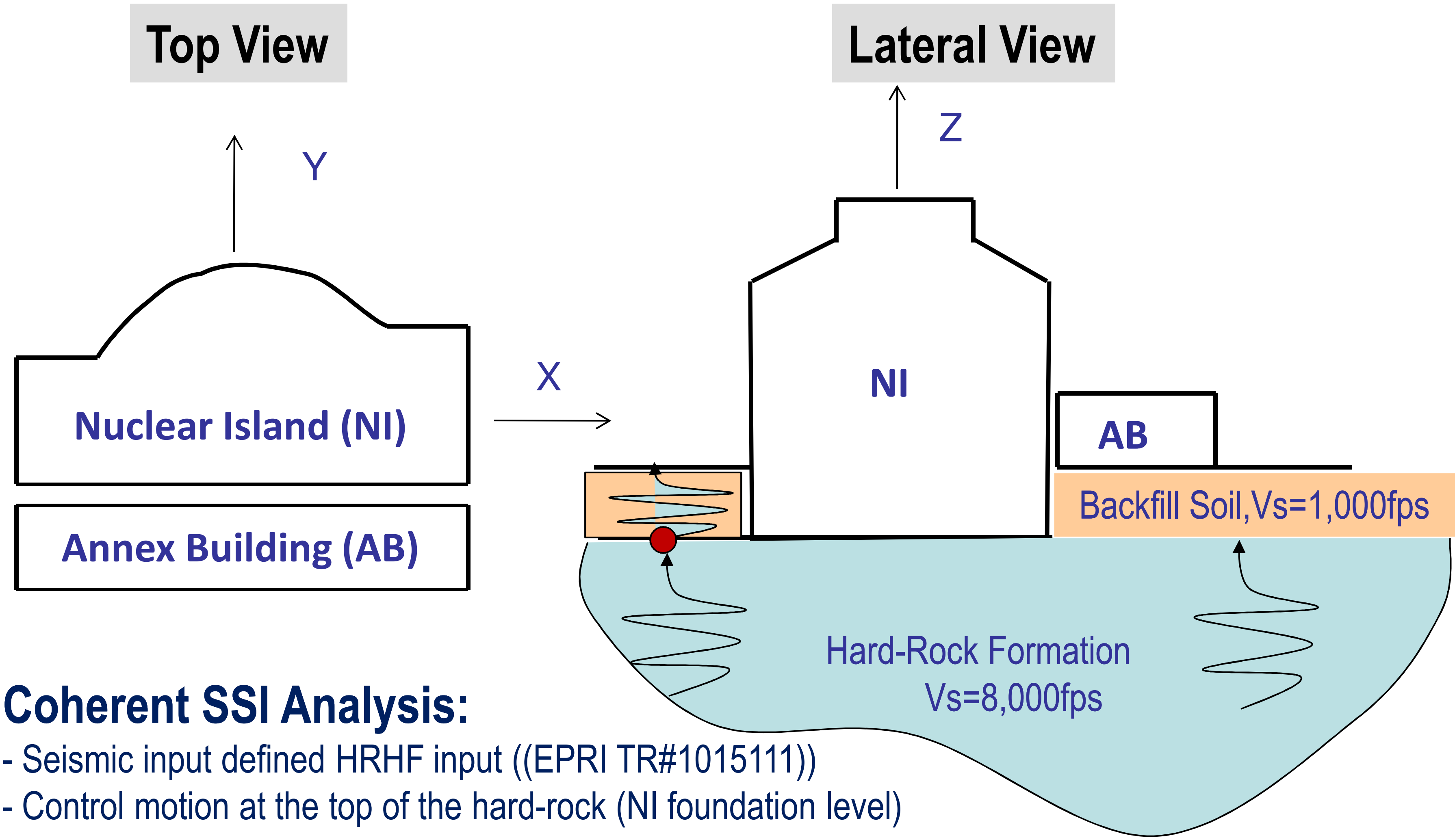
Backfill Soil Layer with Vs = 1.000 on Rock Vs = 5,500fps

Element Center Stresses SYY





AP1000 NI Complex and Annex Bldg Configurations



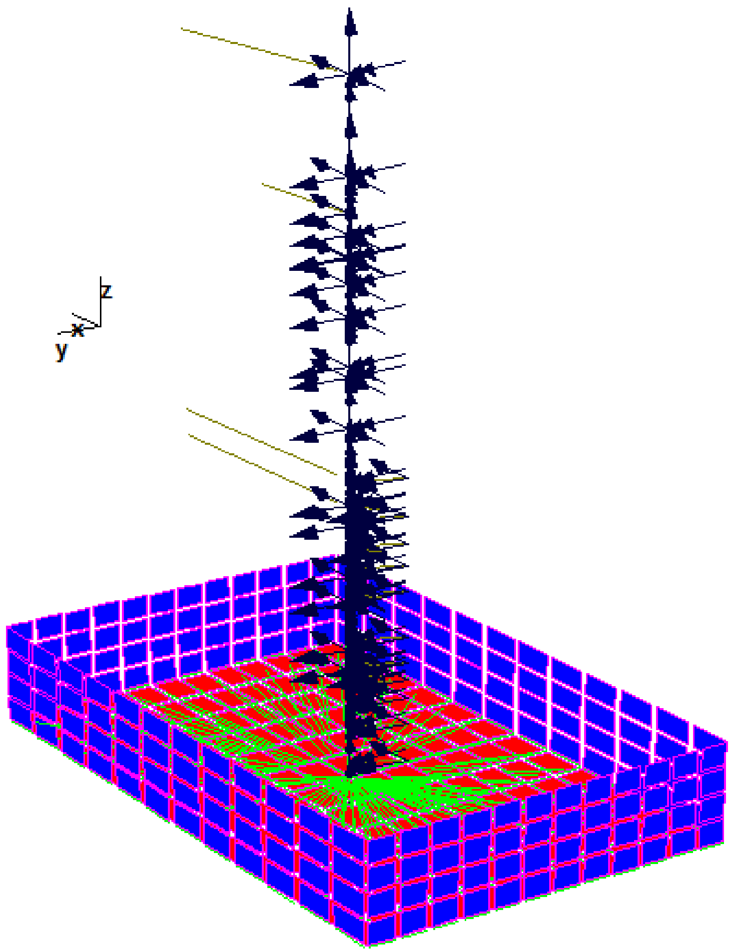
Coherent SSI Analysis:

- Seismic input defined HRHF input ((EPRI TR#1015111))
- Control motion at the top of the hard-rock (NI foundation level)

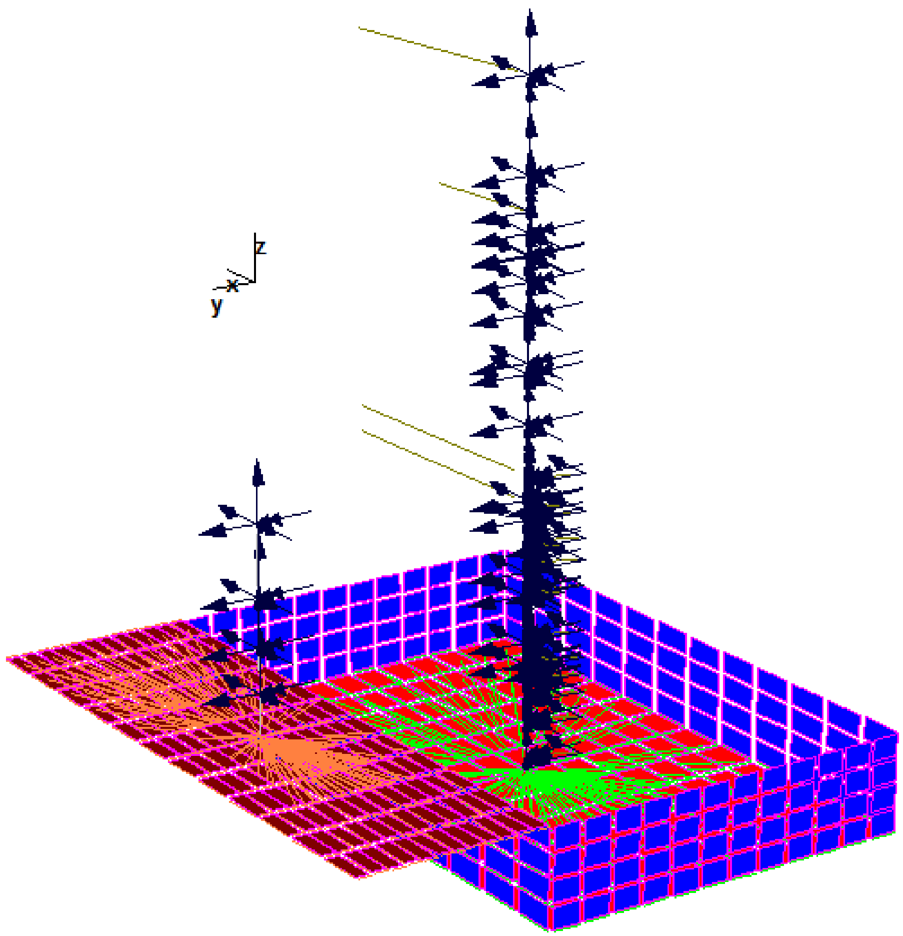
Incoherent SSI Analysis:

- Stochastic Simulation with 8 simulations (EPRI TR#1015111)
- 2007 Abrahamson coherency model for hard-rock sites (EPRI TR#1015110)

Seismic SSI Stick Model (AP1000 NI) Used for Studies



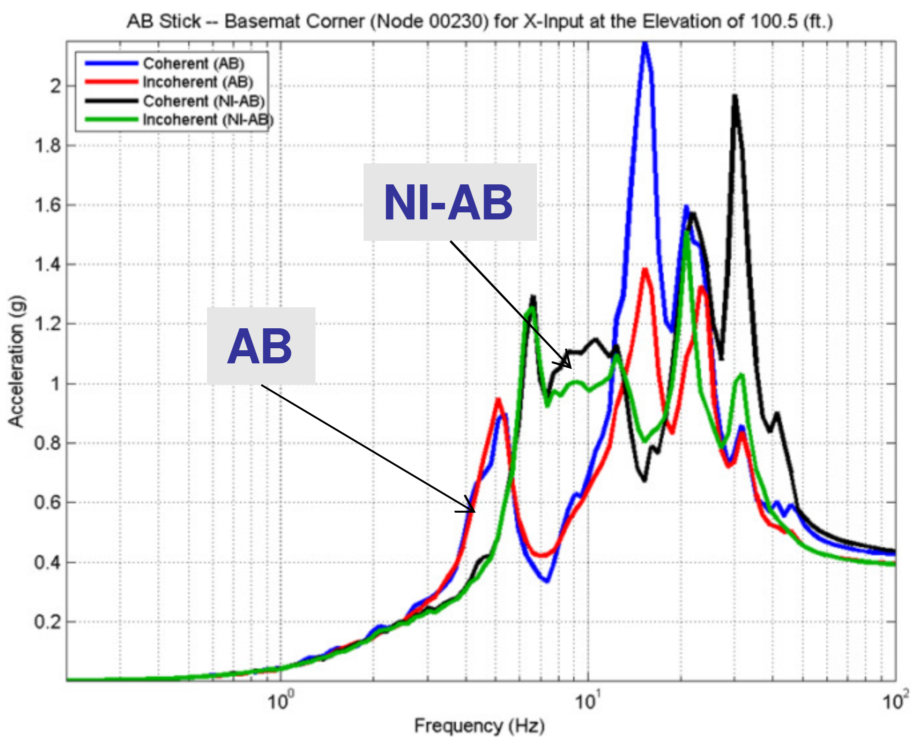
Isolated Structure



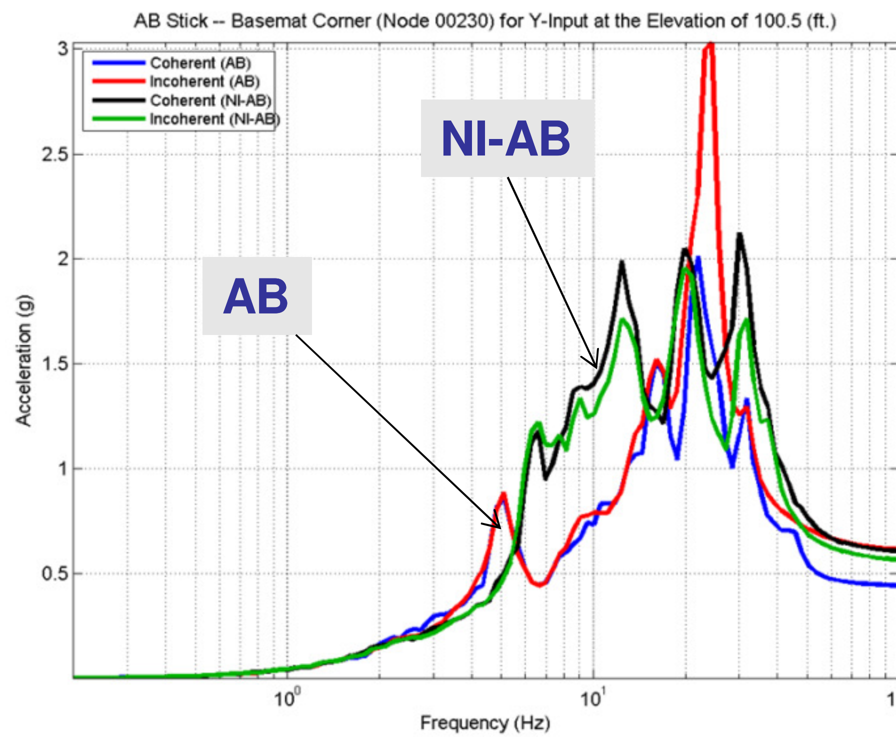
Multiple Structures

AB and Coupled NI-AB Coherent and Incoherent SSI. 5% Damp ISRS Y-Dir at AB Basemat Corner (El. 100ft)

X-Direction



Y-Direction



ANIMATIONS

Two Step Approach to Seismic SSI Analysis (ACS SASSI-ANSYS Interfacing)

ACS SASSI-ANSYS integration provides new SSI analysis capabilities:

For structural stress analysis:

- *ANSYS Equivalent-Static Seismic SSI Analysis* Using Refined Mesh FE Models
- *ANSYS Dynamic Seismic SSI Analysis* Using Nonlinear or More Refined FE Models

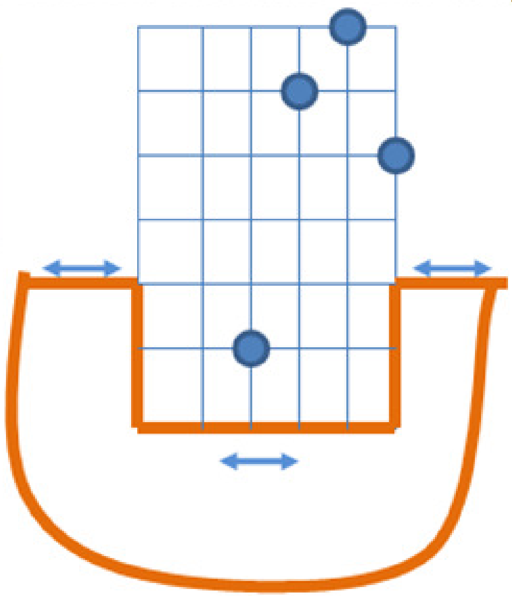
(including refined mesh, element types including local nonlinearities, nonlinear materials, contact elements, etc.)

For soil pressure computation:

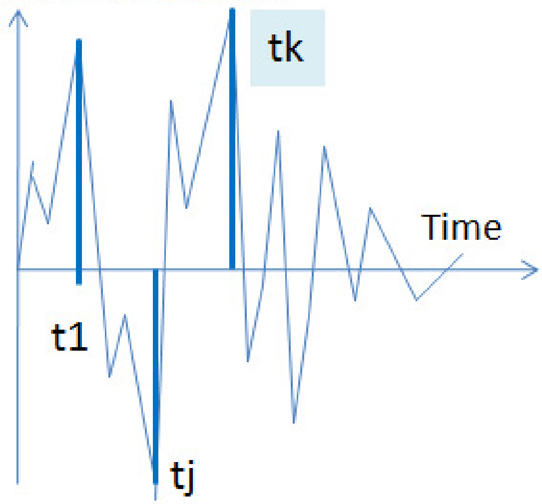
- *ANSYS Equivalent-Static Seismic Soil Pressure Computation* Including Soil-Foundation Separation Effects

ACS SASSI Seismic SSI Analysis

Computing Structural Stress/Forces

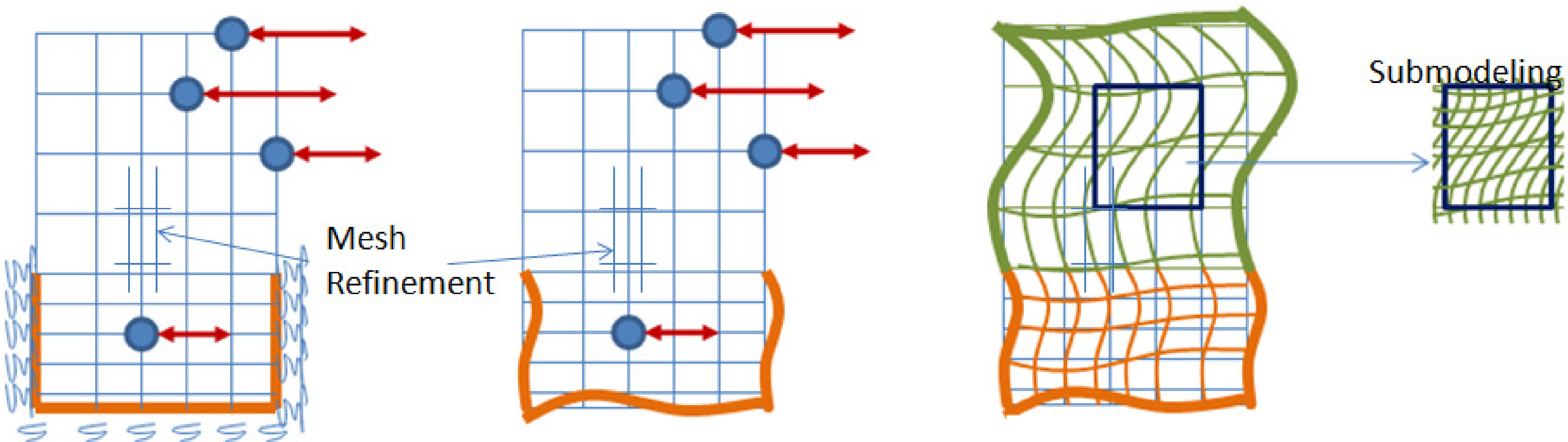


Selected Critical Time Steps for Maximum Stresses
To be Used for Equivalent Static Structural Analysis



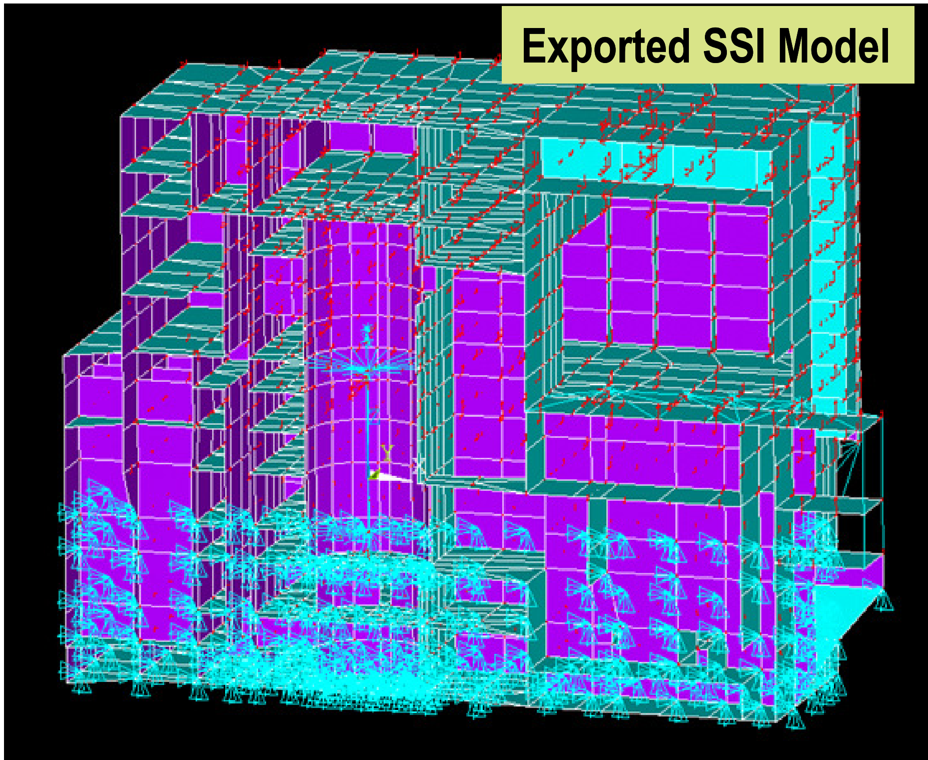
SSI Solution Time Frames As Equivalent Static Structural Loading at Critical Time Steps

EQS Forces + BC Springs | EQS Forces + BC Displacements | EQS Relative Displacements



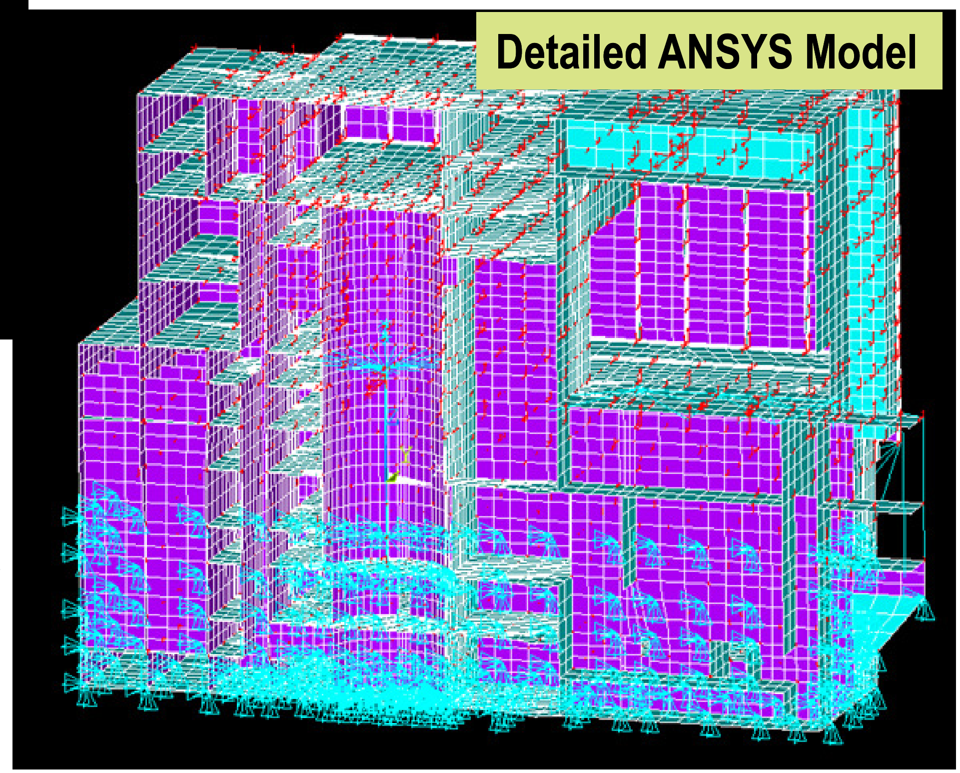
Variable Accuracy C-by-C | “Exact” | “Exact”

ACS SASSI – ANSYS Interface for Refined Seismic Stress Analysis



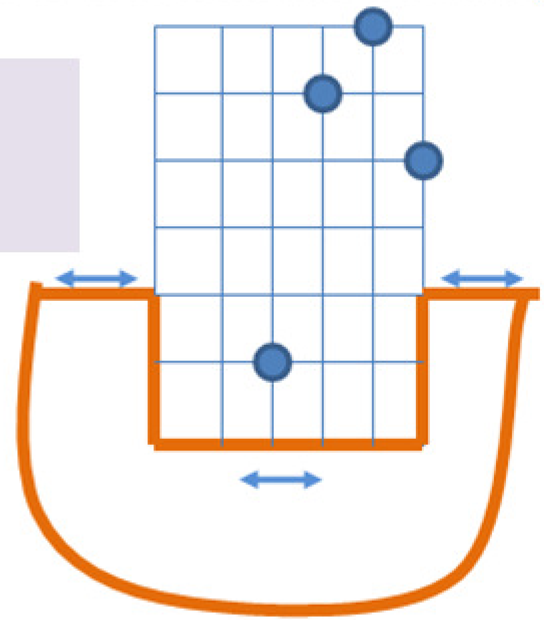
ANSYS Structural Model Automatically Converted From ACS SASSI Using PREP Module

ANSYS Refined Structural Model Using EREFINE command or ANSYS GUI (rank 1-6)

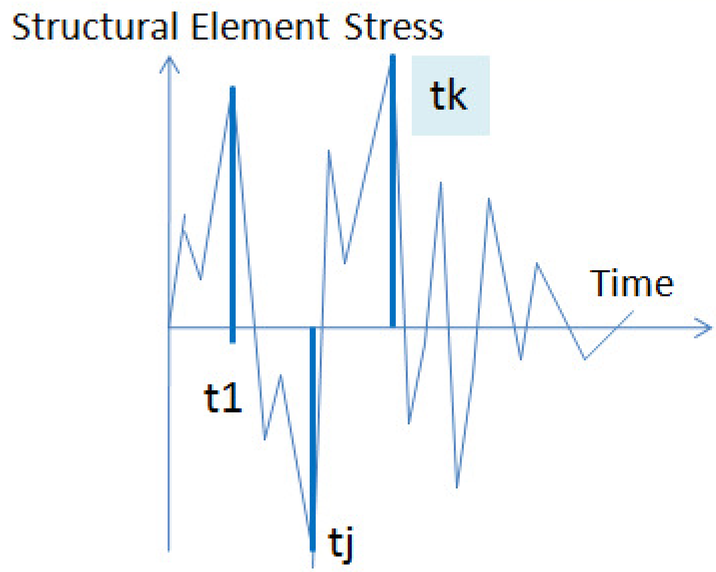


ACS SASSI Seismic SSI Analysis

Computing Seismic Soil Pressures

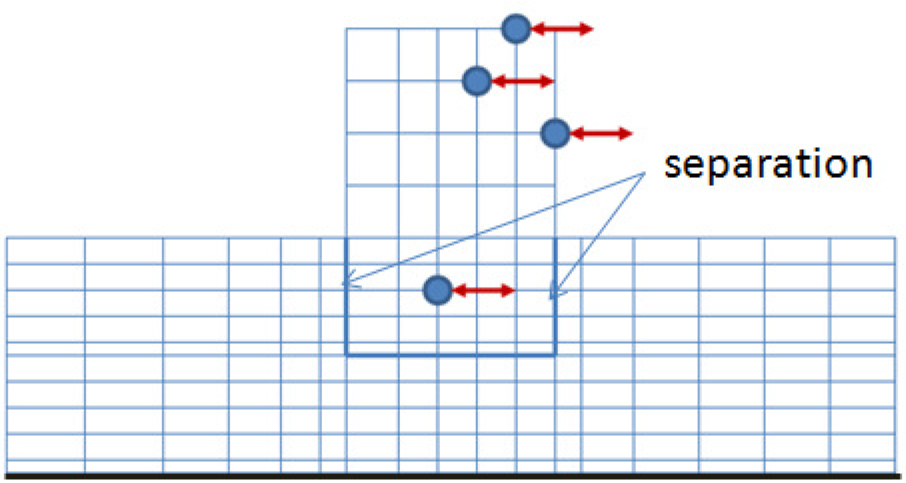


Selected Critical Time Steps for Maximum Stresses
To be Used for Equivalent Static Structural Analysis

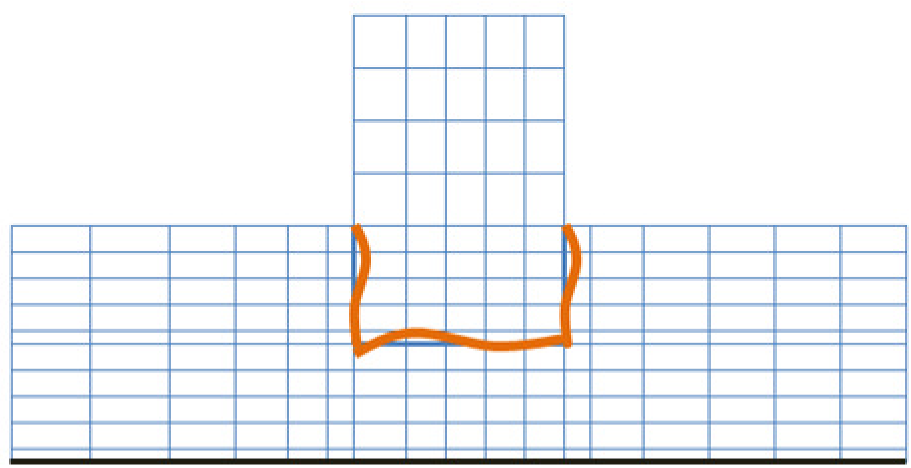


SSI Solution Time Frames As Equivalent Static Loading at Critical Time Steps

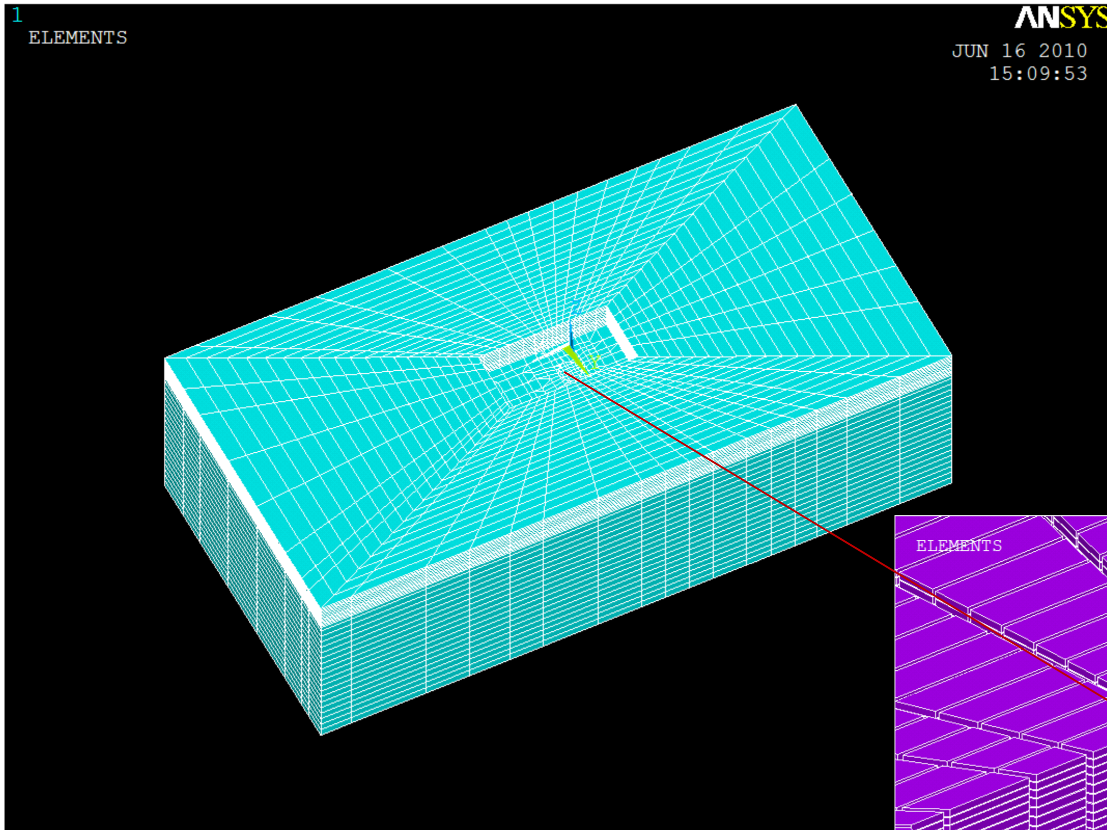
EQS Forces – Linear & Nonlinear



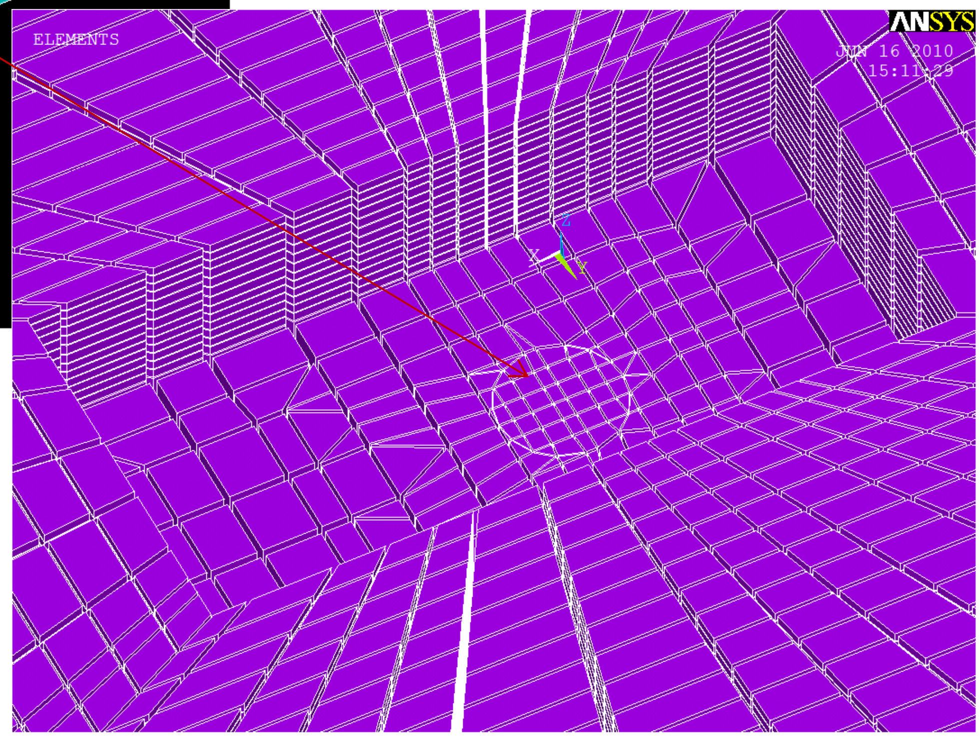
EQS Relative Displacements – Linear (Welded)



ACS SASSI – ANSYS Interface for Seismic Soil Pressure Analysis



ANSYS Soil FE Model
Is Automatically Generated
by SOILMESH Module

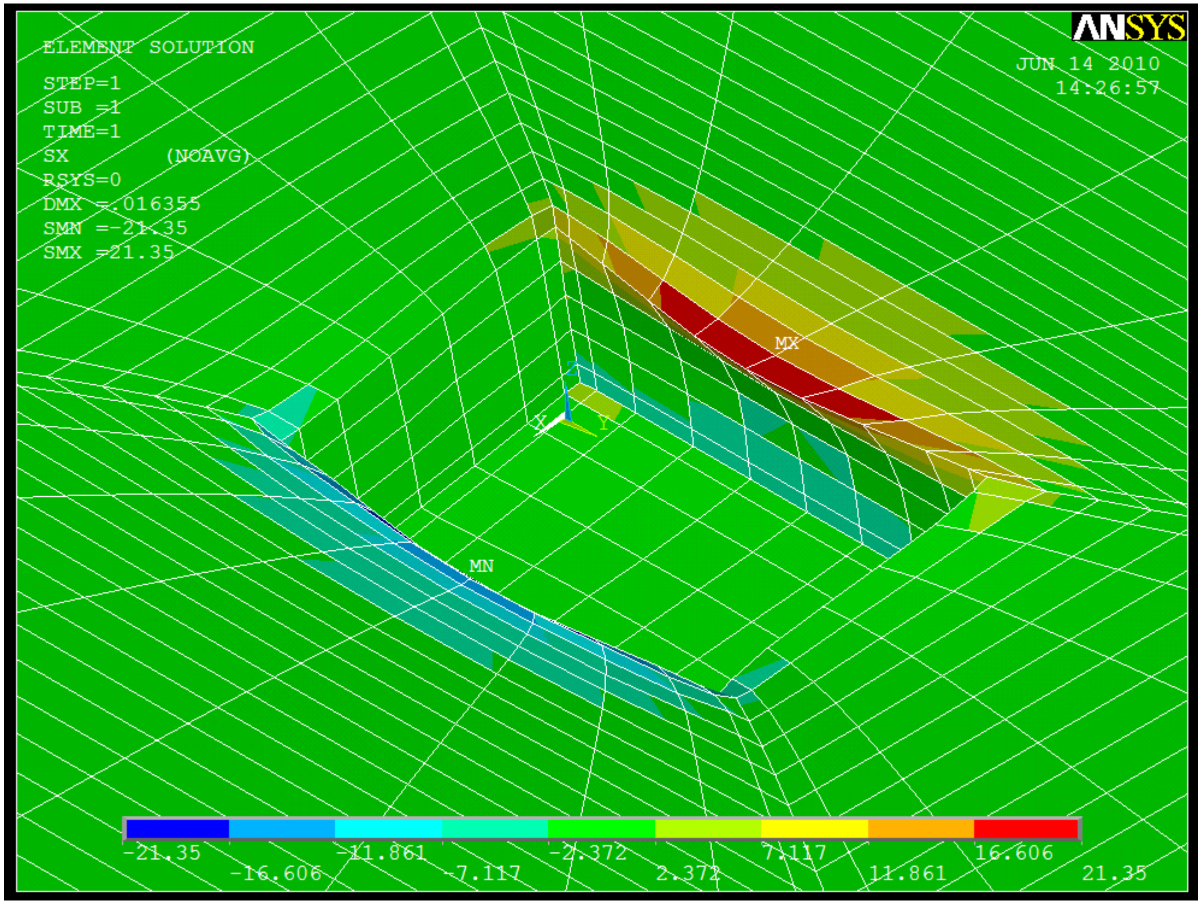


Embedment mesh is extended.
User controls extension size and
mesh density. Can use EREFINE.
Contact surfaces automatically added
By ACS SASSI SOILMESH module.

Linear Seismic Soil Pressure Analysis

LINEAR (WELDED SOIL)

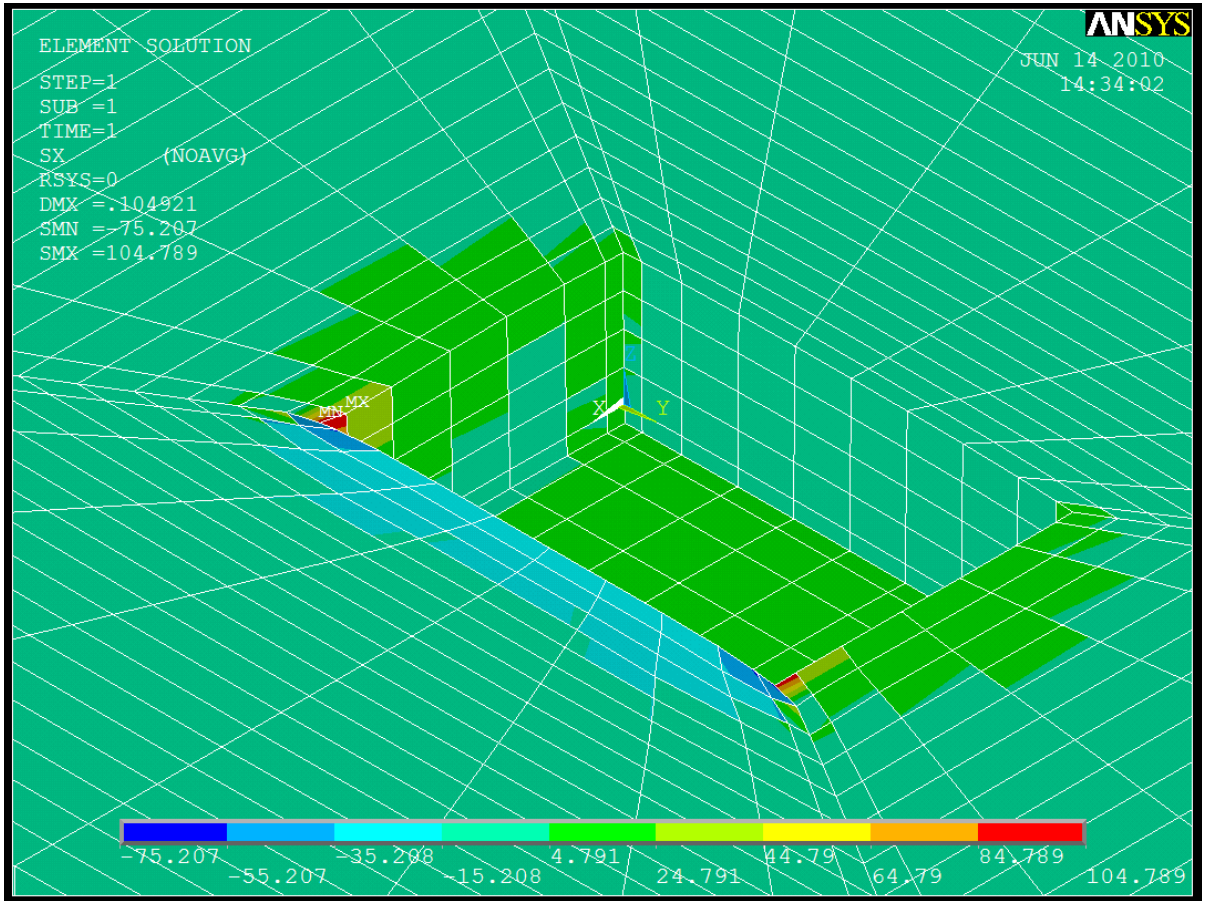
- This option provides for a basic soil pressure analysis assuming there is no separation possible between the structure and the soil
- Displacements from the interaction nodes of the structure are applied directly to the soil FE model. The structural FE model is not required for this case



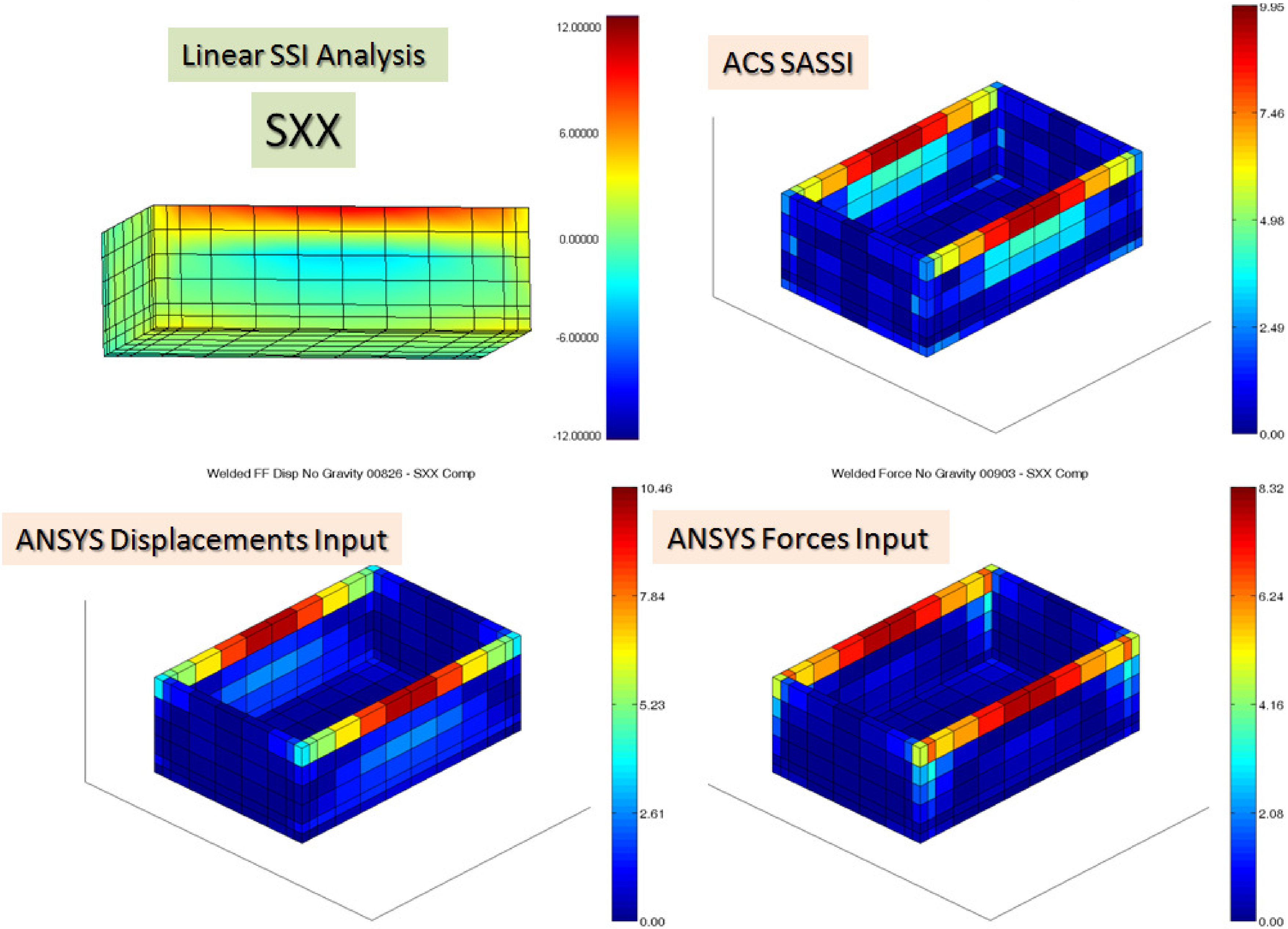
Nonlinear Seismic Soil Pressure Analysis

NONLINEAR CONTACT (FOUNDATION SEPARATION)

- This option allows for the structure to separate from the soil using surface to surface contact elements in ANSYS
- Both the structural elements and the soil elements are required. Both APDL files written from SOILMESH must be loaded into ANSYS.
- Inertial Force should be applied to the structure.
- Contact and target surfaces are included in the soil FE model



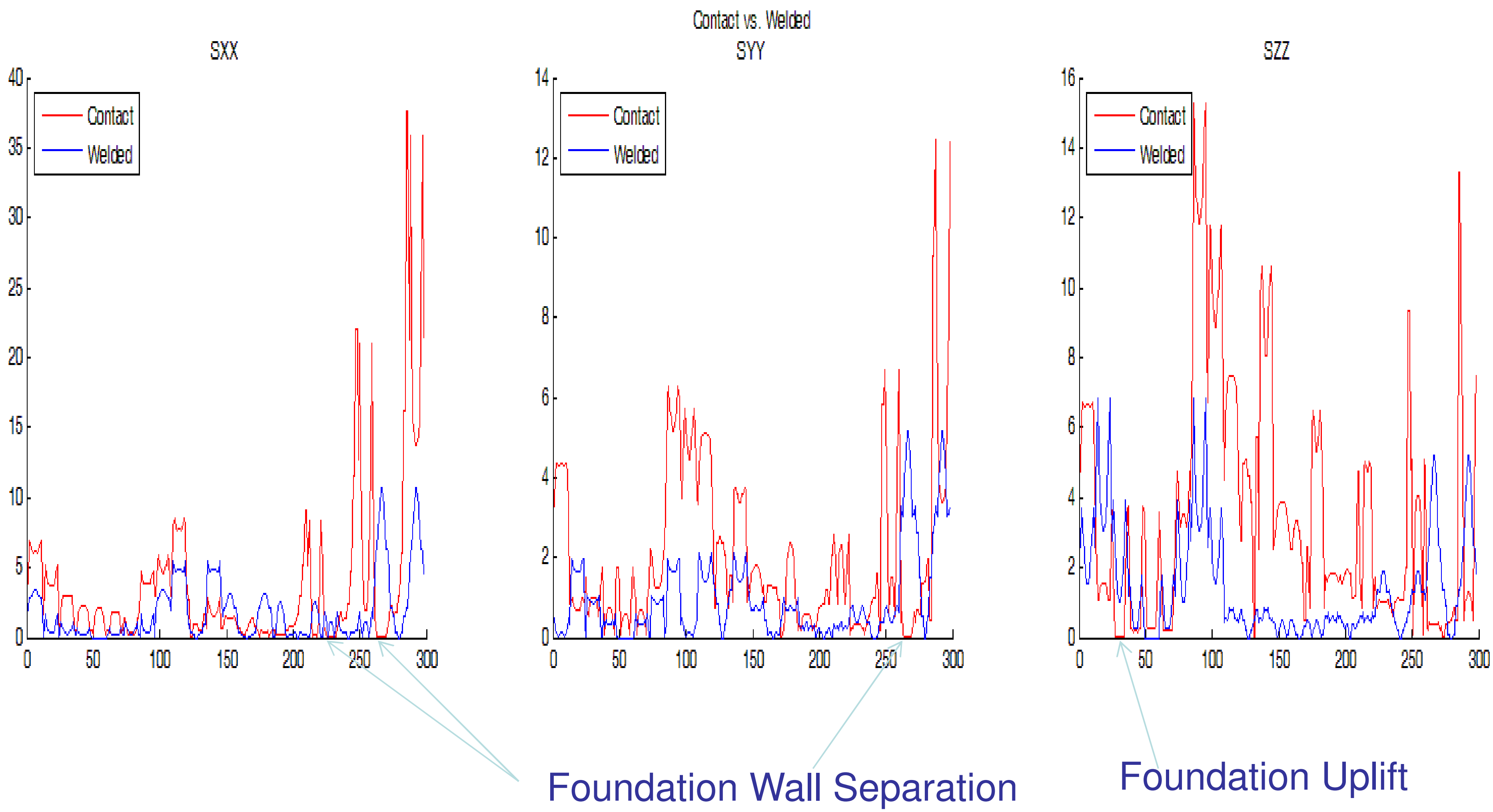
ACS SASSI and ANSYS Element Stresses for X-Input (Frame 903)



Effects of SSI Soil Separation for X-Input (Frame 903)

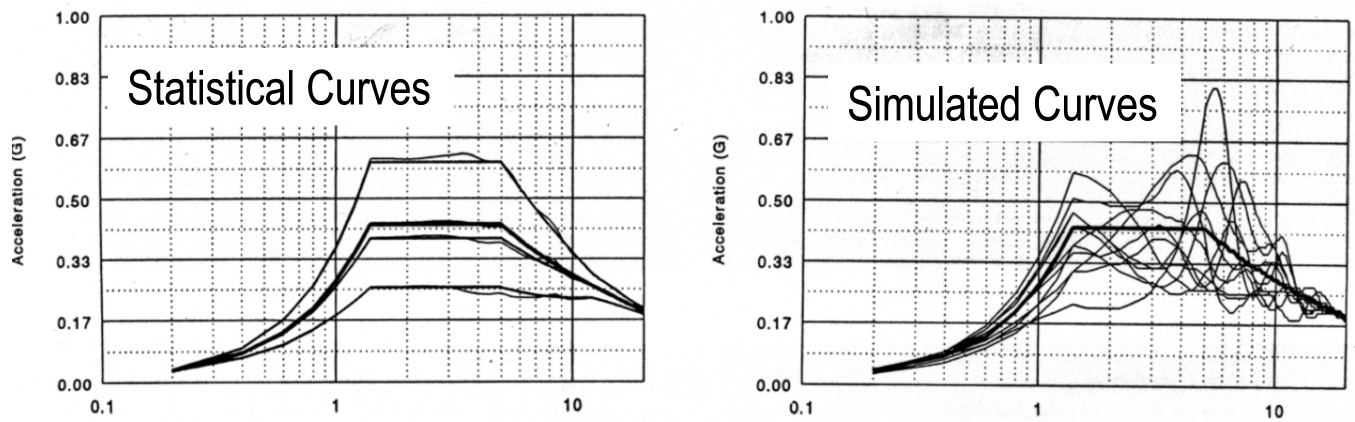
ANSYS Equivalent-Static Seismic Force Loading Option

Absolute Values of Element Center Stresses SXX, SYY, SZZ

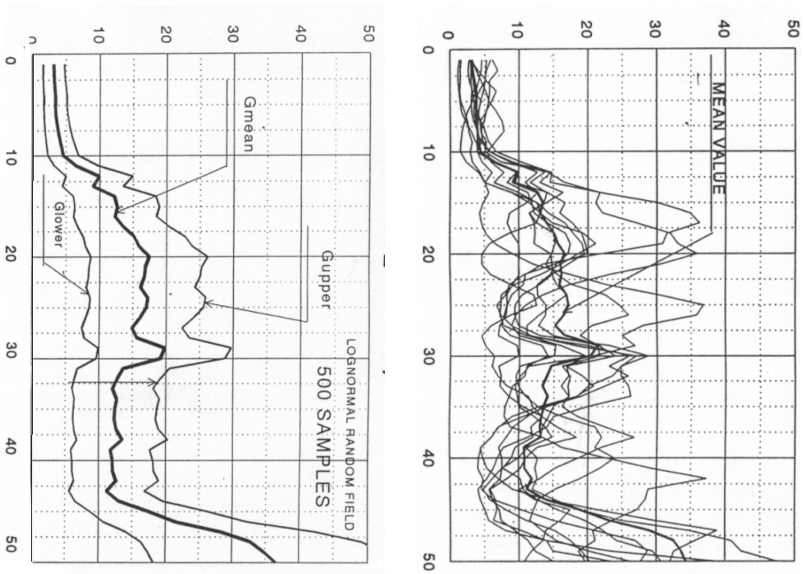


Probabilistic Seismic SSI Analysis (ASCE04 Draft 2012)

SEISMIC INPUT: Statistical UHRS Input

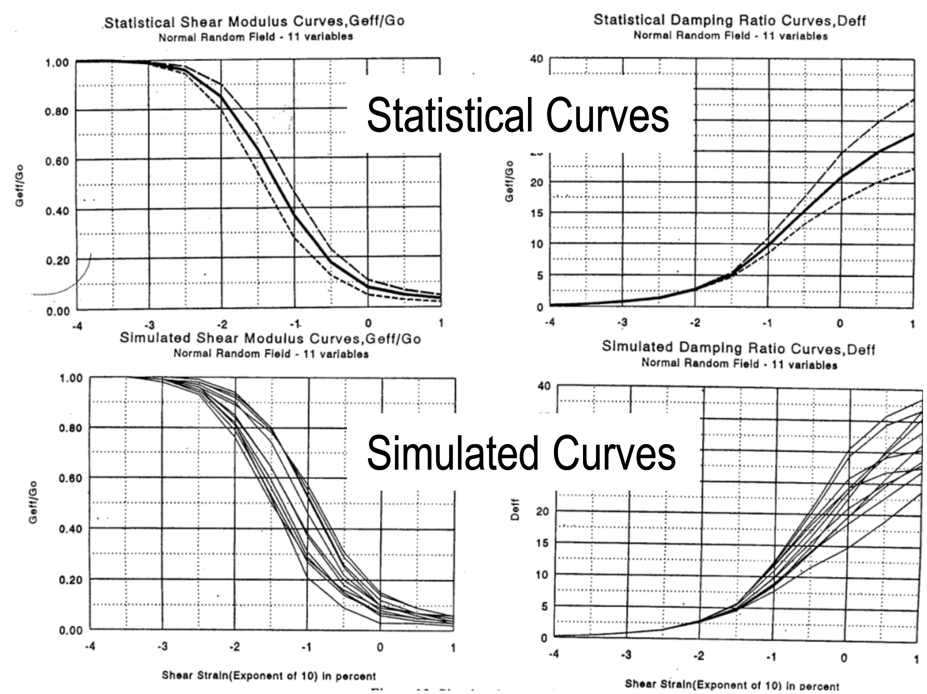


SOIL LAYERING: Random Profile (G, D))

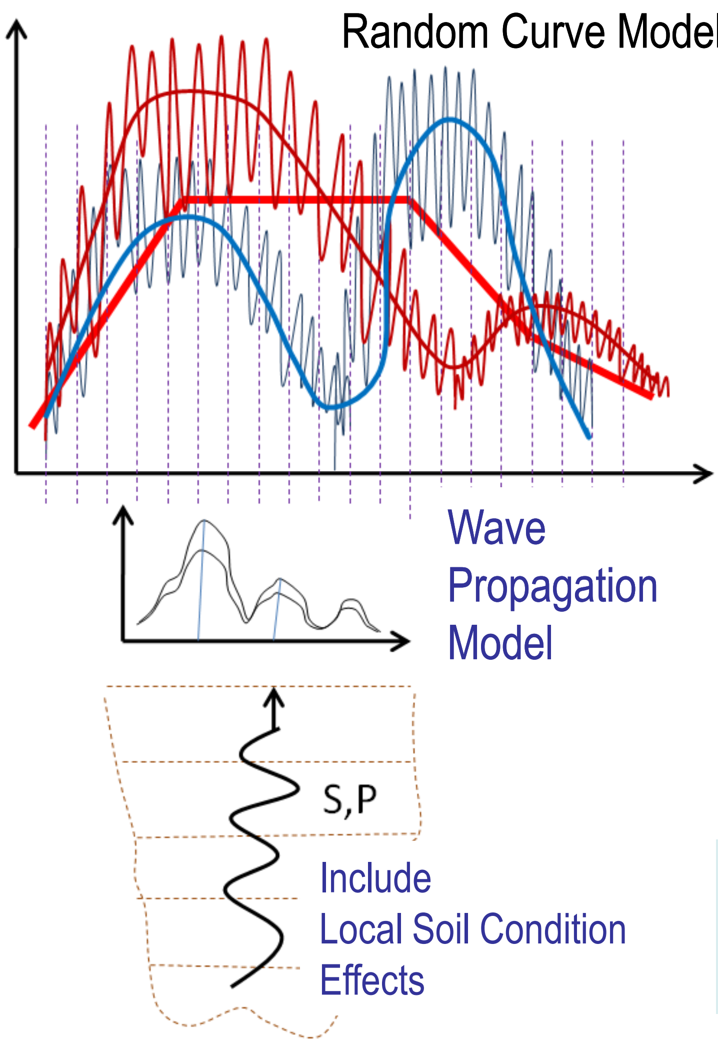


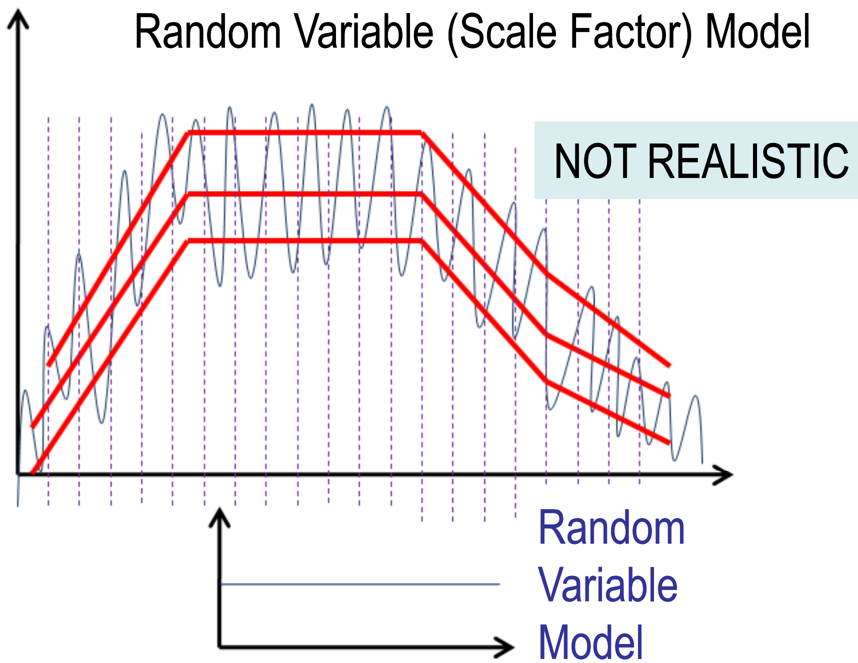
Statistical Curves Simulated Curves
(Ghiocel and Ghanem, 1996, 2002)

SOIL CURVES: Geff/Gmax and Deff Curves



Seismic Motion Shows Correlation in Frequency



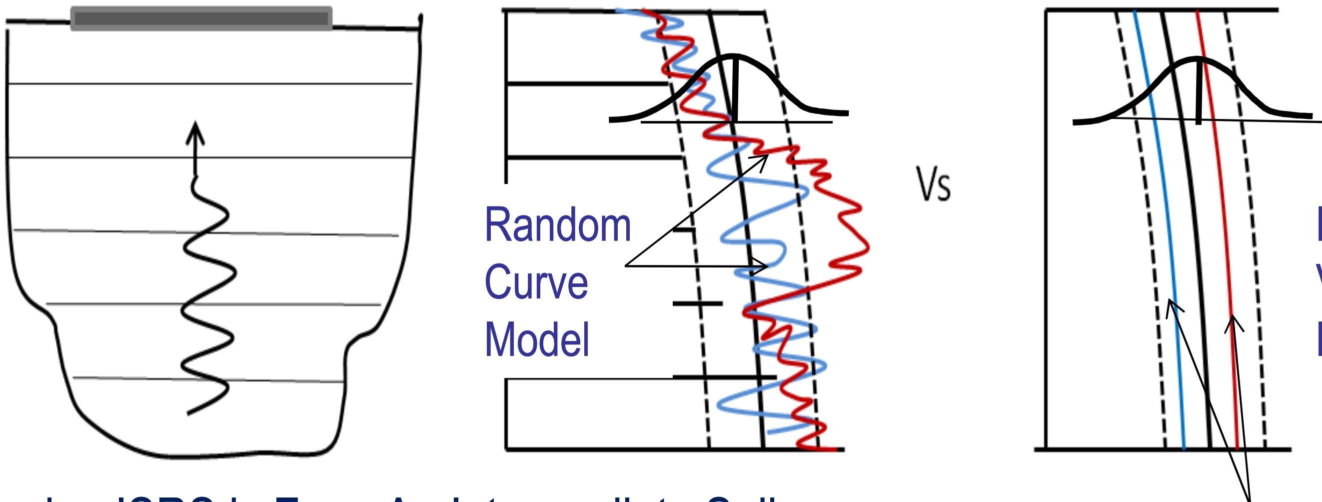


No correlation = Noise = No physics!

Soil Acting As A Frequency Filter on Seismic Incident Waves

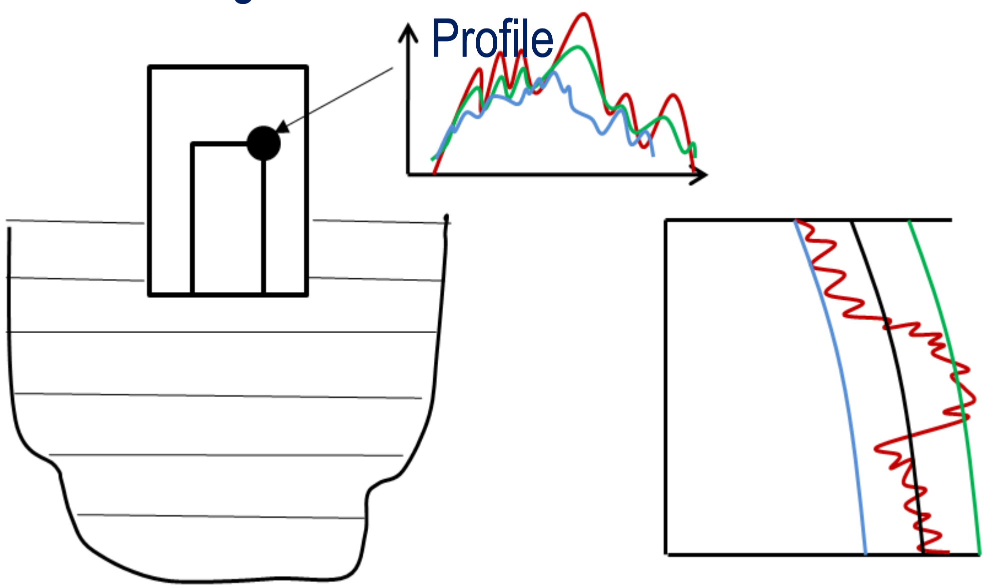
Soil Property Local and Spatial Variations (Low Strains)

Soil Layering | Real Soil Profiles | Ideal Soil Profiles



Perfect Correlation looses physics!

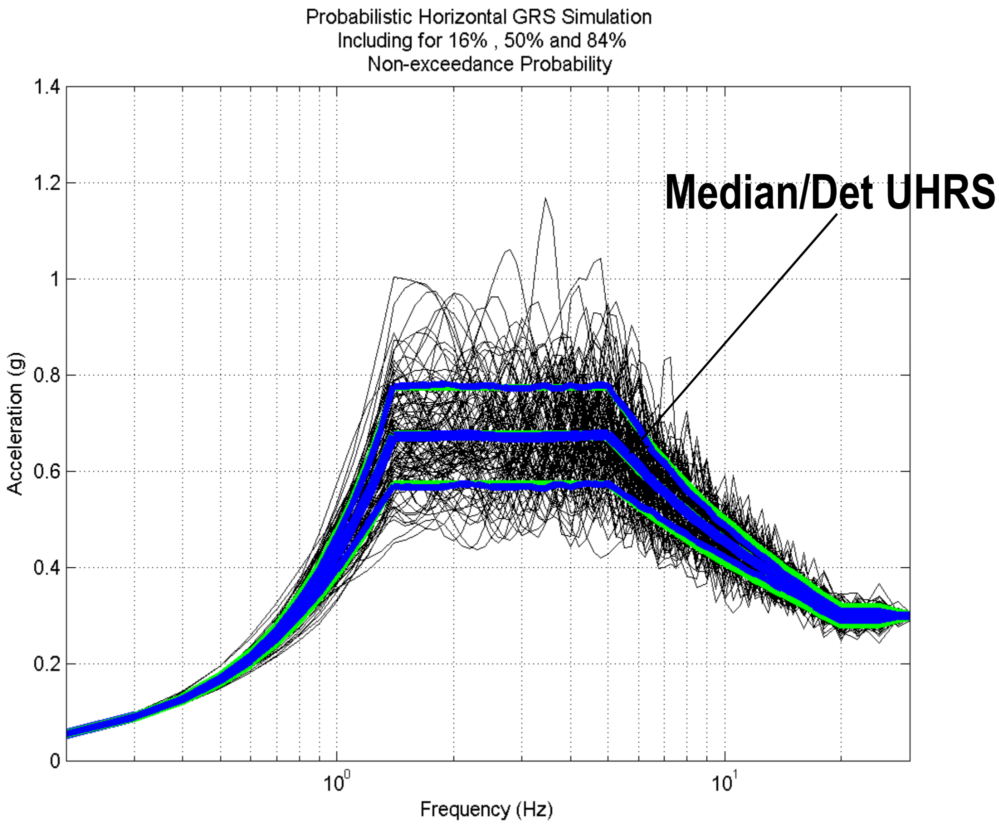
Governing ISRS is From An Intermediate Soil Profile



REMARK:
It could be that more than 3 soil profiles, LB, BE and UB, are needed to avoid "spectral valleys" in FIRS. Envelope of deterministic FIRS (deconvolved-down) should cover probabilistic-mean FIRS (convolved-up) – Recent discussions on ASCE04 Ch. 2 Draft 2011

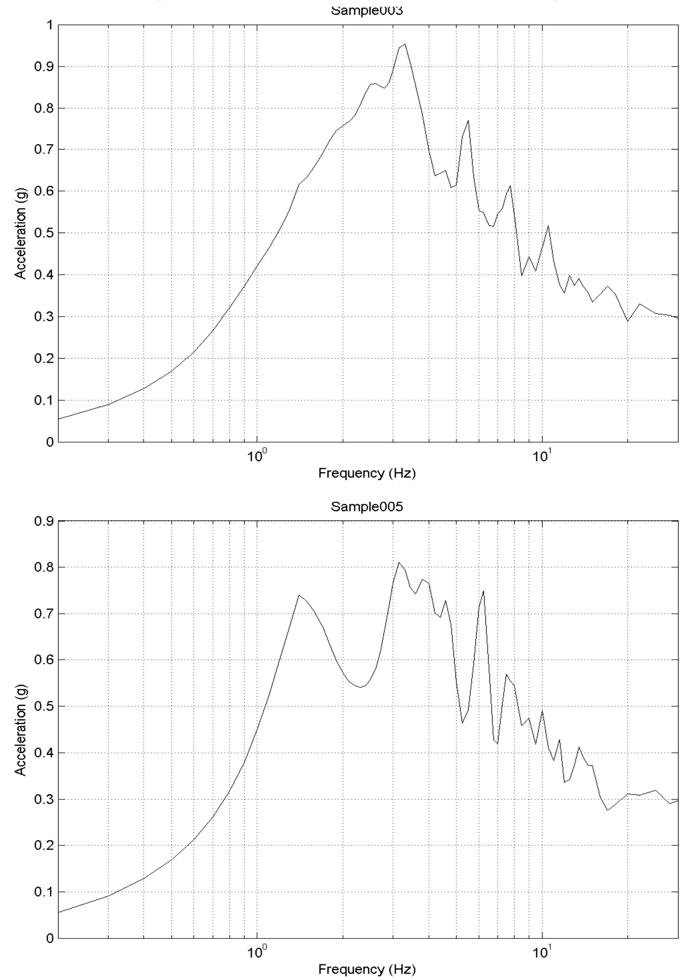
AP1000 Stick Model Studies: Soil Site (Option Pro)
2013 ASCE 04 Standard Draft

Seismic Probabilistic UHRS Input Anchored at 0.30 ZPGA



c.o.v. = 15%; Corr. Length = 1 Hz

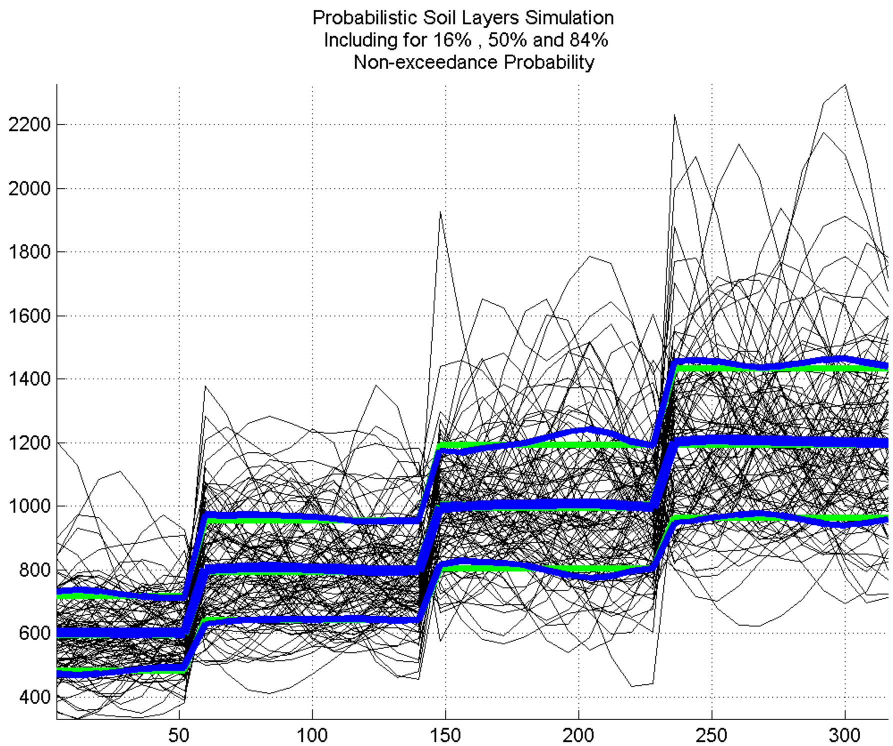
Simulated Ground RS



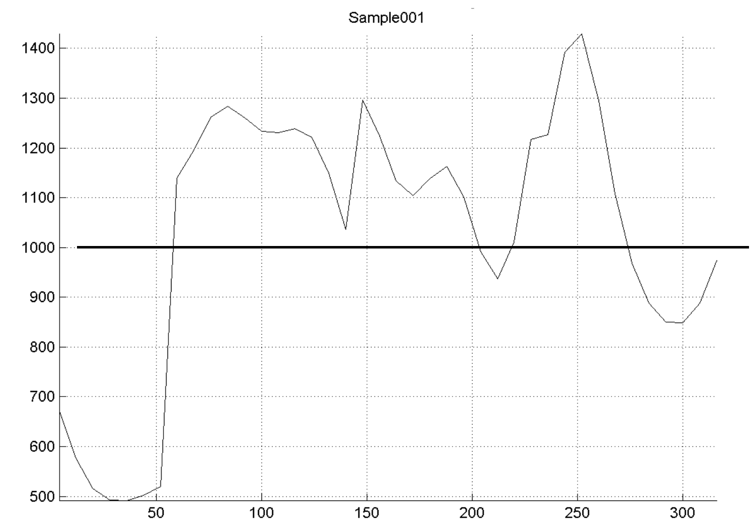
Random Samples

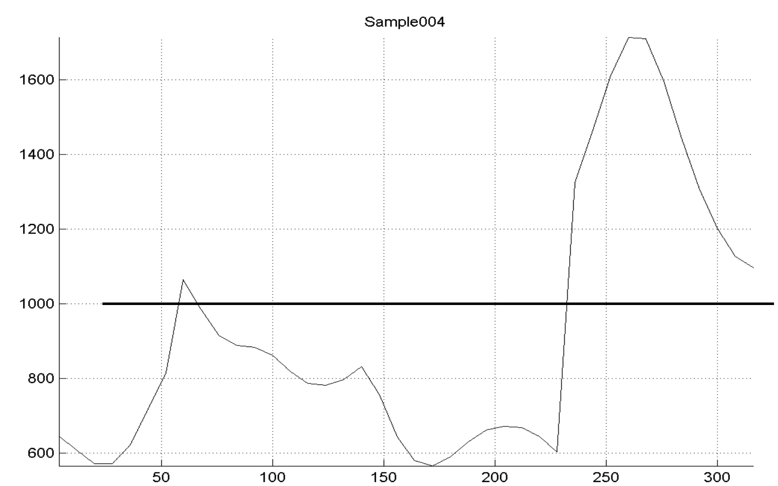
Simulated Soil Profiles

Probabilistic Soil Profile



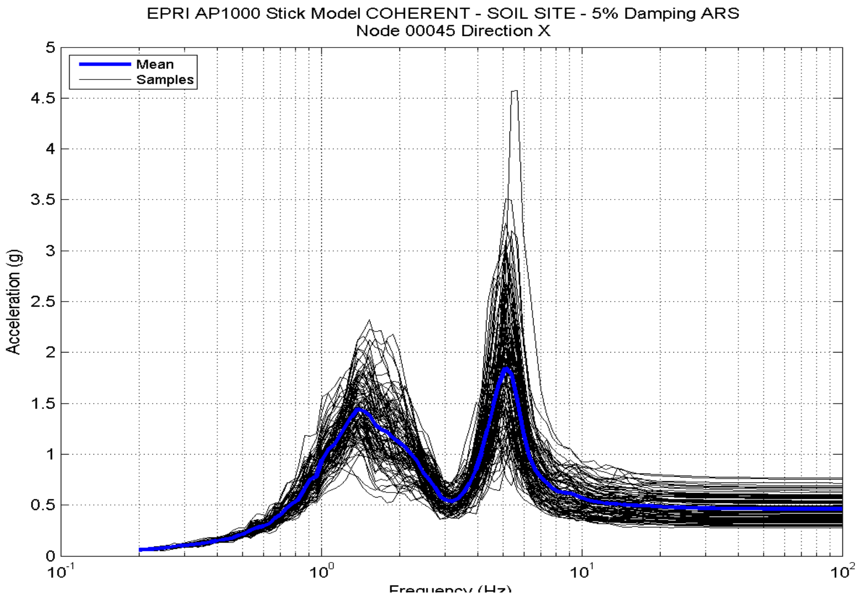
c.o.v. = 20%; Corr. Length = 20 ft



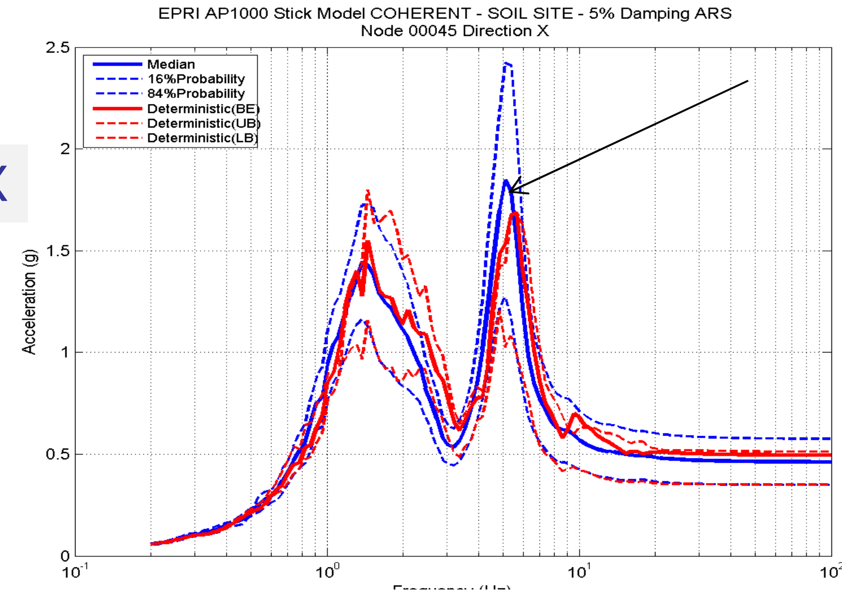


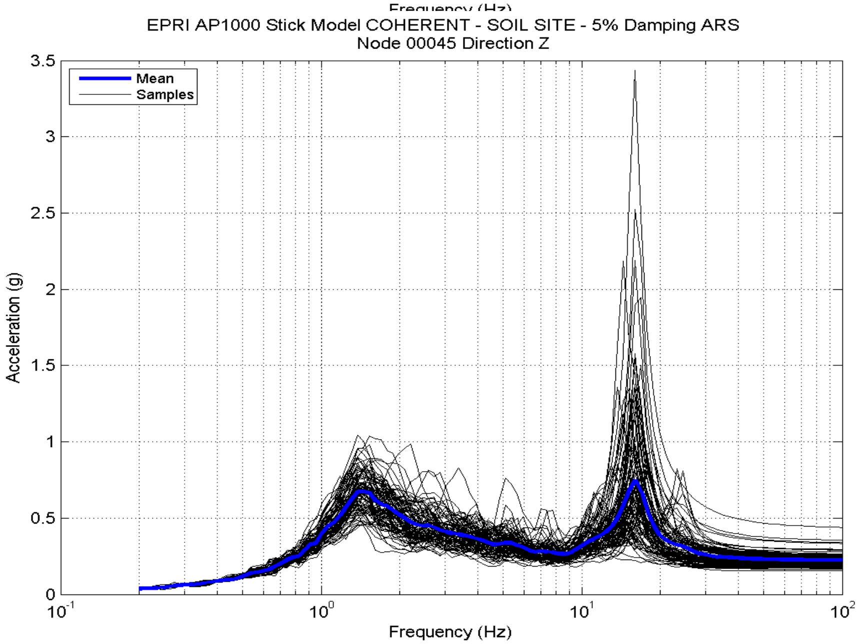
Random Samples

5% Damping Coherent ARS at Top of SCV (Node 45)

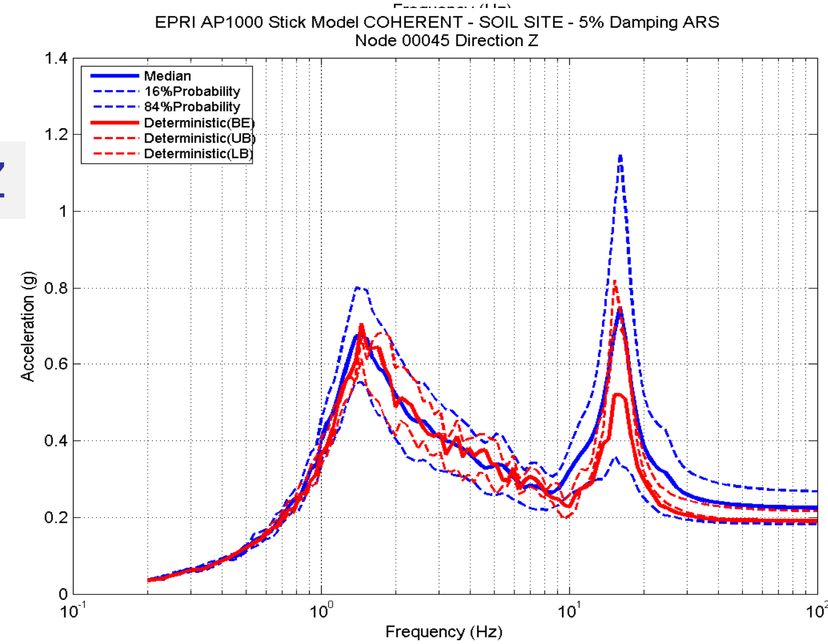


X



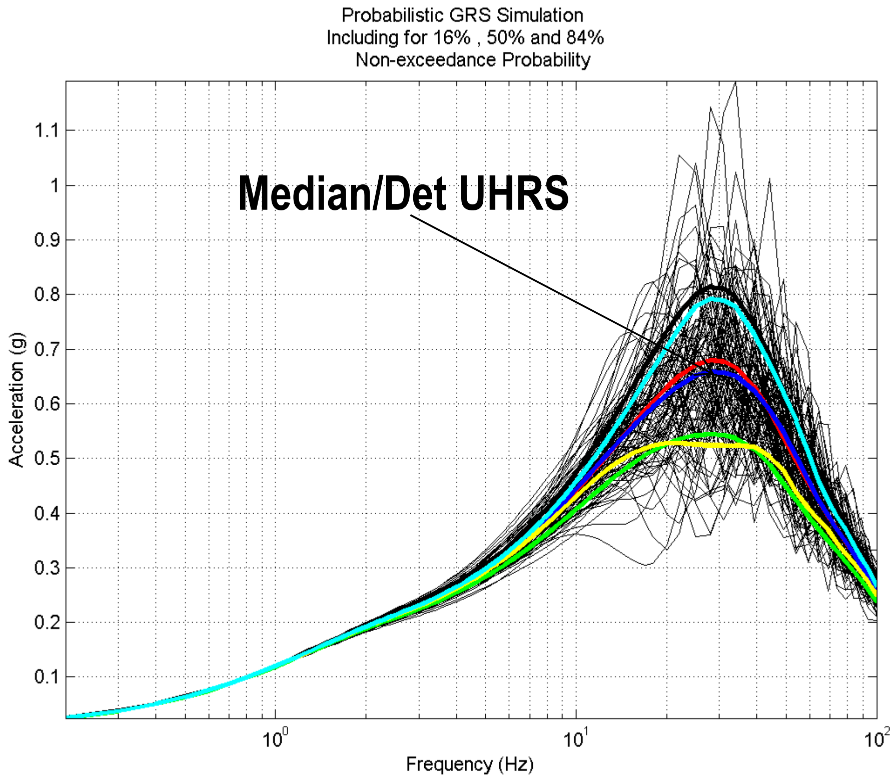


Z



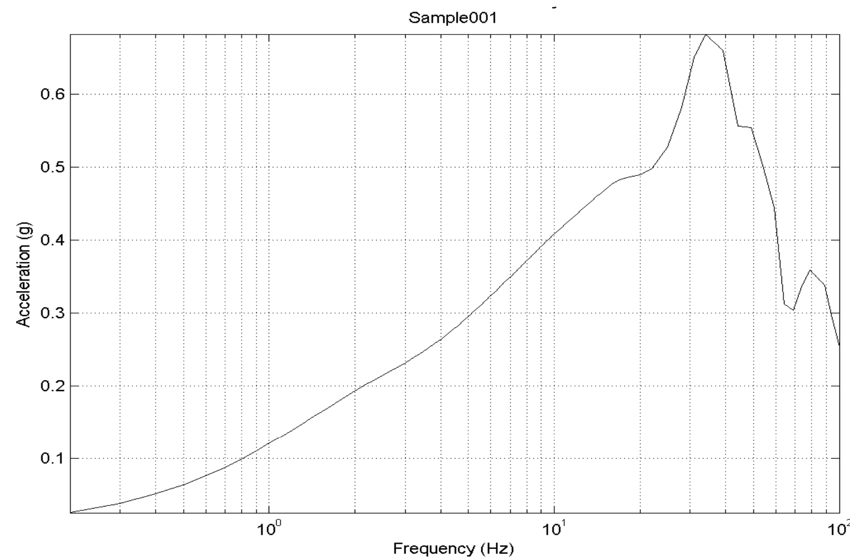
EPRI AP1000 Model Studies: Rock Site (Option Pro)

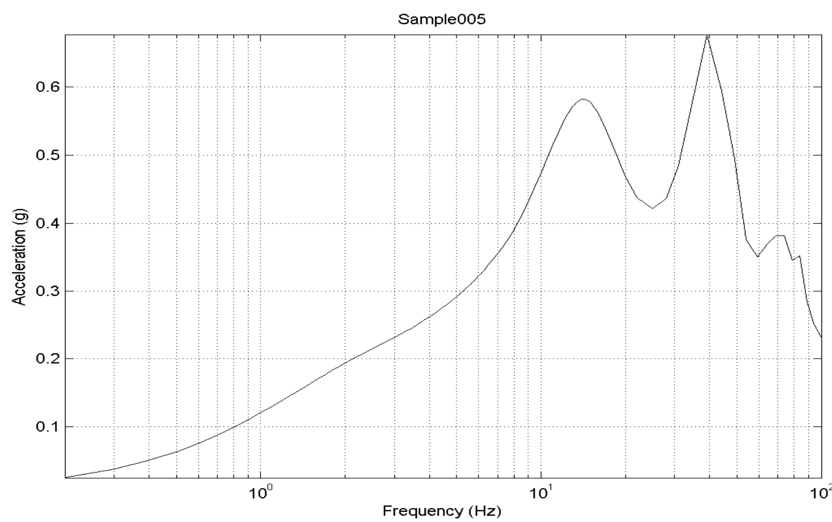
Seismic Probabilistic UHRS Input Anchored at 0.30 ZPGA



c.o.v. = 20%; Corr. Length = 5 Hz

Simulated Ground RS

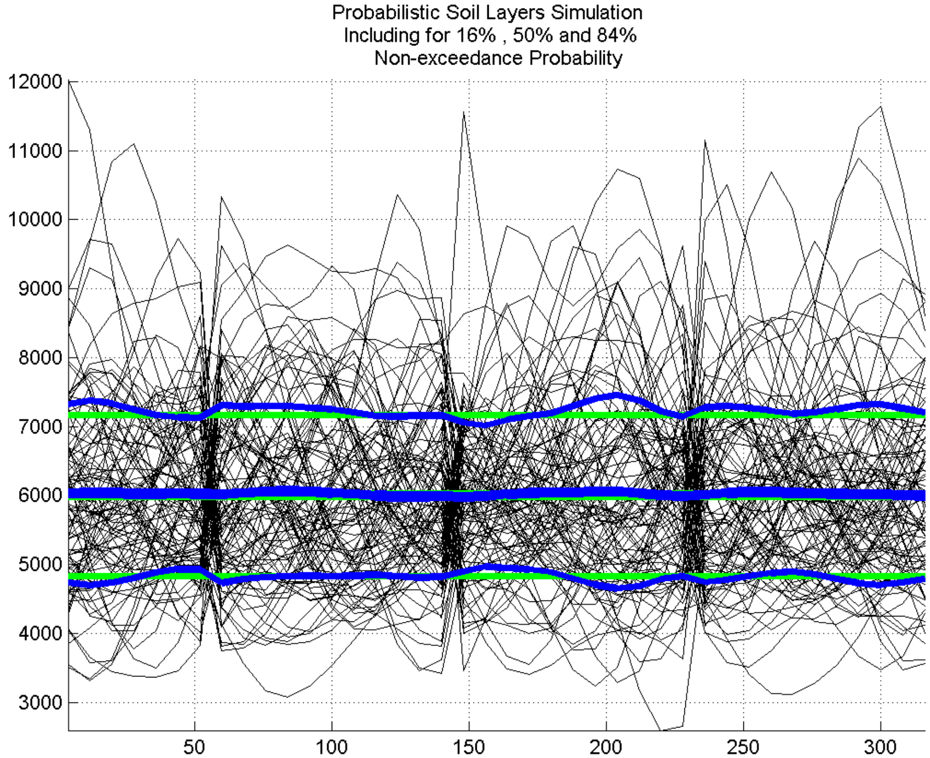




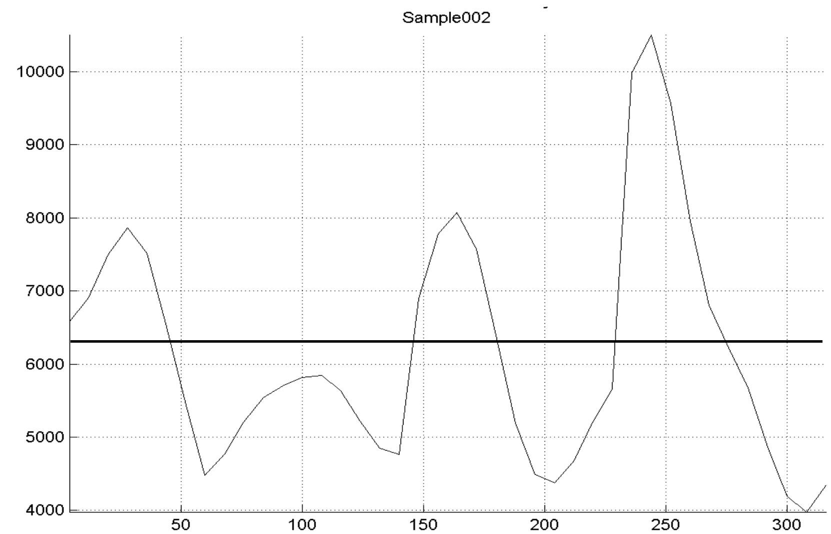
EPRI AP1000 Model Studies: Rock Site (Option Pro)

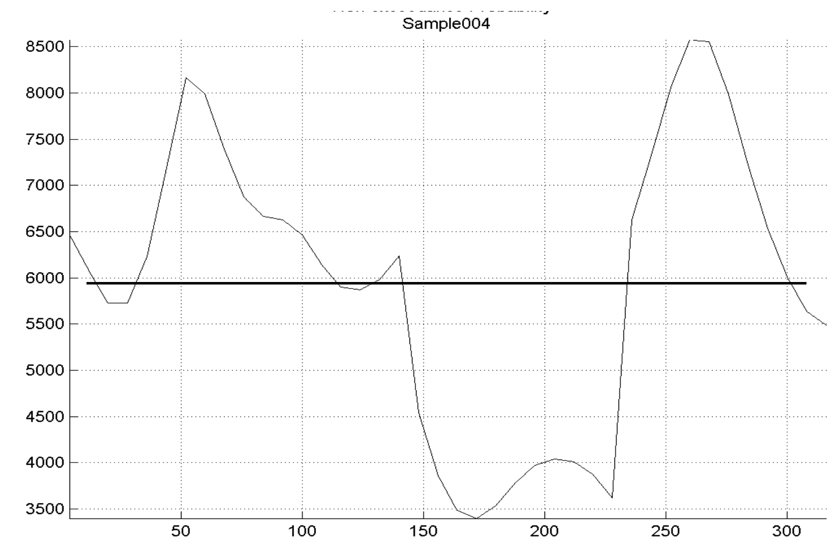
Simulated Ground RS

Seismic Soil Profile
Vs=6,000 fps

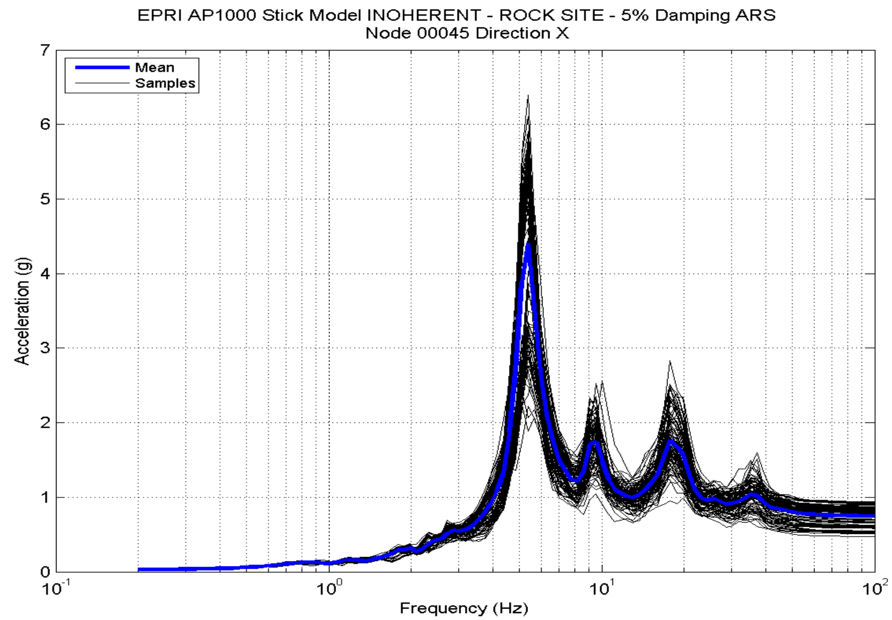


c.o.v. = 20%; Corr. Length = 20 ft

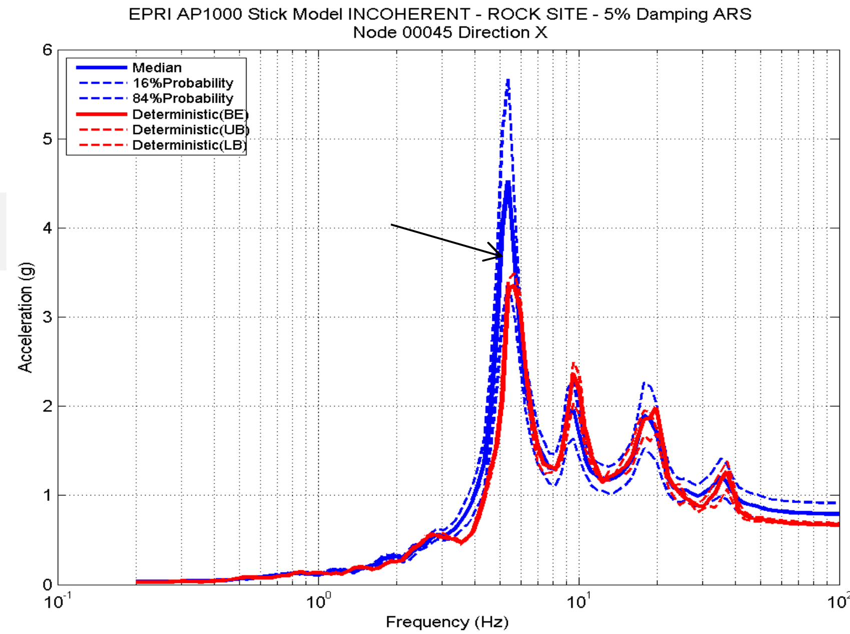


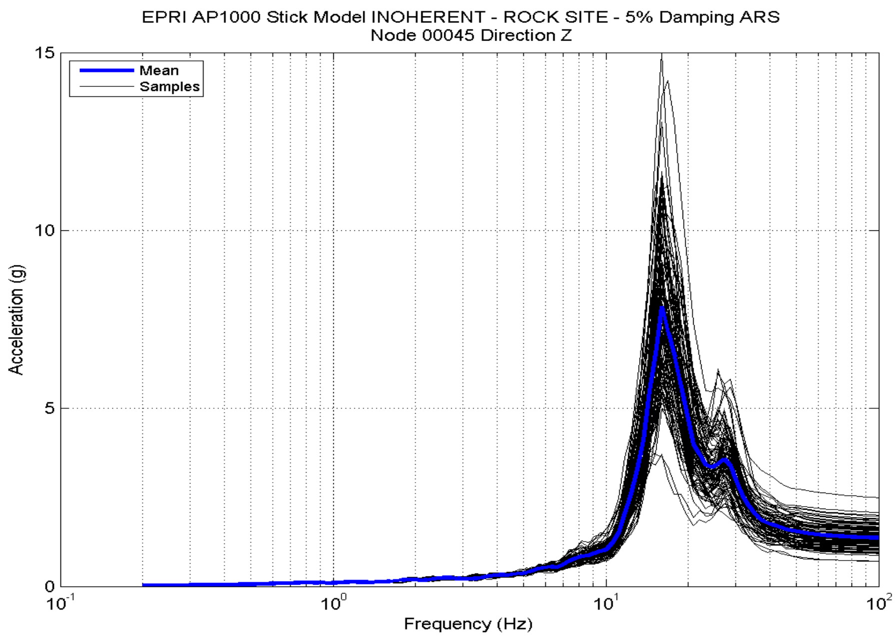


5% Damping Incoherent ARS at Top of SCV (Node 45)



X





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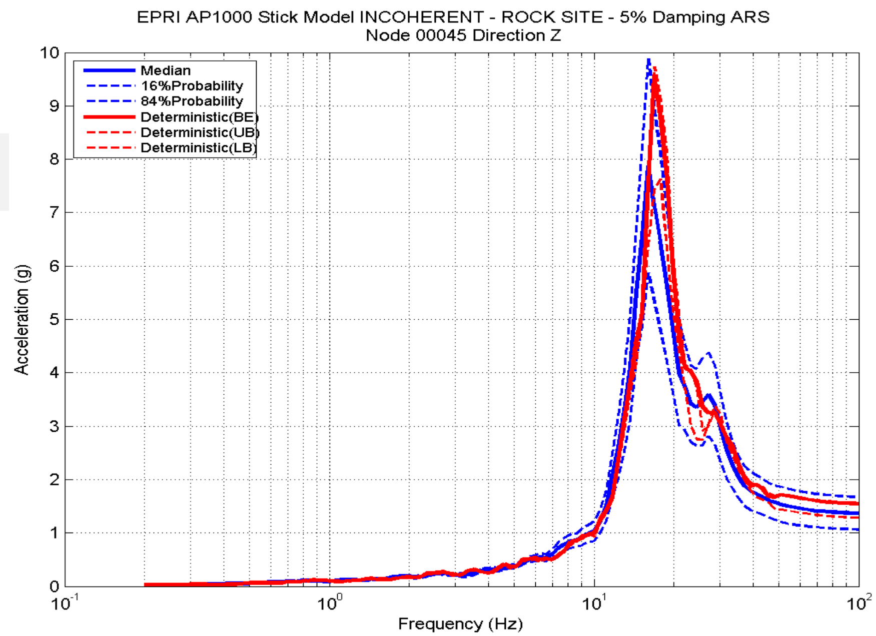
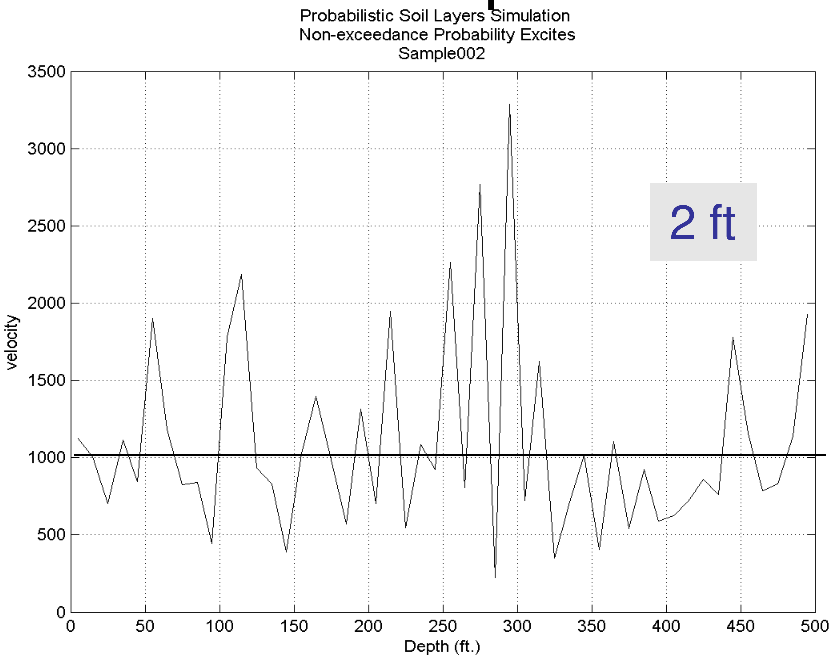
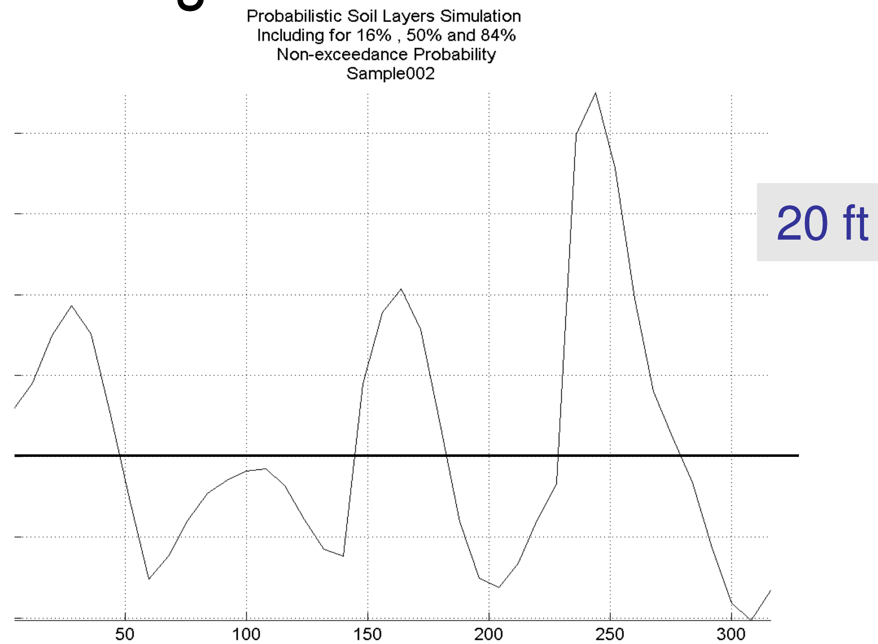
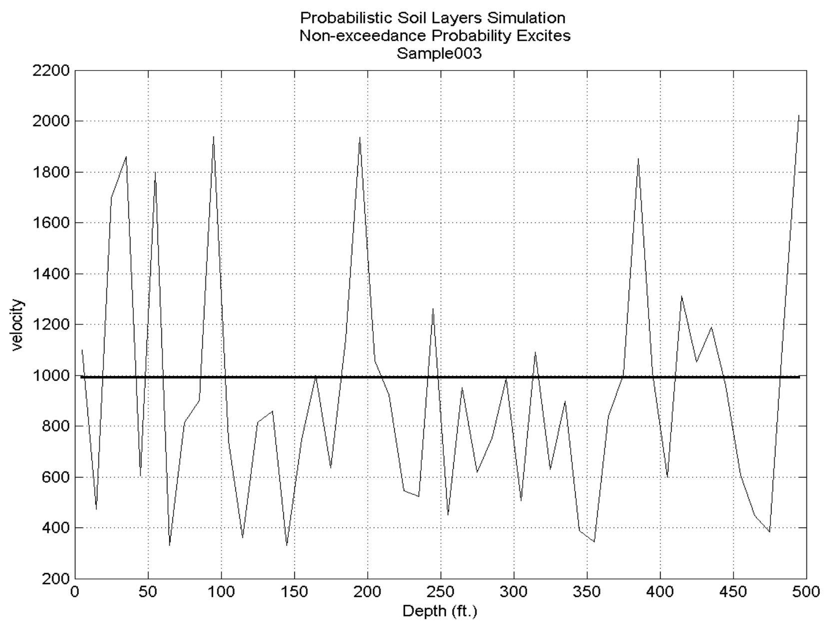
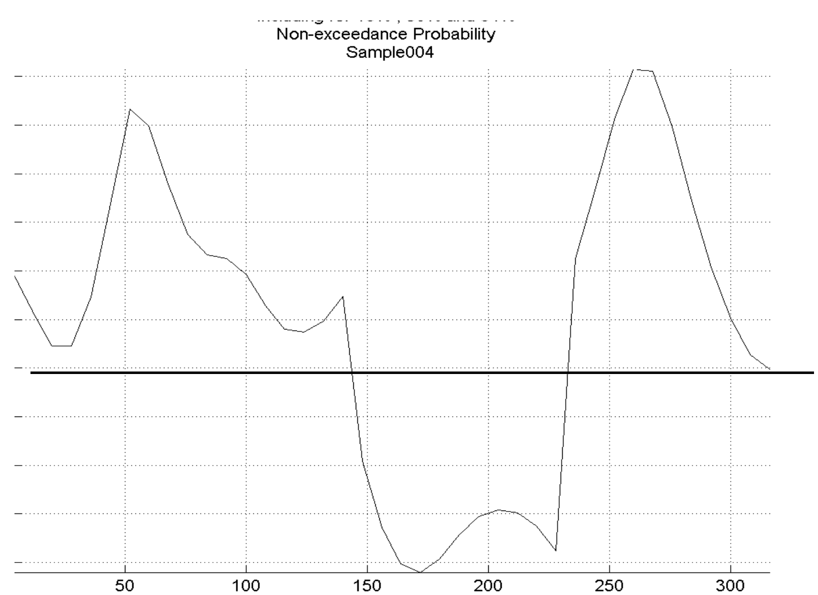


Effect of Spatial Correlation Length on Soil Profiles

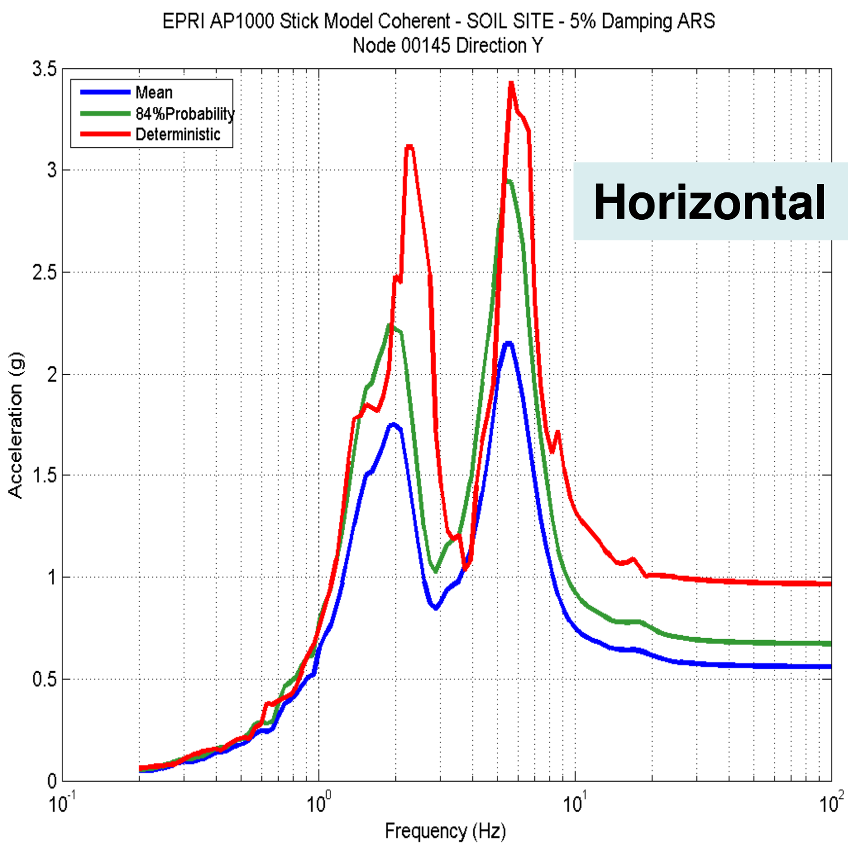


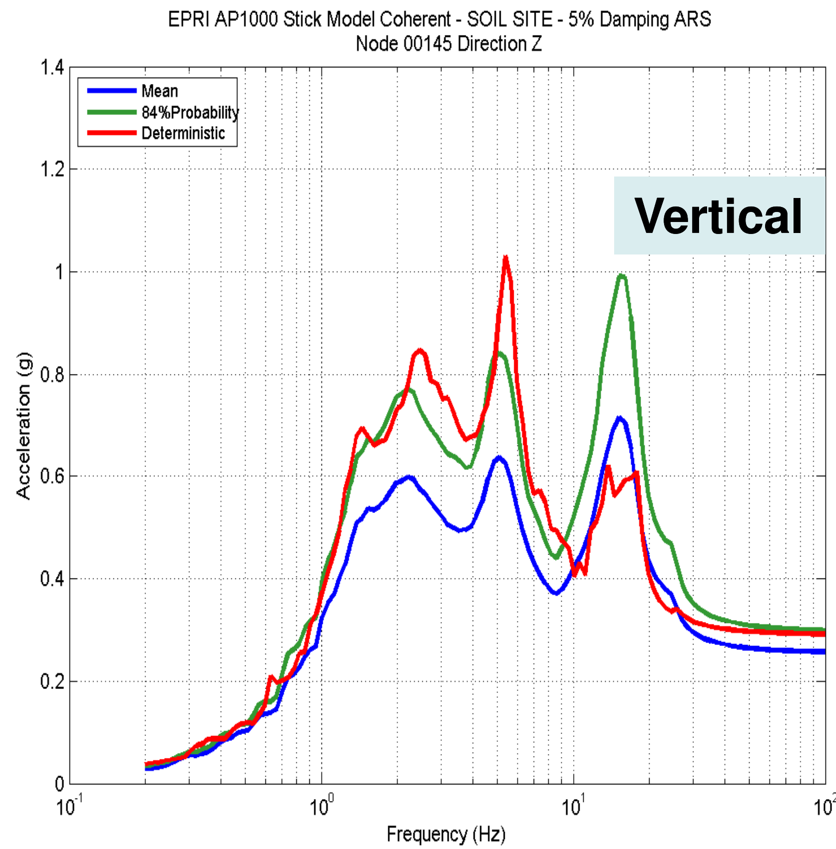




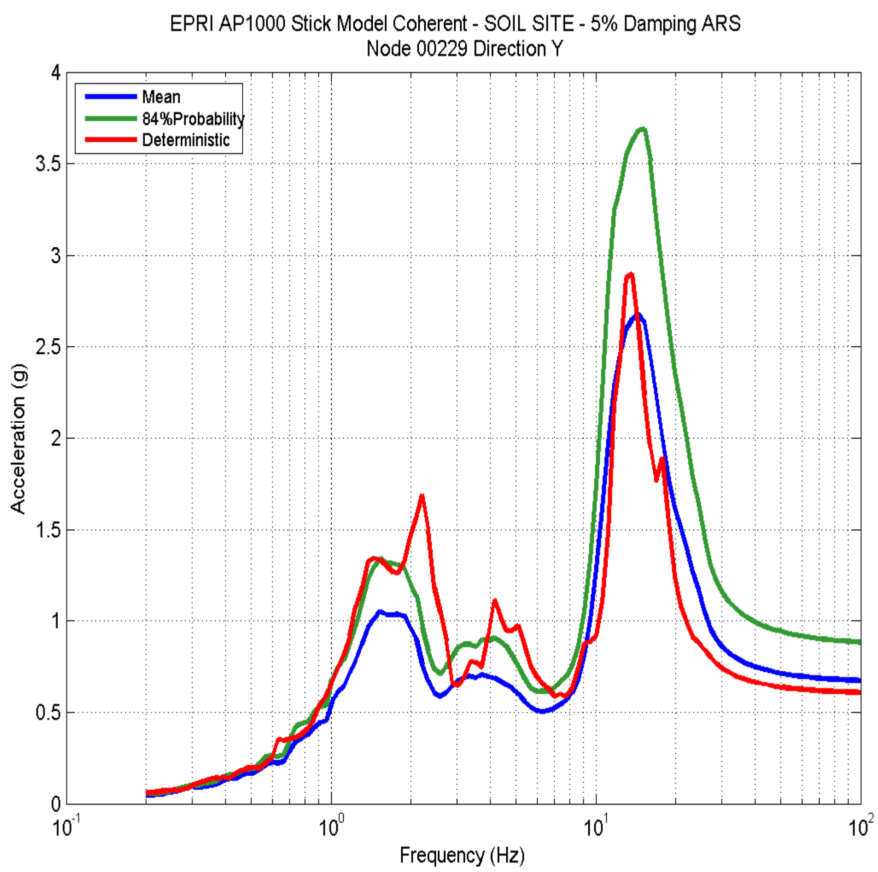


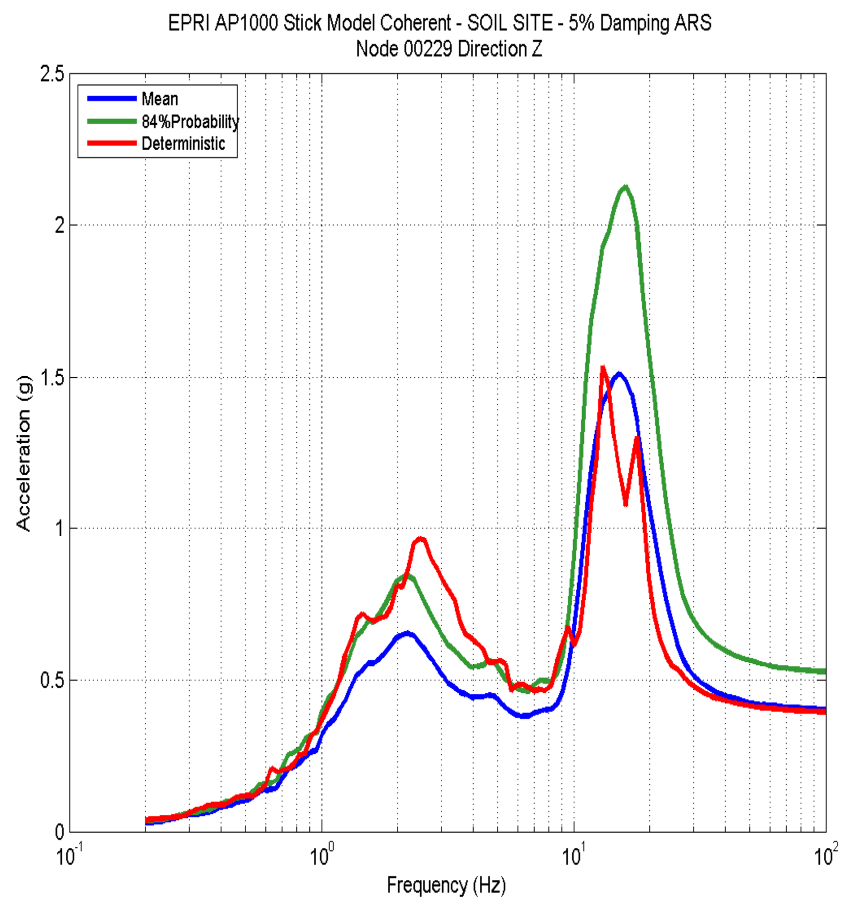
5% Damping Coherent ARS at Top of SCV (Node 145)
Soil Site (Vs=2,000 fps) - Deterministic Input = GRS 84% Probability





5% Damping Coherent ARS at Top of CIS (Node 229)
Soil Site (Vs=2,000 fps) - Deterministic Input = GRS 84% Probability





Random Vibration Theory (RVT) Approach

Frequency domain convolution:

$$S_{a,r}(\omega,\xi,\omega_0) = \left|H_{SDOF}(\omega,\xi,\omega_0)\right|^2 \left|H_{STRU}(\omega)\right|^2 S_{a,i}(\omega)$$

$$H_{SDOF}(\omega,\xi,\omega_0) = \frac{\omega^2 + 2i\omega\xi\omega_0}{\left(\omega_0^2 - \omega^2\right) + 2i\omega_0\xi\omega}$$

$$\sigma_{a,r}^2(\xi,\omega_0) = \int_0^\infty S_{a,r}(\omega,\xi,\omega_0)\,d\omega$$

Spectral Moments for stochastic process X:

$$\lambda_i = \int_0^\infty \omega^i S_X(\omega)\,d\omega$$

$$\lambda_0 = \sigma_X^2$$

$$\lambda_2 = \sigma_{\dot{X}}^2$$

Response Spectrum as Extreme Response for T

$$R(\xi, \omega_0) = F(\omega_0, T)\,\sigma(\xi, \omega_0)$$

Stochastic Model Using Extreme Type 1 PDF (MK-UK, Kaul, 1978)

$$F_0(\omega_0) = -2\ln\left[\left(-\frac{\pi}{\omega_0 T}\right)\ln(1-p)\right]^{1/2}$$

Stochastic Model Using Extreme Value Statistics (AD and AD-DK, Davenport, 1964, Der Kiureghian, 1980, 1983)

$$p = \sqrt{2\ln(\nu_e T)} + \frac{0.5772}{\sqrt{2\ln(\nu_e T)}}$$

$$\bar{R}(\xi, \omega_0) = p(\nu_e, T)\sigma_{a,r}(\xi, \omega_0)$$

$$q = \frac{1.2}{\sqrt{2\ln(\nu_e T)}} - \frac{5.4}{\left(13 + 2\ln(\nu_e T)^{3.2}\right)}$$

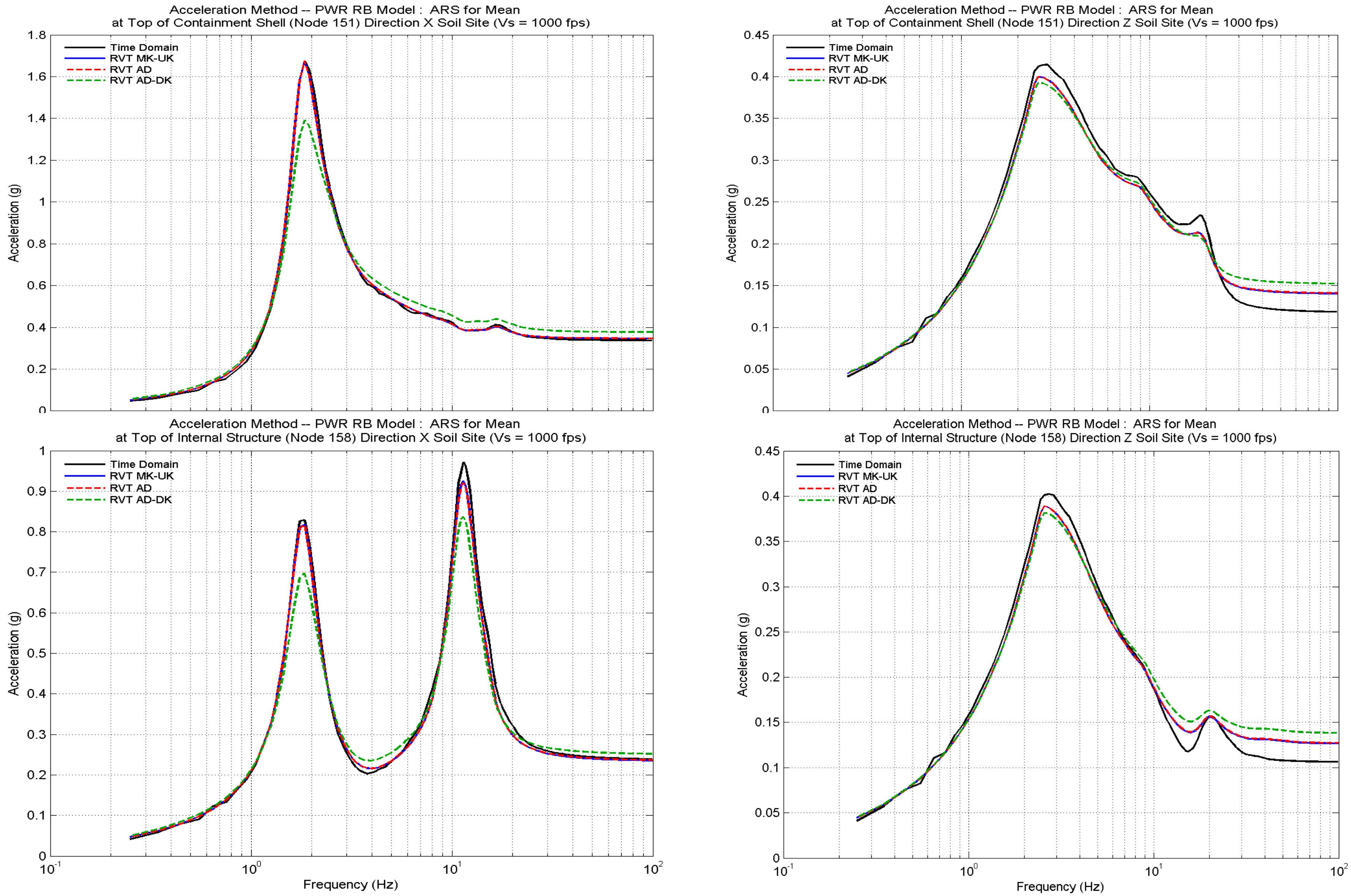
$$\sigma_R(\xi, \omega_0) = q(\nu_e, T)\sigma_{a,r}(\xi, \omega_0)$$

$$\nu_0 = \frac{1}{\pi}\frac{\sigma_{\dot{X}}}{\sigma_X} = \frac{1}{\pi}\sqrt{\frac{\lambda_2}{\lambda_0}} \qquad \delta = \sqrt{1 - \frac{\lambda_1^2}{\lambda_0 \lambda_2}}$$

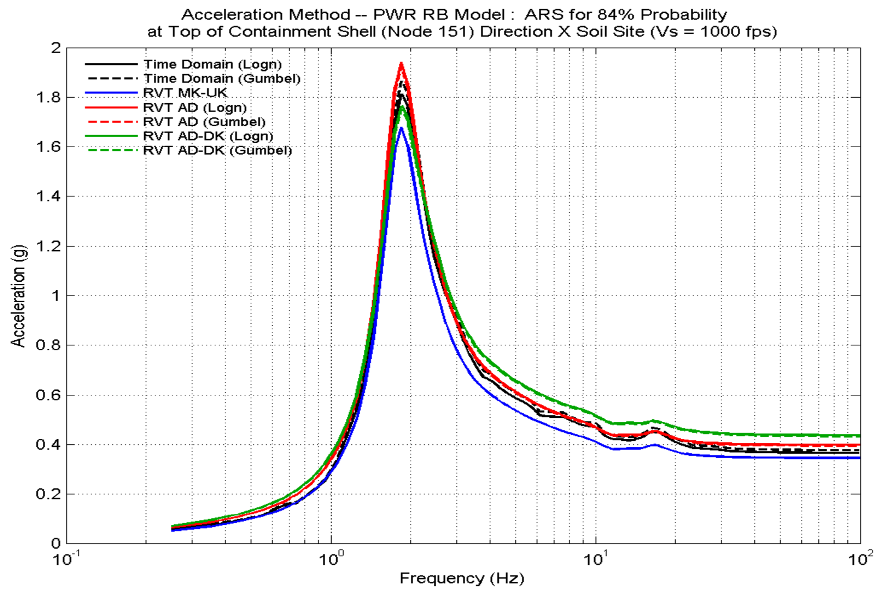
$\nu_e = \nu_0$ (AD for BBp)

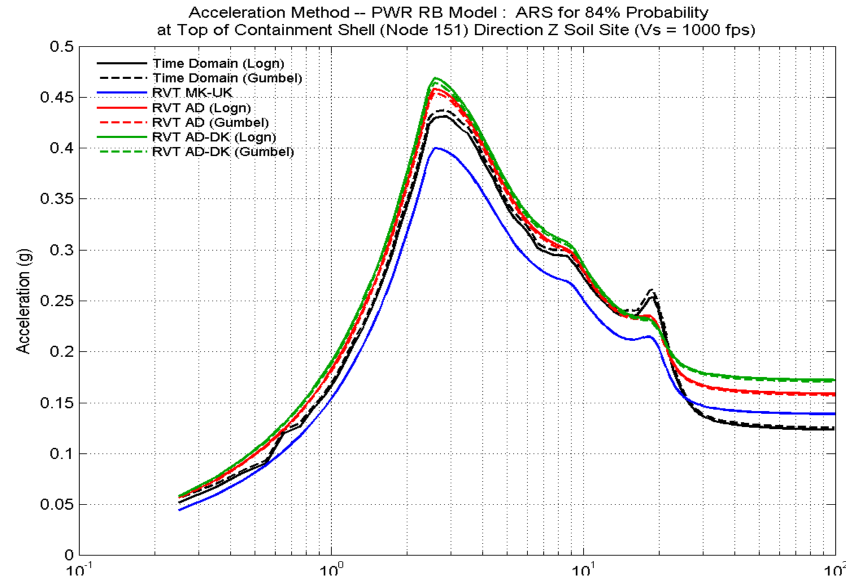
$\nu_e = f(\delta)\nu_0$ (AD-DK) for NBp

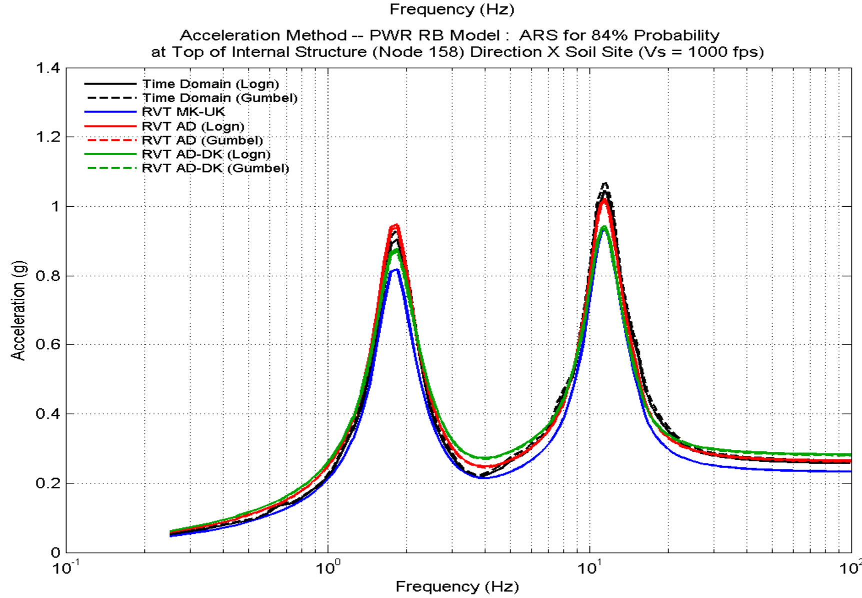
PWR RB Model: Soil Site (Vs=1,000) – RG 1.60 Input Acceleration Method (RVT Module) – Mean ARS

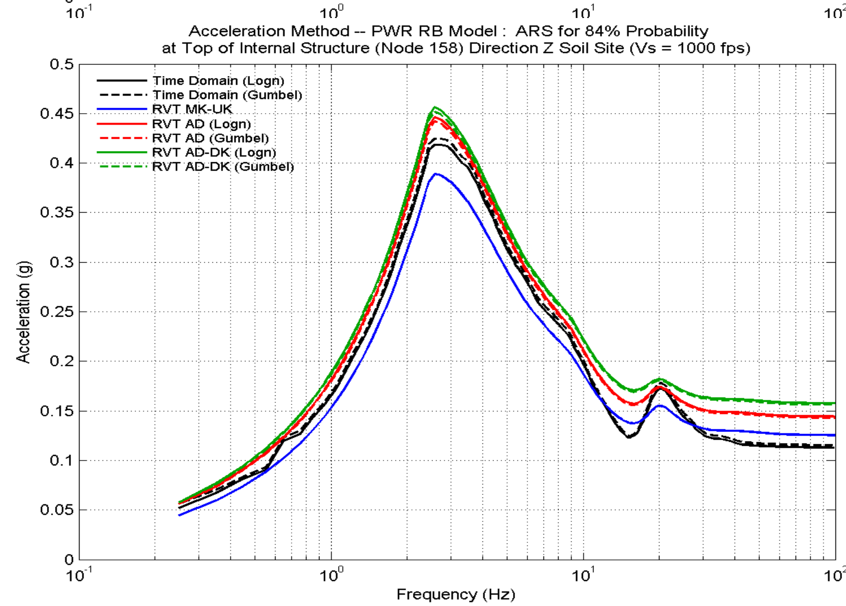


PWR RB Model: Soil Site (Vs=1,000) – RG 1.60 Input Acceleration Method (RVT Module) - ARS 84%

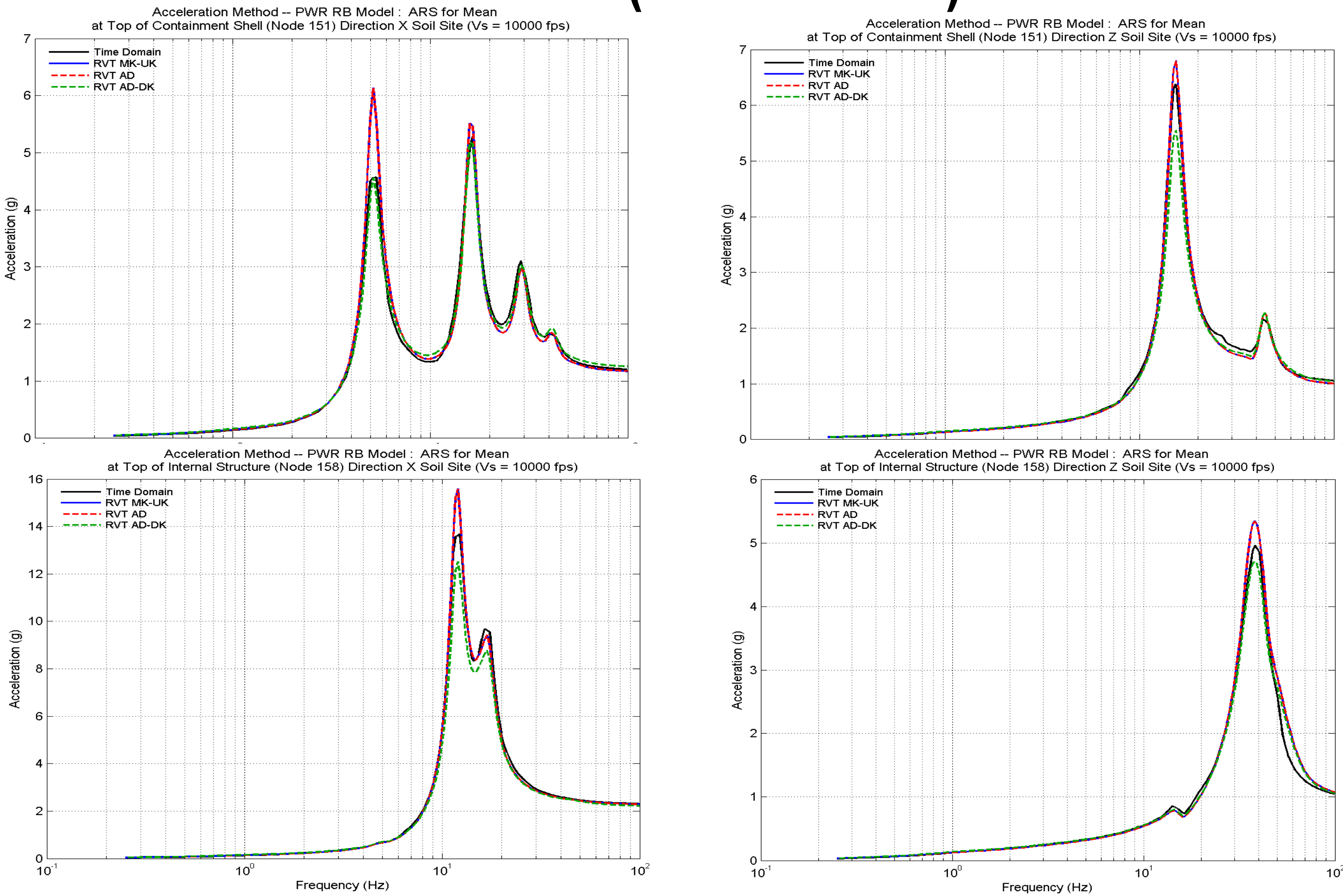




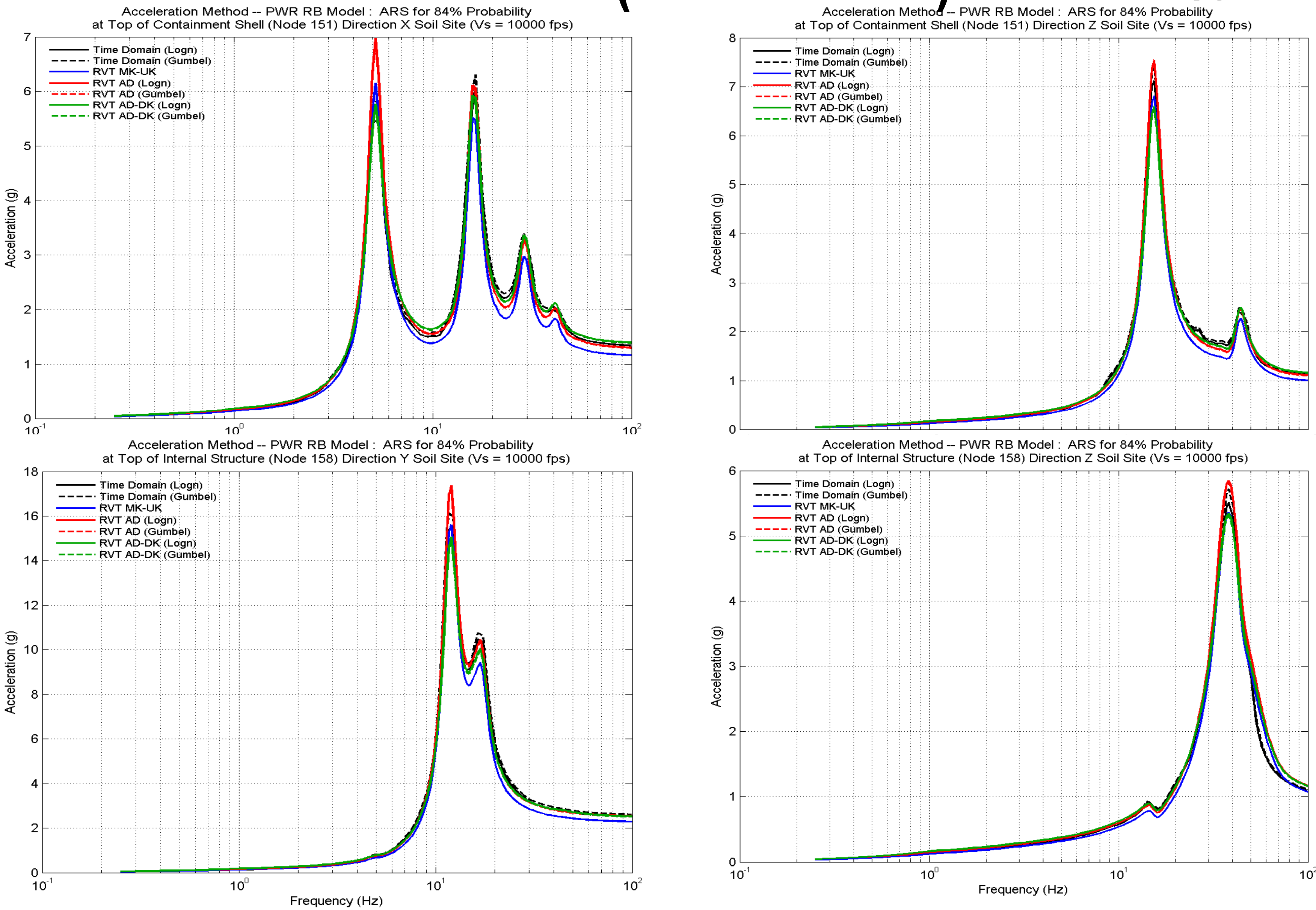




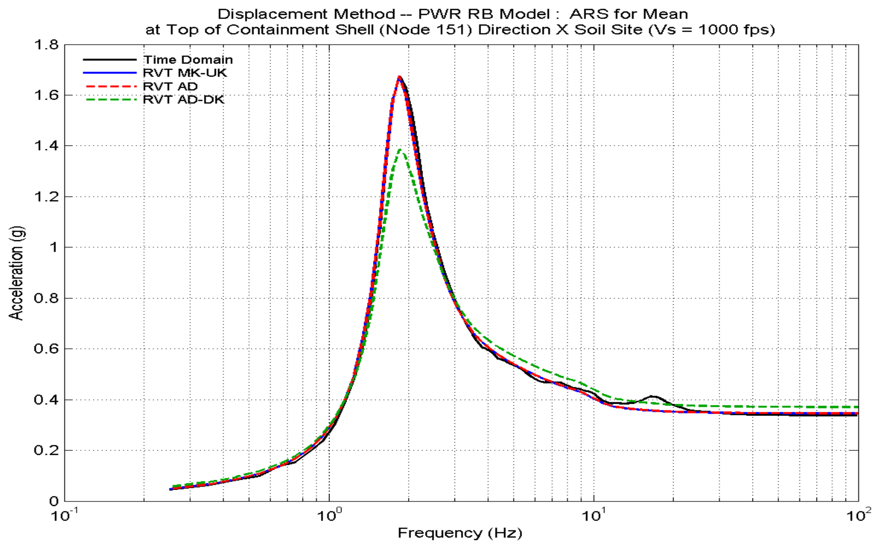
PWR RB Model: Rock Site (Vs=10,000) – UHRS Input Acceleration Method (RVT Module) – ARS Mean

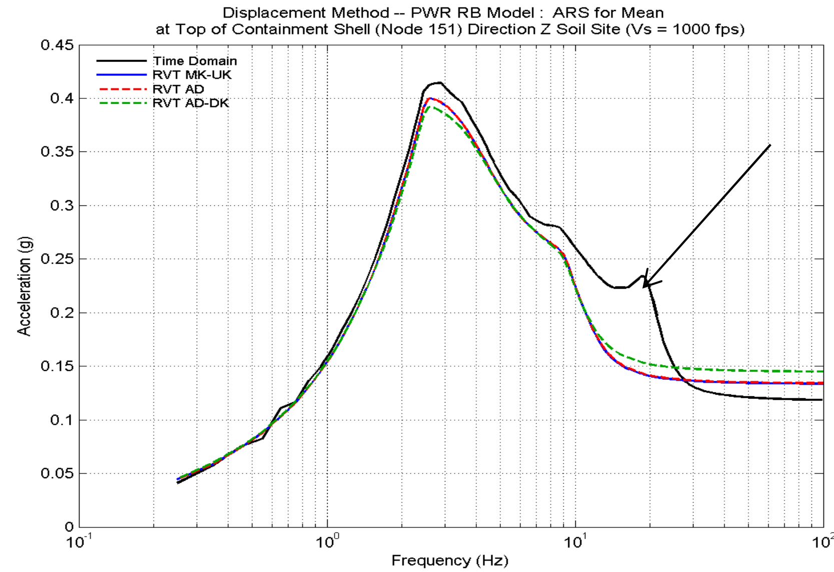


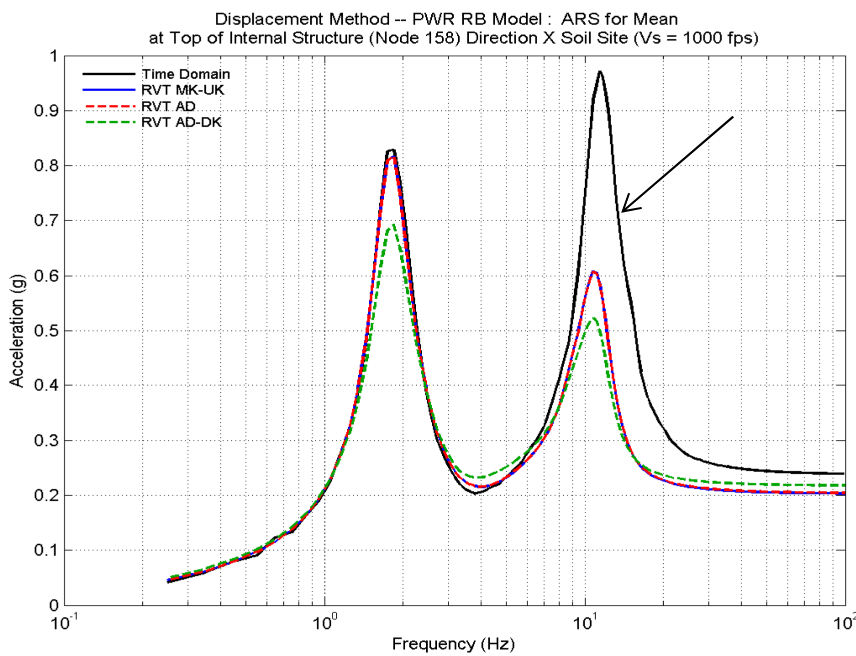
PWR RB Model: Rock Site (Vs=10,000) – UHRS Input Acceleration Method (RVT Module) - ARS 84%

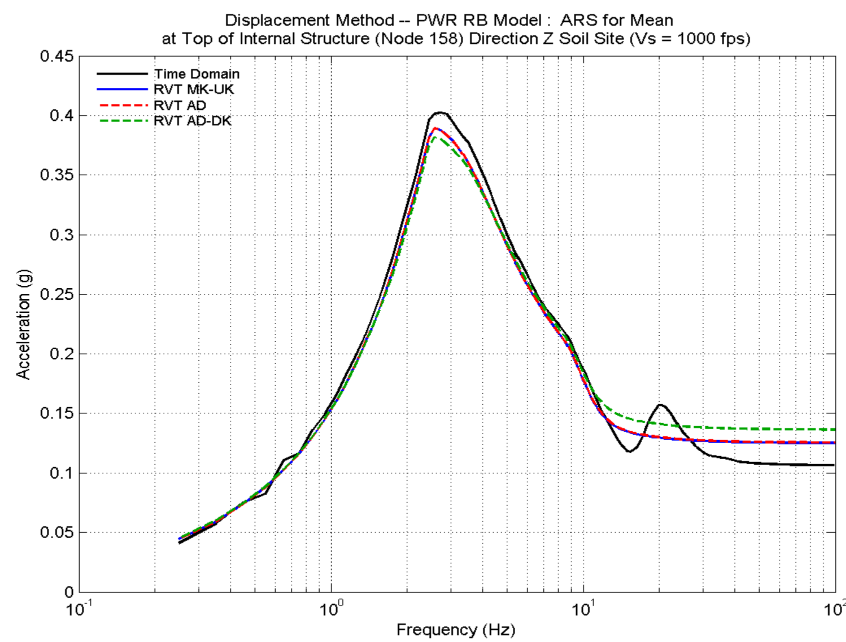


PWR RB Model: Soil Site (Vs=1,000) – RG 1.60 Input Displacement Method (Bechtel – 15WCEE!) – ARS Mean

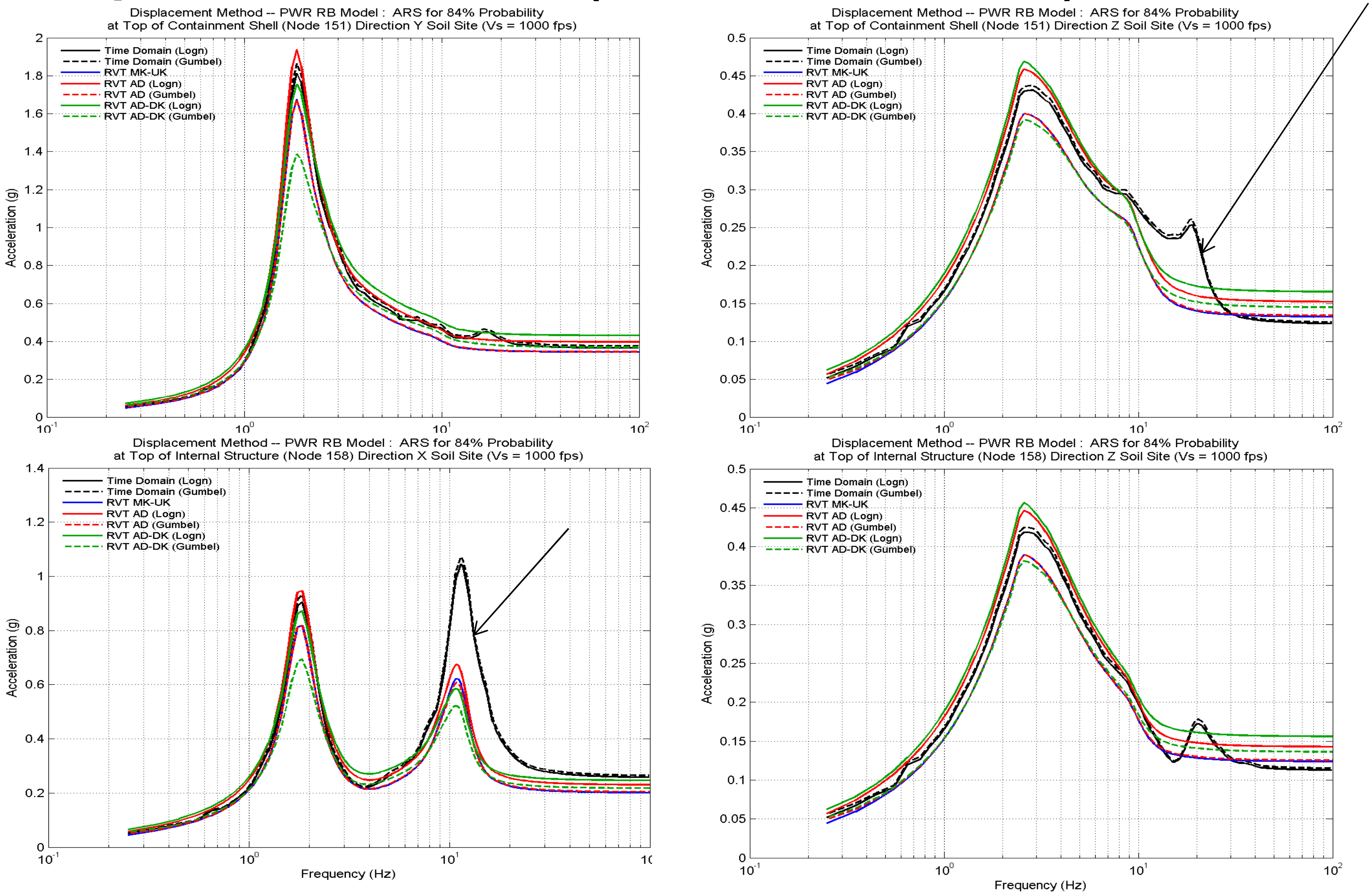








PWR RB Model: Soil Site (Vs=1,000) – RG 1.60 Input Displacement Method (Bechtel – 15WCEE) - ARS 84%



ASCE 04 Standard Draft 2012 – to be completed by 2012
Chapters 2 and 5 on Seismic Input and SSI Analysis

1) Improves the seismic input definition for FIRS
2) Recognize the significance of seismic input phasing – 5 input histories
3) Improves selection of deterministic soil profiles, LB, BE, UB and others
4) Recognizes the spatial correlations between soil layers
5) Provides many details for incoherent SSI analysis
6) Recognizes the basemat flexibility effects for incoherent inputs
7) Introduces probabilistic SSI methodologies
8) Limits incoherency effects for rock sites; in future to be extended to soils
9) Recognize the effects of vertical motion incoherency for flexible baseslab
10) Does not provide guidelines yet on the incoherent SSSI effects on ISRS, structural forces and relative displacements
11) No recommendations for incoherency effects on deeply embedded structures; effects of seismic soil pressures on flexible walls

Presentation Conclusions

New nuclear energy project demands in US and oversee produced a significant and quick improvement of the seismic SSI analysis methodologies that are applicable to any large-size, massive concrete infrastructure constructions.

In the last 5 years, great efforts in US, including both industry and Government, produced significant advancements in structural engineering with emphasis on seismic SSI analysis methodologies as described in the 2013 Draft of ASCE 04 Standard as partially discussed in this presentation.