Recent Advances Implemented in ACS SASSI Software for Linear and Nonlinear Seismic Soil-Structure Interaction (SSI) Analysis

Dr. Dan M. Ghiocel

Email: dan.ghiocel@ghiocel-tech.com

Phone: 585-641-0379

Ghiocel Predictive Technologies Inc.

http://www.ghiocel-tech.com

Ghiocel Predictive Technologies Inc.

Part 1

Tokyo Station Convention Center, Japan

March 24-25, 2014

Scope of this Presentation:

To present an overview on recent advances in seismic SSI analysis capabilities, as implemented in the new ACS SASSI Version 3.0 software, that will be commercially available tentatively with May 1, 2014. These advances were partially a result of the new recommendations of ASCE 04-2014 standard on “*Seismic Analysis of Safety-Related Nuclear Structures*”.

This presentation will discuss the new ACS SASSI Version 3.0 capabilities for seismic SSI analysis, most of them related to the new ASCE 04-2014 recommendations. The presentation will include key SSI modeling aspects, and recommended approaches. The presentation will include case studies using the new ACS SASSI Version 3.0 software.

This presentation is made from my own personal perspective, not from the ASCE DANS committee perspective, based on a good number of years of involvement in the development of the ASCE 04-2014 standard.

Application of ACS SASSI to non-nuclear structures will be illustrated by few case studies.

Content of this Presentation:

DAY 1: NEW ACS SASSI SSI ANALYSIS CAPABILITIES RELATED TO ASCE 04-2014 (Rev 0, May 2014)

1) *Introduction to the New ASCE 04-2014 Requirements for SSI Analysis.*
   - *Seismic input motion:* spatial variation and directionality (phasing)
   - *SSI modeling aspects:* flexible foundations, motion incoherency, structure-soil-structure interaction (SSSI), nonlinear aspects
   - *SSI analysis approaches:* probabilistic SSI analysis, RVT-based SSI analysis, new flexible volume substructuring methods for deeply embedded structures

2) *ACS SASSI Version 3.0 Capabilities Related to ASCE 04-2014*
   - *Probabilistic SSI Analysis* Via Latin Hypercube Sampling (Option Pro)
   - *RVT-based SSI Analysis* Via Different Methods (Option RVT)
   - *Two Step SSI Approach* Via ANSYS Interfacing (Options A, and AA)
   - Fast Flexible Volume (FFV) method for deeply embedded structures

DAY 2: OTHER NEW ACS SASSI CAPABILITIES AND APPLICATION TO URBAN AREAS BUILDINGS AND BRIDGES

1) *New GUI Capabilities for Checking and Improving Numerical Conditioning of Complex SSI Models*
   - Improve Numerical Modeling for Thin Shell FEA Models
   - Checking Element Compatibility
   - Combine FEA Models, Extract Excavation
   - Automatic Selection of Interaction Nodes for FV, FI and Fast FV

2) *Fast Nonlinear SSI Analysis In Complex Frequency (Rev 1, Sept. 2014)*
   - Nonlinear SSI Structural Analysis for Low-Rise Shearwall Buildings

ACS SASSI APPLICATION TO NON-NUCLEAR STRUCTURES

1) Application to Civil Buildings in Dense Urban Areas
   - SSI analysis of a multistory shearwall building and a subway station
   - SSSI analysis of a subway station near a multistory building

2) Application to Concrete Bridges With Deep Foundations

New Recommendations in ASCE 04 Standard 2014

1) Improves the seismic input definition for FIRS based on probabilistic site response simulations (60 LHS realizations)
2) Recognize the significance of seismic input phasing by using 5 seismic input acceleration histories
3) Improves selection of deterministic soil profiles, LB, BE, UB soil profiles based on probabilistic site response simulations (60 LHS realizations)
4) Recognizes the existence of spatial correlations between soil layer properties
5) Recognizes the significance of SSSI effects on ISRS. Mandatory SSI analyses. Final ISRS should be based on enveloping the ISRS from standalone SSI and SSSI analysis results
6) Provides many details for incoherent SSI analysis needed for high-frequency inputs and rock sites.
7) Recognizes the significance of the foundation wall and baseslab flexibility effects for both coherent and incoherent inputs.

8) Introduces probabilistic SSI analysis for design analysis. The 80% probability of non-exceedance results should be used for design.
9) Introduces the Random-Vibration Theory (RVT) analysis for deterministic SSI analysis. No time history needed. Not sufficient guidance of RVT application.
10) It does not include recommendations for considering incoherency effects for SSSI evaluations.
11) It does not provide guidelines on the incoherent SSSI effects on ISRS, structural forces, basemat bending and relative displacements.
12) It does not establish the limits of the application of the EPRI-validated deterministic incoherent SSI approaches for FEA SSI models with elastic foundation (not infinitely rigid basemat).
13) It does not provide recommendations for incoherency effects on deeply embedded structures, including the effects on seismic soil pressures on foundation walls and baseslab
14) It does not provide recommendations for inclined soil layers/topography effects on SSI results, when local soil impedances and input motions are varying in horizontal plane.

New ACS SASSI Version 3.0 Capabilities

Site Response Analysis:

1) *Improve simulation of spectrum compatible input acceleration time histories* to include checks for the USNRC SRP 3.7.1 criteria (EQUAKE)

2) *Use up to 100 soil material curves* for site response analysis (SOIL)

3) *Improve motion incoherency modeling* (HOUSE)
   - Include both isotropic (radial) and directional (anisotropic) Abrahamson plane-wave incoherency models for soil and rock sites.
   - Include user defined plane-wave coherency models for X, Y and Z.
   - Include instructions on how to perform a multilevel incoherency analysis for deeply embedded structures, such as SMRs.

4) *Capability to include soil layering and soil motion variations in horizontal plane (modifying soil dynamic stiffness and motion at interaction nodes).*
   - Include instructions on how to handle cases where the soil layering and motion are varying in horizontal direction (need to recompute seismic free-field load vector using restarts 2 and 6)

Seismic SSI Analysis:

5) *No specific software limitation for the number of interaction nodes,* other than 100,000 nodes limitation for all FE model nodes. The practical limitation is the amount of RAM available for the SSI runs *(Option FS).* The V&V tests for the new NQA version were done up 35,000 interaction nodes using a MS Windows 7 workstation with 192GB RAM. For compressed project schedules, it is impractical for to use SSI models with more than 15,000-20,000 interaction nodes under typical PC workstations. Large size SSI models can be used for benchmark, but they might not productive for many SSI runs, especially under tight schedules.
6) *Much faster than Version 2.3.0*. The speed-up of the SSI analysis is about 3 times; no need to do restart analyses for Y and Z inputs *(Option FS).*
7) *Number of Fourier frequencies* up to 32,768 frequencies.
8) *Up to 200 soil layers* for SSI analysis. A larger number of layers might be needed for sites with deep soils. (SITE)

9) *Improved Fast-FV approach* for deeply embedded structures. Automatic interaction nodes generation is included in the new SUBMODELER module. It can be used also for FI-EVBN (MSM) or FV.

10) *Improved interpolation scheme for ATF.* New interpolation scheme is based on a complex bicubic spline function that is highly effective for performing incoherent SSI analysis using stochastic simulation with a larger number of SSI frequencies. It should be applied without smoothing.(MOTION, STRESS)

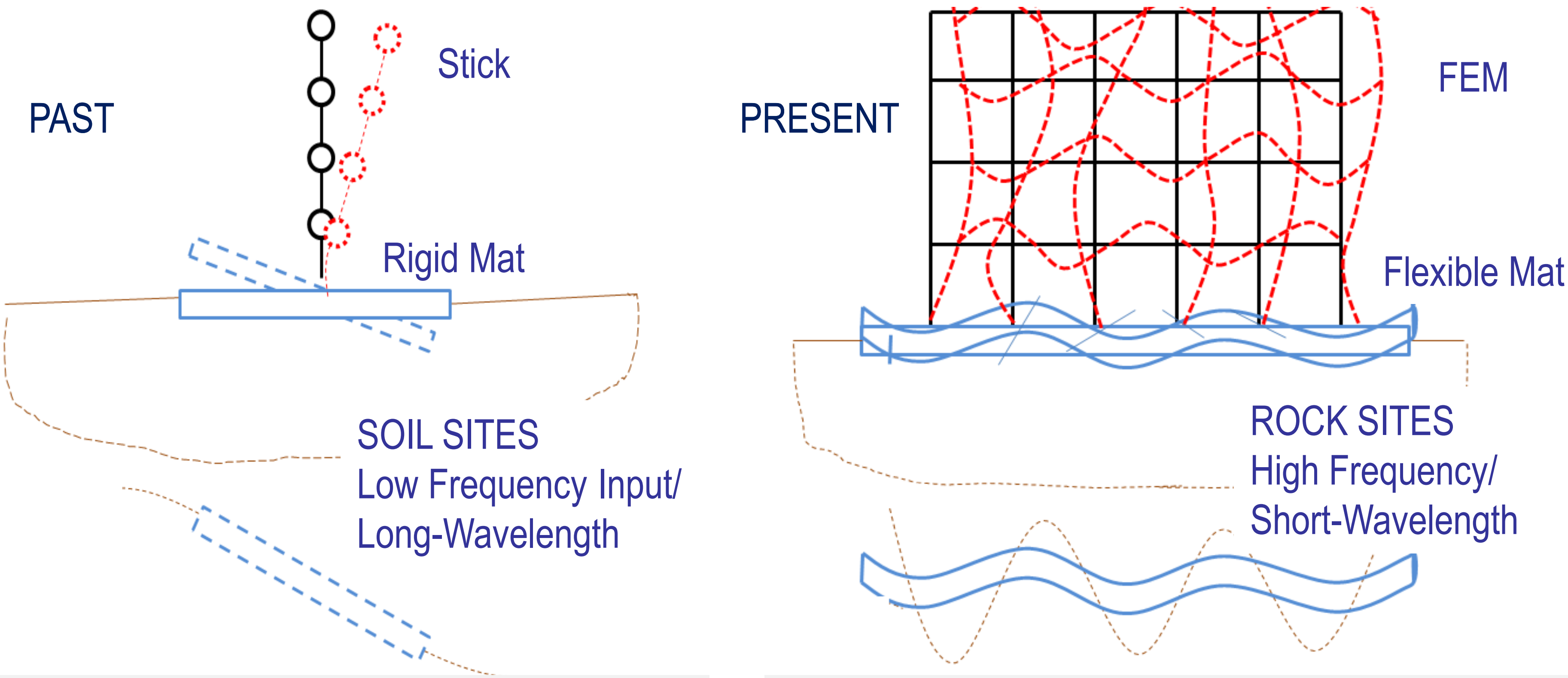
11) *Probabilistic SSI analysis capability* in accordance with ASCE 04-2014 (Section 5.5). Use LHS simulations that are faster than MC simulations. Include all recommended methods, plus enhancements. *(Option Pro)*

12) *RVT SSI analysis capability* in accordance with ASCE 04-2014 recommendations. Include several RVT methods. Includes more methods than mentioned in Section 5.0 on Seismic SSI Analysis.Needs careful use and user understanding of modeling limitations. *(Option RVT)*

13) *New ACS SASSI-ANSYS interfacing* that using ANSYS FE model K and M matrices directly for SSI analysis. It has the benefit of using ANSYS refined FE modeling, including new elements like pipes, shell with shear flexibility, rigid links, etc. *(Option AA).*

14) *Fast Nonlinear Analysis for Low-Rise Shearwall Structures in complex frequency* (based on ASCE 43 and 41 recommendations). It is by several hundreds of times faster than traditional nonlinear time-history analysis by direct integration. Plus much more numerically robust. Plus the structure and soil material damping is handled correctly, independent of frequency. *(Option Non, later in 2014)*

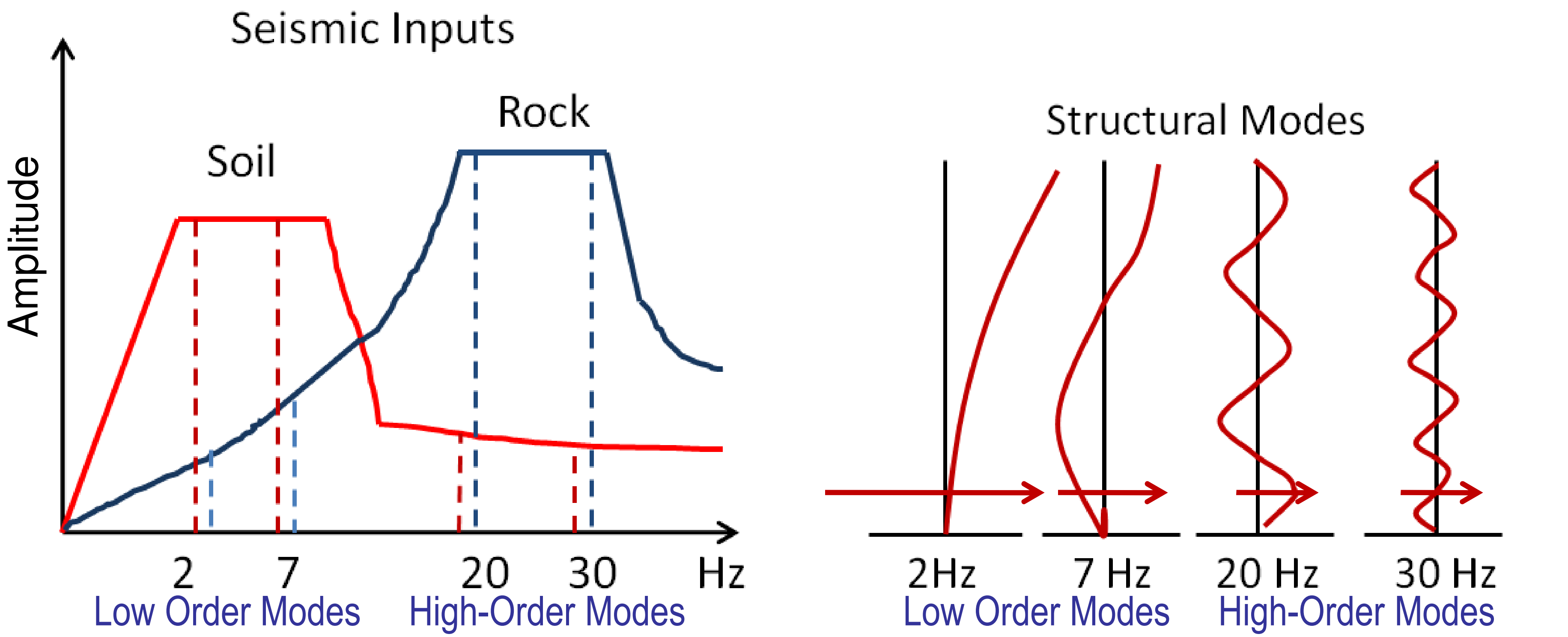
Past and Present Engineering Applications



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



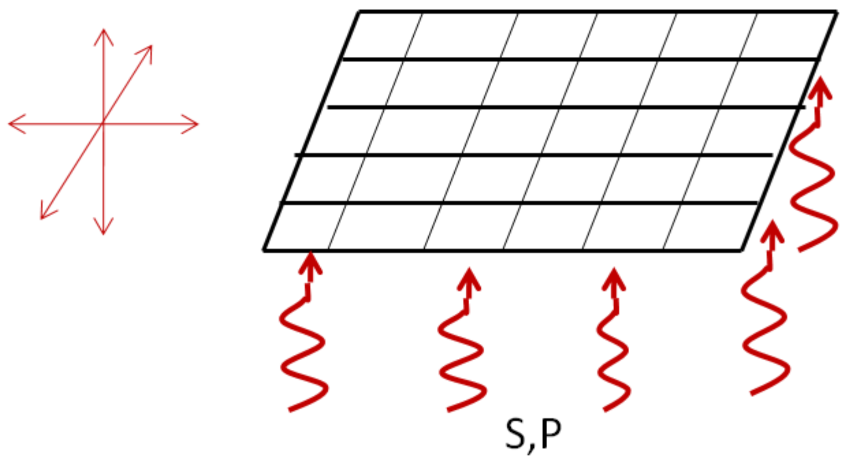
REMARKS:

- 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 Motion Spatial Variation:Coherent vs. Incoherent

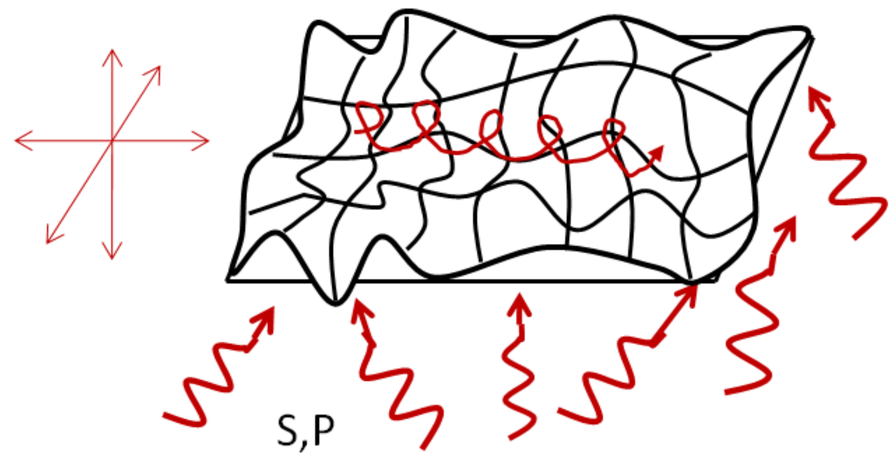
3D Rigid Body Soil Motion (Idealized)



1 D Wave Propagation Analytical Model (Coherent)

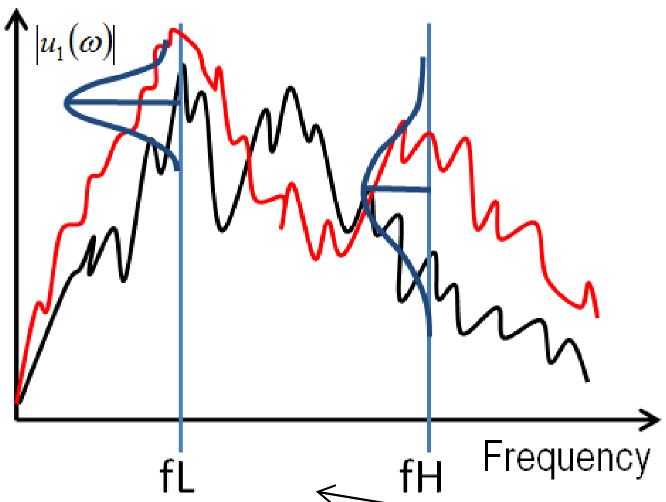
Vertically Propagating S and P waves (1D)
- No other waves types included
- No heterogeneity random orientation and arrivals included
- Results in a rigid body soil motion, even for large-size foundations

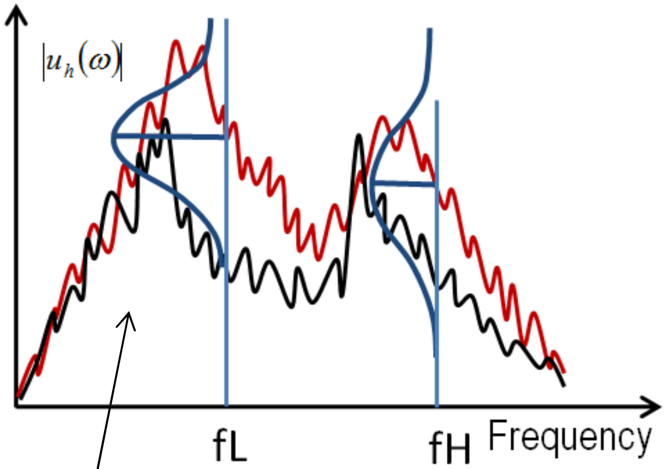
3D Random Wave Field Soil Motion (Realistic)

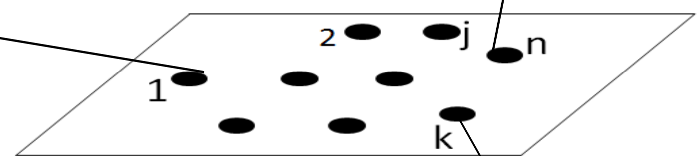


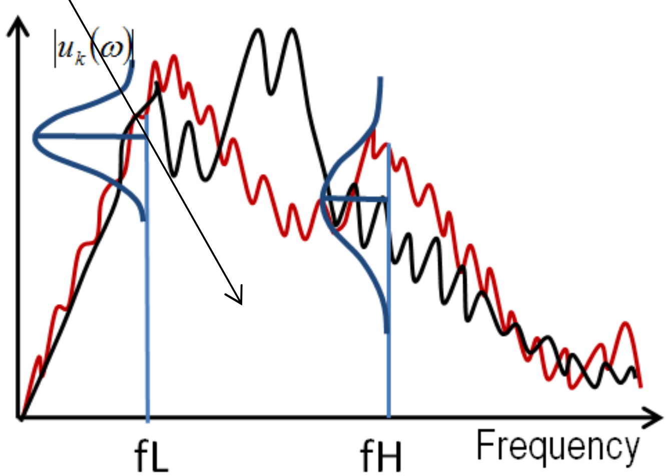
3D Wave Propagation Data-Based Model (Incoherent – Database-Driven Adjusted Coherent)
Amplitude of vertically propagating S and P wave motions are adjusted based on the statistical models derived from various field dense-arrays record databases (plane wave coherency models, plus wave passage – Abrahamson's 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

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

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

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

2007 Abrahamson Coherence for Hard-Rock and Soil Sites

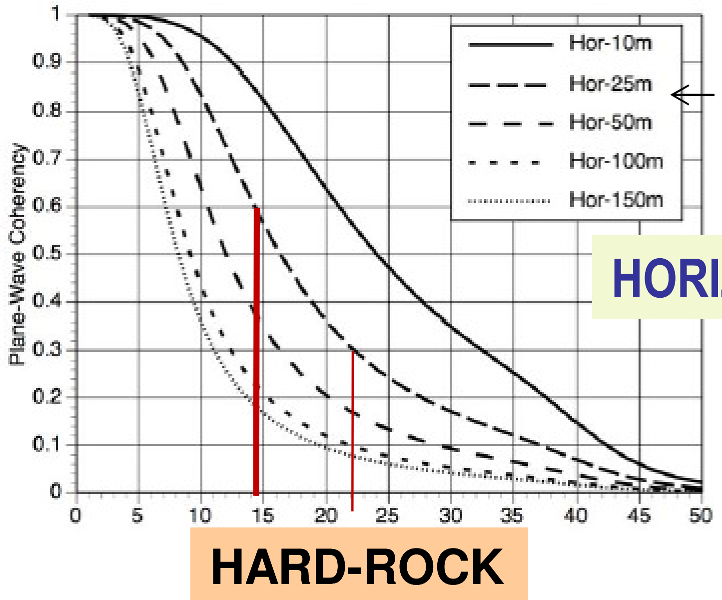


Figure 6-1
Plane-Wave Coherency for the Horizontal Component

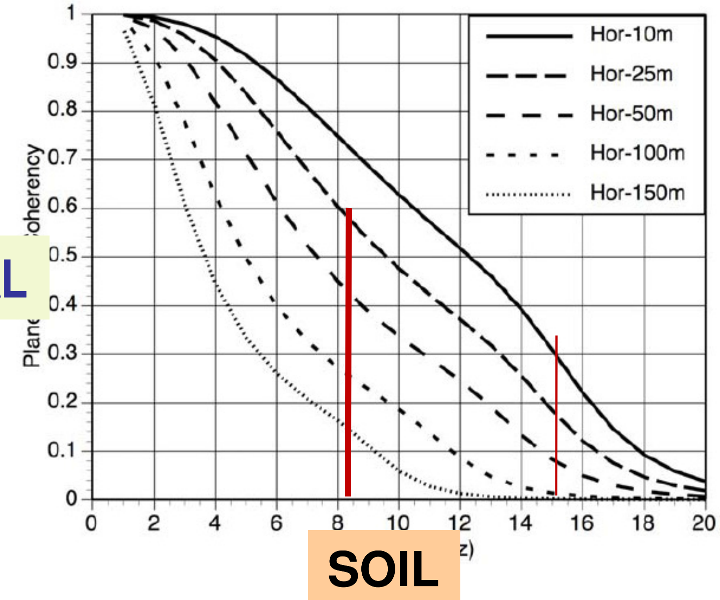


Figure 7-1
Plane-Wave Coherency for the Horizontal Component for Soil Sites

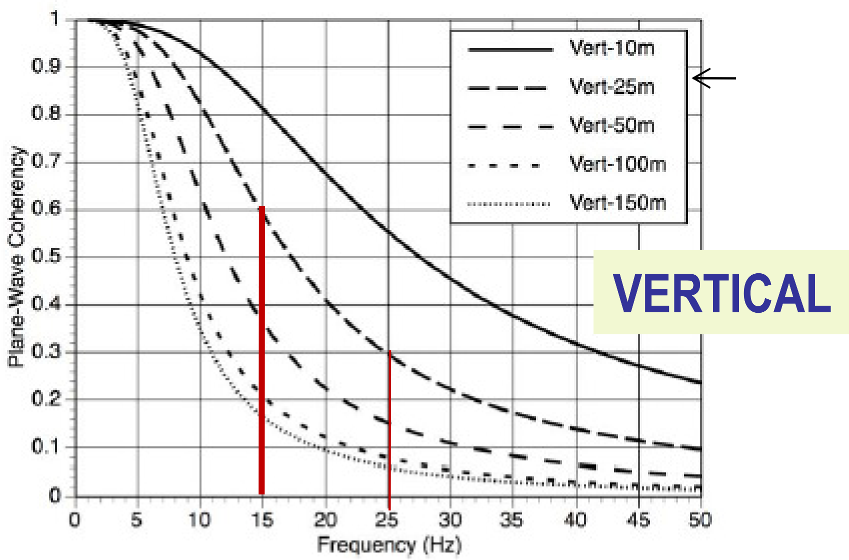


Figure 6-2
Plane-Wave Coherency for the Vertical Component

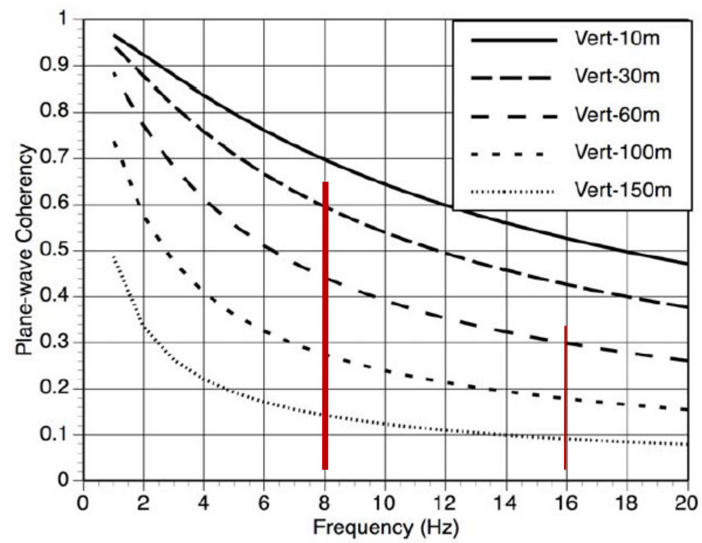
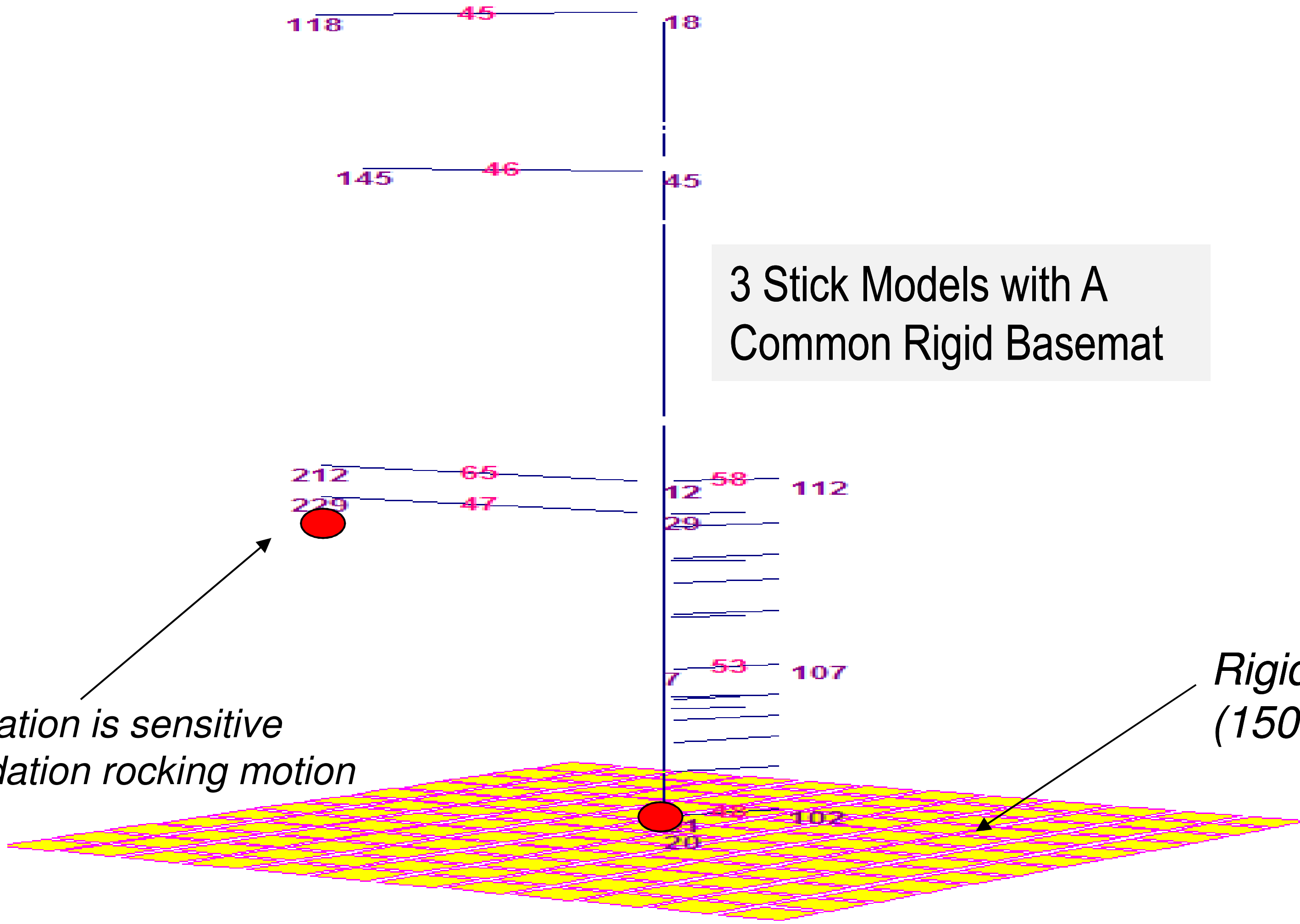


Figure 7-2
Plane-Wave Coherency for the Vertical Component for Soil Sites

(EPRI TR # 1015110, December 2007)

EPRI AP1000 Stick Study on Incoherent SSI Approaches (EPRI TR# 1015111, Nov 2007, NRC ISG-01, May 2008)



3 Stick Models with A Common Rigid Basemat

Z translation is sensitive to foundation rocking motion

Rigid Mat (150'x150')

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

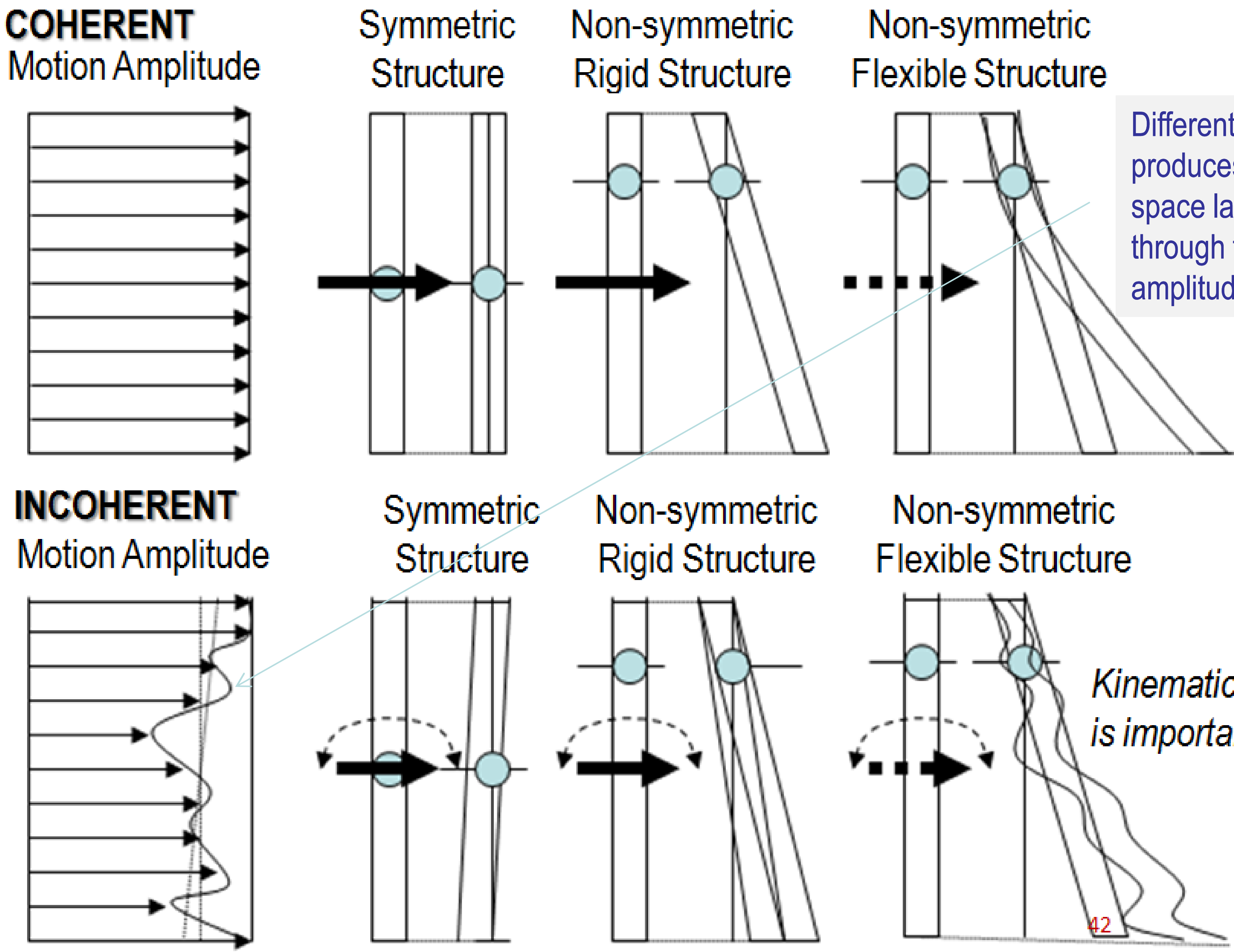
2) SRSS TF Approach – Validated/Accurate, Final Design Calcs

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

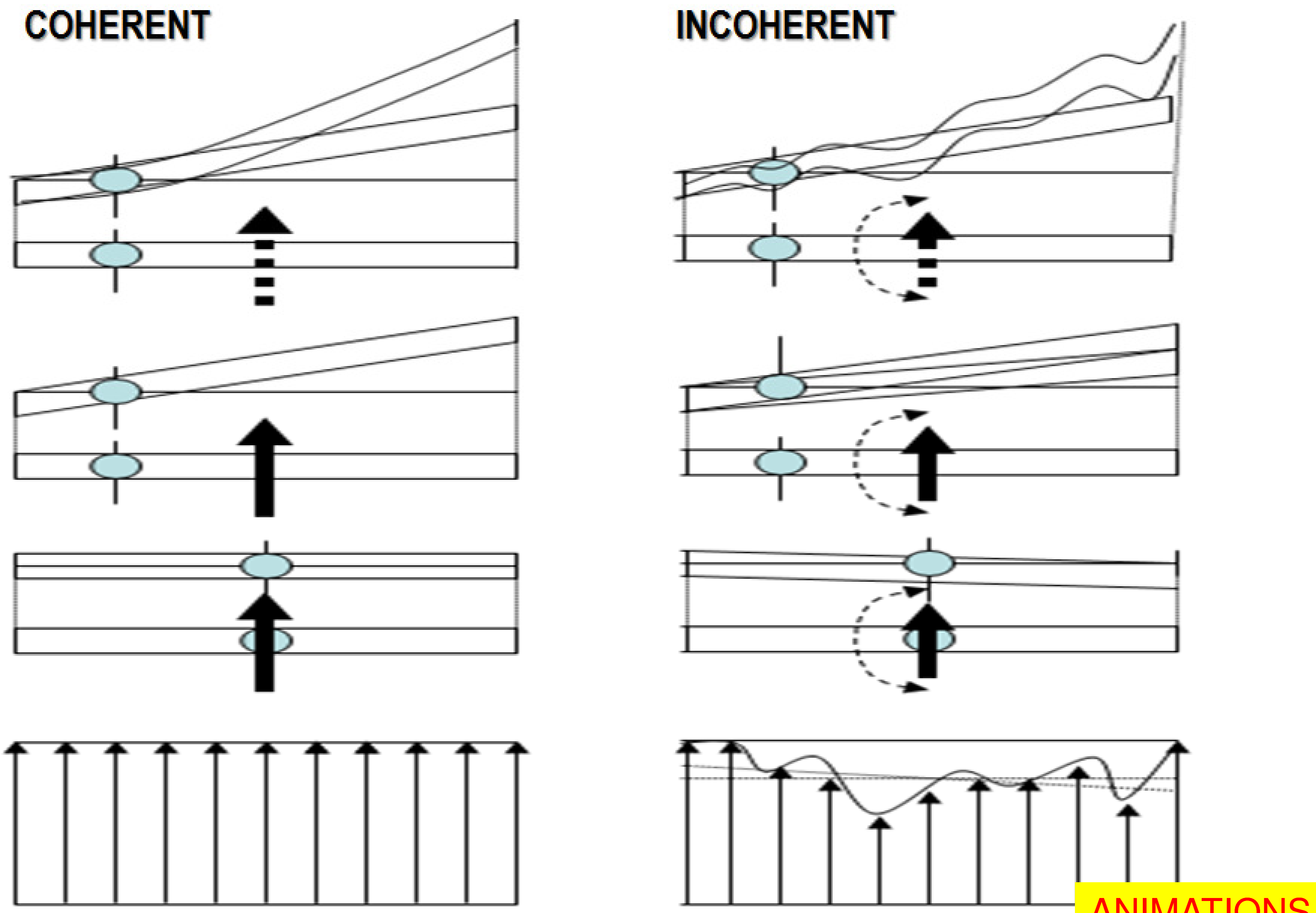
Effect of Motion Incoherency Differential Phasing



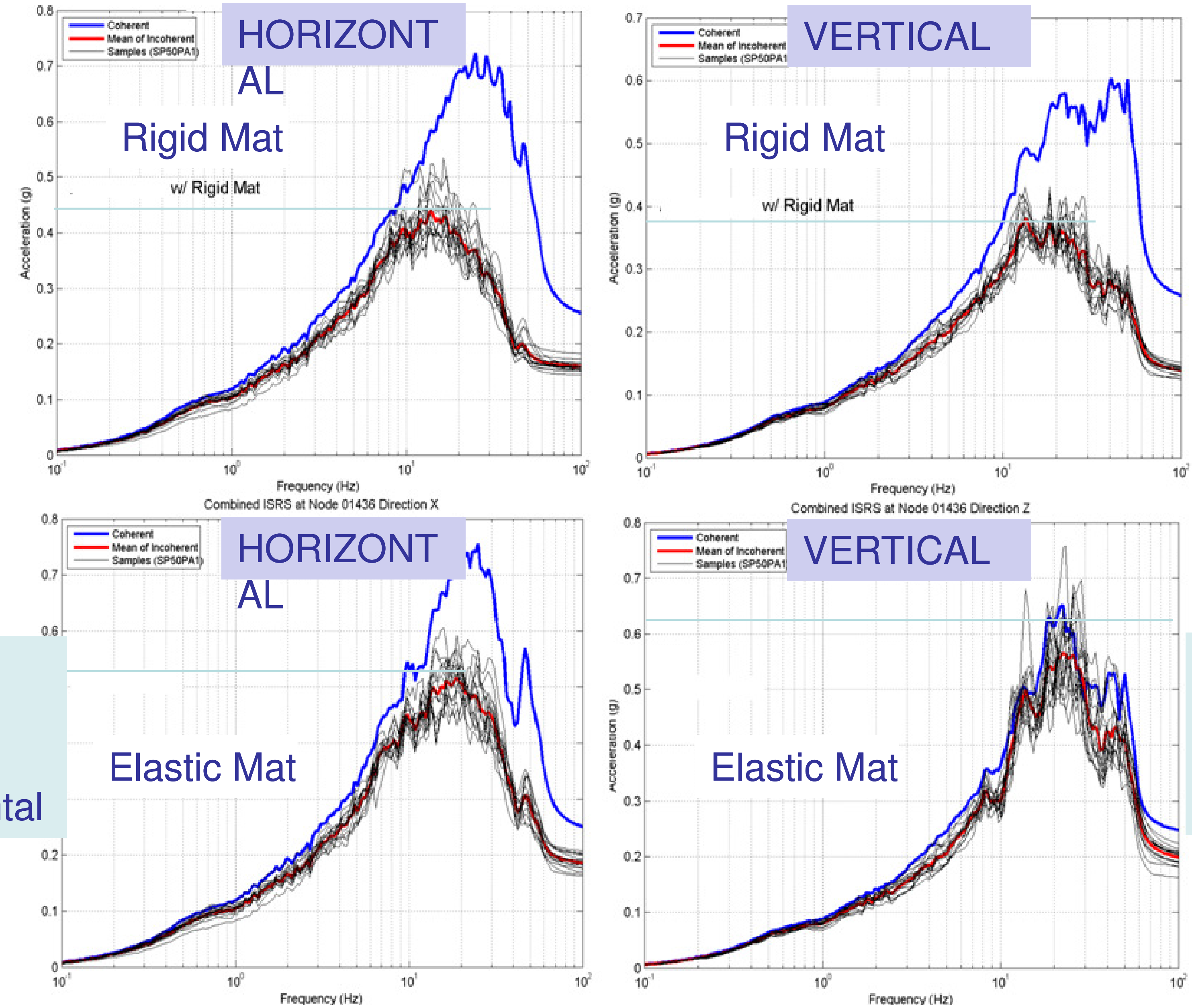
Differential phasing produces time and space lags, and through these, amplitude variations

Kinematic SSI is important

Coherent vs. Incoherent SSI Response – Vertical



Basemat Flexibility Effects on RB Complex ISRS

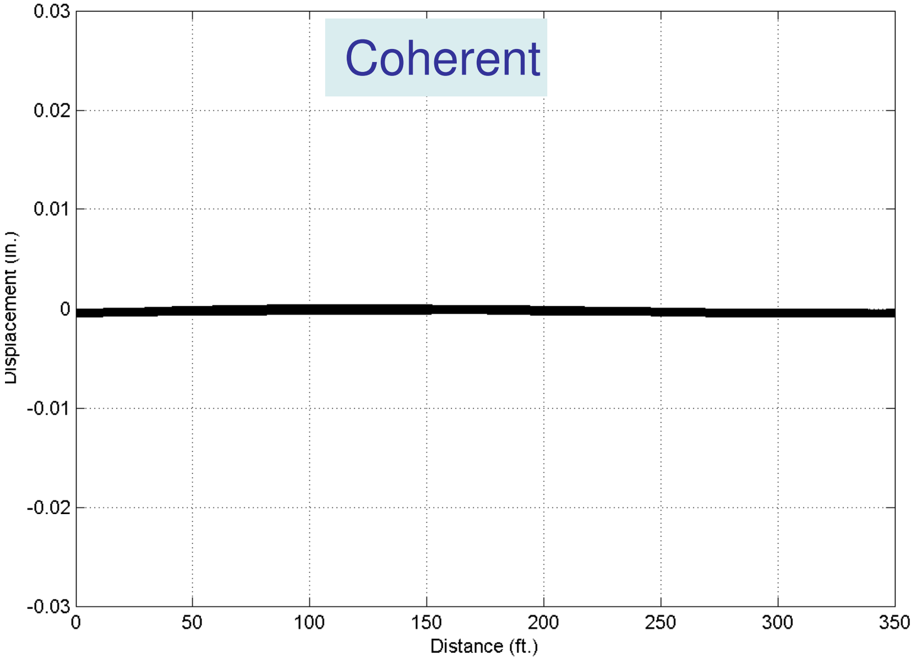


Elastic is 20% up for horizontal

Elastic is 65% (!) up for vertical

Effects of Incoherency on Basemat Bending

Combined THD at Group 1 - COHERENT 5 ft. EConcrete
Y-Direction - Transversal Axis - Frame 1474



Combined THD at Group 1 - INCOHERENT 5 ft. EConcrete
Y-Direction - Transversal Axis - Frame 1474

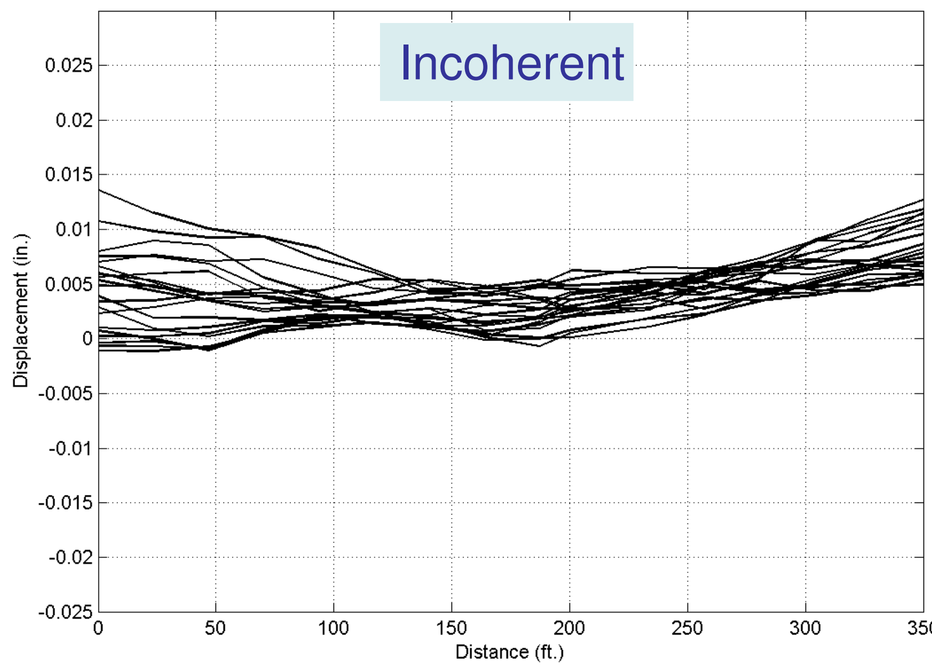


Table 1: Baseslab Bending Moments for A Soil Deposit with Vs = 3,300 ft/s

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

ANIMATIONS

Effects of Incoherency on Basemat Bending

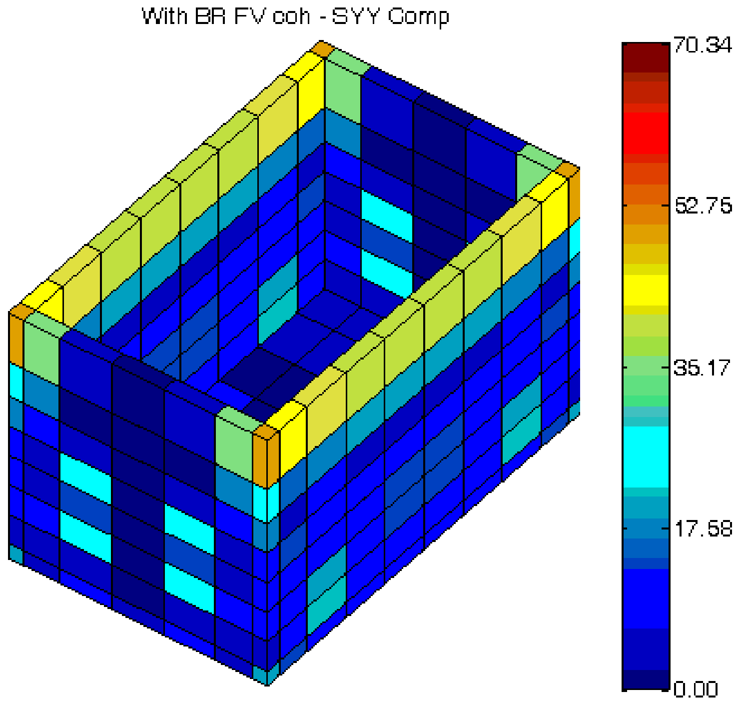
It should be noted that incoherent bending moments increase by 30% to 130% in comparison with coherent bending moments. The relative stiffness between baseslab and soil subgrade is an important parameter that affects the kinematic SSI effects.

It should be noted that the computed baseslab bending moments from SSI analysis include the contributions of both the primary stresses due to structural loads, and the secondary stresses due to SSI induced displacements. *The current ASCE standards do not consider in the structural design procedures for concrete footers below columns or wall lines or basemats, the effects of the secondary stresses produced by the SSI induced displacements. The neglect of the secondary stresses could produce a large under evaluation of the elastic bending moments. However, it should be noted that for the ultimate strength design approach used in the ASCE code for concrete design, the effects of the secondary stresses could be neglected if the baseslab has sufficient ductility to accommodate the SSI induced displacements.*

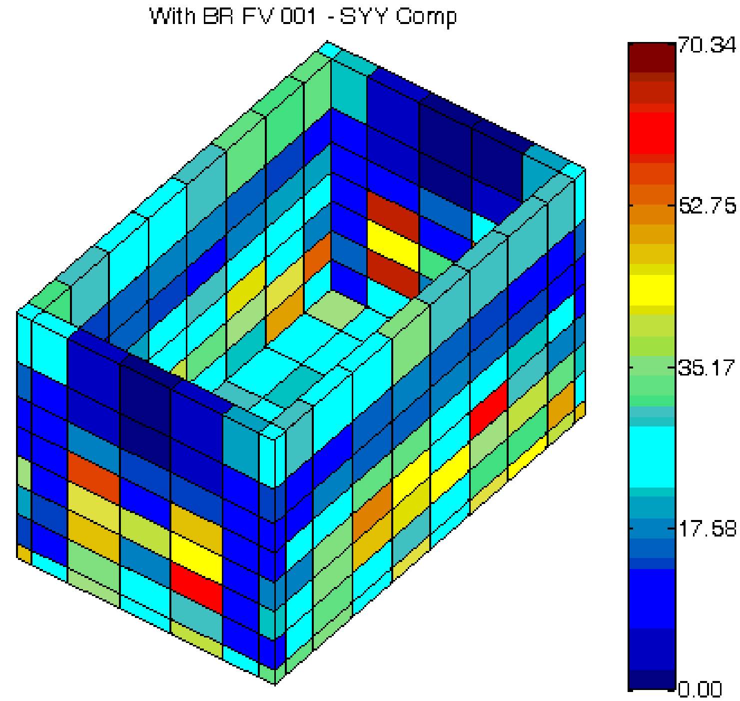
Seismic Coherent vs. Incoherent Stresses for X-Input

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

Element Center Stresses SYY



Coherent



Incoherent

ANIMATIONS

ACS SASSI V3.0 Incoherent SSI Analysis

There are several plane-wave incoherency models (with wave passage effects):

1) 1986 Luco-Wong model (theoretical, unvalidated, geom anisotropic)
2) 1993 Abrahamson model for all sites and surface foundations
3) 2005 Abrahamson model for all sites and surface foundations
4) 2006 Abrahamson model for all sites and embedded foundations
5) 2007 Abrahamson model for hard-rock sites and all foundations (NRC)
6) 2007 Abrahamson model for soil sites and surface foundations
7) *User Defined Plane-Wave Coherency Functions for X, Y and Z (Real). Wave passage is frequency independent (same Va for all frequencies).*
8) *User Defined Unlagged Coherency Functions for X, Y and Z (Complex). More general situations with wave passage frequency dependent.*

NOTE: For general, more complex situations, there will be instructions on how to include nonuniform motion amplitudes in horizontal plane by modify seismic free-field motion load vector (LOADxxxx files) – Advanced users.

Seismic SSI Analysis Using ACS SASSI

The complex frequency response is computed as follows:

- Coherent SSI response:

Structural transfer function given input at interaction nodes

Coherent ground transfer function at interface nodes given control motion

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

Complex Fourier transform of control motion

- Incoherent SSI response:

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

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

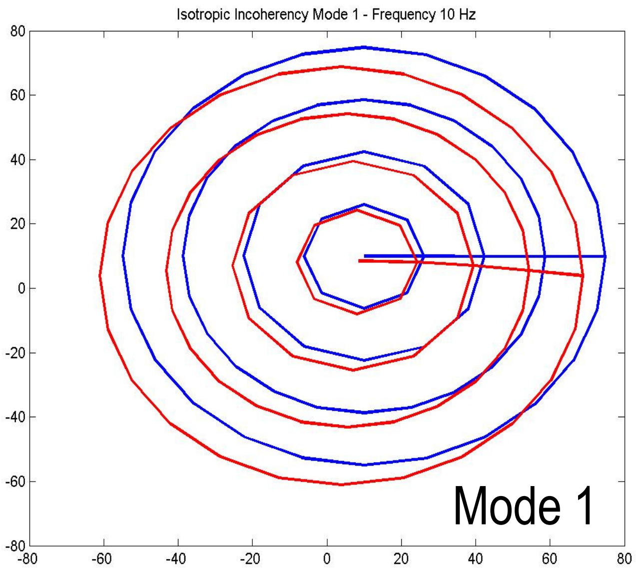
$$S_g(\omega) = [\Phi(\omega)][\lambda(\omega)]\{\eta_\theta\}$$

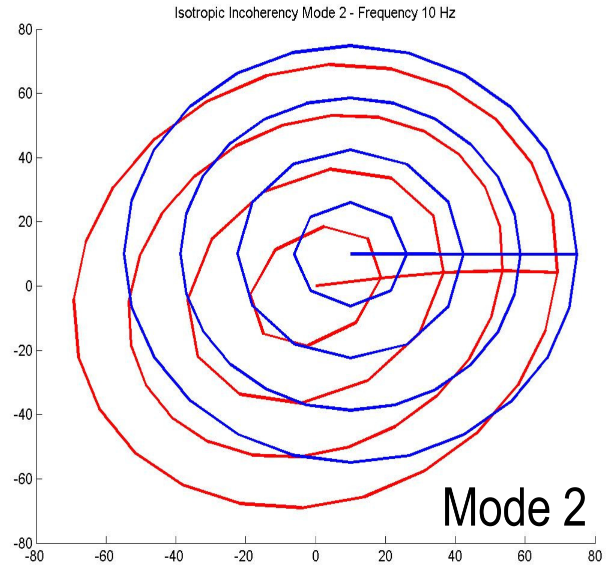
Complex Fourier transform of relative spatial variations of motion at interaction nodes that is stochastic by nature

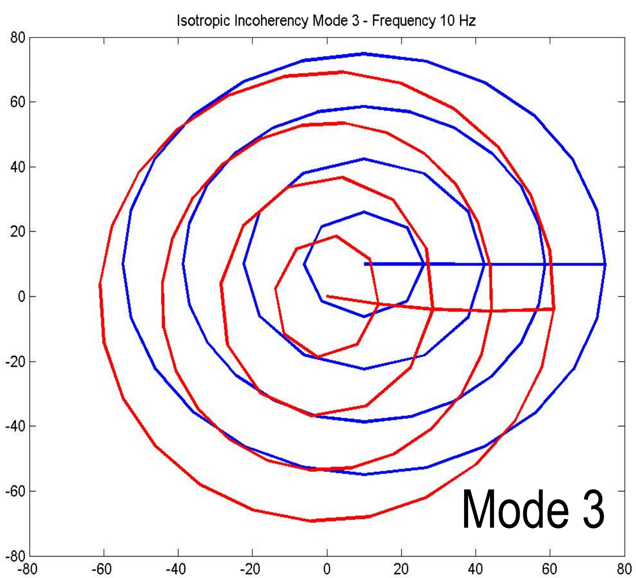
Spectral factorization of coherency kernel

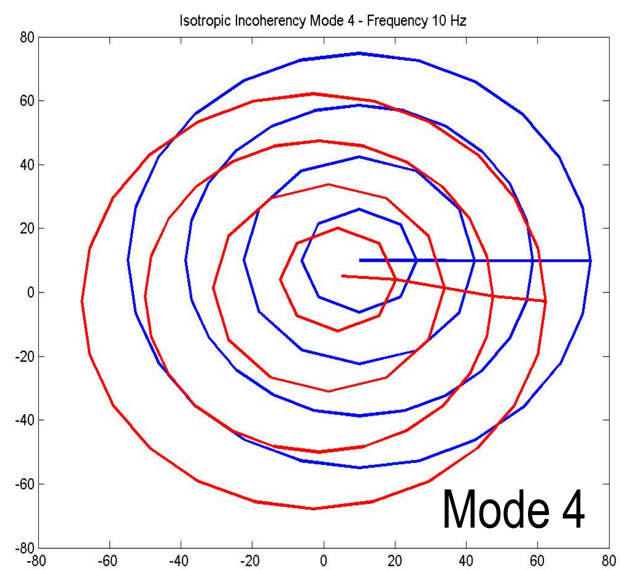
Random phases (stochastic part)

Motion Incoherency Modes of Basemat at 10 Hz









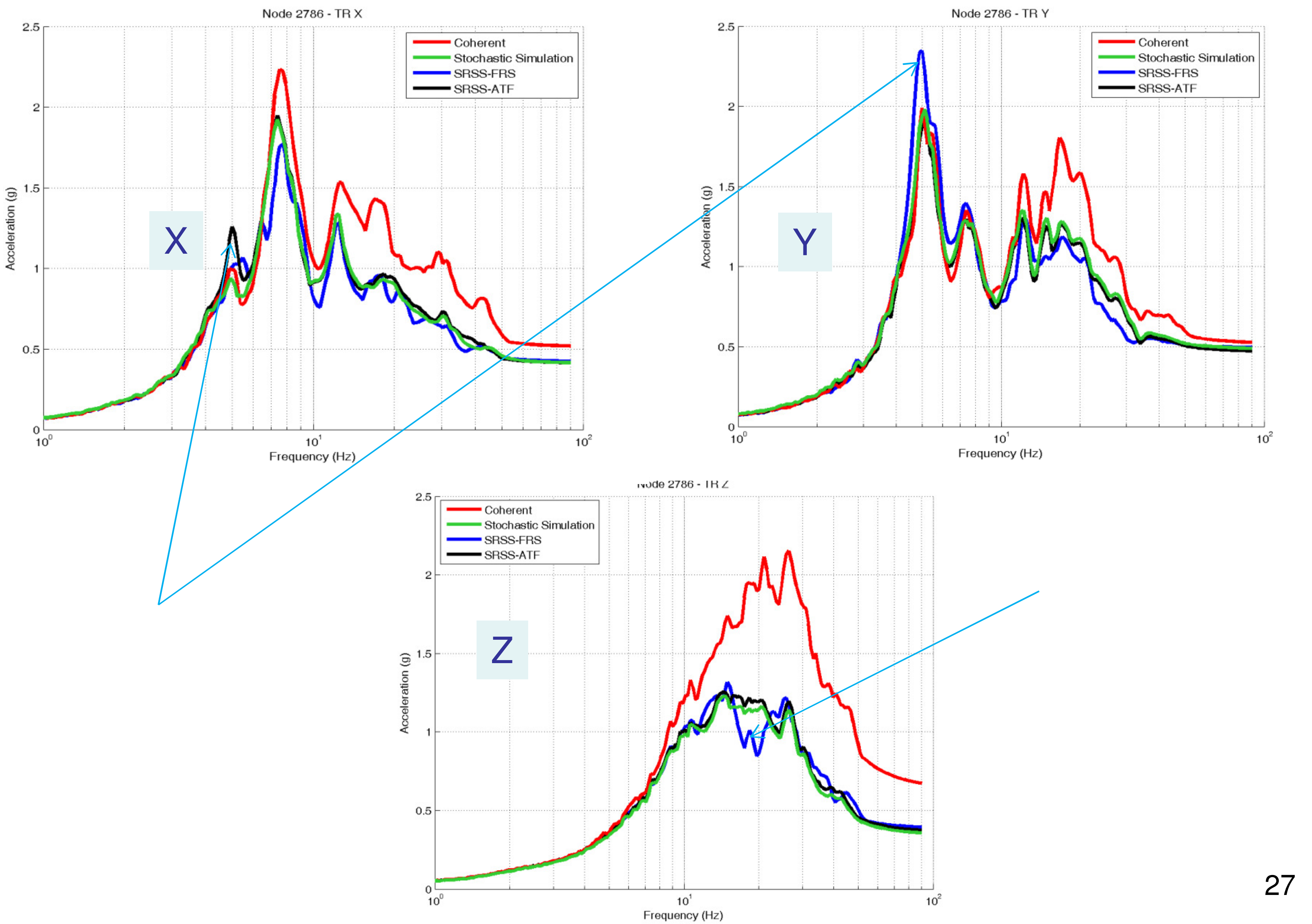
REMARKS:

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

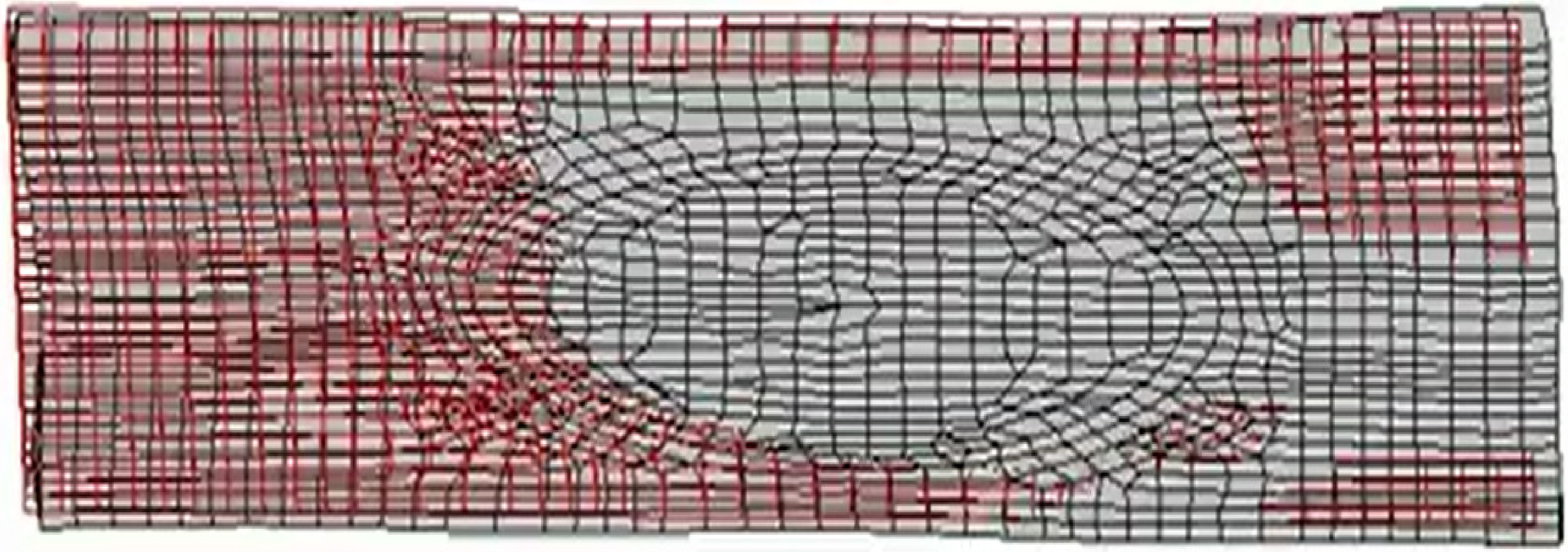
2) Incoherent motion is obtained by combining stochastically the coherency matrix modes.

3) EPRI validated for stick/rigid basemat models simple superposition rules, as SRSS and ACS *(zeroing ATF phases).*

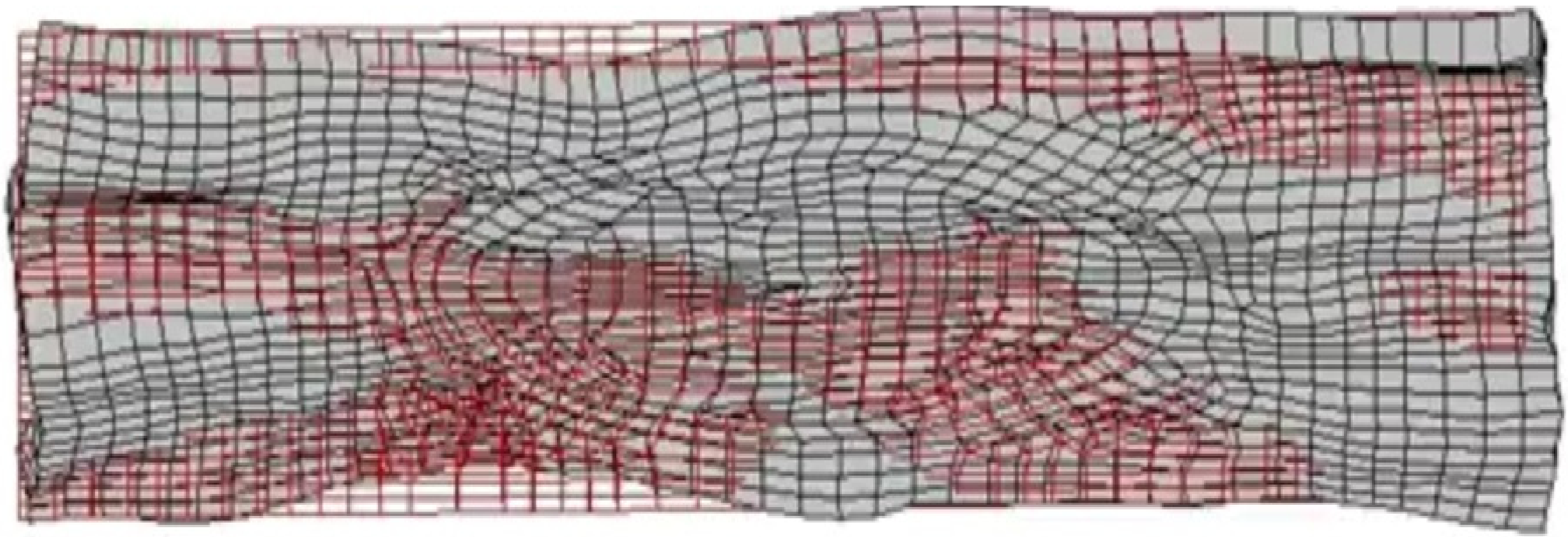
Incoherent SSI Results for RB Stick Model



RB Basemat SSI Response for COHERENT Inputs



RB Basemat SSI Response for INCOHERENT Inputs



```
*** 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
```

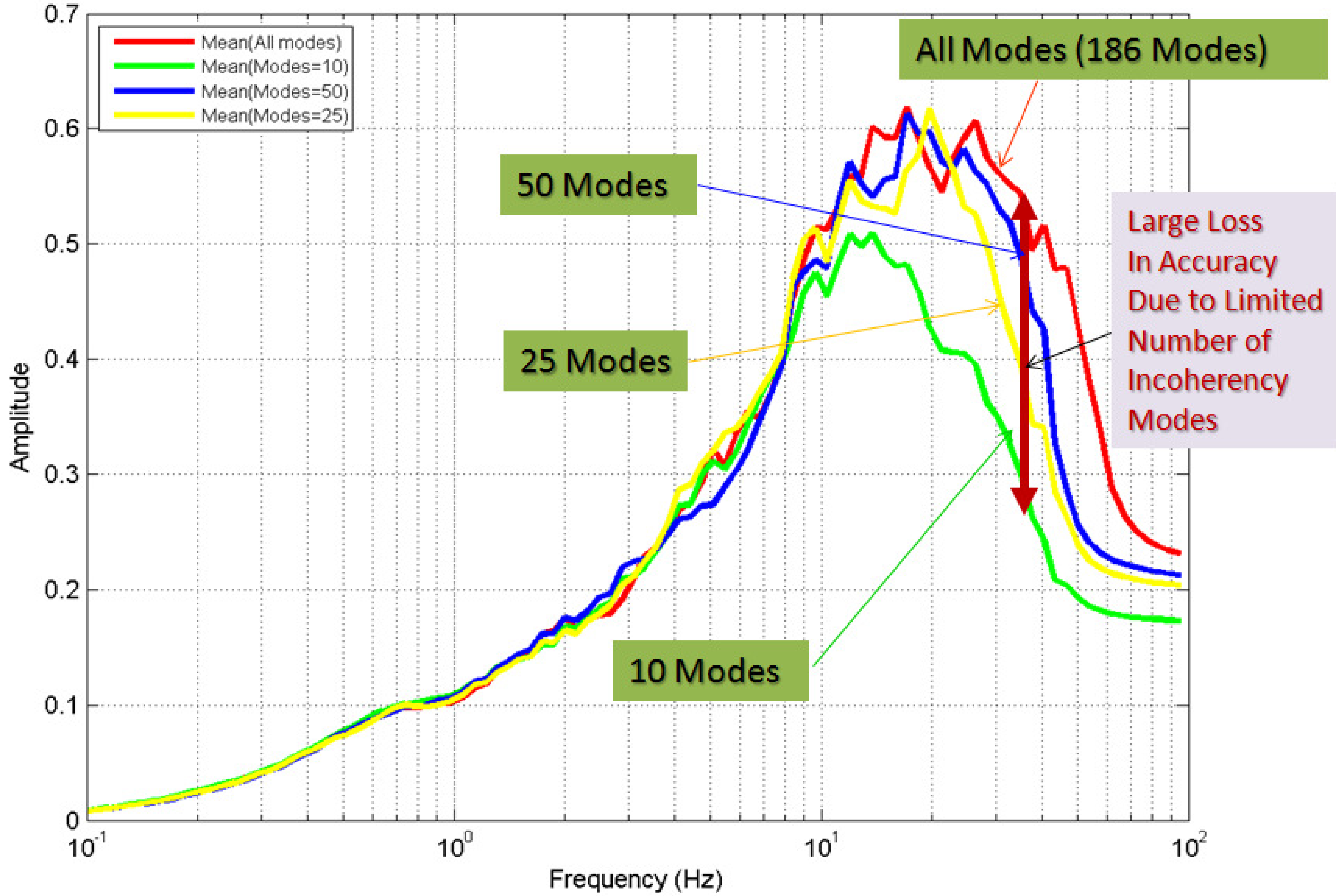
Inaccuracy Effects for Using Only Incoherent 10 Modes for Flexible Mat

```
=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                   =   0.0000000000000000E+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%
```

Cumulative Modal contributions of the first 10 incoherent modes as used in SRSS approach

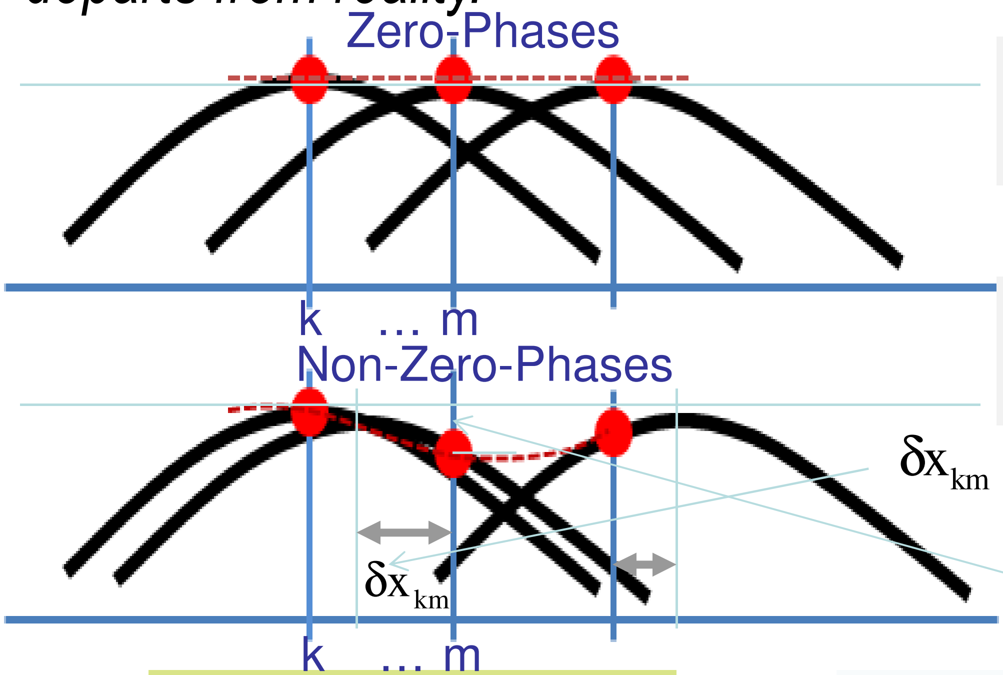
Effects of Number of Incoherent Modes in High Frequency

Elastic Basemat Corner -- XINPUT -- RS at Node 1047X



Effect of Neglecting Incoherent Mode Phases in SRSS

At a given frequency, for dominant single mode situations (in lower frequency range), the *neglect of the (differential) phases* that produce random amplitude variations in space, *basically changes the problem and departs from reality.*



Single Mode "Zero-Phase" Motion produces a "deterministic rigid body" motion

Single Mode "Non-Zero-Phase" Motion produces a "random field" motion

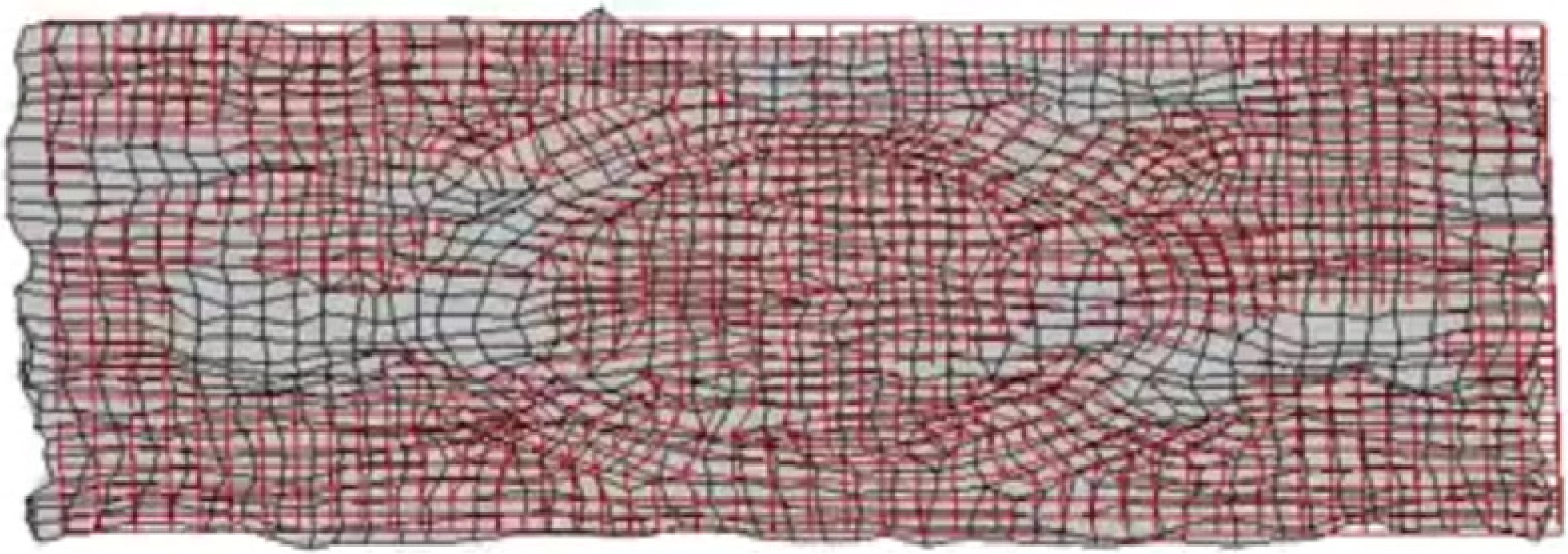
$$\delta x_{km} = (\psi_{j,k} - \psi_{j,m}) / k_j \quad \text{(space lag)}$$

Differential Amplitude Variations due to Differential Random Phasing

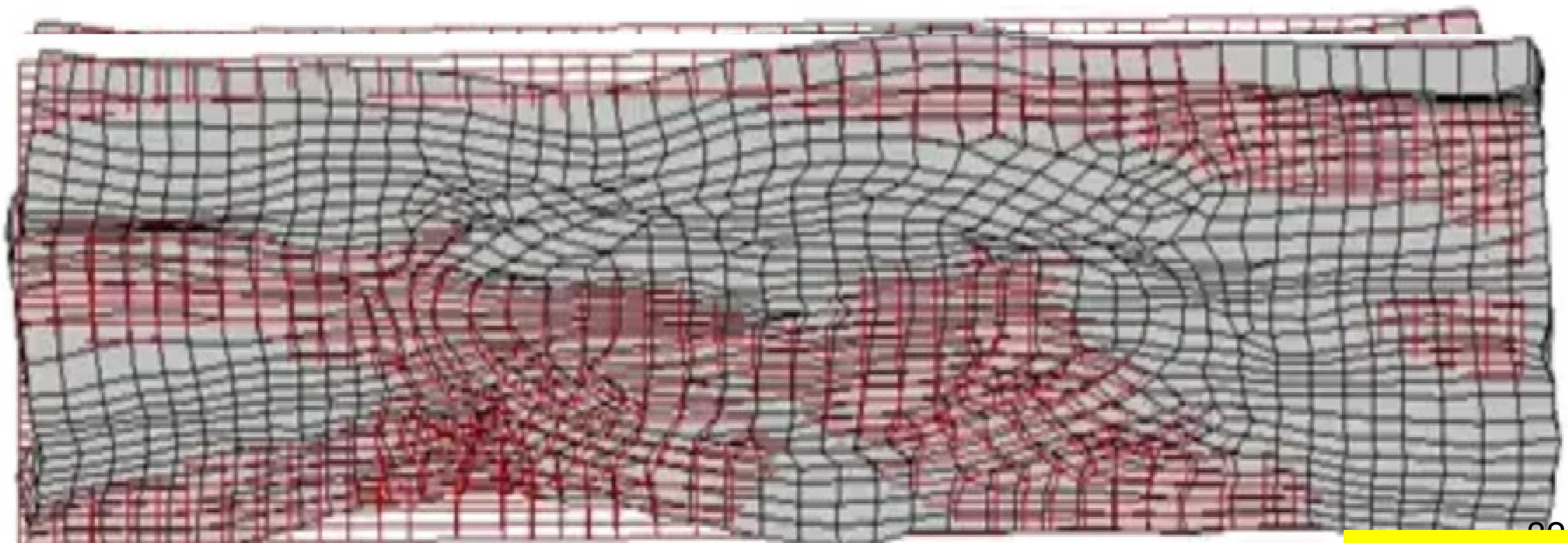
Mode 1 Contribution		
Freq	Part H	Part V
1 Hz	100%	98.2
8 Hz	84%	67%
25 Hz	7%	21%

At the lower frequencies, below 10 Hz, where a single mode (Mode 1) is governing, the zero-phase assumption practically neglects the differential amplitude variations in space due to incoherency.

Incoherency Simulation With Phase Adjustment (Underestimate Incoherency)



Incoherency Simulation Without Phase Adjustment (Unbiased Estimation)



ANIMATIONS

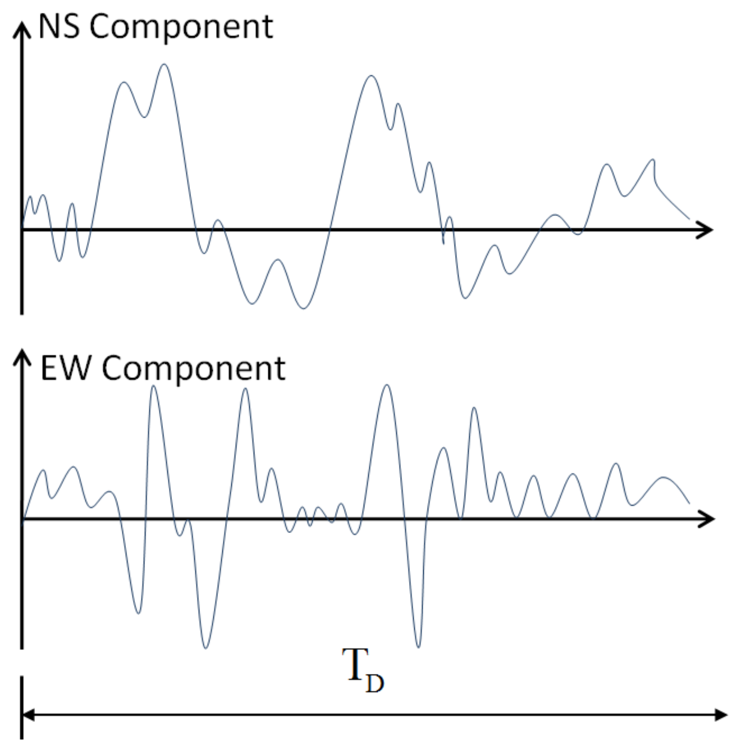
Flexible Foundations vs. Rigid Foundations

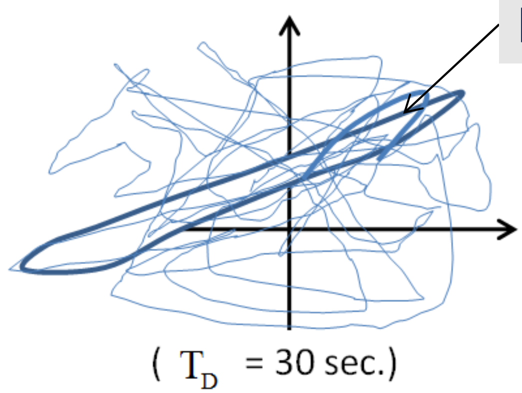
For *rigid foundations* the incoherency-induced stochasticity of the basemat motion is driven by the rigid body spatial variations (smooth, integral variations) of free-field motion. Kinematic SSI interaction is large, so that differential free-field motions are highly constrained by rigid basemat, i.e. shorter wavelength components are filtered out.

For *flexible foundations*, the incoherency-induced stochasticity of the basemat motion is driven by the local spatial variations (point variations) of free-field motion. Therefore, is much more complex and locally random, with an unsmoothed spatial variation pattern. Kinematic SSI is reduced, so that differential free-field motions are less constrained. Short wavelength are not filtered out.

To accurately capture the phasing of the local motion spatial variations that are directly transmitted to flexible basemat motions, the application of the Stochastic Simulation is recommended. CAPABILITY ONLY IN ACS SASSI.

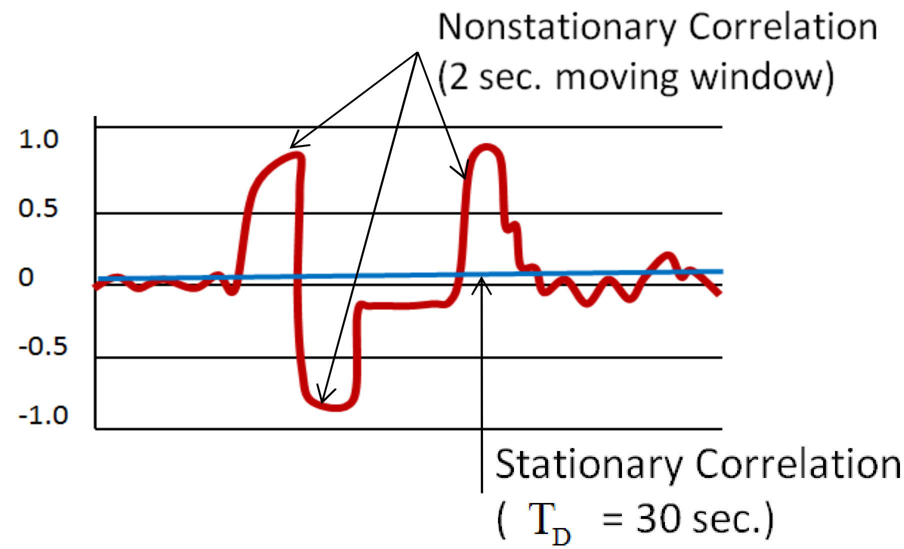
Seismic Input Directionality (Including All 3 Components)



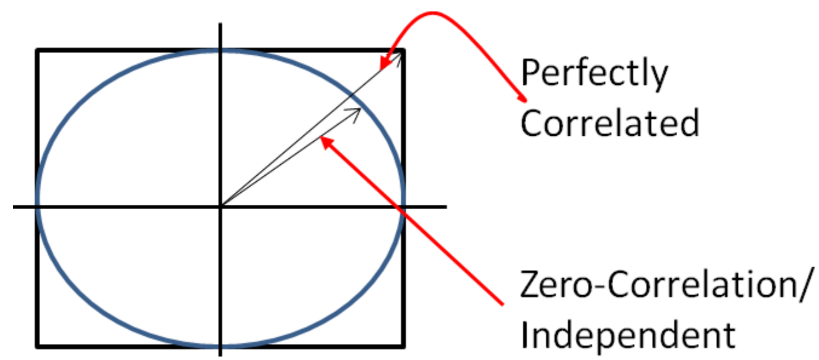


High Correlation!

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



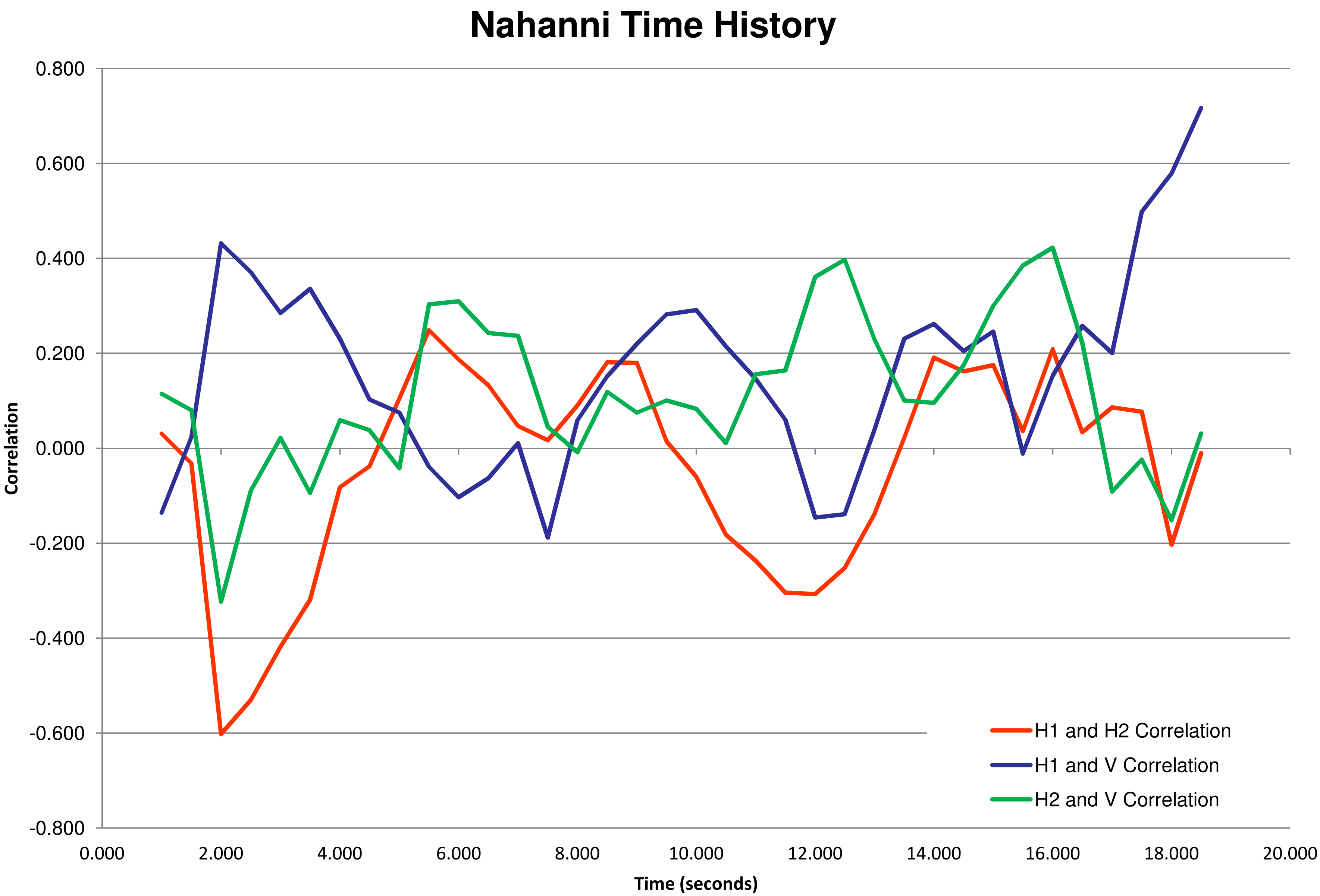
CORNER COLUMN PROBLEM

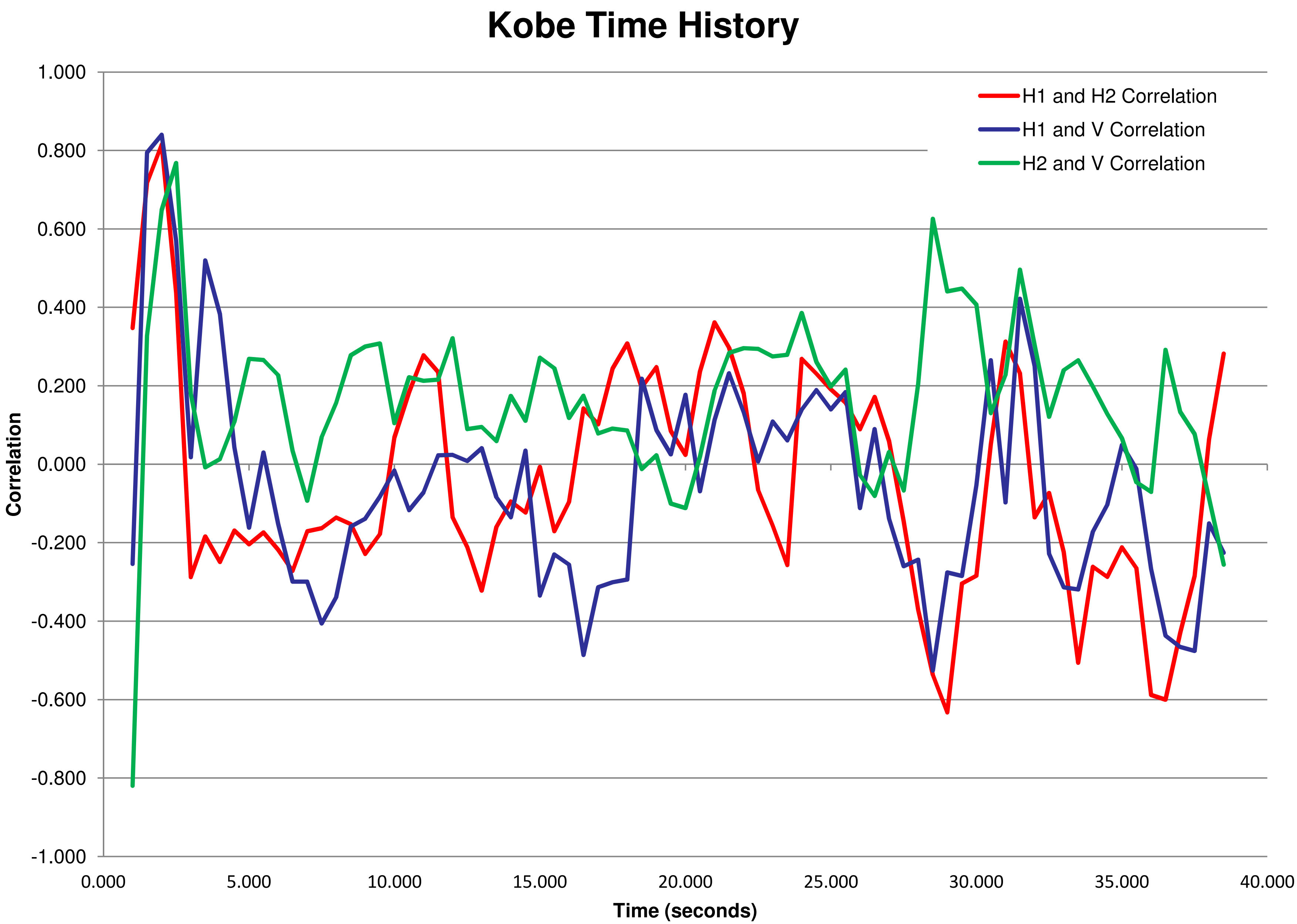


(Agnastopoulos, 1981, Der Kiureghian, 1984)

(SRSS rule neglects correlation effects)

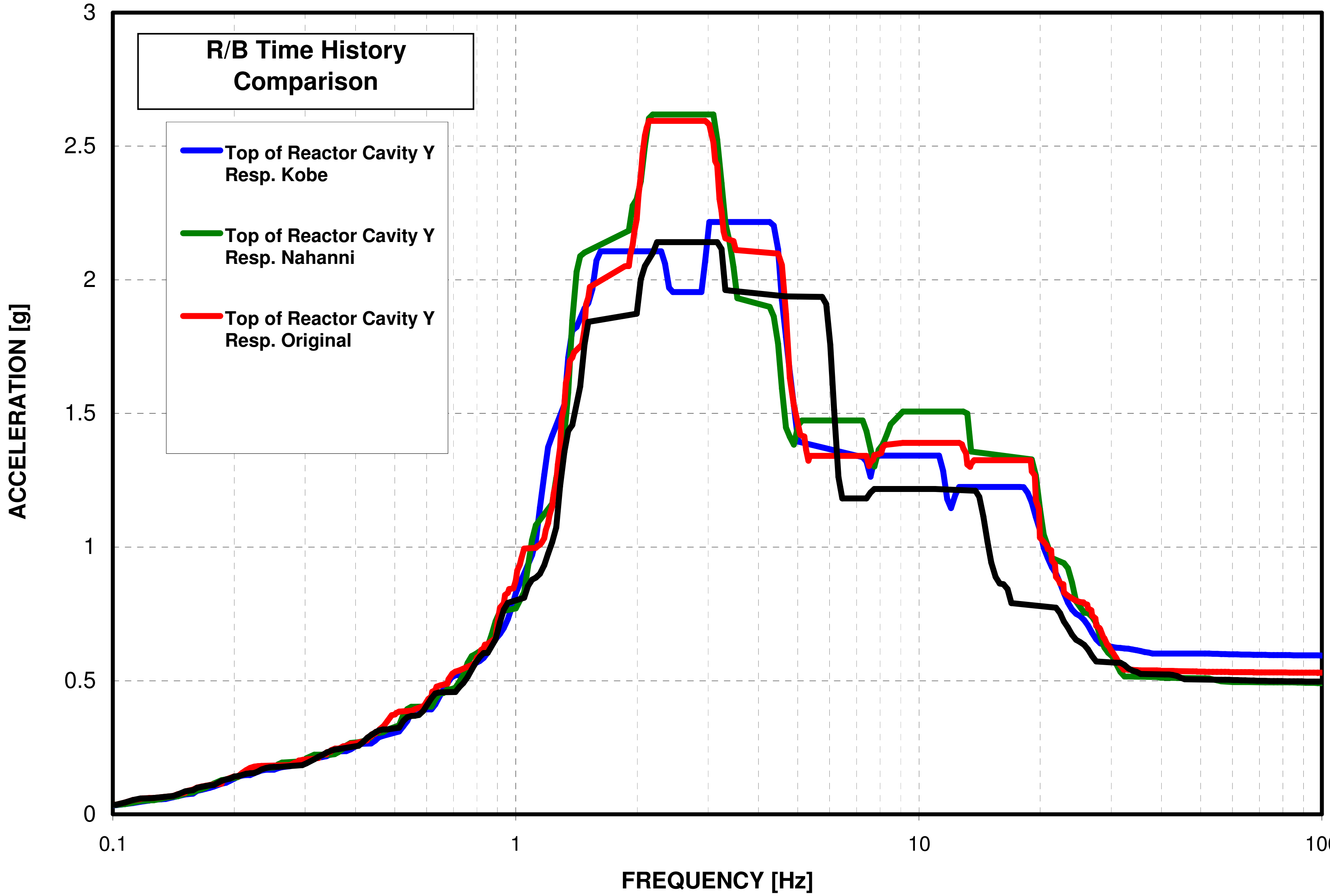
Input Motion Phasing (Non Stationary Correlation)




Kobe Time History
H1 and H2 Correlation
H1 and V Correlation
H2 and V Correlation
Correlation
Time (seconds)
1.000
0.800
0.600
0.400
0.200
0.000
-0.200
-0.400
-0.600
-0.800
-1.000
0.000
5.000
10.000
15.000
20.000
25.000
30.000
35.000
40.000

ANIMATIONS

Effects of Different Phasing on ISRS



Use of 5 Sets of Input Acceleration Time Histories

ASCE 04-2014 recommends for SSI analysis use of 5 seismic input sets of spectrum compatible acceleration time histories X, Y and Z instead of a single set of time histories.

The SSI response is computed as the average response from the 5 responses obtained for the 5 input sets. The 5 input sets can be based on “seed records” (using Fourier phasing from recorded motion components) or artificially generated input histories with uniform random phases.

Using 5 input sets of time histories will cover potential underestimations of SSI response due to input motion phasing.

Single input set is still acceptable, but it will be required to demonstrate that it does not provide unconservative SSI responses.

ASCE 04-2014 Probabilistic Site Response for Computing Deterministic SSI Analysis Inputs

Typical UHSRS shape inputs correspond to the outcrop input motion. For including local soil conditions at the site, site response analyses are required using one or several controlling earthquake RS inputs defined at the baserock (Vs=9200 fps).

Generic Procedure:

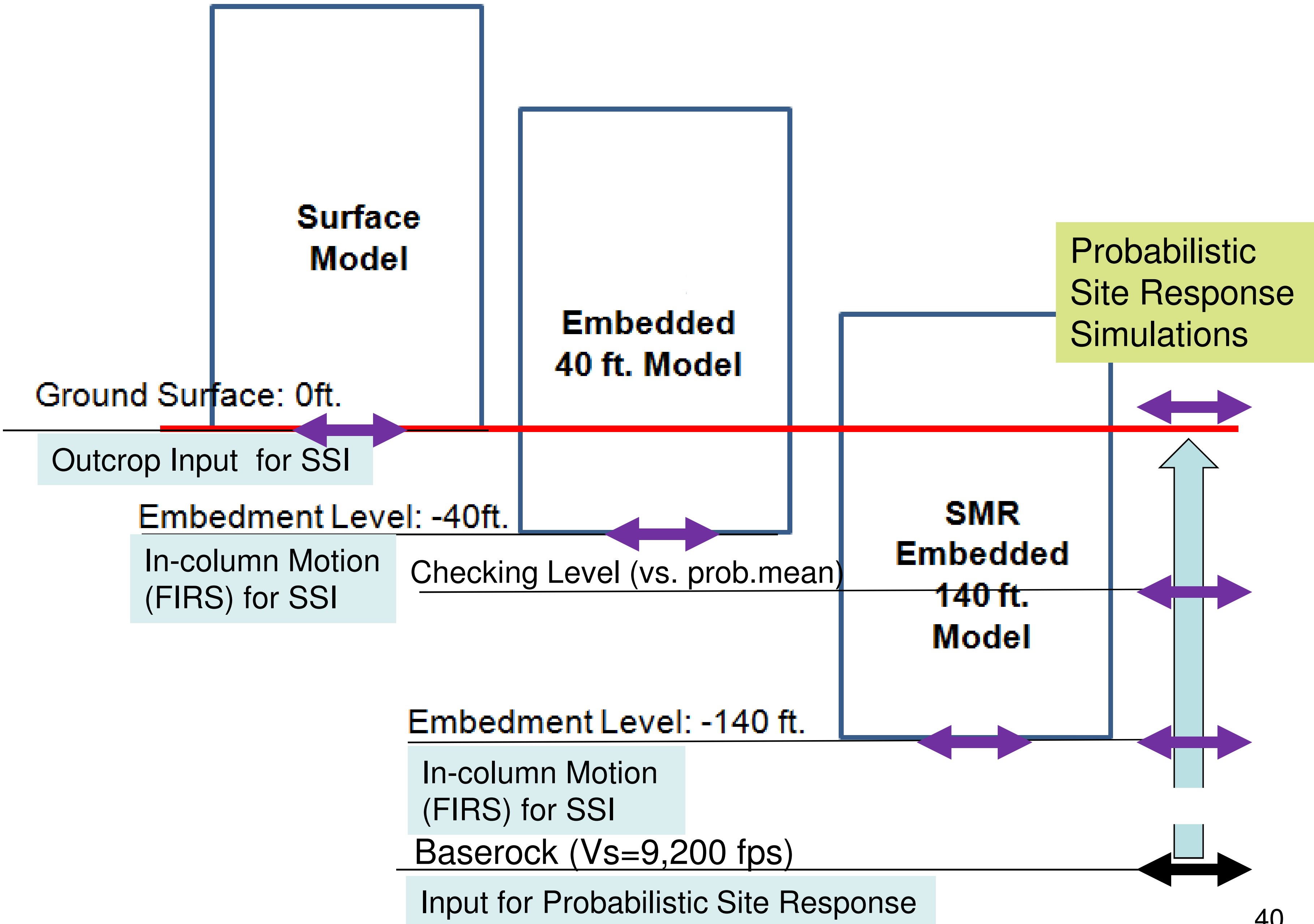
1) Perform 60 probabilistic nonlinear site response simulations (convolutions) using randomized soil layering profiles for the UHS RS inputs at baserock.

2) The outcrop probabilistic mean RS of the 60 simulations defines the outcrop FIRS.

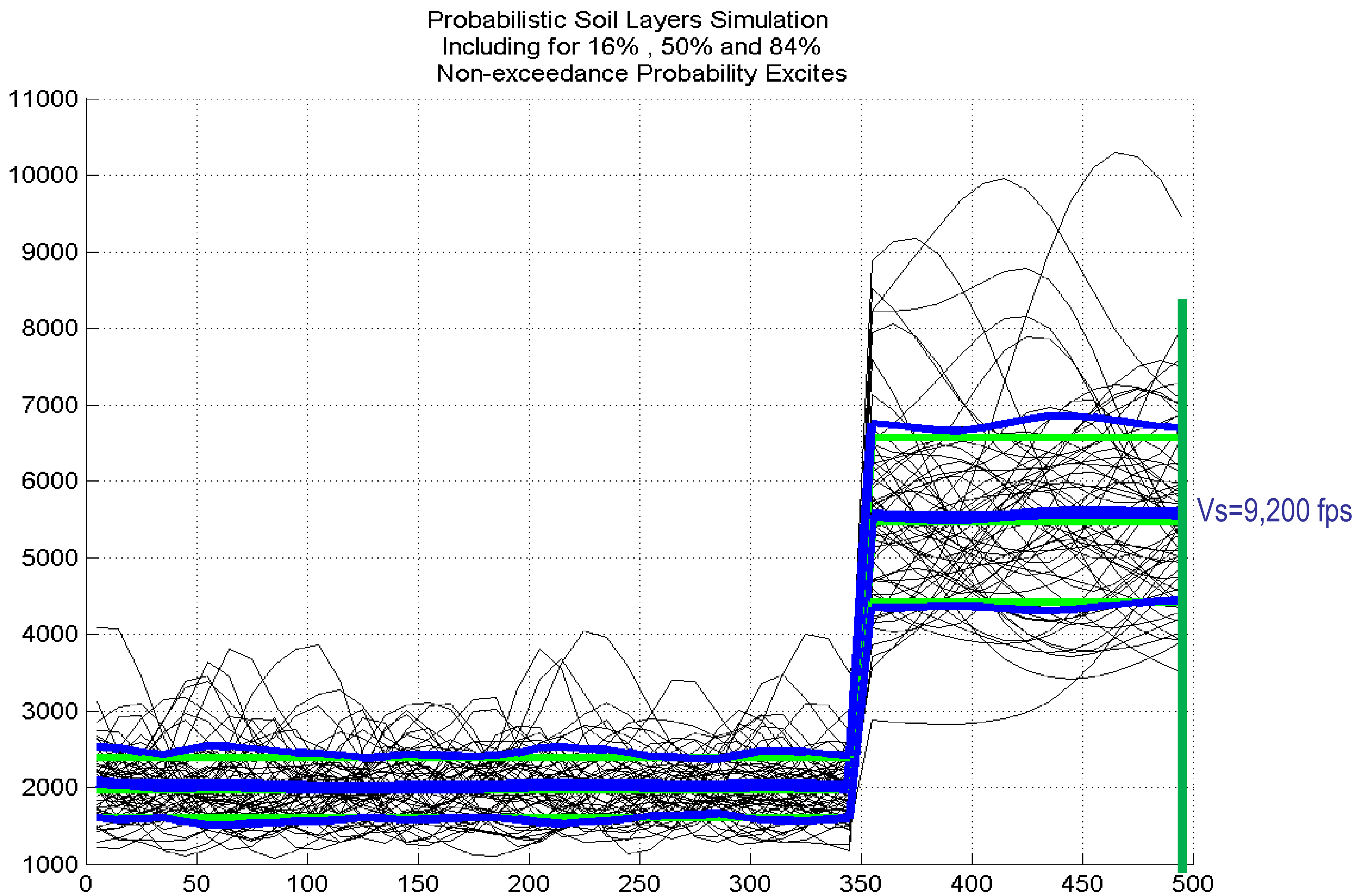
3) Performed 3 SHAKE type deterministic linear site response analyses for LB, BE and UB soil profiles to compute the in-column FIRS motions to be used for the deterministic SSI analysis. Pair LB Vs-UB D and UB Vs-LB D.

4) Check at other levels, if the envelope of the 3 deterministic in-column RS envelope the in-column probabilistic mean FIRS.

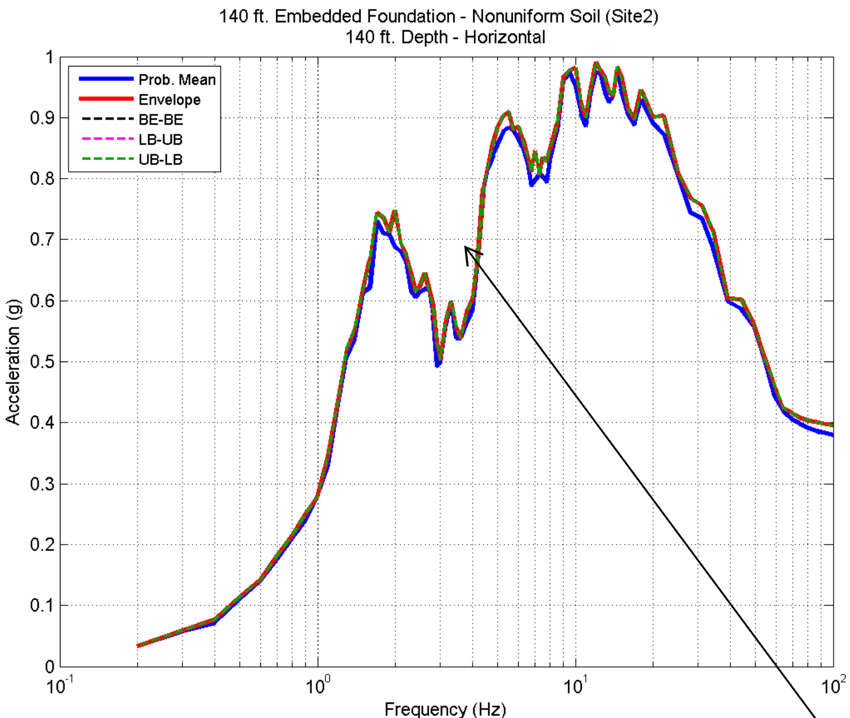
Determination of Seismic Inputs for SSI Analysis



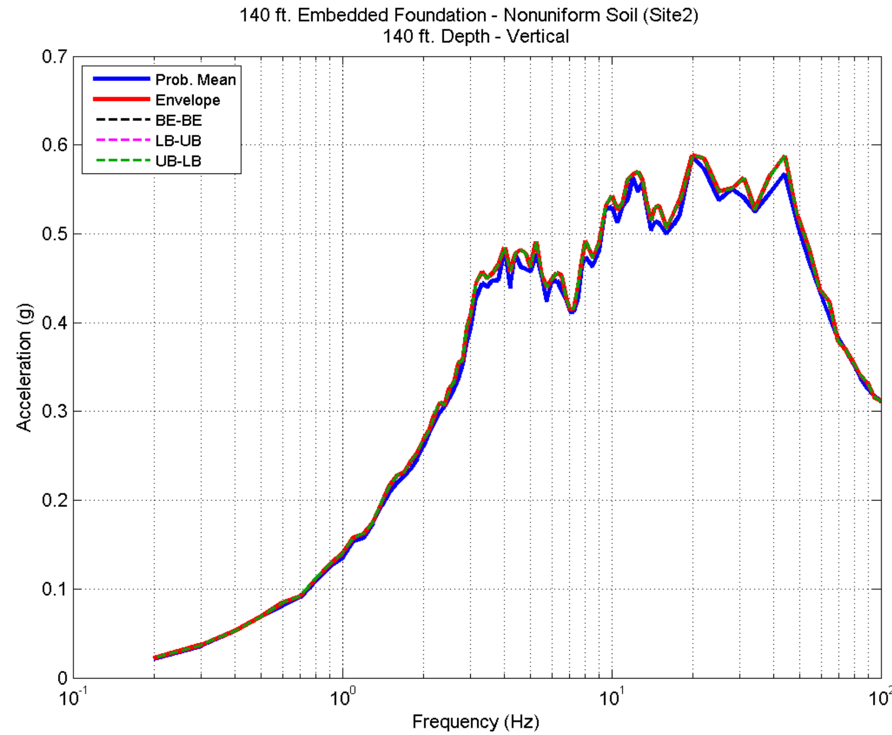
Probabilistic Simulation of Soil Profiles



Deterministic vs. Probabilistic Outcrop FIRS at 140 ft Depth.



Horizontal



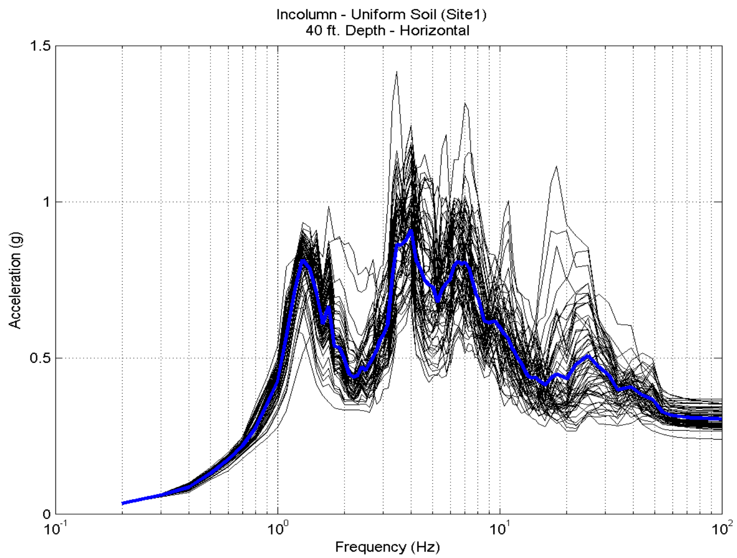
Vertical

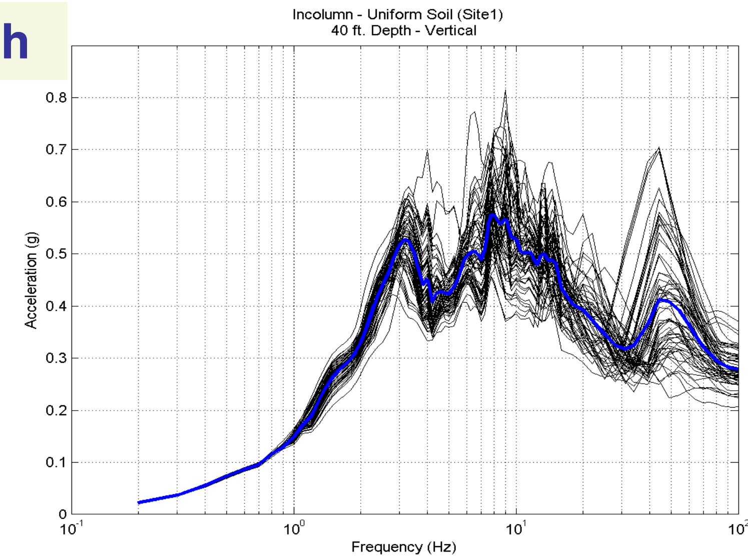
Non-flat RS…

NOTE: Deterministic outcrop FIRS set equal to probabilistic mean outcrop FIRS. Need to check RS results at surface and half of foundation depth. Alternately, it can be defined at surface and checked at selected depths.

Probabilistic Site In-Column Motion Simulations (60 simulations vs. probabilistic mean RS)

40 ft Depth

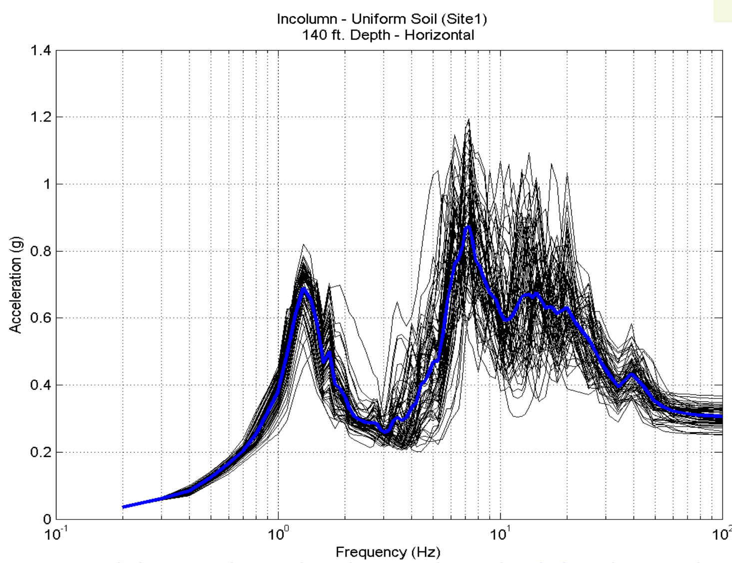


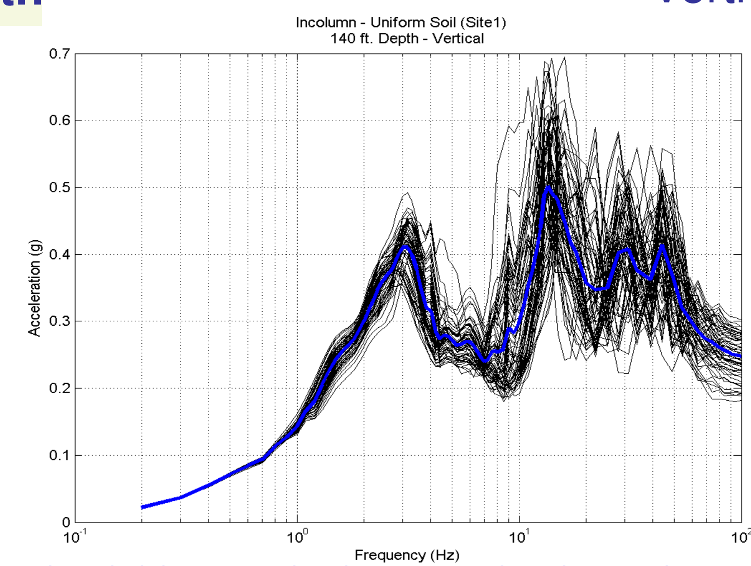


Horizontal

140 ft Depth

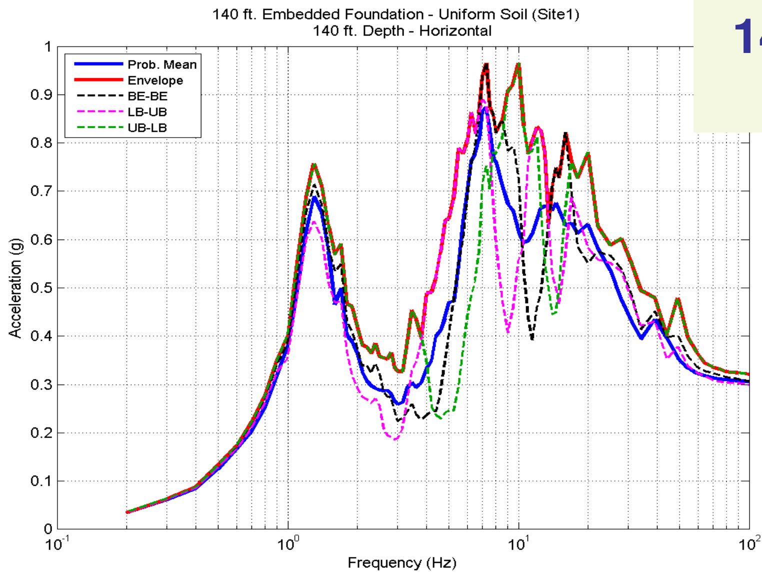
Vertical

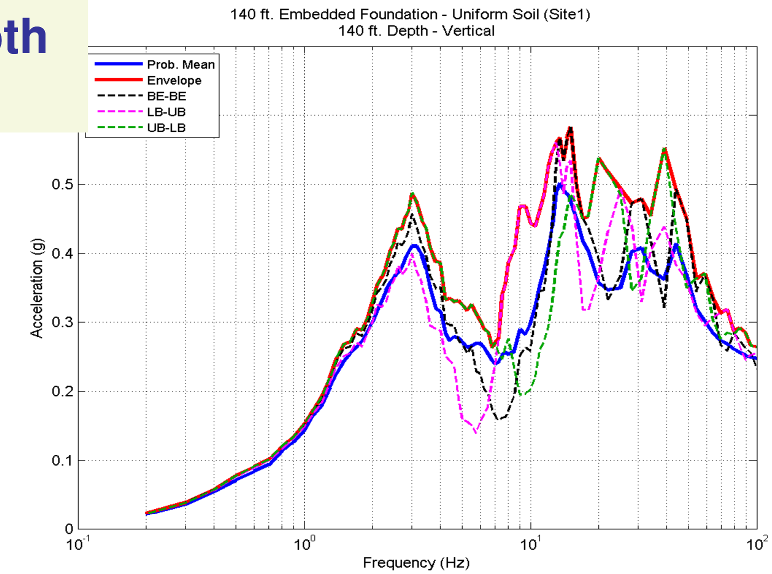




Deterministic vs. Probabilistic In-Column RS for Outcrop FIRS Input Defined at 140 ft Depth

140 ft Depth (FIRS)

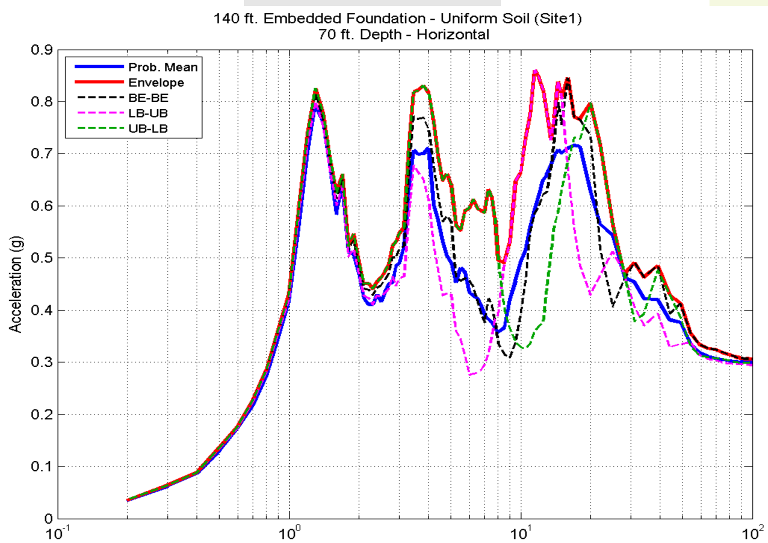


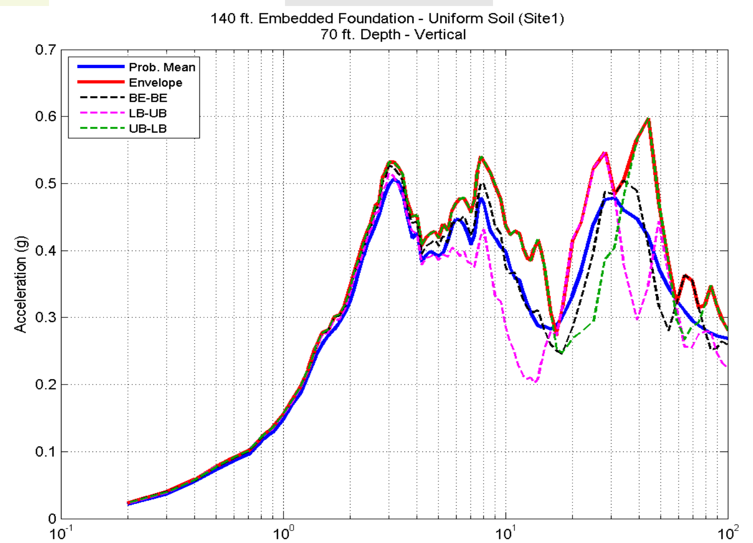


Horizontal

70 ft Depth

Vertical





ASCE 04-2013 Probabilistic SSI Analysis

The new ASCE 04-2013 standard states that the purpose of the analytical methods included in the standard is to provide reasonable levels of conservatism to account for uncertainties. More specifically, in the same section is written that given the seismic design response spectra input, the goal of the standard is based on a set of recommendations to develop seismic *deterministic SSI responses* that correspond approximately to a 80% non-exceedance probability level.

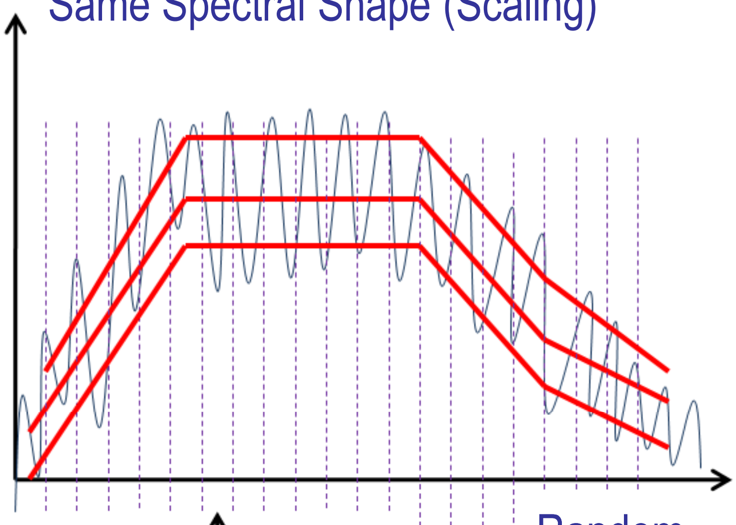
For probabilistic seismic analyses, *probabilistic SSI responses* defined with the 80% non-exceedance probability level are considered adequate.

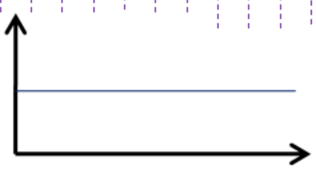
Section 5.5 of the standard provides guidelines for the acceptable probabilistic SSI approaches. The GRS spectral shape could be considered with variable shape or not (Methods 1 and 2). Soil profiles, Vs and D, should include spatial correlation with depth. Structural stiffness and damping should be also modeled by random variables.

Probabilistic Seismic Input Models

Method 1 (Random Variable)

Same Spectral Shape (Scaling)



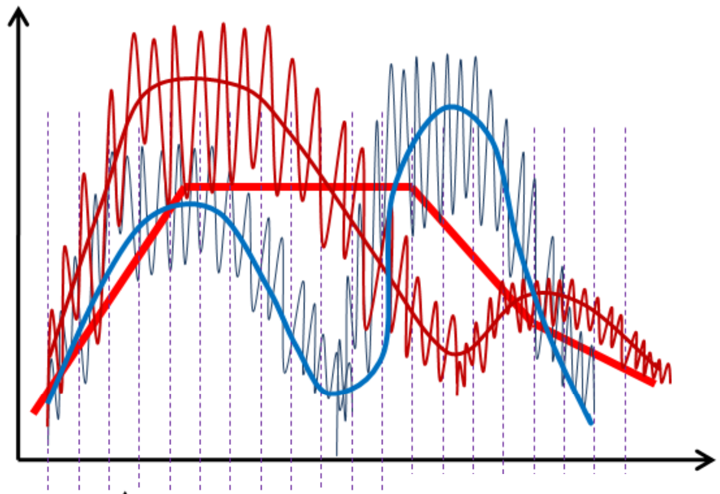


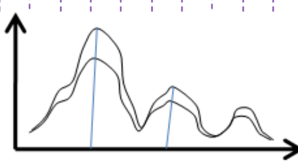
Random
Scale Factor
Model

Full Correlation in Frequency….
Simpler...
Less information required….

Method 2 (Random Field)

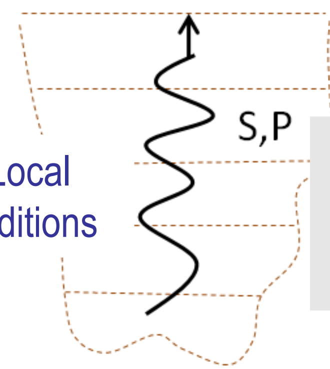
Random Spectral Shape





Random Soil
Amplification

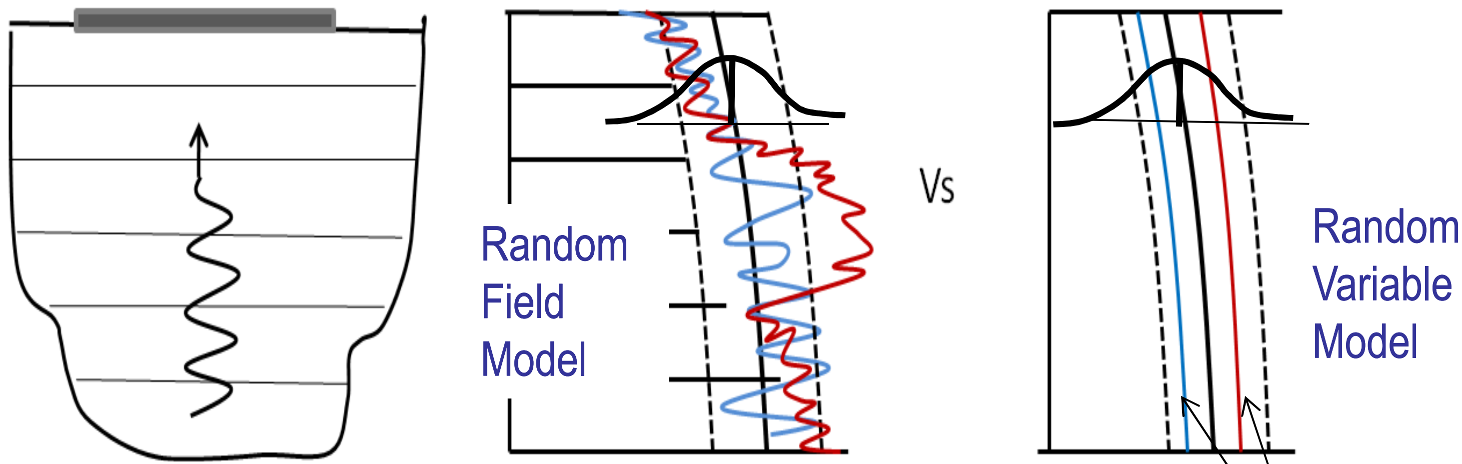
Include Local
Soil Conditions



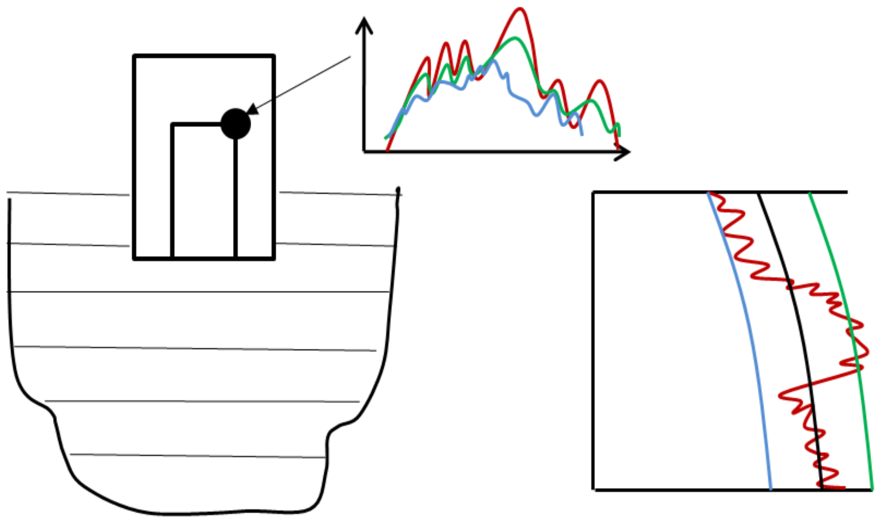
Correlation in Frequency….
More physics-based…
More information required….

Probabilistic Soil Profile Models (Random Field)

Soil Layering | Real Soil Profiles | Ideal Soil Profiles



Potential Situations that are not covered by Deterministic SSI…



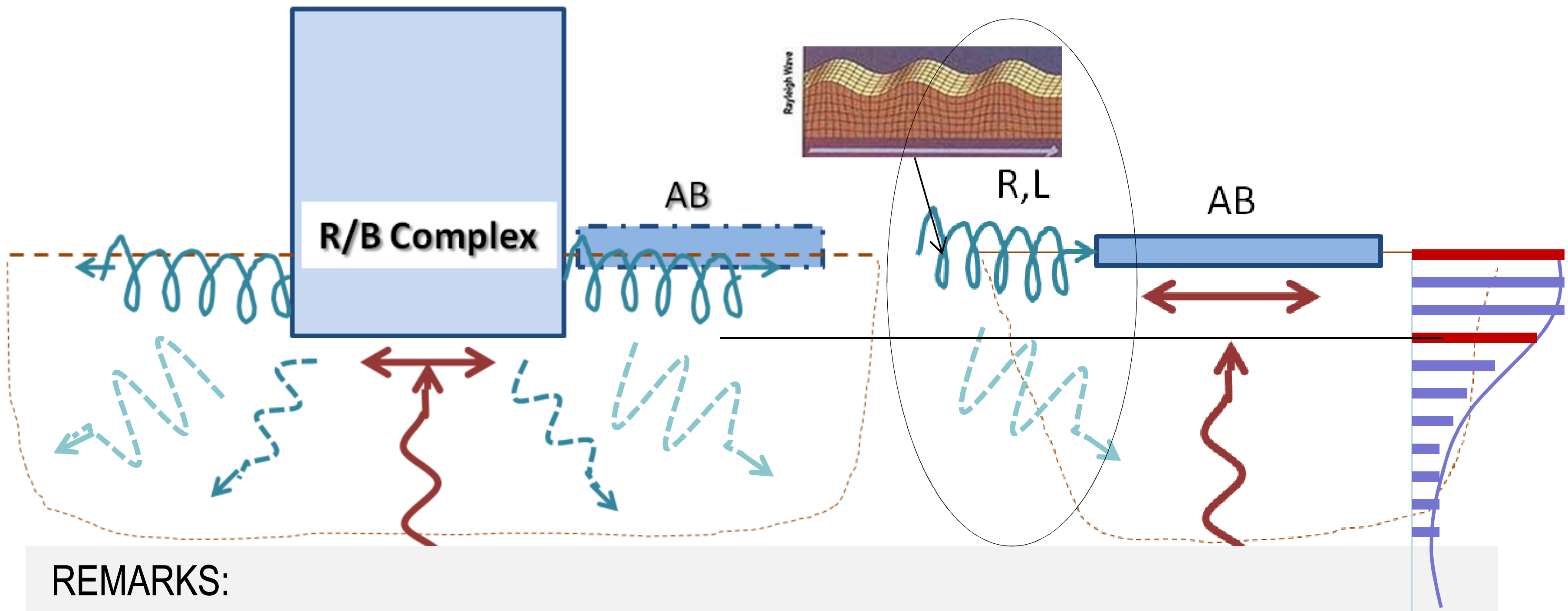
Perfect Correlation with depth looses physics…

No Correlation with depth looses physics…

Seismic Structure-Soil-Structure Interaction (SSSI) Effects

R/B Complex – AB Interaction

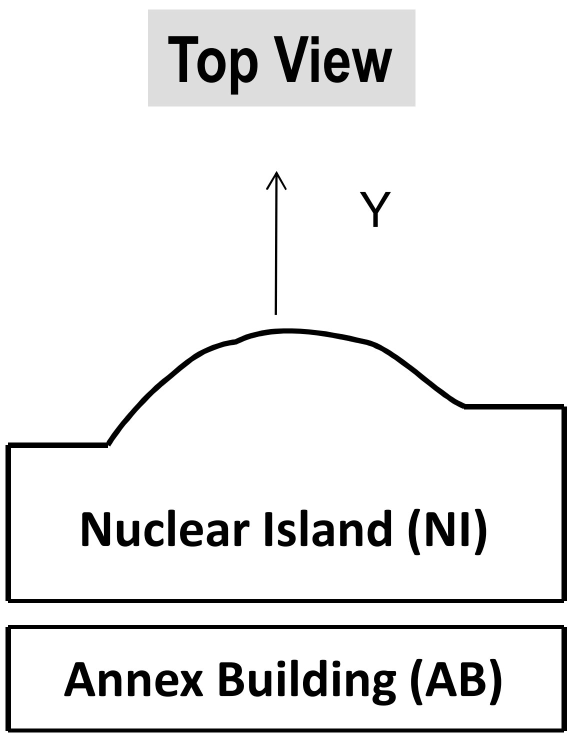
SSSI Effects on AB

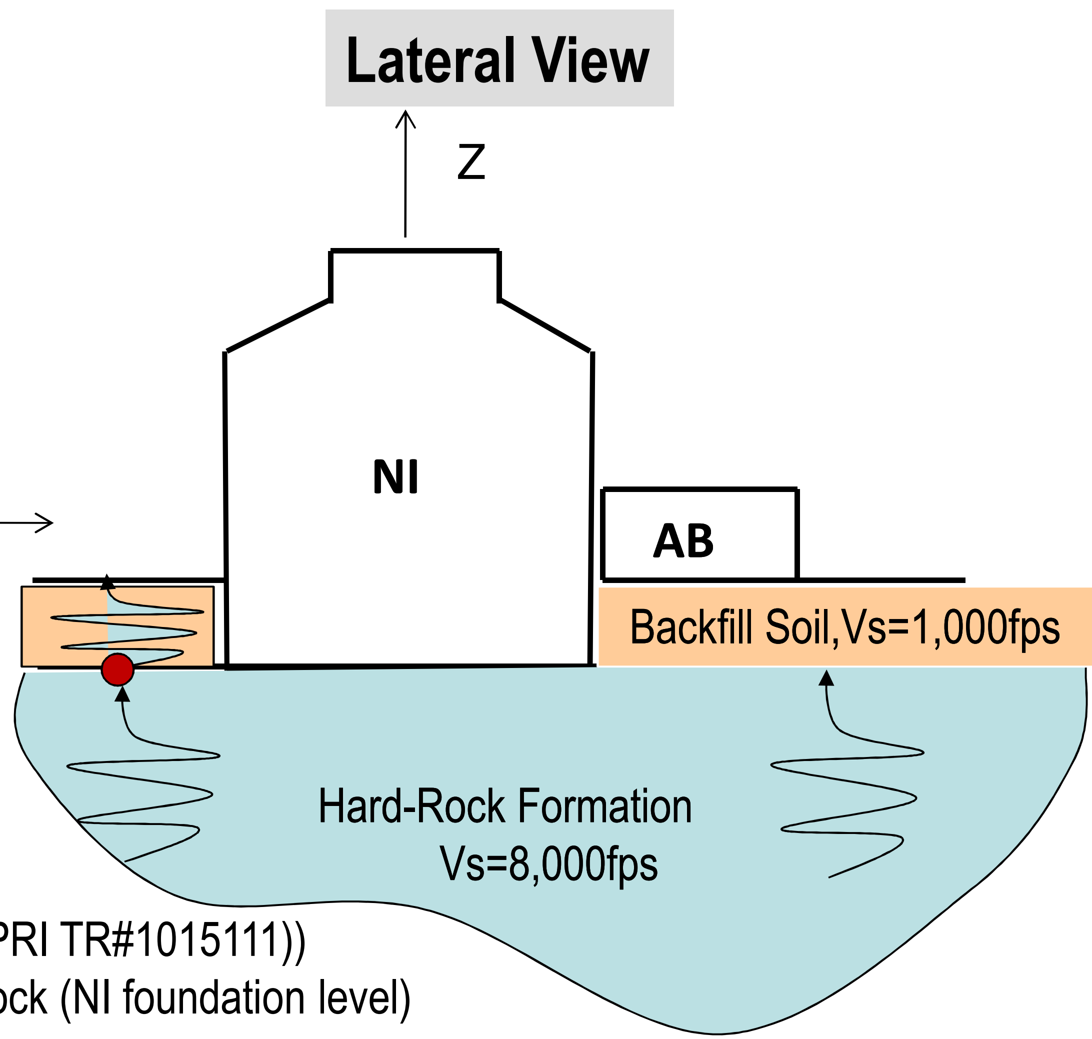


REMARKS:

- 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

AP1000 NI Complex and Annex Bldg Configurations





Coherent SSI Analysis:

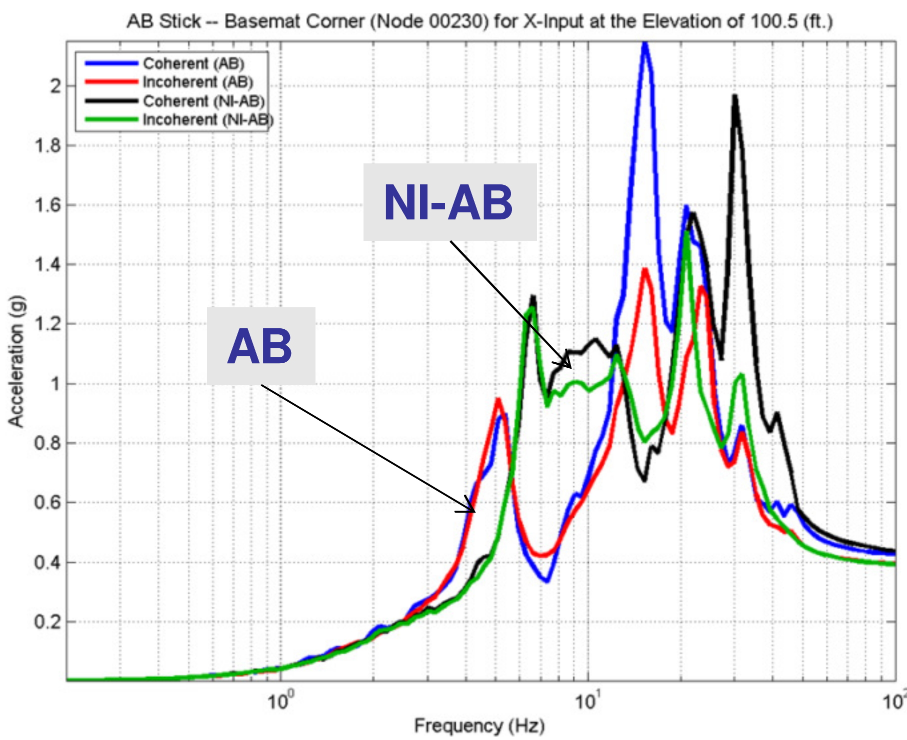
- Seismic input defined HRHF input ((EPRI TR#1015111))
- Control motion at the top of the hard-rock (NI foundation level)

Incoherent SSI Analysis:

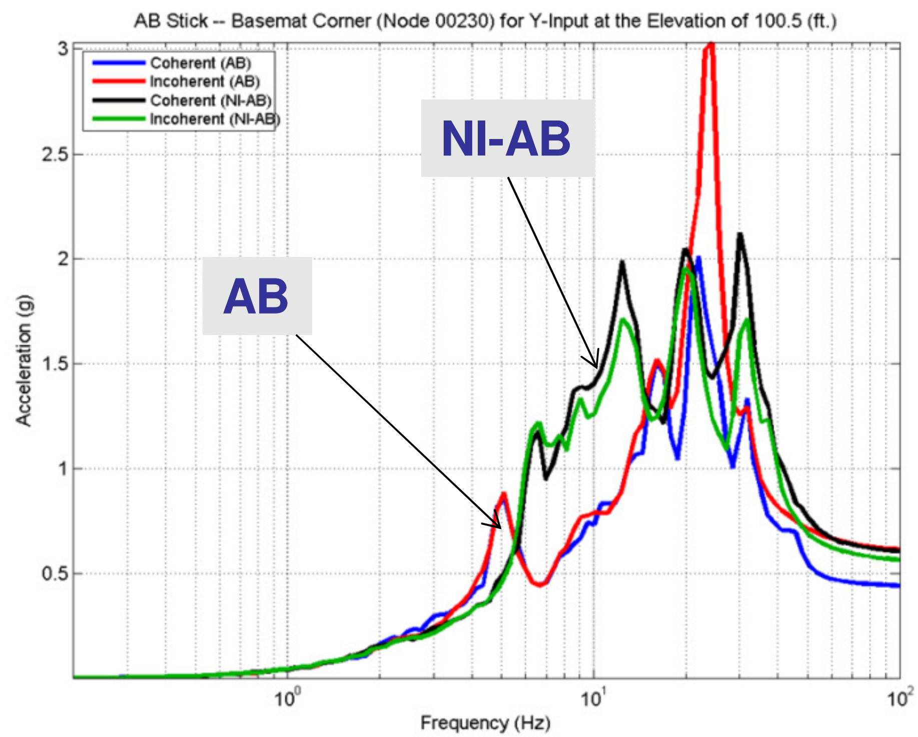
- Stochastic Simulation with 8 simulations (EPRI TR#1015111)
- 2007 Abrahamson coherency model for hard-rock sites (EPRI TR#1015110)

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

X-Direction

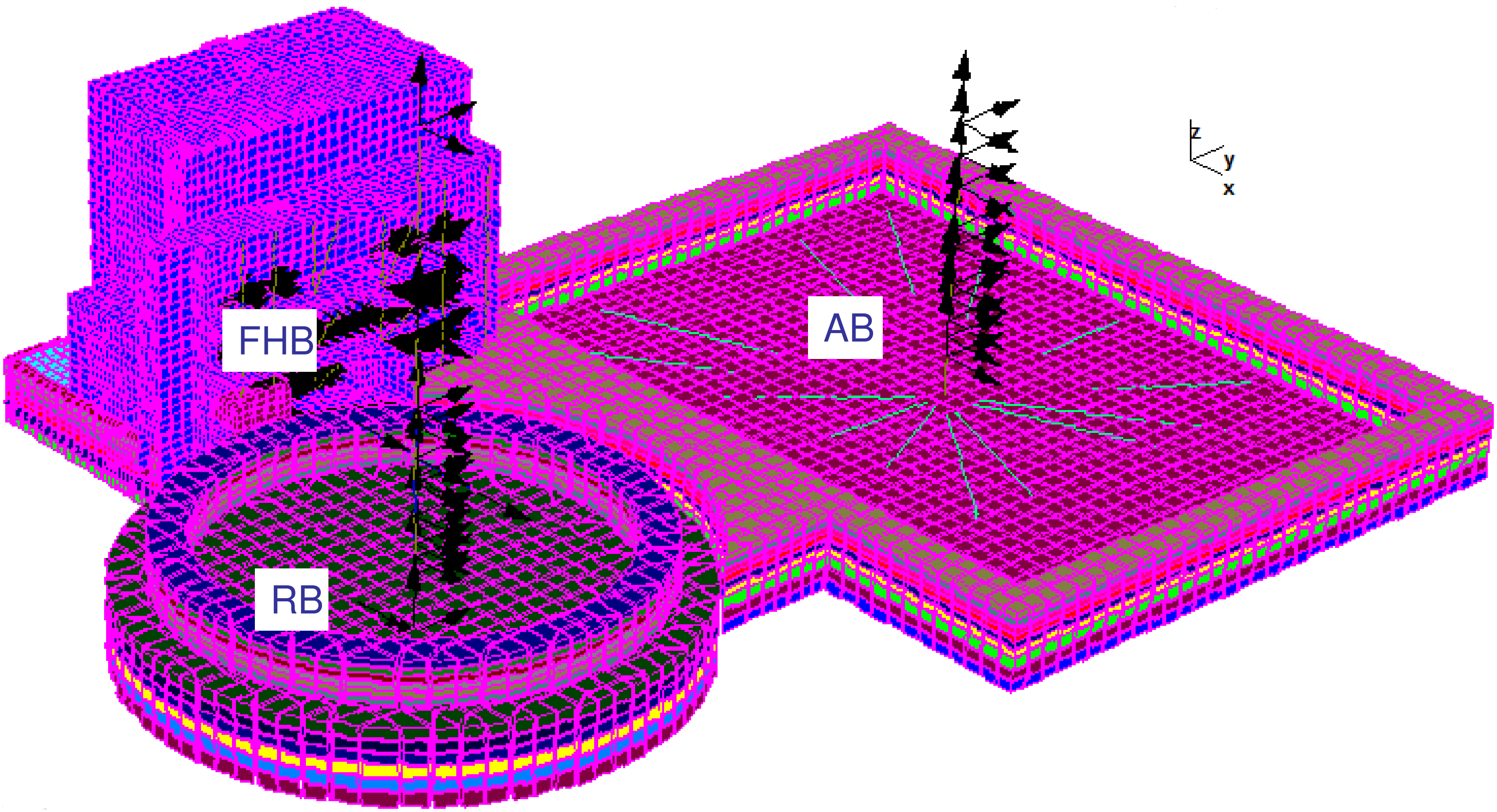


Y-Direction



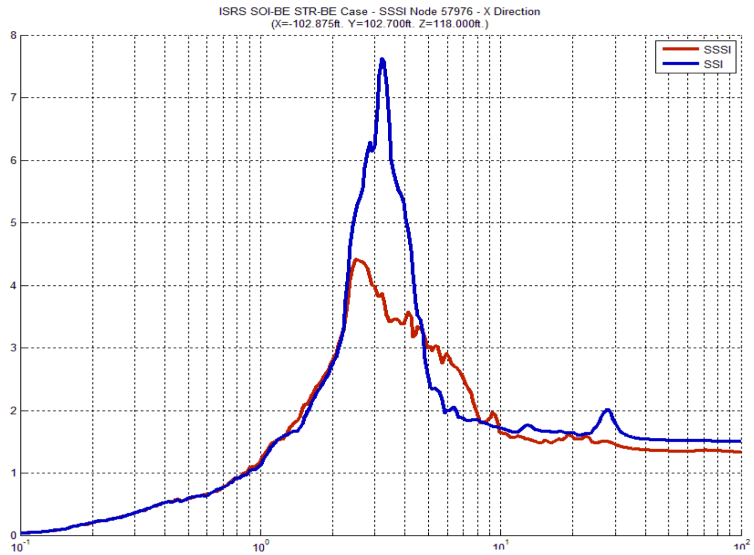
ANIMATIONS

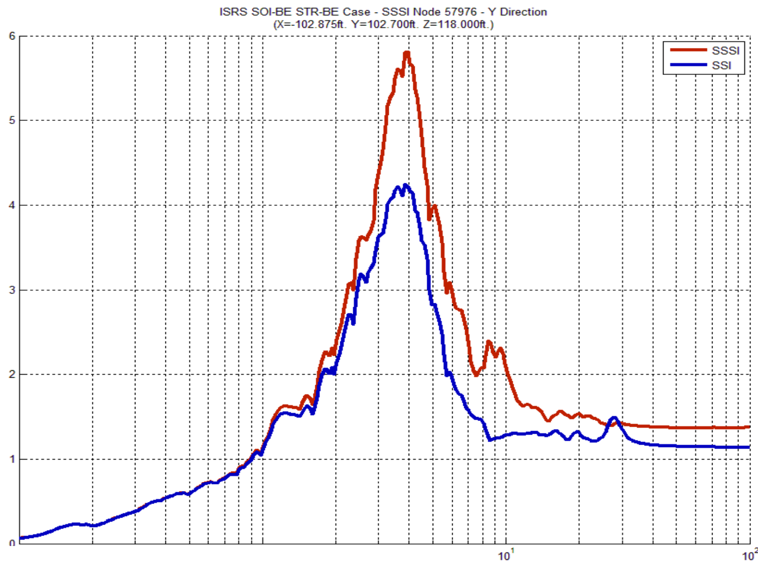
SSSI Model Including 3 Nuclear Structures

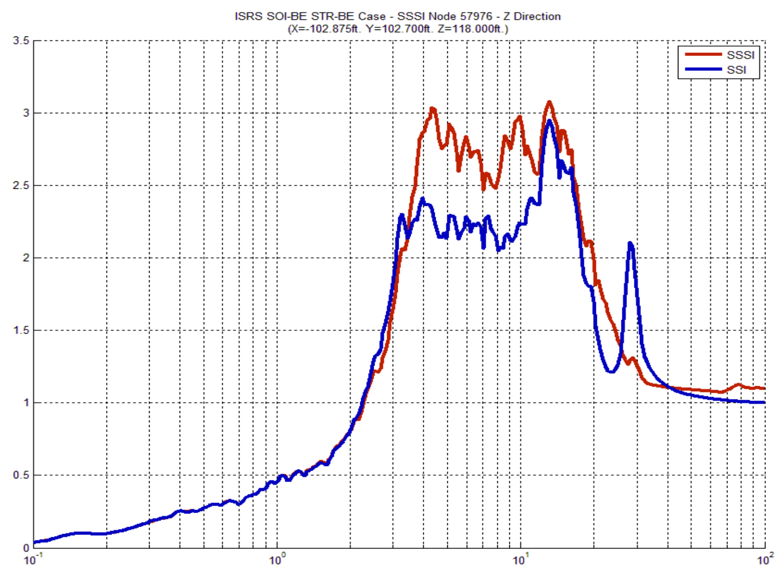


SSI vs. SSSI ISRS Comparisons for FHB Roof

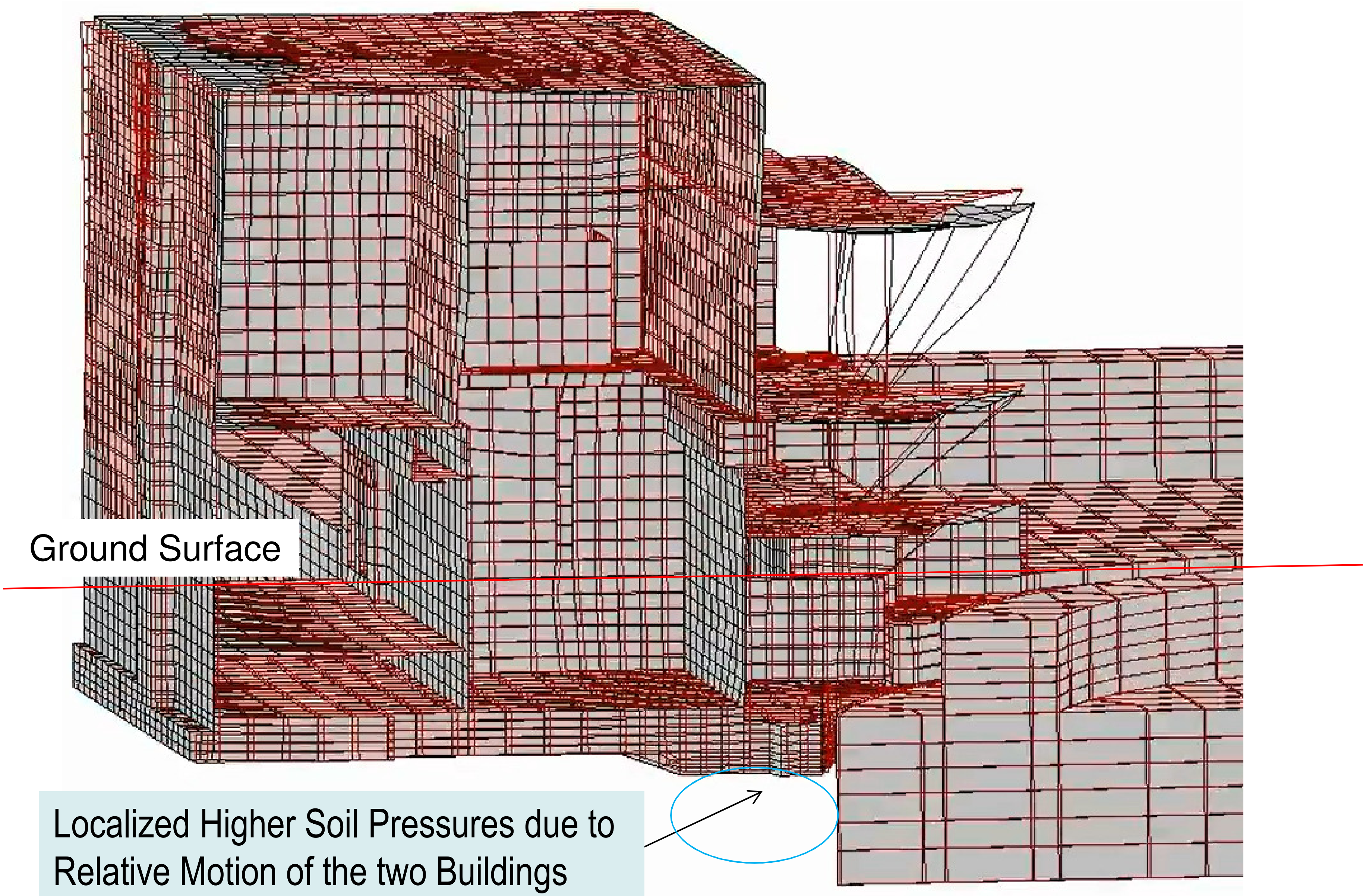
Node 57976 (Roof Elevation)





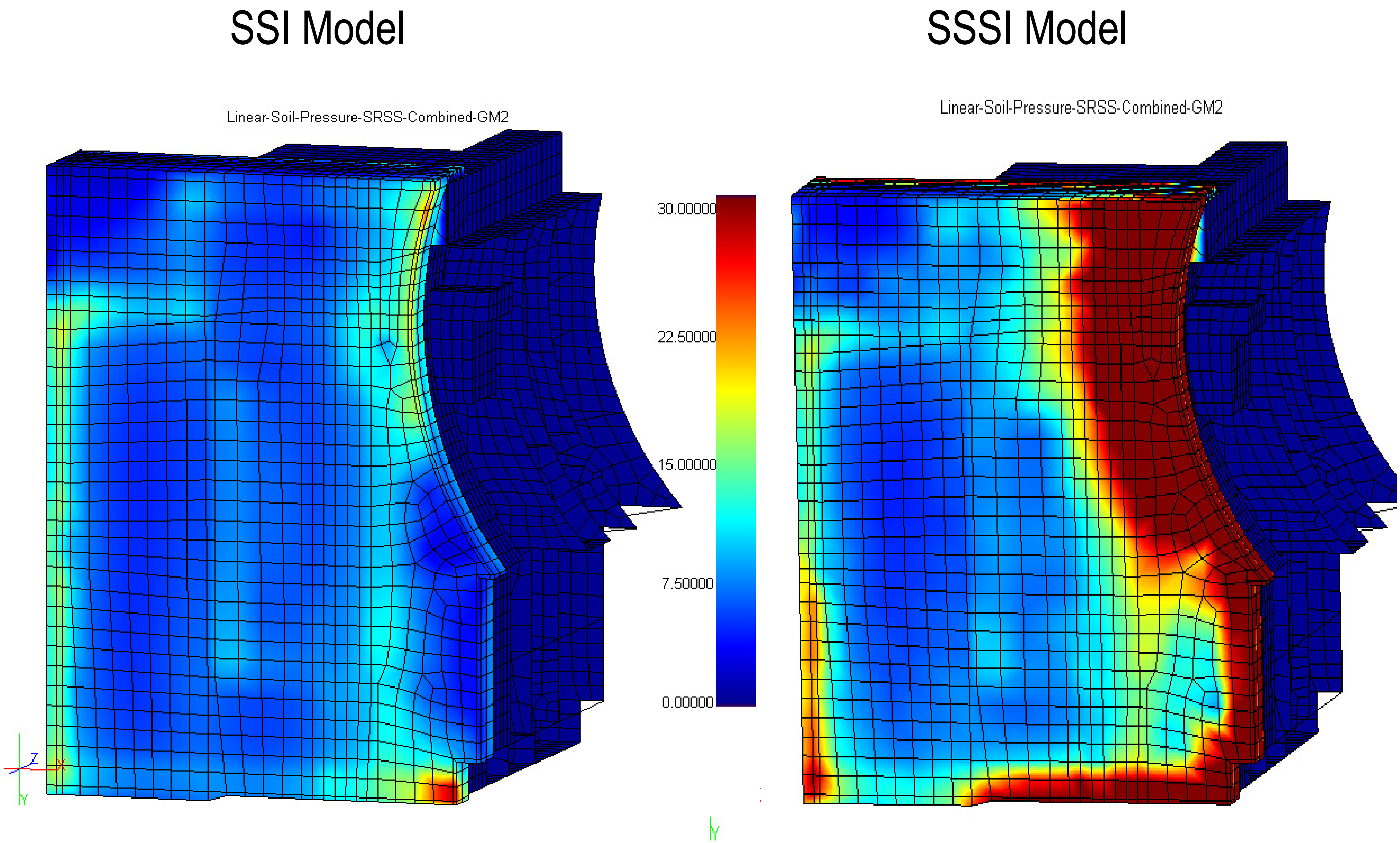


SSSI Effects on Local Soil Pressure Under Basemat

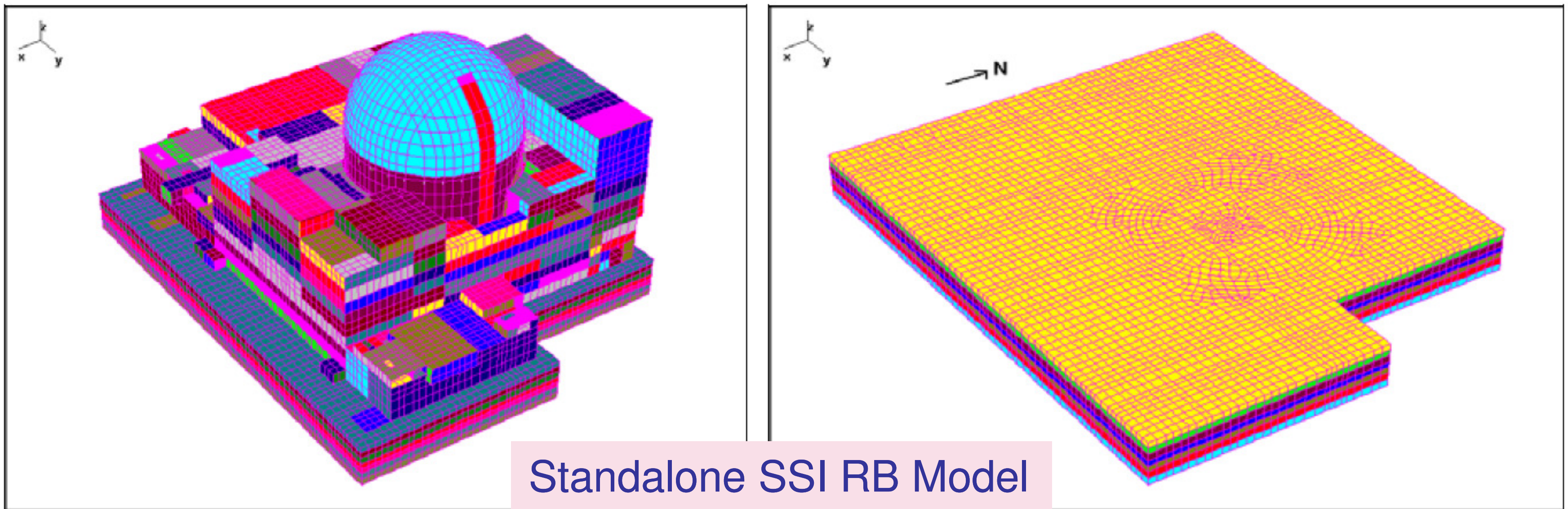


ANIMATIONS

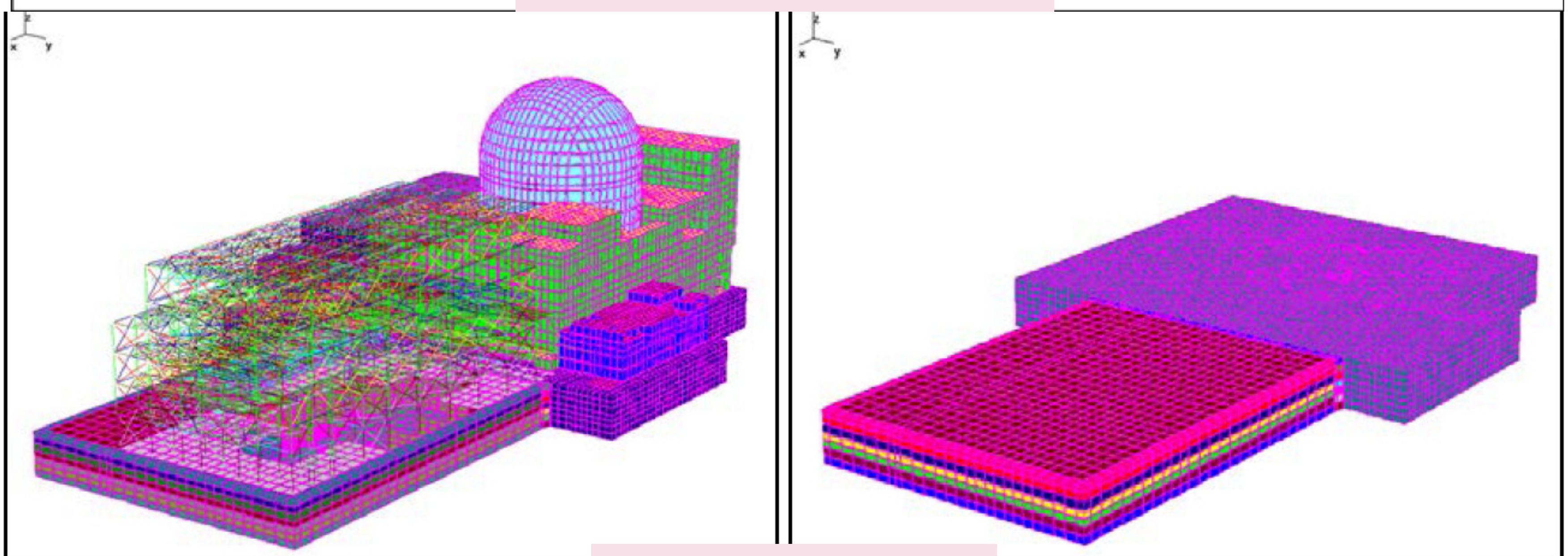
SSI vs. SSSI Basemat Soil Pressure Comparisons



ACS SASSI Seismic US-APWR SSSI Embedded Model



Standalone SSI RB Model

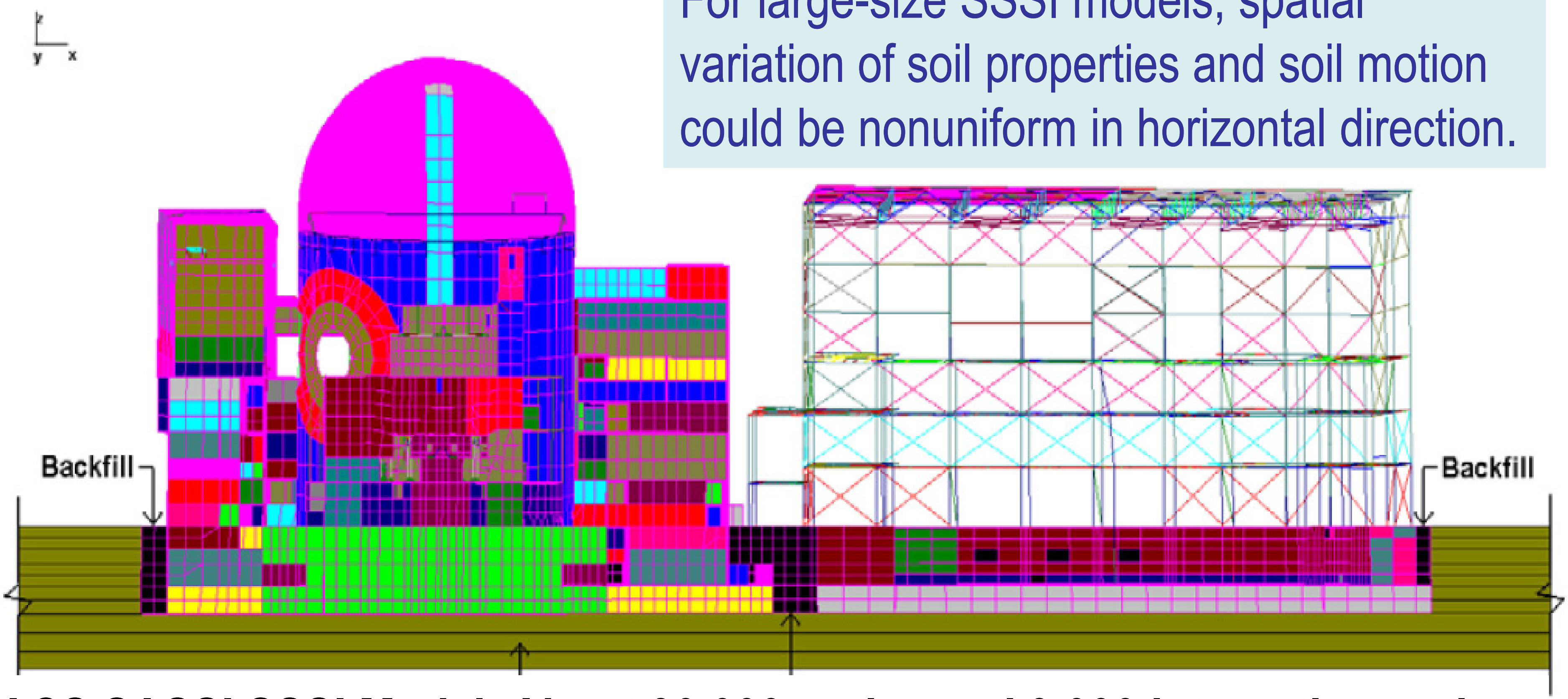


SSSI RB-TB Model

a) Structural Model b) Excavated Volume

US-APWR Standard Plant Seismic SSI Model

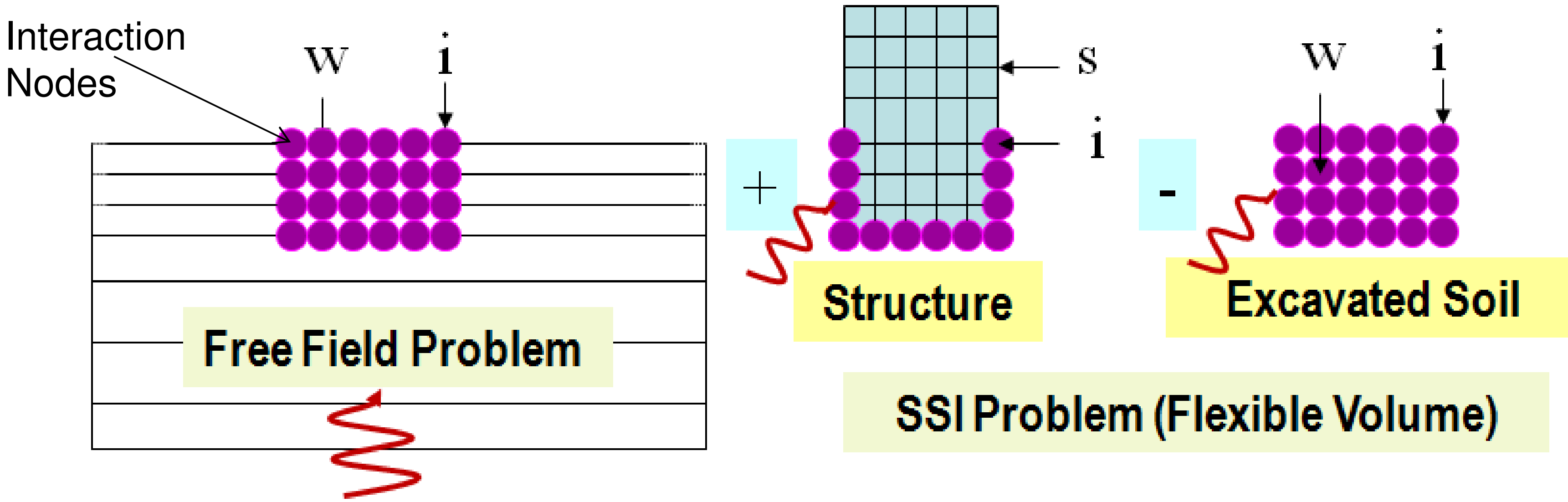
For large-size SSSI models, spatial variation of soil properties and soil motion could be nonuniform in horizontal direction.



ACS SASSI SSSI Model: About 90,000 nodes and 9,000 interaction nodes

NOTE: Using ACS SASSI, 2D/1D soil layering frequency-dependent correction factors can be computed for stiffness and free-field soil motions at interaction nodes. These frequency-dependent complex factors are then applied to the reference1D soil layering local impedances and motions for performing a 3D SSI analysis with nonuniform soil. User can do.

ACS SASSI Flexible Volume Subtructuring for Uniform and Nonuniform Soil

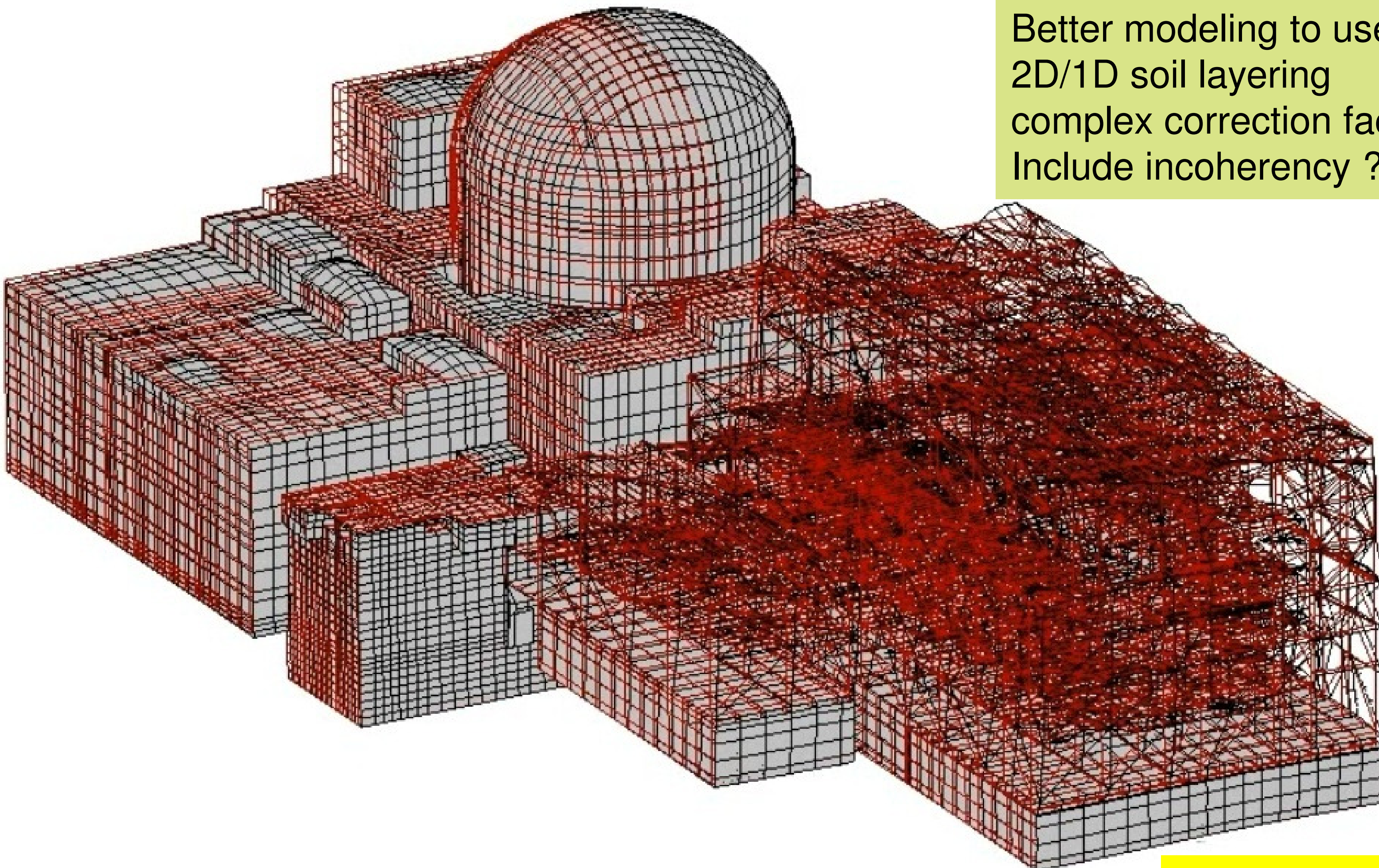


$$\begin{bmatrix} \mathbf{C}^s_{ii} - \mathbf{C}^e_{ii} + \mathbf{X}_{ii} & -\mathbf{C}^e_{iw} + \mathbf{X}_{iw} & \mathbf{C}^s_{is} \\ -\mathbf{C}^e_{wi} + \mathbf{X}_{wi} & -\mathbf{C}^e_{ww} + \mathbf{X}_{ww} & \mathbf{0} \\ \mathbf{C}^s_{si} & \mathbf{0} & \mathbf{C}^s_{ss} \end{bmatrix} \begin{Bmatrix} \mathbf{U}_i \\ \mathbf{U}_w \\ \mathbf{U}_s \end{Bmatrix} = \begin{Bmatrix} \mathbf{X}_{ii}\mathbf{U}'_i + \mathbf{X}_{iw}\mathbf{U}'_w \\ \mathbf{X}_{wi}\mathbf{U}'_i + \mathbf{X}_{ww}\mathbf{U}'_w \\ \mathbf{0} \end{Bmatrix}$$

Apply 2D/1D soil layering corrections to free-field motion and excavated soil stiffness; in ACS SASSI run Rest 2, 3 for 2D and 1D soil layering. Then, apply matrix corrections using the dofs mapping files and run Rest 6 to solve the 3D SSI with nonuniform.

SSSI Model for Standard Plant (7 Buildings)

Single or multiple 1D soil columns can be used. Better modeling to use 2D/1D soil layering complex correction factors. Include incoherency ?….



ANIMATIONS

ACS SASSI V3.0 Probabilistic Site Response and SSI Analysis Inputs (Option Pro)

Seismic Input Spectral Shape (Sa):

- Sa is random variable (scale factor) (Method 1 in ASCE 04)
- Sa is a random field (curve) with given correlation structure (Method 1 in ASCE 04). Correlation from probabilistic simulations or records (ProEQUAKE*)*

Soil Layer Profiles (Vs, D and soil curves G-gama, D-gama)

- Vs and D (at low strain) for each soil layer are two random variables. Vs and D both depend on stress level; they can be negatively correlated, nonlinear stochastic dependence (tests) or independent.(ProSITE)

- Vs and D profiles (for all soil layers) is a random field with given spatial correlation structure (based on geotechnical data). (ProSITE)

- G-gama and D-gama soil material curves are random fields based on laboratory statistical data (ProSITE)

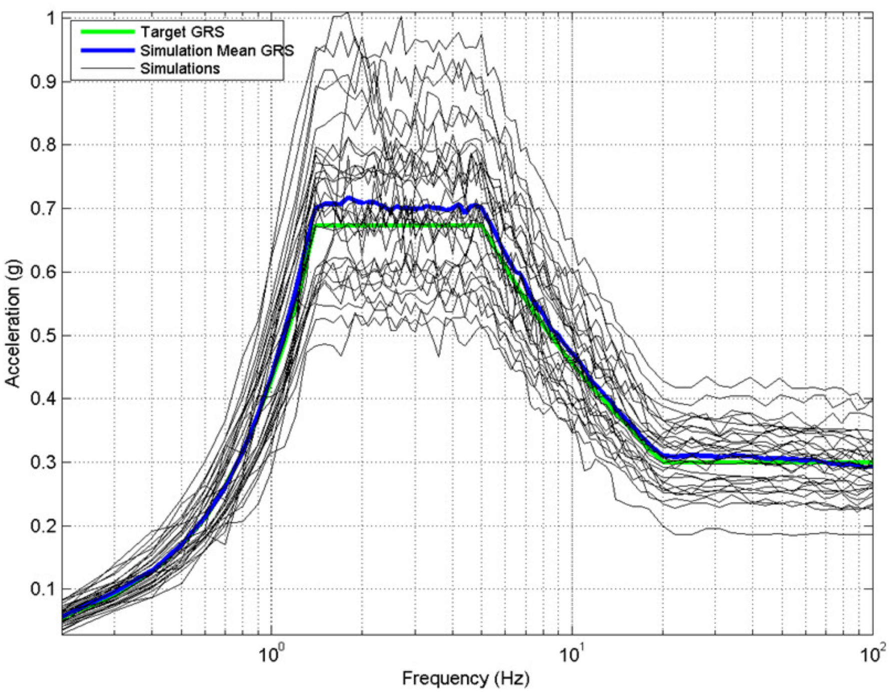
Structural Effective Stiffness and Damping:

- Keff/Kel and D are two random variables that are a function of stress level; they can be negatively correlated, nonlinear stochastic dependence (tests) or independent. (ProHOUSE)

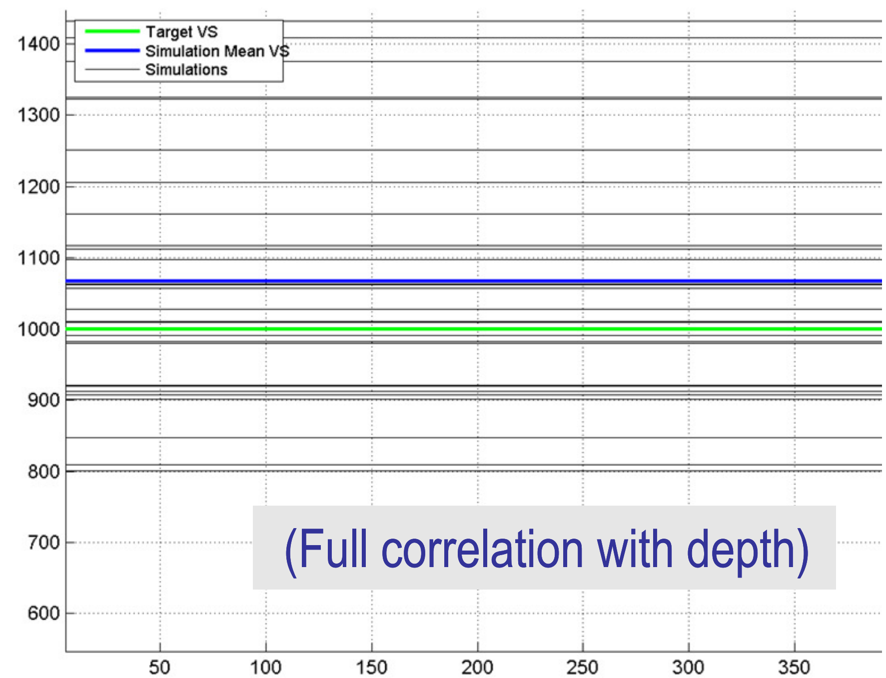
NOTE: Since stress level depends on locations, multiple sets of the two random variables should be defined. In ACS SASSI we considered a random variable pair (Keff/Kel and D) for each group of elements. Correlations between the two random variables of different groups could be considered, as needed.

Simulated Probabilistic Seismic GRS (Method 1) and Soil Profile (Vs and D) Using Random Variables

Simulated GRS Inputs



Simulated Soil Profiles

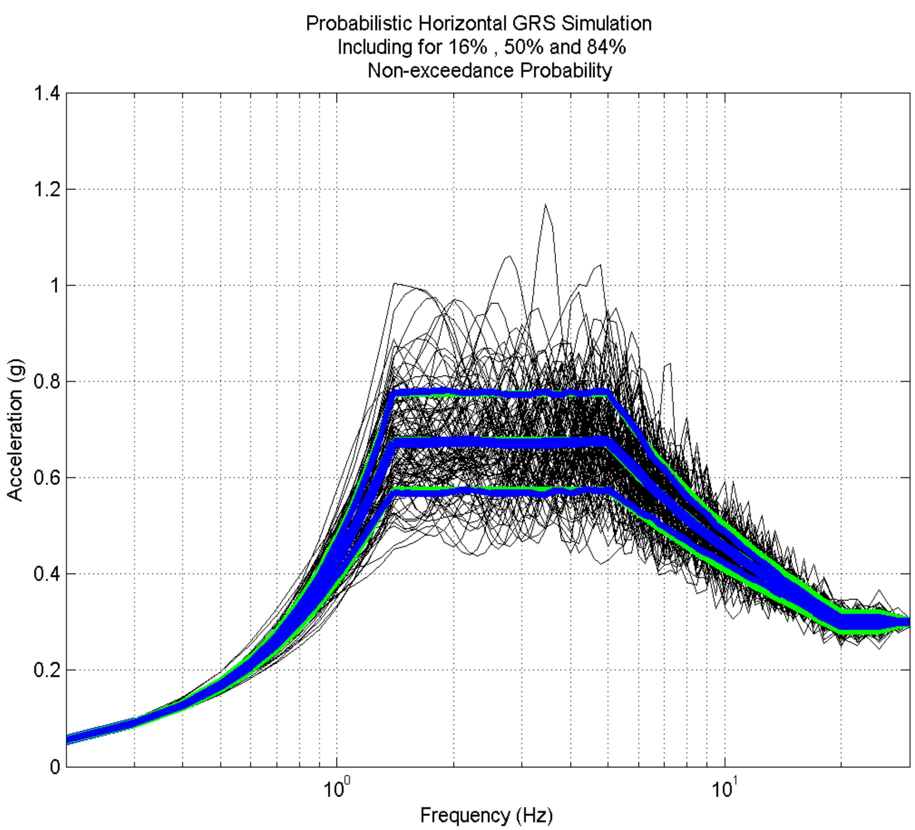


(Full correlation with depth)

Note: Only 30 LSH simulations were used

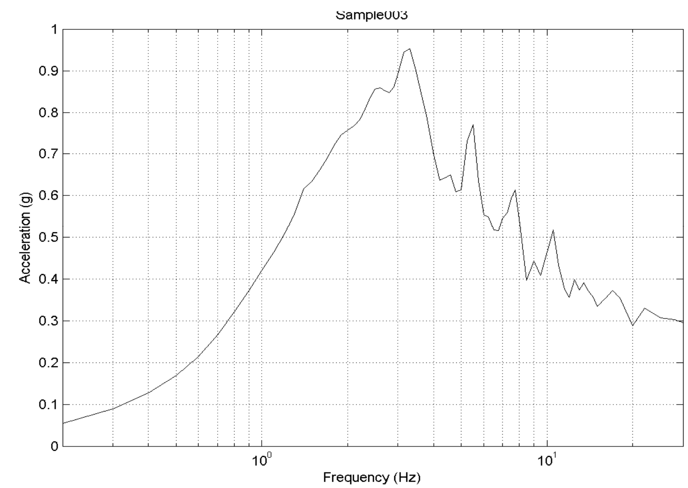
Simulated Probabilistic Seismic GRS (Method 2)

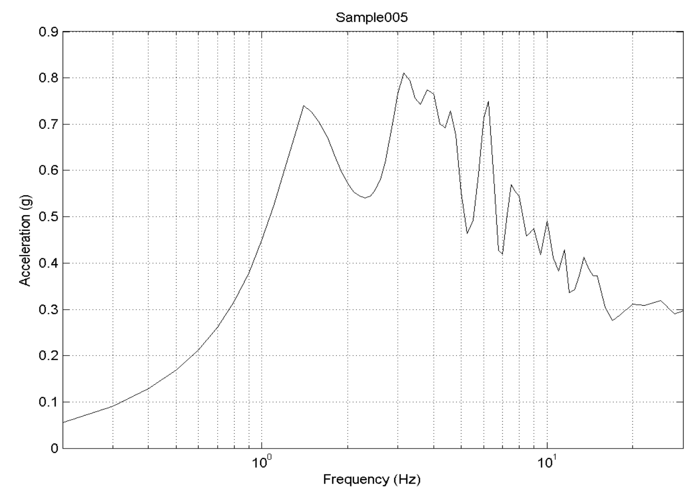
Probabilistic UHRS Input
0.30 ZPGA



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

Simulated GRS

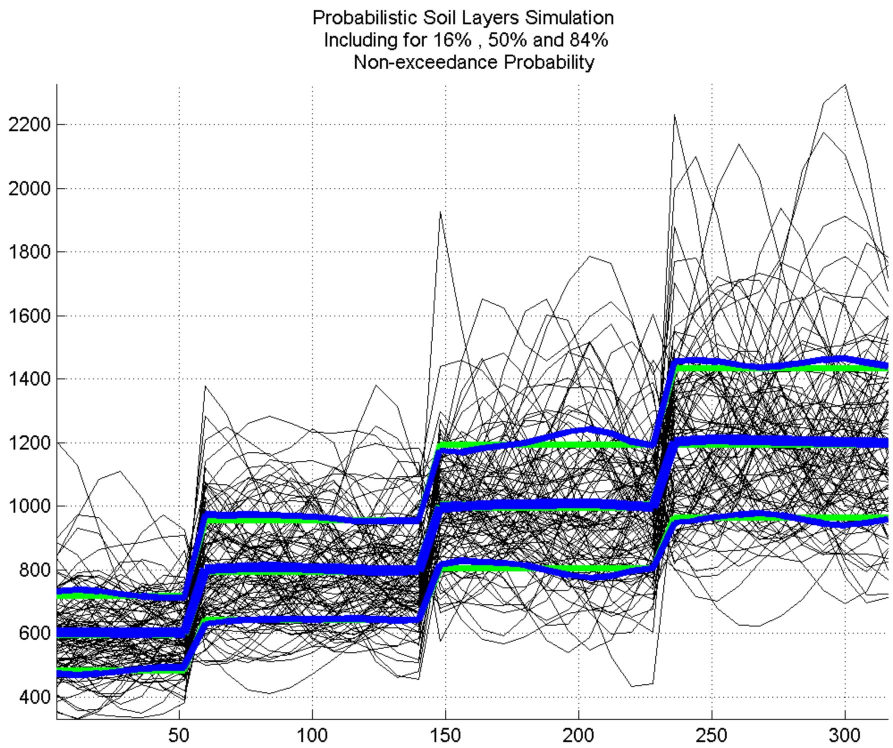




Random Samples

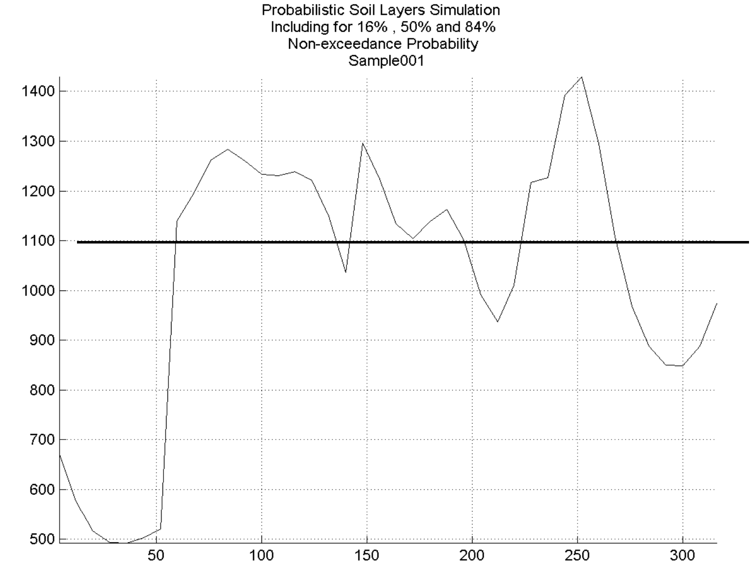
Simulated Probabilistic Soil Layer Profiles

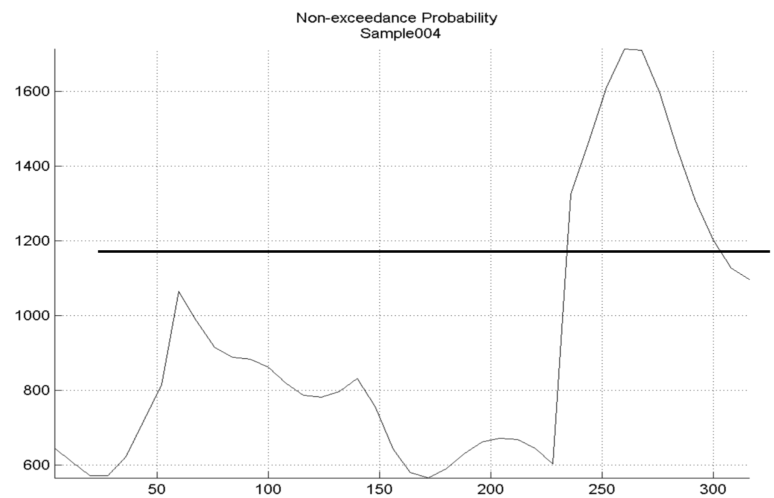
Probabilistic Soil Profile



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

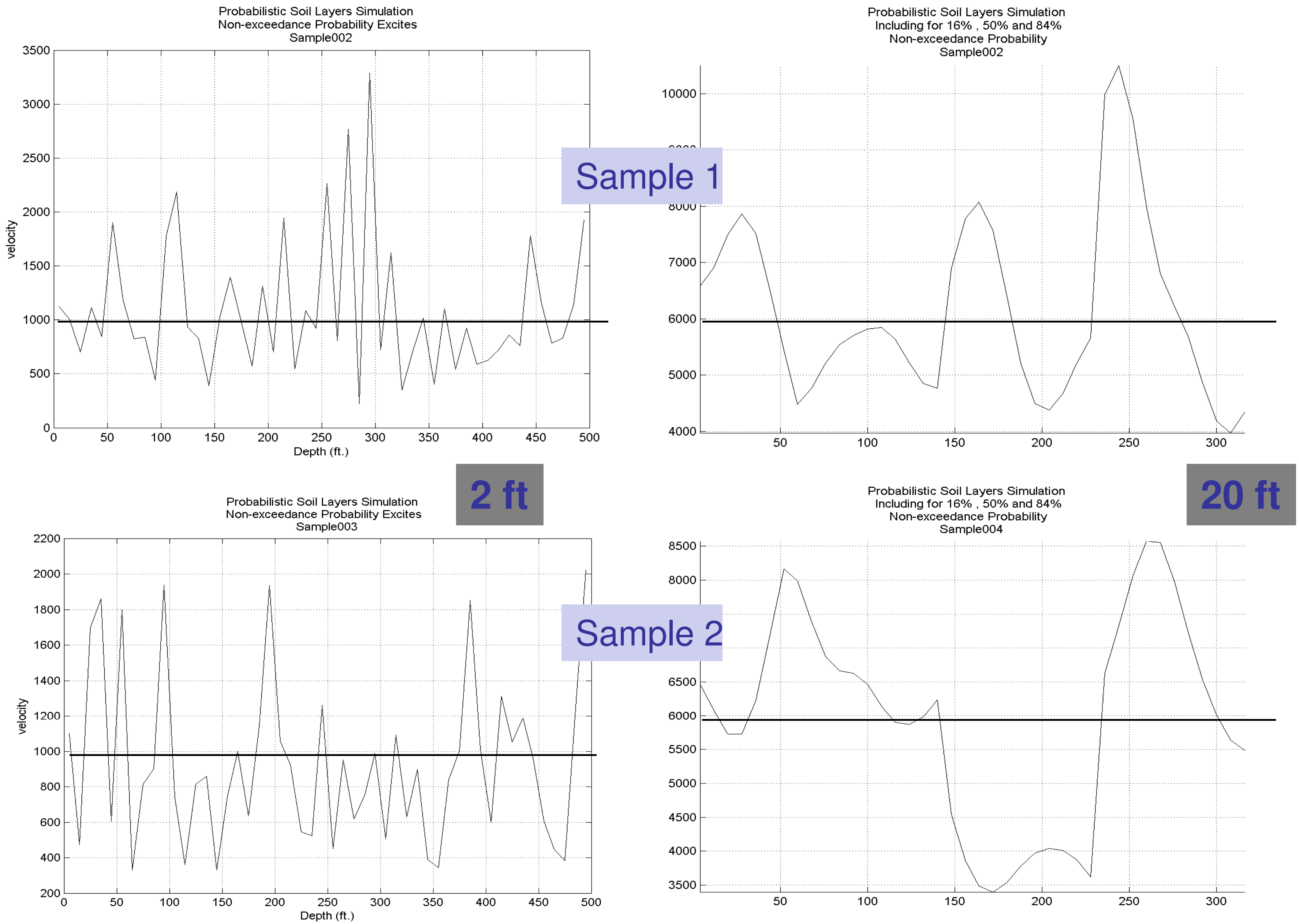
Simulated Soil Profiles





Random Samples

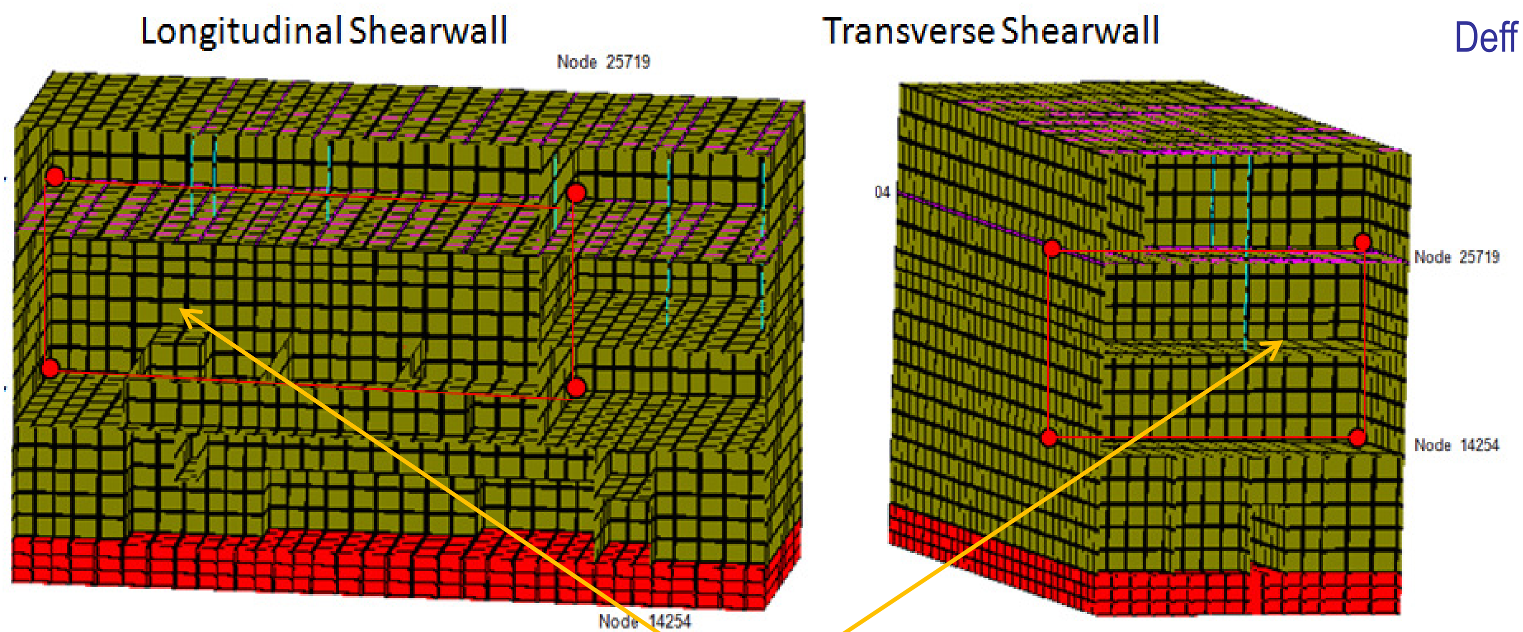
Effect of Spatial Correlation Length on Simulated Soil Profiles



Probabilistic Structural Modeling (Stiffness & Damping)

- Effective stiffness ratio Keff/Kelastic and damping ratio, Deff, are modeled as statistically dependent random variables.

- Keff/Kelastic and Deff can be considered negatively correlated, or having a complementary probability relationship, or Deff be a response function of Keff/Kelastic based on experiments



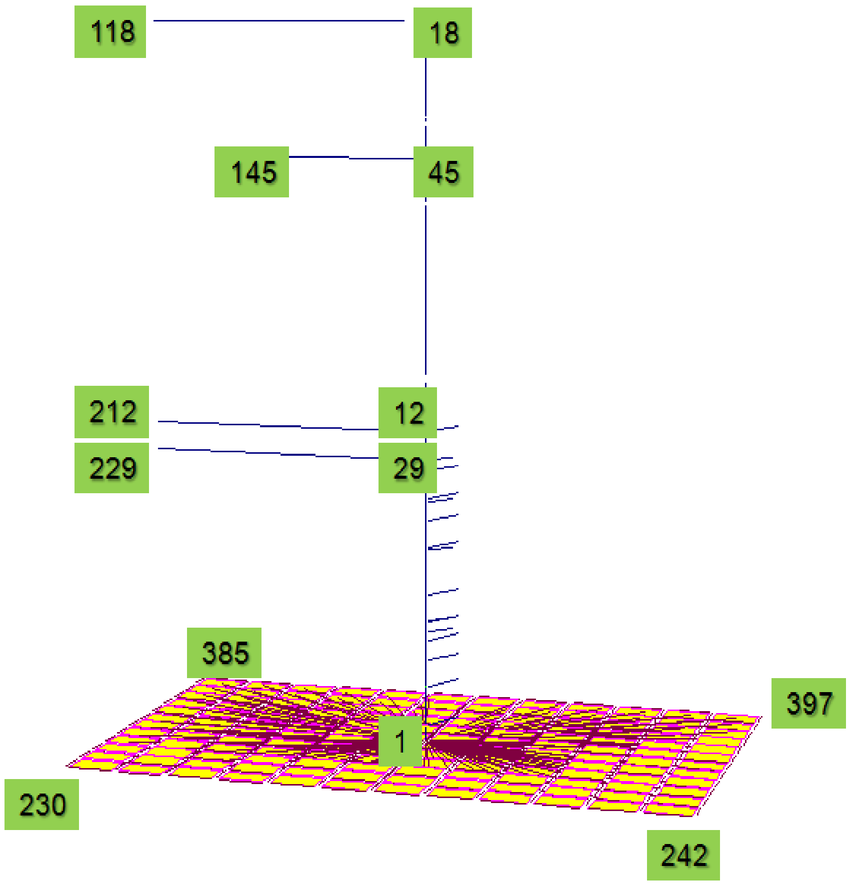
Deff = f (Keff/Elastic)

Stiff	Damp
0.01	0.20
0.10	0.17
0.20	0.15
0.30	0.13
0.40	0.11
0.50	0.10
0.60	0.09
0.70	0.08
0.80	0.07
0.90	0.06
1.00	0.05

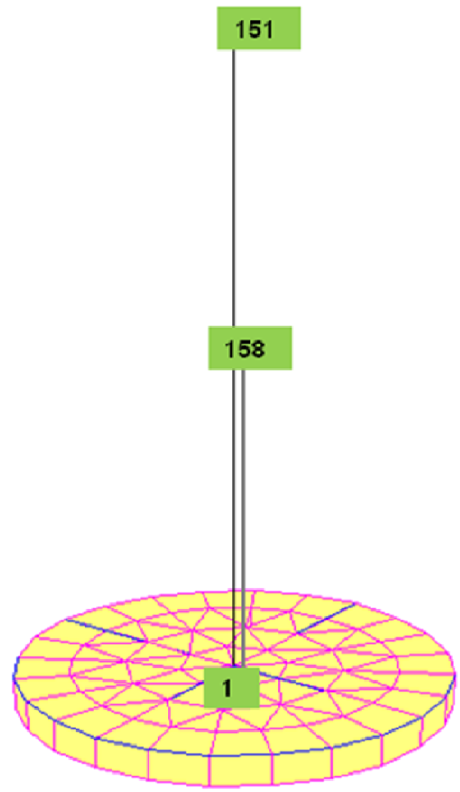
- Keff and Deff are defined separately for each element group. Statistical correl… …een different group Keff variables can be included.

Case Studies: 1) EPRI AP1000 NI & 2) PWR RB Sticks

EPRI AP1000 NI Stick Model



PWR RB Stick Model



Deff = f (Keff)

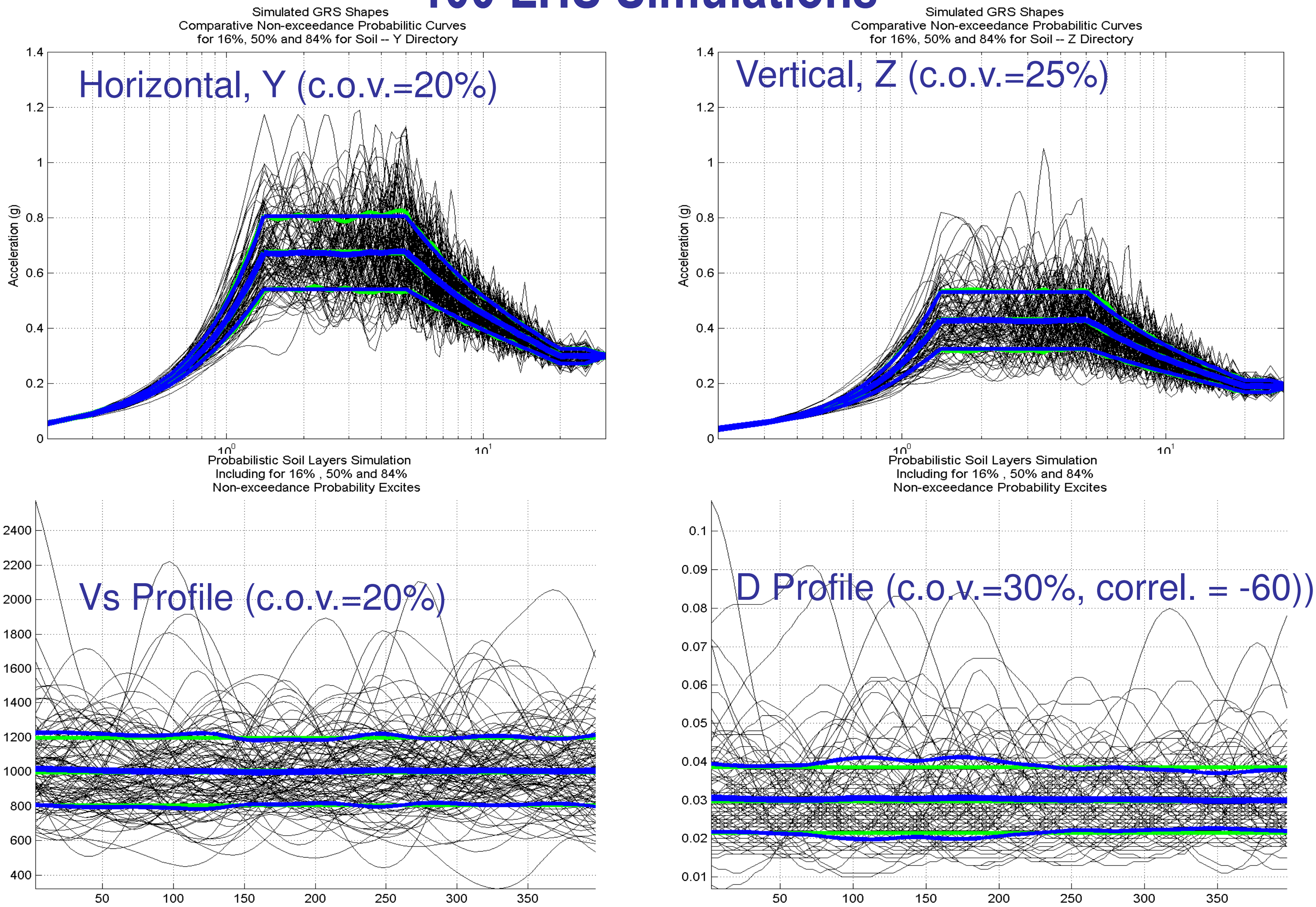
Stiff	Damp
0.01	0.20
0.10	0.17
0.20	0.15
0.30	0.13
0.40	0.11
0.50	0.10
0.60	0.09
0.70	0.08
0.80	0.07
$\boxed{0.90 \quad 0.06}$	
1.00	0.05

Mean Values

Case 1: Soil Site, Vs = 1,000 fps
Case 2: Rock Site, Vs = 6,000 fps

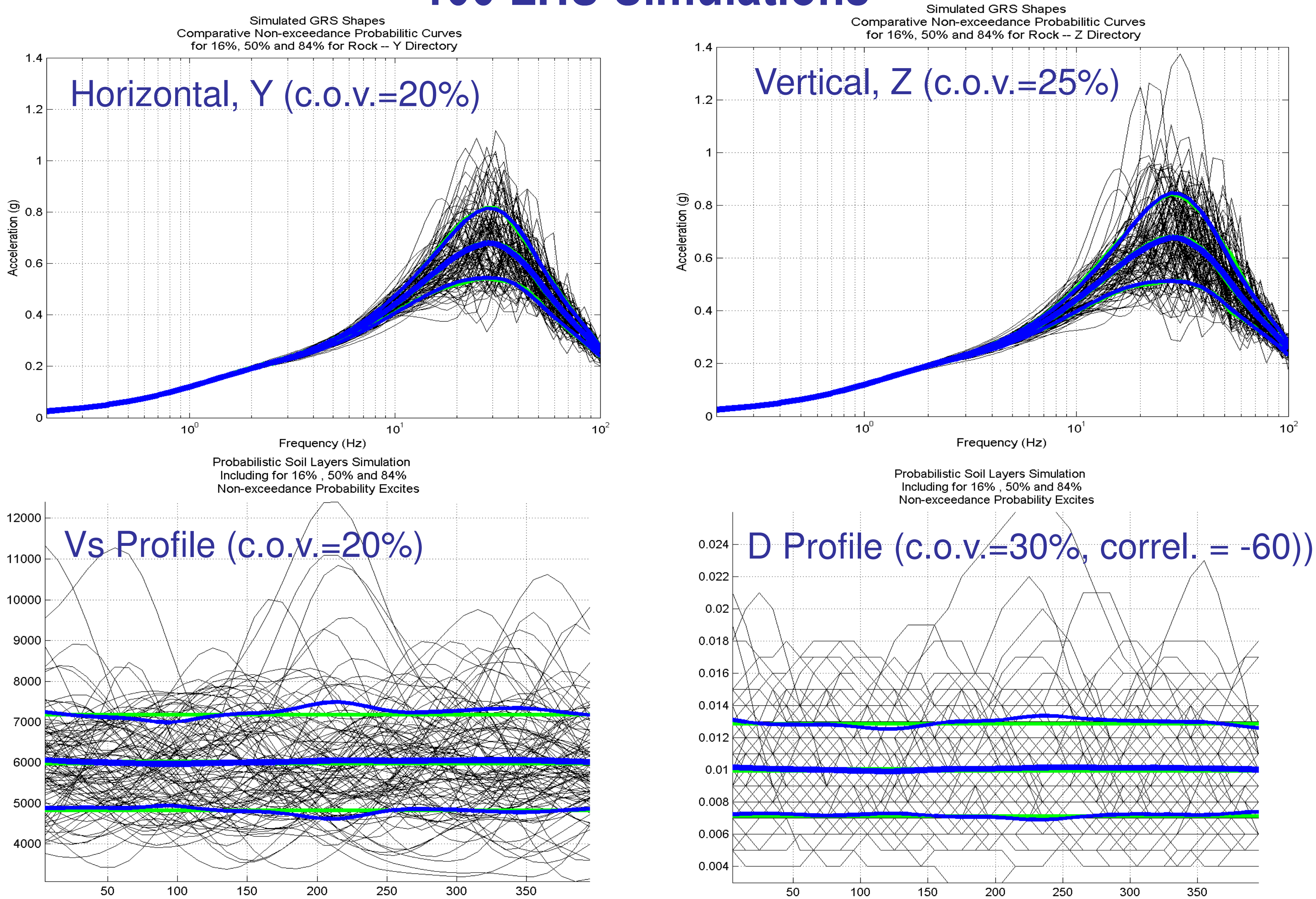
Seismic GRS (Method 2) and Soil Profiles for Soil Site

100 LHS Simulations



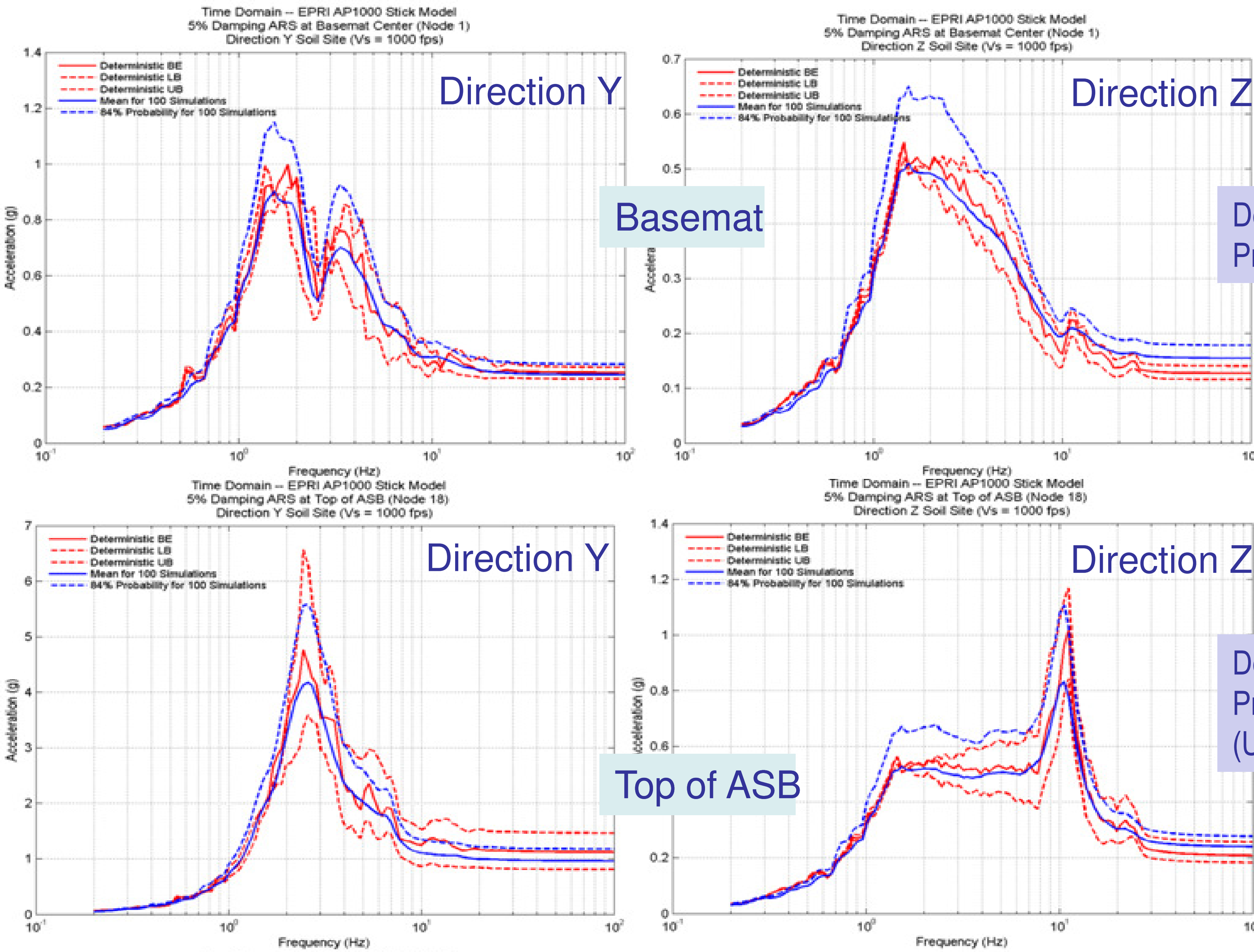
Seismic GRS (Method 2) and Soil Profiles for Rock Site

100 LHS Simulations

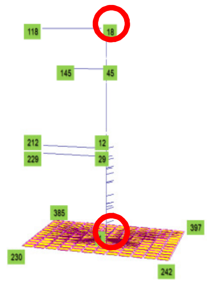


Deterministic vs. Probabilistic SSI Analysis for Soil Site

CASE A: Deterministic Mean (Mean GRS, Soil LB, BE,UB, and Struct Mean Keff=0.90 and Deff=6%)



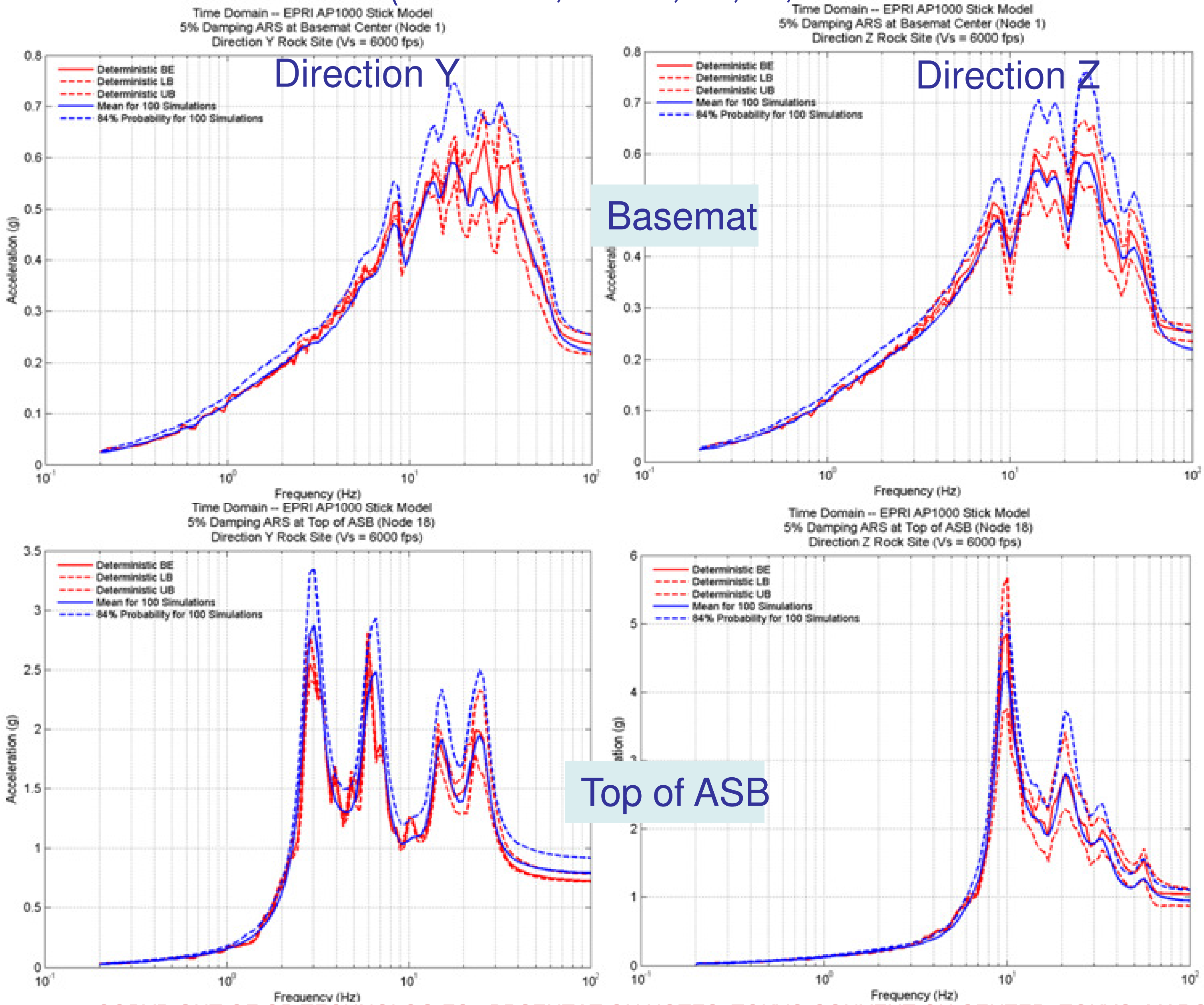
Det ranges
Prob 60%-80%



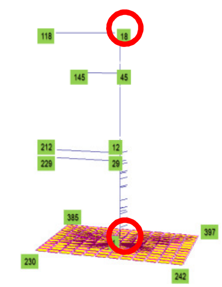
Det ranges
Prob 85%-95%
(UB role)

Deterministic vs. Probabilistic SSI Analysis for Rock Site

CASE A: Deterministic Mean (Mean GRS, Soil LB, BE,UB, and Struct Mean Keff=0.90 and Deff=6%)



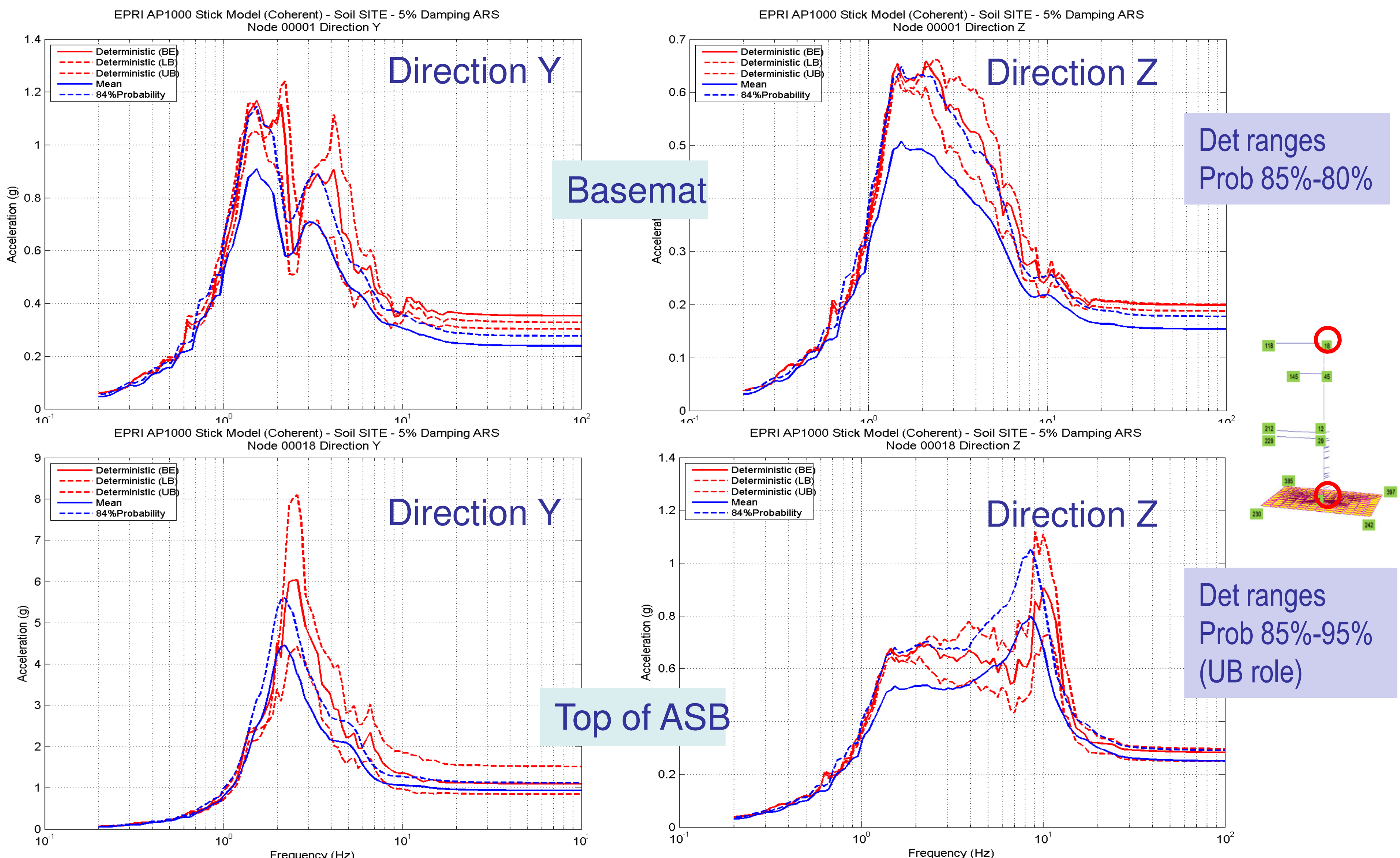
Det ranges
Prob 65%-80%



Det ranges
Prob 65%-95%
(UB role)

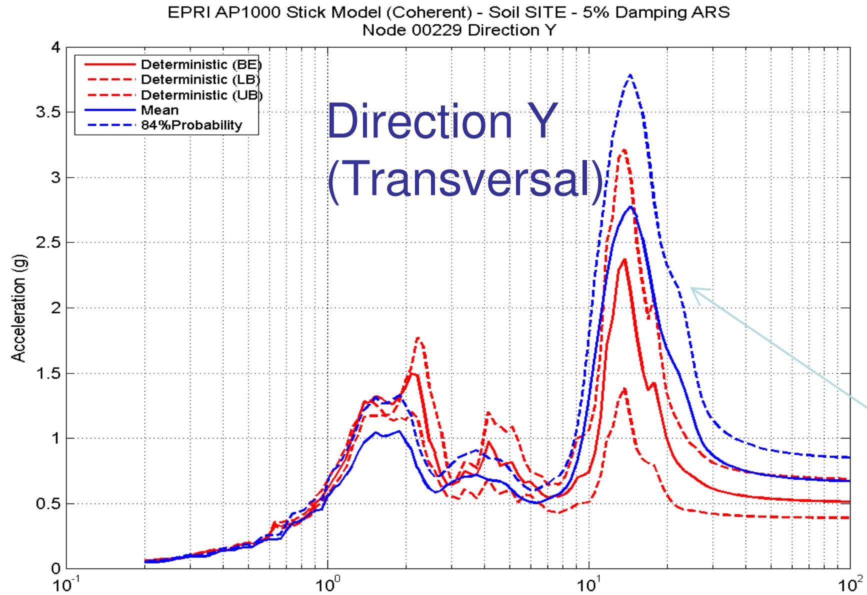
Deterministic vs. Probabilistic SSI Analysis for Soil Site

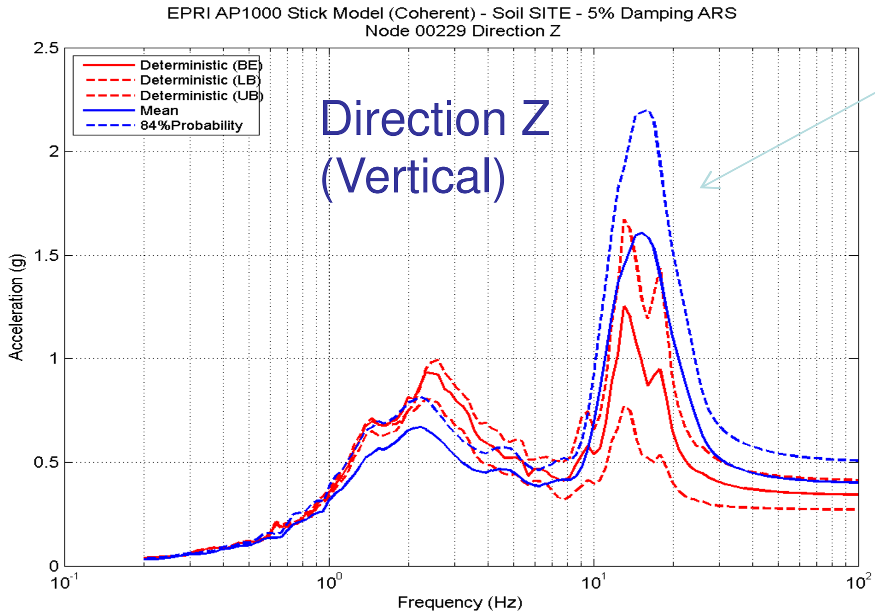
CASE B: Deterministic ASCE (Mean GRS, Soil LB, BE,UB, and Struct Code Keff=1.00 and Deff=4%)



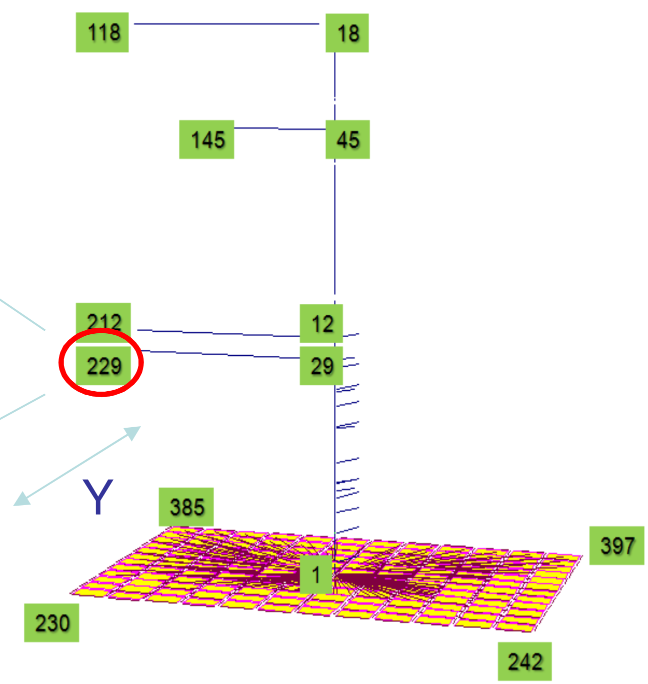
Deterministic vs. Probabilistic SSI Analysis for Rock Site

CASE B: Deterministic ASCE (Mean GRS, Soil LB, BE,UB, and Struct Code Keff=1.00 and Deff=4%)





EPRI AP1000 Stick Model

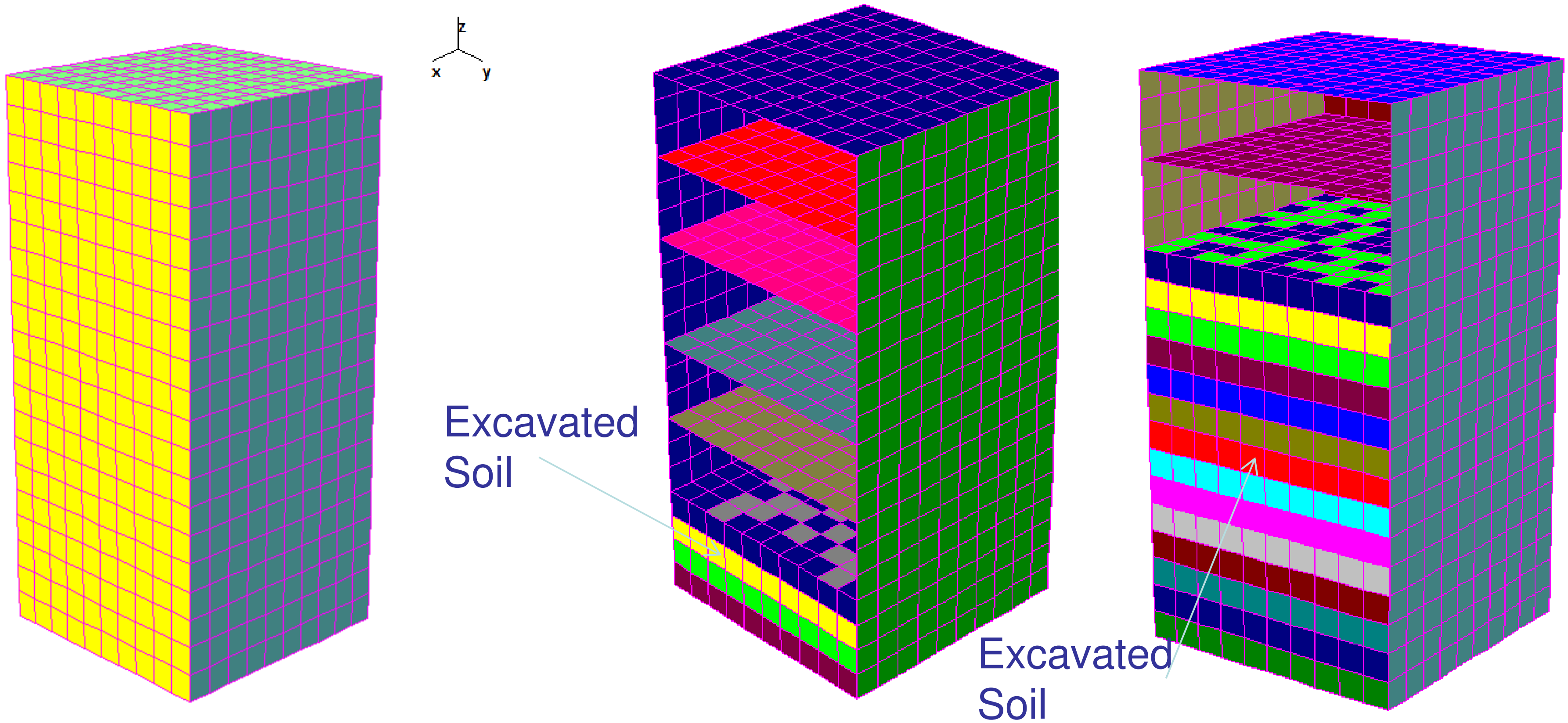


NOTE: 229 node location sensitive to torsional and rocking motion components

Concluding Remarks

- The ASCE 04-2013 standard goal, that Deterministic SSI produces SSI responses that correspond to approximately 80% NEP, is accomplished in an overall, average sense.
- Exceptions appear to corresponds to particular cases of large mass eccentricity structures that are more sensitive to rotational motions, including torsional and rocking motions. More investigations are needed, and currently underway.
- Using lower damping in structure in Deterministic SSI analysis impacts larger for the rock sites for which radiation damping is much lower. More investigations are needed, and currently underway.

ACS SASSI SMR SSI analysis Case Study



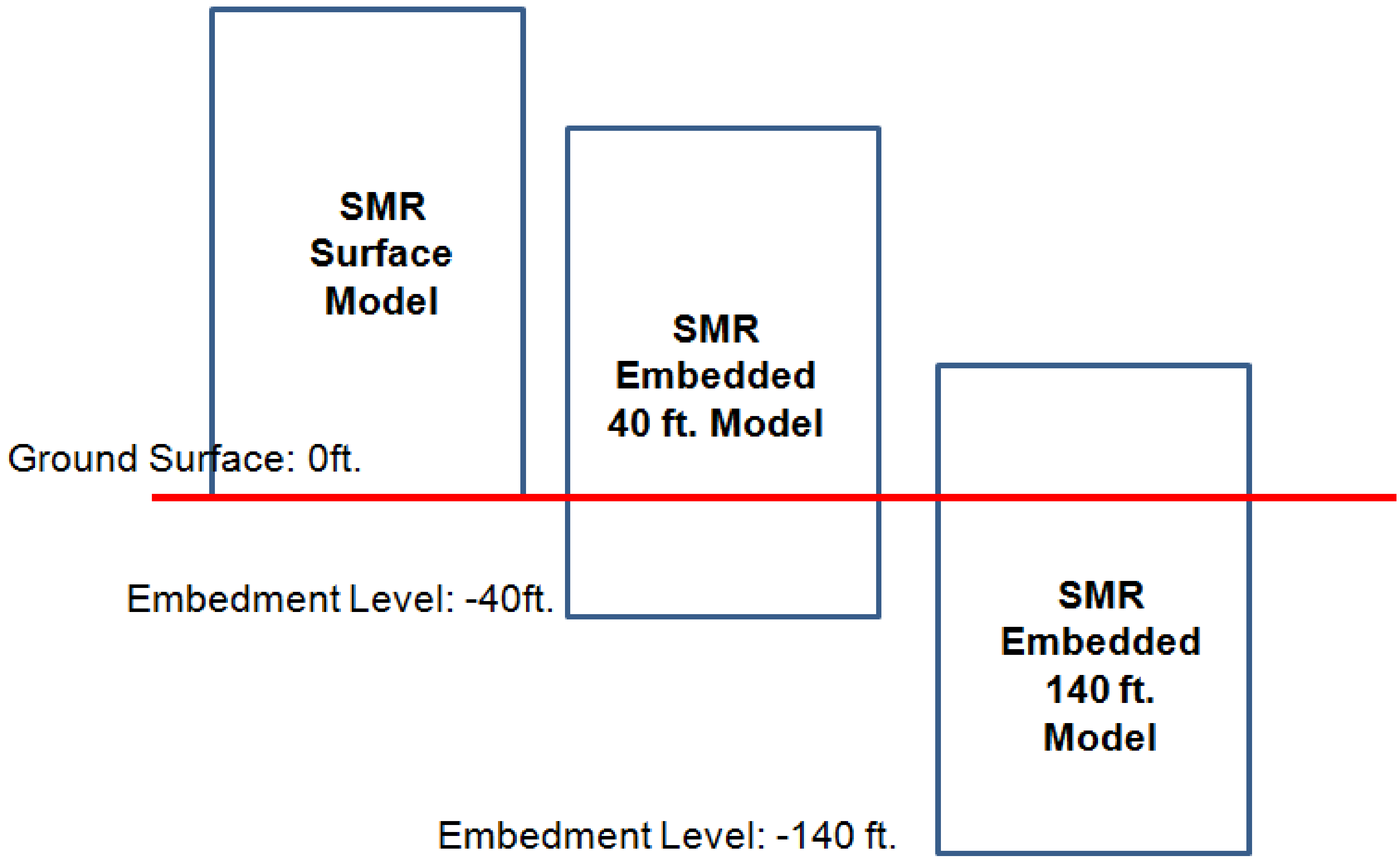
Simple SMR Structure

SMR size: 100 ft x 100 ft X 200 ft
Shell Element size: 10 ft X 10 ft
Shell Thickness: 4ft for floors, 8ft for basemat
Solid size: 10 ft X 10 ft X 10 ft

40 ft Embedment SMR SSI Model (use FV method)

140 ft Embedment SMR SSI Model (use FV method)

SMR SSI Models with Different Embedment Levels



SMR SSI Case Studies

SMR SSI Models:

Case 1: SMR Structure with Surface Foundation (fictious, as a reference)
Case 2: SMR Structure with 40 ft Embedment (fictious, similar to NI embedment)
Case 3: SMR Structure with 140 ft Emdedment (closer to the real design)

Seismic Inputs:

SITE RESPONSE:
We considered a typical UHSRS shape inputs corresponding to the baserock (Vs=9200 fps) at the 500ft depth. 60 probabilistic site response simulations (convolutions) were performed using randomized soil layering profiles for the UHSRS inputs at the 500 ft depth.

SSI ANALYSIS:
Probabilistic SSI: We considered the 60 simulated in-column soil motions at the foundation level for the embedded models, and simulated surface motions for the surface model.

Deterministic SSI: We considered the outcrop probabilistic mean response spectra of the 60 simulations, as the outcrop FIRS. Then, we performed 3 SHAKE type deterministic analyses for LB, BE and UB soil profiles to compute the in-column FIRS motions to be used for the deterministic SSI analysis. No adjustment was applied to the in-column FIRS to envelope the in-column probabilistic mean FIRS.

SMR SSI Case Studies

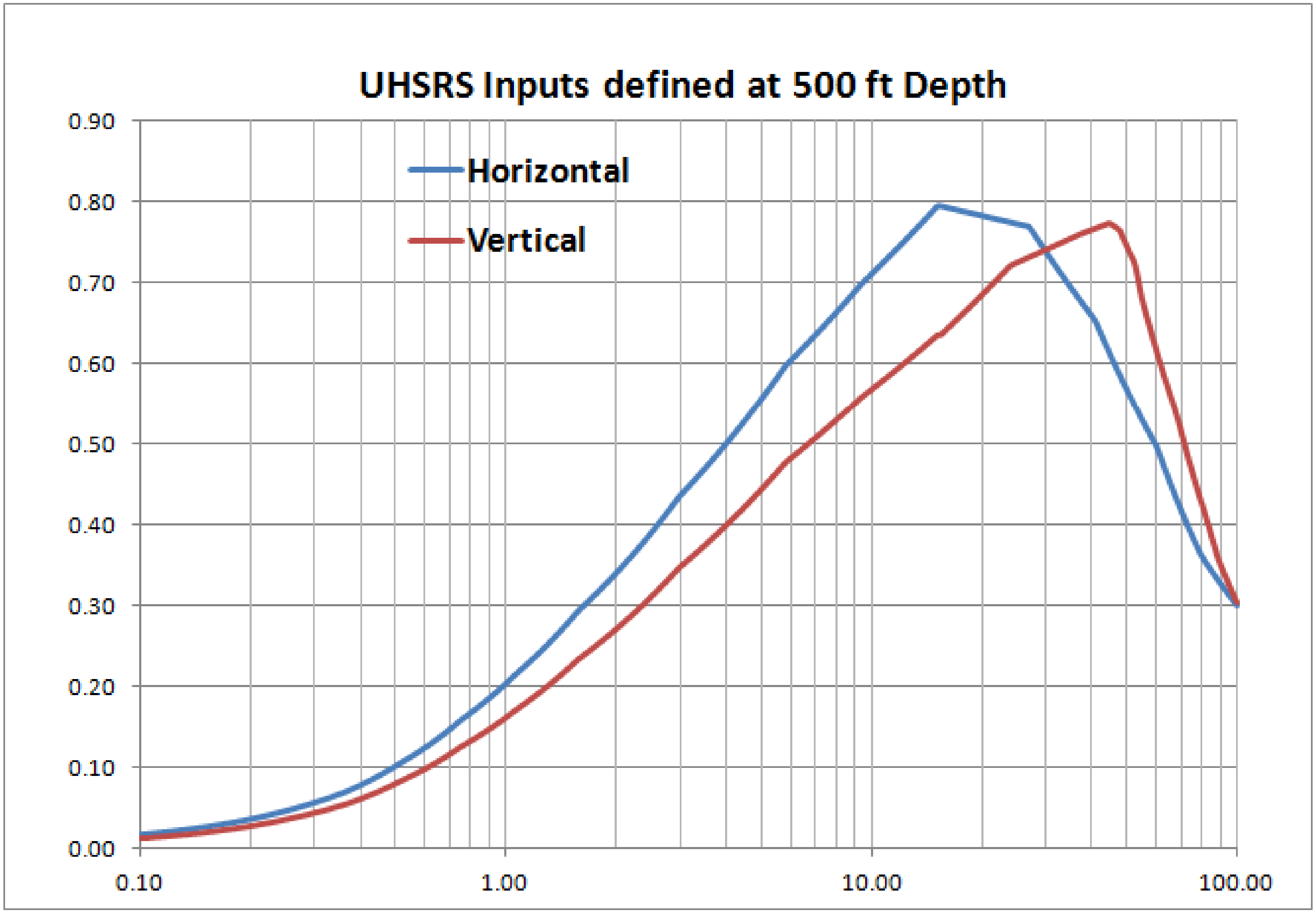
SOIL LAYERING

1) Uniform soil profile
   (Vs = 2,000 fps down to 350 ft depth, baserock at 500 ft depth)
2) Nonuniform soil profile
   (variable Vs profile with stiffer layers about softer layers, baserock at 500 ft depth).

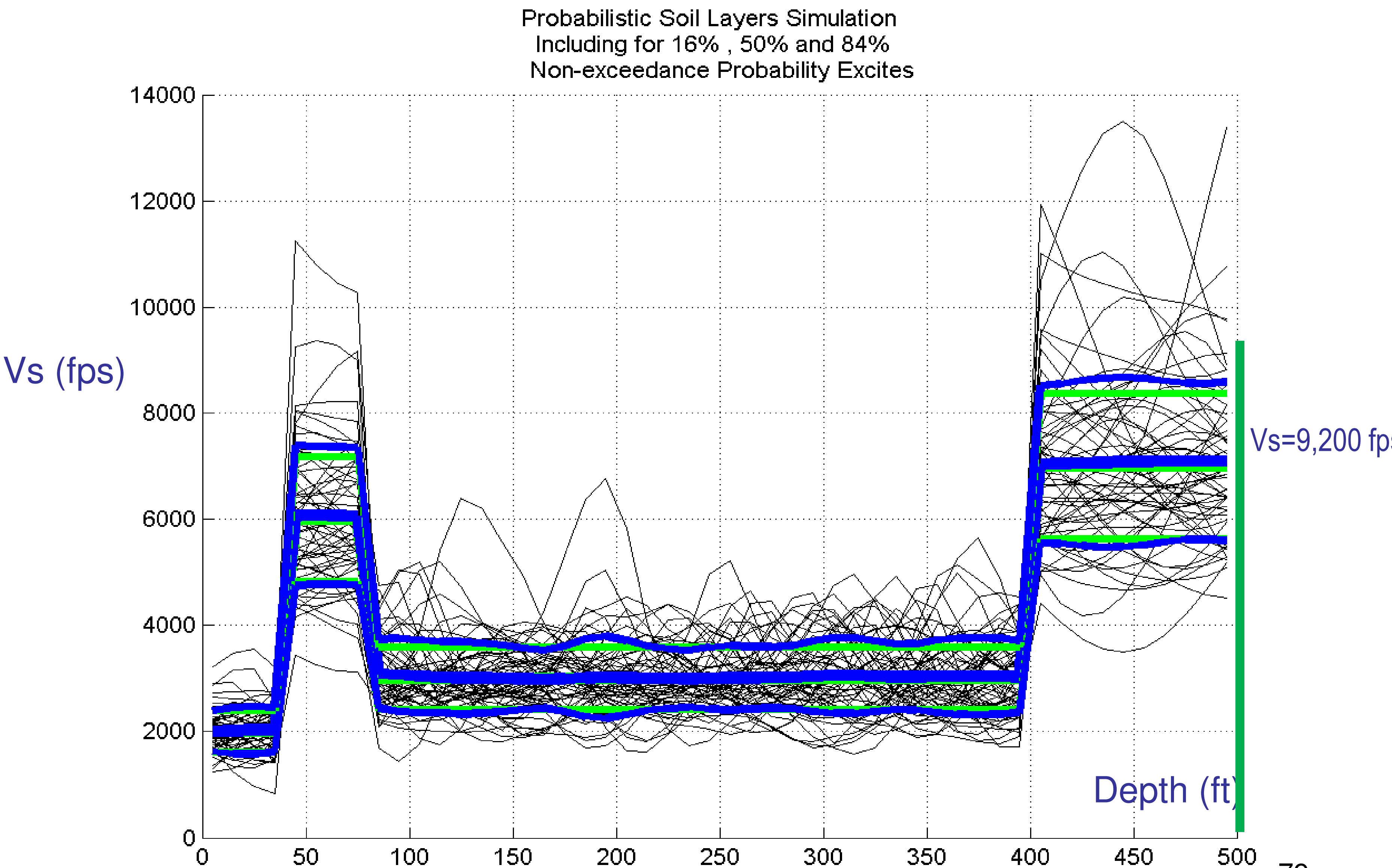
Probabilistic SSI: We considered the 60 randomized soil profiles. The Vs and Damping for each soil profile were considered as dependent random variables with lognormal distribution. Damping variable is considered statistically dependent (varying inversely than Vs) as recommended by ASCE 04-2014. Vs c.o.v. was 0.20 and Damping c.o.v. was 0.35. The Vs profiles were assumed to have a spatial correlation corresponding to a 20 ft correlation length (as recommended by Popescu, Princeton, much lower than 2 ft correlation length recommended by Jeremic, UC Davis – 2ft correlation length appears to be too low for site response simulations, since Vs profile values at different close depths will be basically statistically independent…).

Deterministic SSI: Based on the 60 probabilistic site response simulations we computed the deterministic LB, BE and UB soil profiles based on the 16%, 50% and 84% NEP for the Vs and Damping profiles.

UHSRS Seismic Inputs at the Baserock (Vs= 9,200 fps)

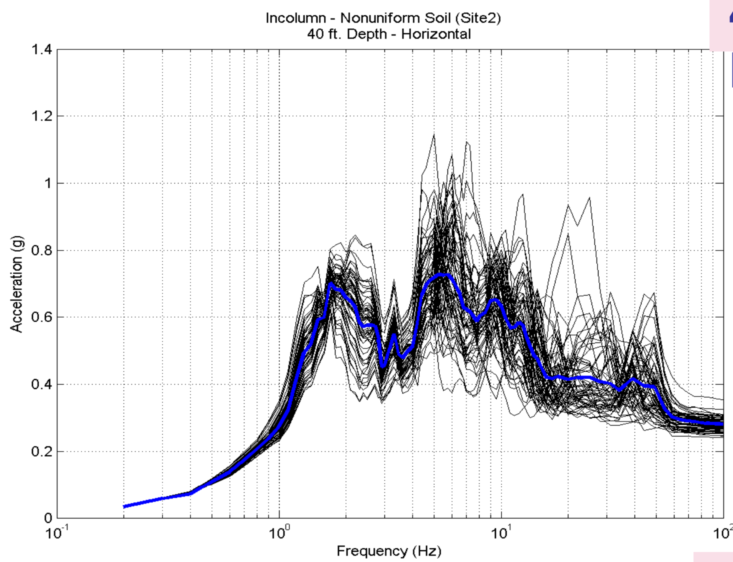


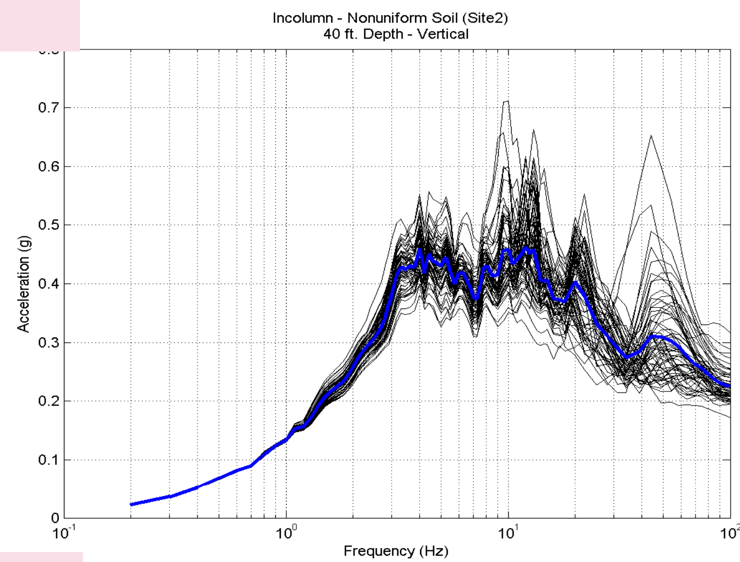
Nonuniform Soil Profile (Site 2)
60 Probabilistic and 3 Deterministic Soil Profiles



Probabilistic Site In-Column Motion Simulations (Site 2) (60 simulations vs. probabilistic mean RS)

40 ft Depth

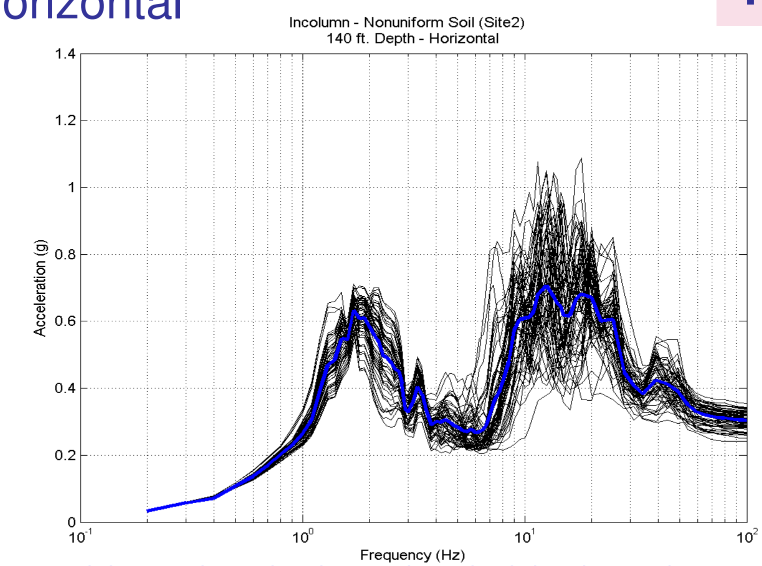


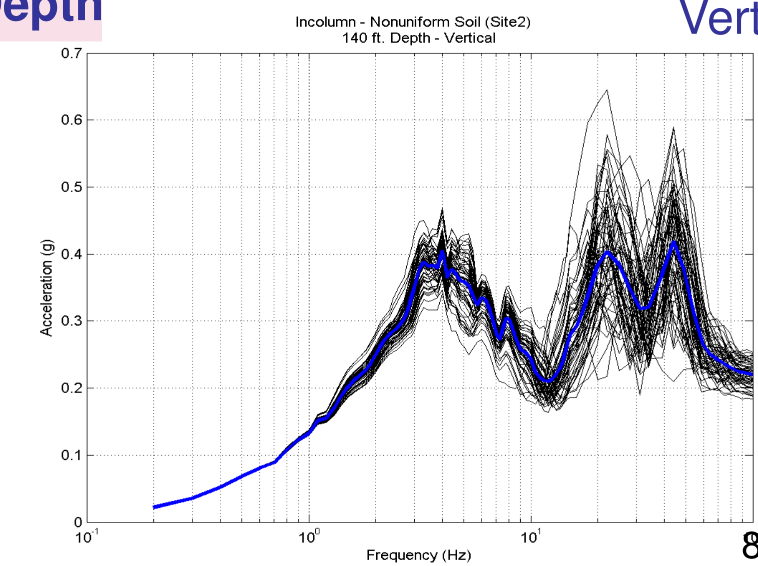


140 ft Depth

Horizontal

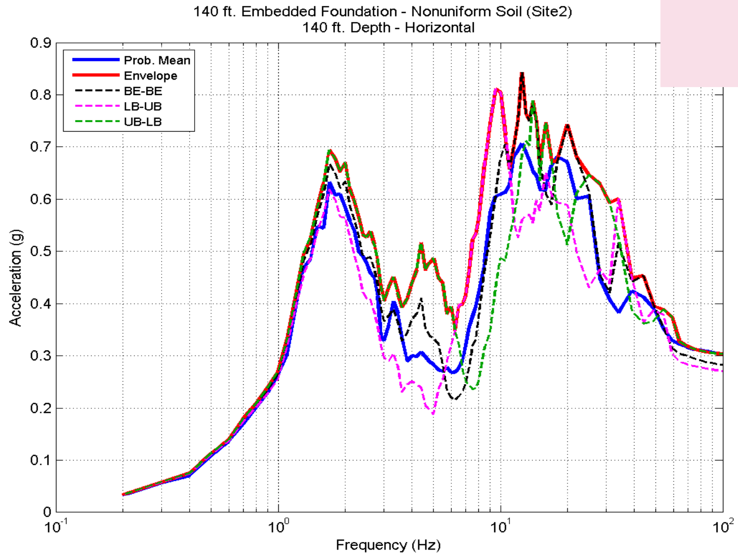
Vertical

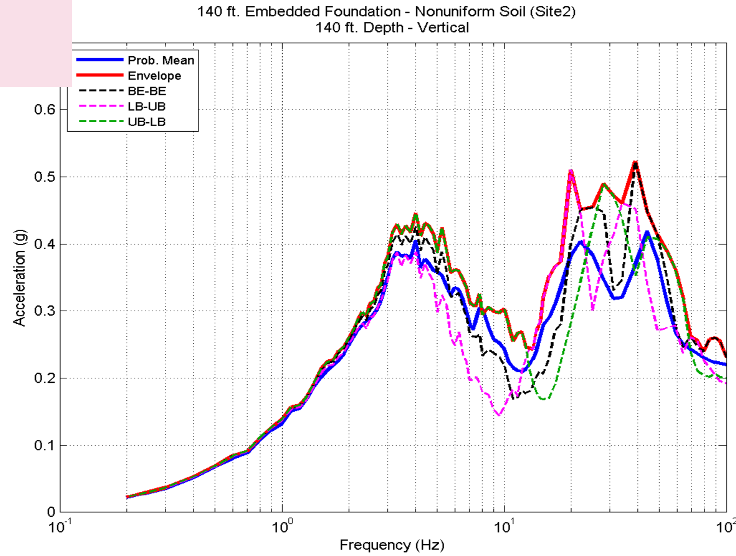




Deterministic vs. Probabilistic In-Column RS for Outcrop FIRS Input Defined at 140 ft Depth (Site 2)

140 ft Depth (FIRS)

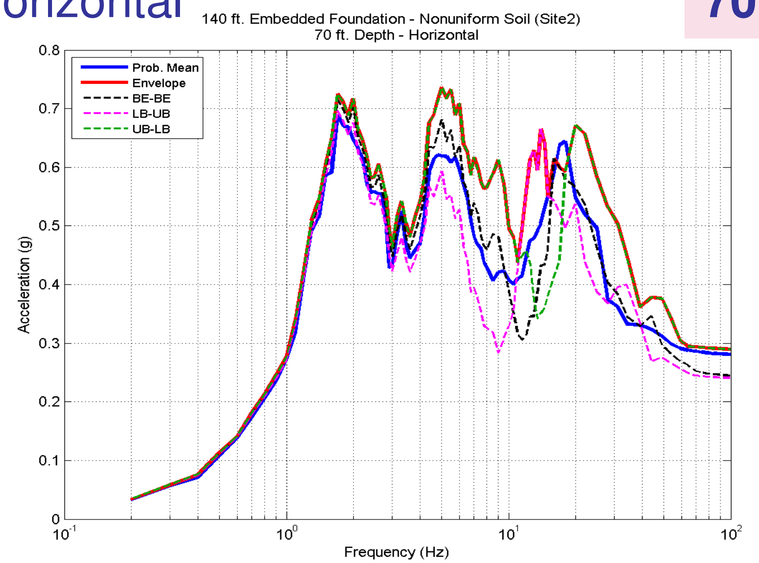


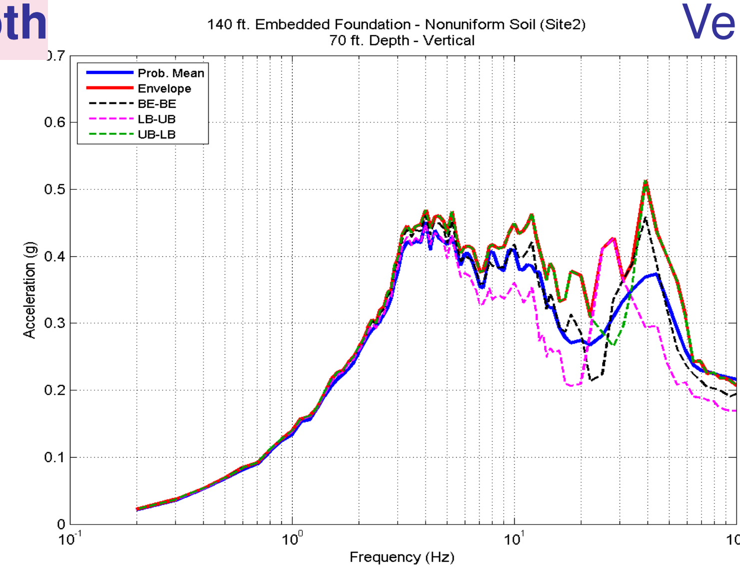


Horizontal

70 ft Depth

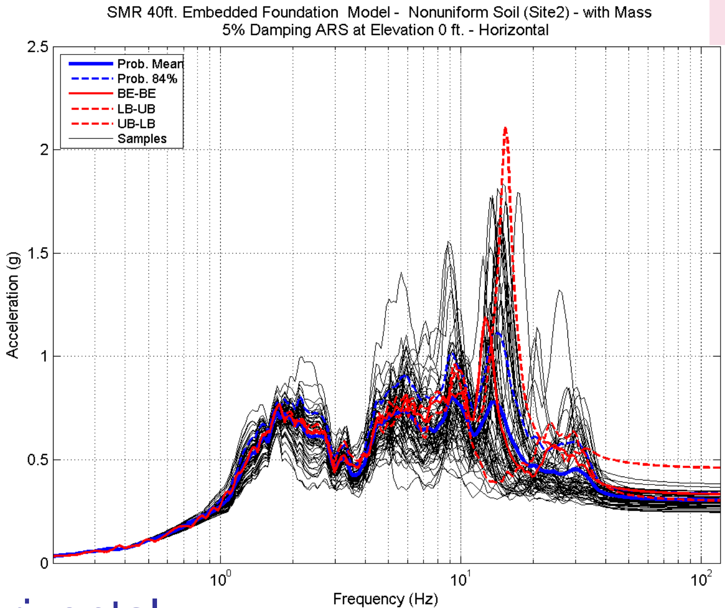
Vertical

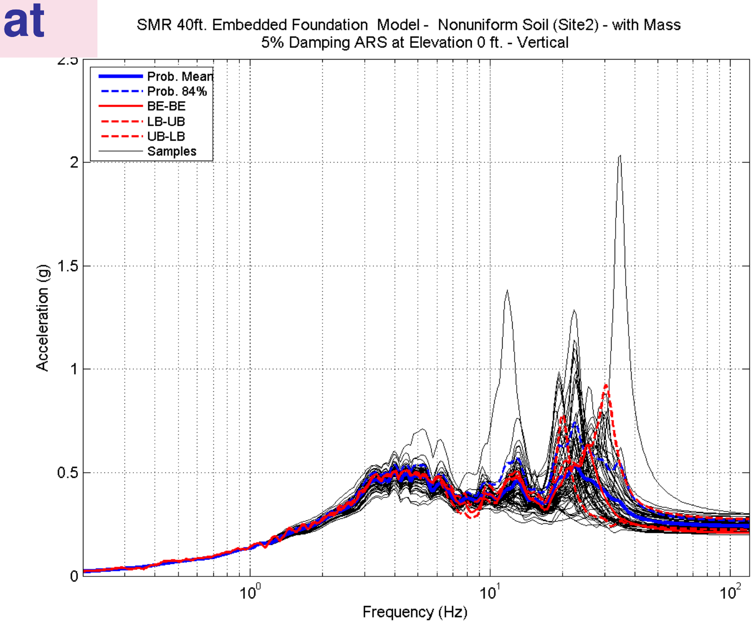




Probabilistic ISRS Simulations for 40ft Embedded Model (Site 2)

Basemat

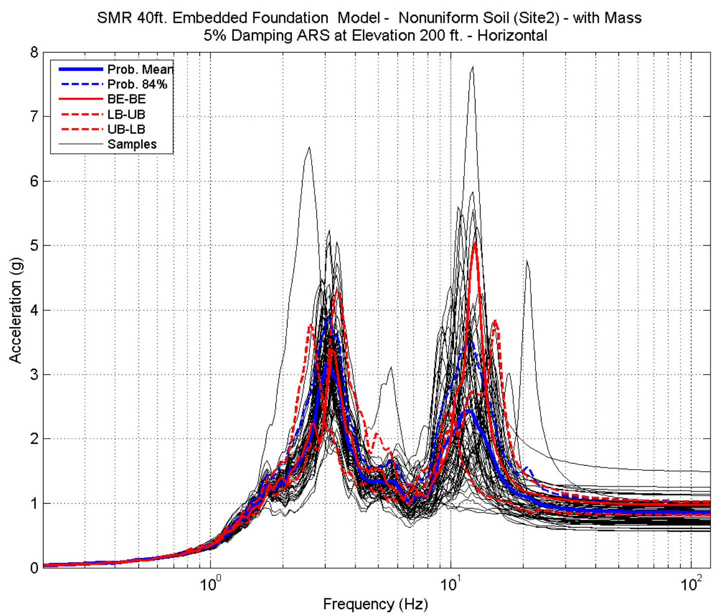


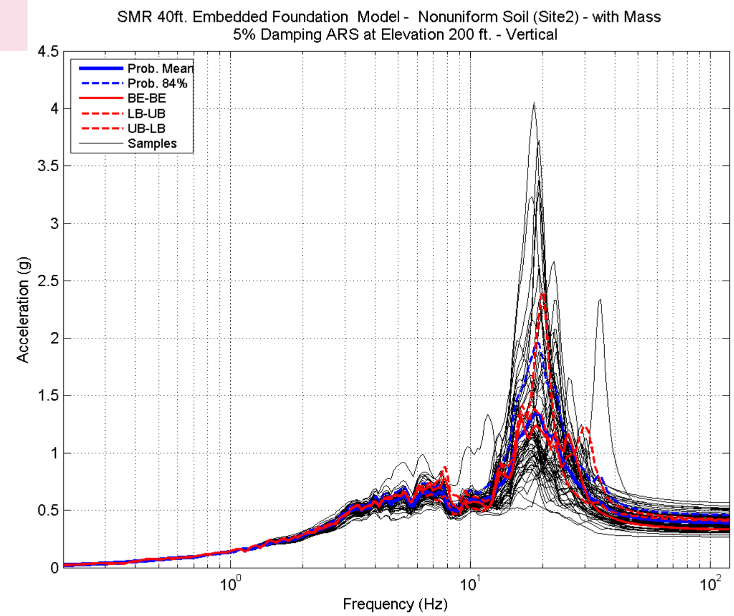


Horizontal

Vertical

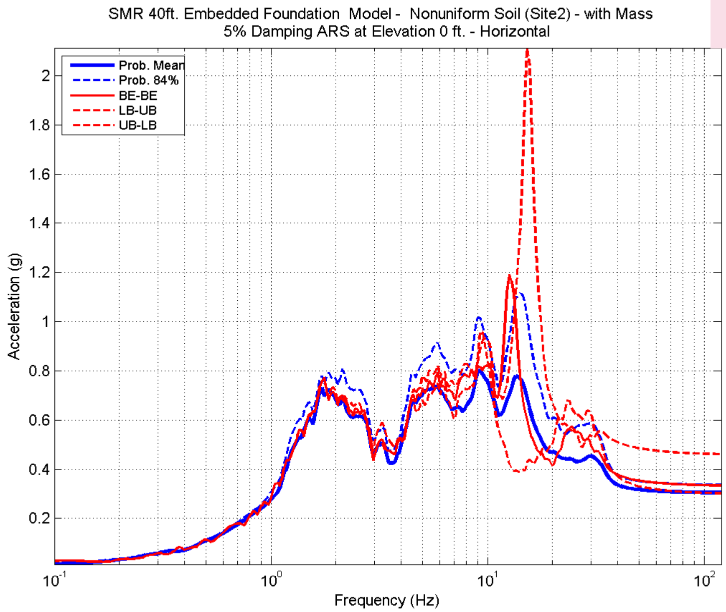
Roof

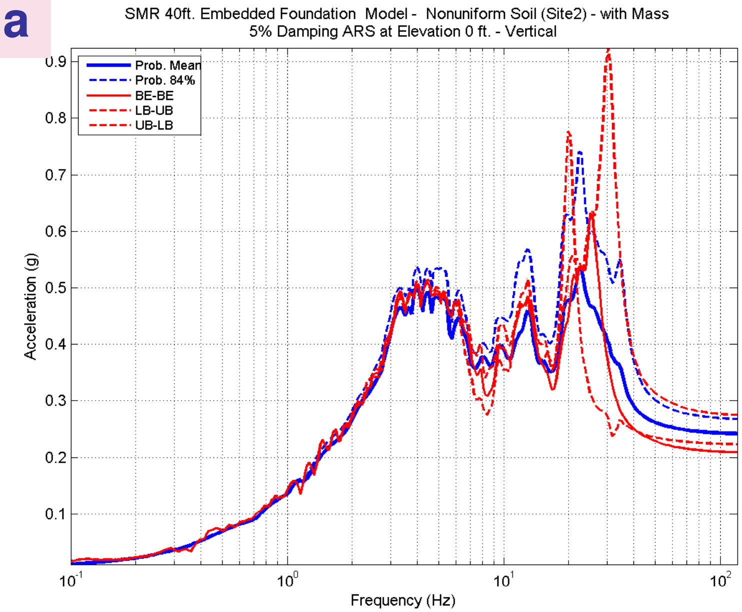




Deterministic vs. Probabilistic ISRS for 40ft Embedded Model (Site 2)

Basema t

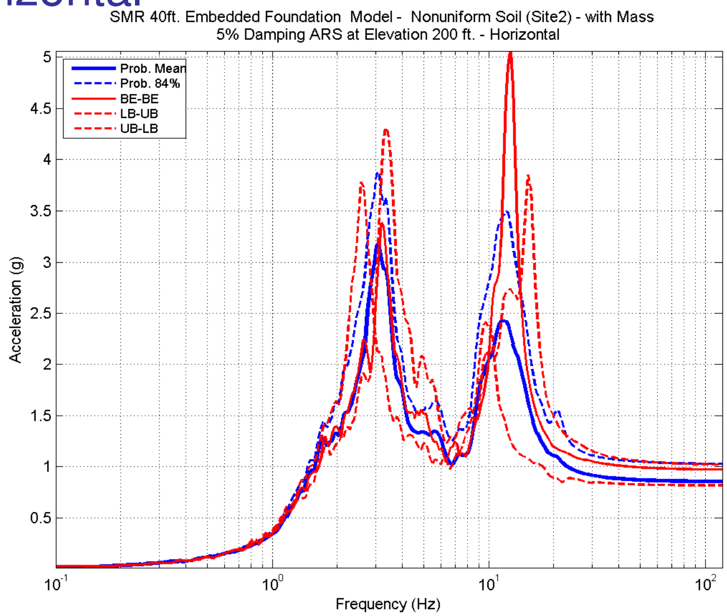


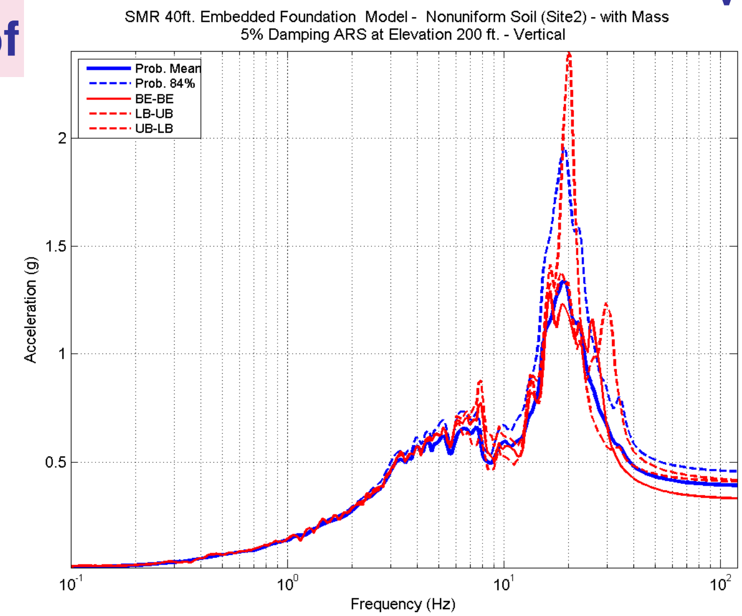


Horizontal

Vertical

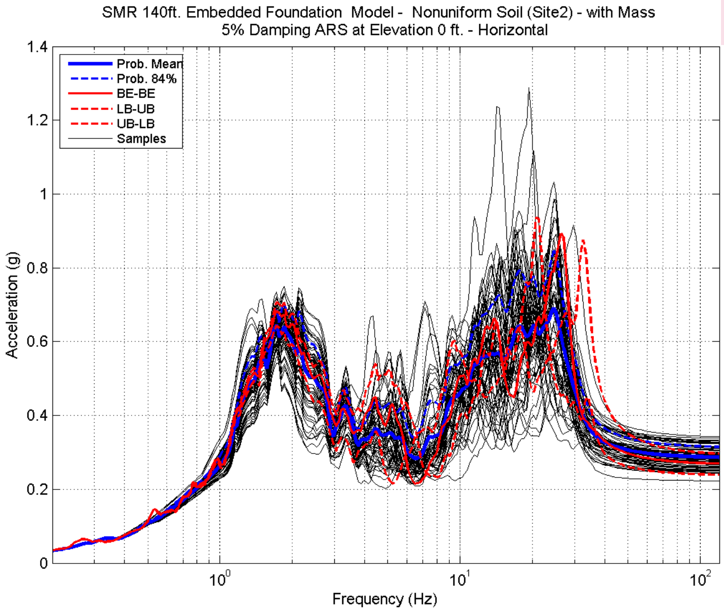
Roof

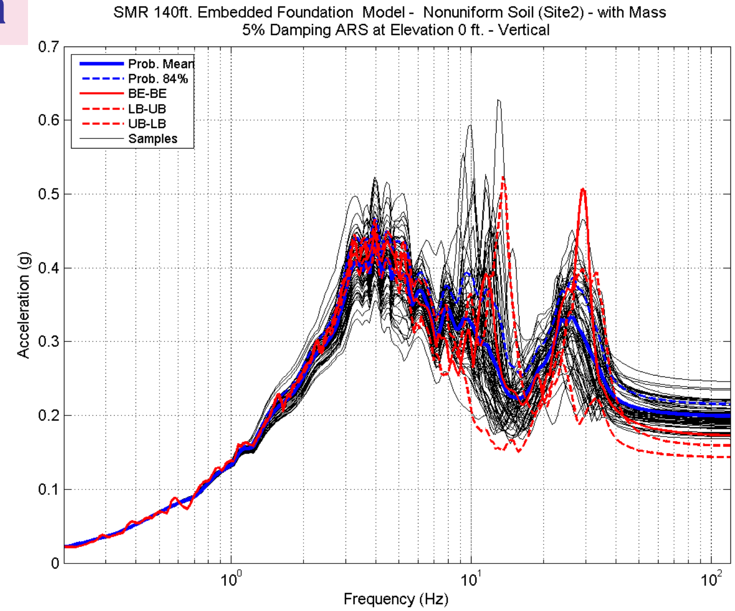




Probabilistic ISRS Simulations for 140ft Embedded SSI Model (Site 2)

Basemat

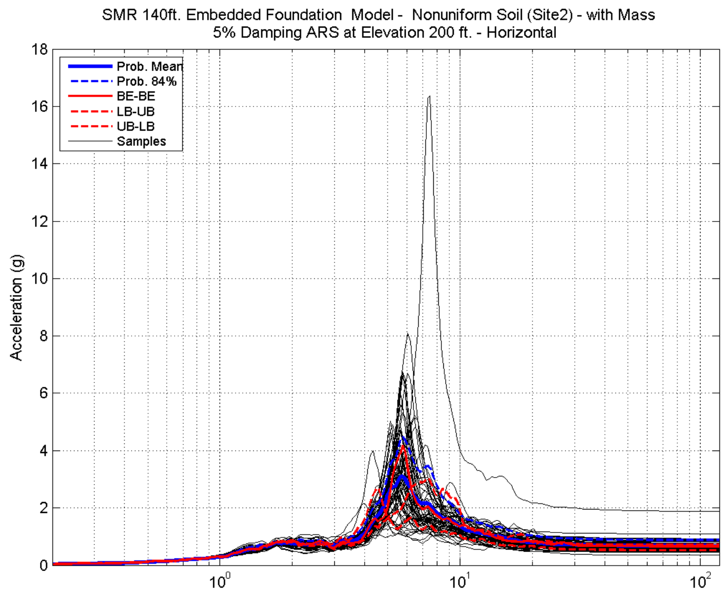


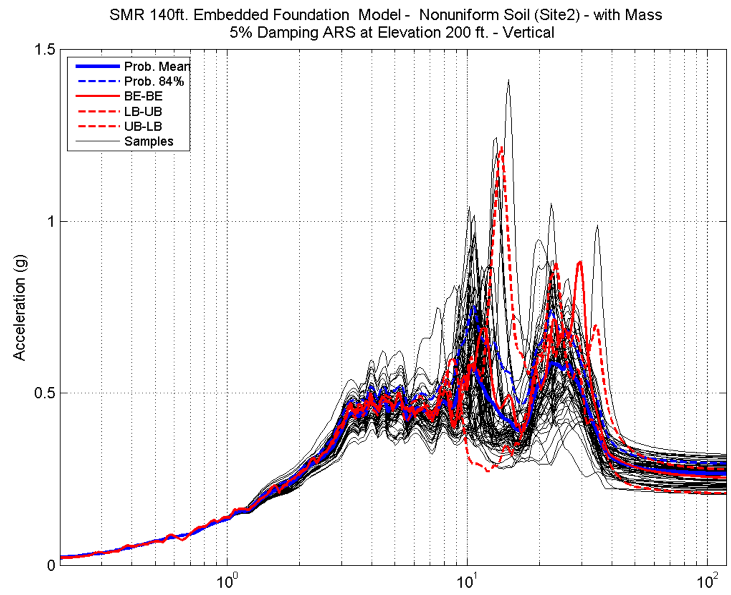


Horizontal

Vertical

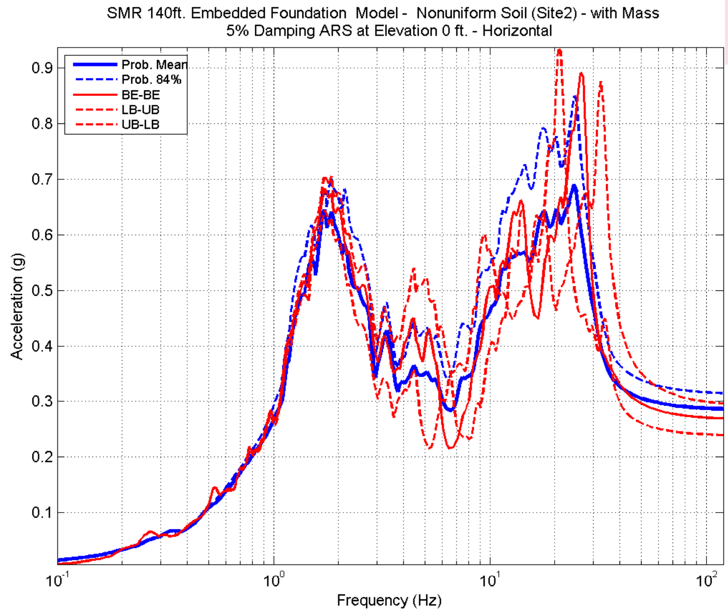
Roof

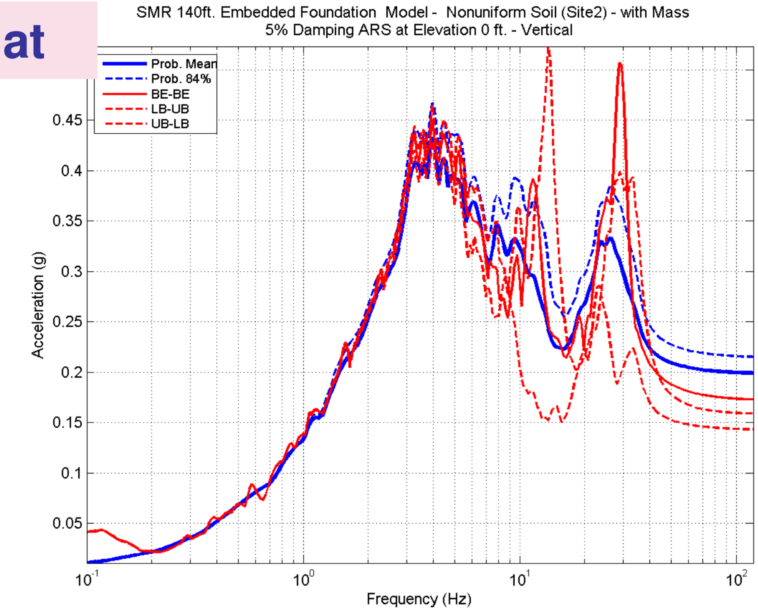




Deterministic vs. Probabilistic ISRS for 140ft Embedded Model (Site 2)

Basemat

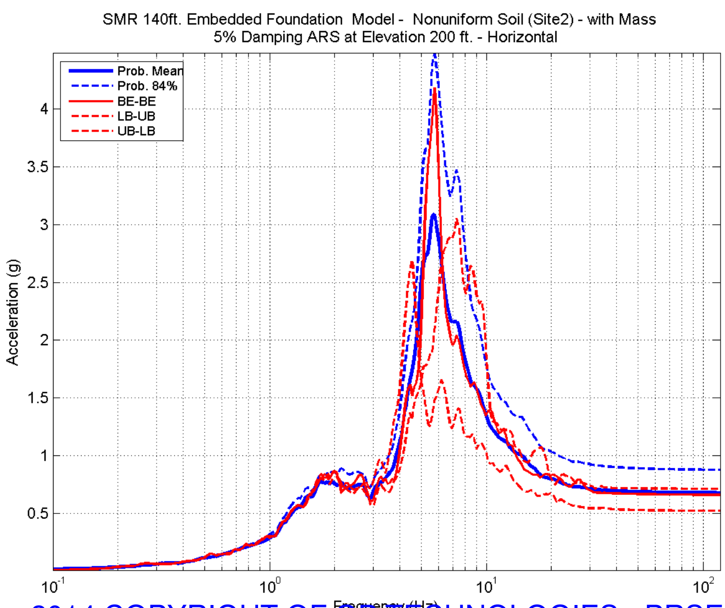


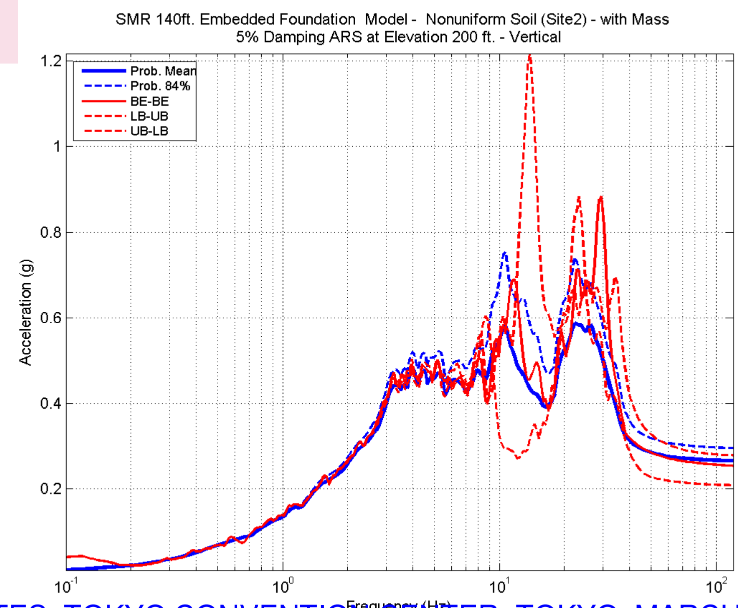


Horizontal

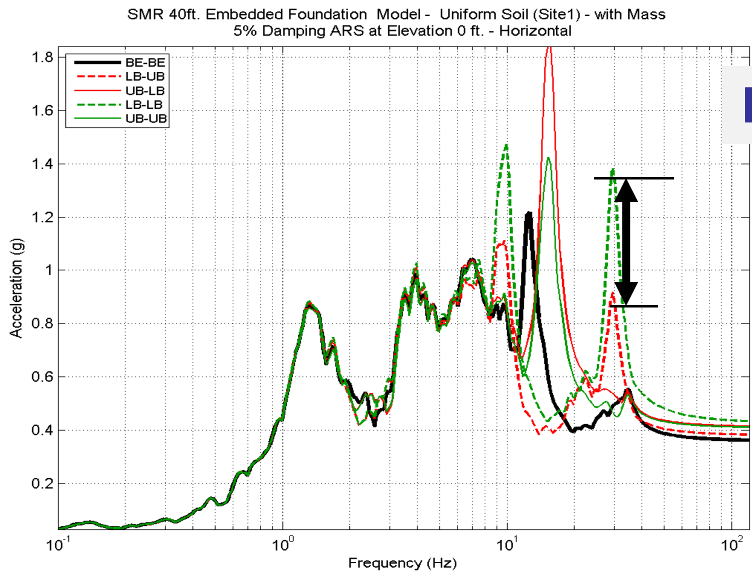
Vertical

Roof

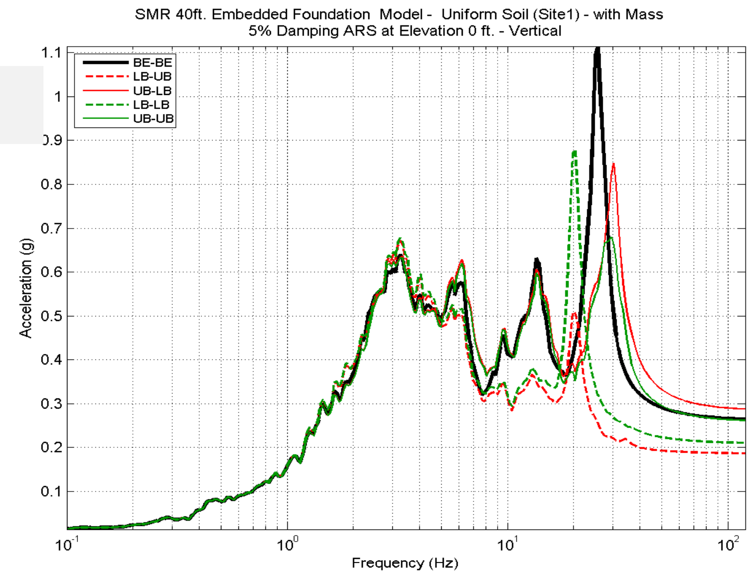




Deterministic ISRS for 40ft Embedded Model for (Site 2) LB, BE and UB Soils with Different Vs and Damping UB and LB Profile Combinations



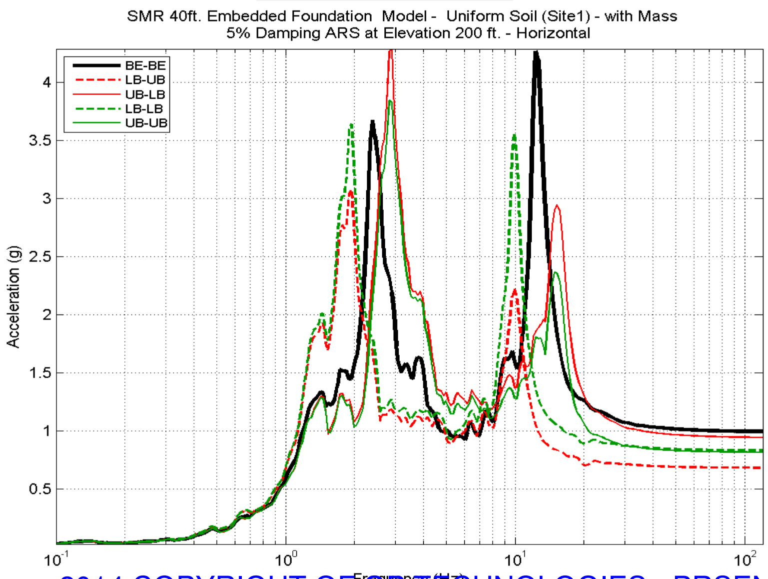
Basemat



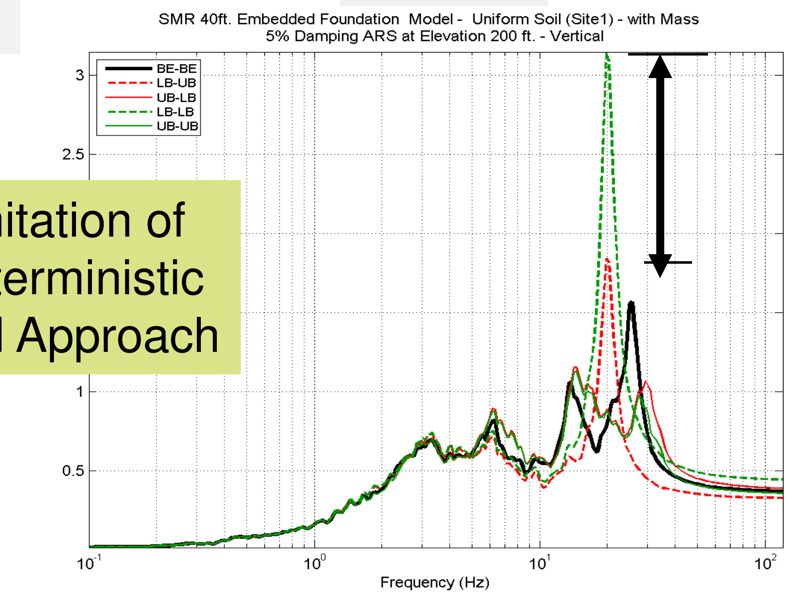
Horizontal

Roof

Vertical

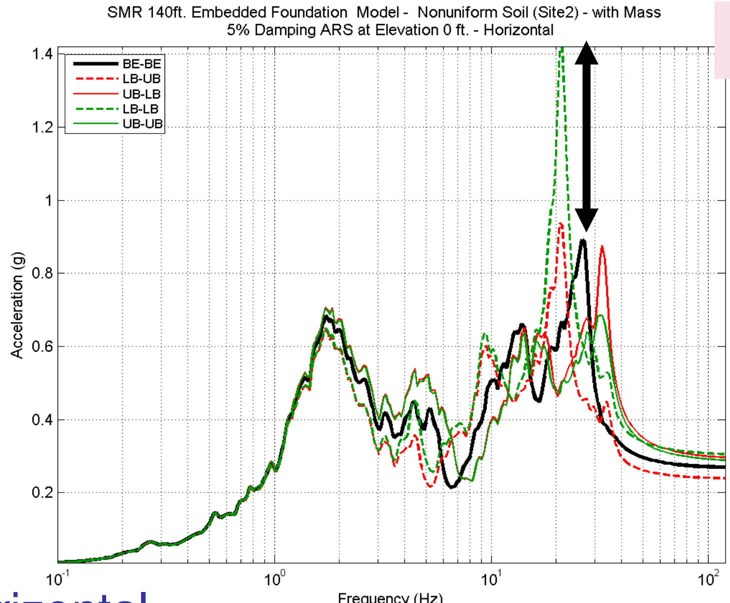


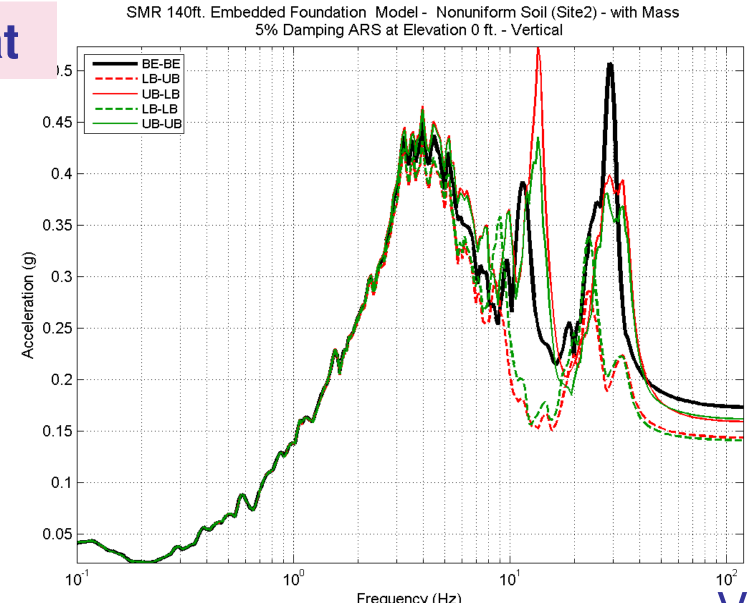
Limitation of Deterministic SSI Approach



Deterministic ISRS for 140ft Embedded Model for (Site 2) LB, BE and UB Soils with Different Vs and Damping UB and LB Profile Combinatior

Basemat

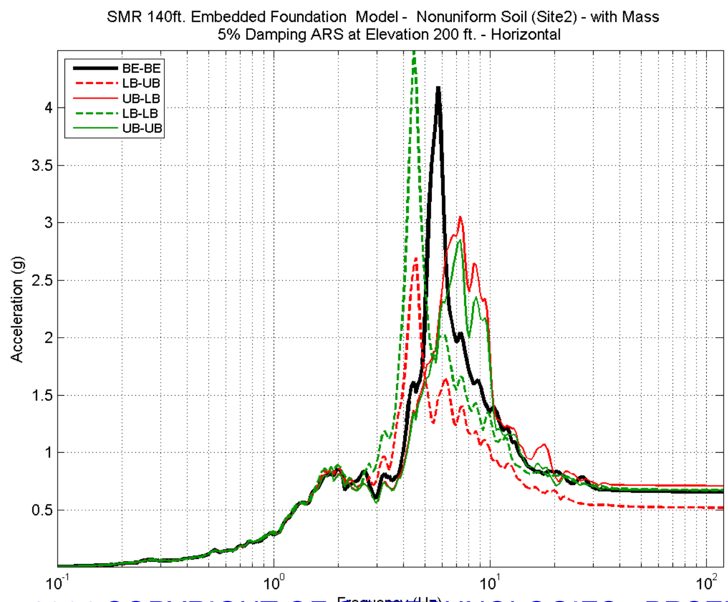


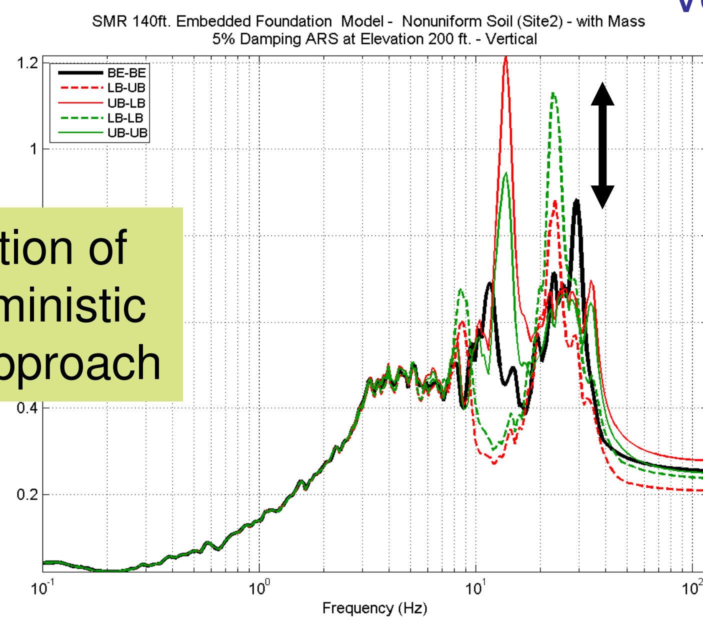


Horizontal

Vertical

Roof





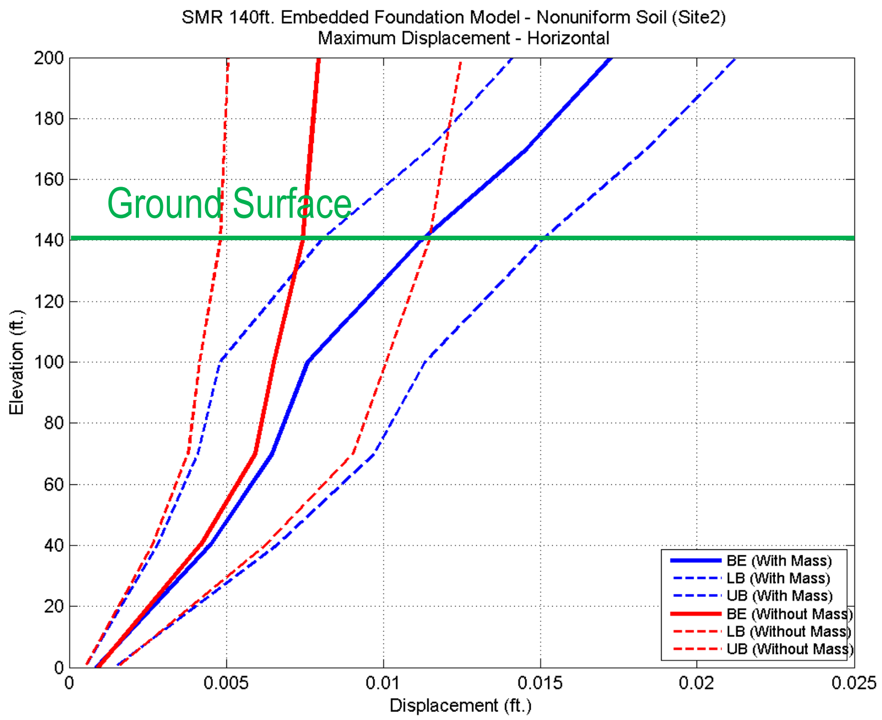
Limitation of Deterministic SSI Approach

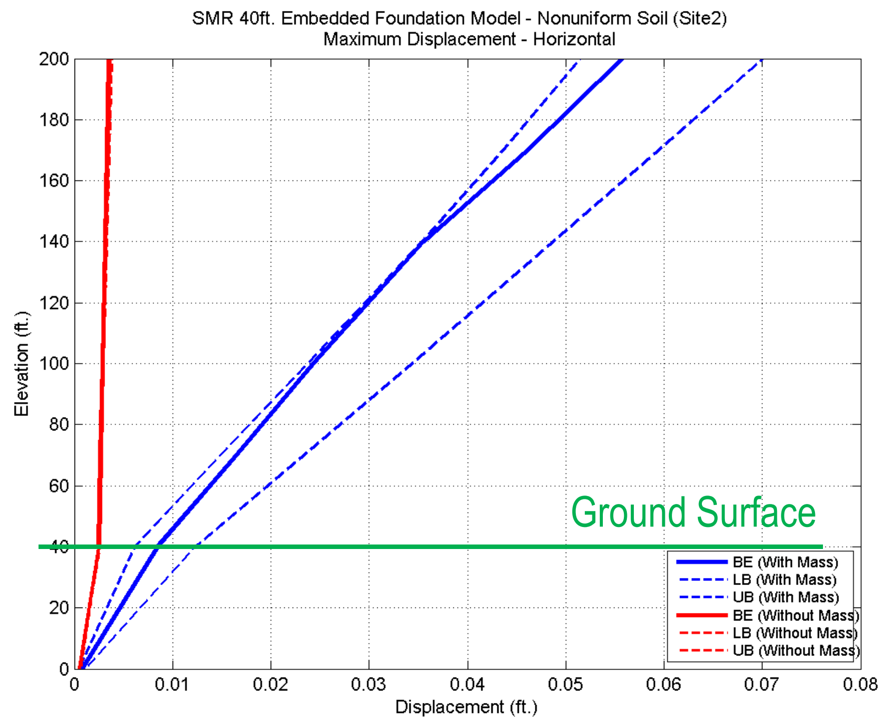
Effects of Kinematic SSI for Embedded SMRs (Site 2)

140 ft Embedment

40 ft Embedment

Displacement wrt Basemat Center





NOTE: For 140 ft embedment the kinematic SSI effects are dominant, 80-90%, up to the ground surface elevation at 140 ft.

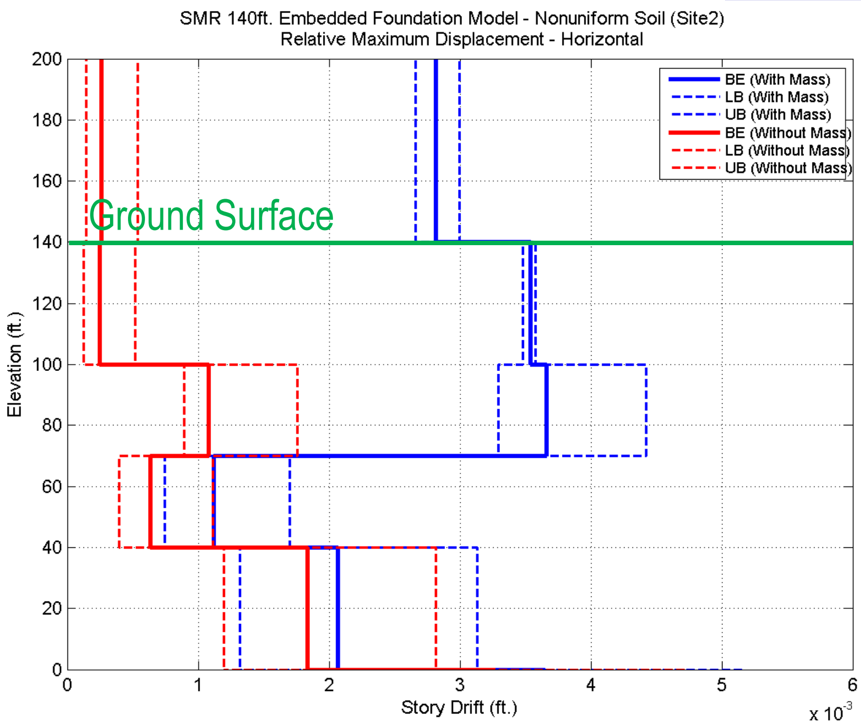
For 40 ft embedment the kinematic SSI much less significant, 20-30%, below the the ground surface elevation at 40 ft.

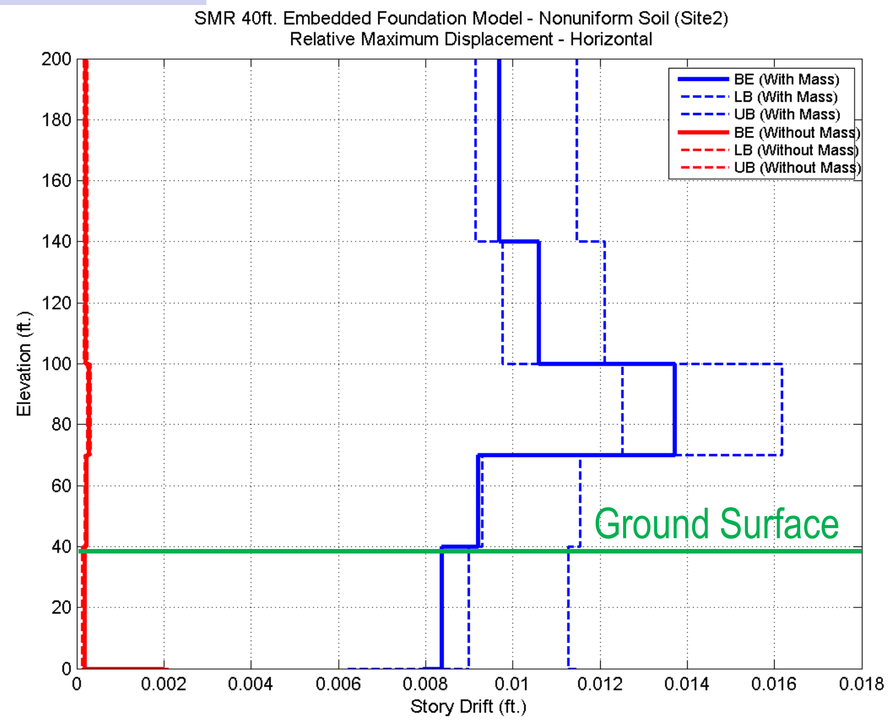
Effects of Kinematic SSI for Embedded SMRs (Site 2)

140 ft Embedment

40 ft Embedment

STORY DRIFTS





NOTE: For 140 ft embedment the kinematic SSI effects are significant, 10-90%, up to the ground surface elevation at 140 ft.

For 40 ft embedment the kinematic SSI much less significant, 1-5%, below the the ground surface elevation at 40 ft.

Concluding Remarks

The current SSI analysis requirements related to the SSI analysis appear to be reasonable for SMRs.

Probabilistic site response simulations based on convolve up procedures could produce highly non-flat FIRS (defined by the mean of outcrop motion RS at the foundation level). As a result of this the structural SSI responses are highly sensitive to the FIRS shapes.

For the SMR embedded models SSI responses produced by the soil variation bounds, UB for shear modulus combined with LB for damping (UB-LB) and LB for shear modulus combined with UB for damping (LB-UB) might not produce upper bounded ISRS.

The effects of the kinematic SSI effects in terms of relative displacements in the basement, are reduced for the 40 ft embedment SMR model, and much larger for the 140 ft embedment SMR model.

ACS SASSI V3.0 RVT SSI Analysis (Option RVT)

Applicable to compute ISRS. Implies the following steps:

Seismic Input (Define GRS)

- For a given damping value, transform GRSa input into GPSDa input (via RVT "first passage problem").

SSI Analysis Solution (compute complex ATFs):

- Compute ATF for the SSI analysis via ACS SASSI ANALYS run

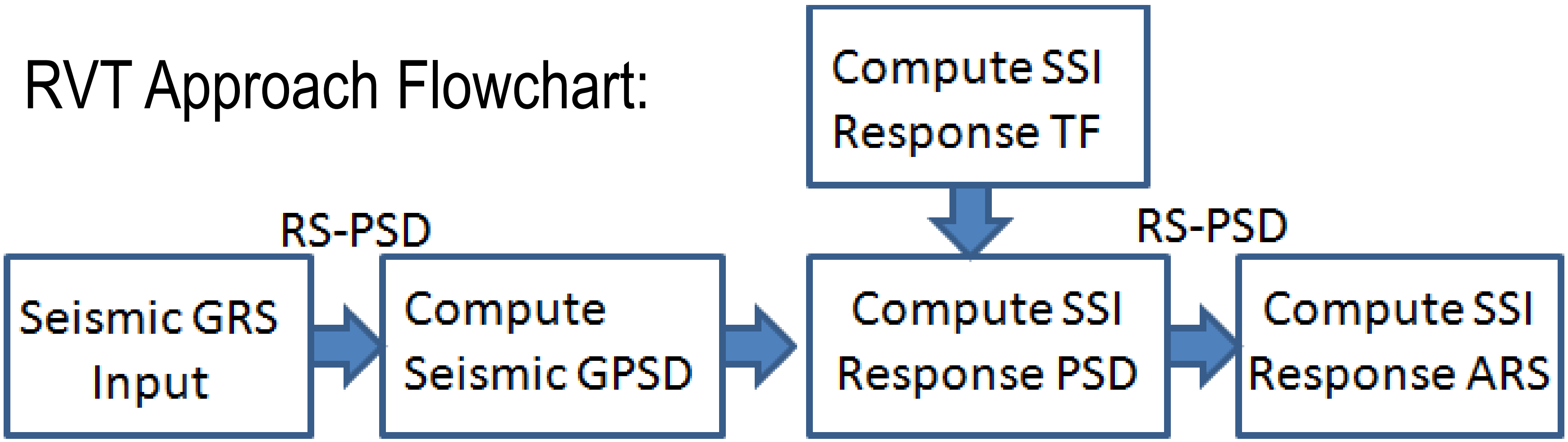
Post-Process (compute ISRS)

- Convolve ATFa with GPSDa based on RVT to compute in-structure PSD (ISPSD). Then, transform ISPSD in ISRS for a given damping value.

NOTE: Not applicable to other SSI responses than ISRS at this time.

RVT Approach for Seismic SSI Analysis

RVT Approach Flowchart:



SDOF Transfer Functions:

$$H_0(\omega) = \frac{\omega_0^2 + 2i\omega_0\xi_0\omega}{\left(\omega_0^2 - \omega^2\right) + 2i\omega_0\xi_0}$$

Absolute Accelerations (ARS-APSD)

$$H_0(\omega) = \frac{\omega}{\left(\omega_0^2 - \omega^2\right) + 2i\omega_0\xi_0}$$

Relative Velocities (VRS-VPSD)

$$H_0(\omega) = \frac{1}{\left(\omega_0^2 - \omega^2\right) + 2i\omega_0\xi_0}$$

Relative Displacements (DRS-RPSD)

RVT Approach for SSI Analysis (Only Seismic Input)

The RVT based approach uses frequency domain convolution computations (no need to use time-histories) assuming a Gaussian seismic input:

$$S_X(\omega) = \left|H(\omega)\right|^2 \left|H_0(\omega)\right|^2 S_u(\omega)$$

Response SSI SDOF Input

The RVT-based approaches include several options related to the *PSD-RS transformation*. These options are related to the stochastic approximation models used for computing the maximum SSI response overt a time period T, i.e. during the earthquake intense motion time interval.

The maximum SSI response can be expressed by using peak factors that are applied to the stochastic motion standard deviation (RMS). These quantities depend on the duration T, the mean crossing rate of the motion and probability level associated to the maximum response (“first passage problem”).

Computation of Maximum SSI Response (RS)

$$\bar{X}_{\max} = p\,\sigma_X$$
$$\sigma_{X_{\max}} = q\,\sigma_X$$

1) M Kaul-Unruh-Kana stochastic model (MK-UK) (1978, 1981) :

$$p = \left[-2\ln\left(-\left(\frac{\pi}{T}\right)\left(\frac{\sigma_X}{\sigma_{\dot{X}}}\right)\ln(P)\right)\right]^{1/2}$$

Please note that this *p* is not the mean peak factor, since it provides maximum peak factor for any given NEP P

2) A Davenport (AD) (1964) for p and Der Kiureghian (1980) for q

$$p = \sqrt{2\ln(\nu_0 T)} + \frac{0.5772}{\sqrt{2\ln(\nu_0 T)}} \qquad q = \frac{1.2}{\sqrt{2\ln(\nu_0 T)}} - \frac{5.4}{\left[13 + \left(2\ln(\nu_0 T)\right)^{3.2}\right]}$$

3) A Davenport Modified by Der Kiureghian (AD-DK) (1981,1983)

$$\nu_e T = \begin{cases} \max\left(2.1, 2\delta\nu_0 T\right) & ;0 < \delta \le 0.1 \\ \left(1.63\delta^{0.45} - 0.38\right)\nu_0 T & ;0.1 < \delta < 0.69 \\ \nu_0 T & ;0.69 \le \delta < 1 \end{cases} \qquad \delta = \sqrt{1 - \frac{\lambda_1^2}{\lambda_0 \lambda_2}}$$

Warning Remarks on RVT Approach

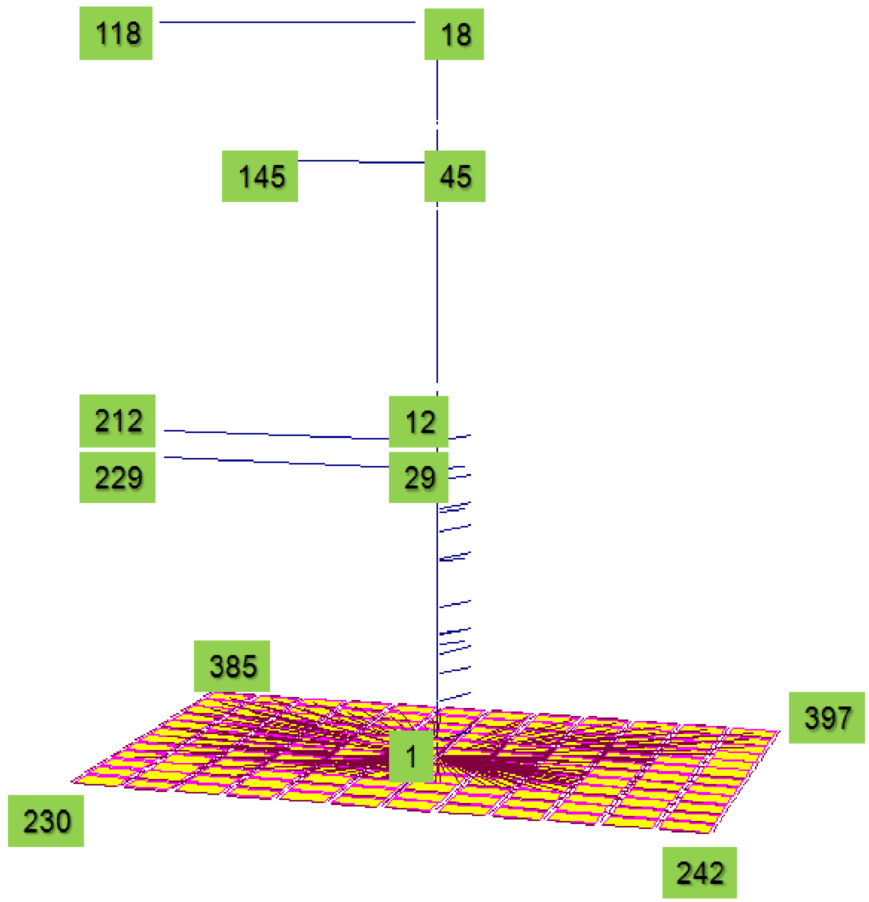
1) It is based on the assumption that the seismic ground motion is a Gaussian stationary stochastic process.

This assumption might not be true if highly non-Gaussian “seed” records are used to generate the design-basis input time histories. Unfortunately, some recent publications show inconsistent results by comparing the RVT-based approach ISRS results with time-domain statistical ISRS results for highly non-Gaussian seismic input histories. If the Gaussianity modeling aspect is ignored, the RVT-based approach application becomes quite arbitrary, with results based on a case-by-case luck, and without a sound theoretical basis.

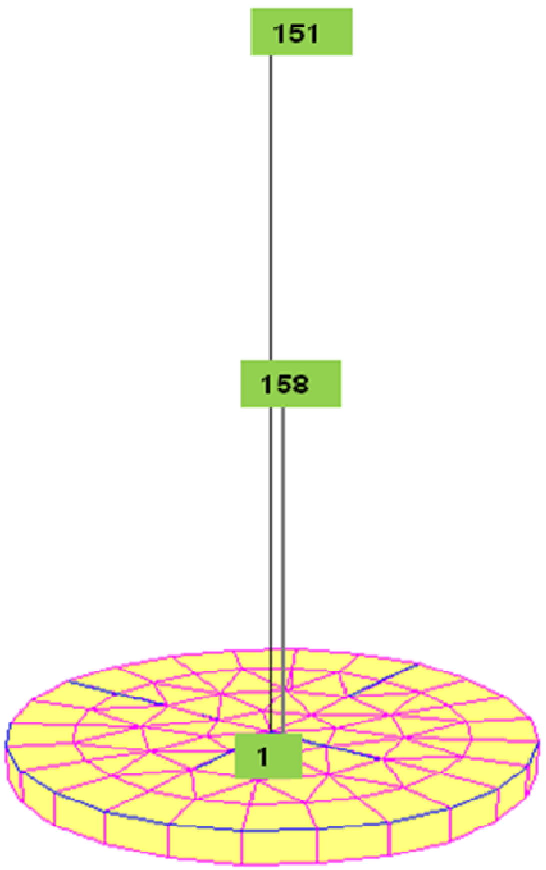
2) The ASCE 04-2013 referenced RVT approaches do not include the cross-correlations between the SSI response motions at different locations. Innaplicable to mutiple support time domain analysis of piping systems.

Case Studies: 1) EPRI AP1000 NI & 2) PWR RB Sticks

EPRI AP1000 NI Stick Model

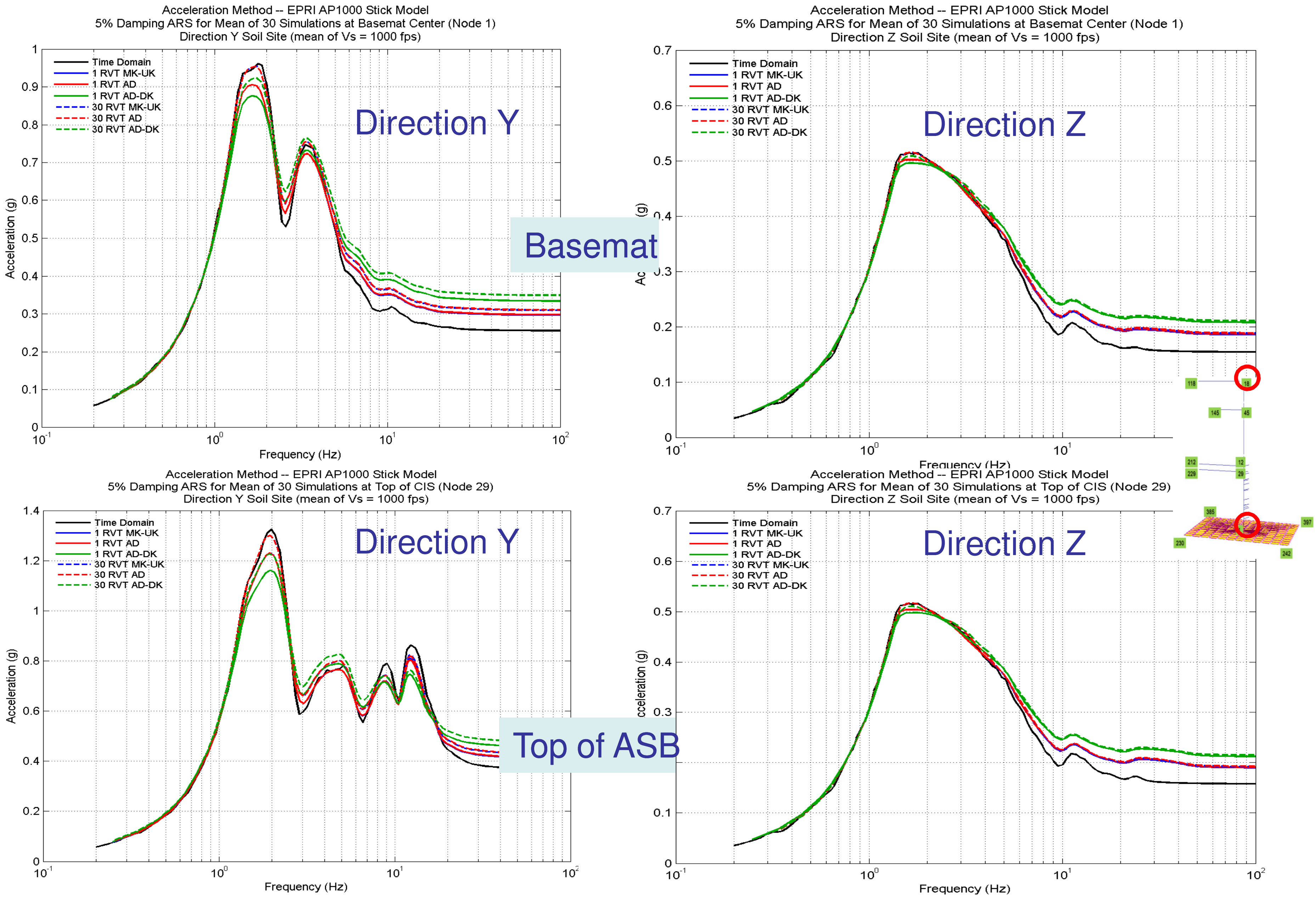


PWR RB Stick Model

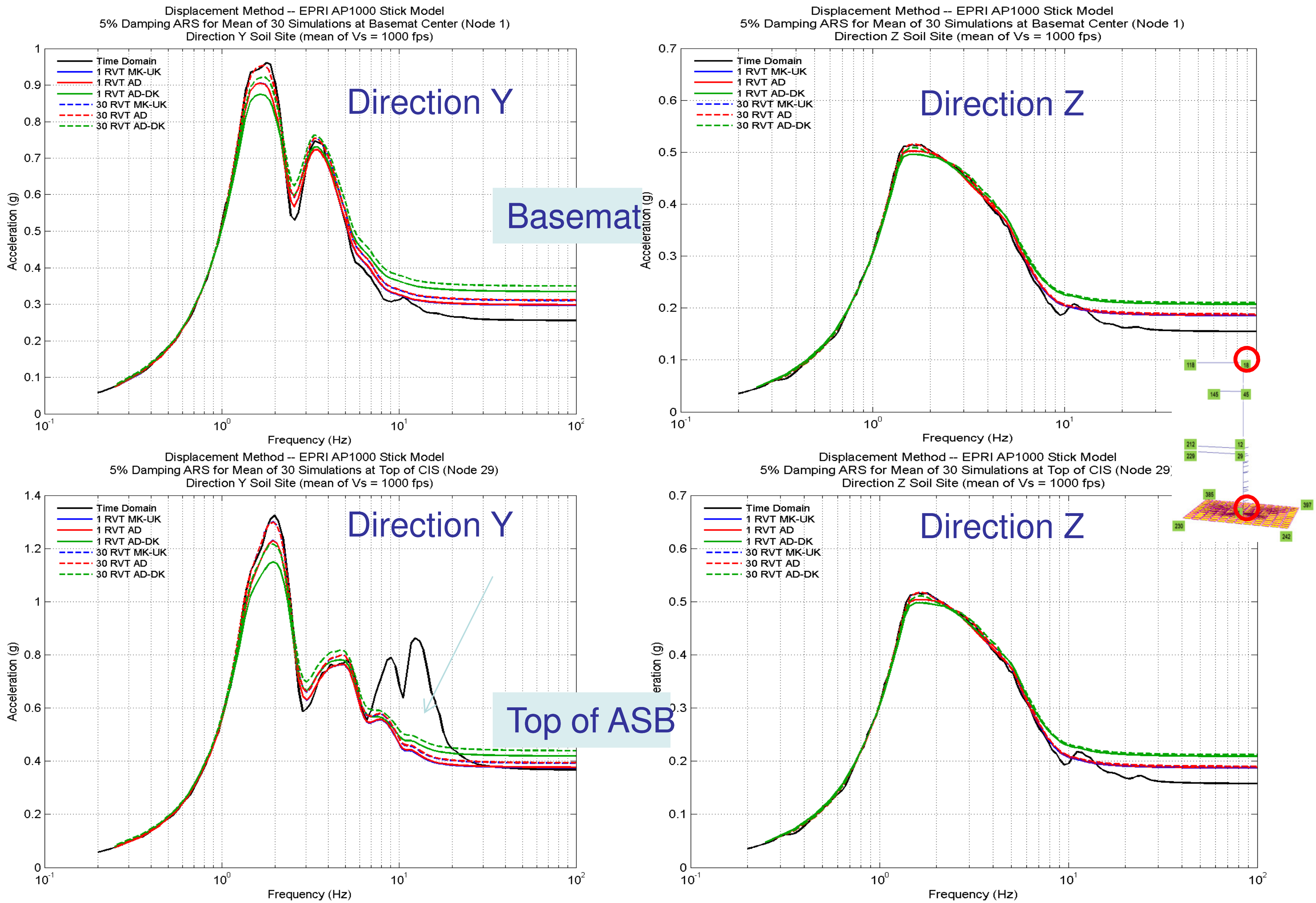


Case 1: Soil Site (BE Soil and Random Soil), Vs = 1,000 fps
Case 2: Rock Site (BE Soil and Random Soil), Vs = 6,000 fps

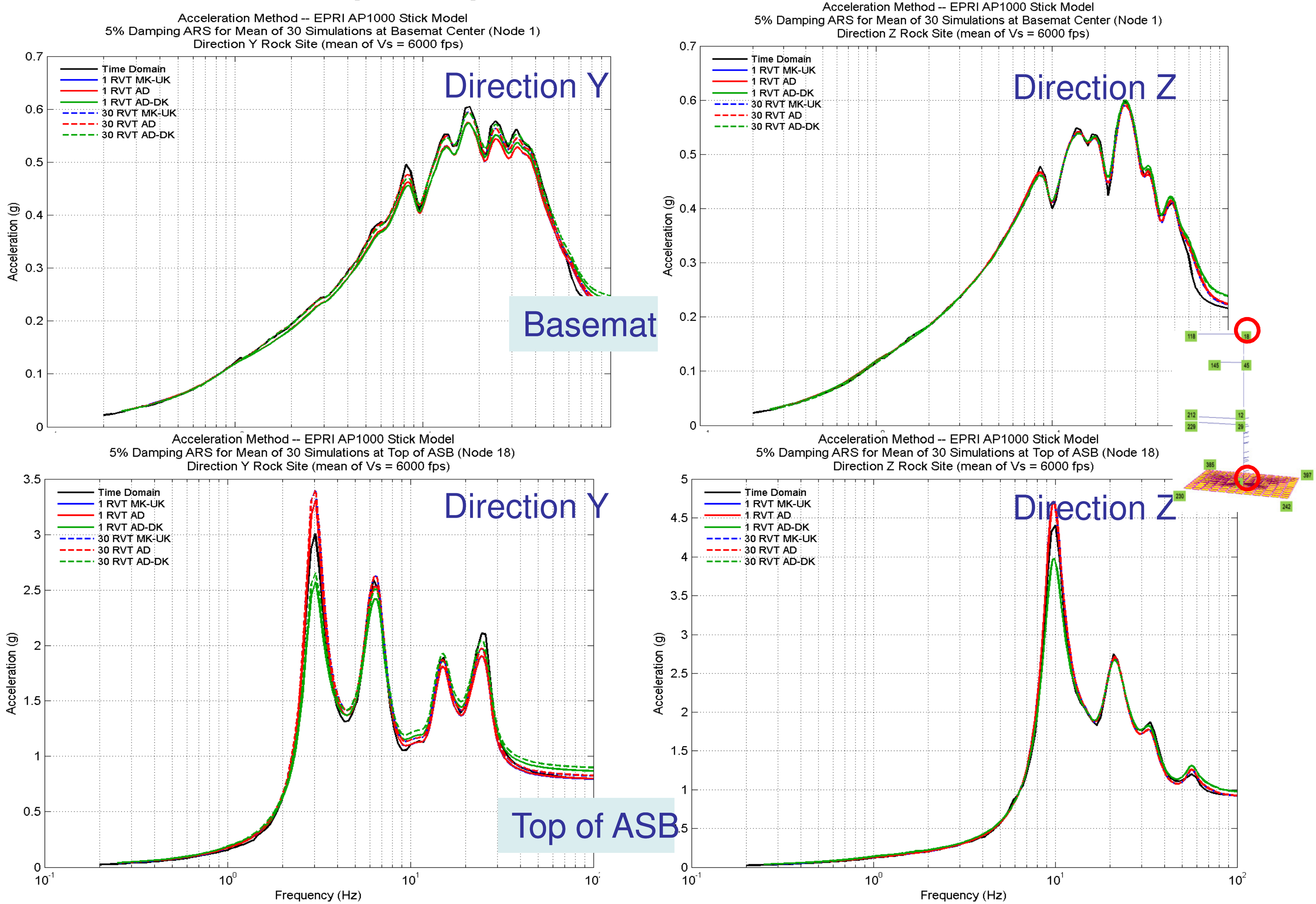
RVT Approach (ACC) vs. LHS for BE Soil – Mean ISRS



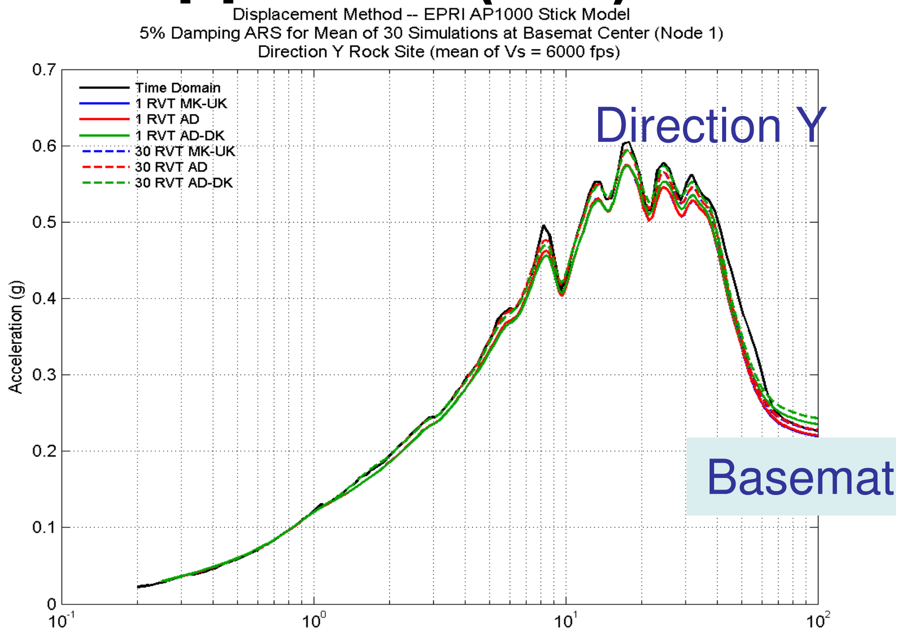
RVT Approach (DIS) vs. LHS for BE Soil – Mean ISRS

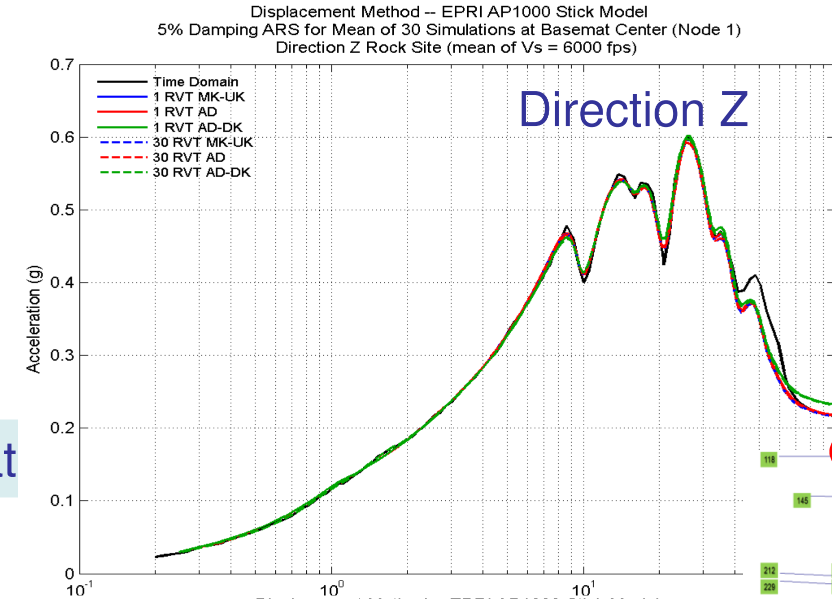


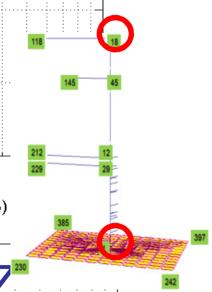
RVT Approach (ACC) vs. LHS for BE Rock – Mean ISRS

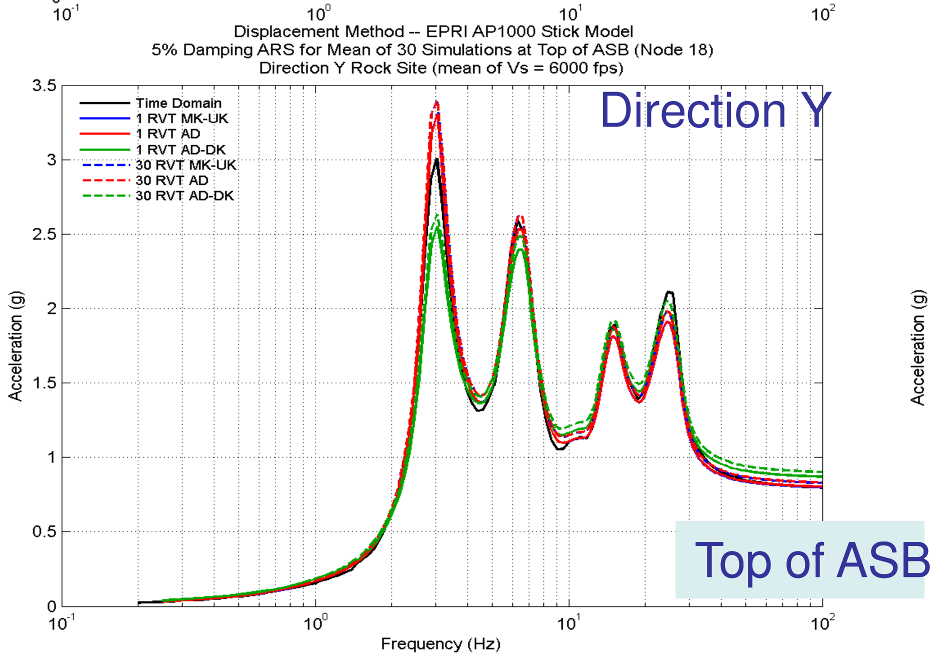


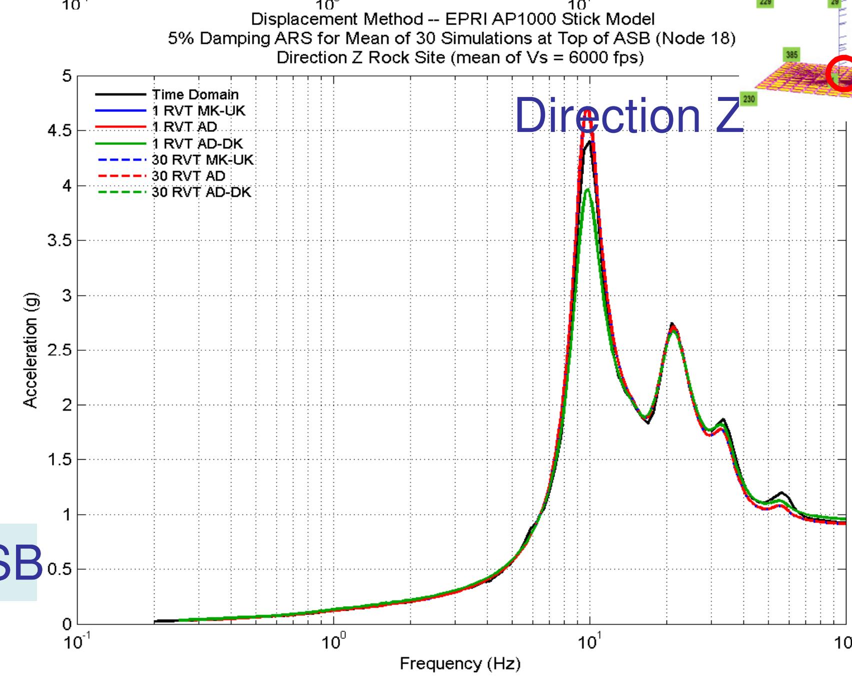
RVT Approach (DIS) vs. LHS for BE Rock – Mean ISRS



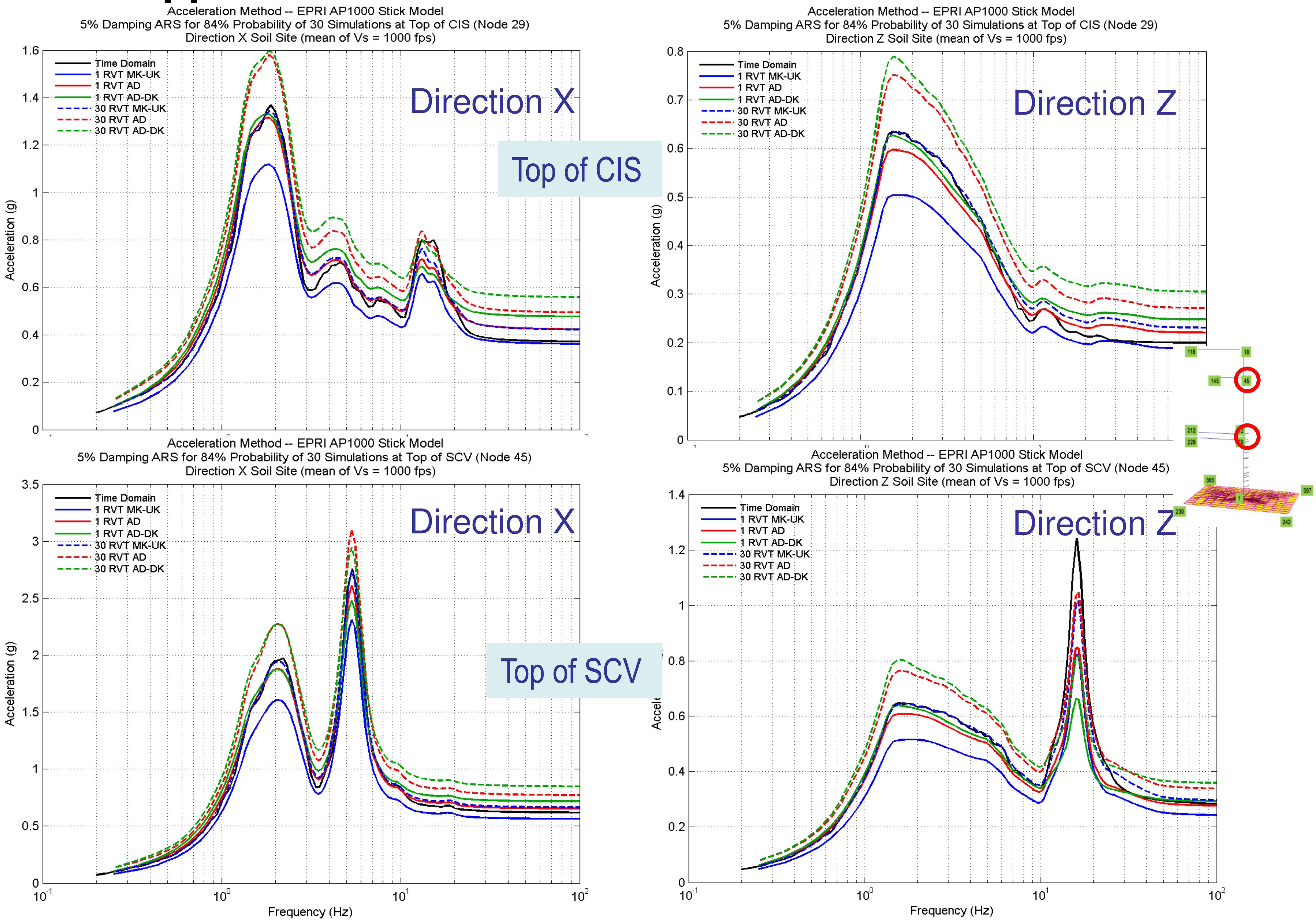




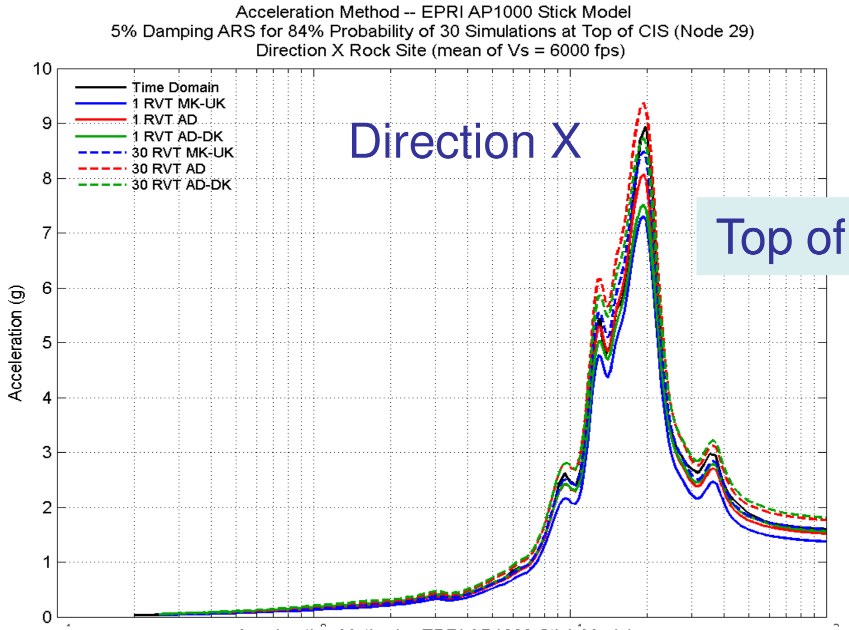


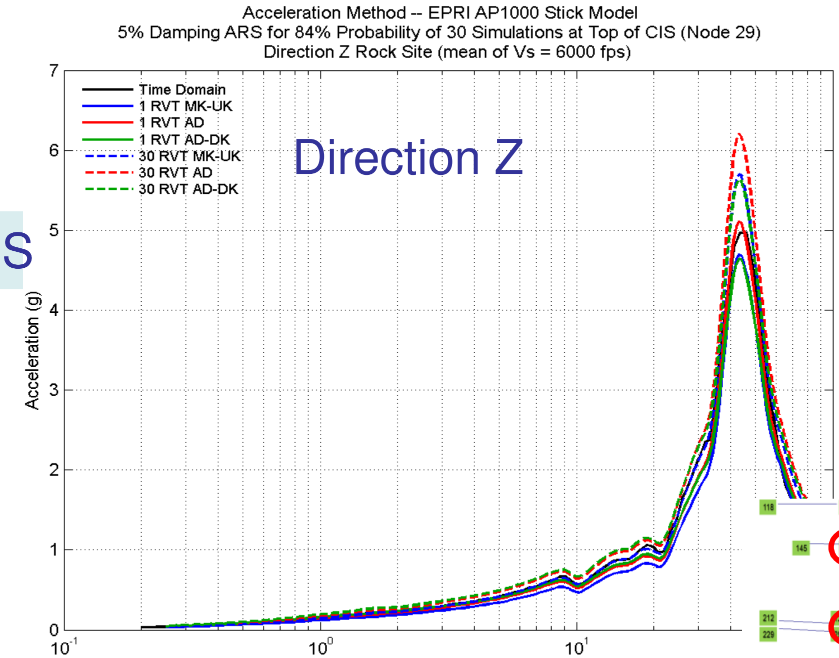


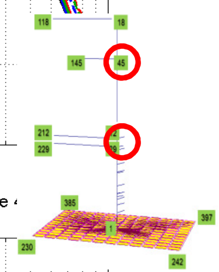
RVT Approach vs. LHS Results for BE Soil – 84% NEP ISRS

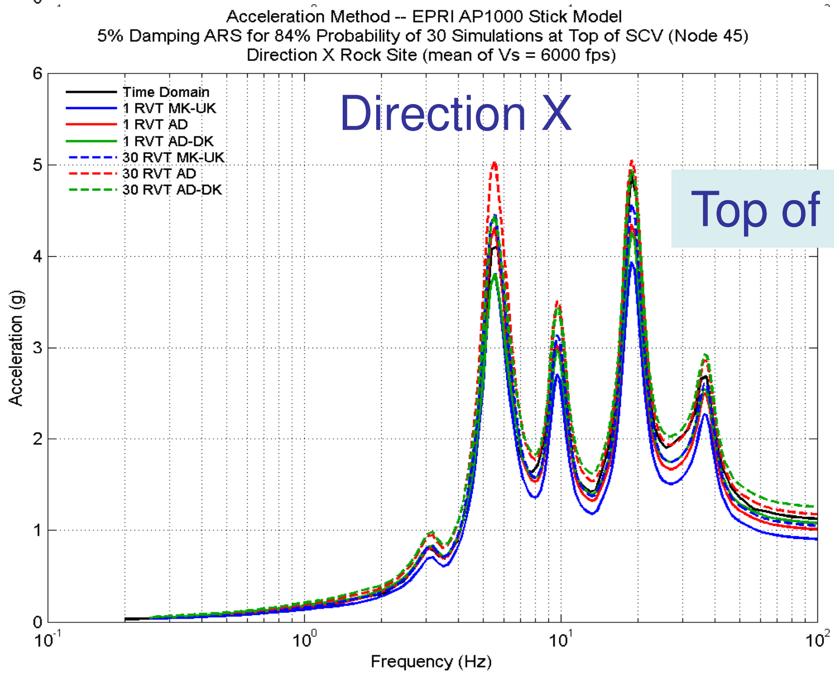


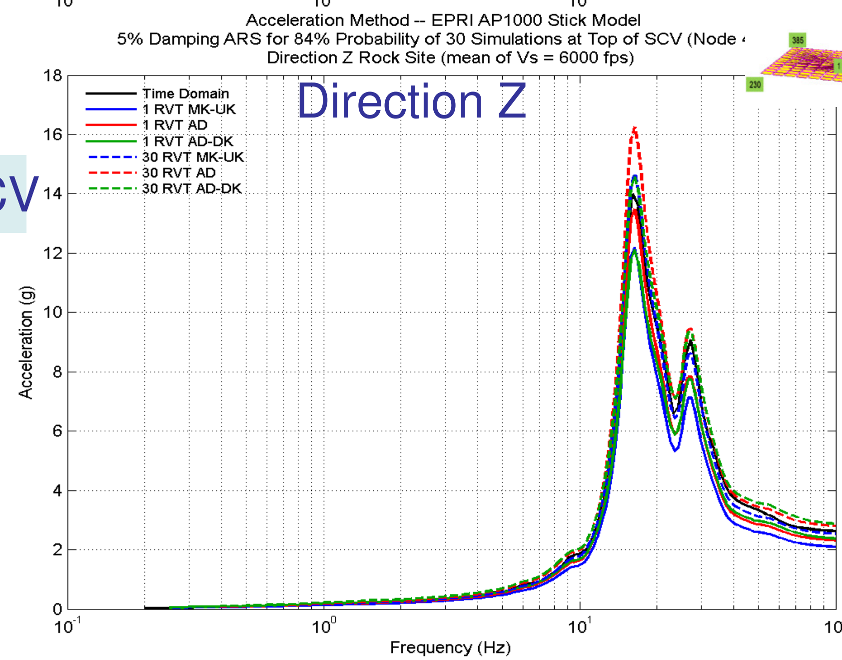
RVT Approach vs. LHS Results for BE Rock – 84% NEP ISRS



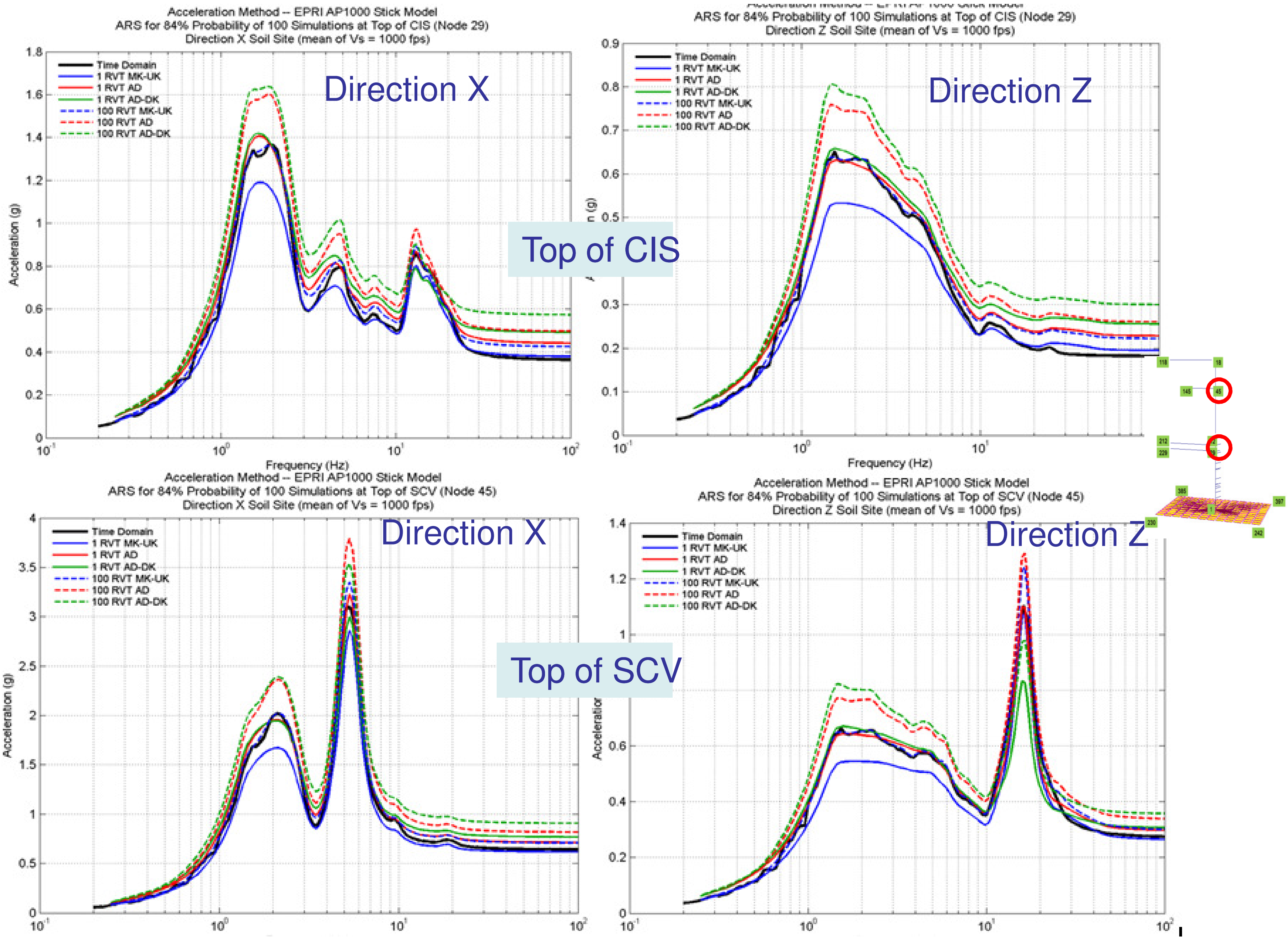




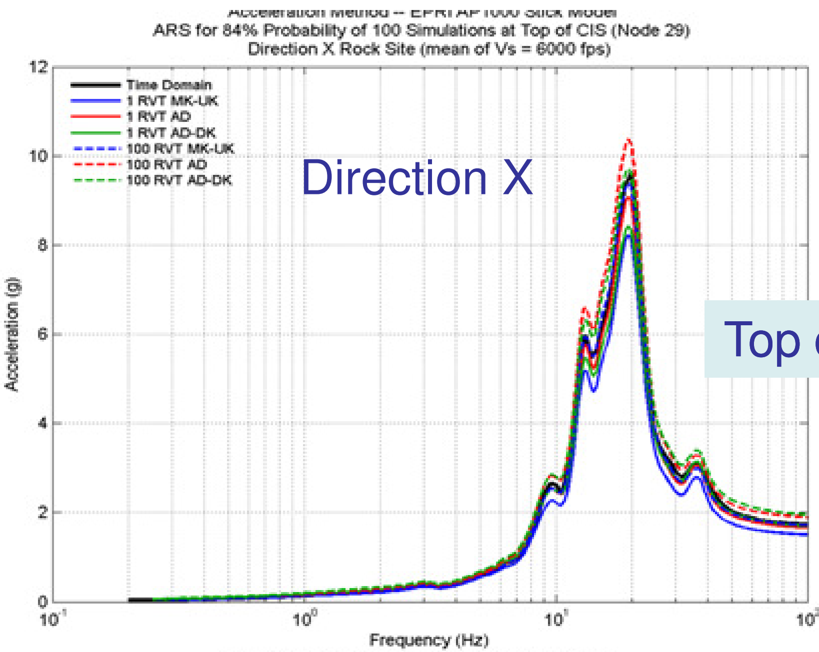


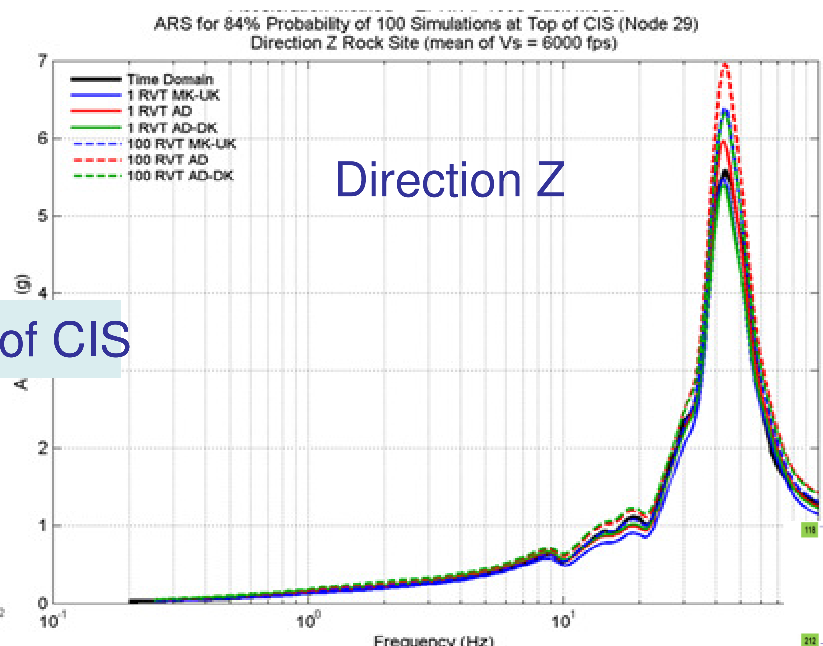


RVT vs. LHS Results for Random Soil – 84% NEP ISRS

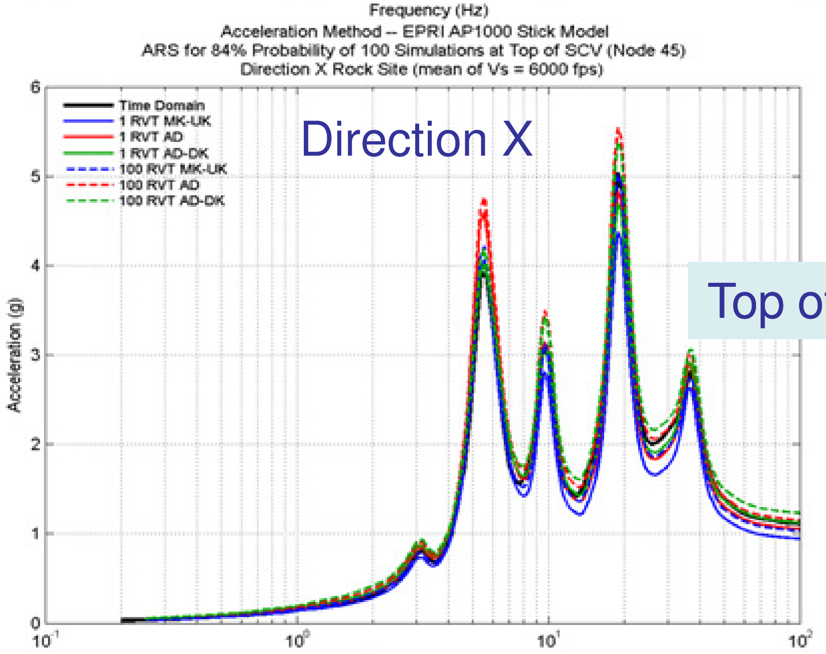


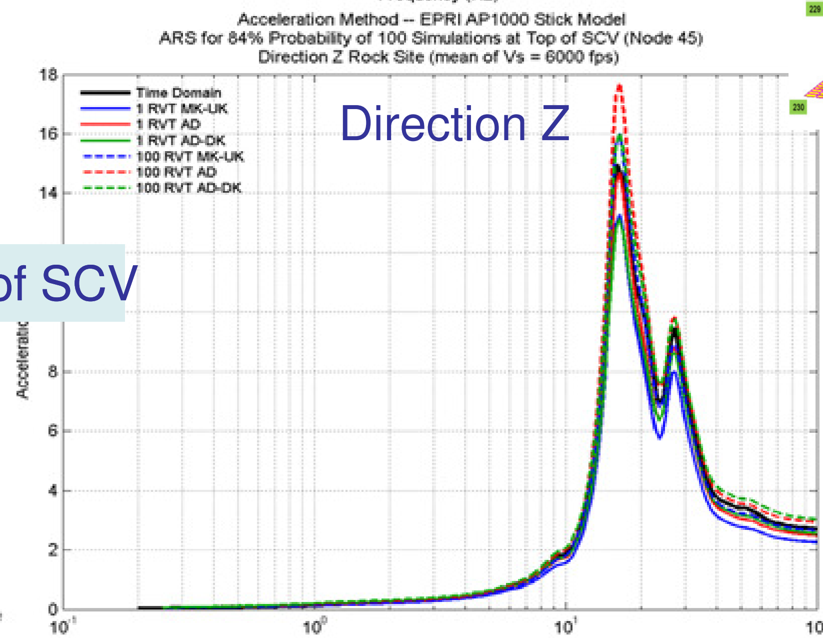
RVT vs. LHS Results for Random Rock – 84% NEP ISRS



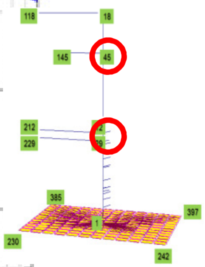


Top of CIS





Top of SCV



Concluding Remarks

- The LHS approach is the reference method for “Probabilistic SSI Analysis” that is recommended by the ASCE 04-2013 standard. LSH is much faster than MCS (30 LHS samples vs. 200 MCS samples). It is accurate and robust.

- The RVT approach can provide reasonably accurate results, if appropriately used. Unfortunately, there are no engineering guidelines by EPRI, ASCE or NRC on which method is most accurate, and what is the impact on accuracy, if other methods are used.
  - The accuracy RVT results varies significantly from method to method (MK-UK, AD and AD-DK). The RVT results variability is more drastically for the soil sites than for the rock sites as shown in the paper.
  - For non-Gaussian seismic inputs (could occur when “seed” records are used), the RVT approach could become arbitrary, potentially inaccurate. The RVT approach is expected to provide reasonably accurate results for Gaussian inputs, but not for non-Gaussian.
  - Based on limited investigations, the MK-UK100 appears to out outperform the other methods in terms of accuracy. AD1 appears to be reasonable accurate and robust. Carefulness is need when using other RVT methods, and displacement-based approach.

- The SROM approach is an efficient and accurate approach that has open future for fast probabilistic FEA analysis, including both linear and nonlinear analyses with complex FEA SSI models.

ACS SASSI Version 3.0 Two-Step SSI Analysis Using ANSYS Interfacing (Options A and AA)

Two engineering analysis option in ACS SASSI:

i) *One step analysis using ACS SASSI* for computing overall SSI responses motions, including ISRS, maximum accelerations and relative displacements within the structure, and structural forces and stresses (Option AA)

ii) *Two step analysis using ACS SASSI in 1st step and ANSYS in 2nd step* for computing forces and stresses in structure using a more refined structural FEA modeling via ANSYS. The 1st step is the overall SSI analysis that is identical with the analysis above mentioned at item i). The 2nd step uses SSI responses as input BCs. The 2nd step consists in an equivalent (quasi)static stress analysis using a much more refined FE mesh structural model (via ANSYS static analysis). The 2nd step can be also a ANSYS transient analysis (no soil need to included in ANSYS model). (Option A)

The ACS SASSI-ANSYS interface is extremely efficient, very easy to use.

ACS SASSI Version 3.0 Advanced ANSYS Integration (Option AA, in addition to Option A)

Two ANSYS interfacing options available:

1) **Option A or ANSYS** (updated for ANSYS V13-V14)
Perform ANSYS FEA based on ACS SASSI SSI analysis results (support motions and seismic forces) . Consider basemat flexibility. Nonlinear aspects, as plasticity, uplift, sliding, gaps can be included in ANSYS second step.

2) **Option AA or Advanced ANSYS** (new for ANSYS V13-V14)
Perform ACS SASSI SSI analysis using the ANSYS structural FE matrices (K,M and C)

OPTION A: ACS SASSI-ANSYS Interface for SSI Analysis Using ANSYS Models

ACS SASSI-ANSYS interfacing provides useful analysis capabilities:

For *structural stress analysis*:

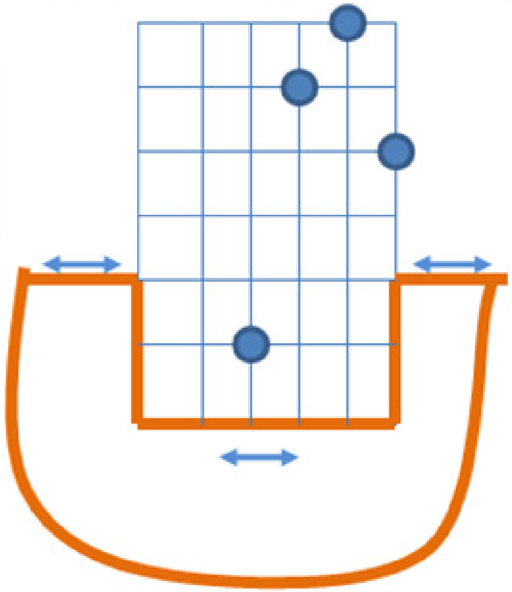
- *ANSYS Equivalent-Static Seismic SSI Analysis* Using Refined FE Models (including refined mesh, element types including local nonlinearities, nonlinear materials, contact elements, etc.)
- *ANSYS Dynamic Seismic SSI Analysis* Using More Refined FE Models (including refined mesh, element types including local nonlinearities, nonlinear materials, contact elements, etc.)

For *soil pressure computation (approximate):*

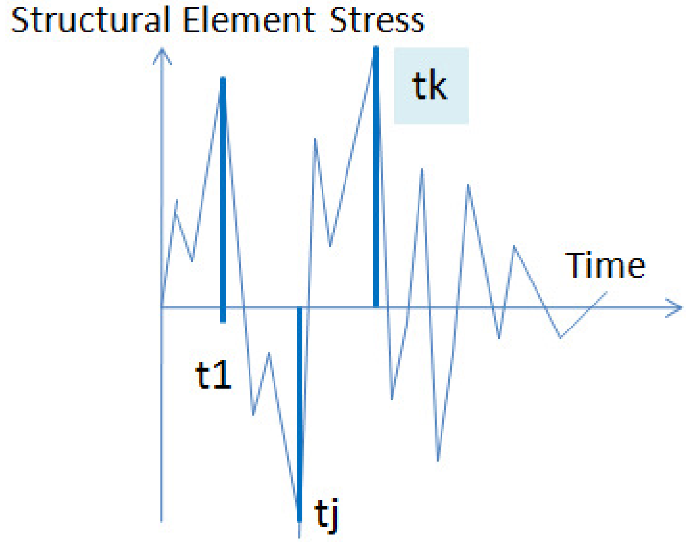
- *ANSYS Equivalent-Static Seismic Soil Pressure Computation* including Soil-Foundation Separation Effects

ACS SASSI Seismic SSI Analysis

Computing Structural Stress/Forces

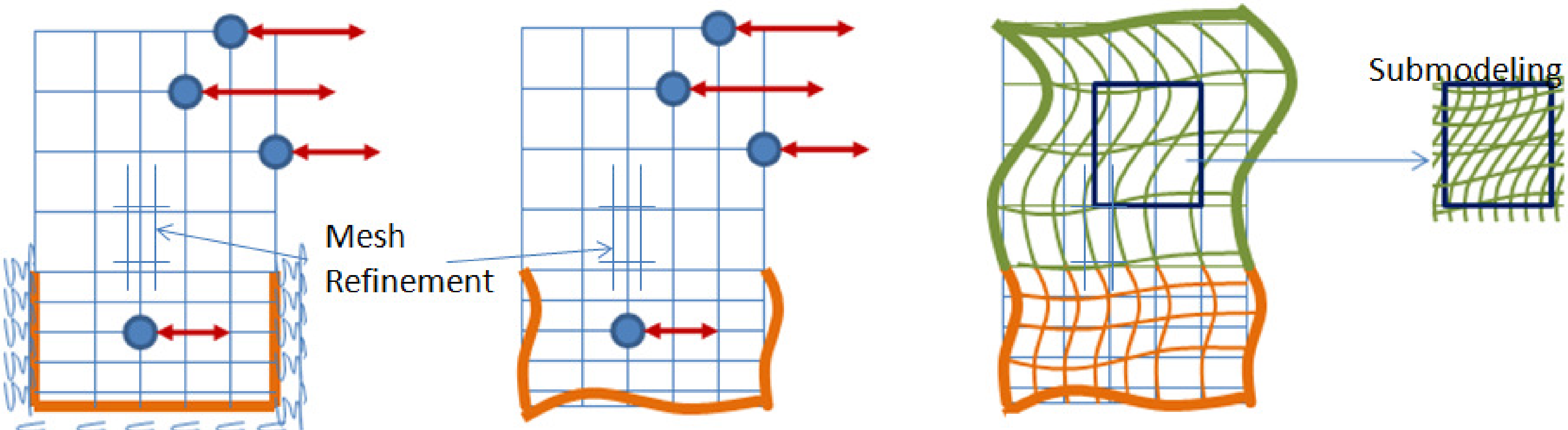


Selected Critical Time Steps for Maximum Stresses
To be Used for Equivalent Static Structural Analysis



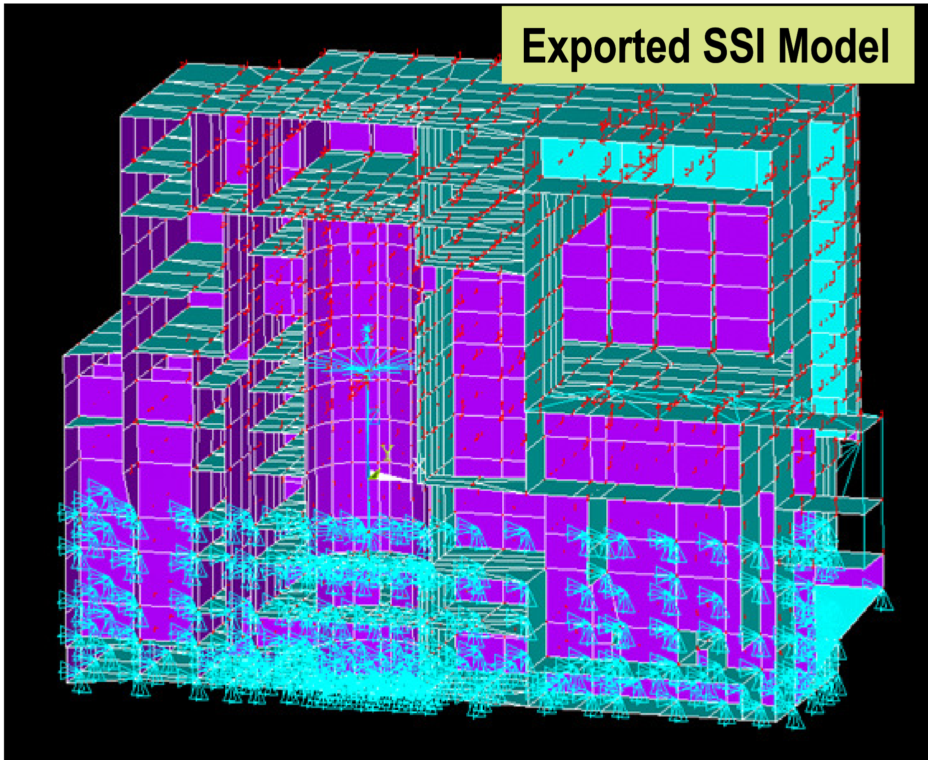
SSI Solution Time Frames As Equivalent Static Structural Loading at Critical Time Steps

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



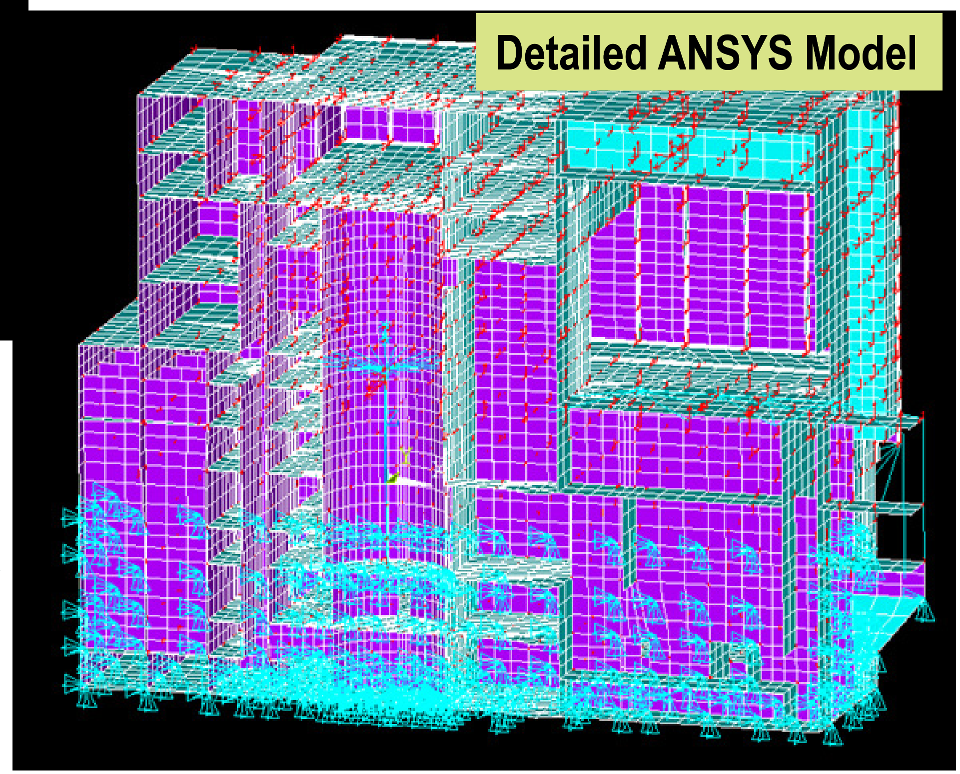
Variable Accuracy C-by-C | "Exact" | "Exact"

ACS SASSI – ANSYS Interface for Refined Seismic Stress Analysis

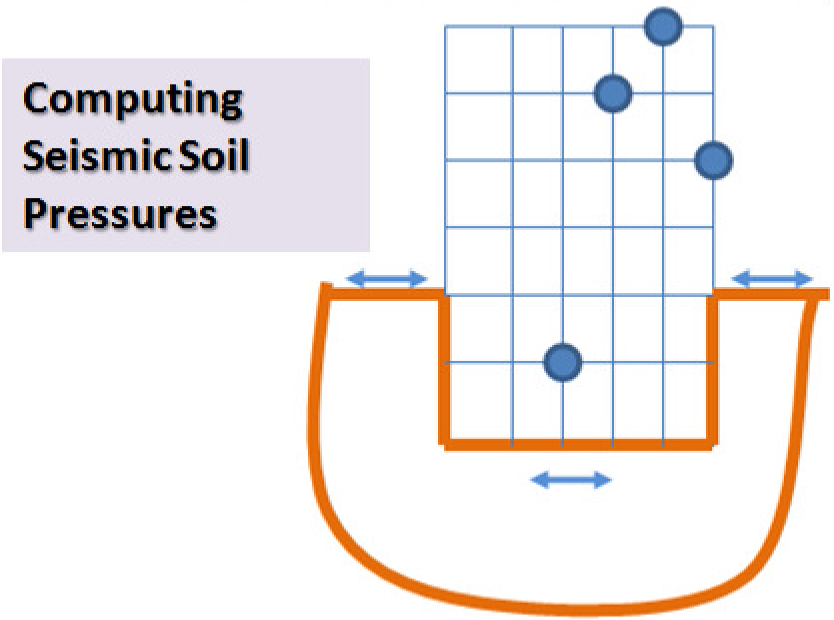


ANSYS Structural Model Automatically Converted From ACS SASSI Using PREP Module

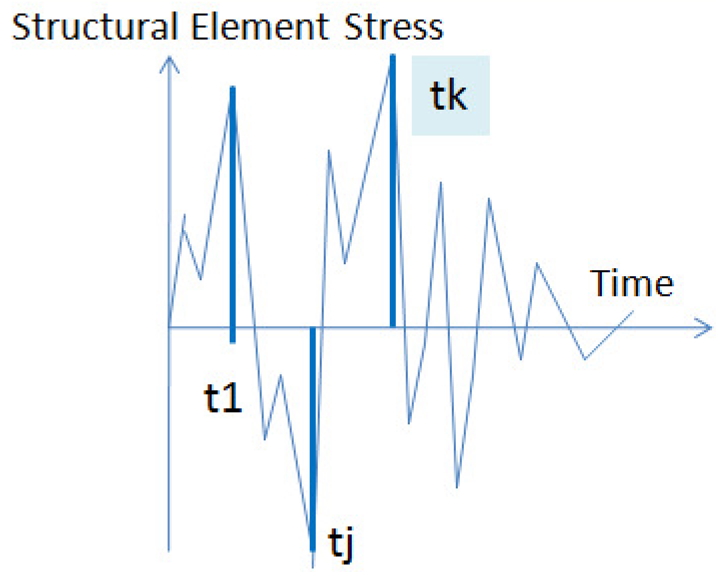
ANSYS Refined Structural Model Using EREFINE command or ANSYS GUI (rank 1-6)



ACS SASSI Seismic SSI Analysis

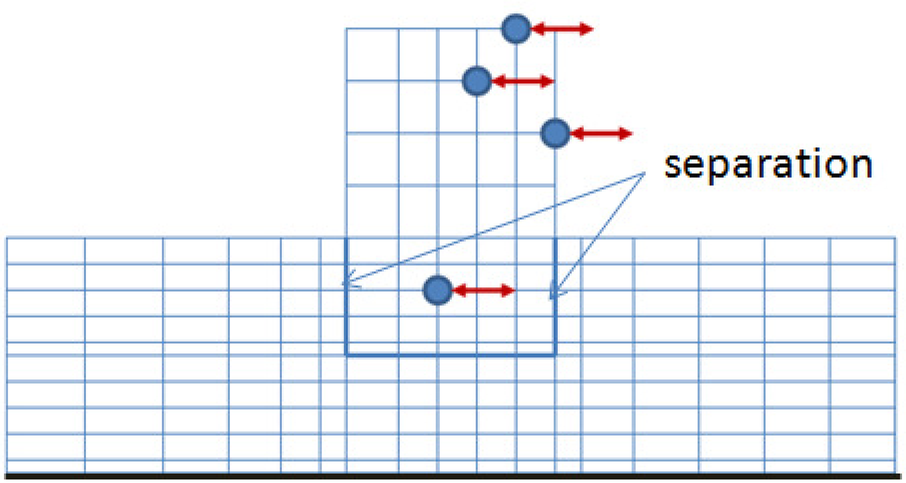


Selected Critical Time Steps for Maximum Stresses
To be Used for Equivalent Static Structural Analysis

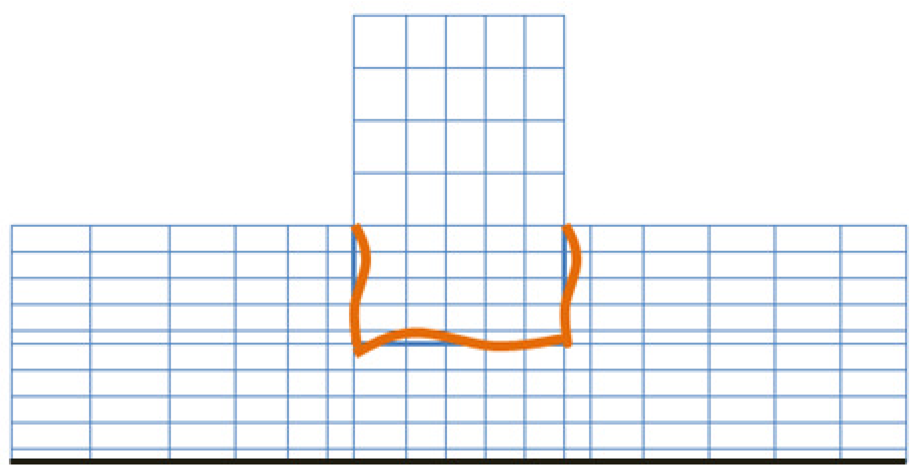


SSI Solution Time Frames As Equivalent Static Loading at Critical Time Steps

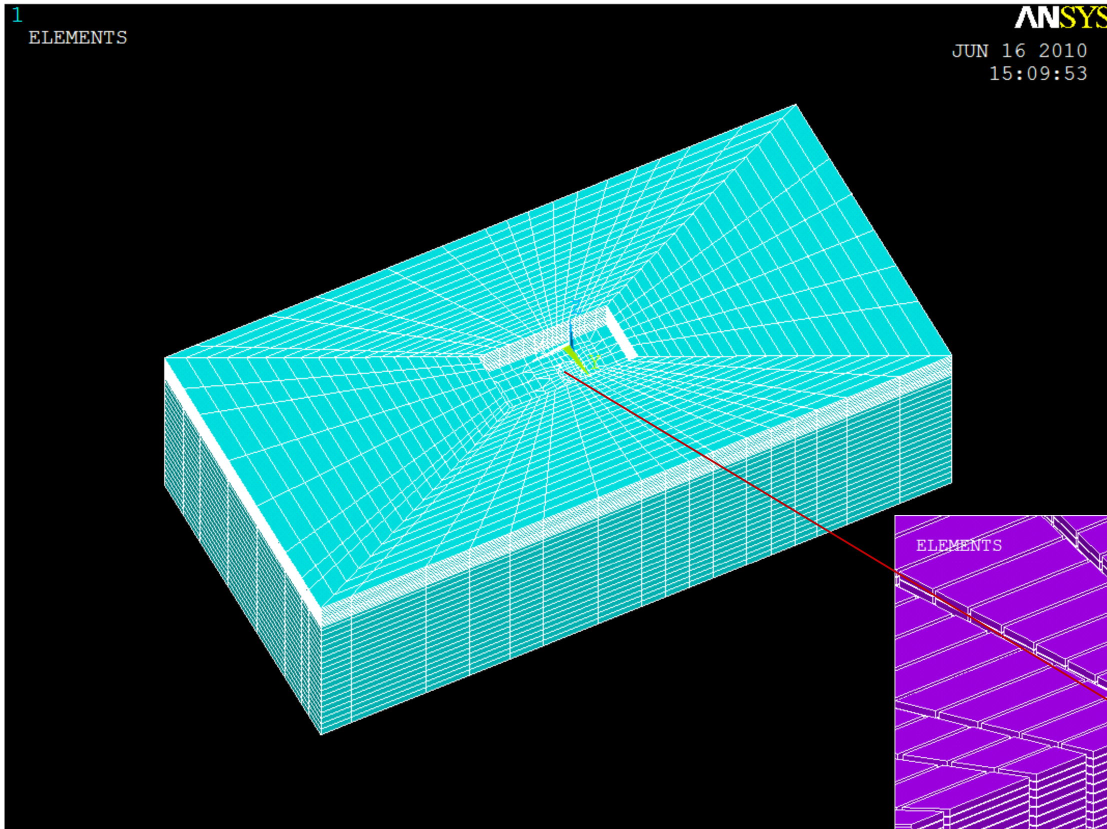
EQS Forces – Linear & Nonlinear



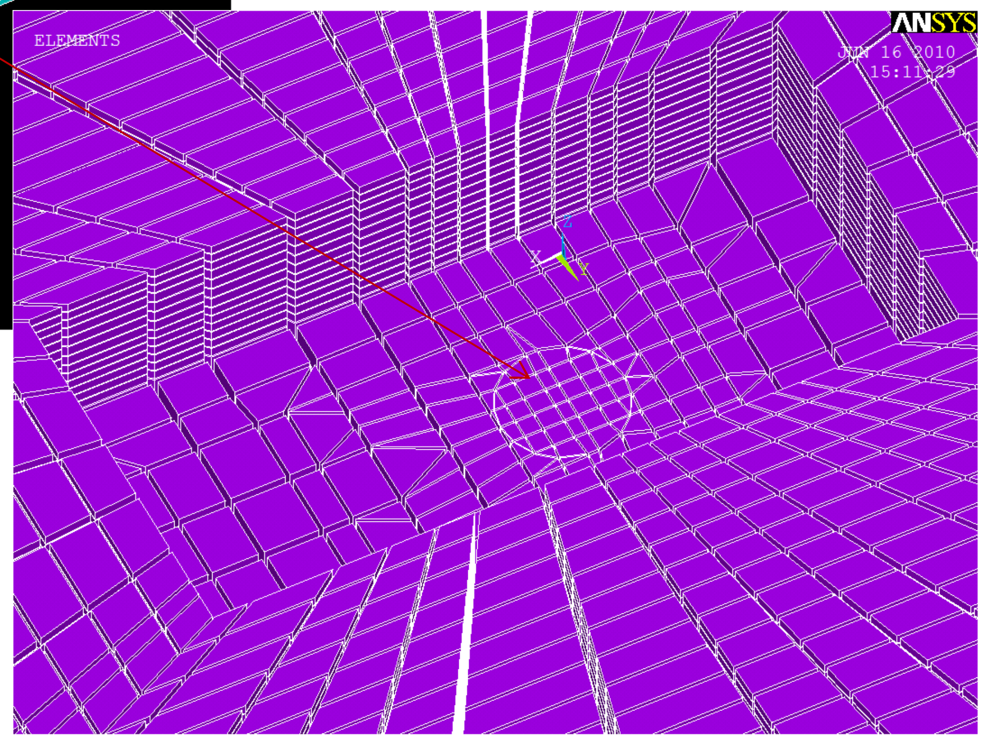
EQS Relative Displacements – Linear (Welded)



ACS SASSI – ANSYS Interface for Seismic Soil Pressure Analysis



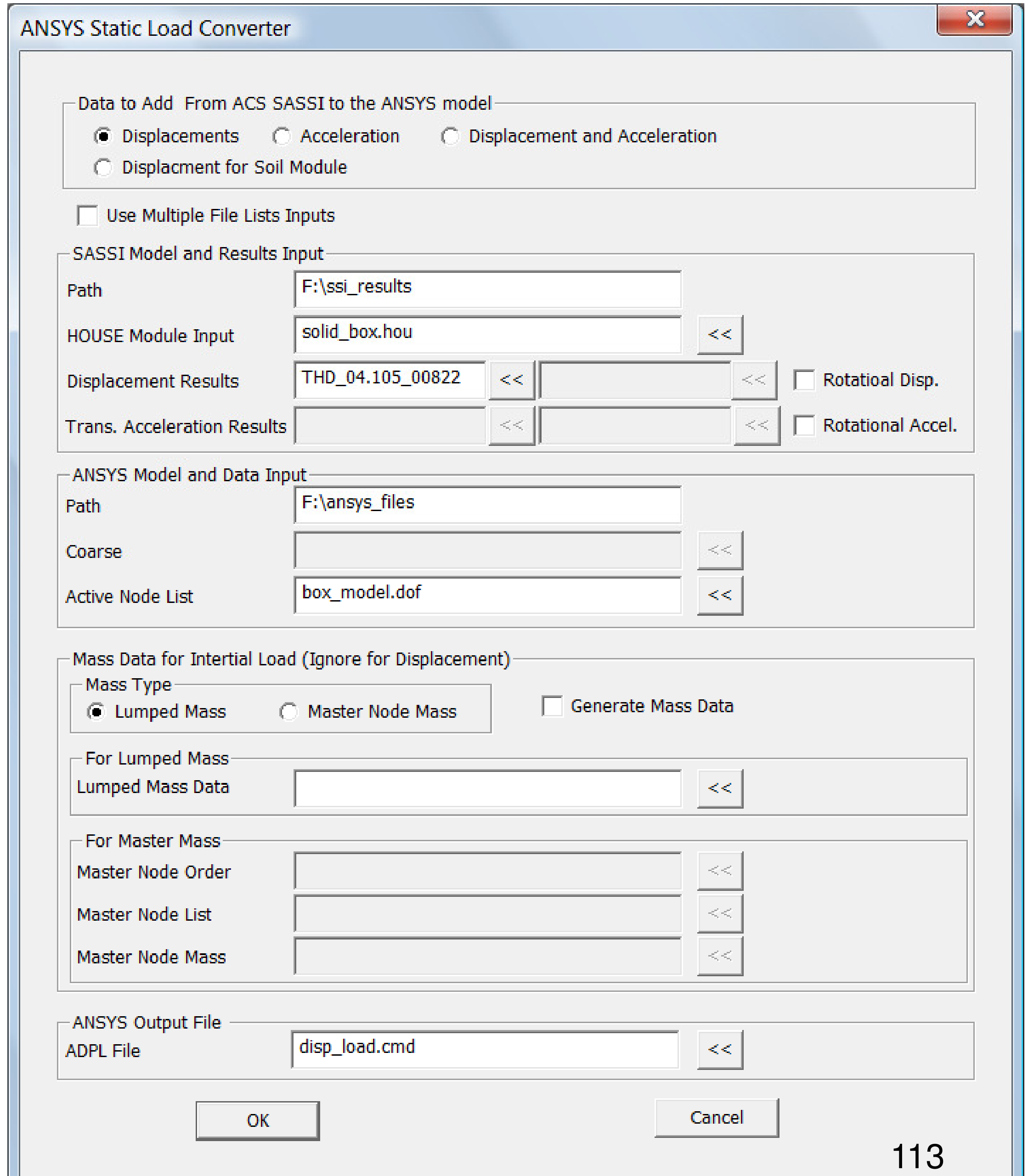
ANSYS Soil FE Model
Is Automatically Generated
by SOILMESH Module



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

Exporting Equivalent Static Loads to ANSYS

- From ACS SASSI-MAIN select “ANSYS Static Load” from the Run menu
- Fill in the appropriate boxes as described in the documentation
- ANSYS APDL input files are created containing the load data are created when the user clicks “OK”



Example of Equivalent Static APDL File Created

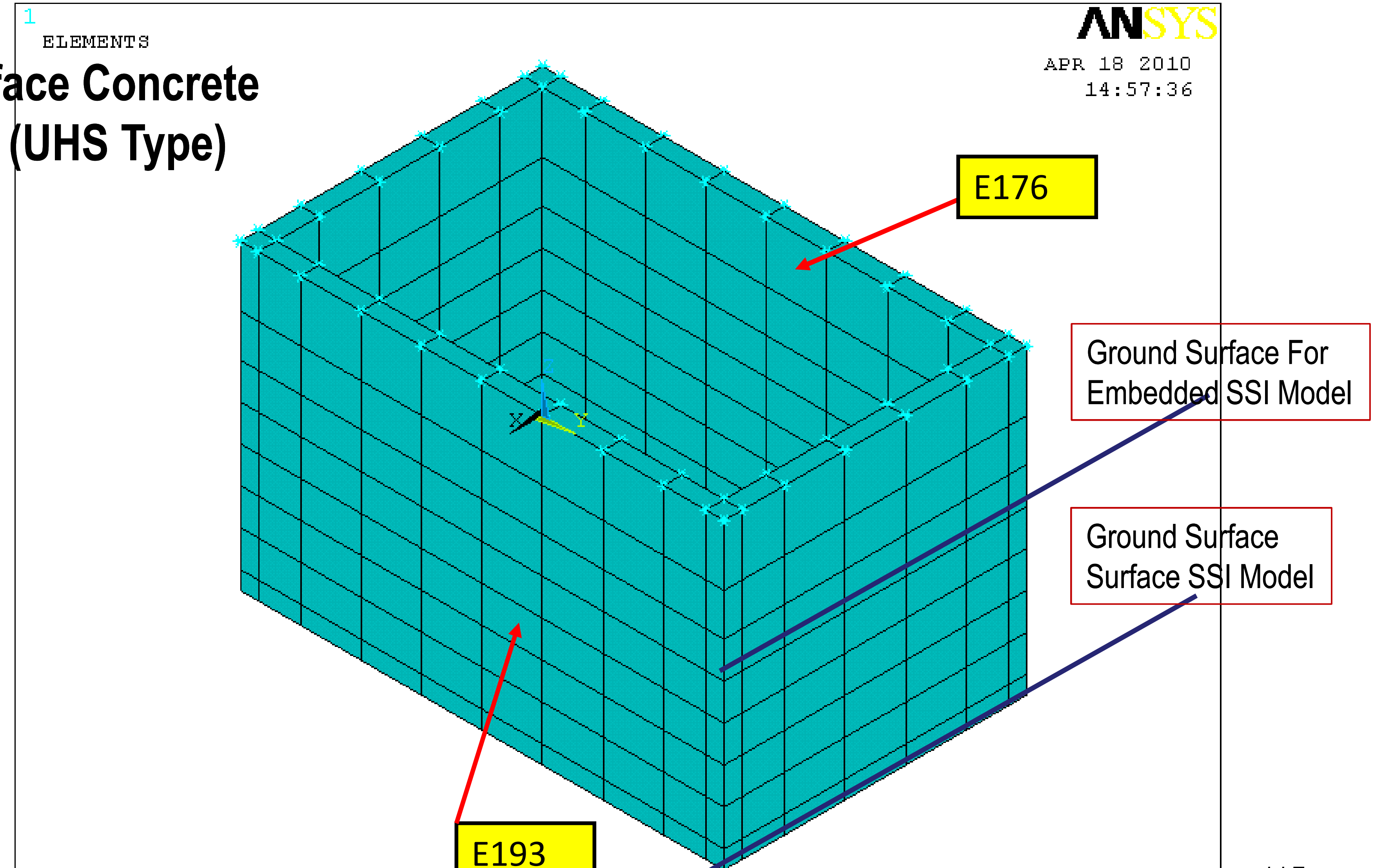
forces.inp - Notepad

File Edit Format View Help

```
FINIsh
/prep7
Node_Id=Node( 0.300000000E+01, 0.300000000E+01, 0.530000000E+02)
F,Node_Id,FX, 0.120690430E+03
F,Node_Id,FY, 0.179244520E+02
F,Node_Id,FZ, 0.259900690E+02
Node_Id=Node( 0.300000000E+01, 0.600000000E+01, 0.530000000E+02)
F,Node_Id,FX, 0.133931875E+03
F,Node_Id,FY, 0.197587250E+02
F,Node_Id,FZ, 0.250601330E+02
Node_Id=Node( 0.300000000E+01, 0.130000000E+02, 0.530000000E+02)
F,Node_Id,FX, 0.187532156E+03
F,Node_Id,FY, 0.221239760E+02
F,Node_Id,FZ, 0.247980250E+02
Node_Id=Node( 0.300000000E+01, 0.230000000E+02, 0.530000000E+02)
F,Node_Id,FX, 0.265551468E+03
F,Node_Id,FY, 0.163200870E+02
F,Node_Id,FZ, 0.259055440E+02
Node_Id=Node( 0.300000000E+01, 0.330000000E+02, 0.530000000E+02)
F,Node_Id,FX, 0.313659073E+03
F,Node_Id,FY, 0.795919600E+01
F,Node_Id,FZ, 0.262560410E+02
Node_Id=Node( 0.300000000E+01, 0.430000000E+02, 0.530000000E+02)
F,Node_Id,FX, 0.328311039E+03
F,Node_Id,FY, 0.000000000E+00
F,Node_Id,FZ, 0.258664210E+02
Node_Id=Node( 0.300000000E+01, 0.530000000E+02, 0.530000000E+02)
F,Node_Id,FX, 0.313659073E+03
F,Node_Id,FY,-0.795919600E+01
F,Node_Id,FZ, 0.262560410E+02
Node_Id=Node( 0.300000000E+01, 0.630000000E+02, 0.530000000E+02)
F,Node_Id,FX, 0.265551468E+03
F,Node_Id,FY,-0.163200870E+02
F,Node_Id,FZ, 0.259055440E+02
Node_Id=Node( 0.300000000E+01, 0.730000000E+02, 0.530000000E+02)
F,Node_Id,FX, 0.187532156E+03
F,Node_Id,FY,-0.221239760E+02
F,Node_Id,FZ, 0.247980250E+02
Node_Id=Node( 0.300000000E+01, 0.800000000E+02, 0.530000000E+02)
F,Node_Id,FX, 0.133931875E+03
F,Node_Id,FY,-0.197587250E+02
F,Node_Id,FZ, 0.250601330E+02
Node_Id=Node( 0.300000000E+01, 0.830000000E+02, 0.530000000E+02)
F,Node_Id,FX, 0.120690430E+03
F,Node_Id,FY,-0.179244520E+02
F,Node_Id,FZ, 0.259900690E+02
Node_Id=Node( 0.600000000E+01, 0.300000000E+01, 0.530000000E+02)
F,Node_Id,FX, 0.121983904E+03
F,Node_Id,FY, 0.360173100E+01
```

ACS SASSI-ANSYS Equivalent-Static SSI Stress Analysis for Surface and Embedded Structure

Surface Concrete Box (UHS Type)



TER,

ANSYS Equivalent-Static vs. ACS SASSI

SSI Analysis

Surface Concrete Box
SOLID Elements

Soil Vs=1000fps

Flexible Base

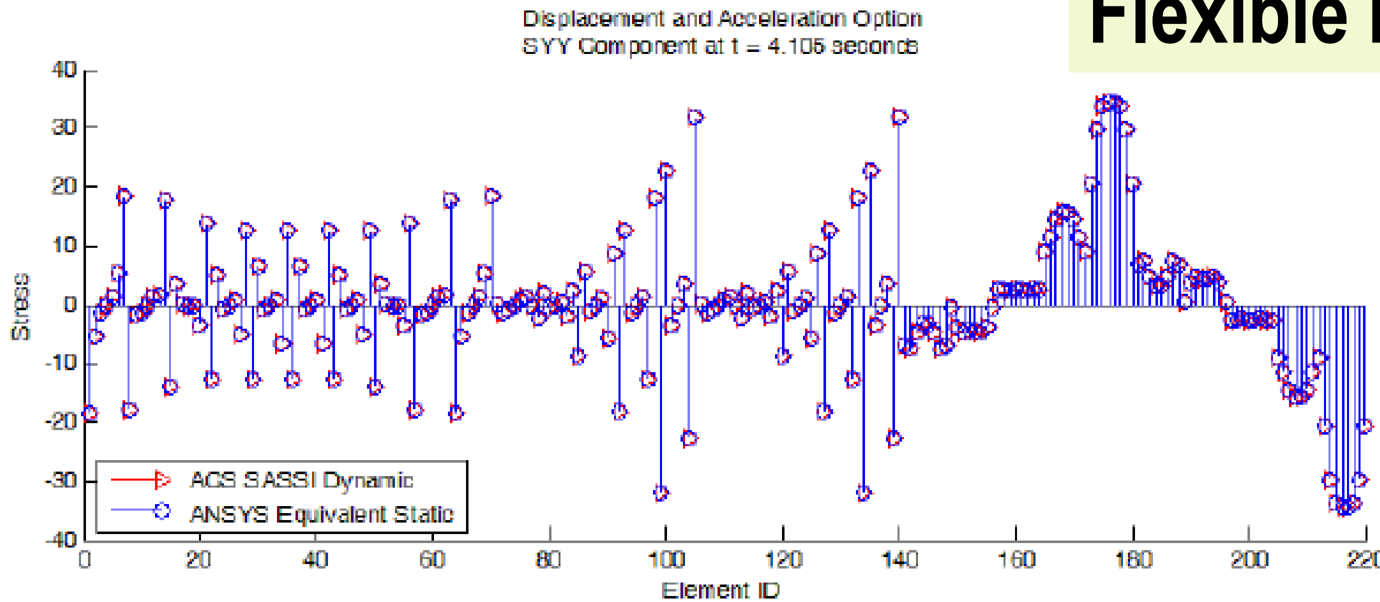


Figure 193: Case b) SYY Element Center Stresses for "Displacement and Acceleration" Option

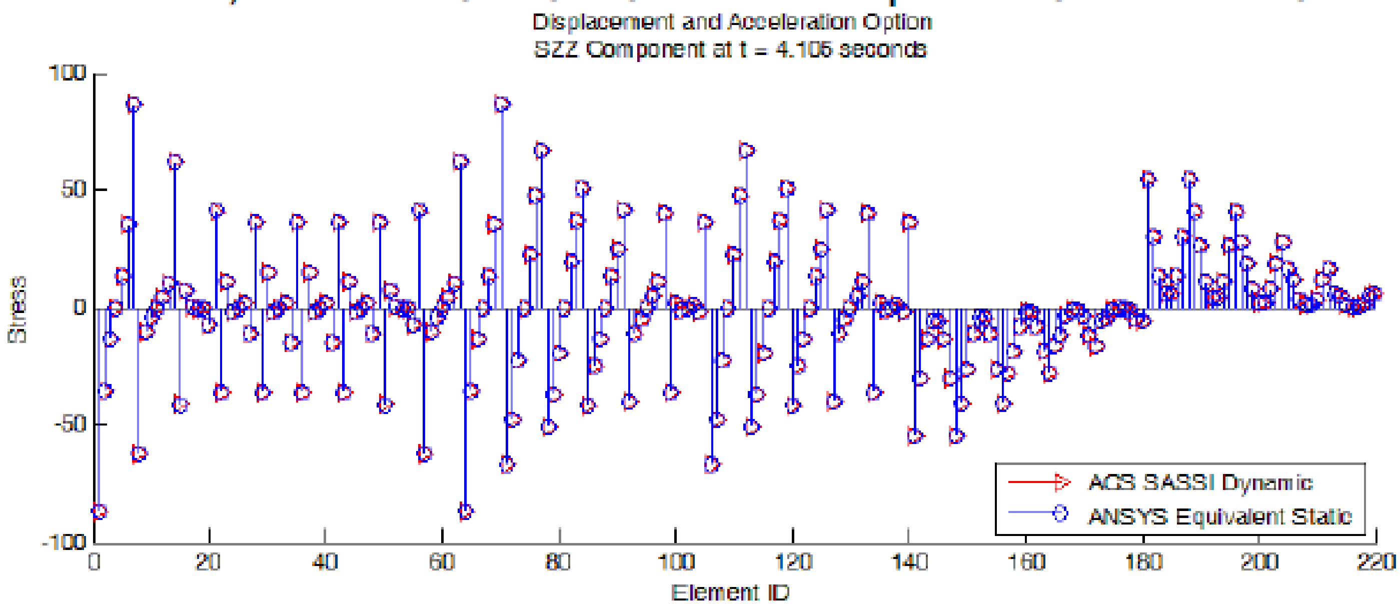


Figure 194: Case b): SZZ Element Center Stresses for "Displacement and Acceleration" Option

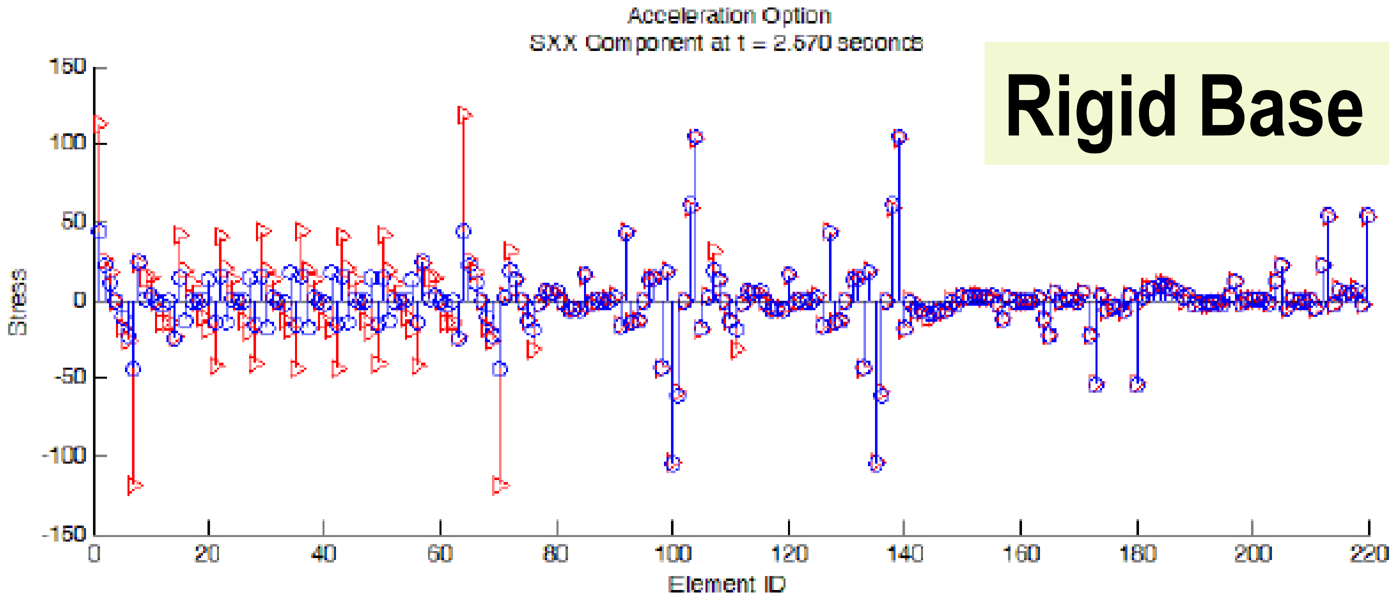


Figure 197: Case c): SXX Element Center Stresses for "Acceleration" Option

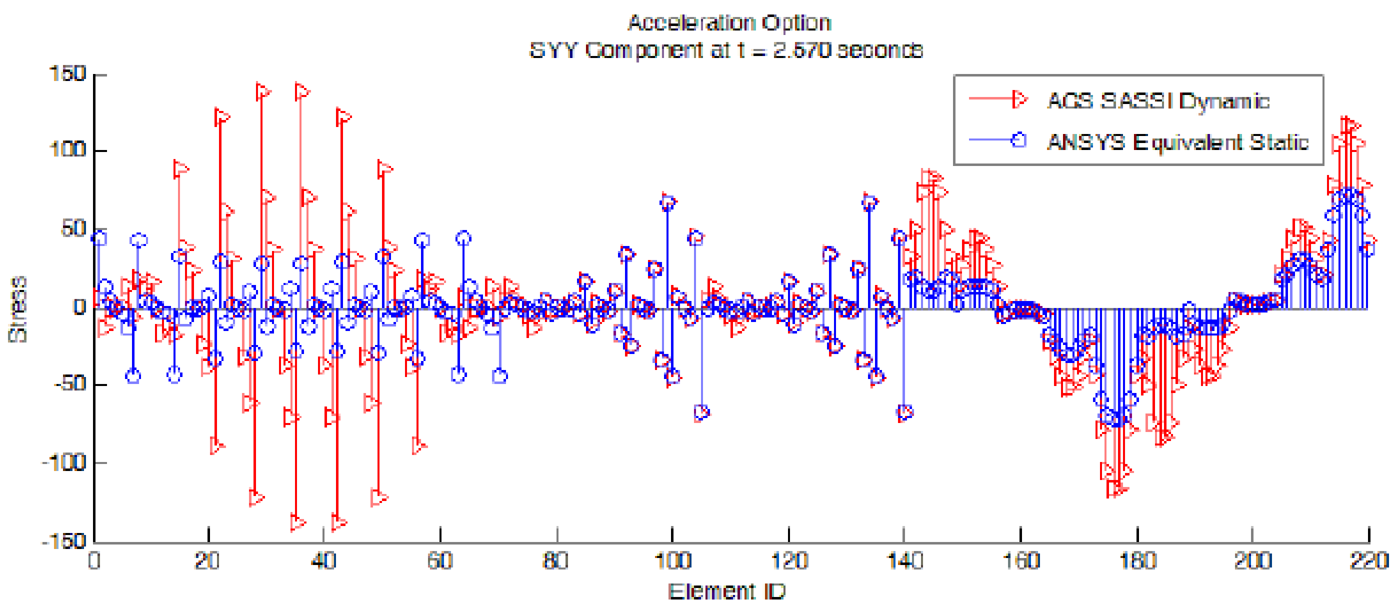


Figure 198: Case c): SYY Element Center Stresses for "Acceleration" Option

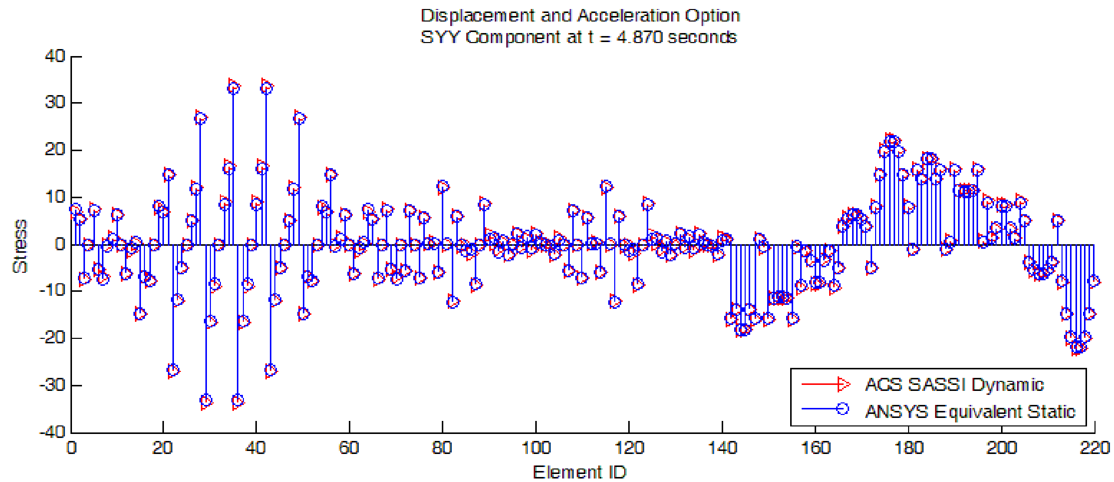
ANSYS Equivalent-Static vs. ACS SASSI

SSI Analysis

Deeply Embedded Concrete Box
SOLID Elements

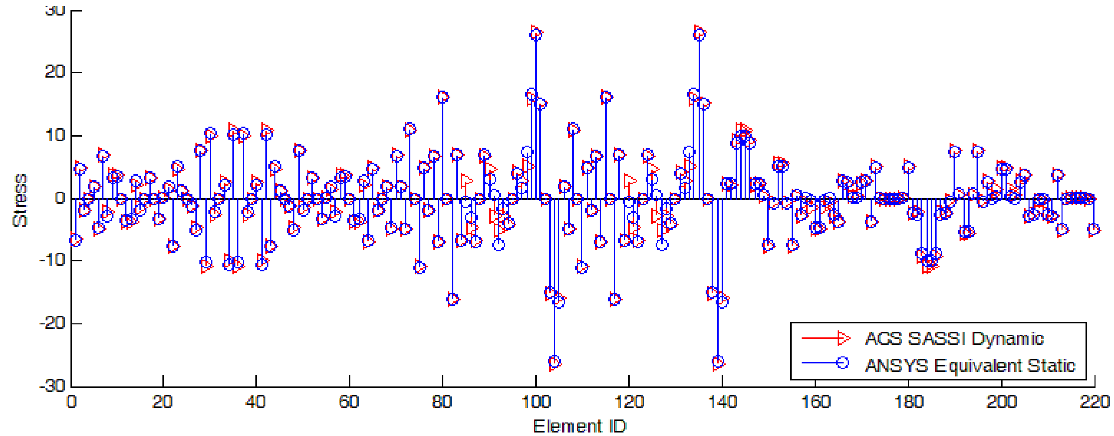
Soil Vs=1,000 fps

SXX



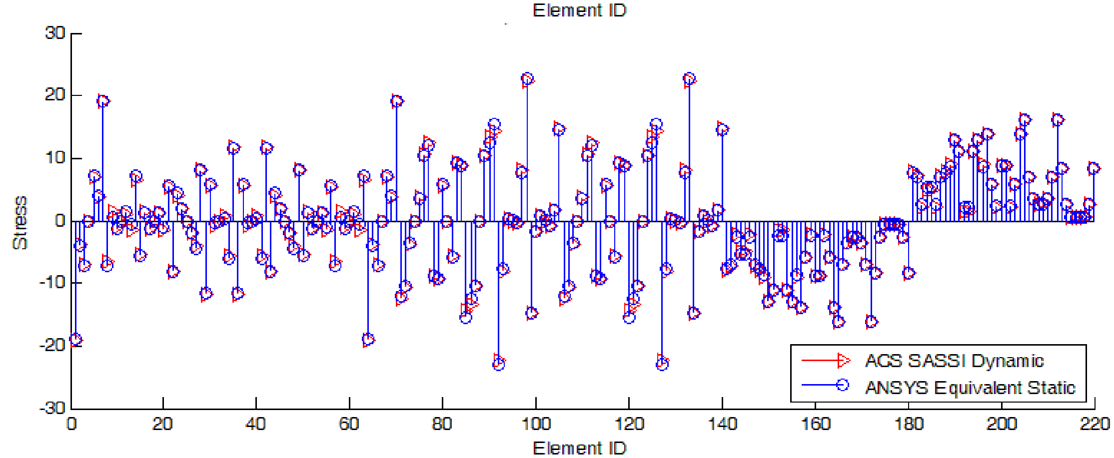
Displacement and Acceleration Option
SYY Component at t = 4.870 seconds
Stress
Element ID
ACS SASSI Dynamic
ANSYS Equivalent Static

SYY



Stress
Element ID
ACS SASSI Dynamic
ANSYS Equivalent Static

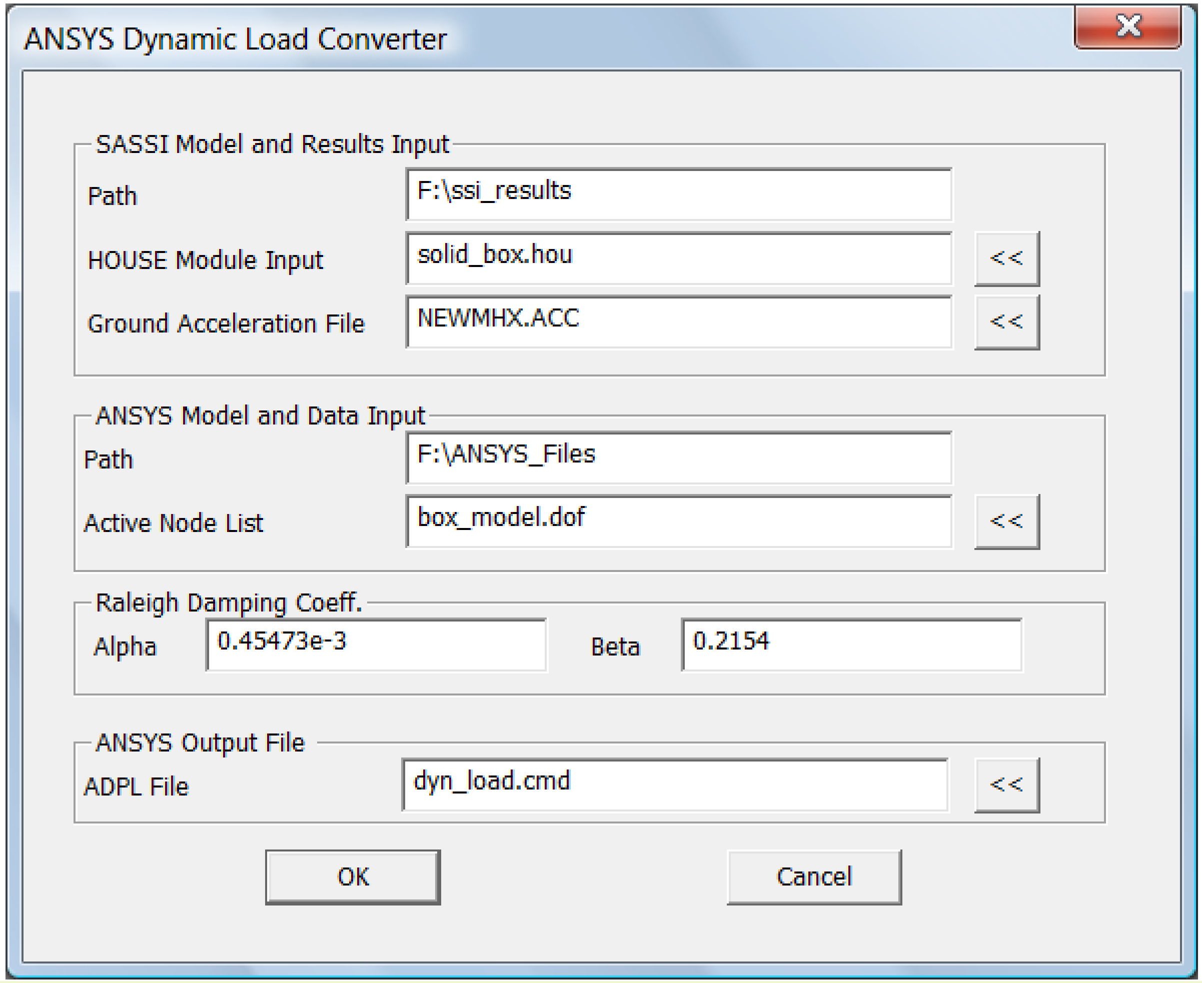
SZZ



Stress
Element ID
ACS SASSI Dynamic
ANSYS Equivalent Static

ANSYS Dynamic Load Generation from ACC Frames

- From ACS SASSI-MAIN select "ANSYS Dynamic Load" from the Run menu
- Fill in the appropriate boxes as described in the documentation
- ANSYS APDL input files are created containing the load data are created when the user clicks "OK"



NOTE: For embedded models, the input is the kinematic SSI accelerations and relative displacements calculated at different embedment depth levels.

REMARK: Rayleigh damping assumption in ANSYS less realistic!

ANSYS Dynamic Load APDL File Created

dynamic.inp - Notepad

File Edit Format View Help

```
FINISh
/Config,NRes,   6000
/SOLU
ANTYPE,TRANS
TRNOPT,FULL
 ALPHAD, 0.45473e-3
 BETAD, 0.2154
 DELTIM 0.005
!
 /INPUT,disp_gacc_load_00001
 TIME,  0.0001
 KBC,1
 OUTRES,ALL,LAST
 SOLVE
!
 /INPUT,disp_gacc_load_00002
 TIME,  0.0050
 KBC,1
 OUTRES,ALL,LAST
 SOLVE
!
 /INPUT,disp_gacc_load_00003
 TIME,  0.0100
 KBC,1
 OUTRES,ALL,LAST
 SOLVE
!
 /INPUT,disp_gacc_load_00004
 TIME,  0.0150
 KBC,1
 OUTRES,ALL,LAST
 SOLVE
!
 /INPUT,disp_gacc_load_00005
 TIME,  0.0200
 KBC,1
 OUTRES,ALL,LAST
 SOLVE
!
 /INPUT,disp_gacc_load_00006
 TIME,  0.0250
 KBC,1
 OUTRES,ALL,LAST
 SOLVE
!
 /INPUT,disp_gacc_load_00007
 TIME,  0.0300
 KBC,1
 OUTRES,ALL,LAST
```

ANSYS Dynamic vs. ACS SASSI
SSI Analysis

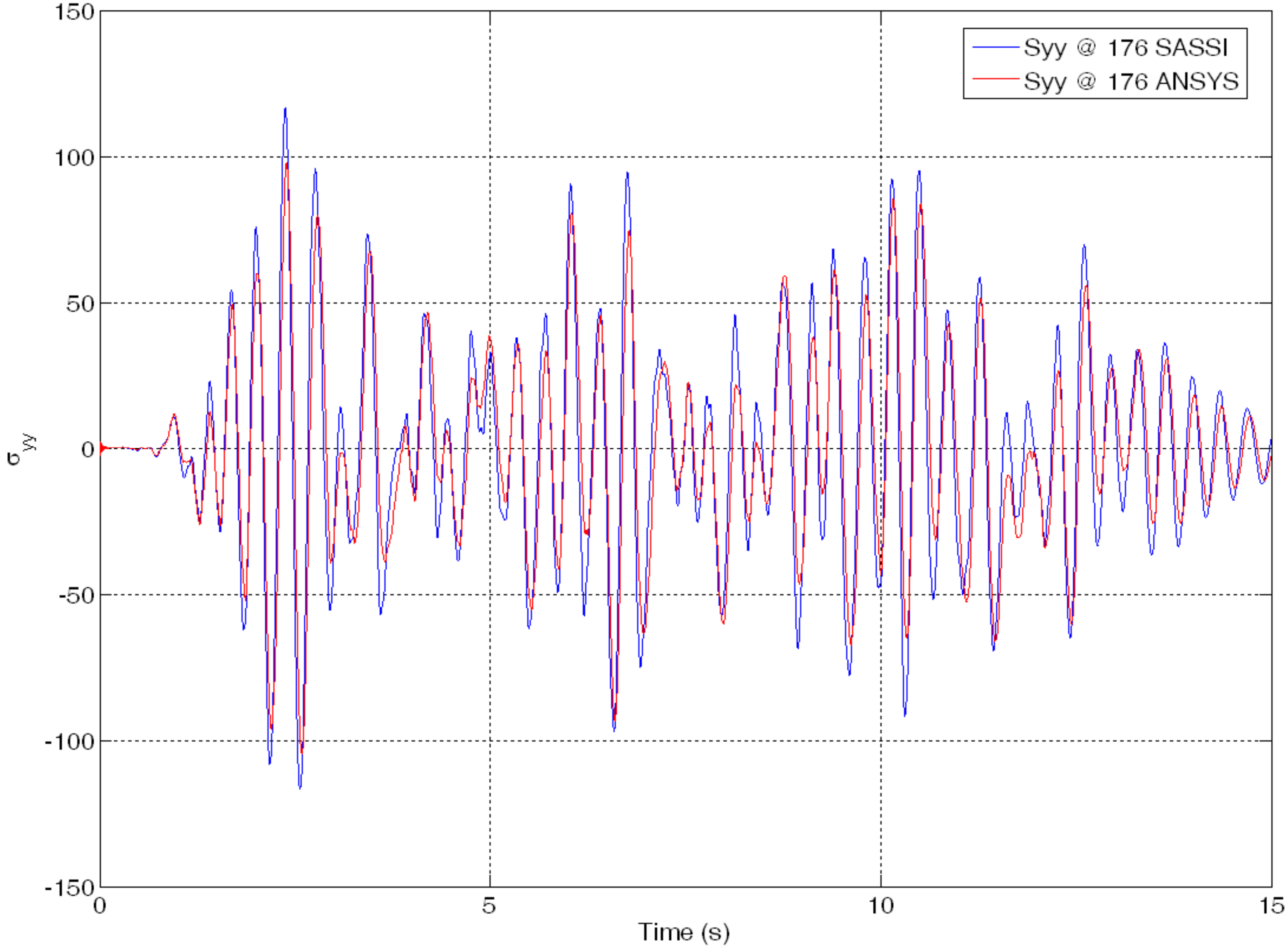
Surface Concrete Box
SOLID Elements
Soil Vs=1,000 fps

Seismic Loading for ANSYS:
Ground Acceleration Histories and Relative Displacement Histories wrt Free-Field Surface Motion

ANSYS Dynamic vs. ACS SASSI – Surface SSI Model

Above Ground Surface

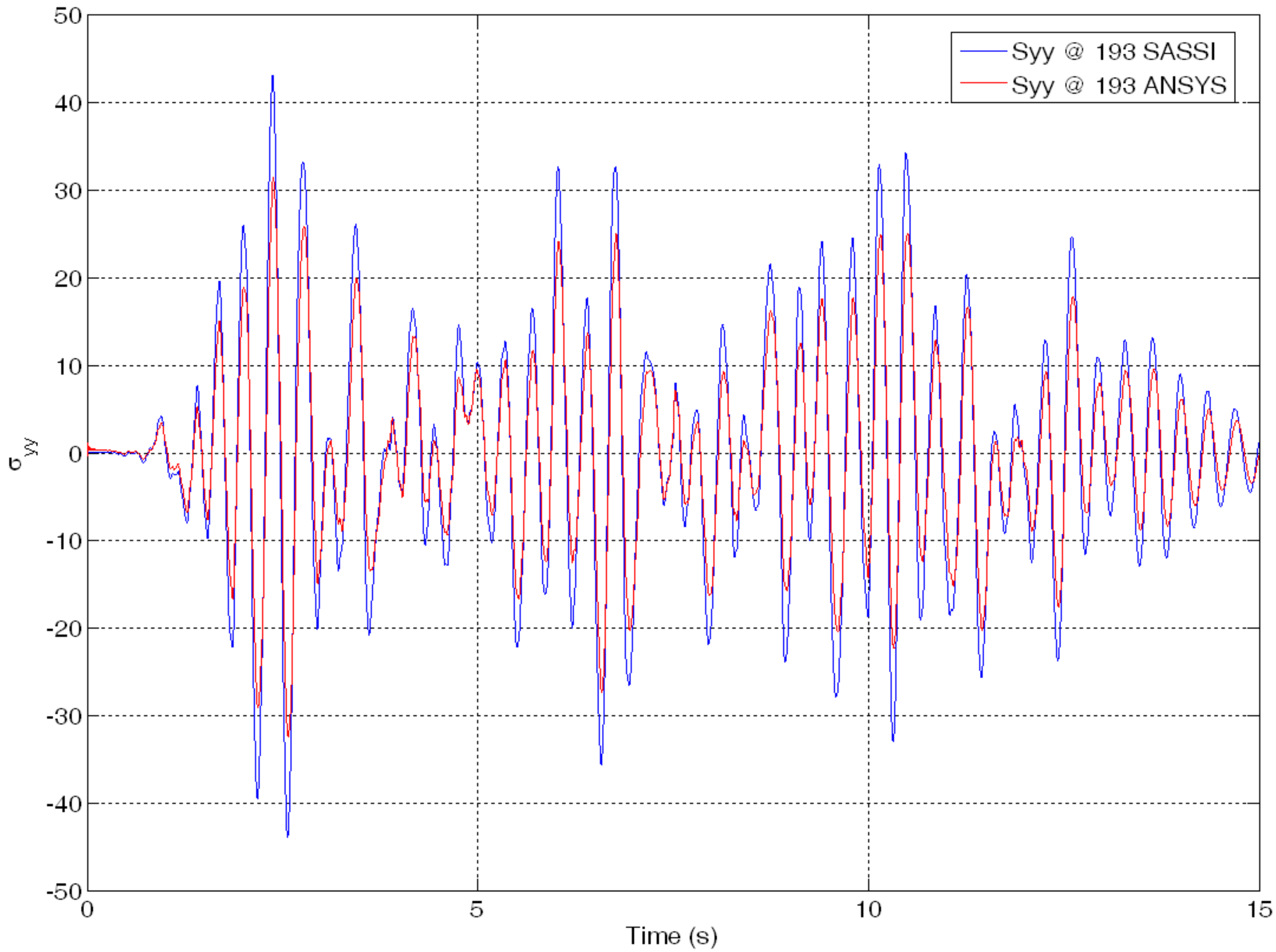
SYY



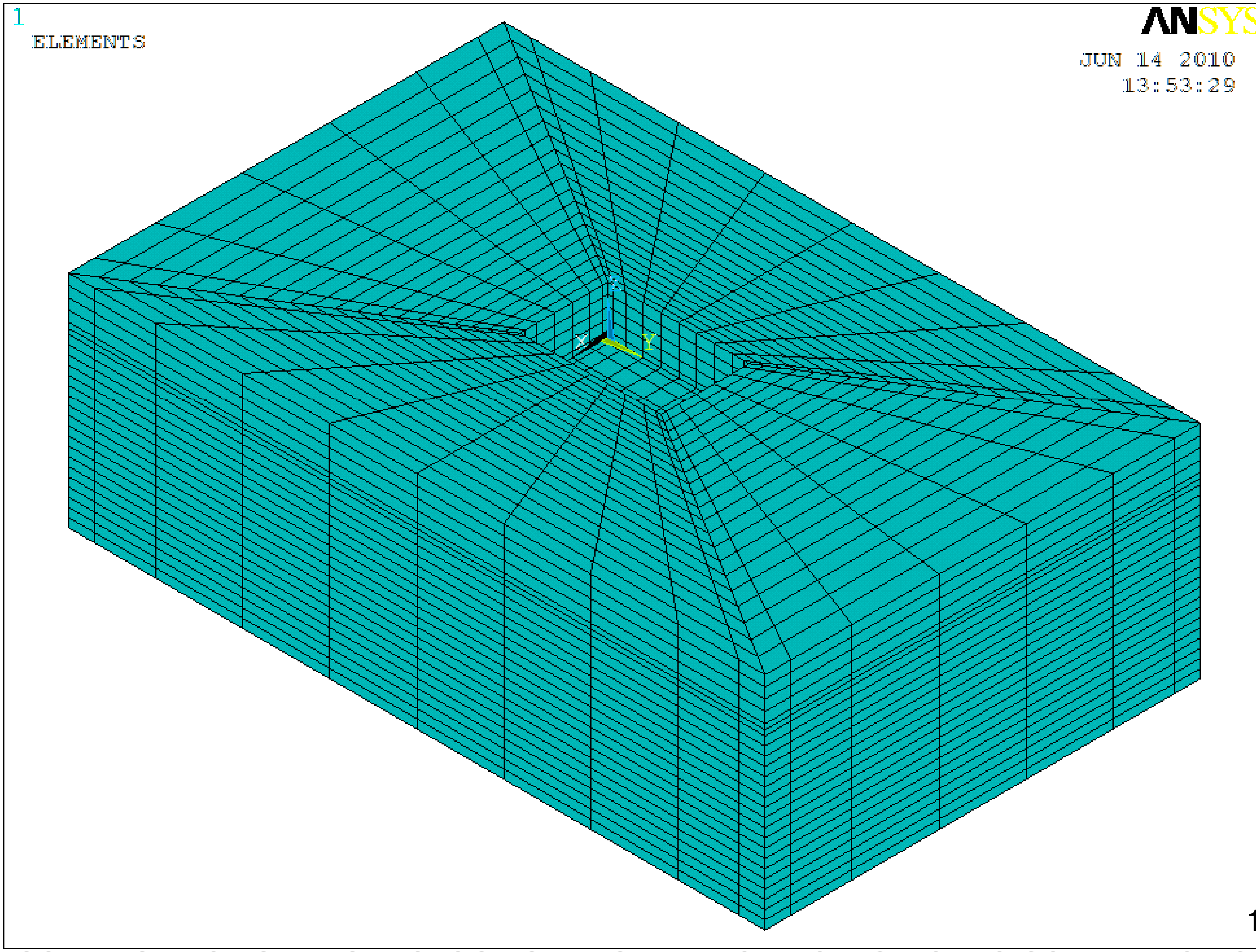
ANSYS Dynamic vs. ACS SASSI – for Surface SSI Model

Below Ground Surface

SYY



Example of Soil FE model Created Automatically by New SOILMESH Module for A Box Structural Model



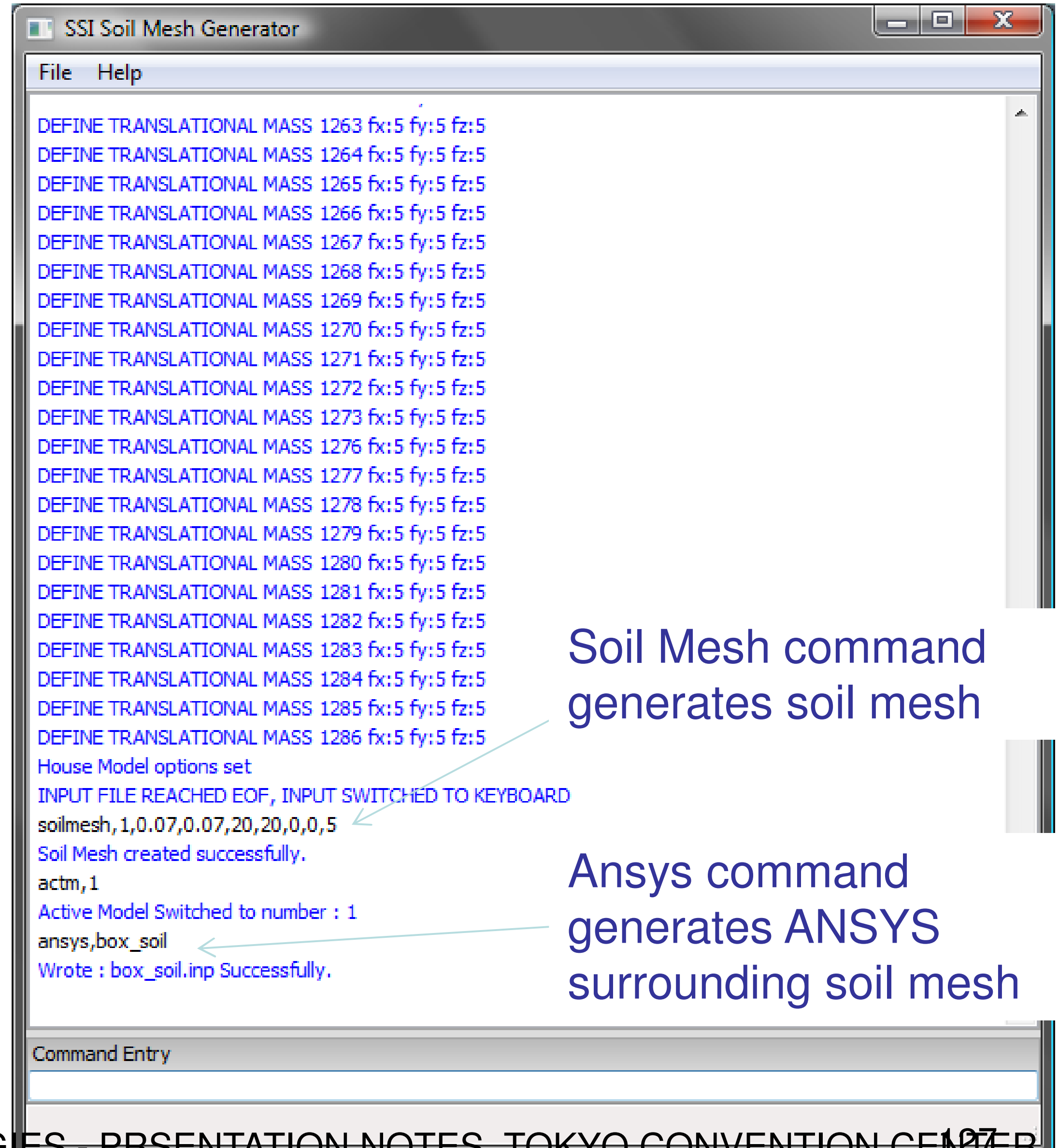
SUBMODELER Module for Soil Pressure Computation

- Input .pre file with SSI model data
- Generates a soil FE model for soil pressure analysis using the "soilmesh" command
- Can export either structural or soil FE model to ANSYS APDL input file
- Computes seismic soil pressures produced using either

  i) the foundation seismic forces pushing on surrounding soil, or

  ii) the relative motion of the foundation wrt to the free-field soil motion.

Soil is assumed to be at rest. Soil stiffness is not frequency dependent. The new implementation produces "approximate" seismic soil pressures. Significant analysis improvement in comparison with the current practice.



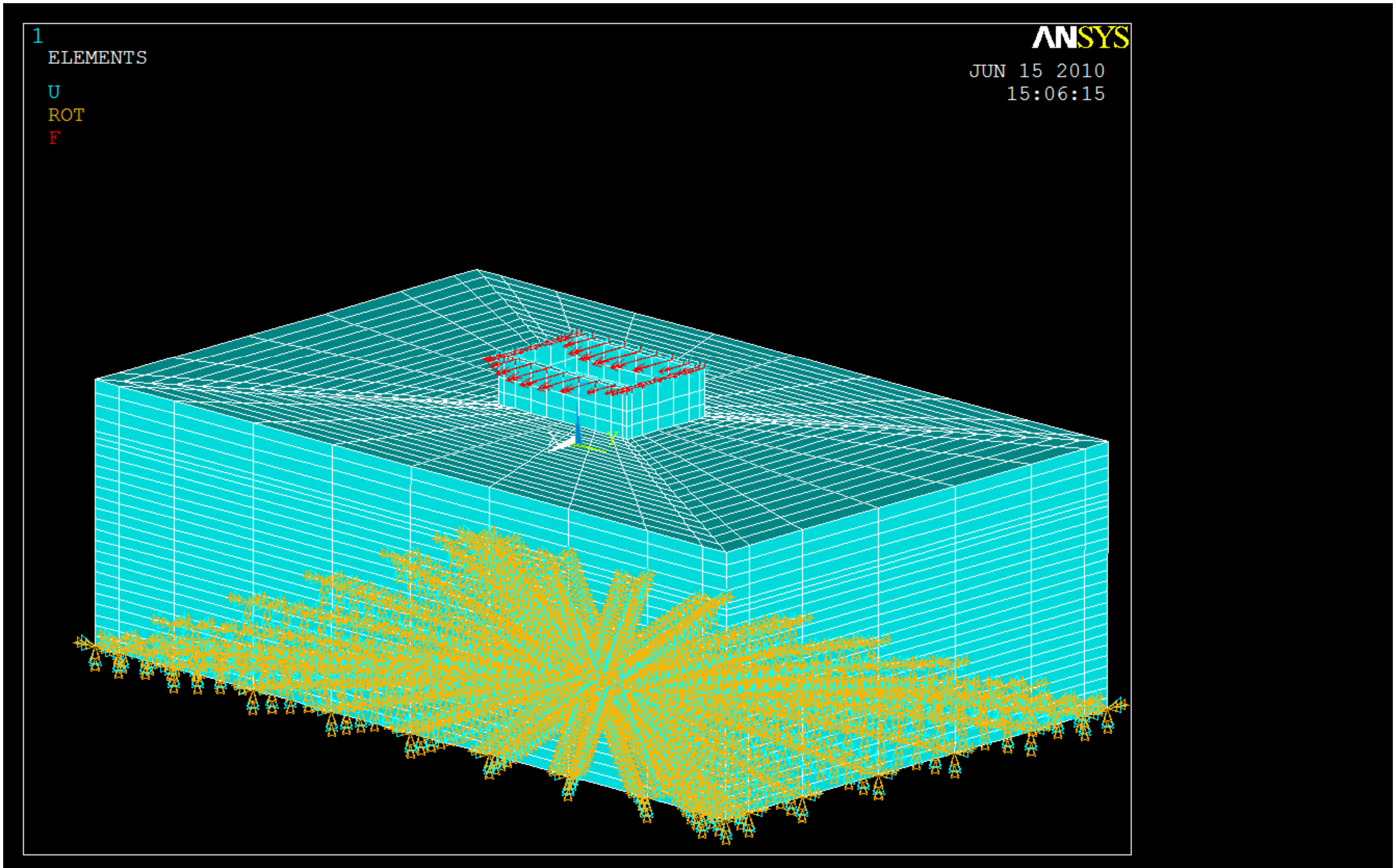
Example of APDL file for Soil FE Model

box_soil.inp - Notepad

File Edit Format View Help

```
/PREP7
! Element Type
ET,101,CONTA173
ET,102,TARGE170
ET,103,SOLID45
! Nodes
N,145,3,3,3
N,146,3,6,3
N,147,3,13,3
N,148,3,23,3
N,149,3,33,3
N,150,3,43,3
N,151,3,53,3
N,152,3,63,3
N,153,3,73,3
N,154,3,80,3
N,155,3,83,3
N,158,6,3,3
N,159,6,6,3
N,160,6,13,3
N,161,6,23,3
N,162,6,33,3
N,163,6,43,3
N,164,6,53,3
N,165,6,63,3
N,166,6,73,3
N,167,6,80,3
N,168,6,83,3
N,171,13,3,3
N,172,13,6,3
N,173,13,13,3
N,174,13,23,3
N,175,13,33,3
N,176,13,43,3
N,177,13,53,3
N,178,13,63,3
N,179,13,73,3
N,180,13,80,3
N,181,13,83,3
N,184,23,3,3
N,185,23,6,3
N,186,23,13,3
N,187,23,23,3
N,188,23,33,3
N,189,23,43,3
N,190,23,53,3
N,191,23,63,3
N,192,23,73,3
N,193,23,80,3
```

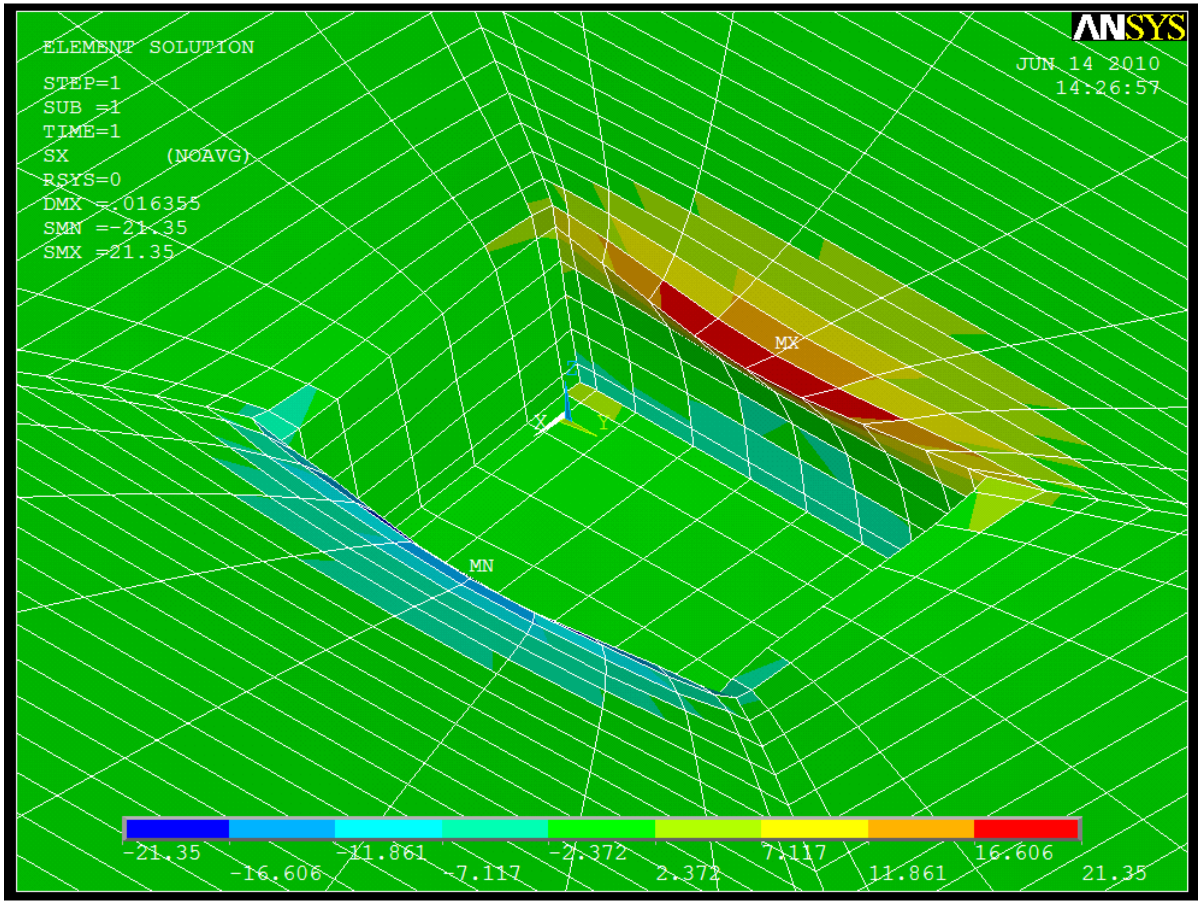
Equivalent-Static Stress Analysis for Structure-Soil System Model (Generated by SOILMESH)



Linear Seismic Soil Pressure Analysis

LINEAR (WELDED)

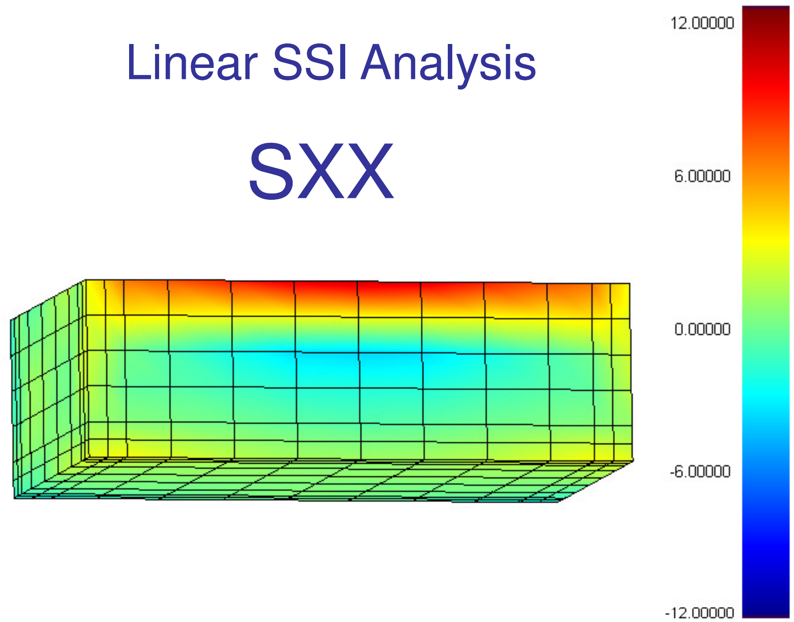
- This option provides for a basic soil pressure analysis assuming there is no separation possible between the structure and the soil
- Displacements from the interaction nodes of the structure are applied directly to the soil FE model. The structural FE model is not required for this case

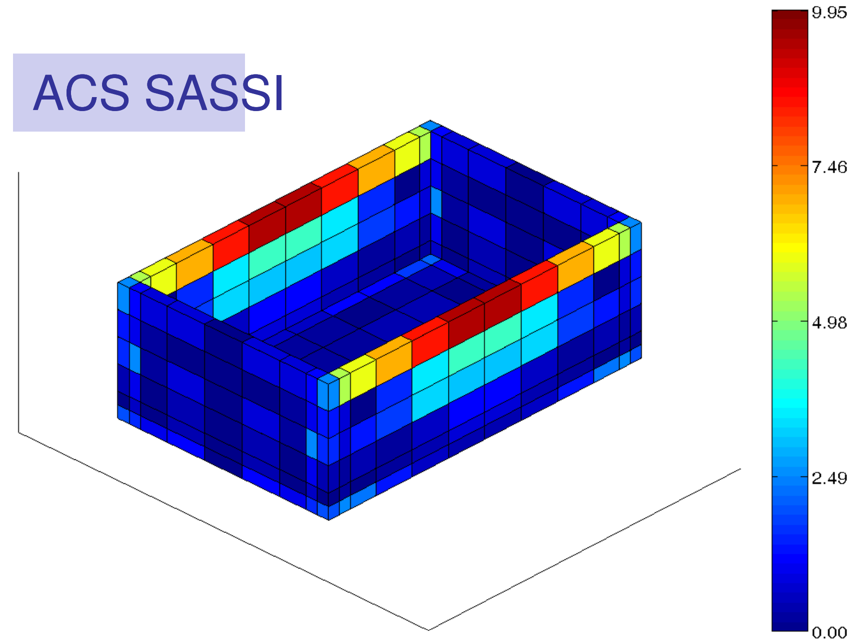


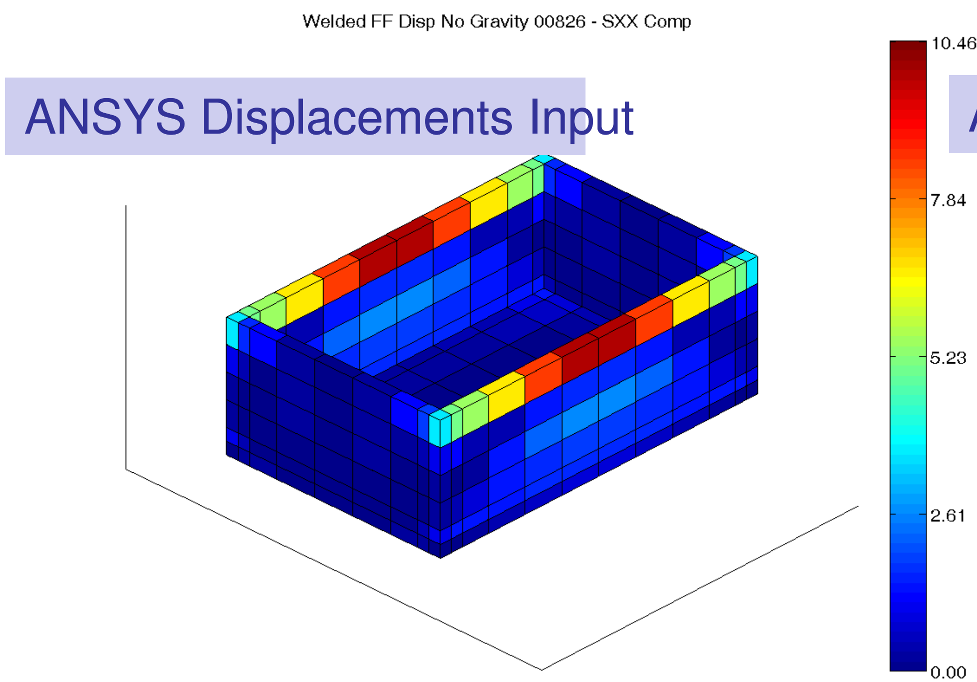
ACS SASSI and ANSYS Element Stresses for X-Input (Frame 903)

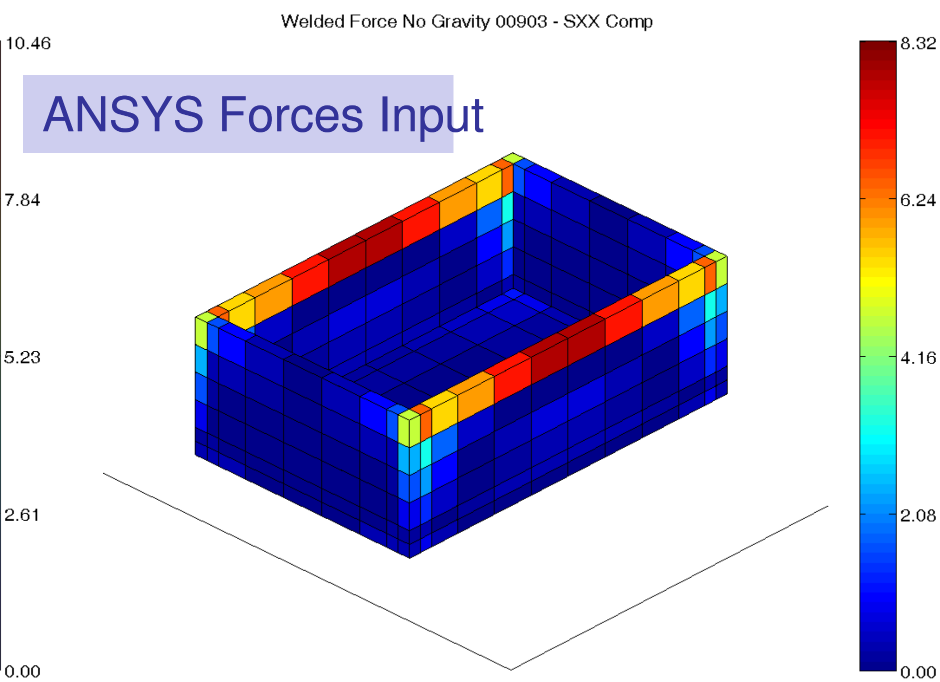
Linear SSI Analysis

SXX





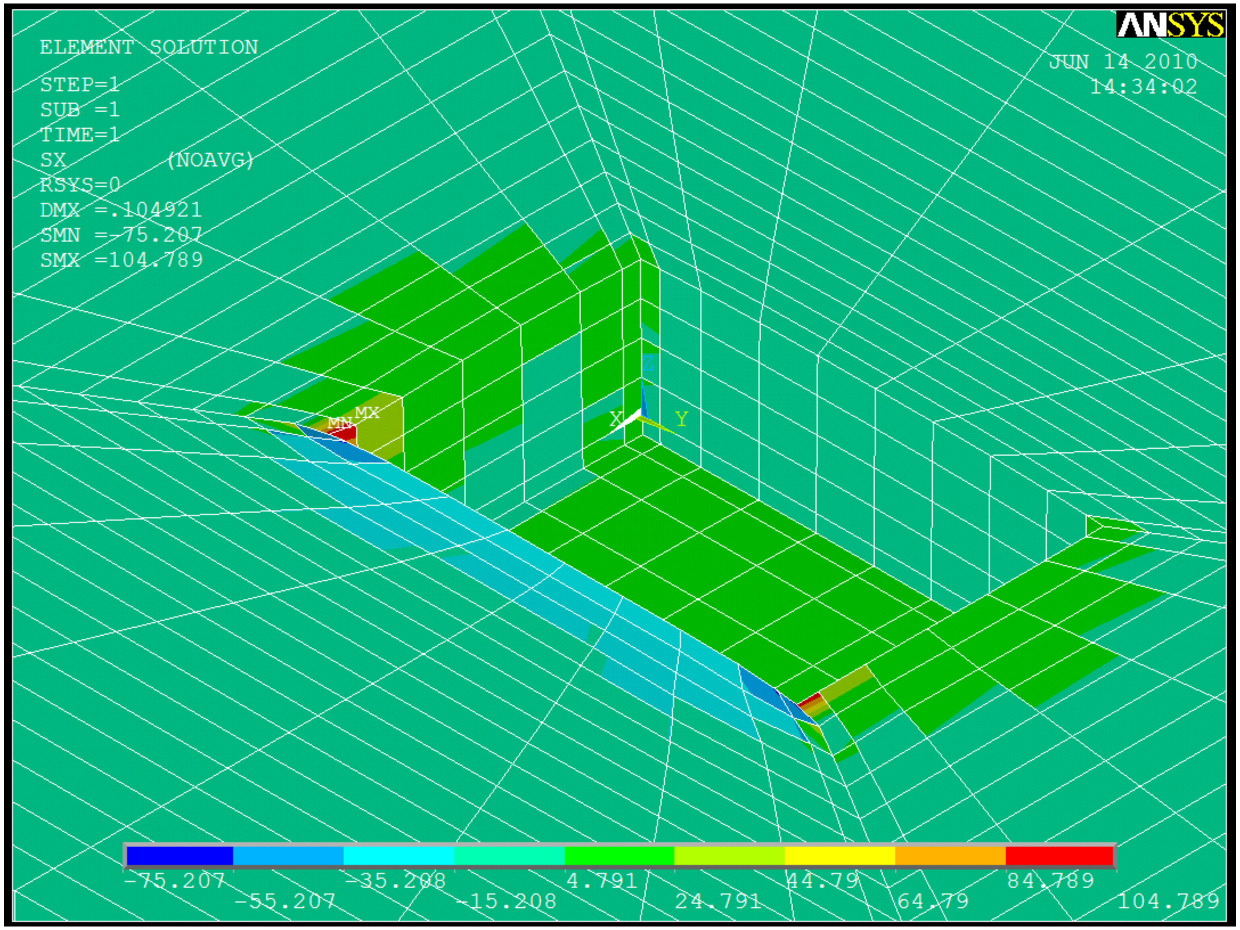




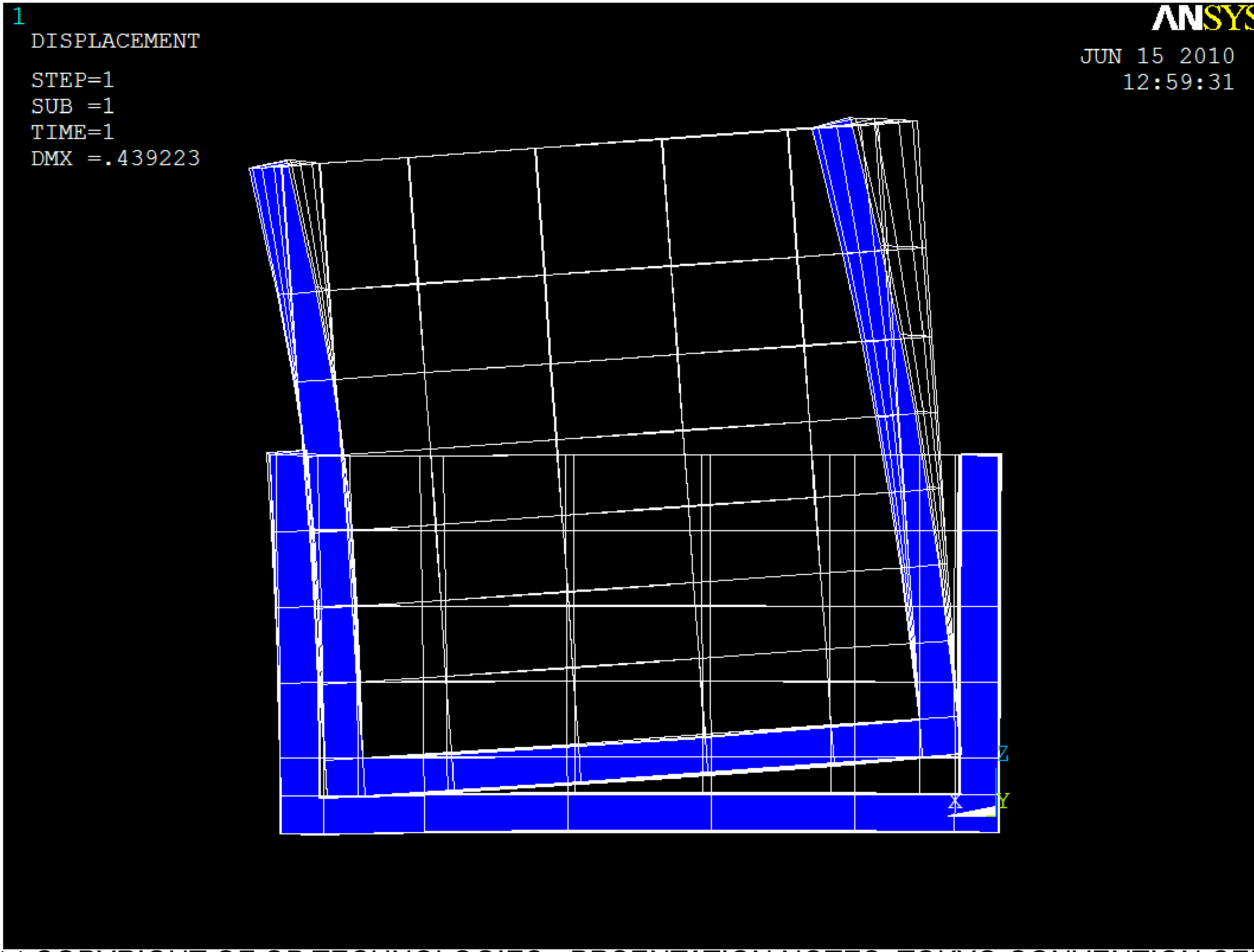
Nonlinear Seismic Soil Pressure Analysis

NONLINEAR CONTACT (SOIL 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



Nonlinear Seismic Soil Pressure Analysis



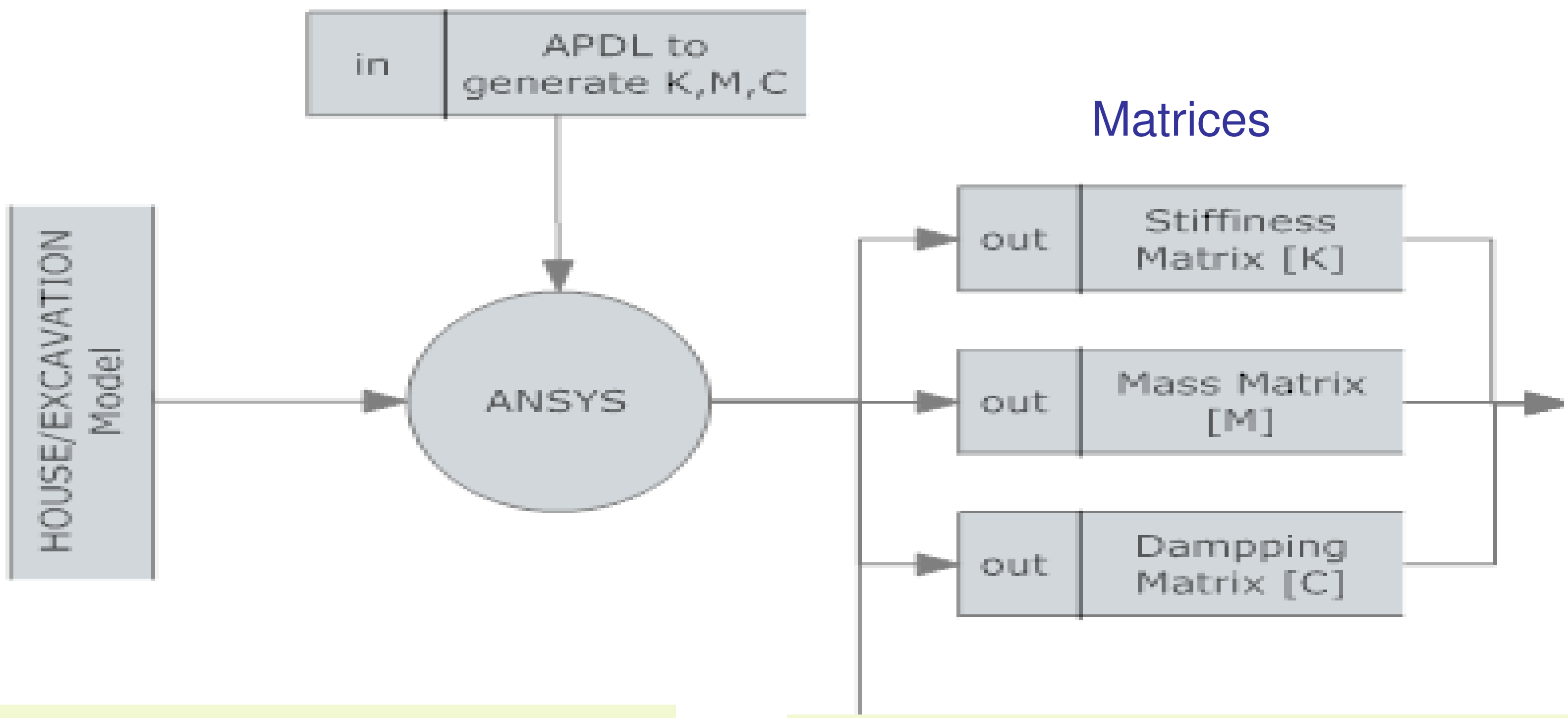
OPTION AA: ACS SASSI-ANSYS Interface for SSI Analysis Using ANSYS Models

OPTION AA uses directly ANSYS structural model for SSI analysis

Sequence of Steps:

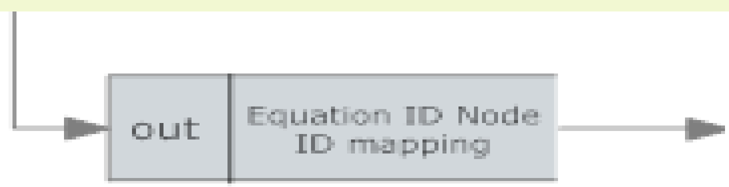
1) Develop ANSYS structural FEA model with no restrictions (any FE type, CE, rigid links)
2) If embedded, develop ANSYS excavated soil FEA model
3) Using ADPL generate matrices K, M, C
4) Using ACS SASSI GUI read ANSYS model .cdb to convert geometry configuration for post-processing
5) Using modified HOUSE read and merge K, M and C matrices for FV, FI or FFV methods, and produce FE complex K matrix and mixed M matrix for SSI analysis
6) Perform SSI analysis with the same ANALYS module

OPTION AA: Preliminary ANSYS steps for SSI analysis

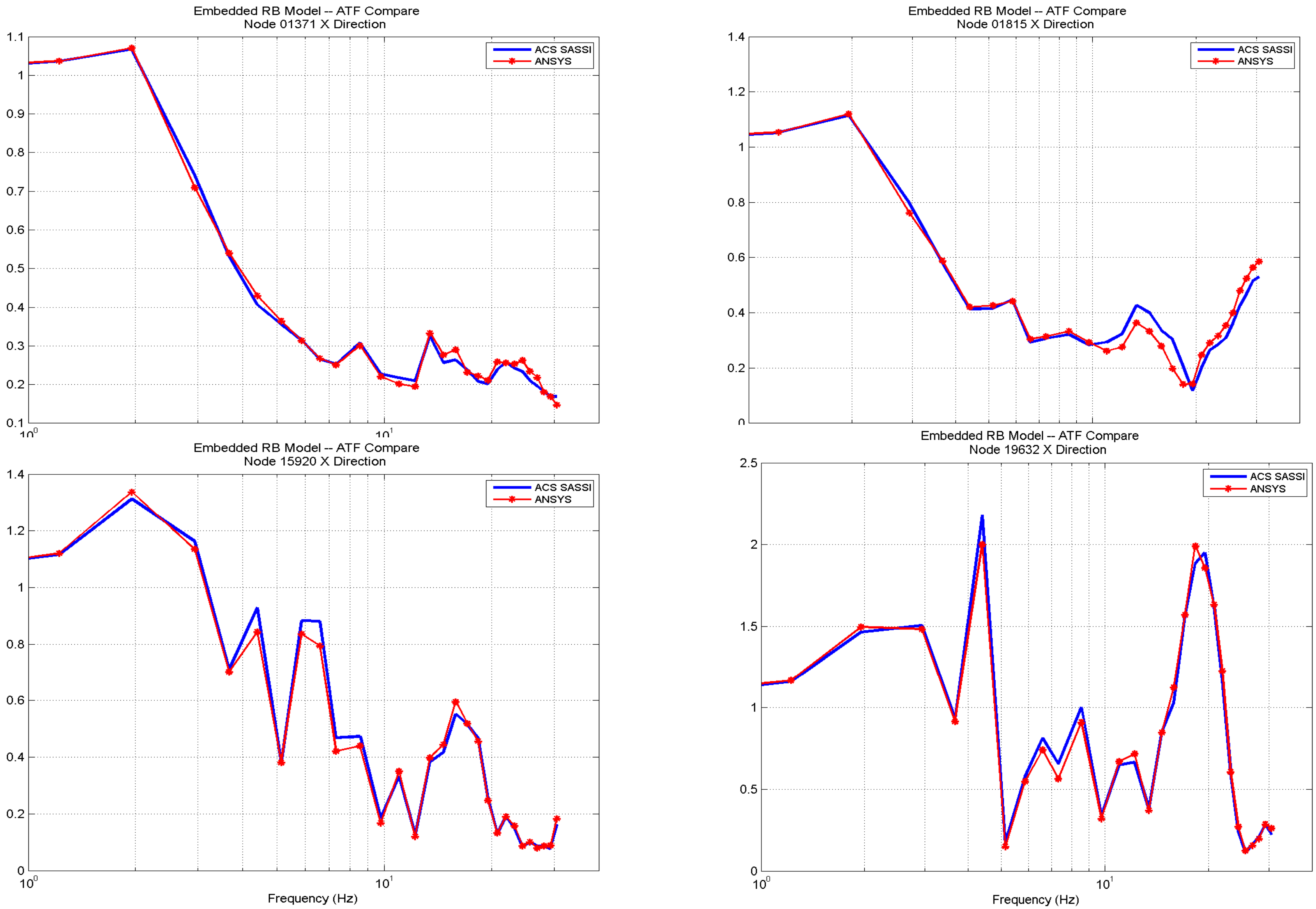


Step 1: ANSYS is used to build FEA Models for Structure and Excavated Soil and produces K, M and C matrices for these

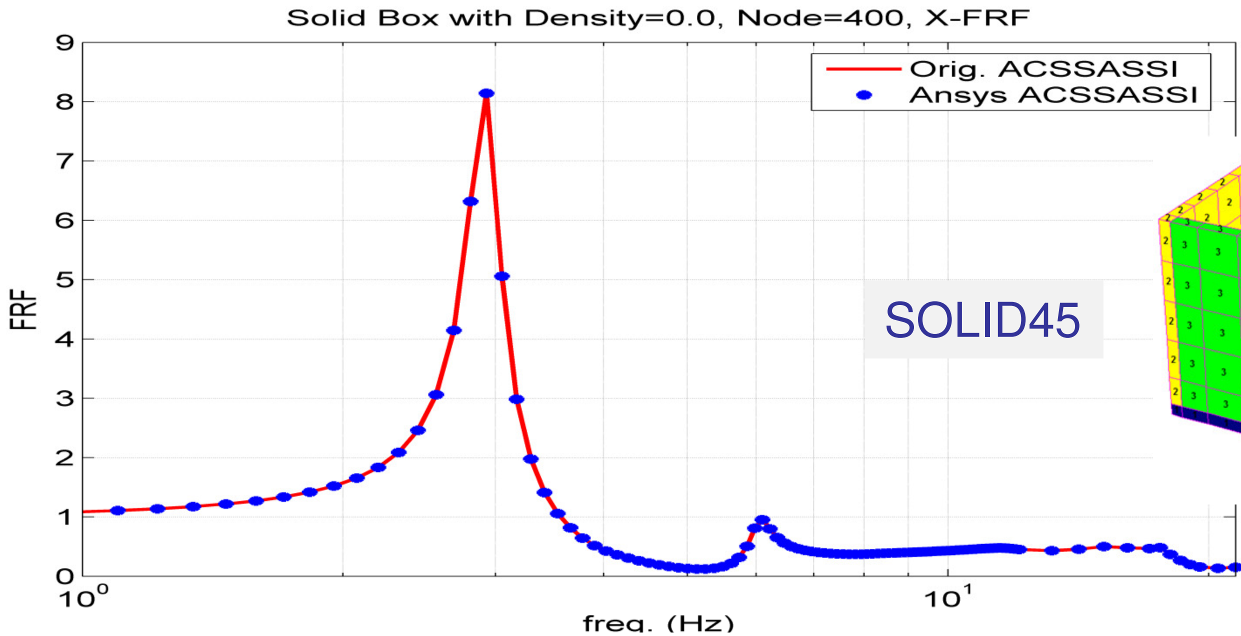
Step 2: ACS SASSI SUBMODELER combines Structure and Excavated Soil after converting their ANSYS .cdb to ACS SASSI .pre format

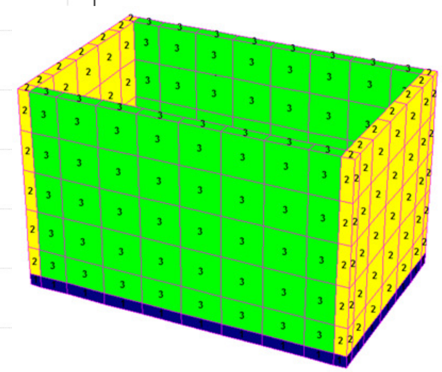


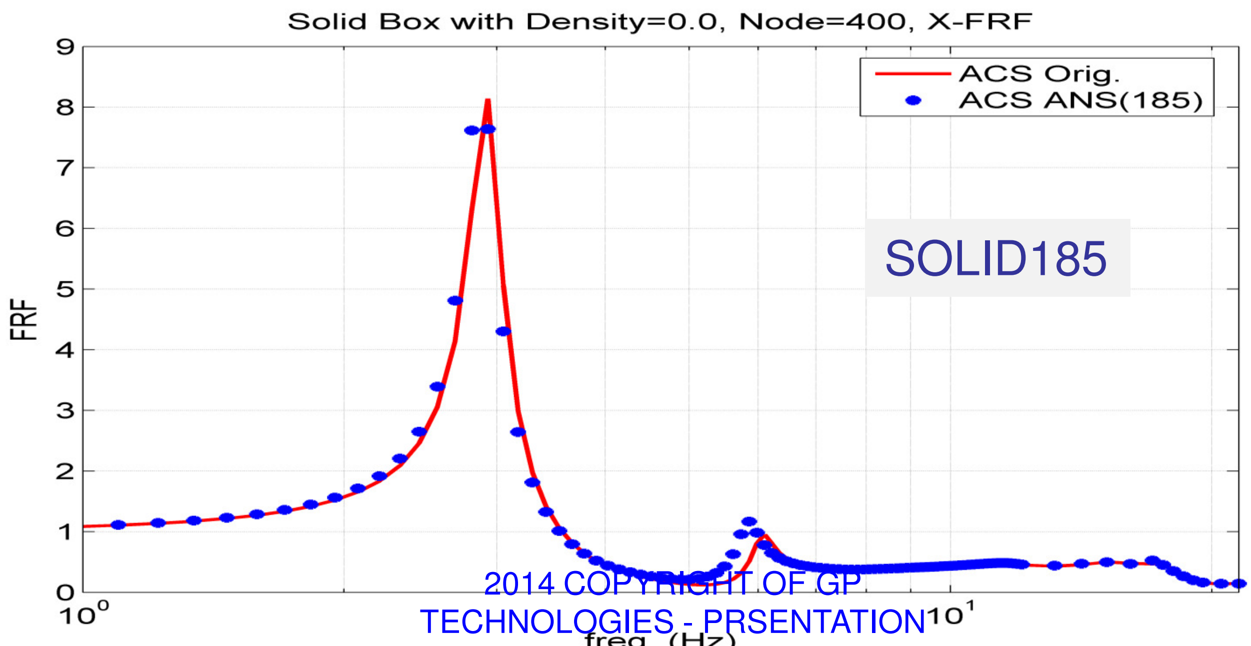
OPTION AA: 35,000 Node Embedded RB Complex; Acceleration Transfer Function (ATF) Various Locations



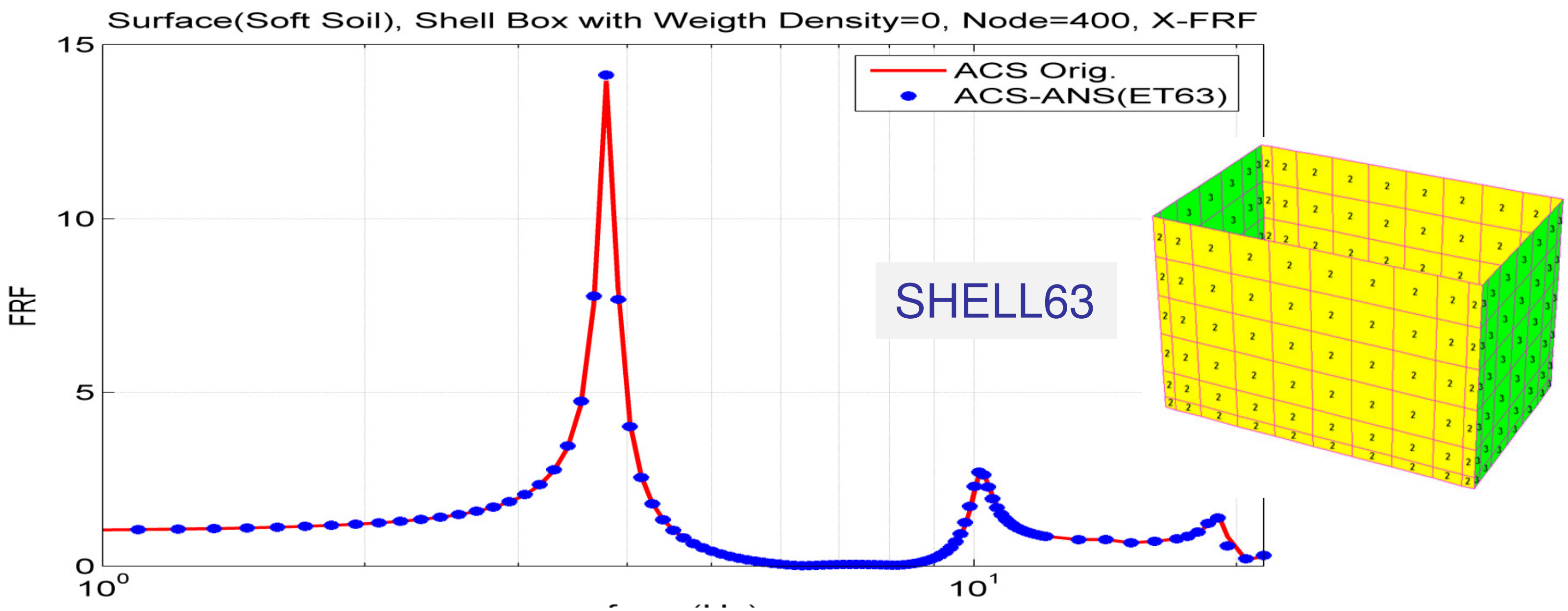
Concrete Pool ANSYS SOLID Model Example

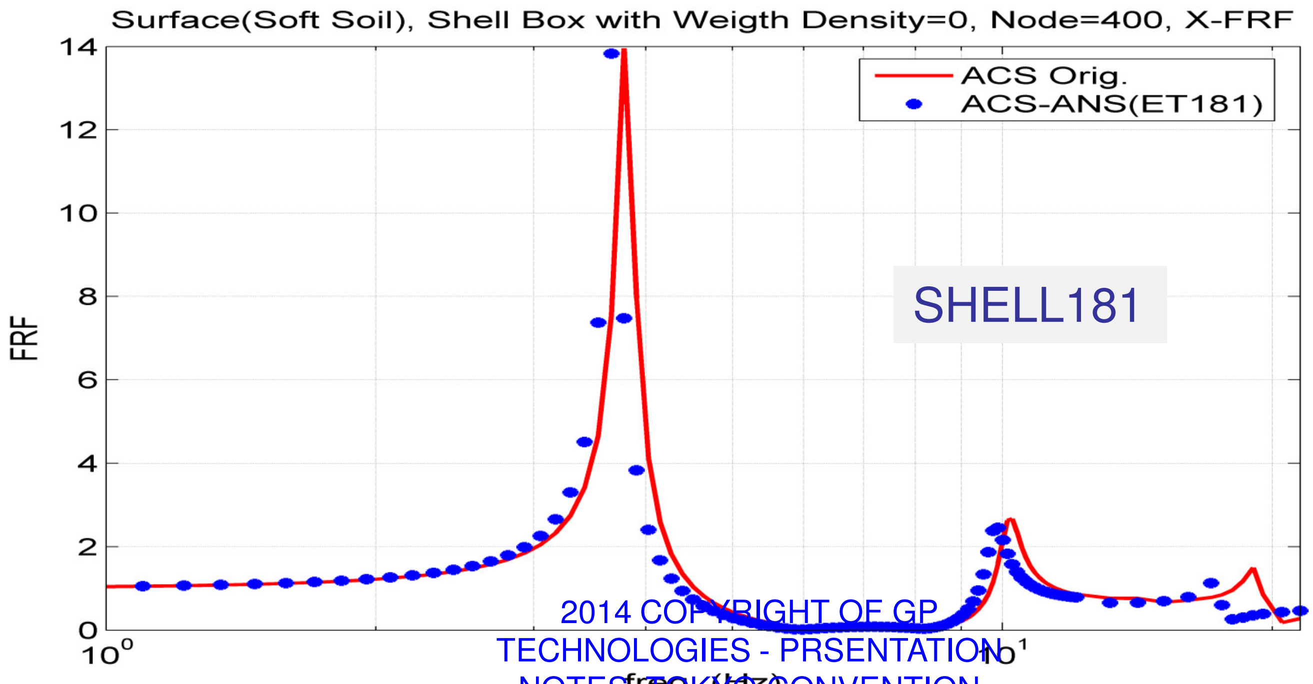






Concrete Pool ANSYS SHELL Model Example





Concluding Remarks

New Option AA capability will improve significantly the FEA modeling by using up-to-date ANSYS FE types.

- Build excavated soil and structural models in ANSYS basically with no special restriction other than those of ANSYS
- Access to various ANSYS FE types, including piping, shell elements including shear flexibility, etc.
- Include rigid links, constrained equations, etc.

Very practical, useful capability…