Recent Advances in Seismic Soil-Structure Interaction (SSI) Analysis of Special Structures Using ACS SASSI

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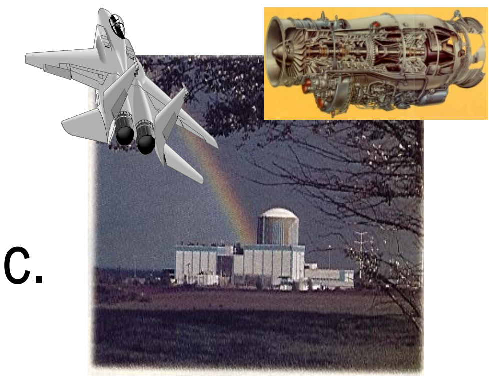


Part 1: Safety-Related Structures

Shanghai Fangzhen Information Technology Co. Seminar

Shanghai, China, April 3, 2014

Purpose of This Presentation:

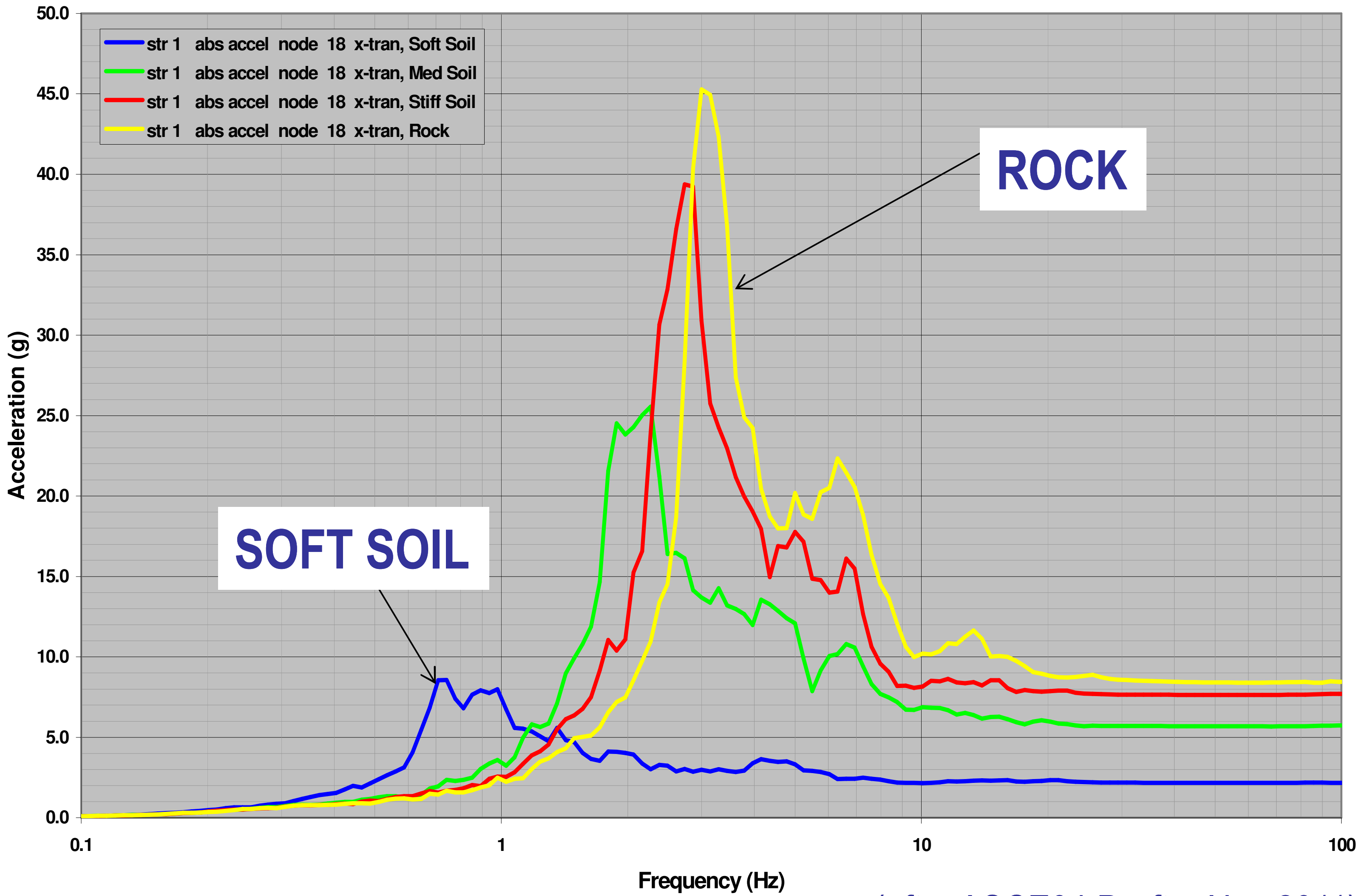
To present an overview on the ACS SASSI software application to seismic SSI analysis of nuclear and non-nuclear structures.

The ACS SASSI code includes unique SSI analysis capabilities.

The new version coming next month includes a number of advances that were developed based on the *new recommendations of the ASCE 04-2014 standard on "Seismic Analysis of Safety-Related Nuclear Structures"* that will be published in the next months. The new US standard includes a number of engineering analysis advancements of SSI analysis.

SSI Effects on Nuclear Structures

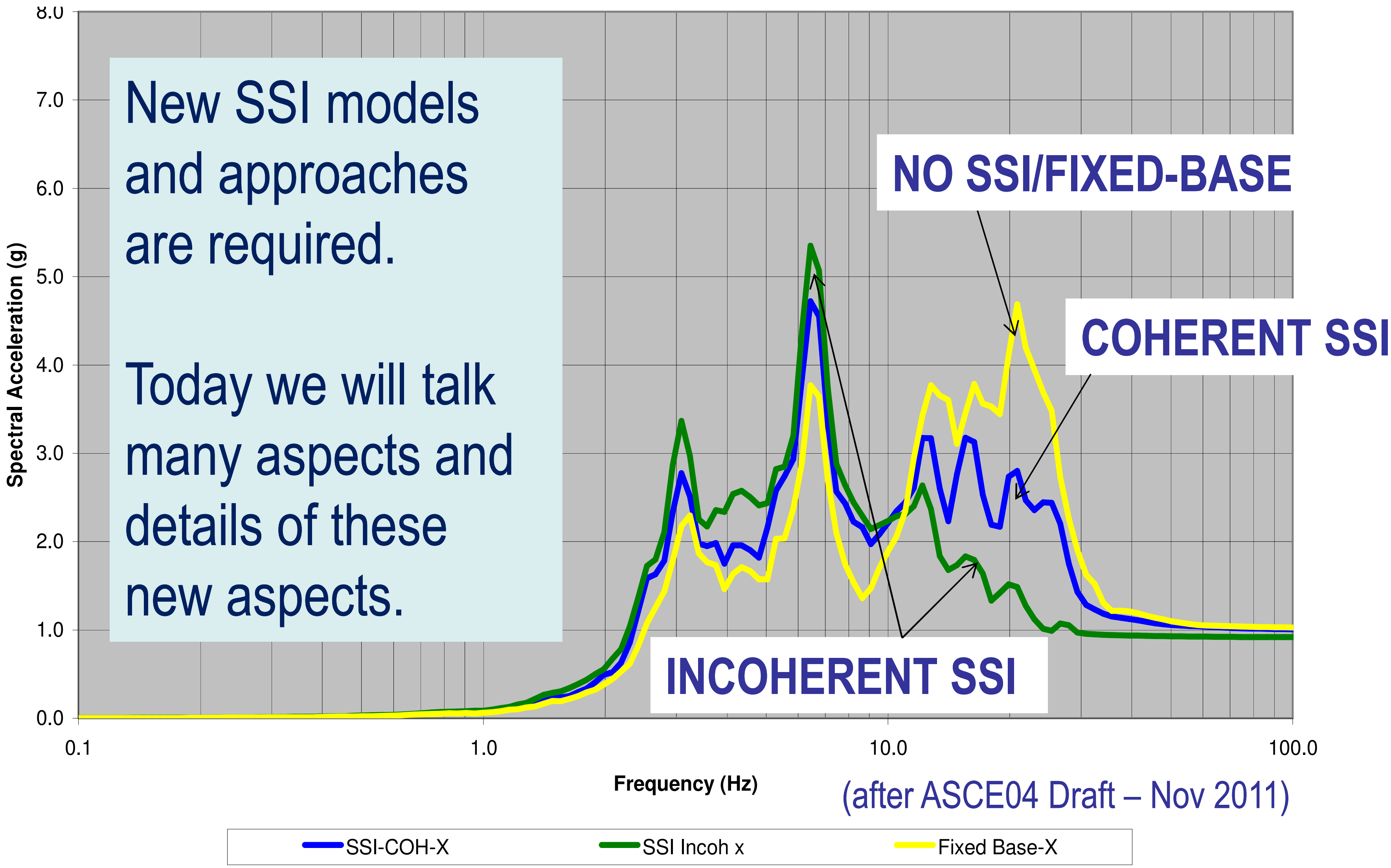
EPRI AP1000 Stick 5% Damping ISRS at Top of SCV



(after ASCE04 Draft – Nov 2011)

SSI Effects on Nuclear Structures on Rock Sites

EPRI AP1000 Stick 5% Damping ISRS at Top of SCV



(after ASCE04 Draft – Nov 2011)

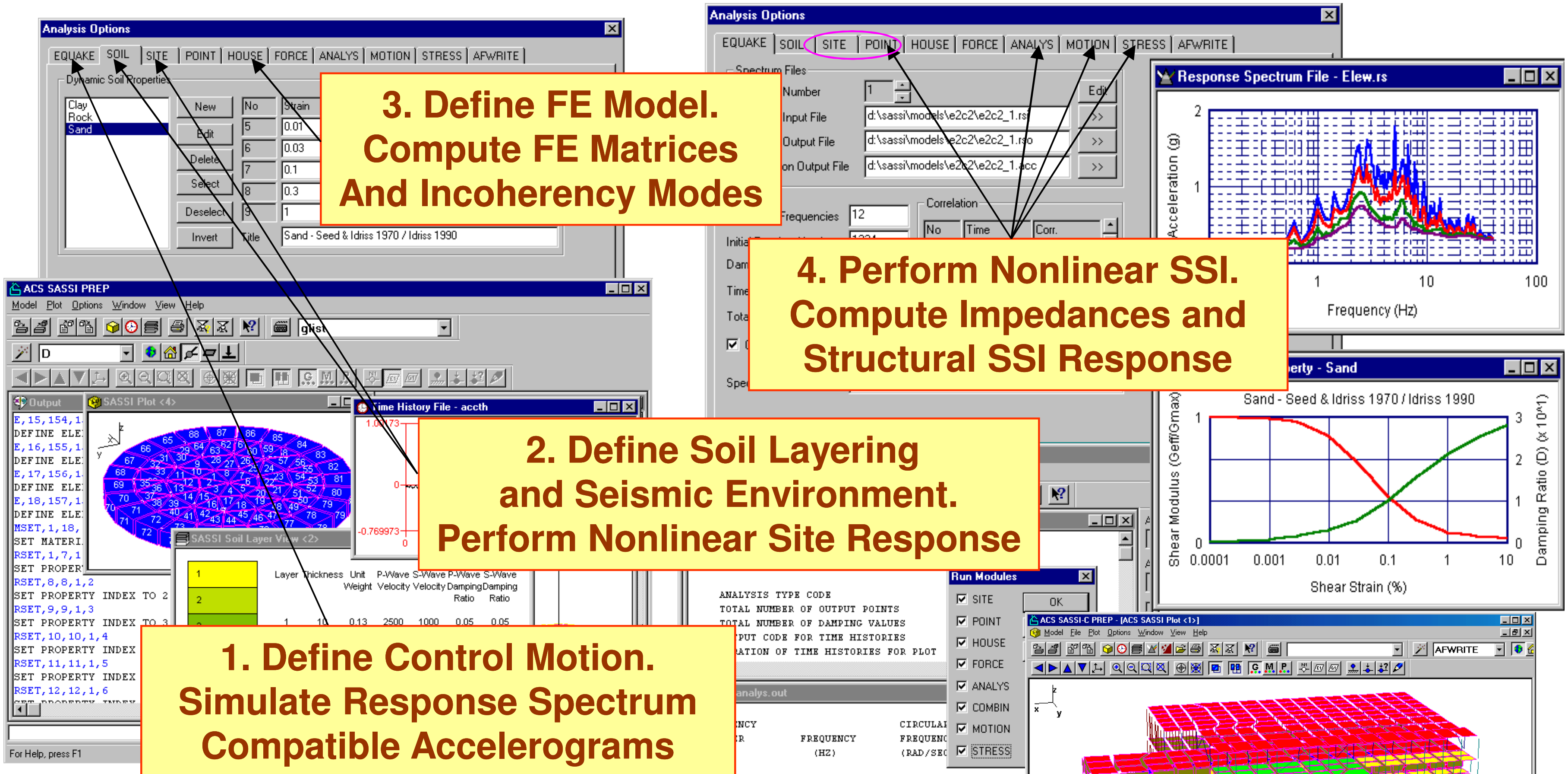
ACS SASSI NQA Software for Seismic SSI

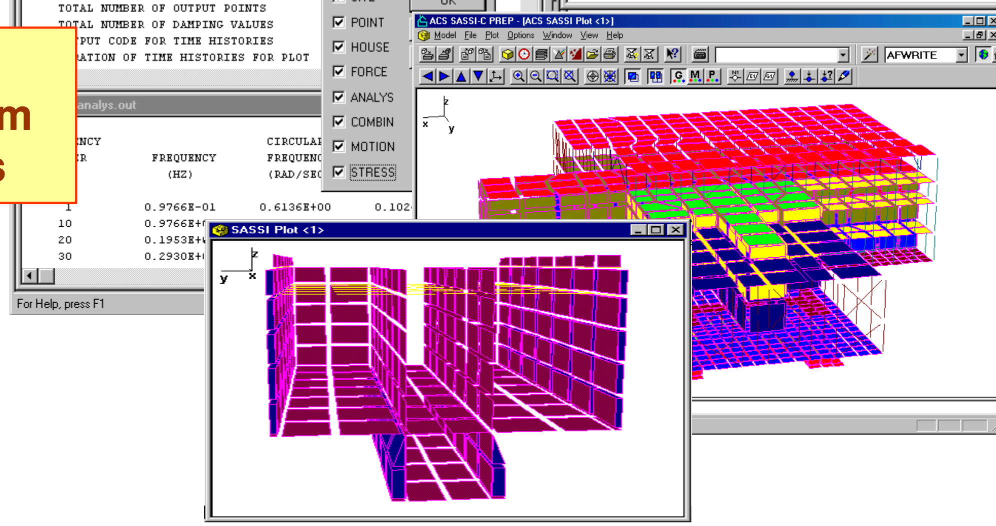
The ACS SASSI software is a *specialized seismic soil-structure interaction (SSI) analysis computer code with unique engineering capabilities, that combines stochastic 3D seismic wave modeling and simulation with finite element computations.* To access the ACS SASSI page click http://www.ghiocel-tech.com/engineeringTools.html#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

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

ACS SASSI approaches includes all the SSI approaches validated by EPRI (2007 EPRI TR# 1015111) and accepted by US NRC (ISG-01,2008) for new reactor designs in US, plus new ones included in ASCE 04-2014.

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





ACS SASSI

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ACS SASSI Used for Many US and International Commercial Projects for NPP Structures

Unique specialized SSI software used by large nuclear energy design corporations including Westinghouse for AP1000 and SMRs, Toshiba for AP1000S and ABWR, Mitsubishi Heavy Industries for APWR, Hitachi-GE for ABWR, KEPCO for APR1400, CANDU Energy for CANDU 6, AREVA/MHI for ATMEA1, AREVA for US-EPR1500. Used by many civil engineering structural design subcontractors for NPPs or other corporations for large bridges on piles, caissons, dams, tunnels, buried storage tanks, etc.

In US also used by DNFSB and NRC for confirmatory SSI analysis and by some DOE national labs, as Brookhaven National Labs and Argonne National Labs.

In China, used by CNPE Beijing on various projects, SNERDI Shanghai and SNPDRI Beijing for CAP1000, GEDI Guangzhou for CPR1400. Used by NSC Beijing for confirmatory SSI analyses.

Used by IAEA for several projects in Armenia and Russia.

Application Areas for Dynamic SSI Analysis

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

SSI Analysis Inputs and Outputs

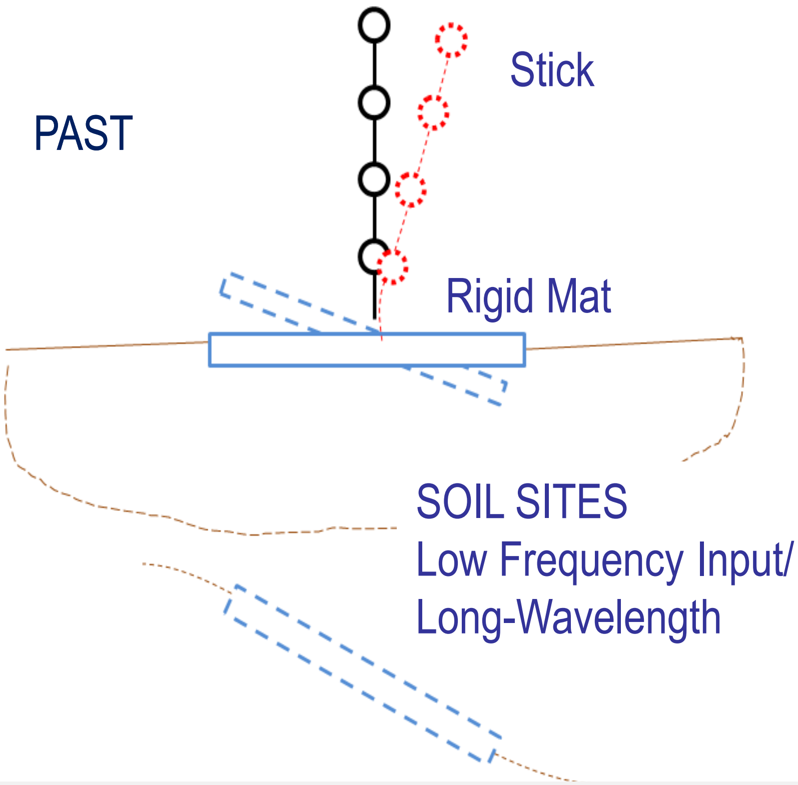
Inputs:

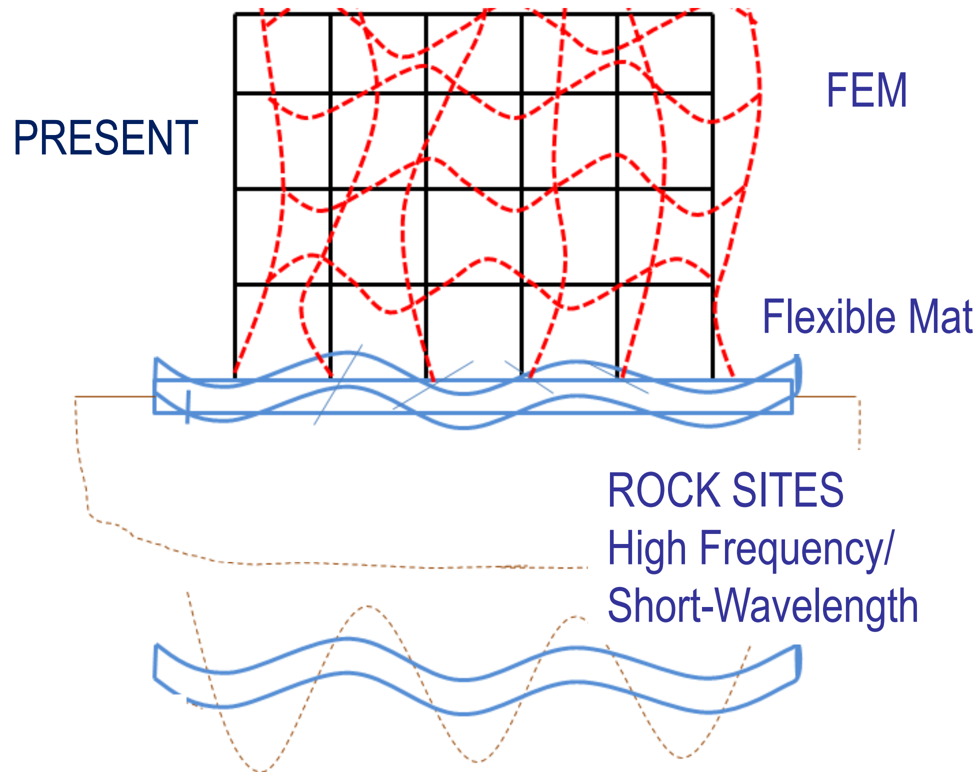
1. Seismic Input: Control Motion, Local Correlation and Spatial Coherency
2. Vibration: External Force Time Histories
3. Soil Layering: Geometry and Dynamic Properties (Geff, Deff) per Layer
4. Baserock: Depth & Dynamic Properties (G,D)
5. Structure: Structural Configuration - FE Modeling, Nodal Masses,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

Outputs:

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

Past and Present Engineering Applications



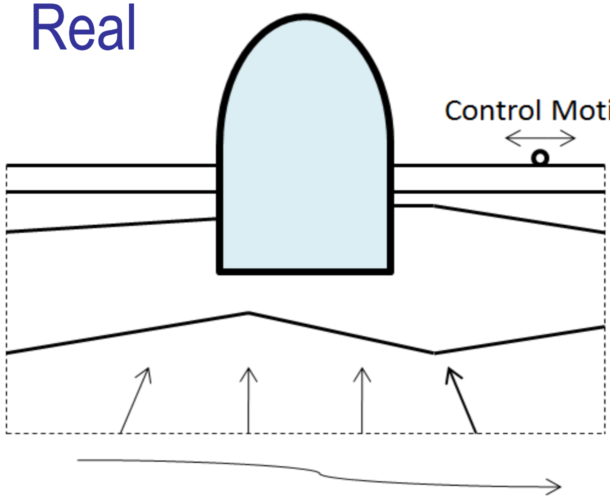


PAST EXPERIENCE:
- Low Frequency Inputs (Long-Wavelength)
- Soil Sites
- Stick Models with Rigid Mats
-Input Soil Motion as Rigid Body Motion (Coherent, 1D Propagation of S and P Waves)

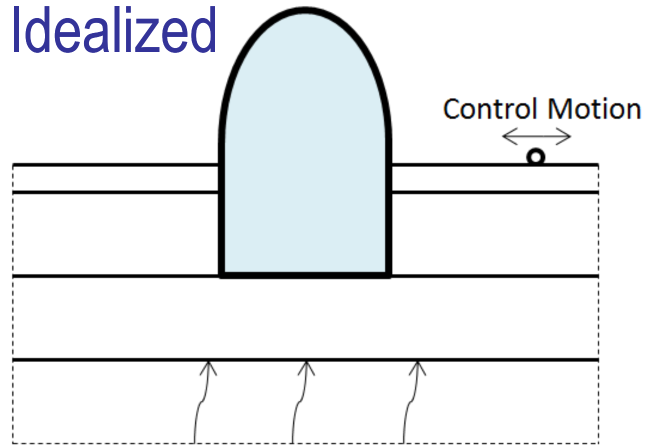
PRESENT EXPERIENCE:
- Low and High Frequency Inputs (Long-and Short Wavelengths)
- Soil and Rock Sites
- Finite Element Models, Stick for Preliminary
- Input Soil Motions as Rigid Body (Coherent) and Elastic Body Wave Motion (Incoherent, 3D Waves)

Nuclear Structure SSI Analysis Methods

Real

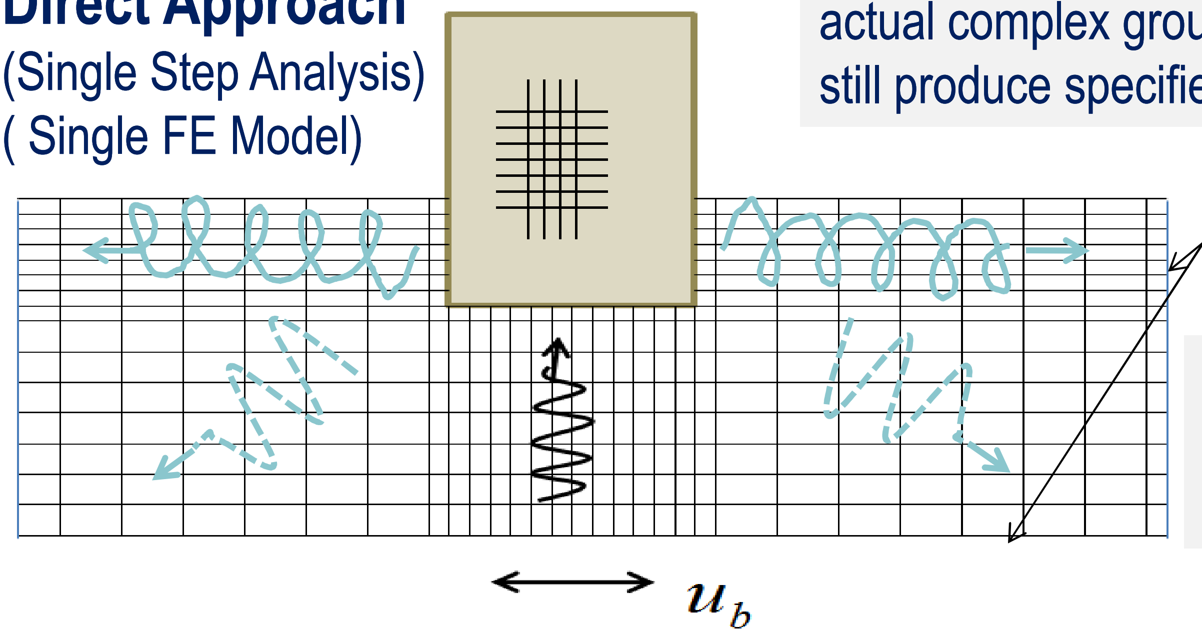


Idealized



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

Direct Approach
(Single Step Analysis)
(Single FE Model)



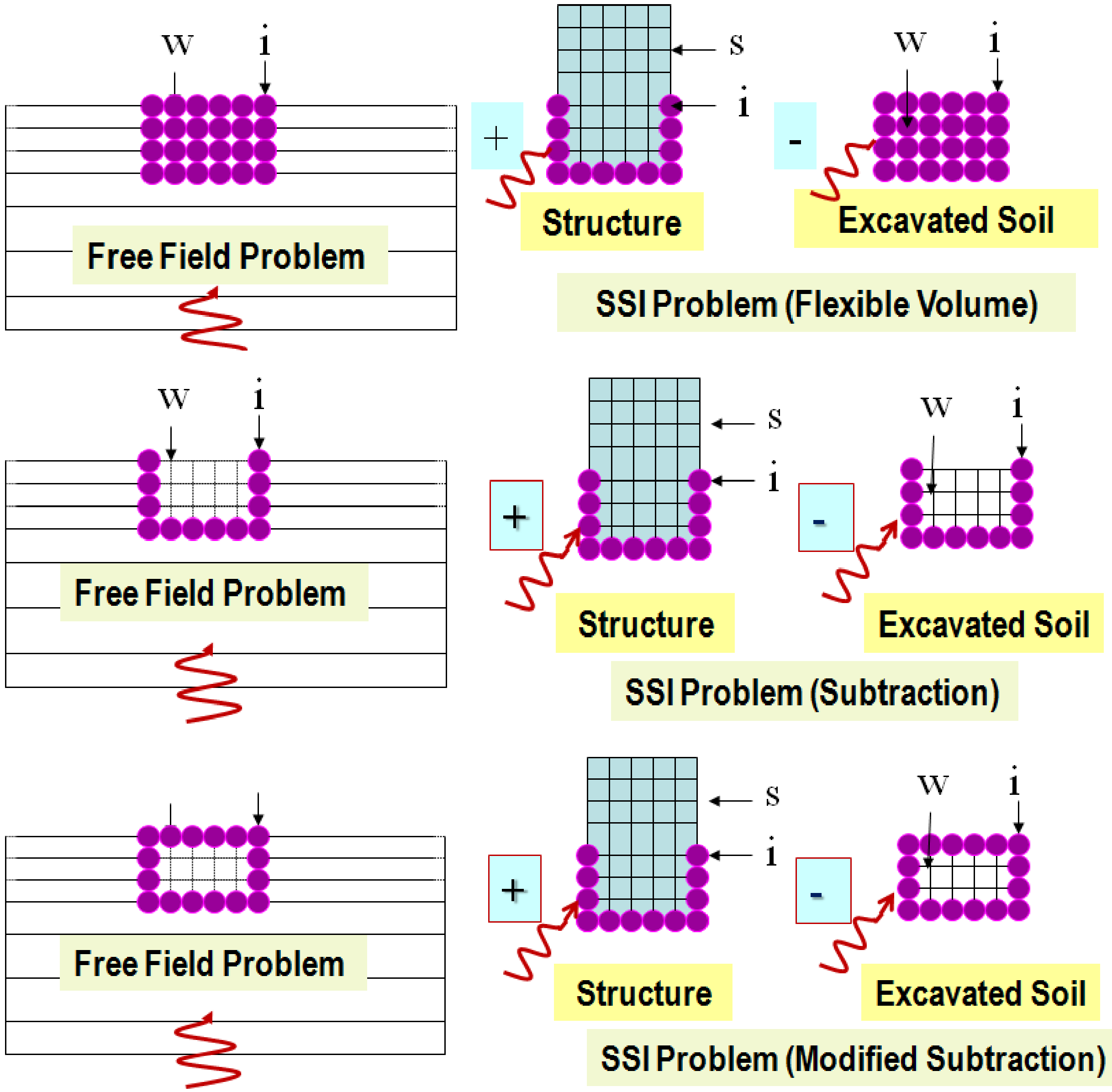
Enormous amount of solid elements; 90% of FE elements are in soil media

ACS SASSI Flexible Volume Substructuring

FV

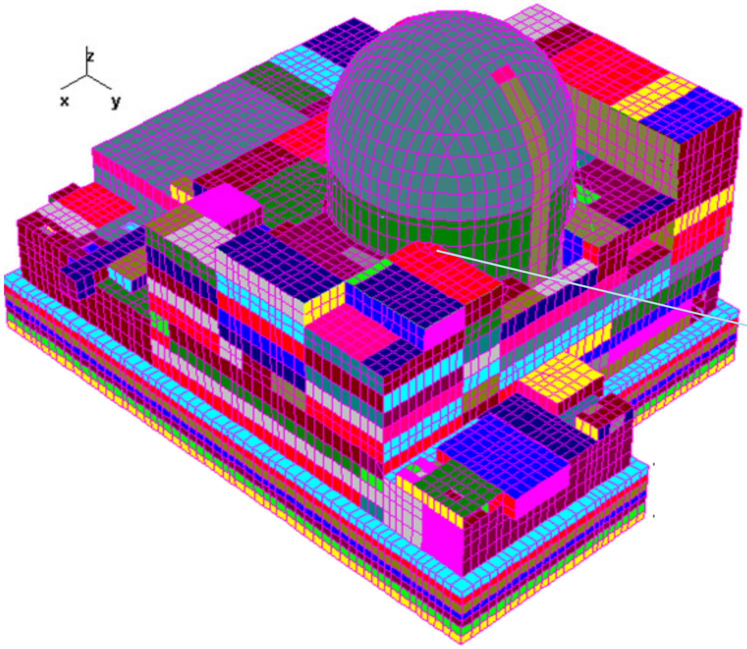
FI-FSIN
SM

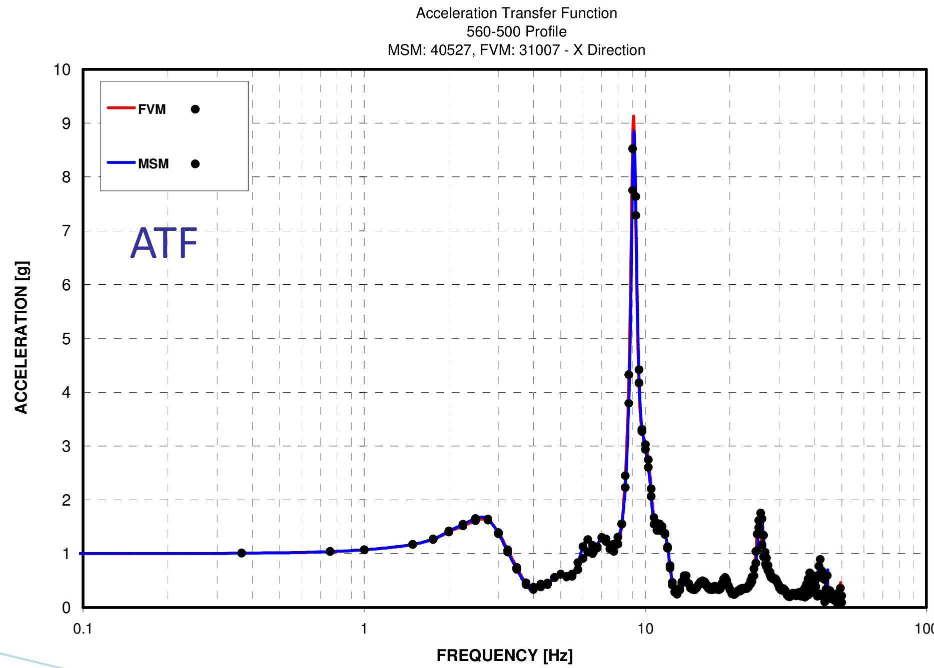
FI-EVBN
MSM

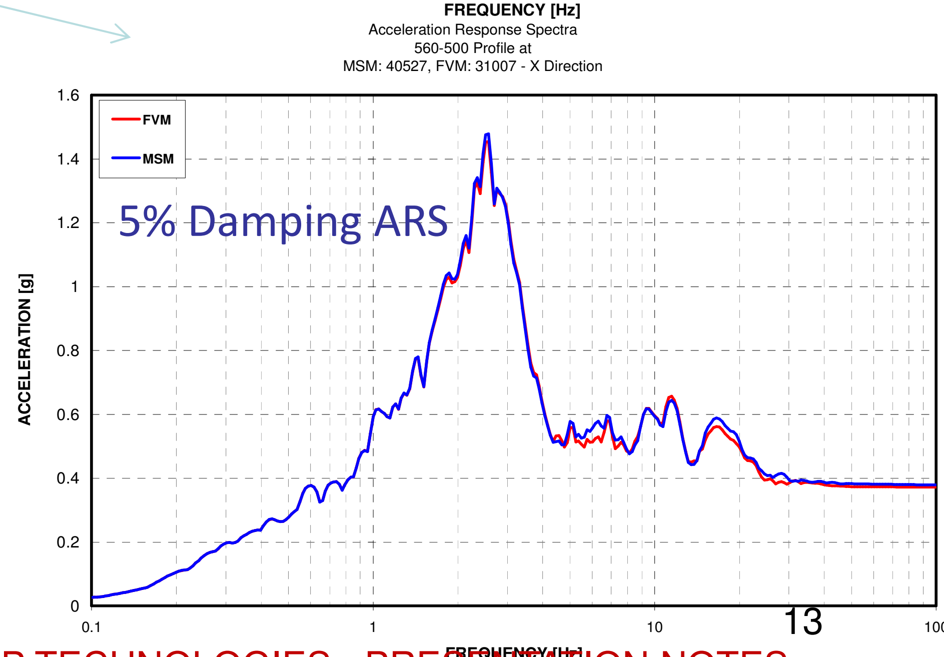


Flexible Volume Method Comparisons for A NI Complex

RB Complex SSI Model

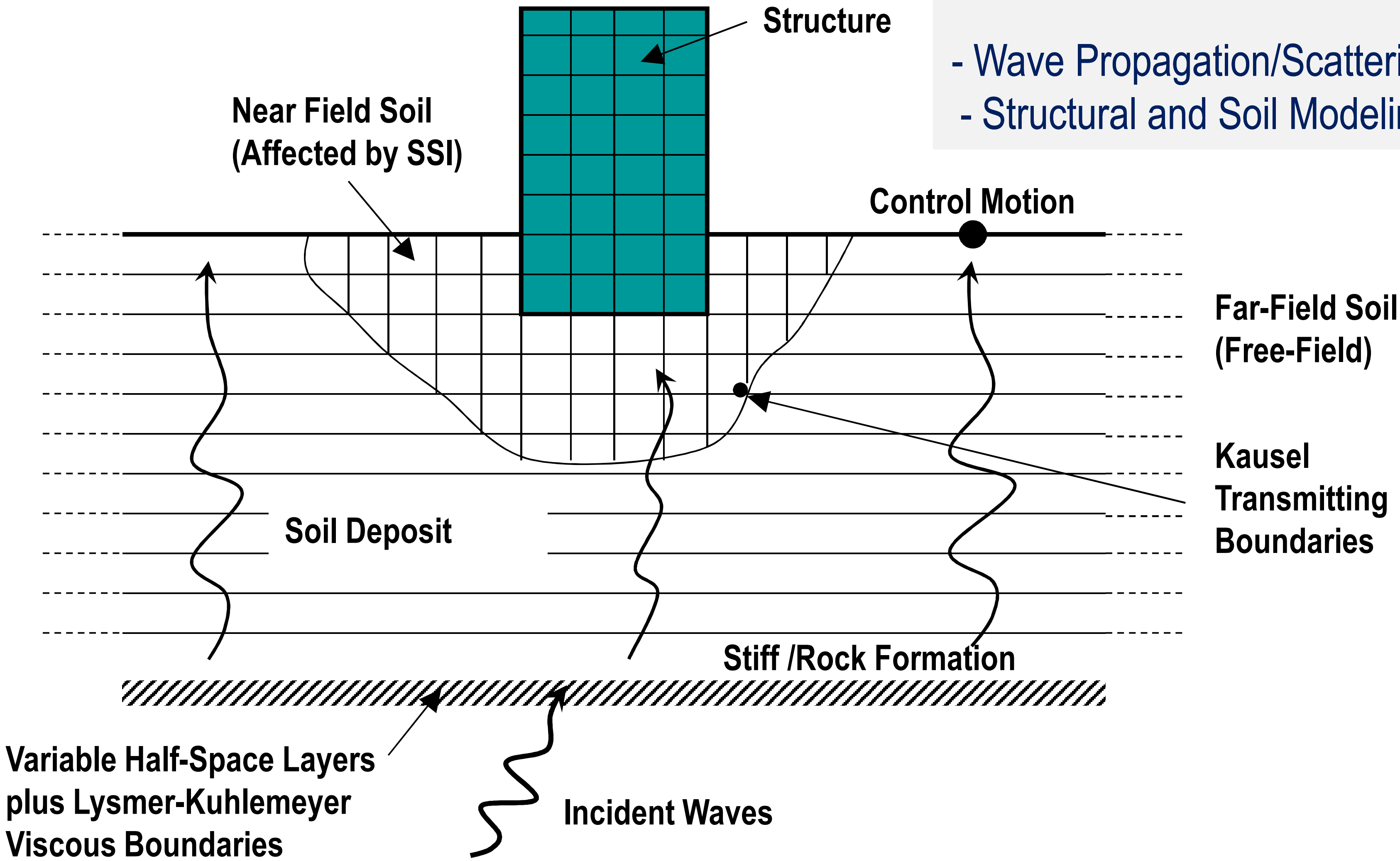






Ghiocel et al., SMIRT22, 2013

Seismic SSI Modeling in ACS SASSI

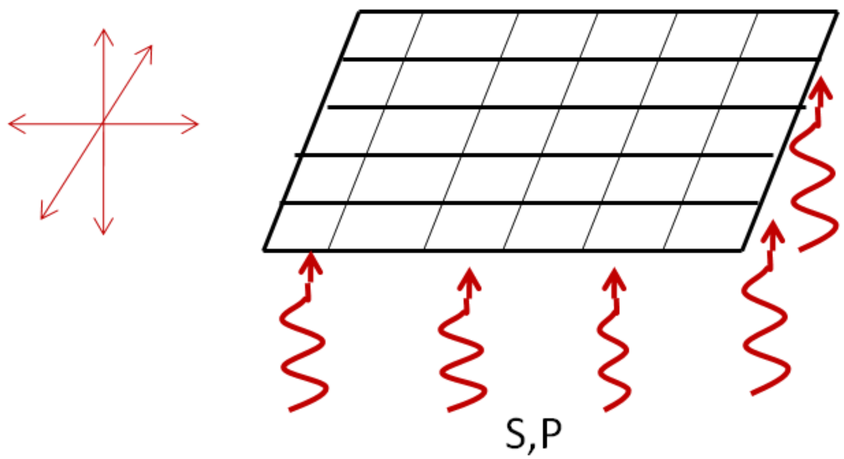


Seismic SSI Analysis Aspects:

- Wave Propagation/Scattering
- Structural and Soil Modeling

Wave Propagation Models: Coherent vs. Incoherent

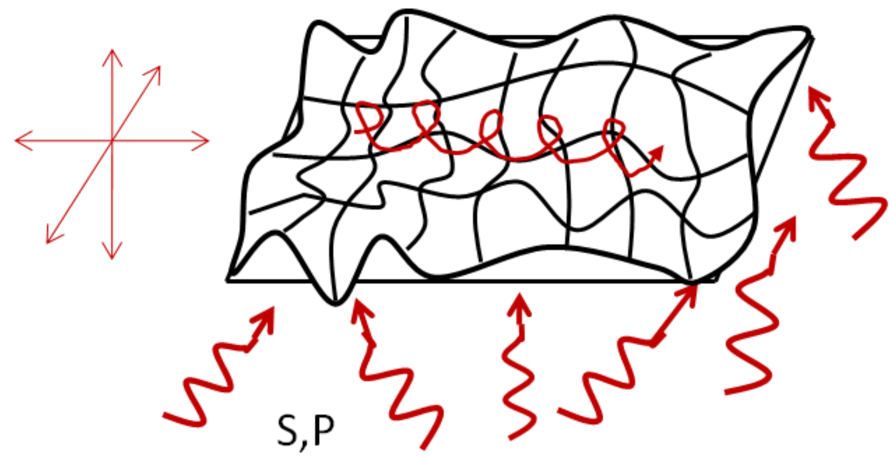
3D Rigid Body Soil Motion (Idealized)



1 D Wave Propagation Analytical Model (Coherent)

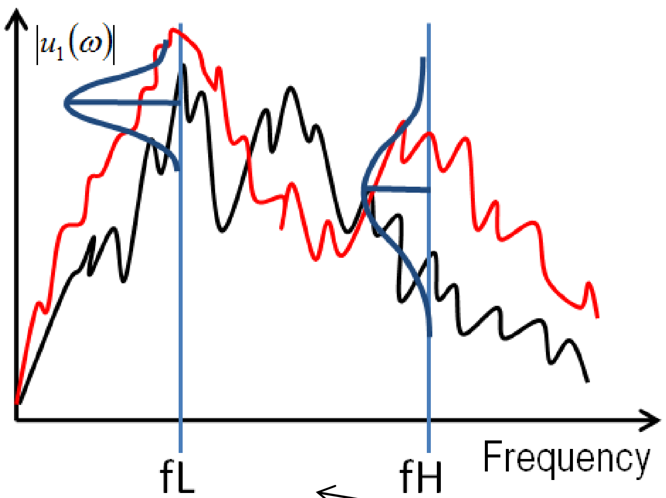
Vertically Propagating S and P waves (1D)
- No other waves types included
- No heterogeneity random orientation and arrivals included
- Results in a rigid body soil motion, even for large-size foundations

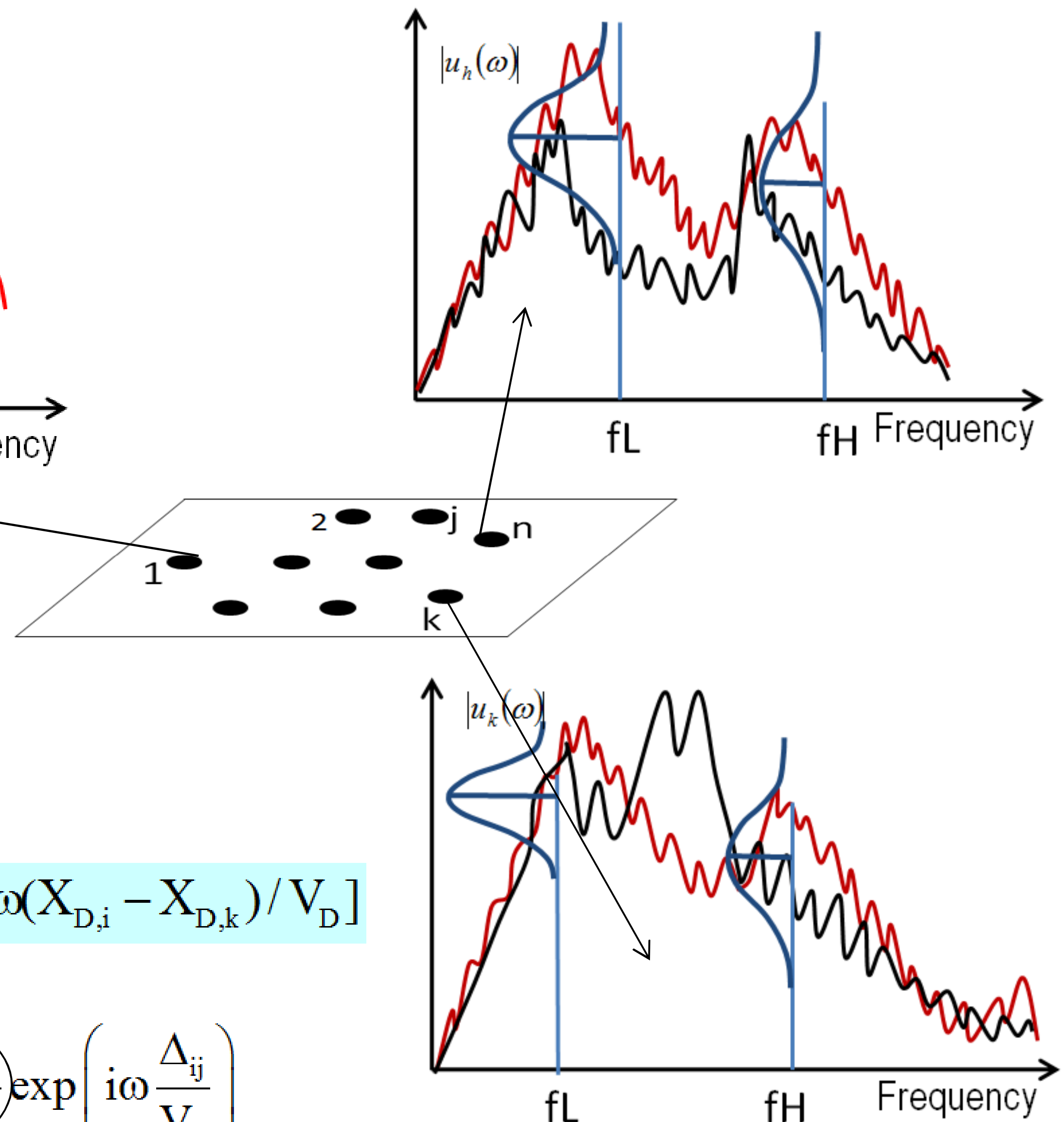
3D Random Wave Field Soil Motion (Realistic)



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

3D Stochastic Wave Model: Incoherent Motion Field





Coherent Function

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

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

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

2007 Abrahamson Coherence for Hard-Rock and Soil Sites

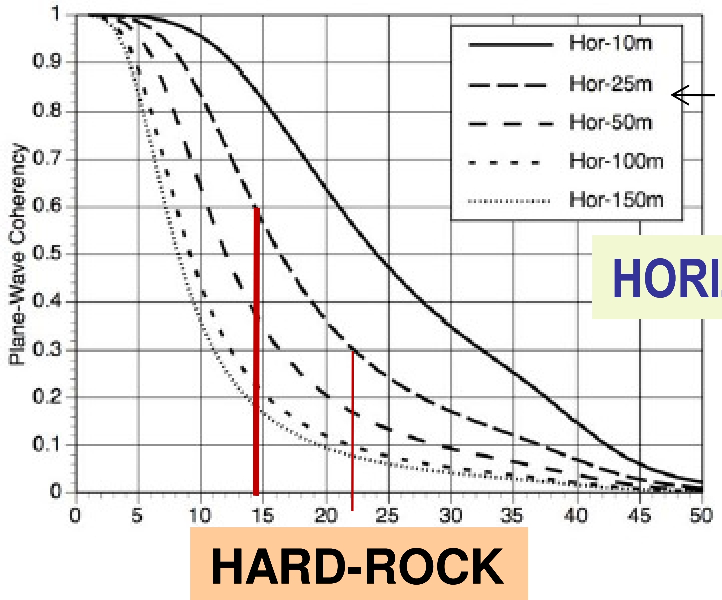


Figure 6-1
Plane-Wave Coherency for the Horizontal Component

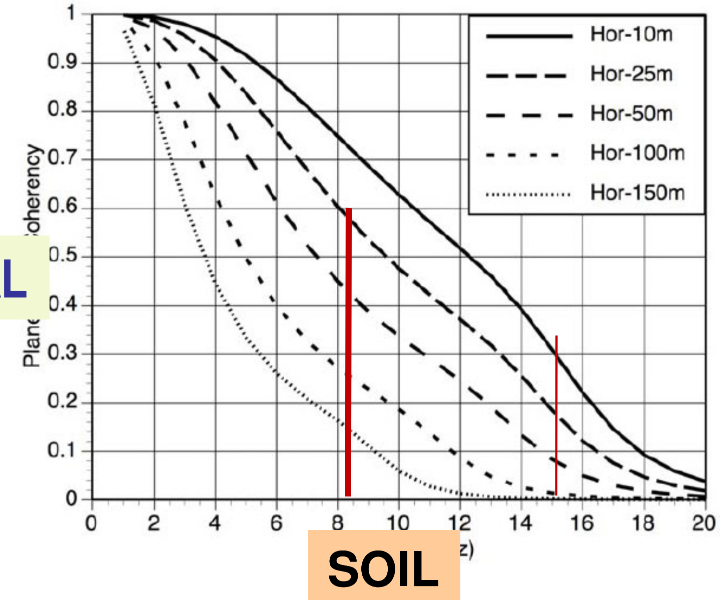


Figure 7-1
Plane-Wave Coherency for the Horizontal Component for Soil Sites

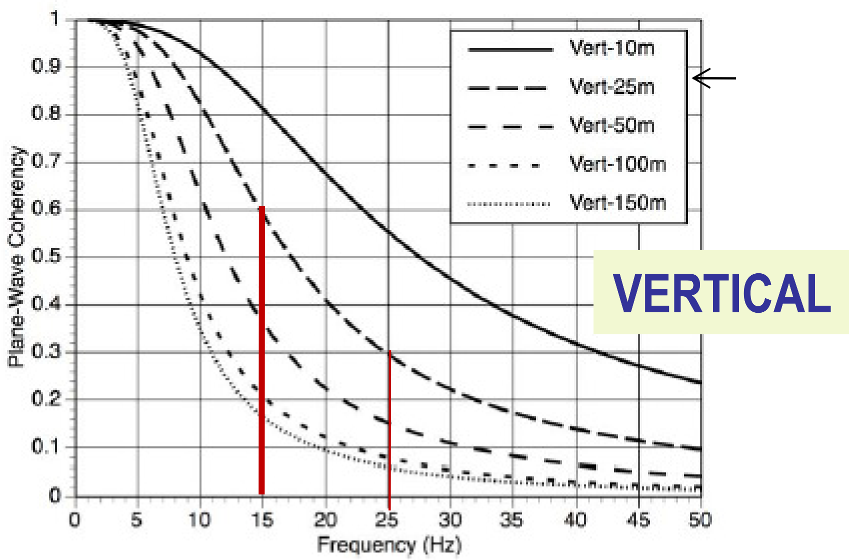


Figure 6-2
Plane-Wave Coherency for the Vertical Component

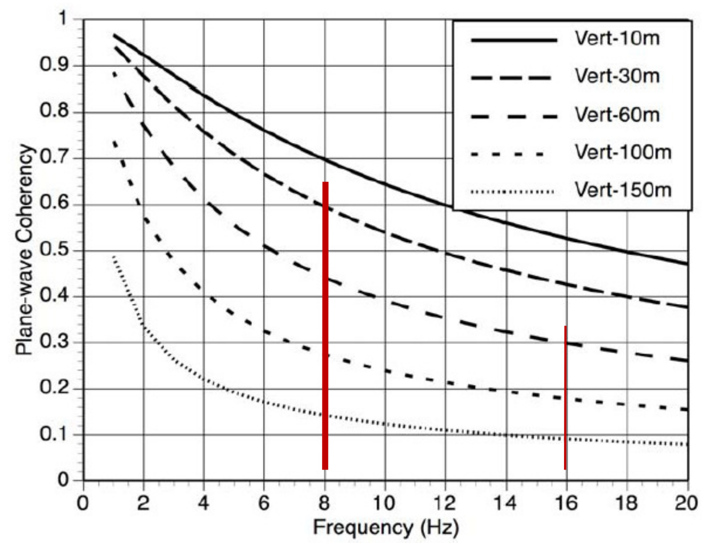
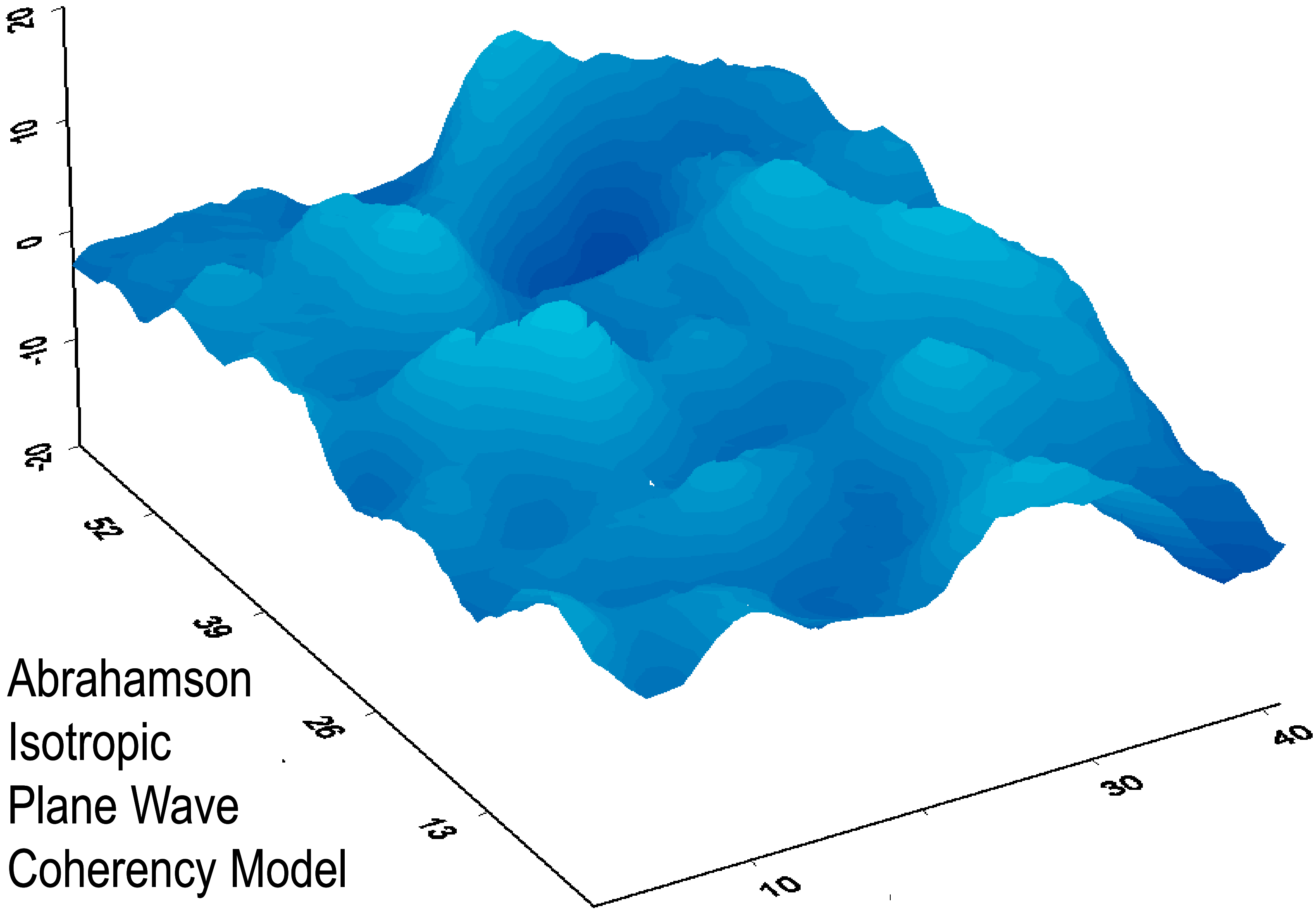


Figure 7-2
Plane-Wave Coherency for the Vertical Component for Soil Sites

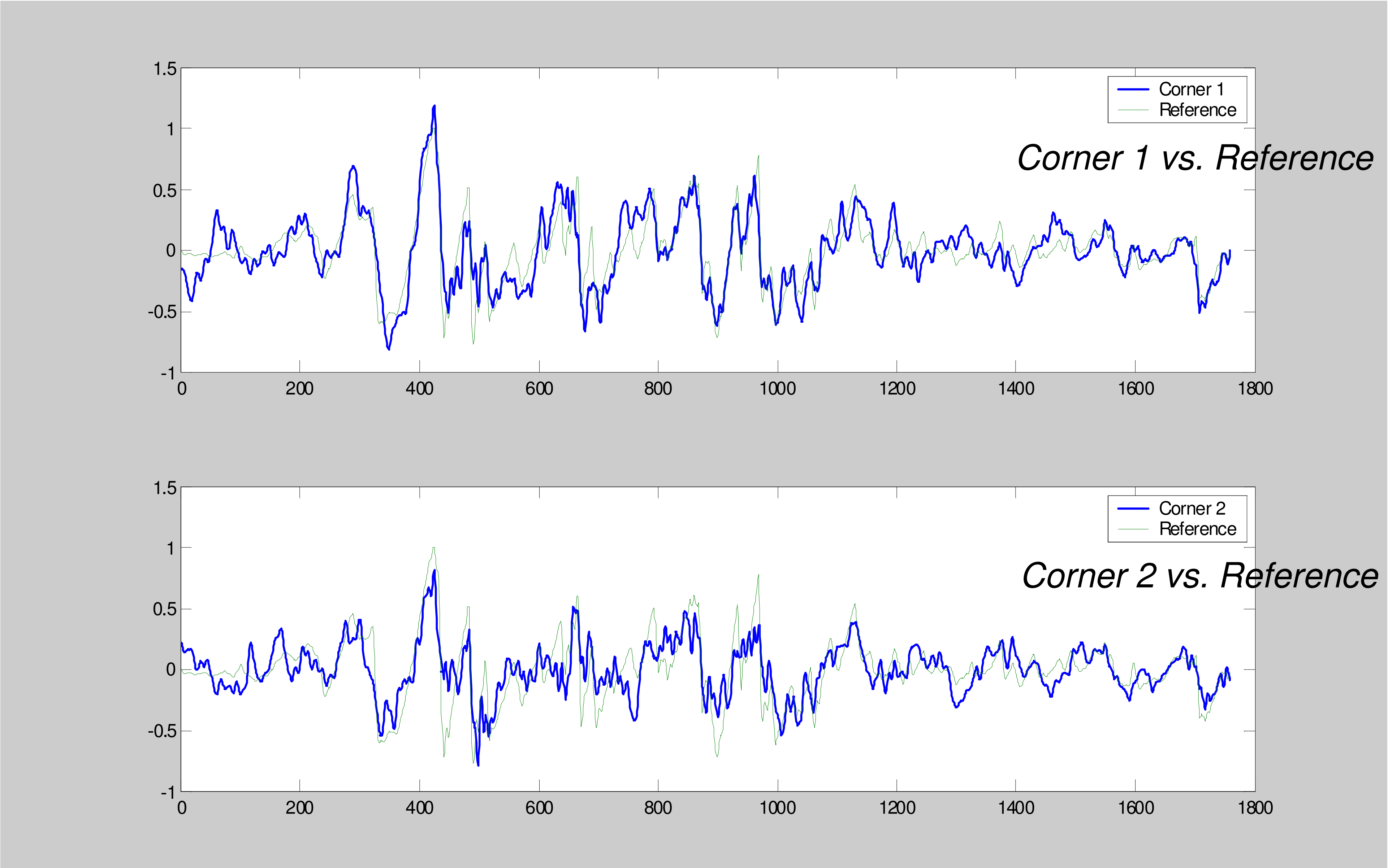
(EPRI TR # 1015110, December 2007)

Simulated Incoherent Motion Amplitude at 10 Hz



Abrahamson
Isotropic
Plane Wave
Coherency Model

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



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:

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

Structural transfer function given input at interaction nodes

Coherent ground transfer function at interface nodes given control motion

Complex Fourier transform of control motion

•Incoherent SSI response:

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

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

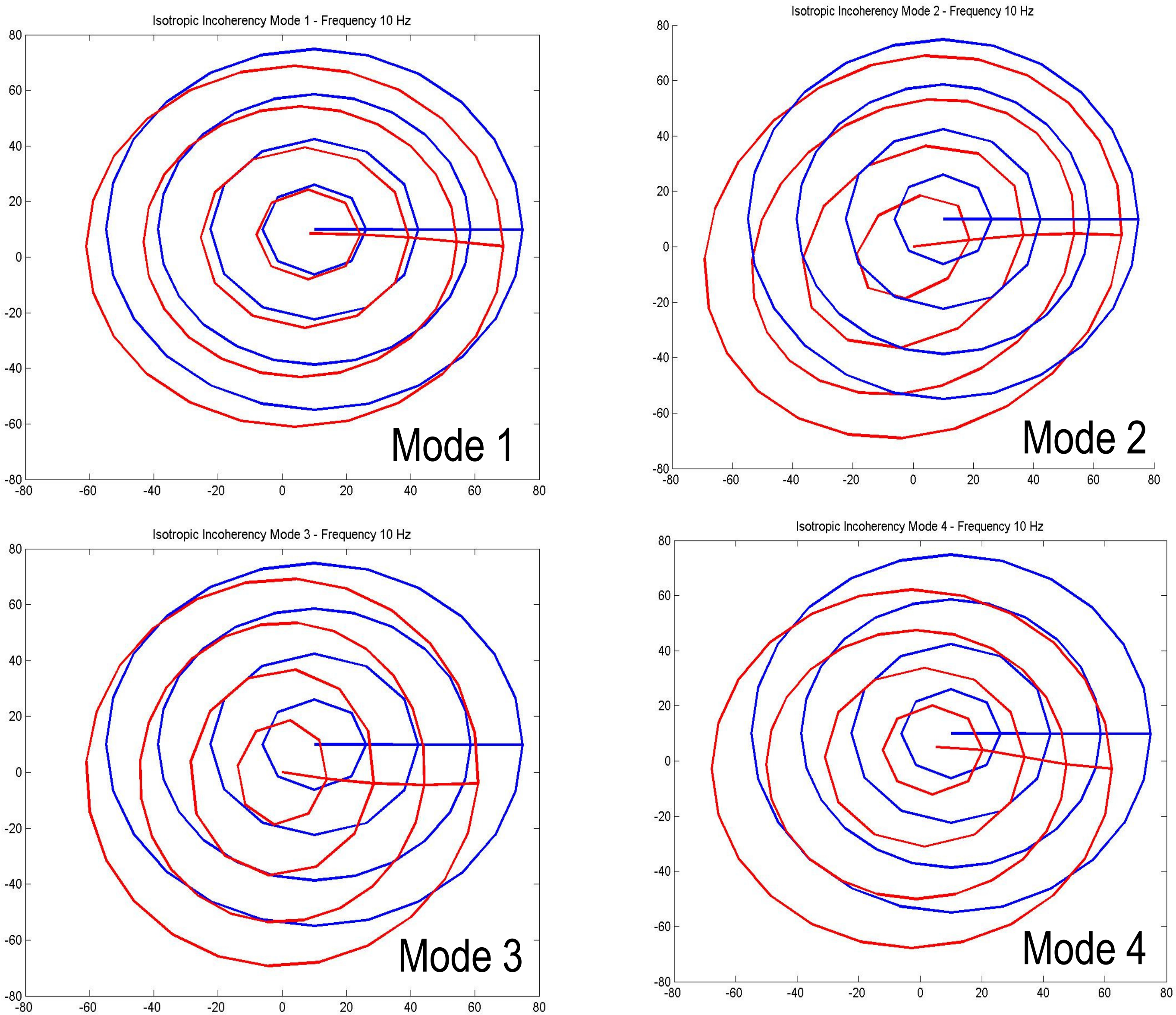
$$S_g(\omega) = [\Phi(\omega)][\lambda(\omega)]\{\eta_\theta\}$$

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

Spectral factorization of coherency kernel

Random phases (stochastic part)

Motion Incoherency Modes of Basemat at 10 Hz



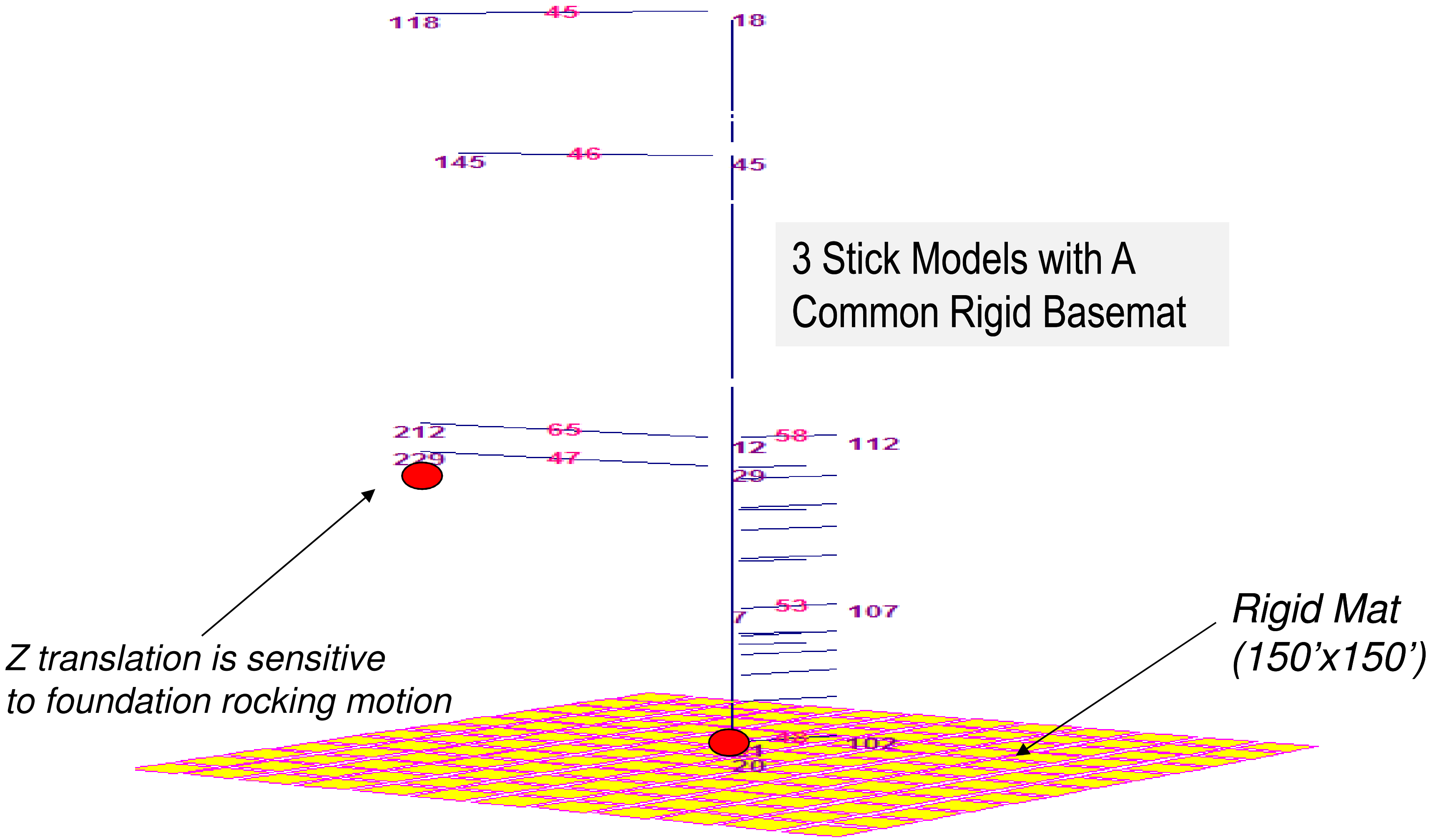
REMARKS:

1) For low frequencies 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).*

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



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.

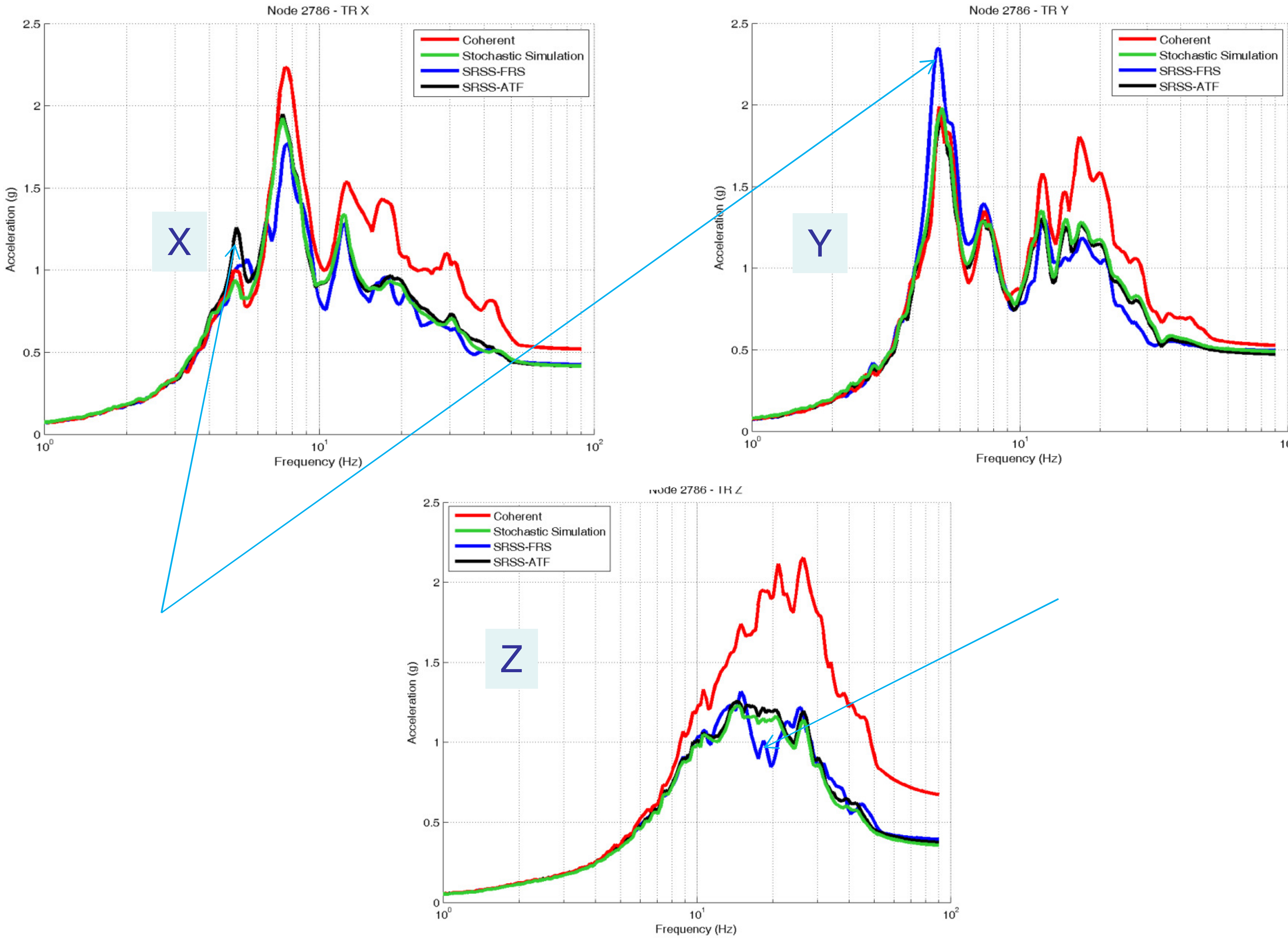
Benchmarked SASSI-Based Approaches:

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

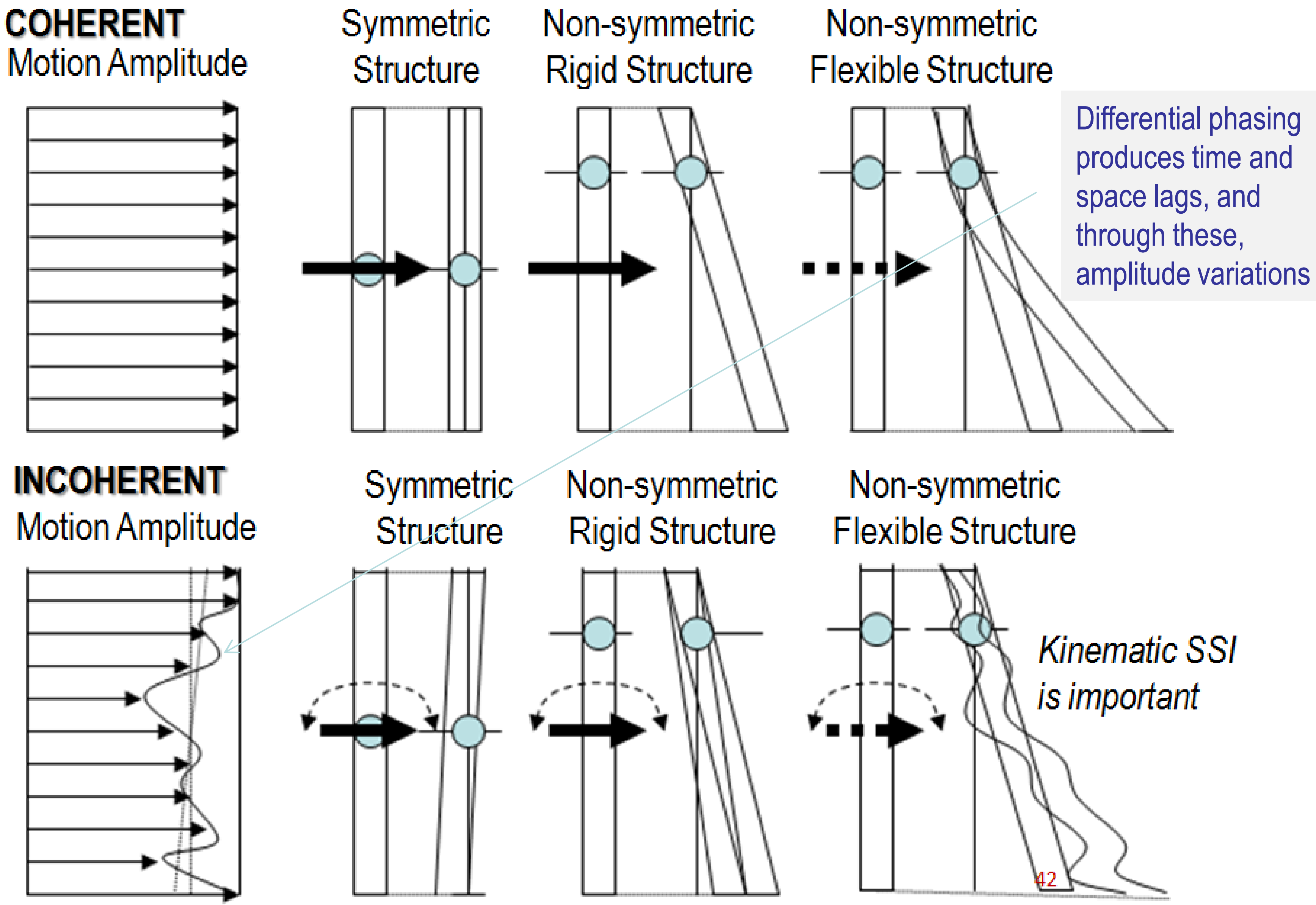
Other remarks:

- 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

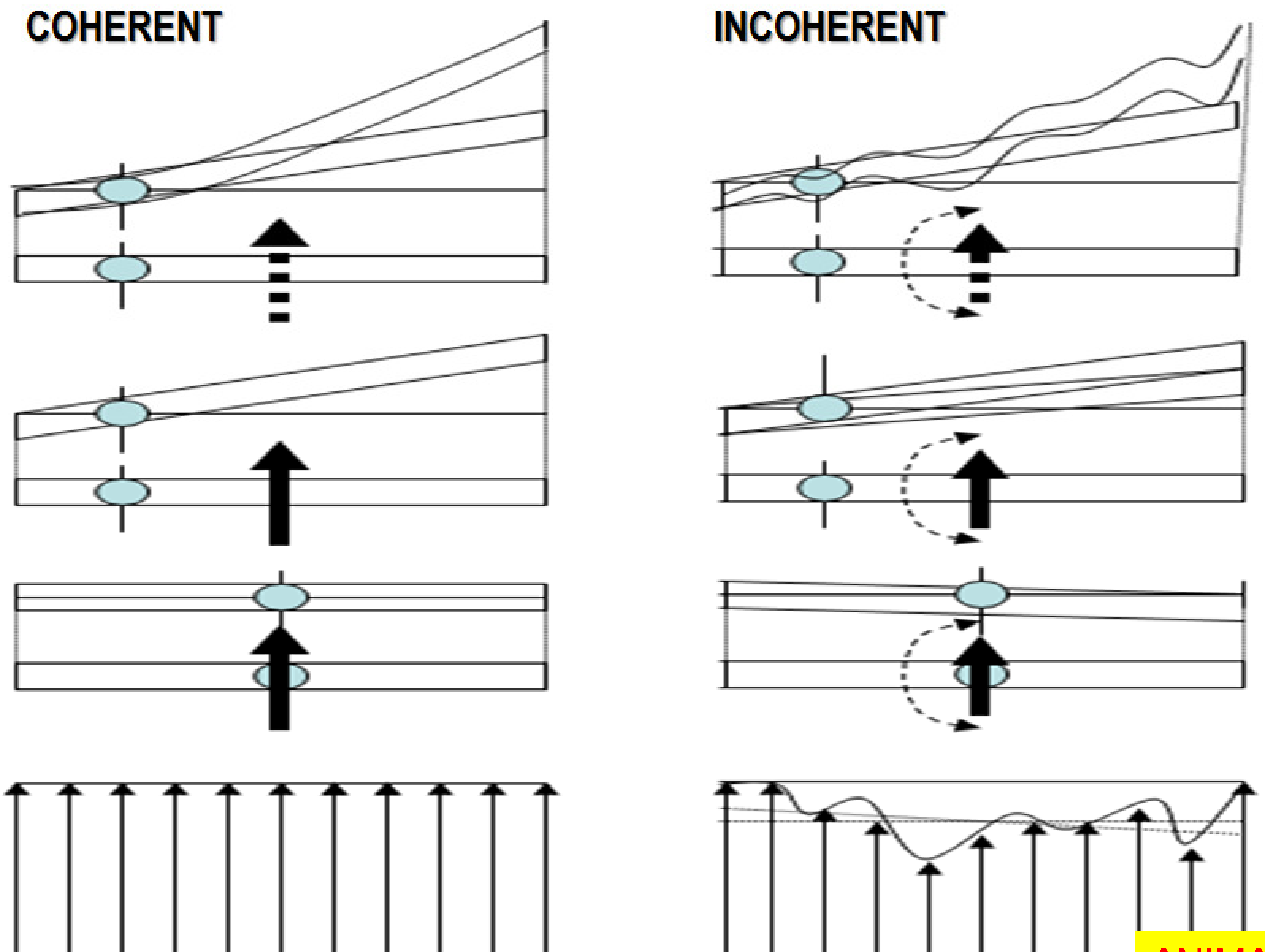
Incoherent SSI Results for RB Stick Model



Effect of Motion Incoherency Differential Phasing

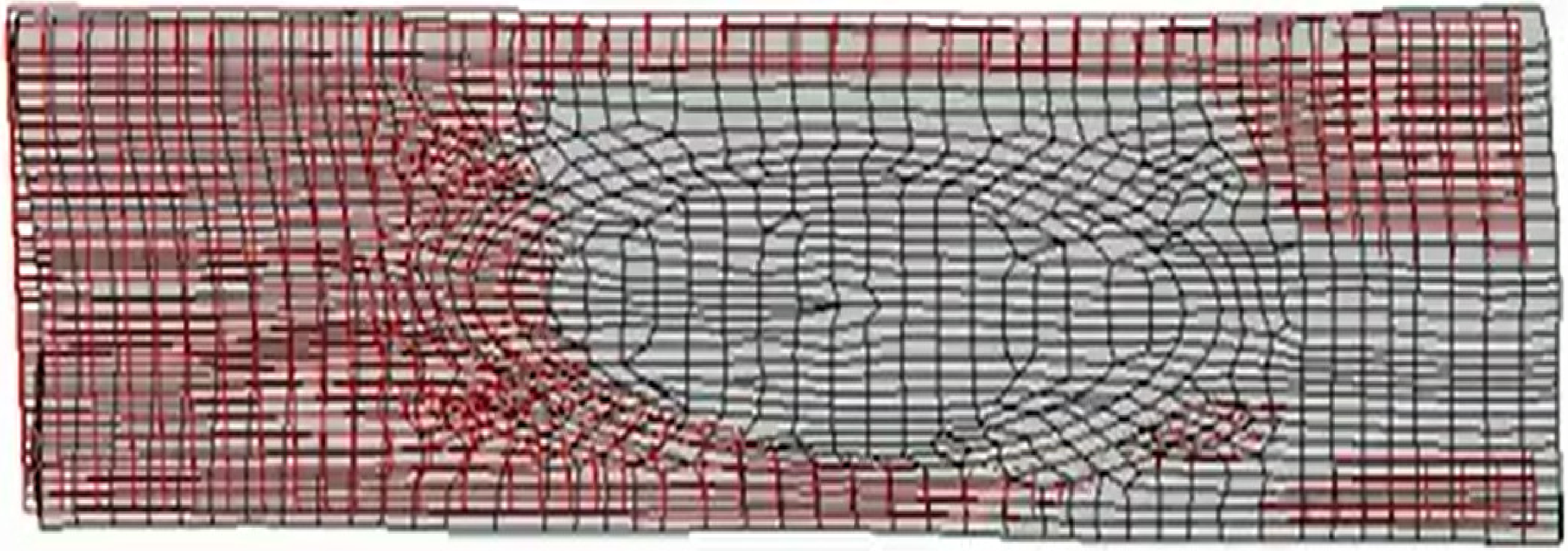


Coherent vs. Incoherent SSI Response – Vertical

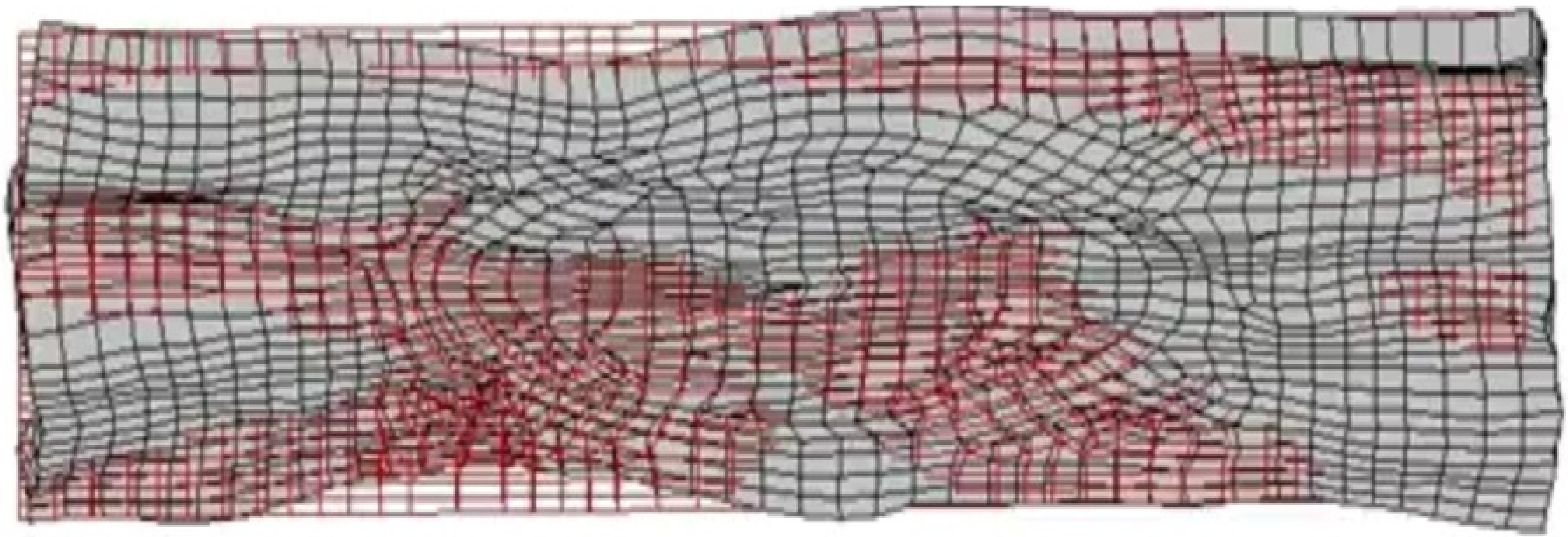


ANIMATIONS

RB Basemat SSI Response for COHERENT Inputs



RB Basemat SSI Response for INCOHERENT Inputs



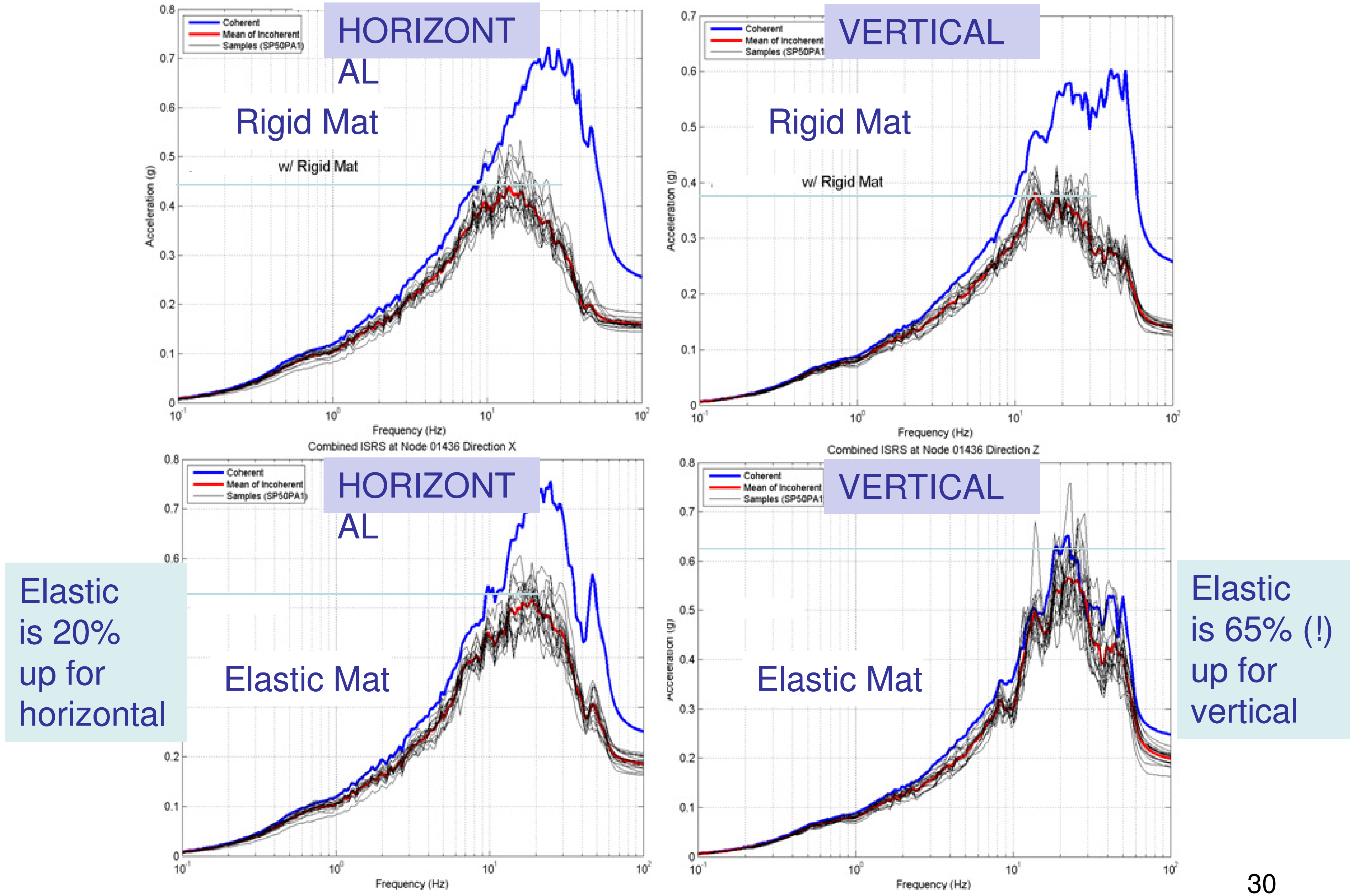
Flexible Foundations vs. Rigid Foundations

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.

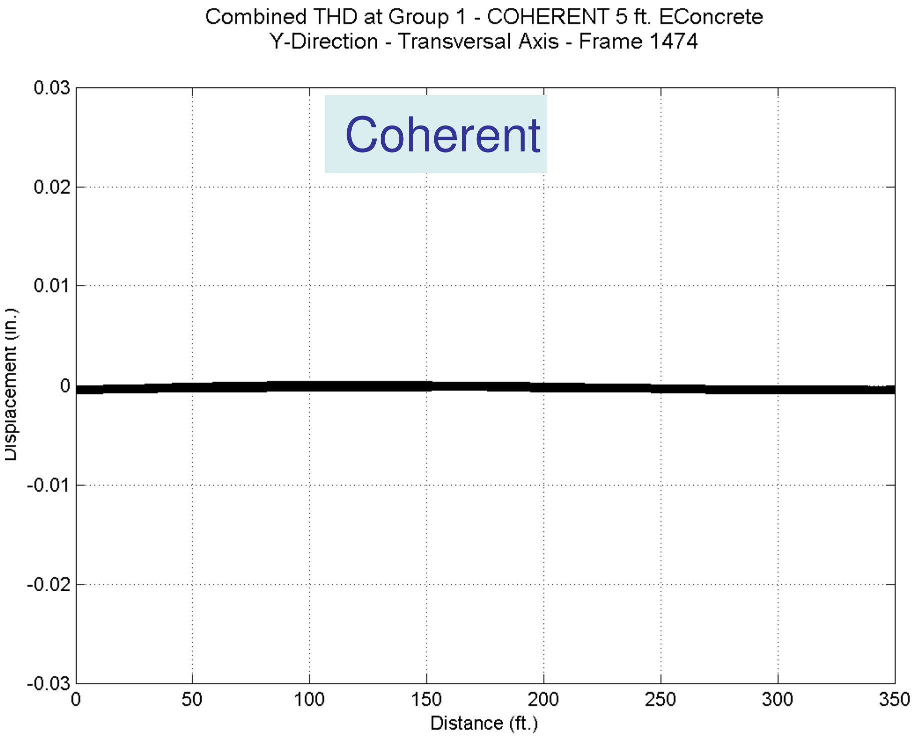
For *flexible foundations*, the incoherency-induced stochasticity of the basemat motion is driven by the local spatial variations (point variations) of free-field motion. Therefore, is much more complex and locally random, with an unsmoothed spatial variation pattern. Kinematic SSI is reduced, so that 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.

Basemat Flexibility Effects on RB Complex ISRS



Effects of Incoherency on Basemat Bending



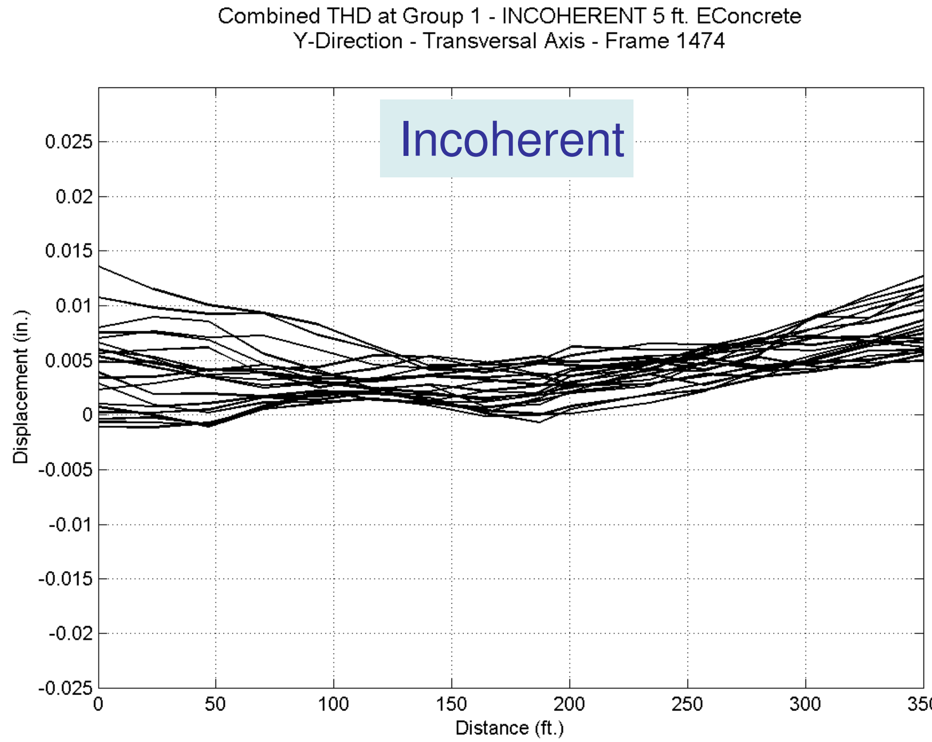


Table 1: Baseslab Bending Moments for A Soil Deposit with Vs = 3,300 ft/s

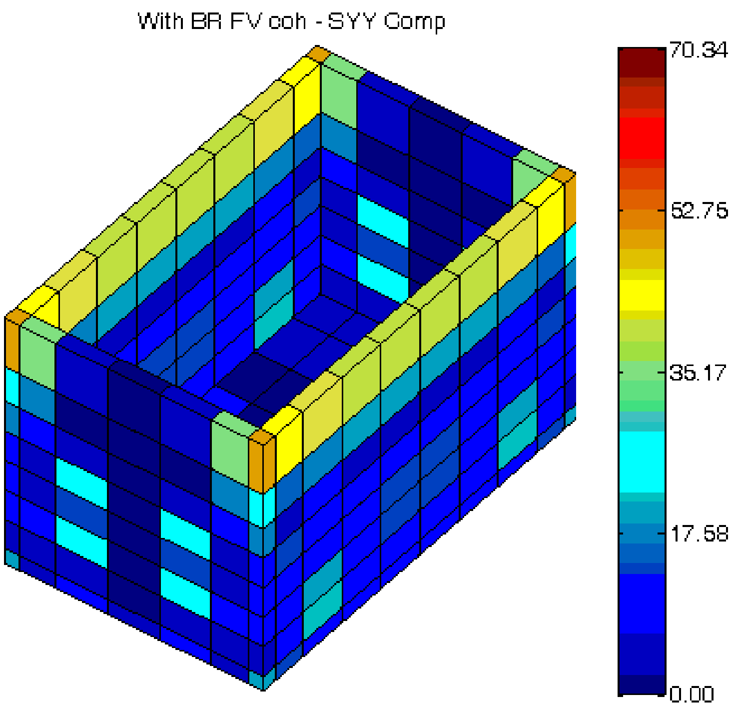
Zone #	Coherent MXX	Incoherent MXX	Ratio Inc/Coh MXX	Coherent MYY	Incoherent MYY	Ratio Inc/Coh MYY
1	10.293	15.196	1.476	9.567	14.812	1.548
2	8.345	19.986	2.395	7.197	14.901	2.070
3	10.291	13.499	1.312	9.695	15.475	1.596
4	7.404	14.859	2.007	8.386	17.199	2.051
5	7.360	14.618	1.986	7.124	14.879	2.089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

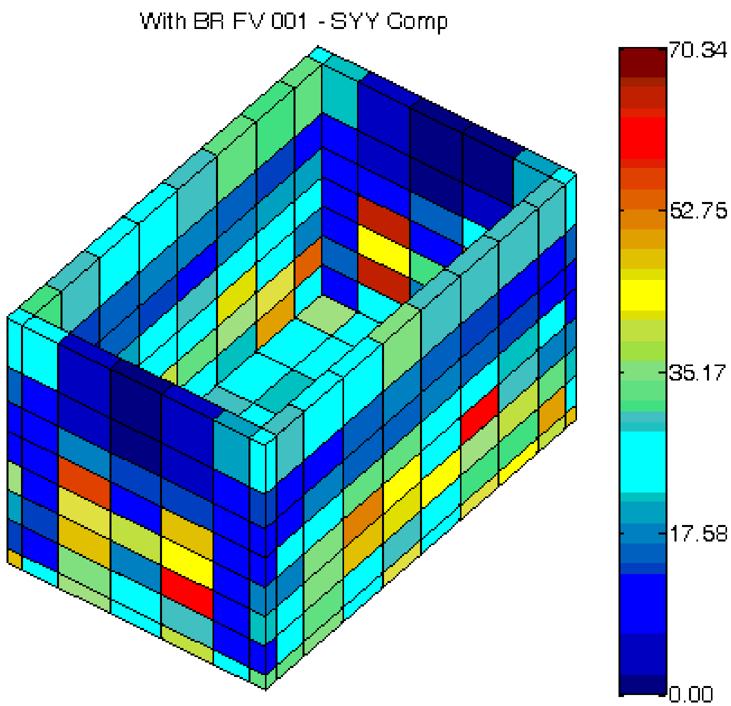
ANIMATIONS

Seismic Coherent vs. Incoherent Stresses for X-Input

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

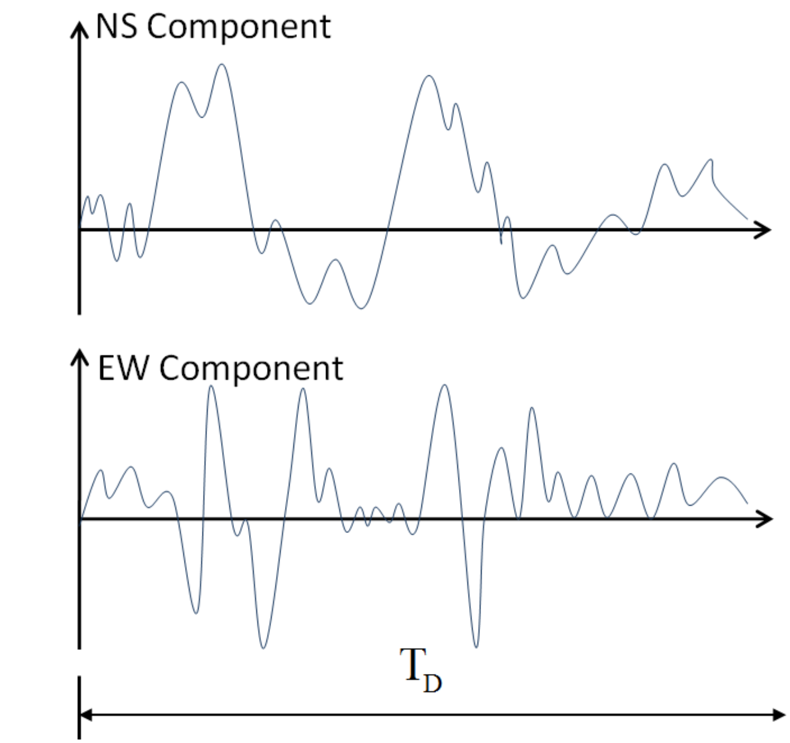
Element Center Stresses SYY

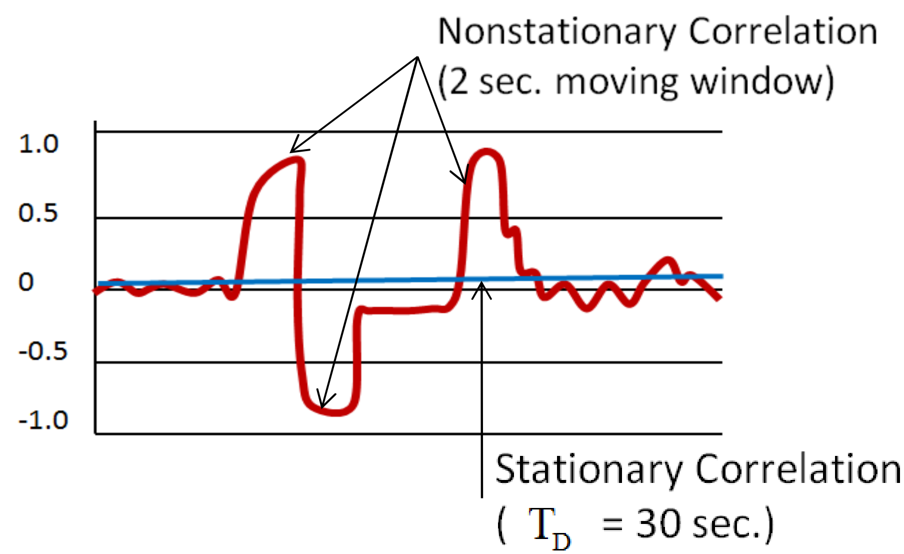


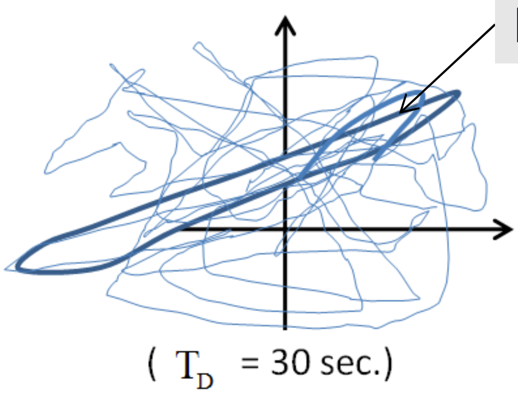


ANIMATIONS

Seismic Input Directionality (Including 3D Direction Variations)



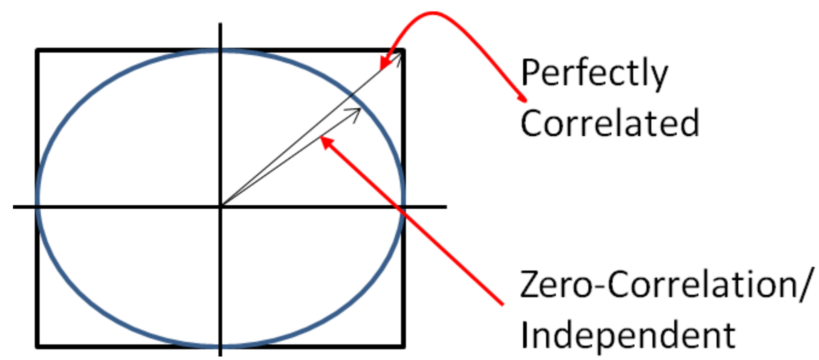




High Correlation!

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

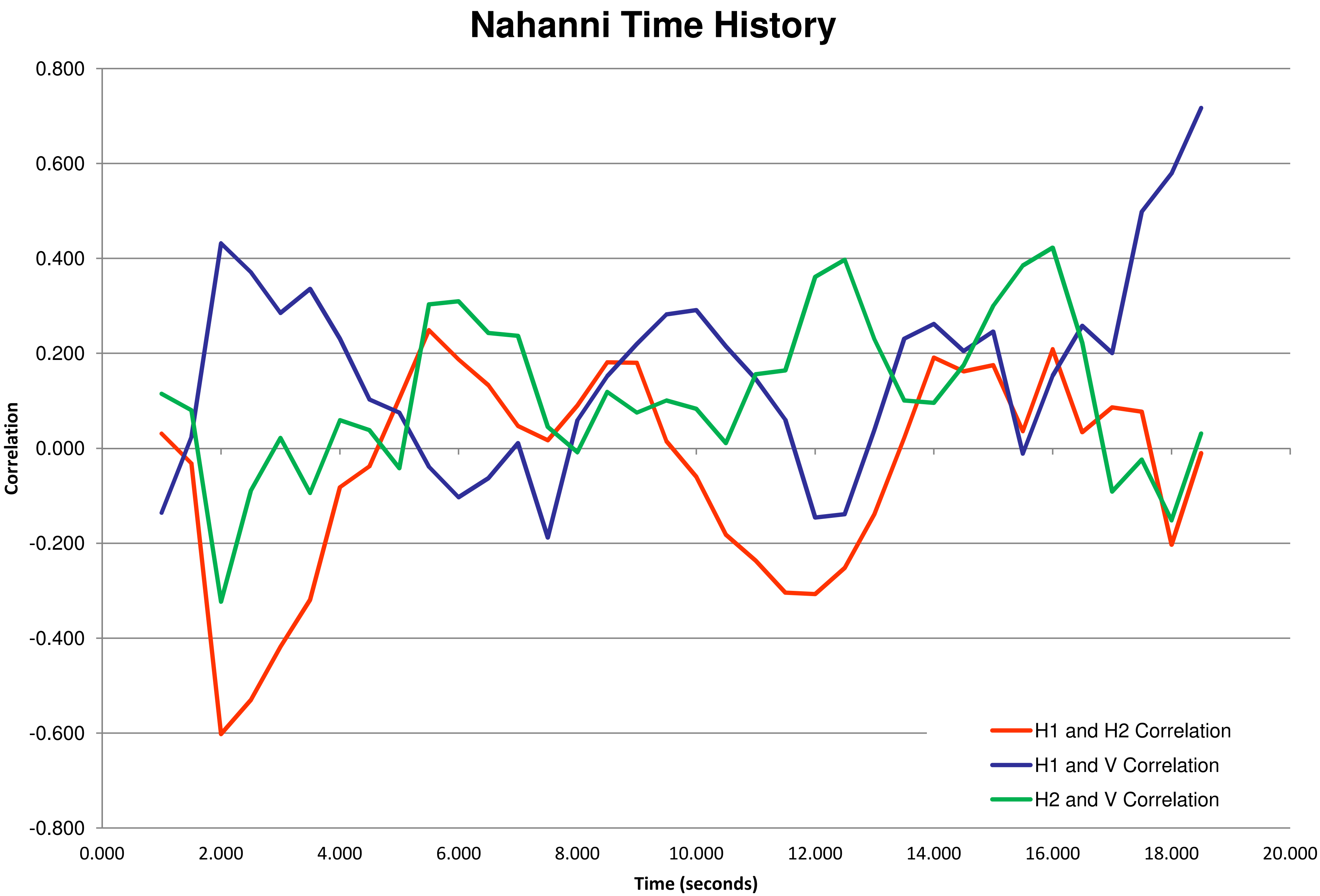
CORNER COLUMN PROBLEM

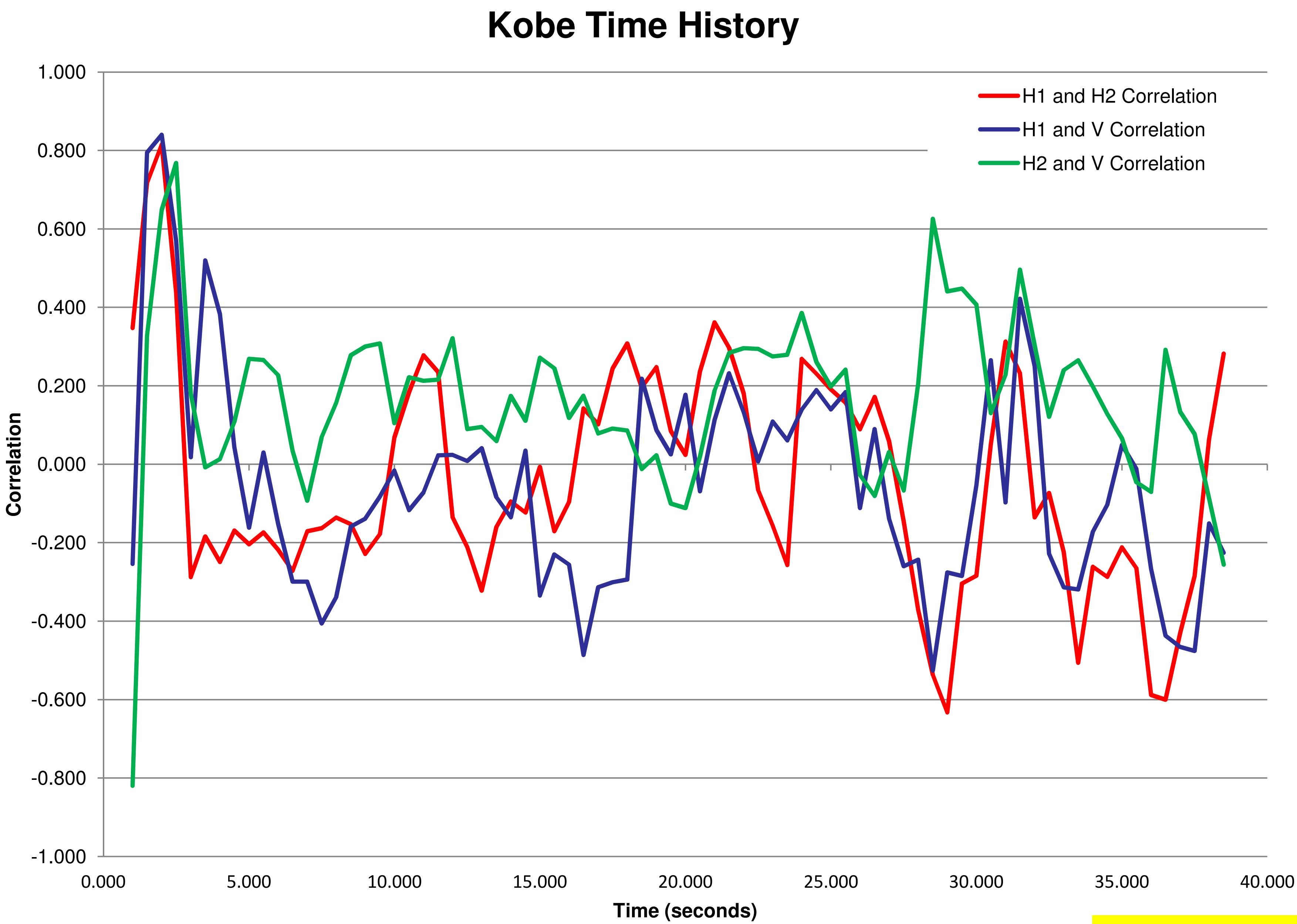


(Agnastopoulos, 1981, Der Kiureghian, 1984)

(SRSS rule neglects correlation effects)

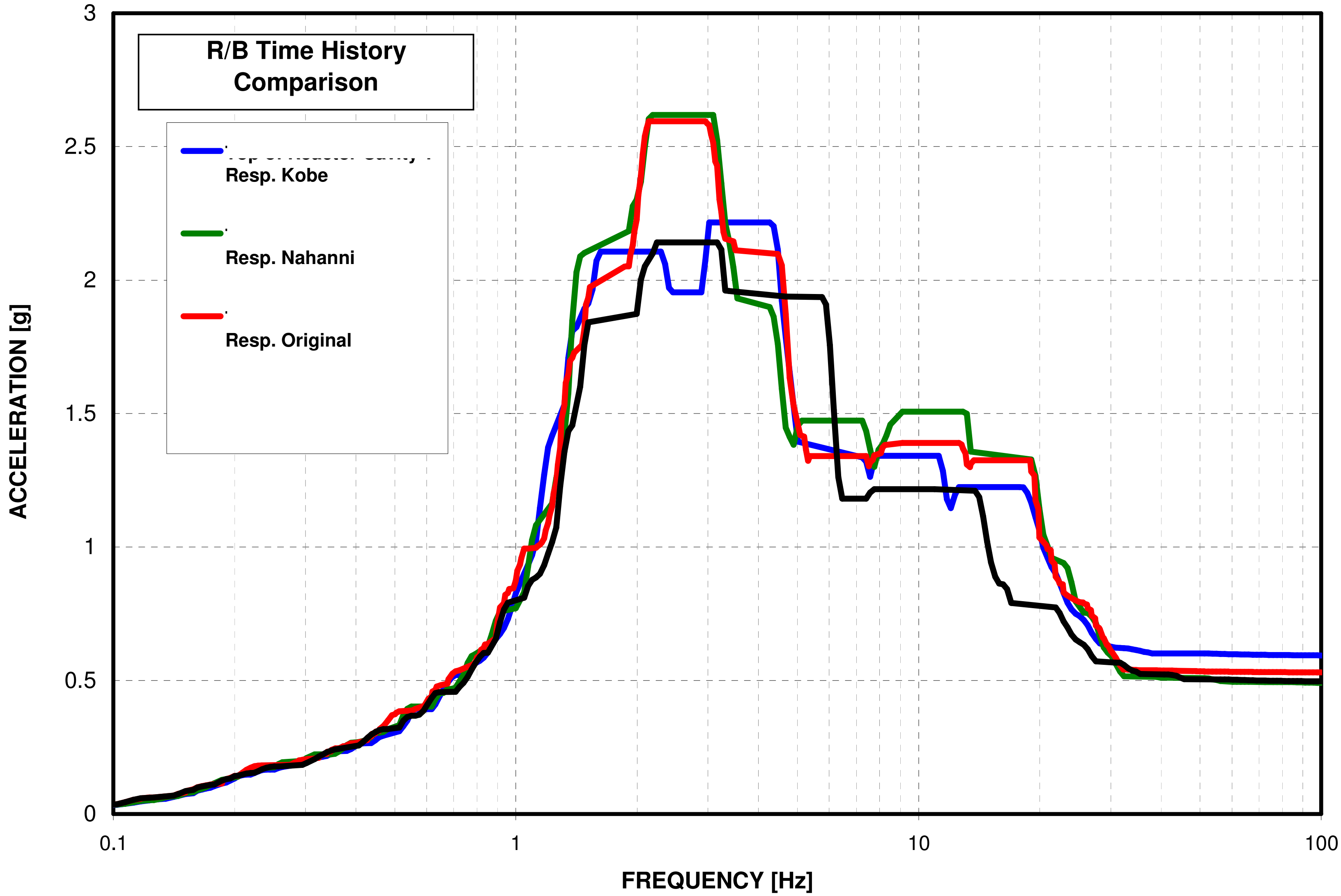
Input Motion Phasing (Non Stationary Correlation)




Kobe Time History
H1 and H2 Correlation
H1 and V Correlation
H2 and V Correlation
Correlation
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
Time (seconds)

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.

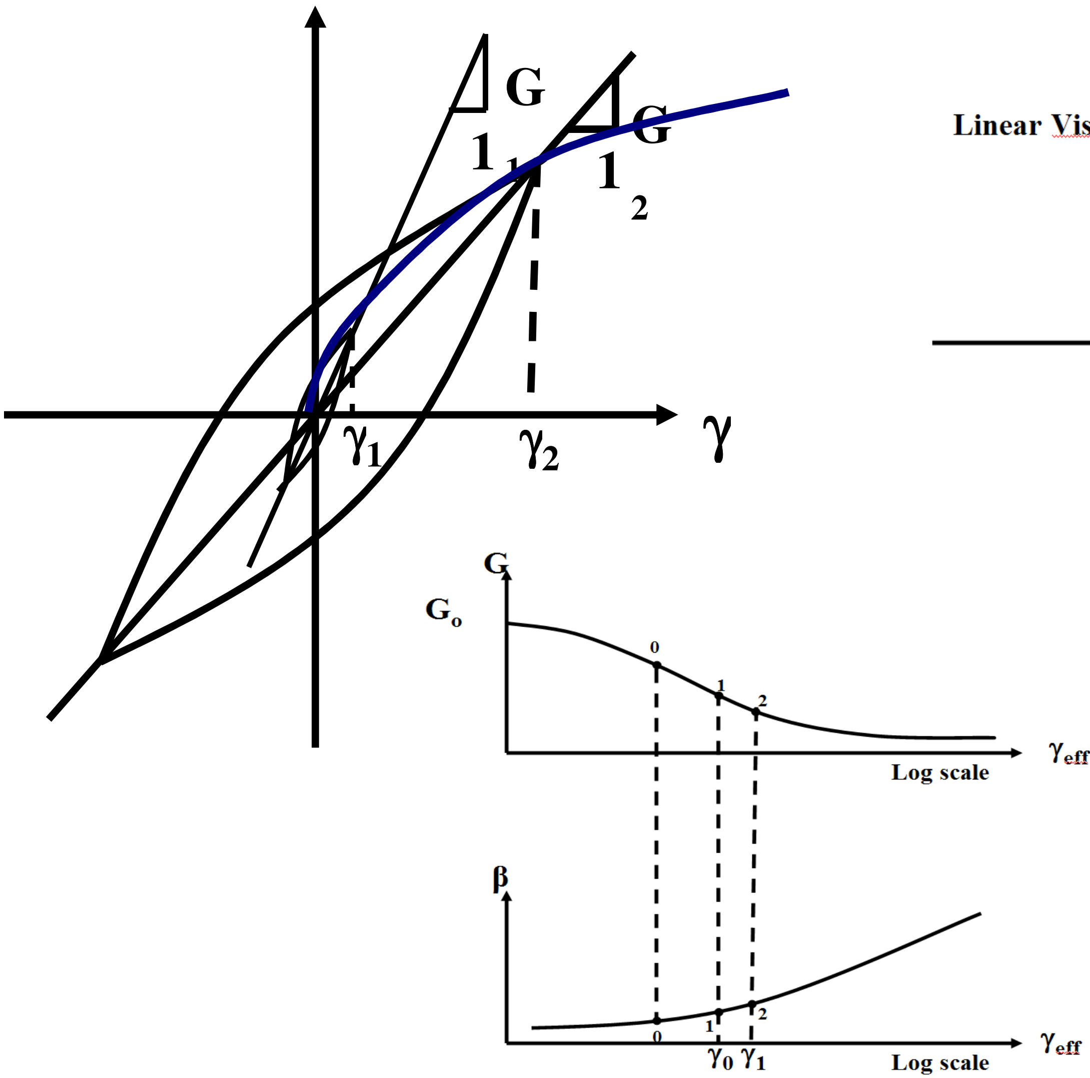
Single input set is still acceptable, but it will be required to demonstrate that it does not provide unconservative SSI responses.

Soil Layering Hysteretic Behavior

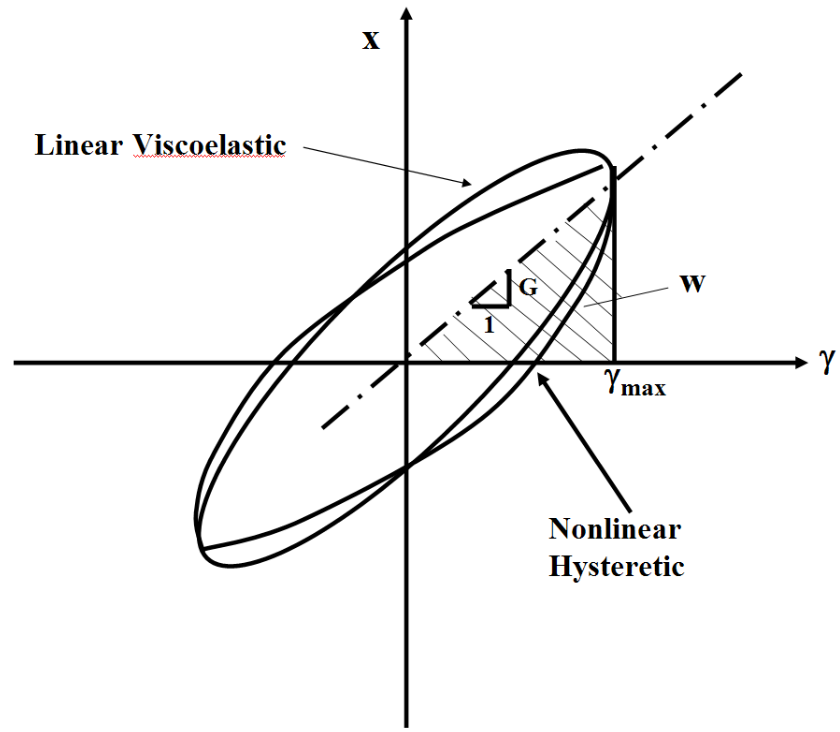
1. The nonlinear properties of the soil are approximated by equivalent linear properties consisting of the shear modulus and damping ratio for the soil which are compatible with the effective shear-strain amplitudes in soil
2. The effects of nonlinear soil behavior include two components:
   (i) The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

Seed-Idriss Equivalent Linear Iterative Method

Shear Modulus Variation



Viscous Damping Variation

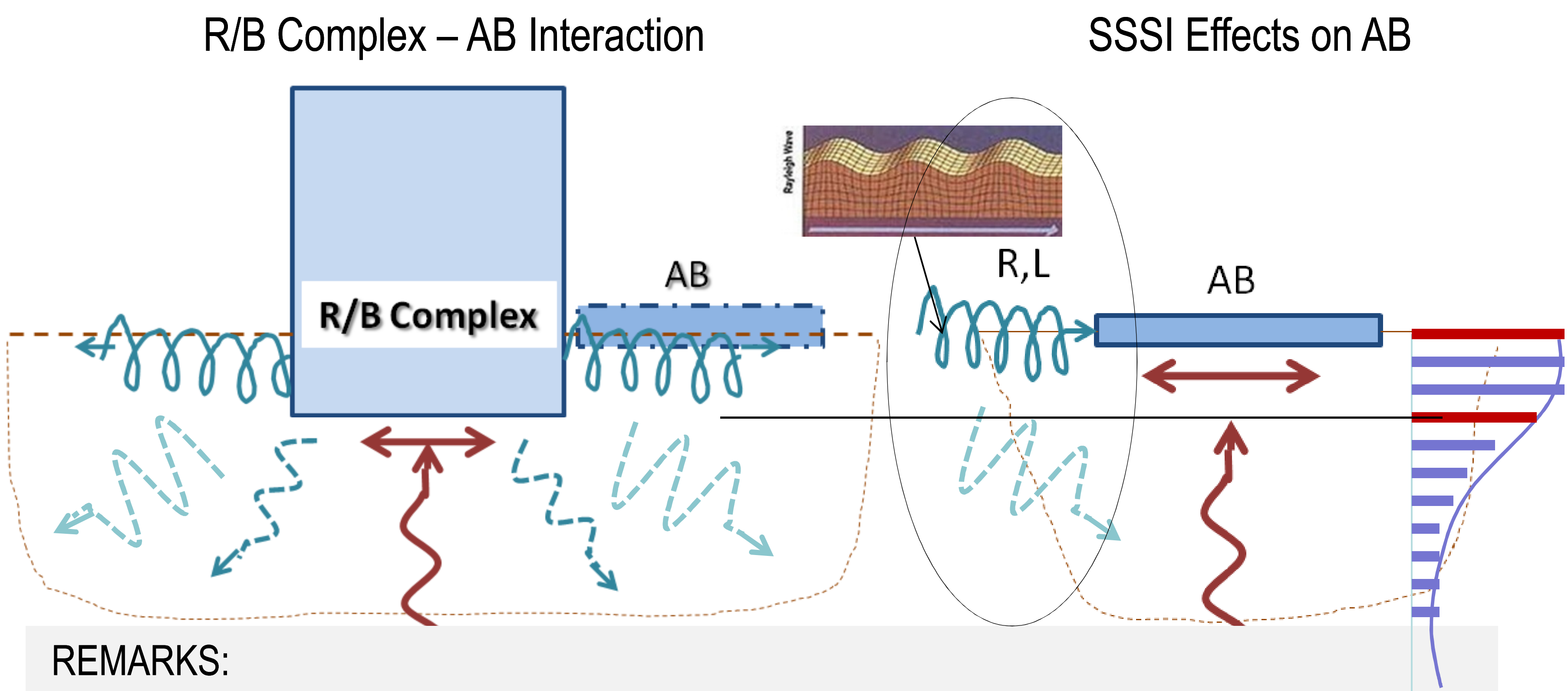


Δw = Area of hysteretic loop

β = critical damping ratio

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

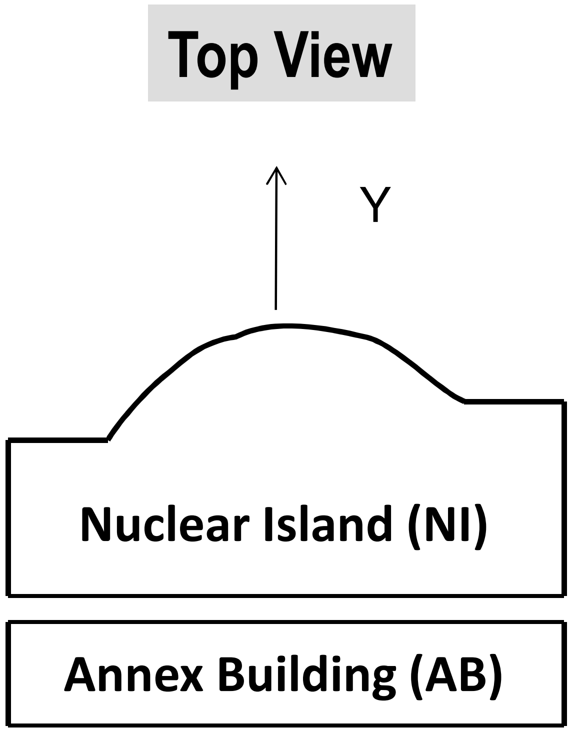
Seismic Structure-Soil-Structure Interaction (SSSI) Effects

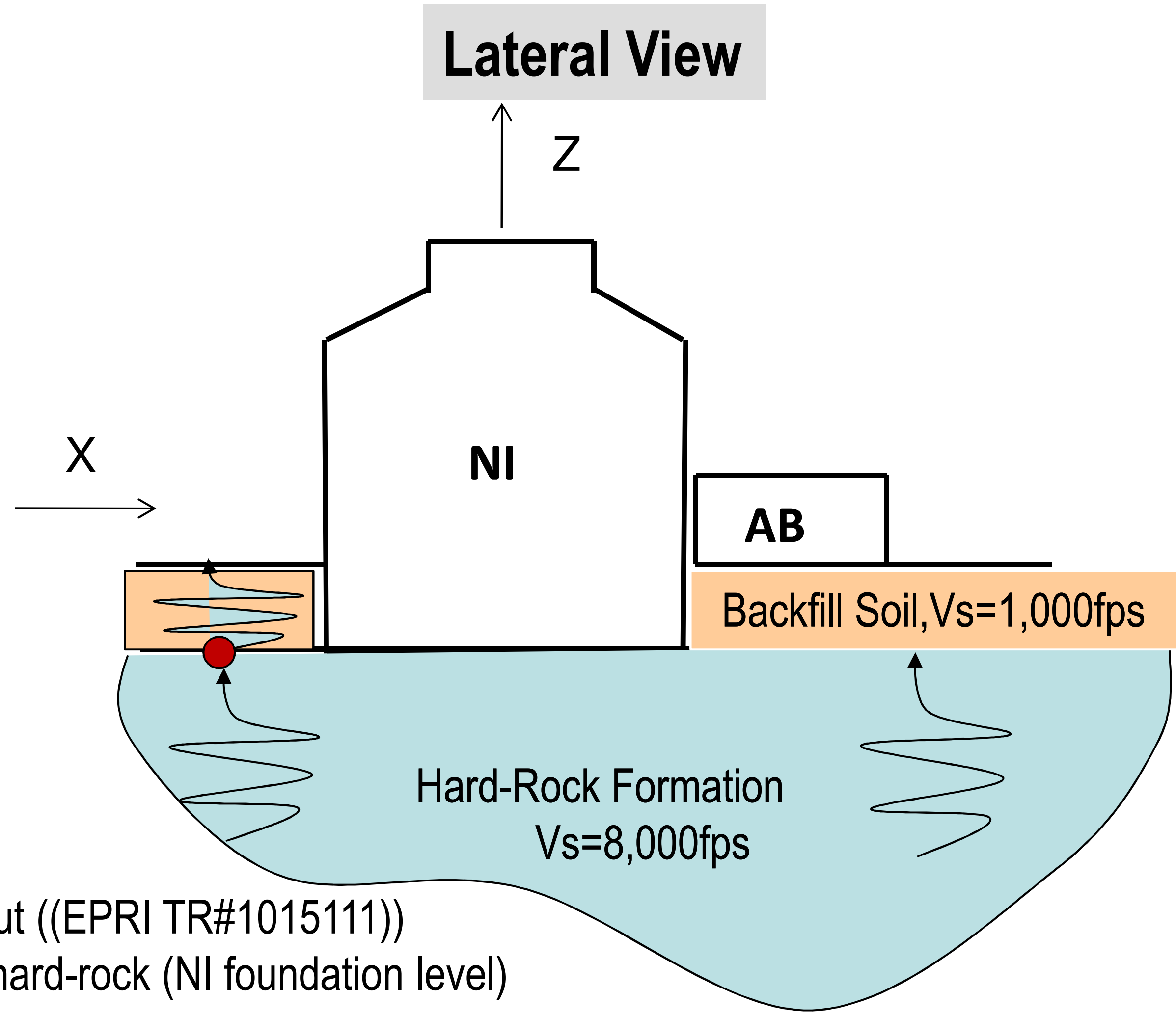


REMARKS:

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

AP1000 NI Complex and Annex Bldg Configurations





Coherent SSI Analysis:

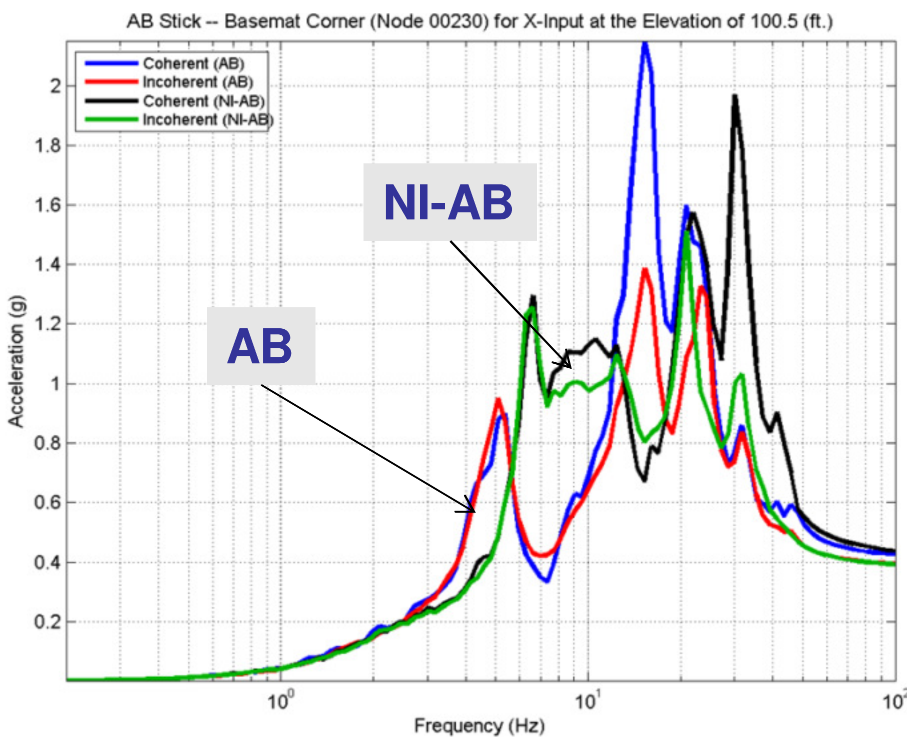
- Seismic input defined HRHF input ((EPRI TR#1015111))
- Control motion at the top of the hard-rock (NI foundation level)

Incoherent SSI Analysis:

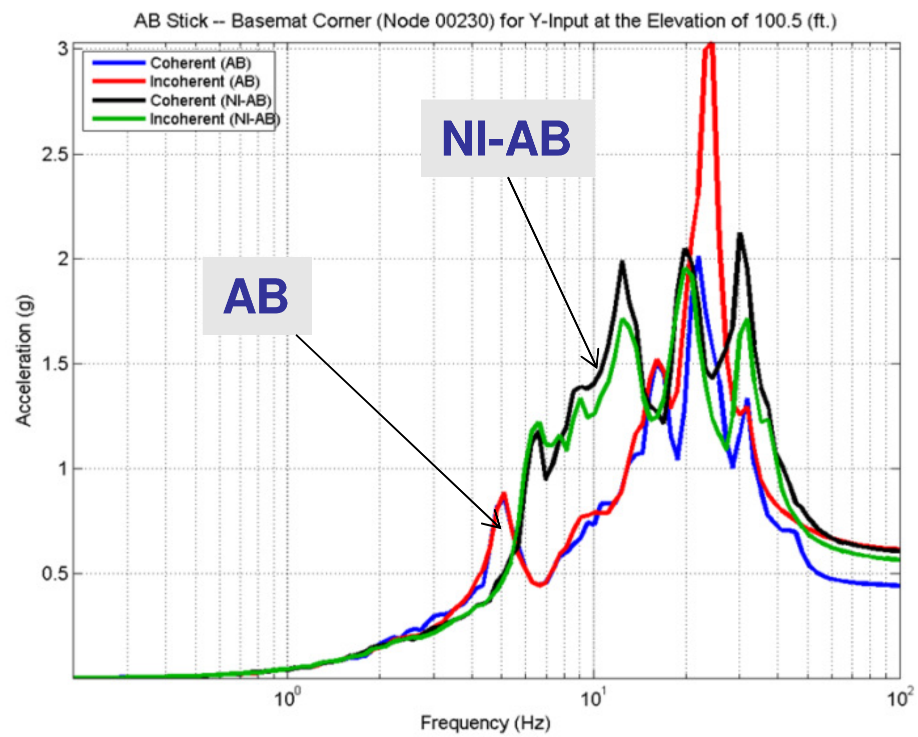
- Stochastic Simulation with 8 simulations (EPRI TR#1015111)
- 2007 Abrahamson coherency model for hard-rock sites (EPRI TR#1015110)

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

X-Direction

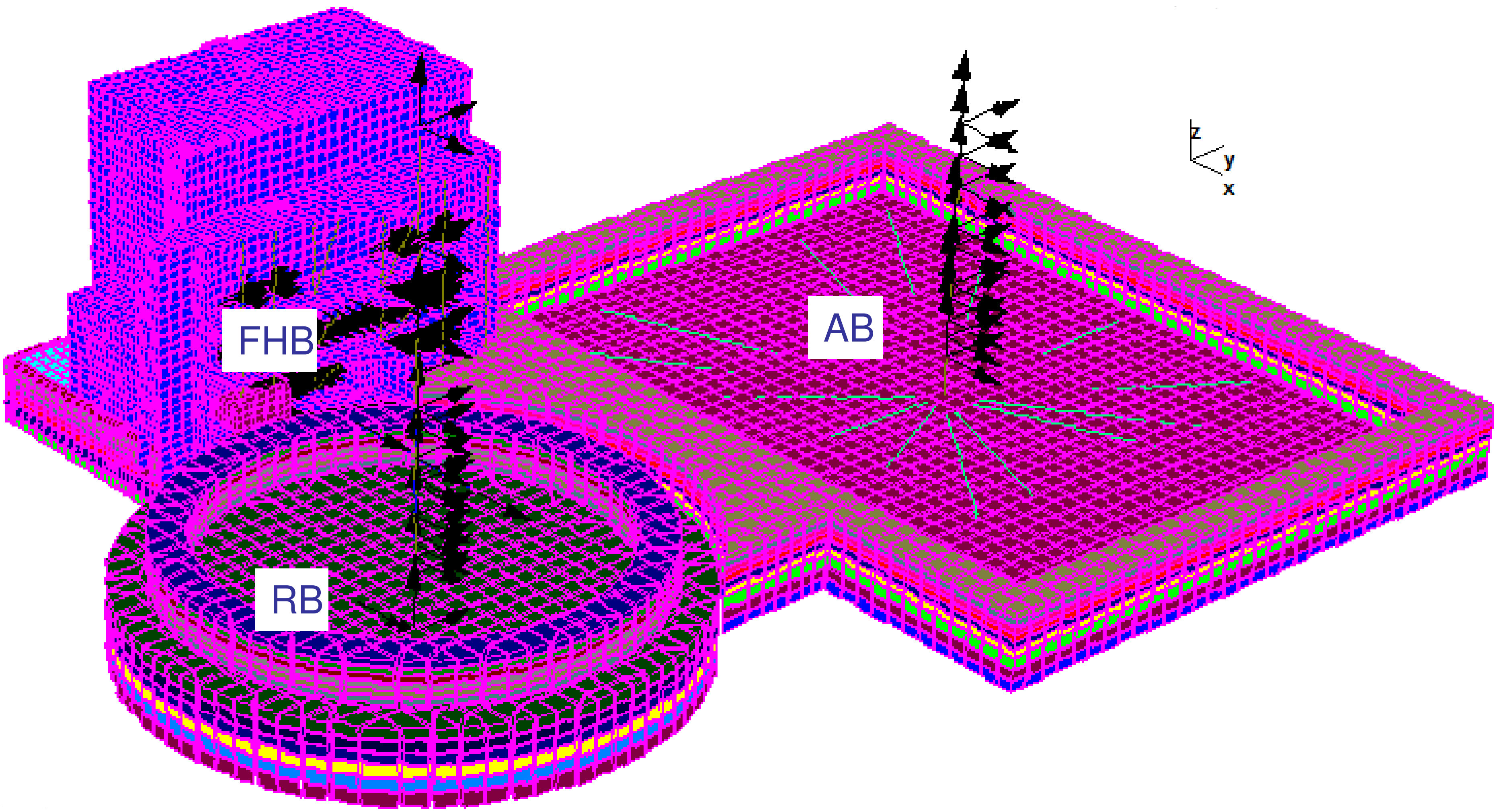


Y-Direction



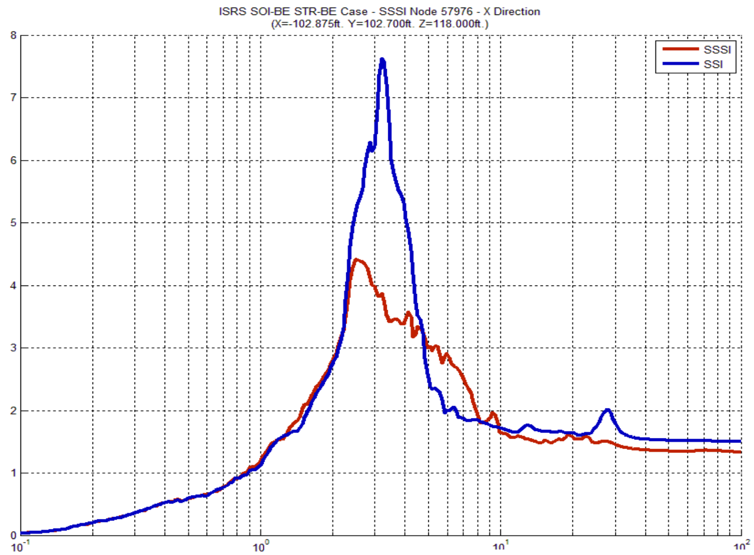
ANIMATIONS

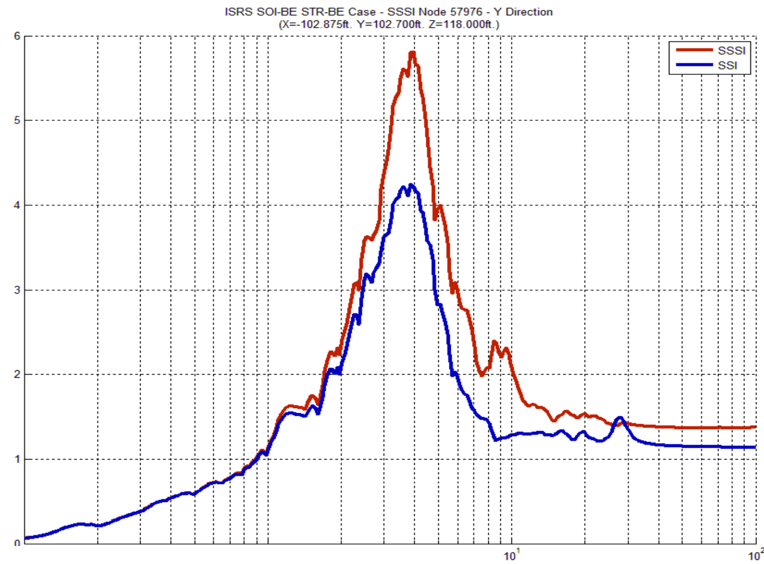
SSSI Model Including 3 Nuclear Structures

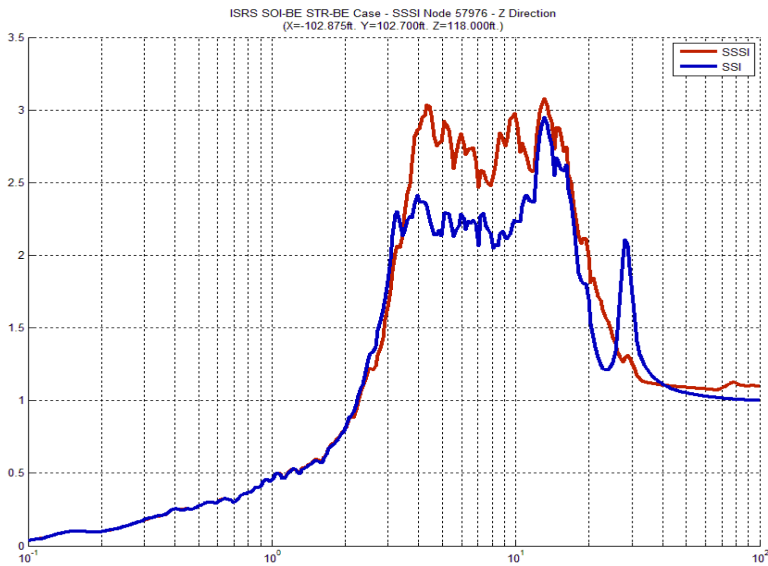


SSI vs. SSSI ISRS Comparisons for FHB Roof

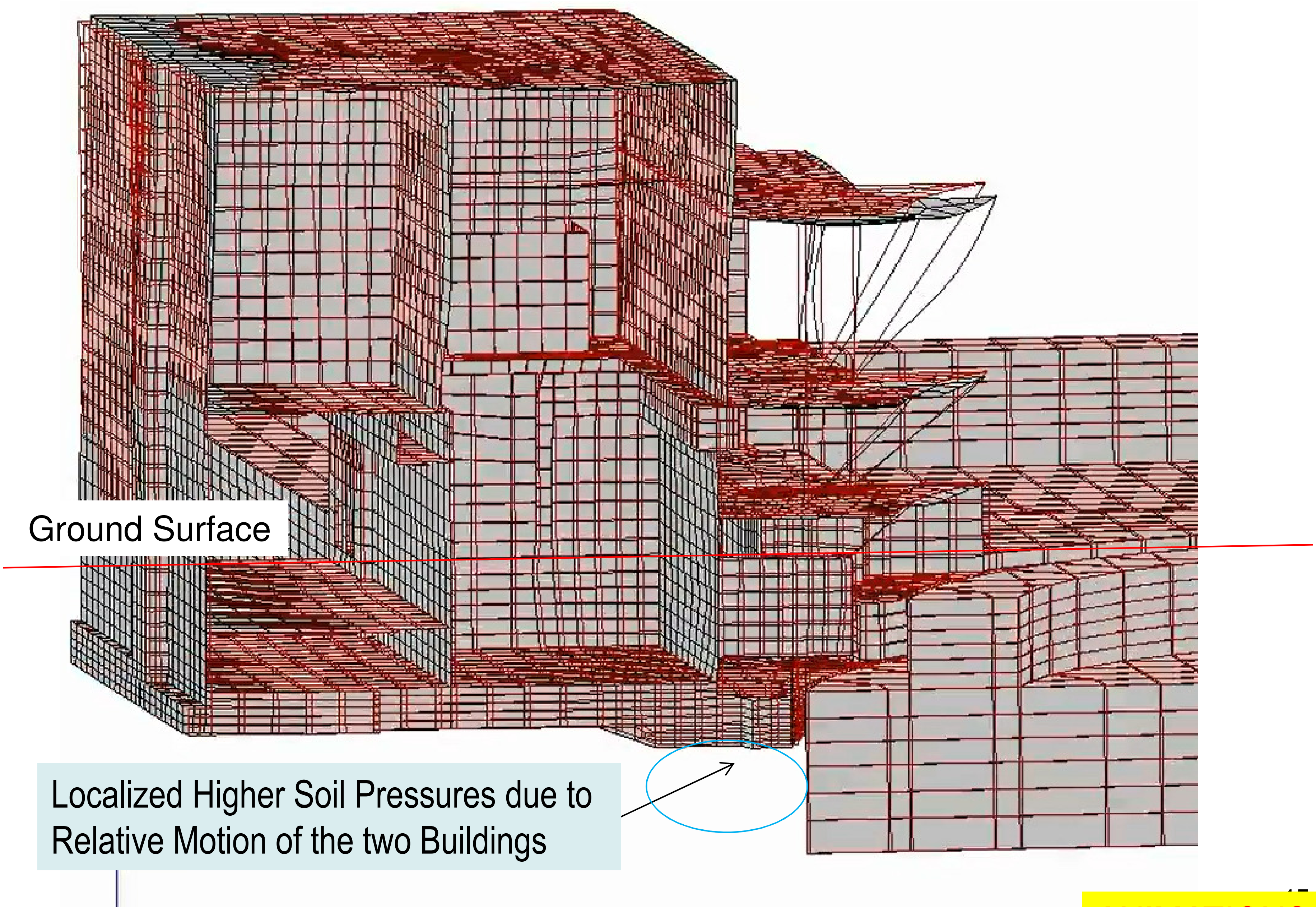
Node 57976 (Roof Elevation)







SSSI Effects on Local Soil Pressure Under Basemat

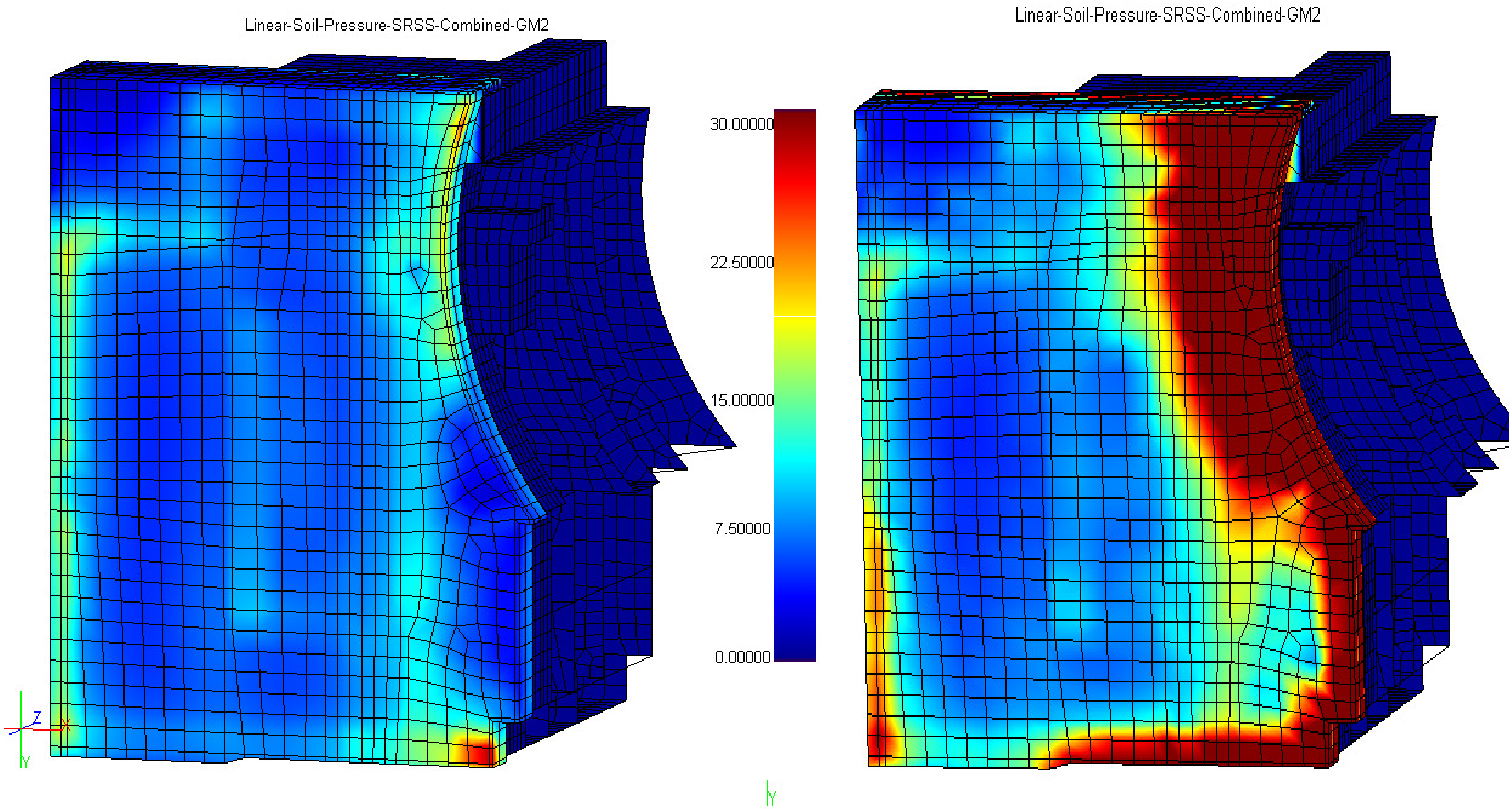


ANIMATIONS

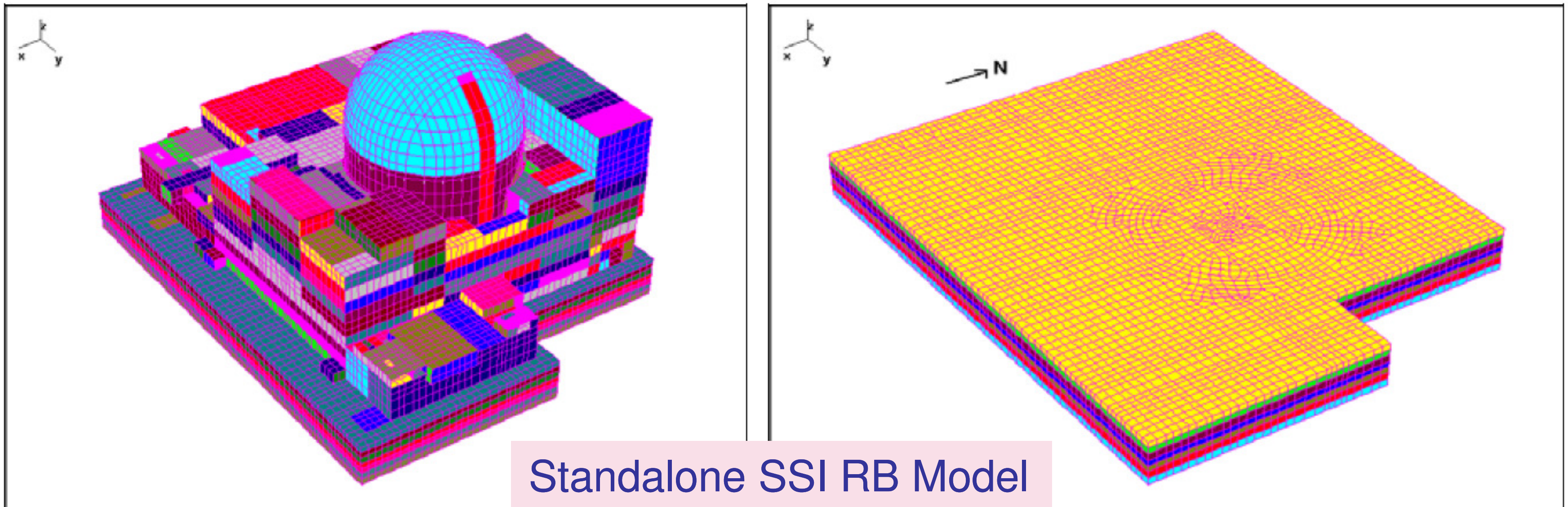
SSI vs. SSSI Basemat Soil Pressure Comparisons

SSI Model

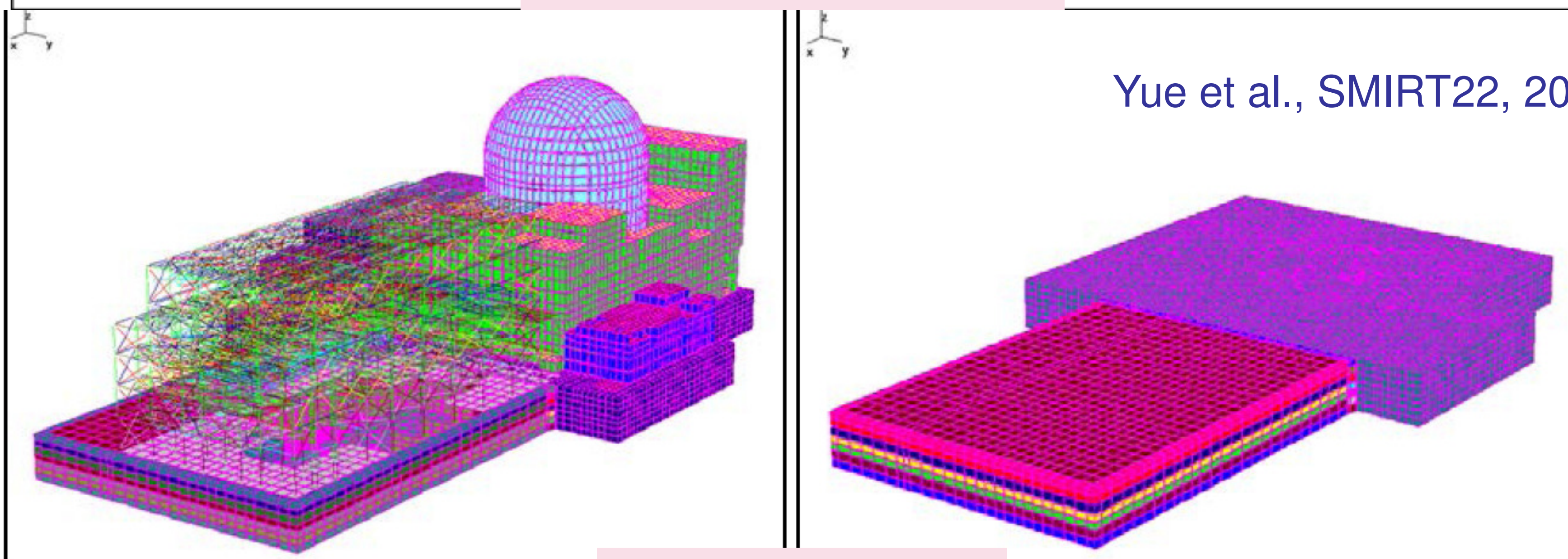
SSSI Model



ACS SASSI Seismic US-APWR SSSI Embedded Model



Standalone SSI RB Model



Yue et al., SMIRT22, 2013

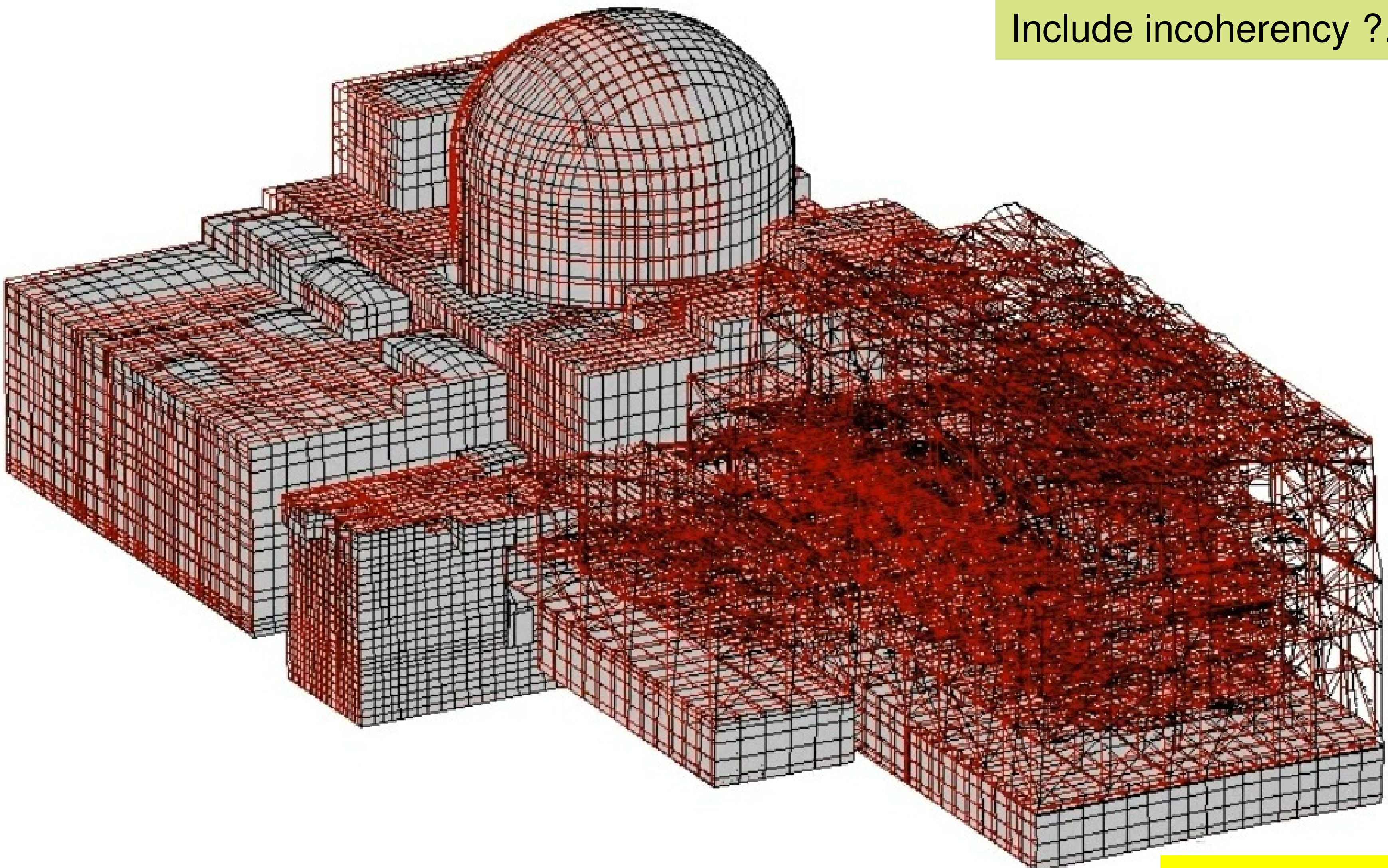
SSSI RB-TB Model

a) Structural Model

b) Excavated Volume

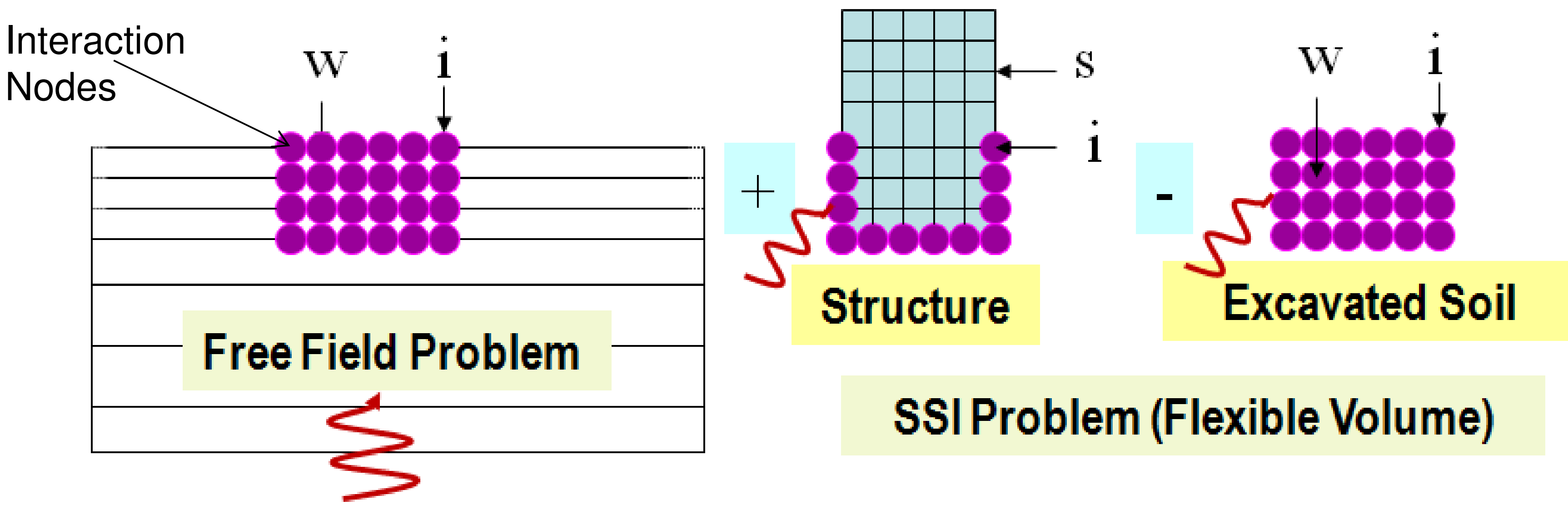
SSSI Model for Standard Plant (7 Buildings)

Single or multiple 1D soil columns can be used. Include incoherency ?….



ANIMATIONS

ACS SASSI Flexible Volume Subtructuring for Uniform and Non-Uniform Soil



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

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.

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:

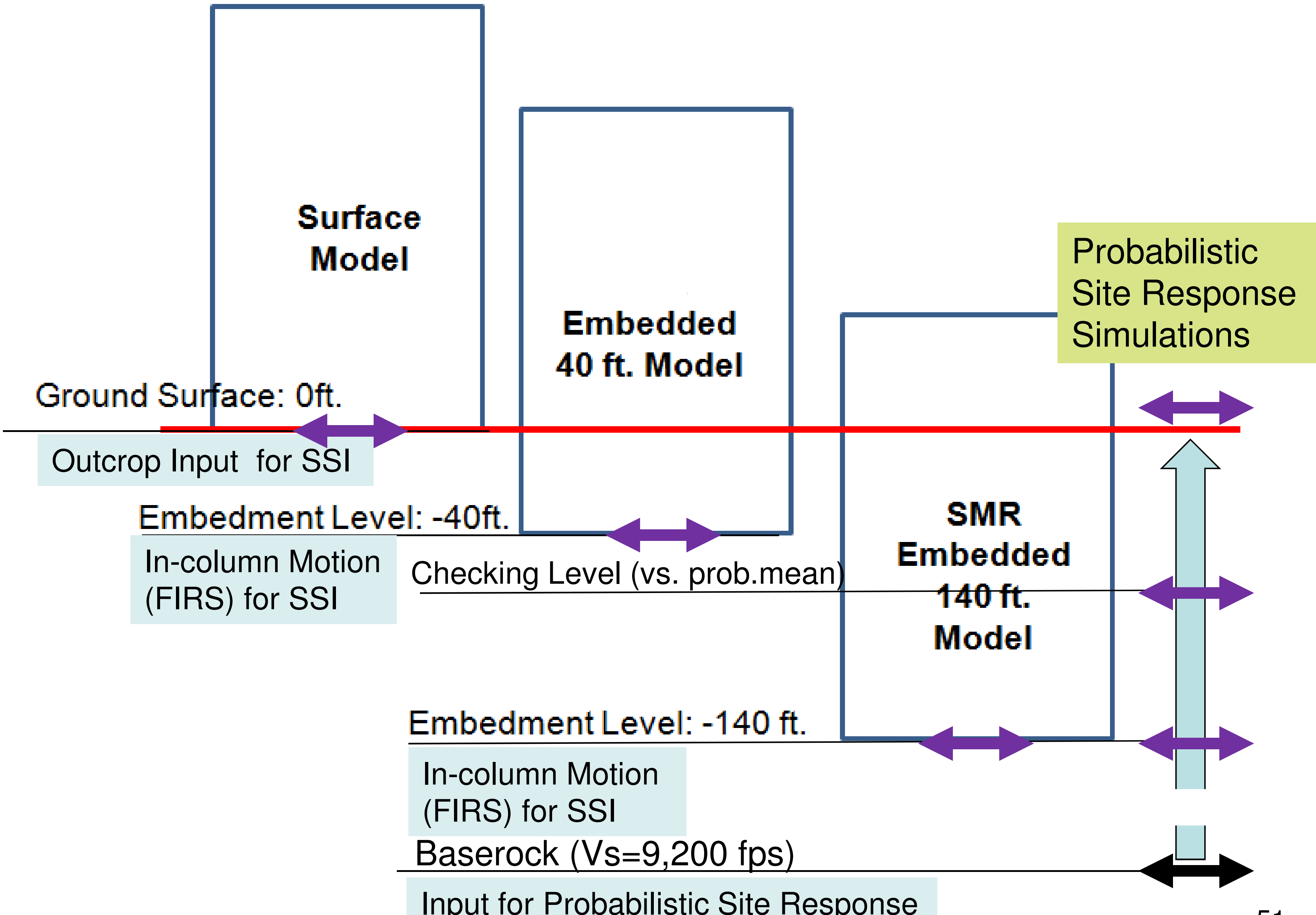
1) Perform 60 probabilistic nonlinear site response simulations (convolutions) using randomized soil layering profiles for the UHS RS inputs at baserock.

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

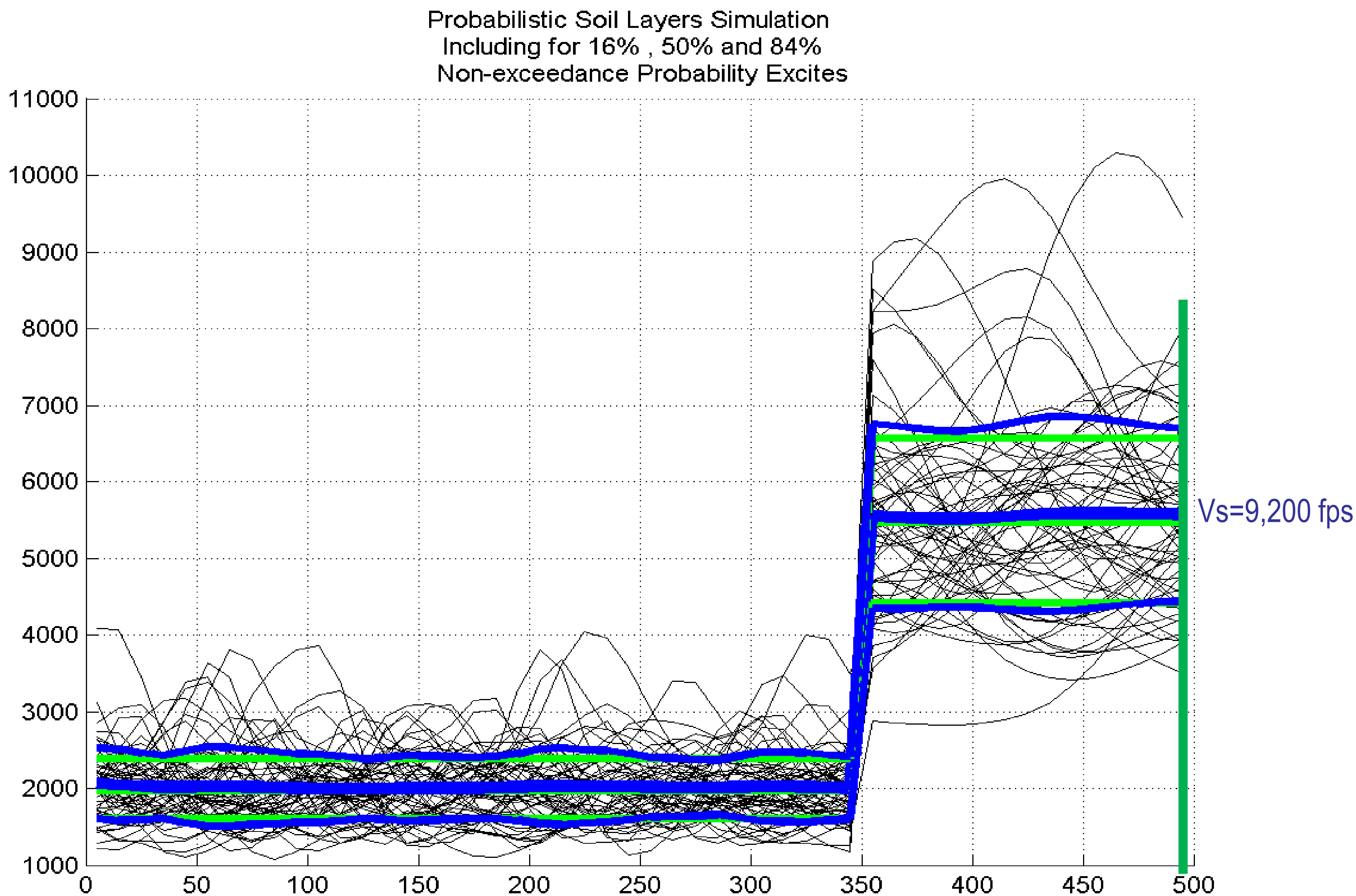
3) Performed 3 SHAKE type deterministic linear site response analyses for LB, BE and UB soil profiles to compute the in-column FIRS motions to be used for the deterministic SSI analysis. Pair LB Vs-UB D and UB Vs-LB D.

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

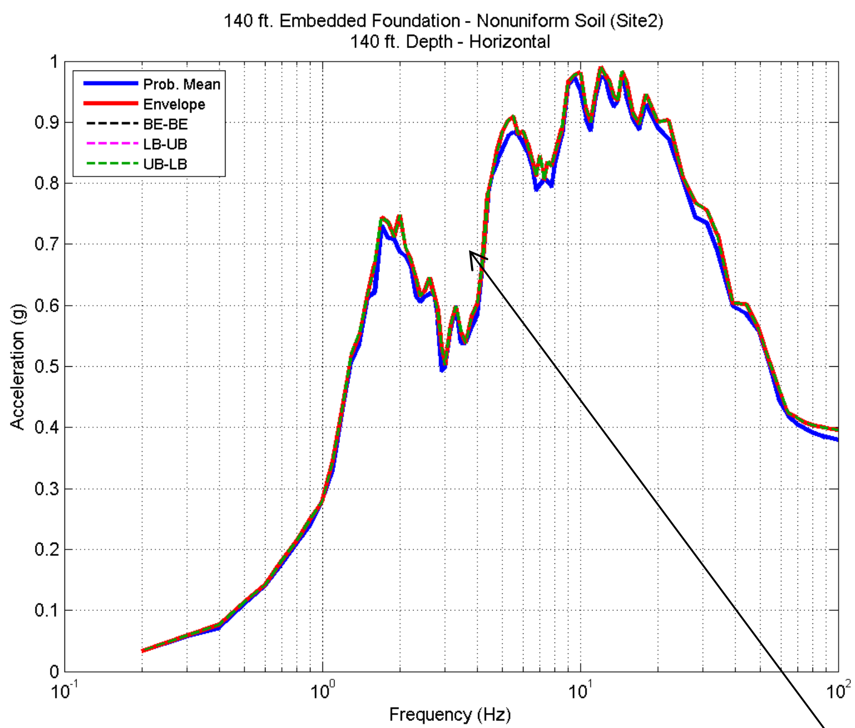
Determination of Seismic Inputs for SSI Analysis



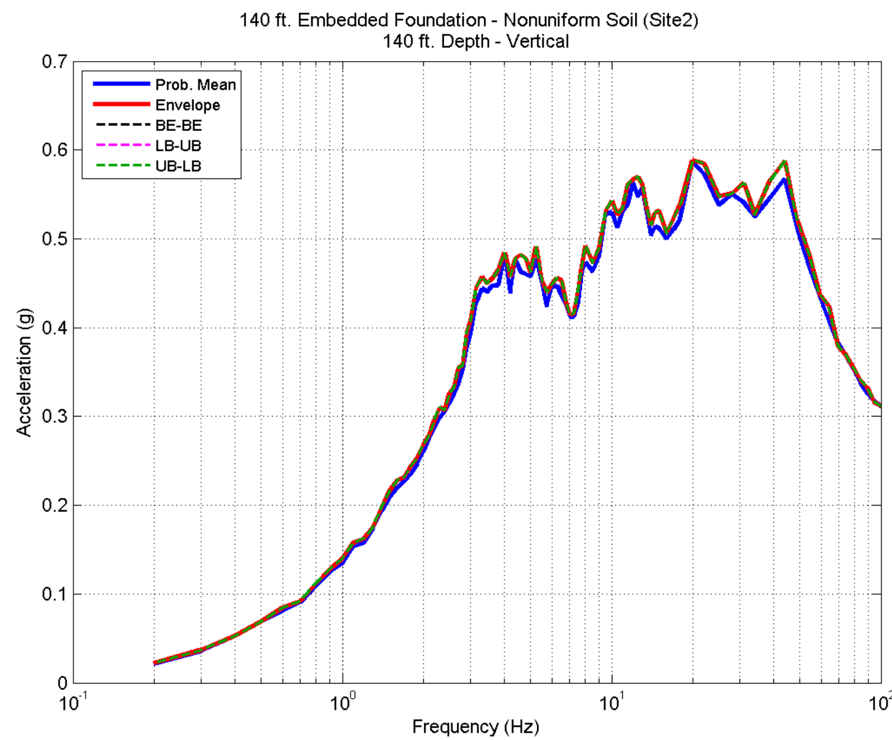
Probabilistic Simulation of Soil Profiles



Deterministic vs. Probabilistic Outcrop FIRS at 140 ft Depth.



Horizontal



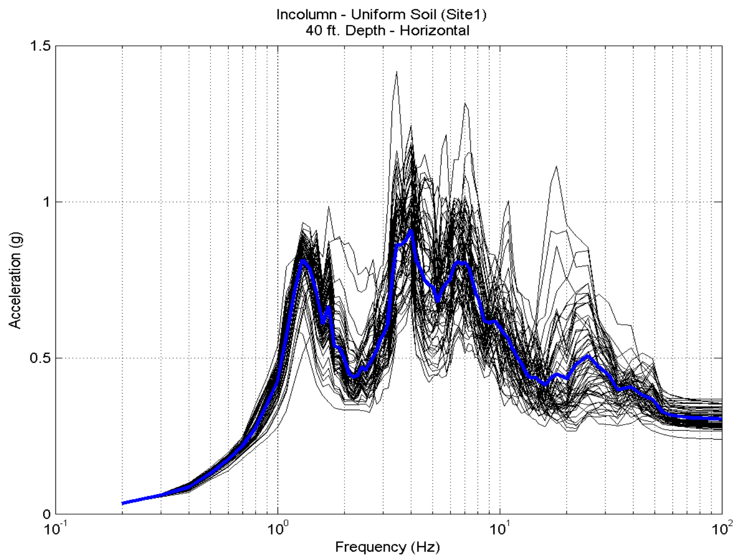
Vertical

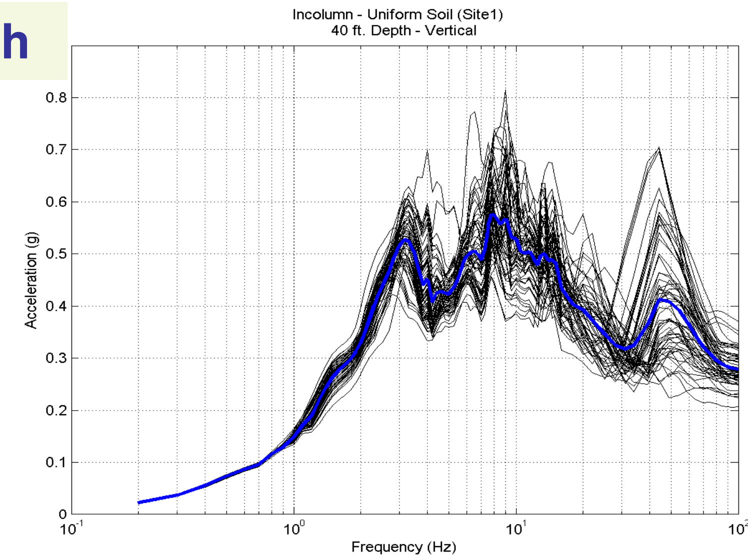
Non-flat RS...

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

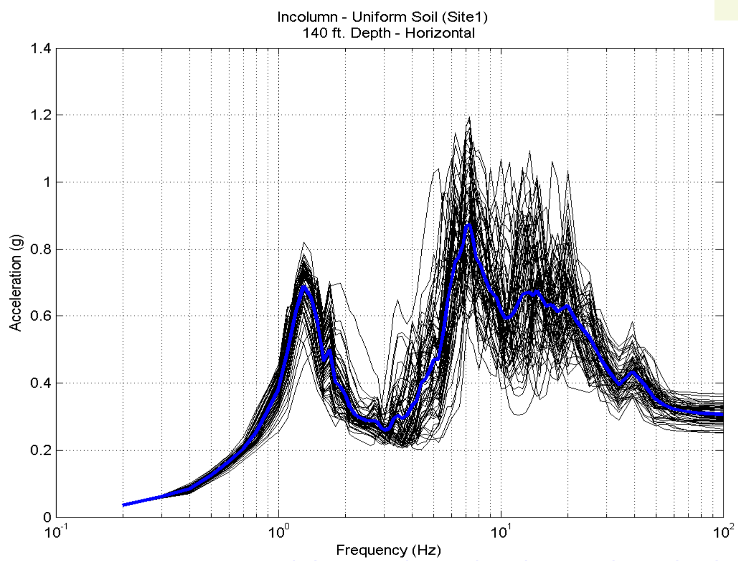


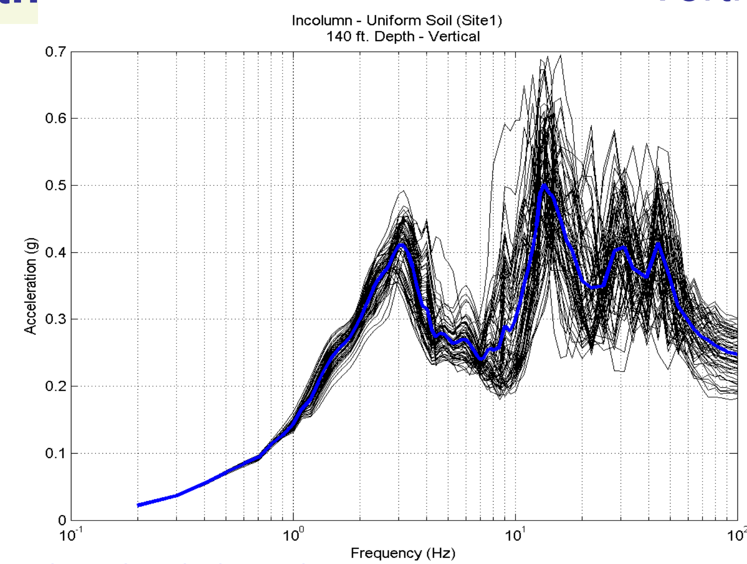


Horizontal

140 ft Depth

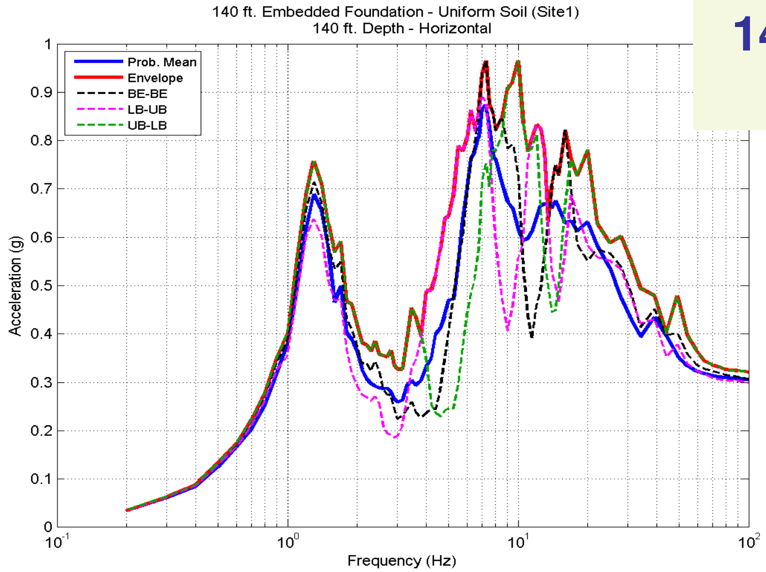
Vertical

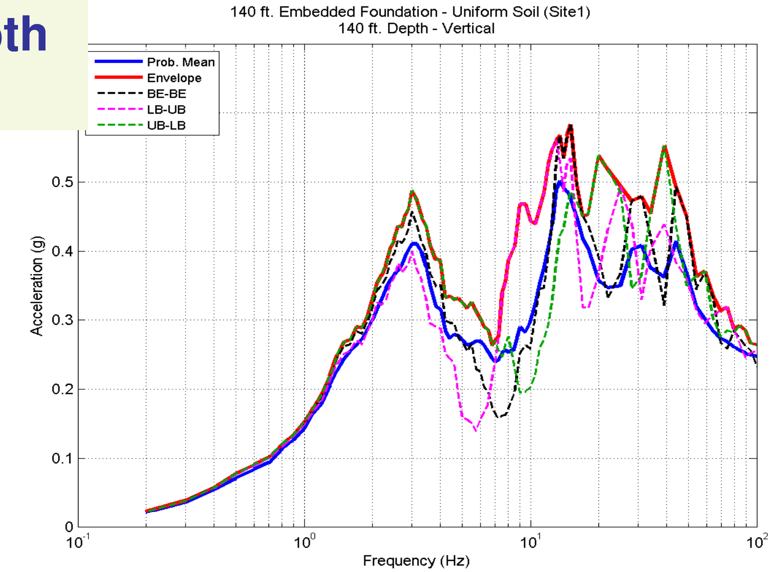




Deterministic vs. Probabilistic In-Column RS for Outcrop FIRS Input Defined at 140 ft Depth

140 ft Depth (FIRS)

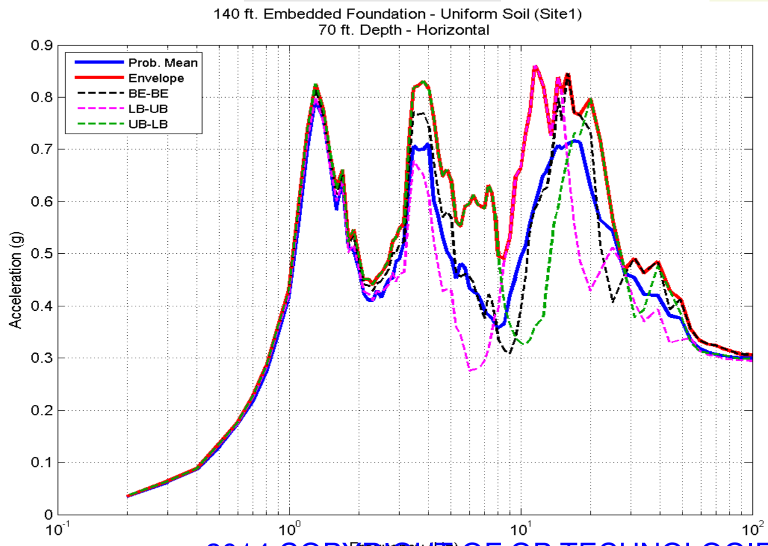


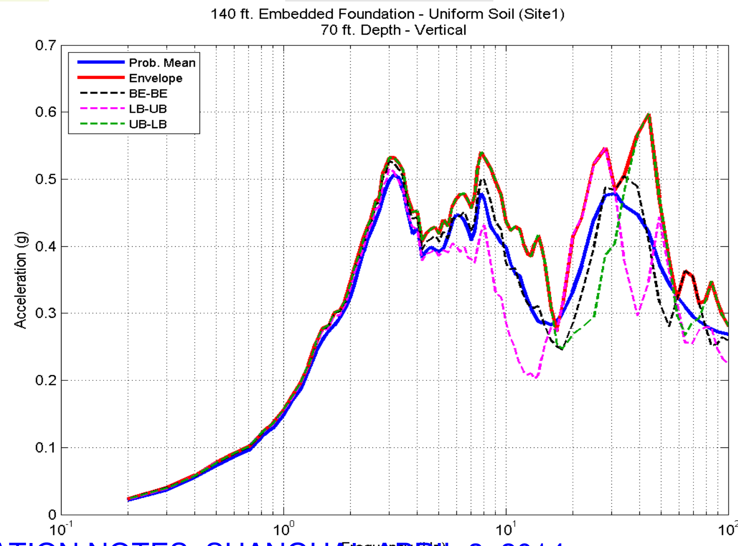


Horizontal

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.

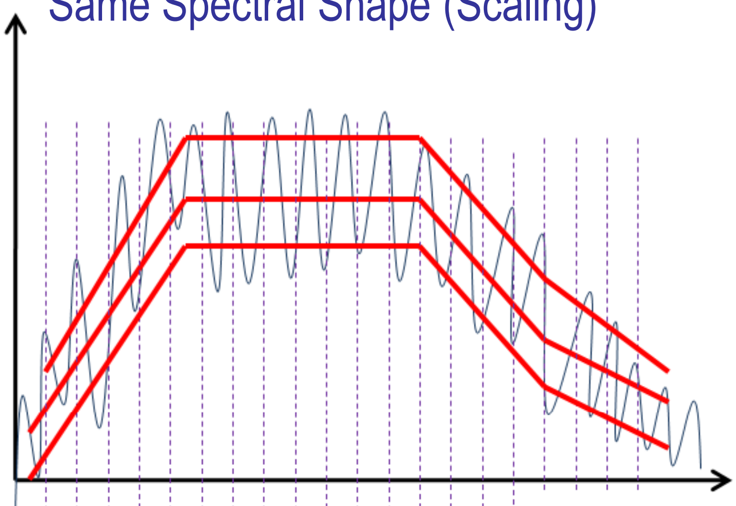
For probabilistic seismic analyses, *probabilistic SSI responses* defined with the 80% non-exceedance probability level are considered adequate.

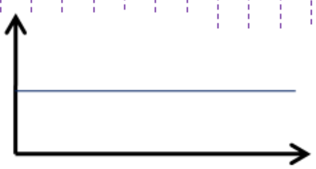
Section 5.5 of the standard provides guidelines for the acceptable probabilistic SSI approaches. The GRS spectral shape could be considered with variable shape or not (Methods 1 and 2). Soil profiles, Vs and D, should include spatial correlation with depth. Structural stiffness and damping should be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

Probabilistic Seismic Input Models

Method 1 (Random Variable)

Same Spectral Shape (Scaling)

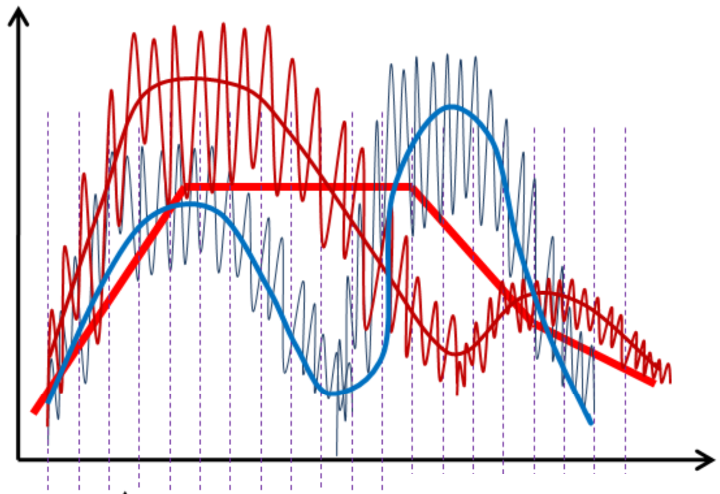


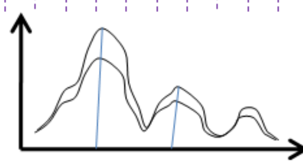


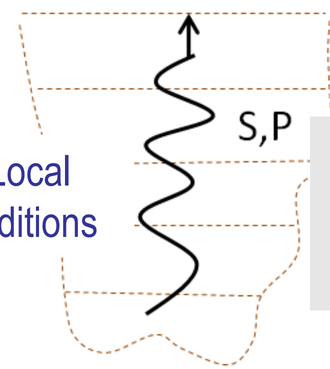
Full Correlation in Frequency….
Simpler...
Less information required….

Method 2 (Random Field)

Random Spectral Shape



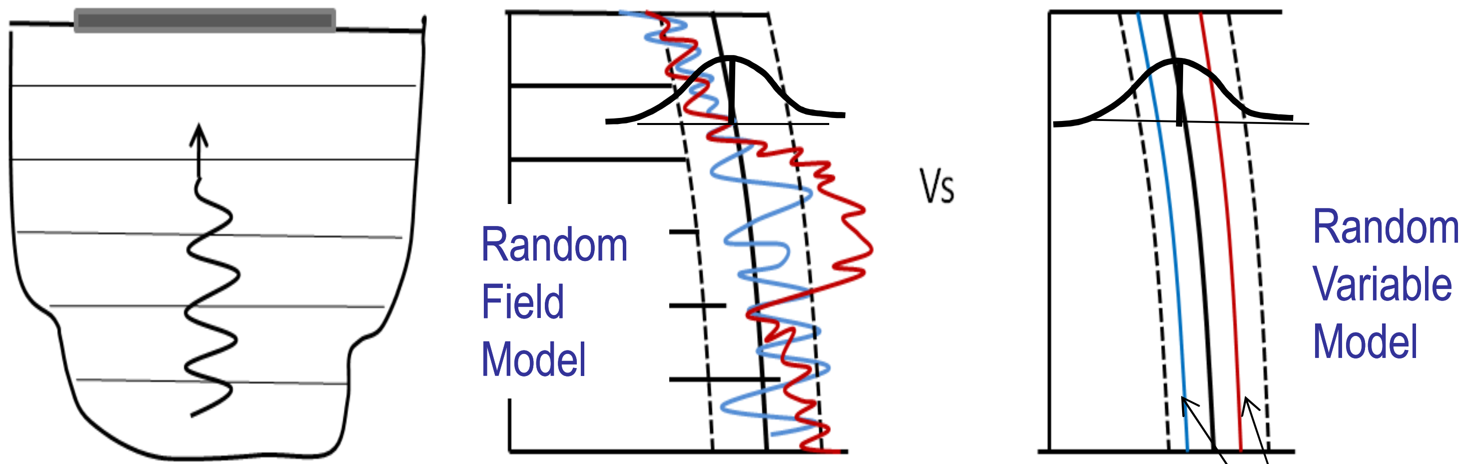




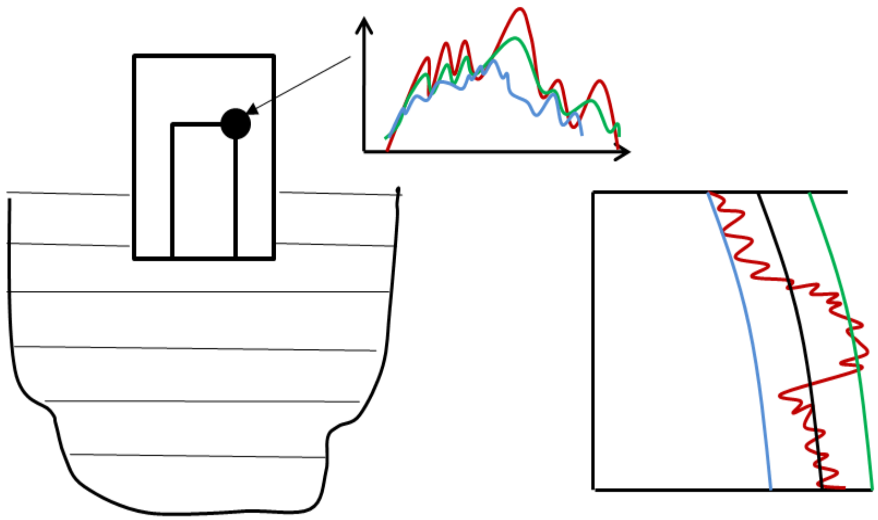
Correlation in Frequency….
More physics-based…
More information required….

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…

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)

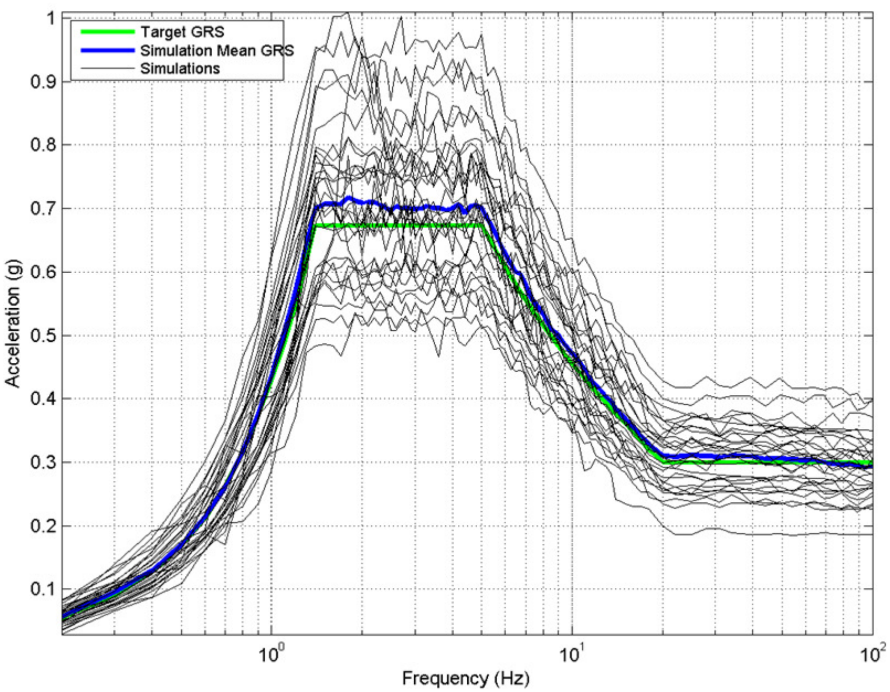
Structural Effective Stiffness and Damping:

- 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)

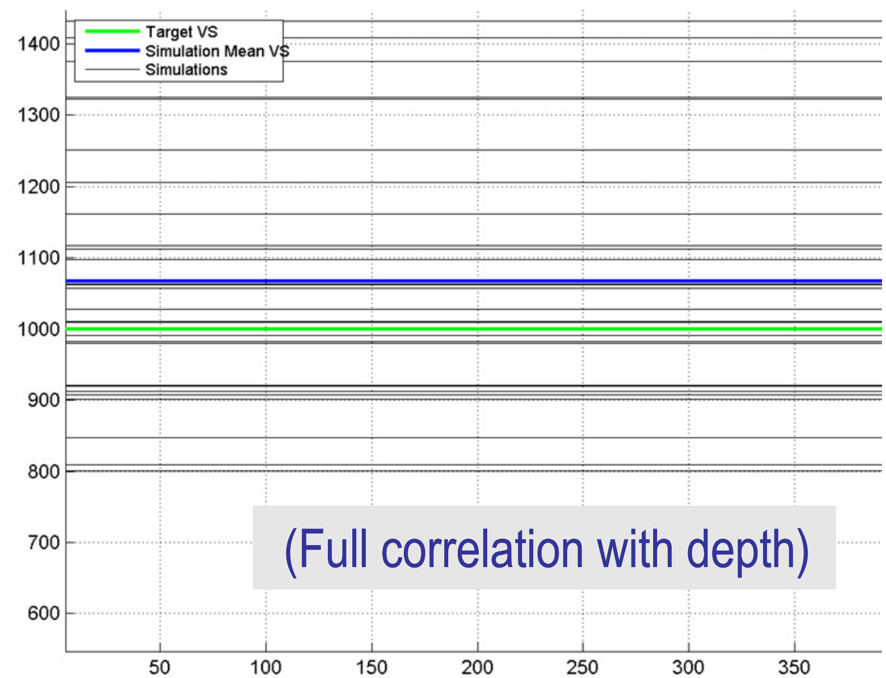
NOTE: Since stress level depends on locations, multiple sets of the two random variables should be defined. In ACS SASSI we considered a random variable pair (Keff/Kel and D) for each group of elements. Correlations between the two random variables of different groups could be considered, as needed.

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

Simulated GRS Inputs



Simulated Soil Profiles

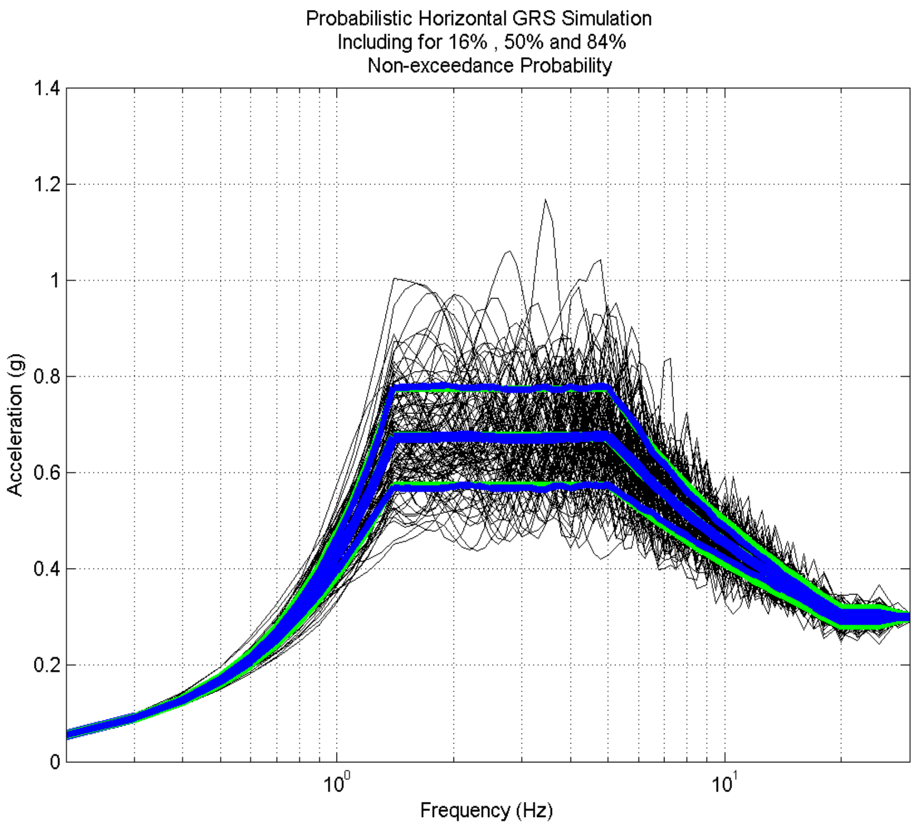


(Full correlation with depth)

Note: Only 30 LSH simulations were used

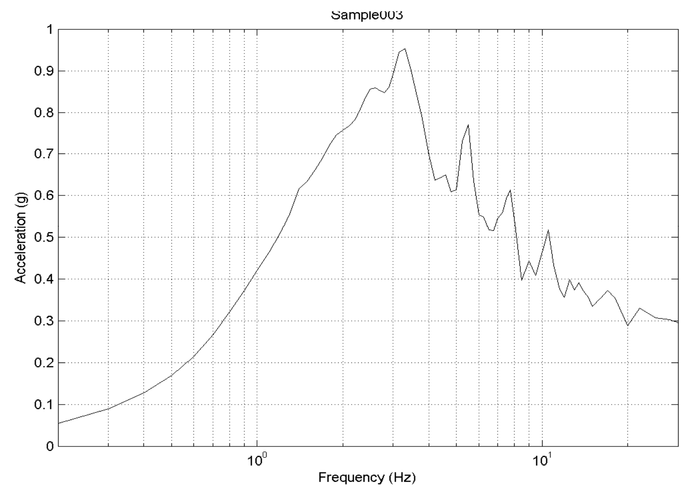
Simulated Probabilistic Seismic GRS (Method 2)

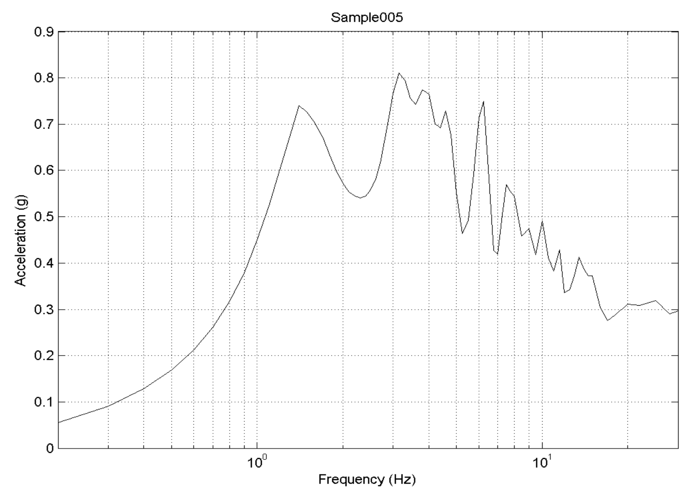
Probabilistic UHRS Input
0.30 ZPGA



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

Simulated GRS

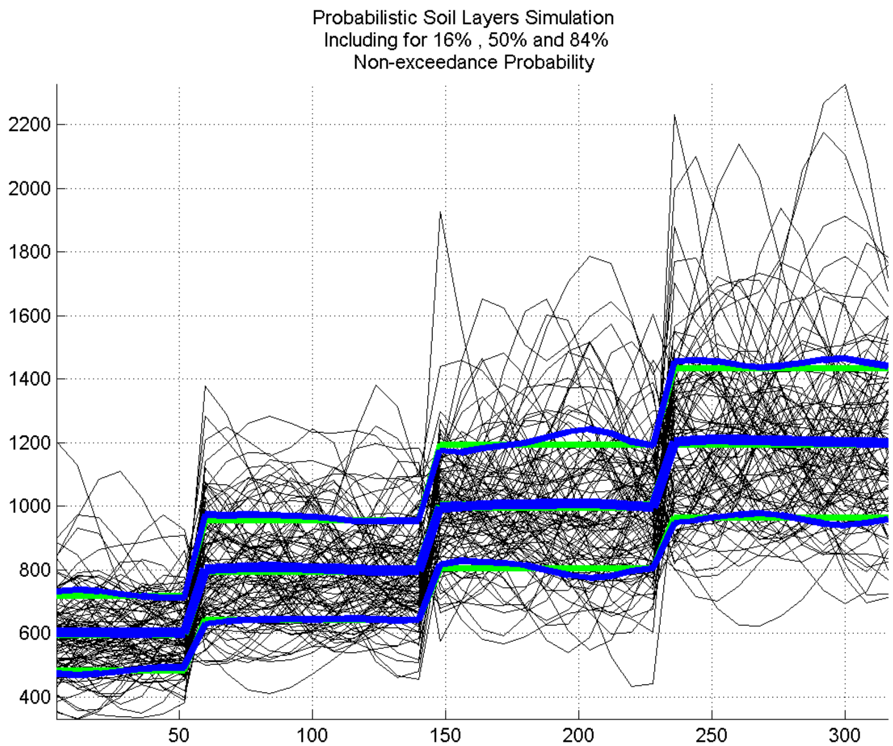




Random Samples

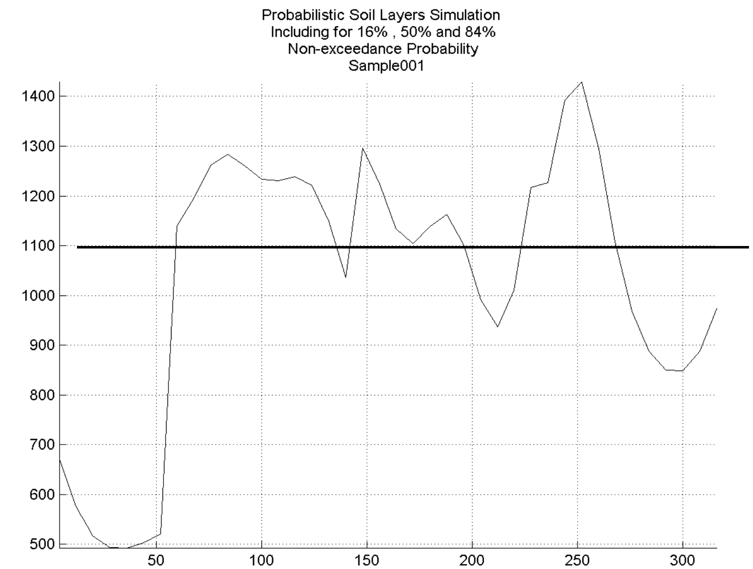
Simulated Probabilistic Soil Layer Profiles

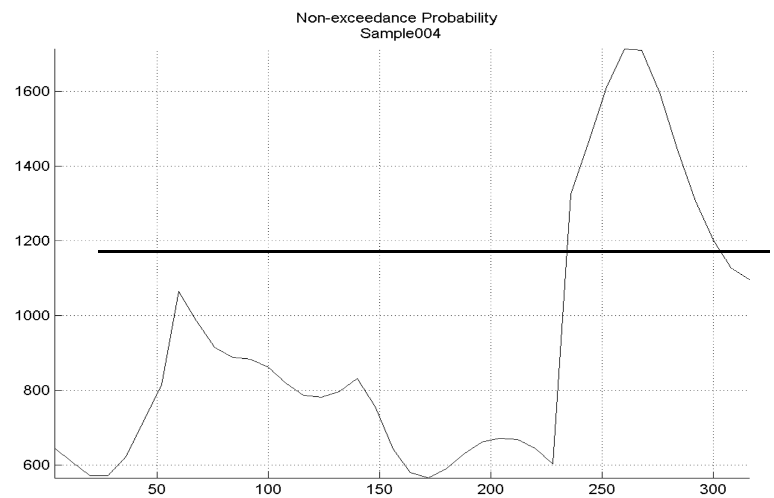
Probabilistic Soil Profile



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

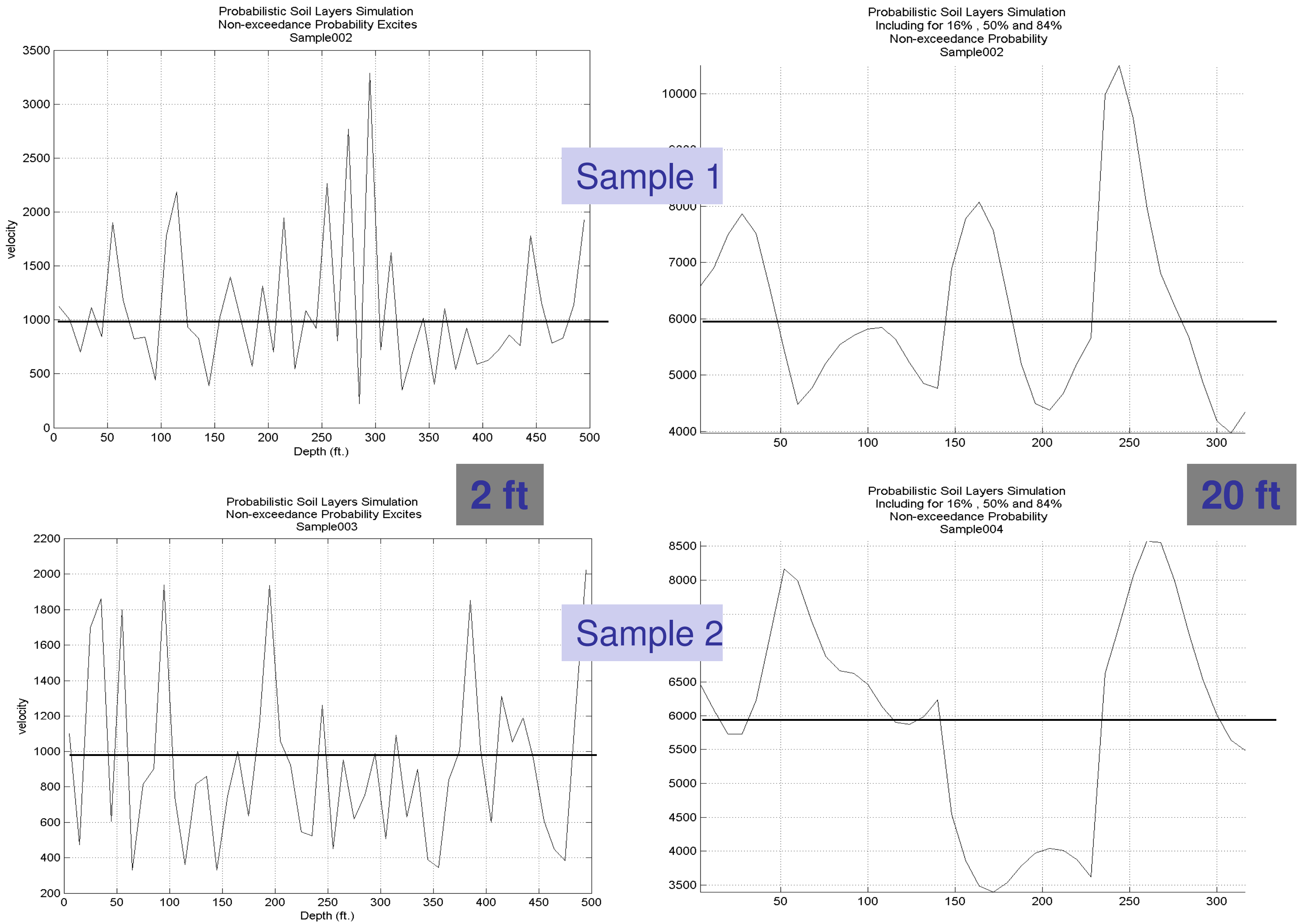
Simulated Soil Profiles





Random Samples

Effect of Spatial Correlation Length on Simulated Soil Profiles

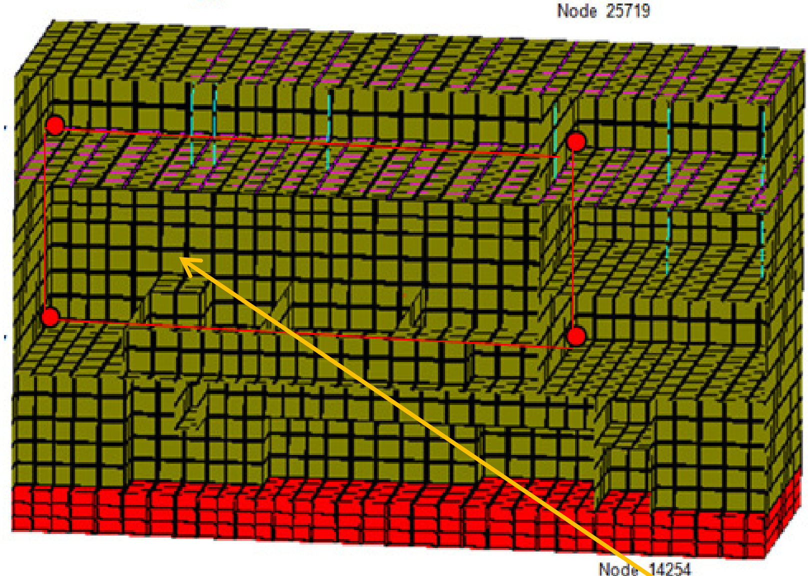


Probabilistic Structural Modeling (Stiffness & Damping)

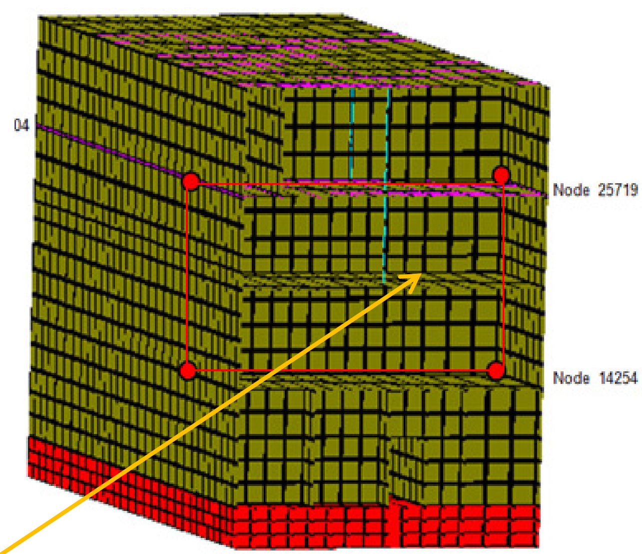
- Effective stiffness ratio Keff/Kelastic and damping ratio, Deff, are modeled as statistically dependent random variables.

- 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

Longitudinal Shearwall



Transverse Shearwall



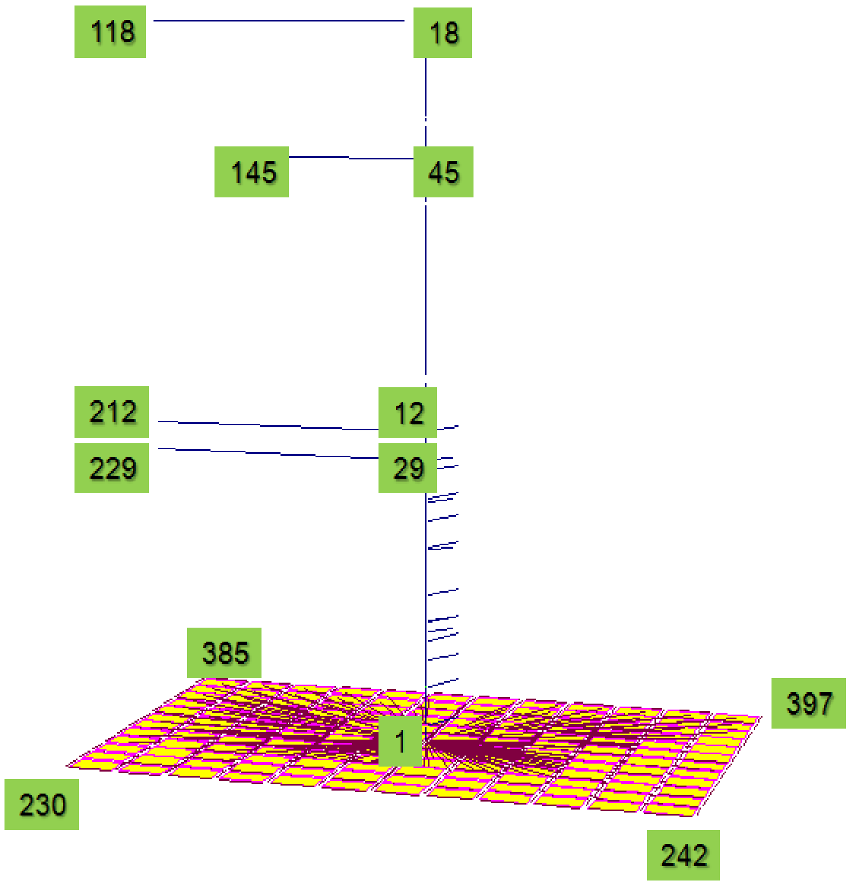
Deff = f (Keff/Elastic)

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

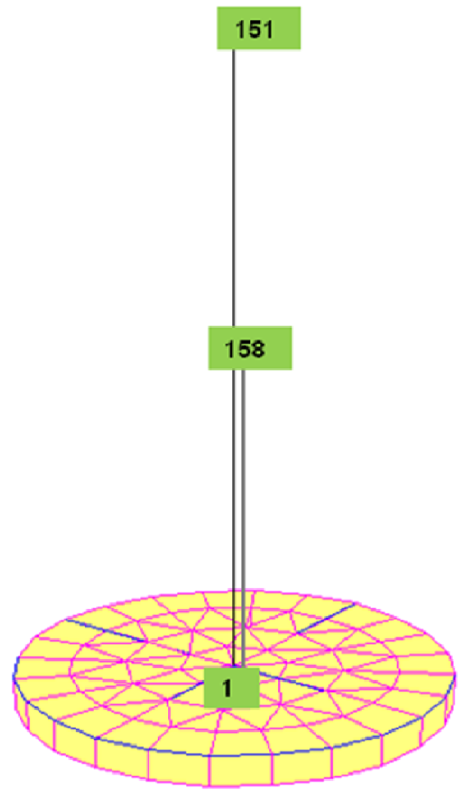
- Keff and Deff are defined separately for each element group. Statistical correl[illegible]een different group Keff variables can be included.

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

EPRI AP1000 NI Stick Model



PWR RB Stick Model



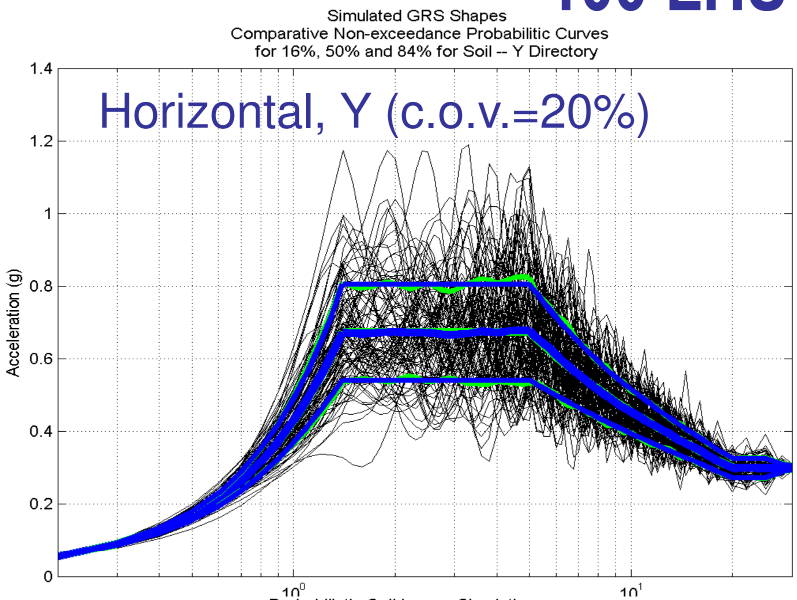
Deff = f (Keff)

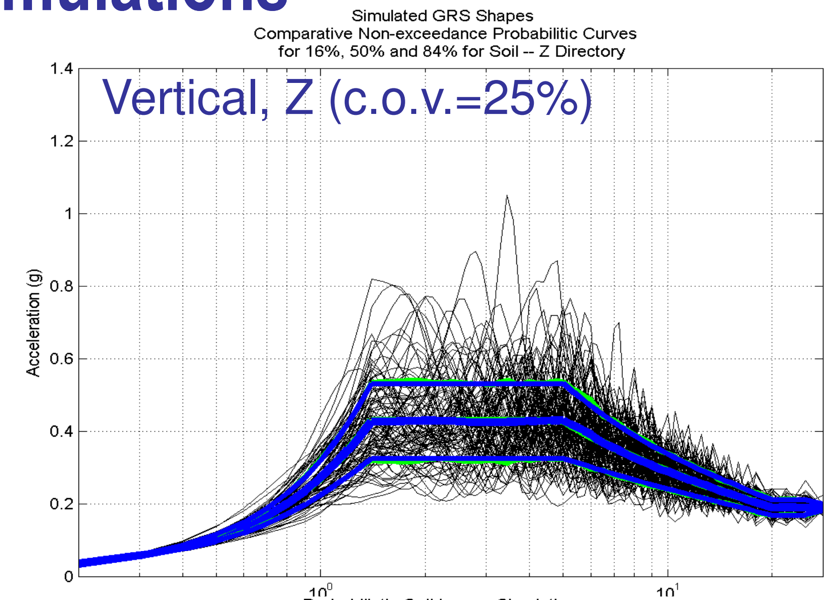
Stiff	Damp
0.01	0.20
0.10	0.17
0.20	0.15
0.30	0.13
0.40	0.11
0.50	0.10
0.60	0.09
0.70	0.08
0.80	0.07
0.90	0.06
1.00	0.05

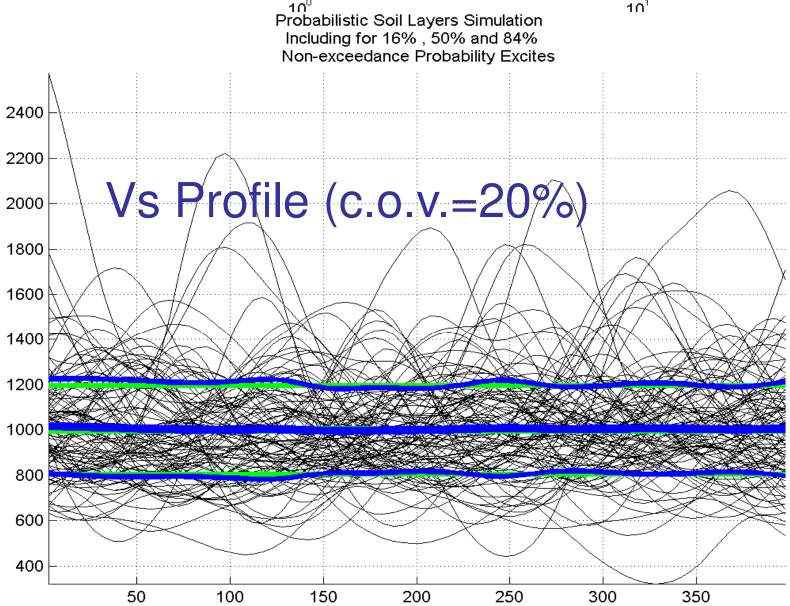
Mean Values

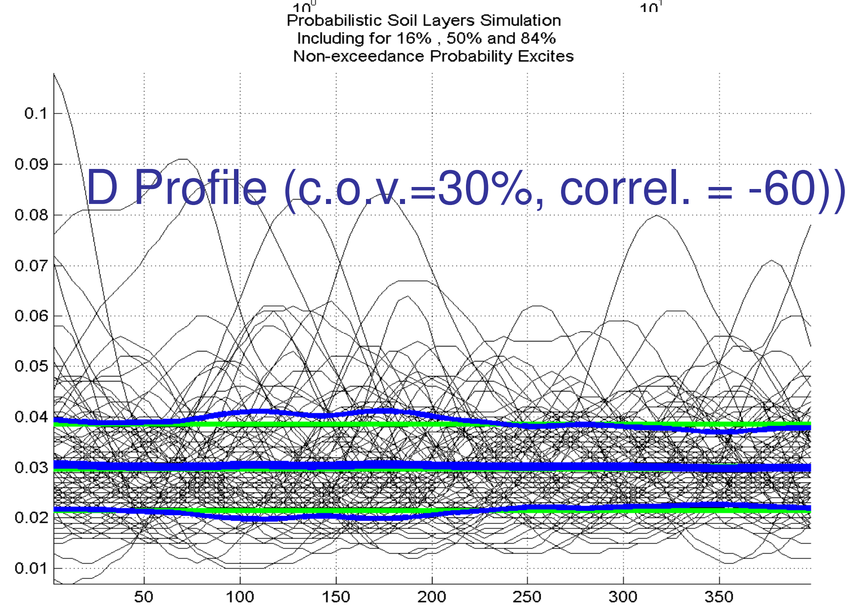
Case 1: Soil Site, Vs = 1,000 fps
Case 2: Rock Site, Vs = 6,000 fps

Seismic GRS (Method 2) and Soil Profiles for Soil Site
100 LHS Simulations



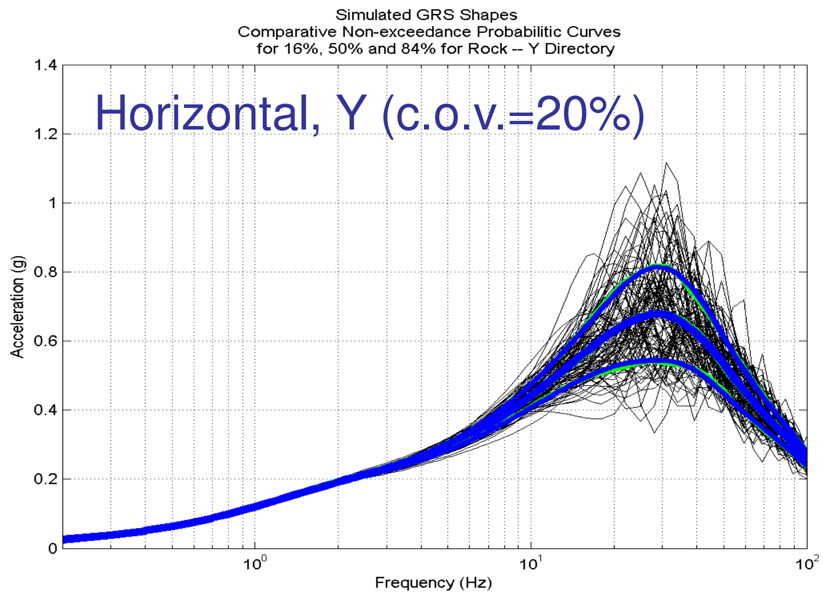


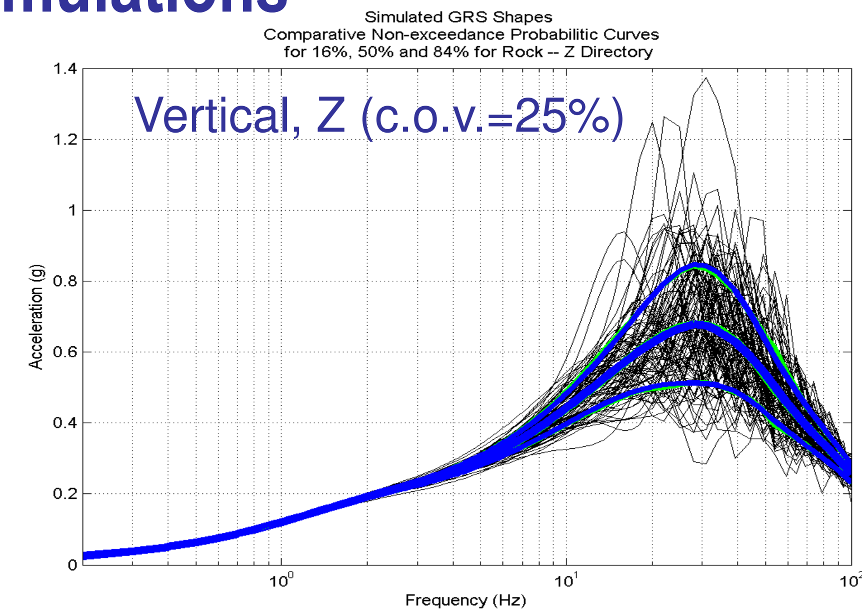


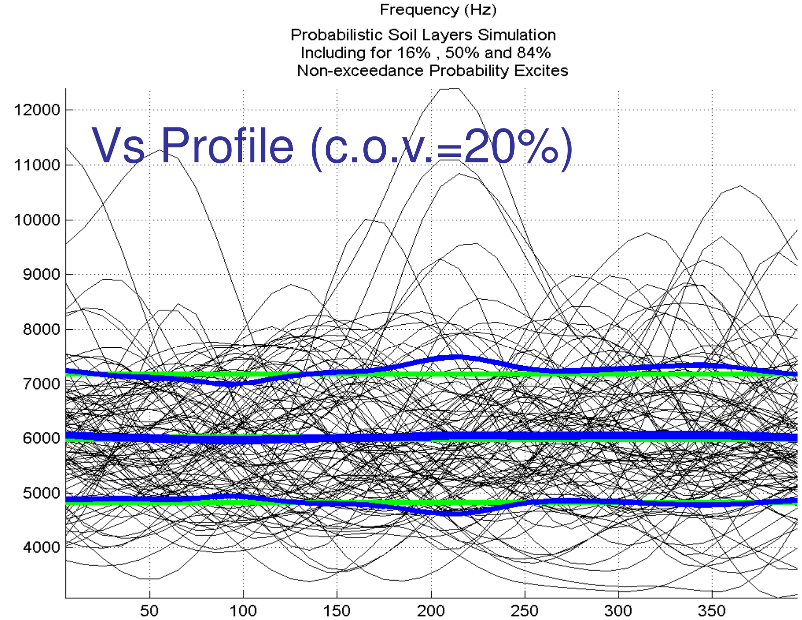


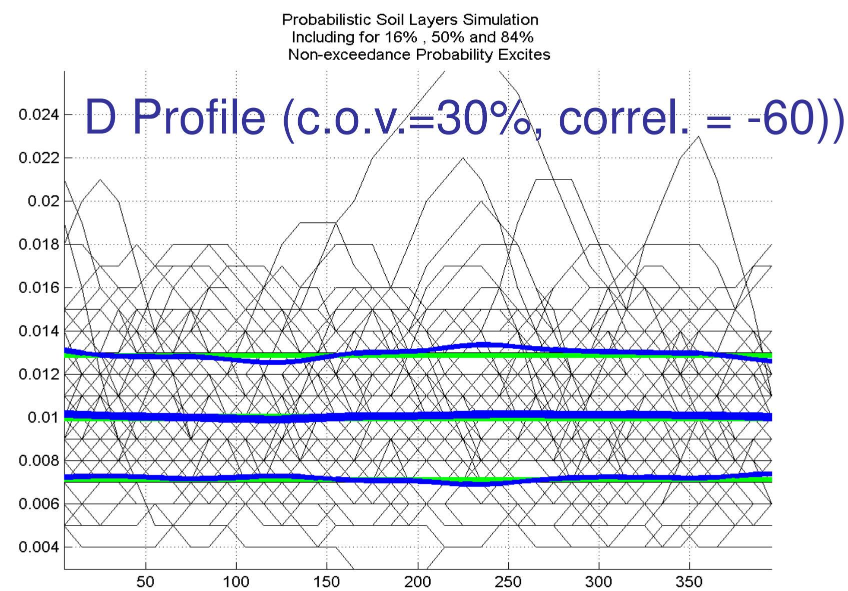
Seismic GRS (Method 2) and Soil Profiles for Rock Site

100 LHS Simulations



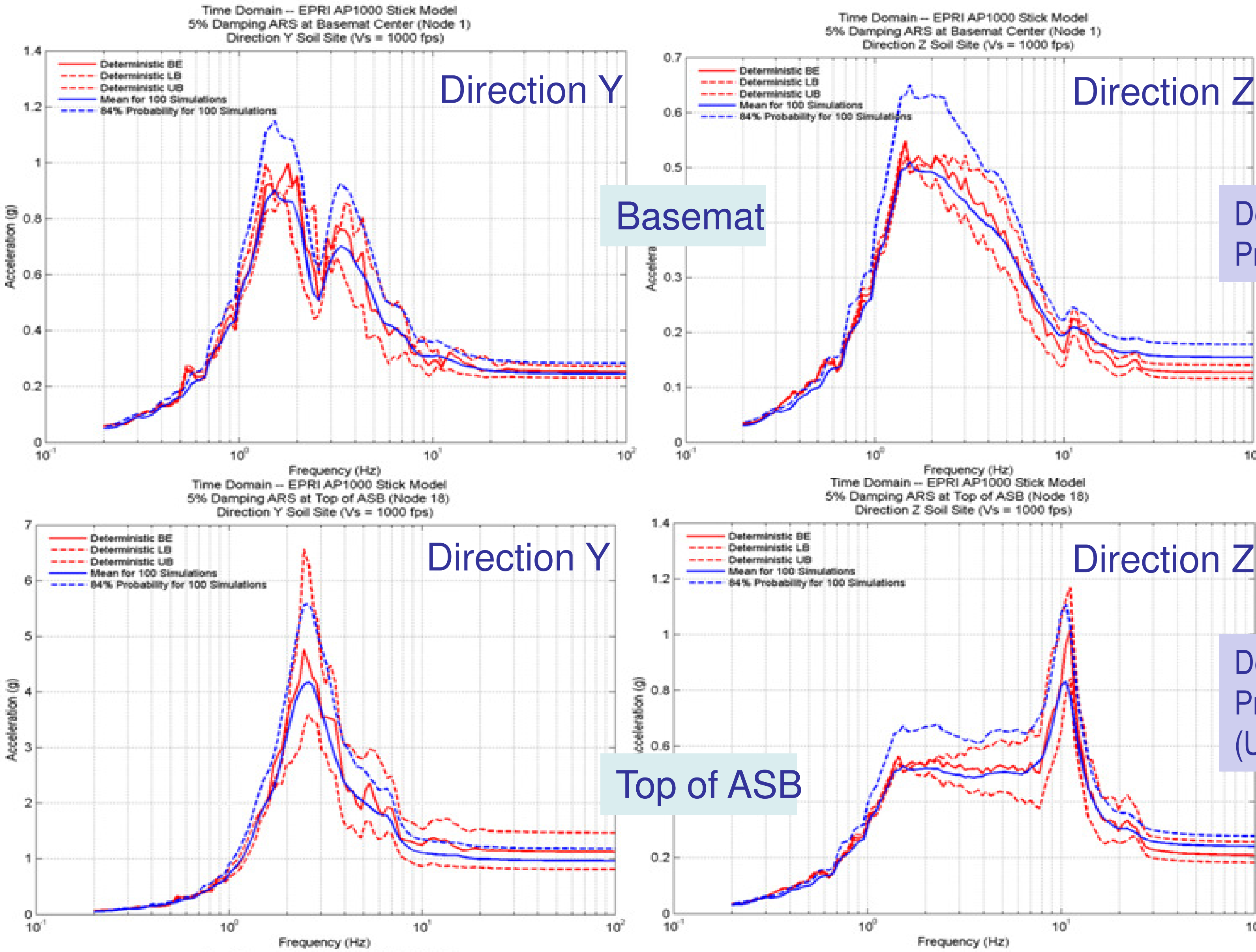




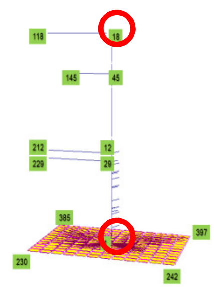


Deterministic vs. Probabilistic SSI Analysis for Soil Site

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



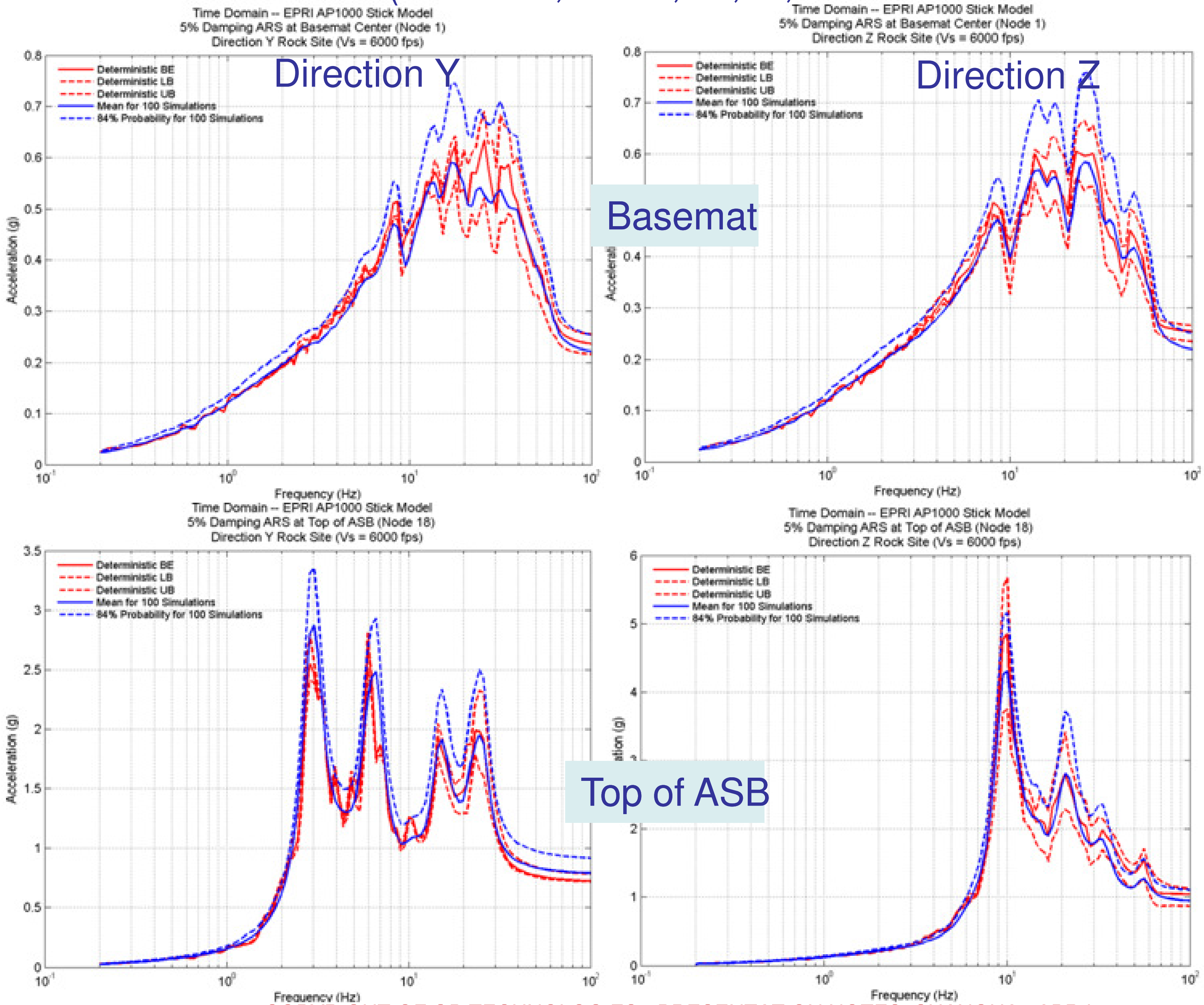
Det ranges
Prob 60%-80%



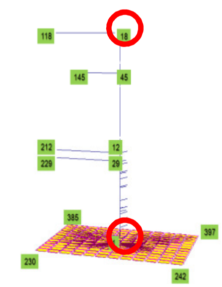
Det ranges
Prob 85%-95%
(UB role)

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%)



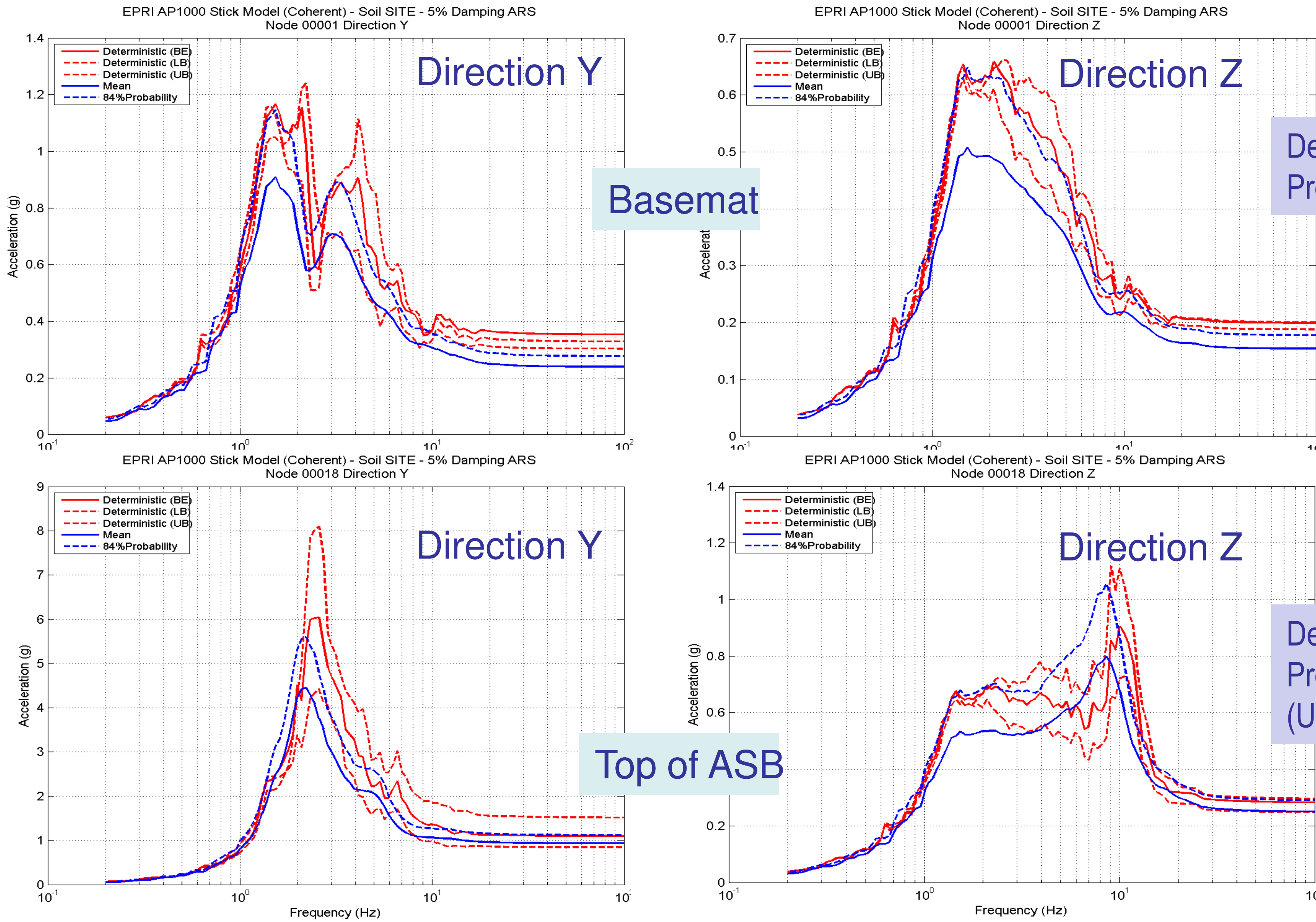
Det ranges
Prob 65%-80%



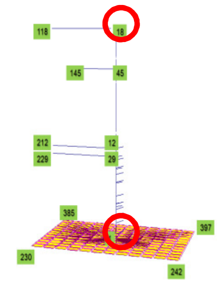
Det ranges
Prob 65%-95%
(UB role)

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%)



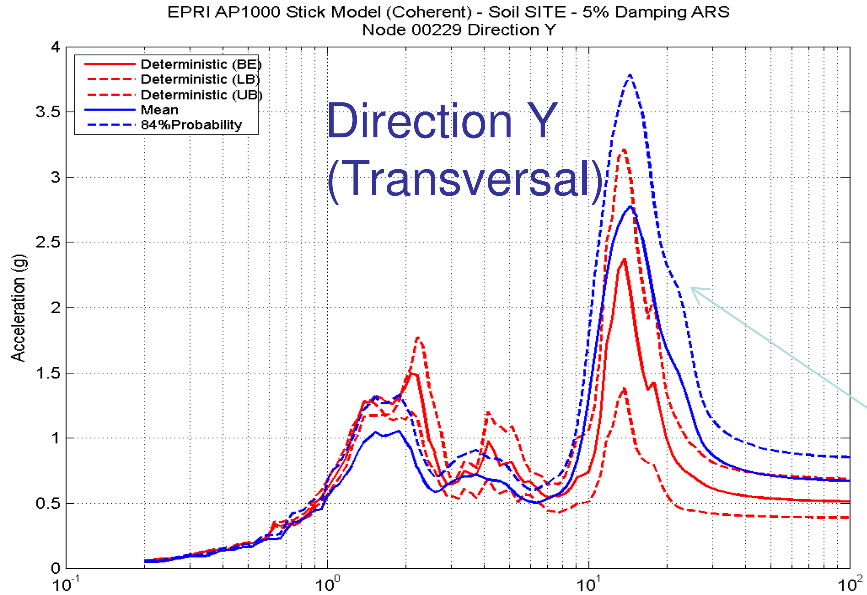
Det ranges
Prob 85%-80%

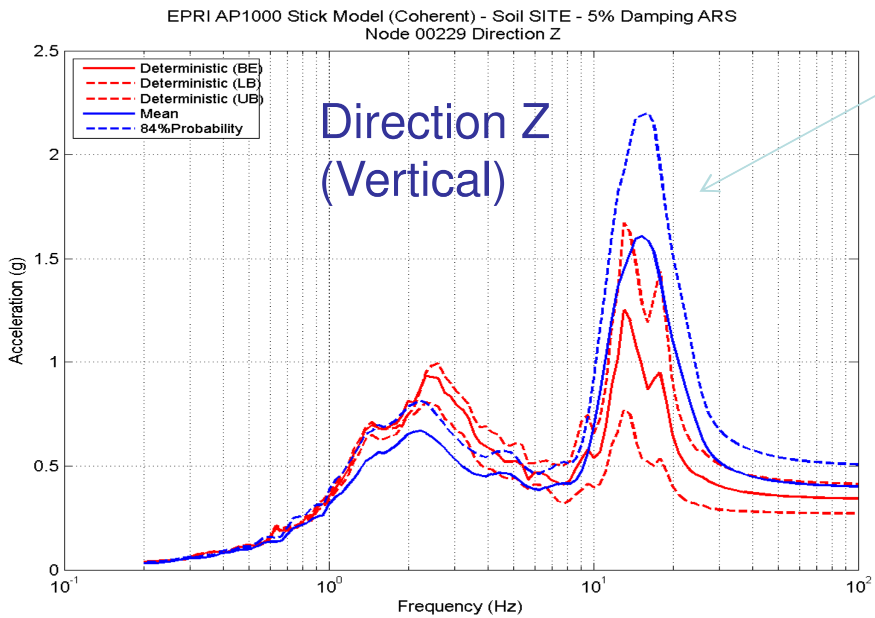


Det ranges
Prob 85%-95%
(UB role)

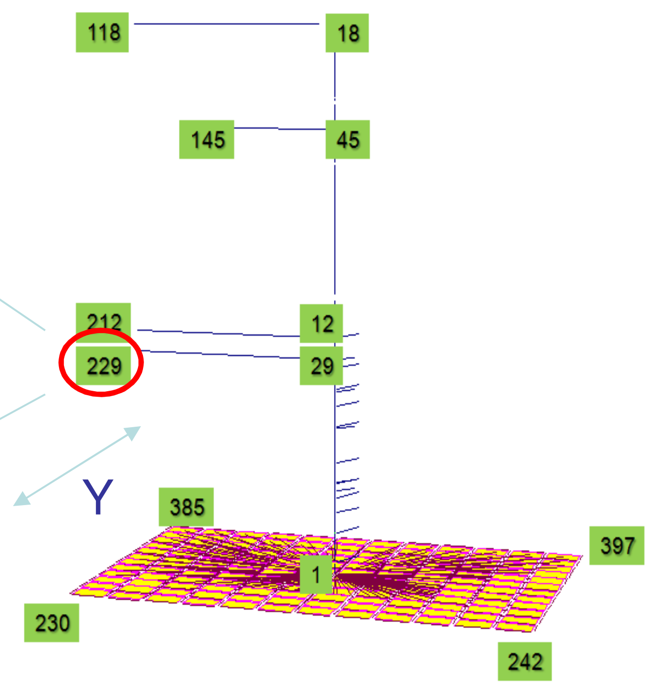
Deterministic vs. Probabilistic SSI Analysis for Rock Site

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





EPRI AP1000 Stick Model

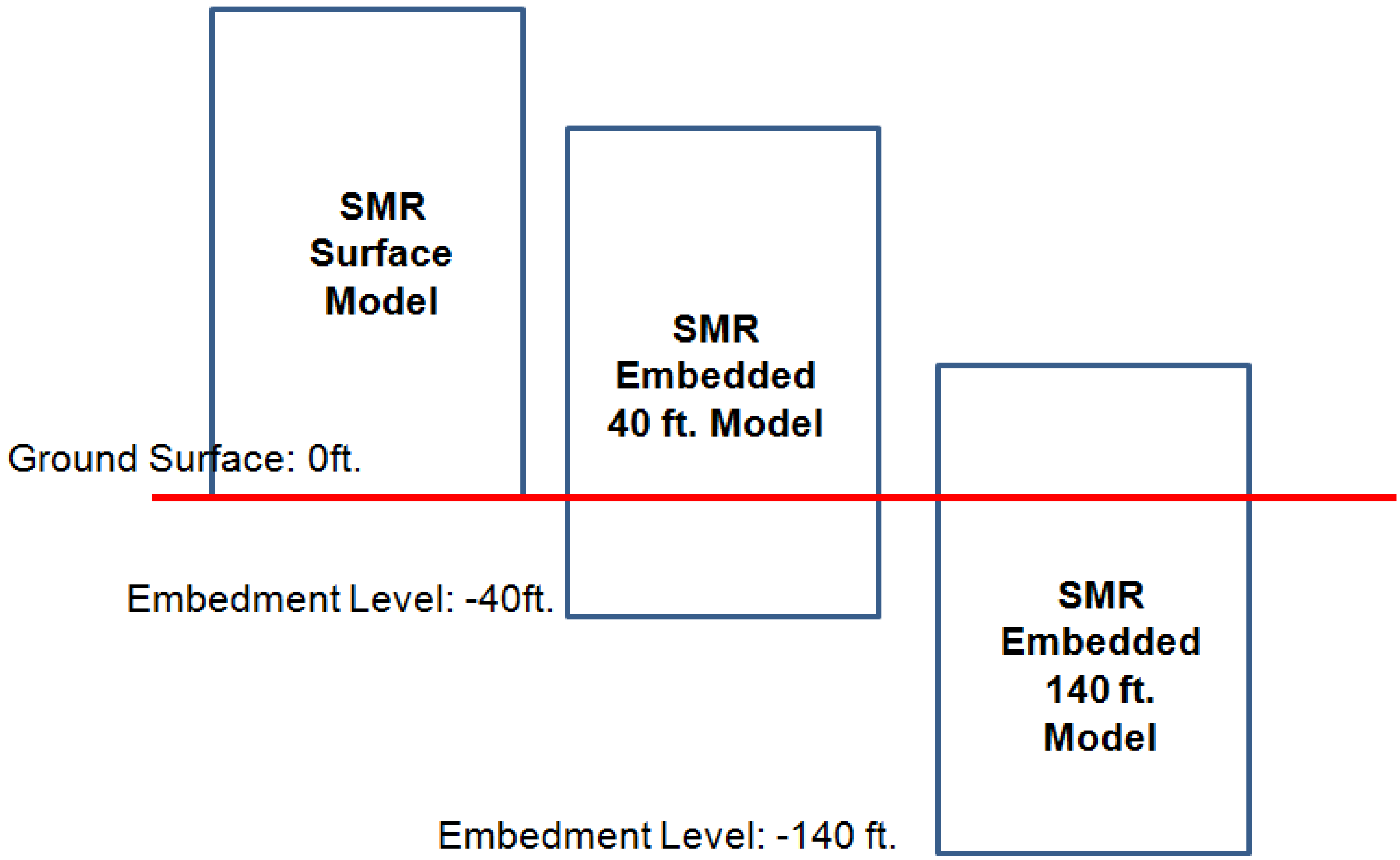


NOTE: 229 node location sensitive to torsional and rocking motion components

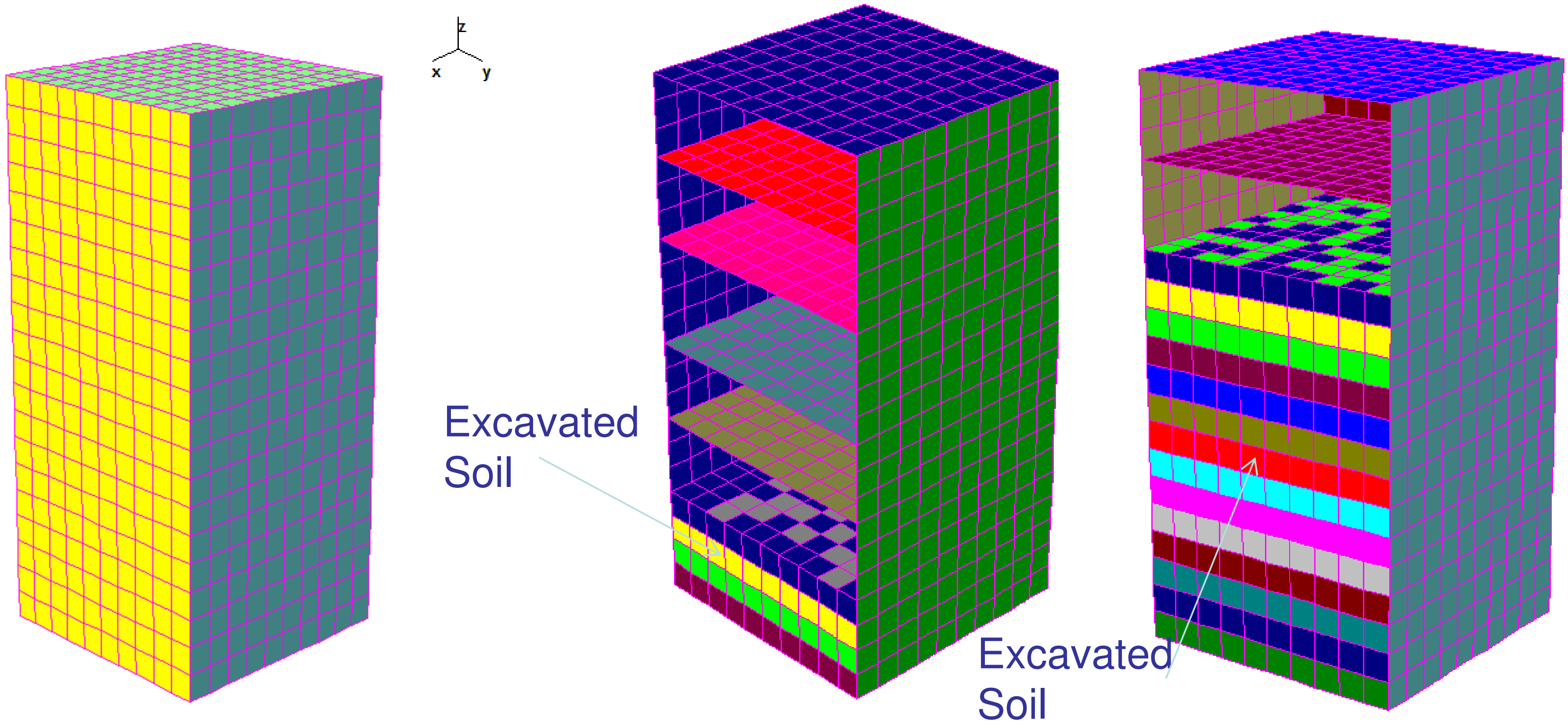
Concluding Remarks

- 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.

SMR SSI Analysis Case Studies



ACS SASSI SMR SSI Models



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 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

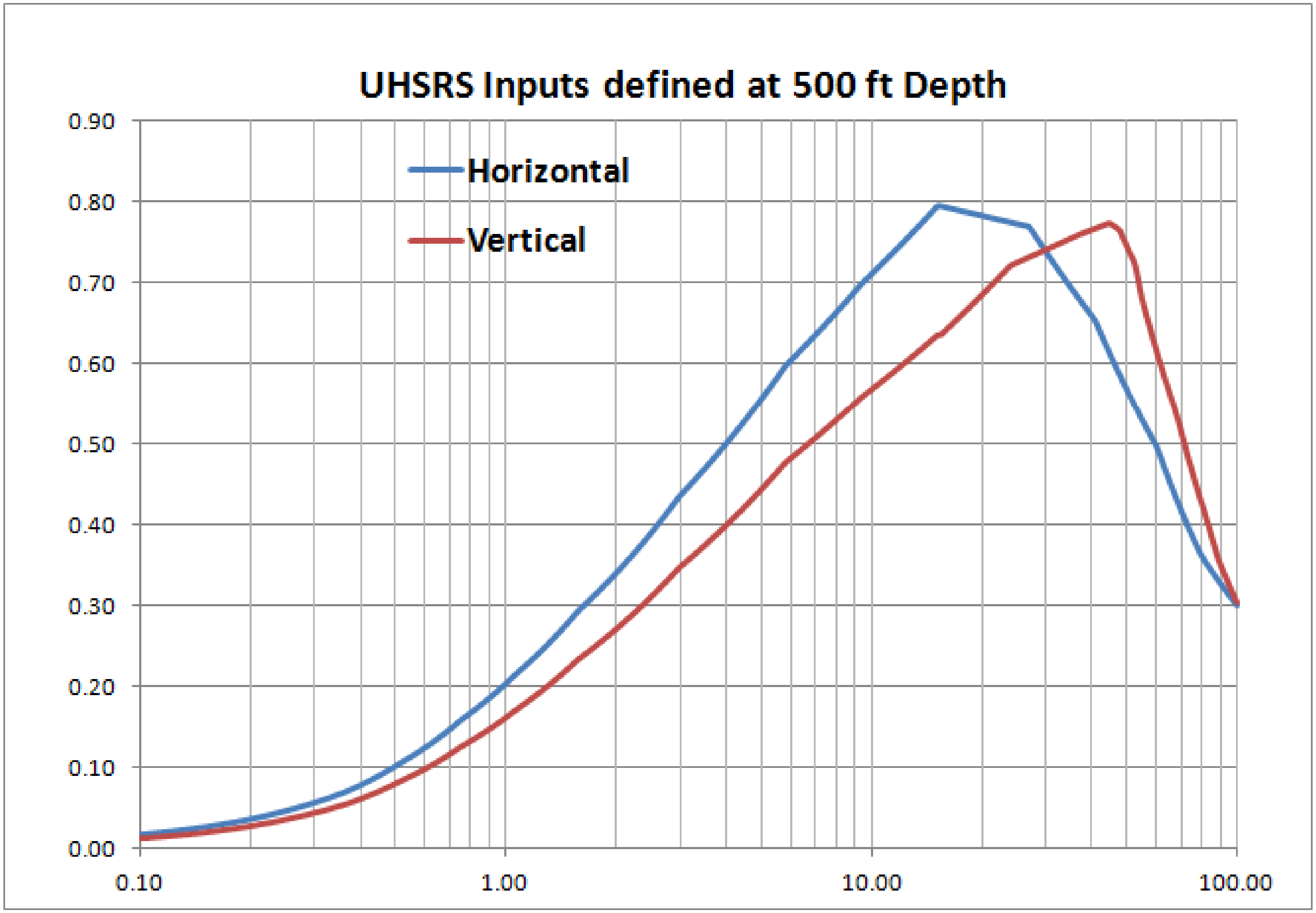
SOIL LAYERING

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).

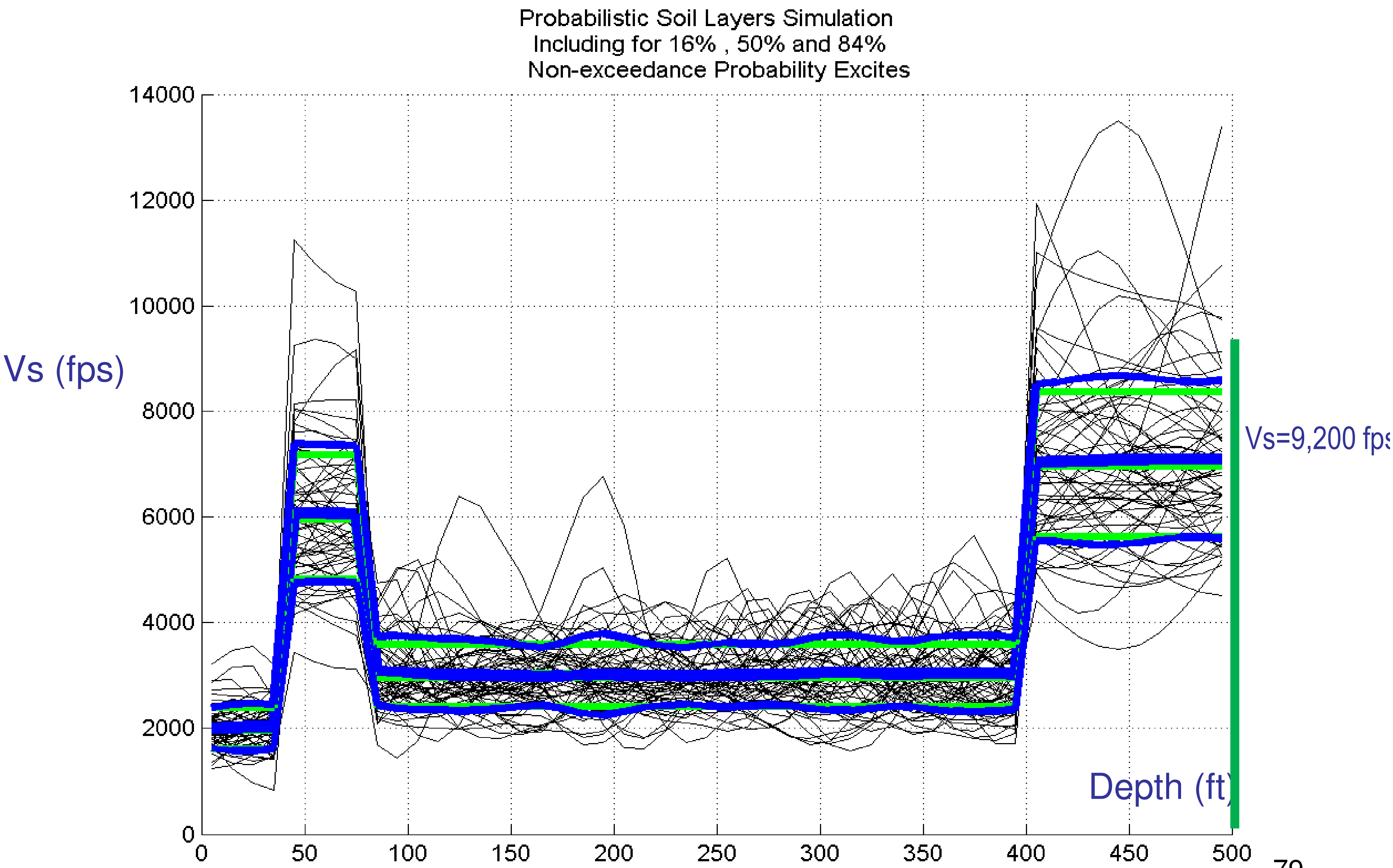
Probabilistic SSI: We considered the 60 randomized soil profiles. The Vs and Damping for each soil profile were considered as dependent random variables with lognormal distribution. Damping variable is considered statistically dependent (varying inversely than Vs) as recommended by ASCE 04-2014. Vs c.o.v. 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)

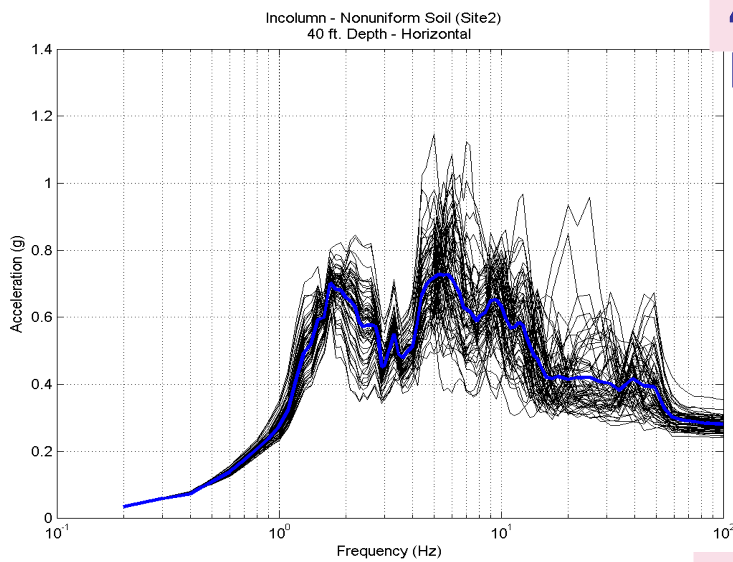


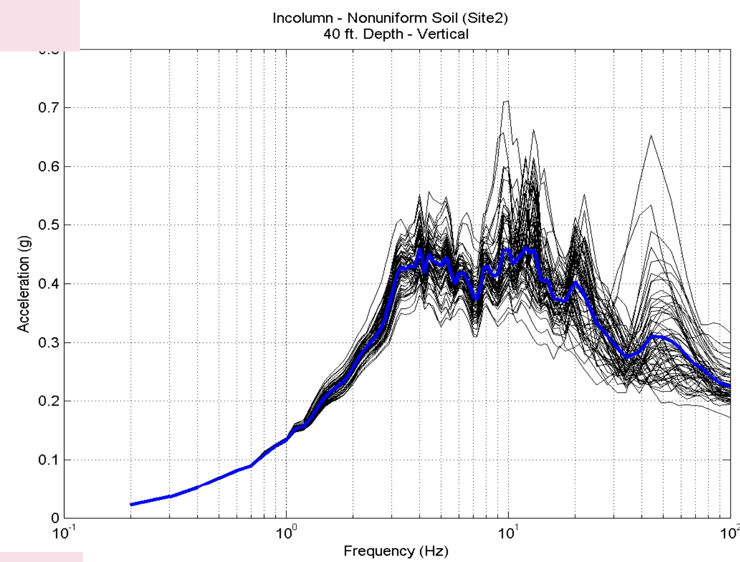
Nonuniform Soil Profile (Site 2)
60 Probabilistic and 3 Deterministic Soil Profiles



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

40 ft Depth

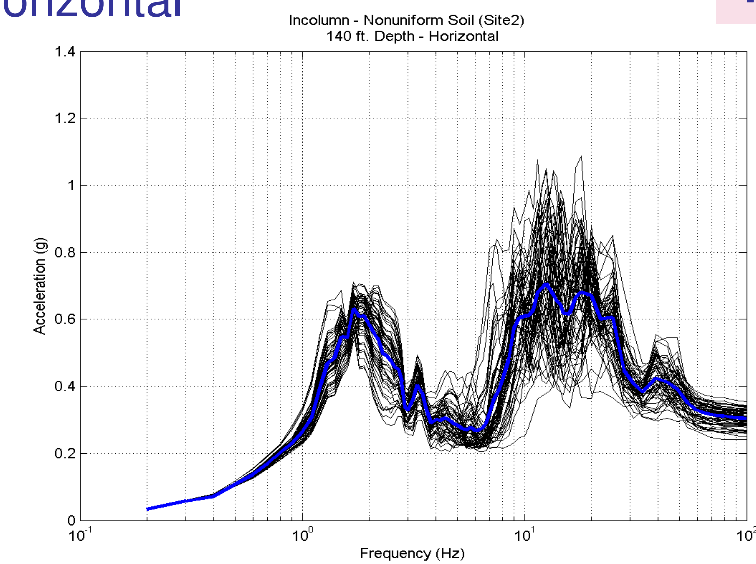


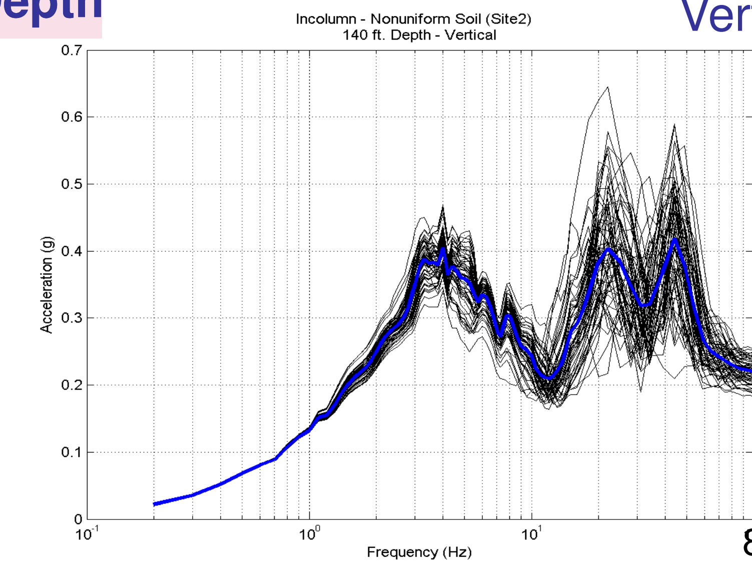


Horizontal

140 ft Depth

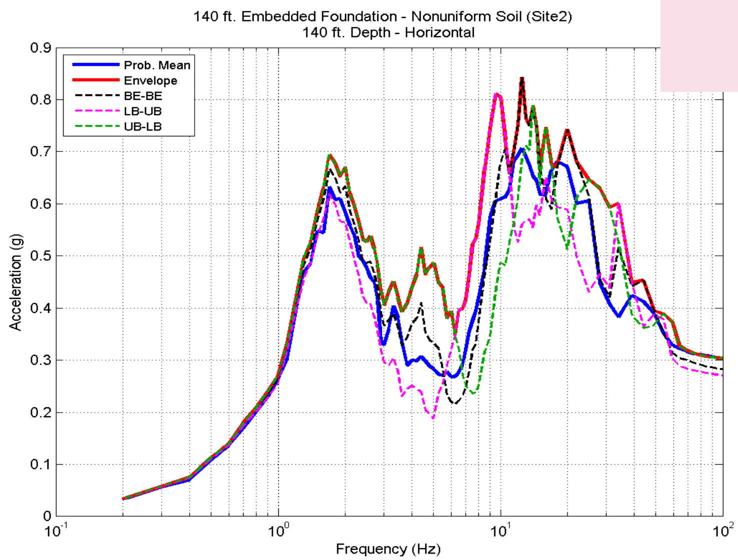
Vertical

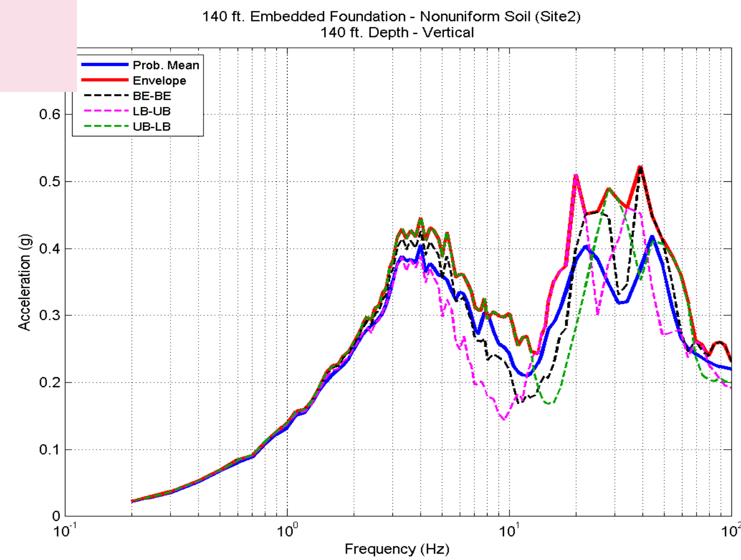




Deterministic vs. Probabilistic In-Column RS for Outcrop FIRS Input Defined at 140 ft Depth (Site 2)

140 ft Depth (FIRS)

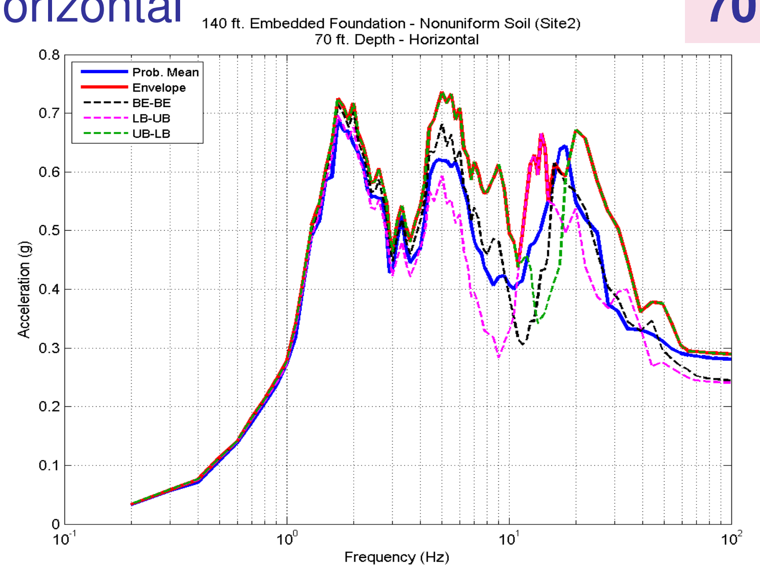


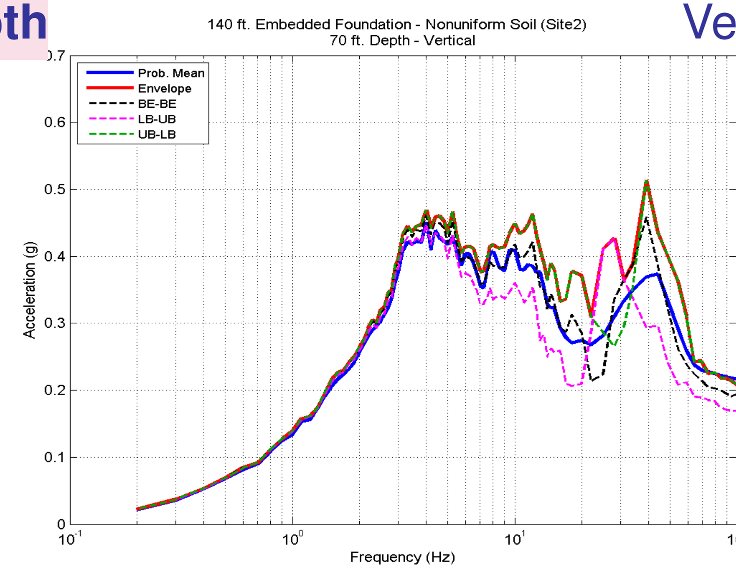


Horizontal

70 ft Depth

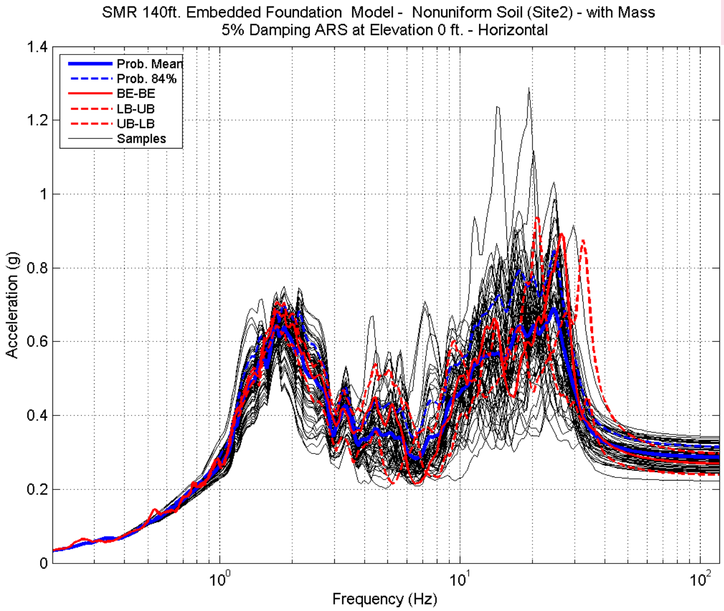
Vertical

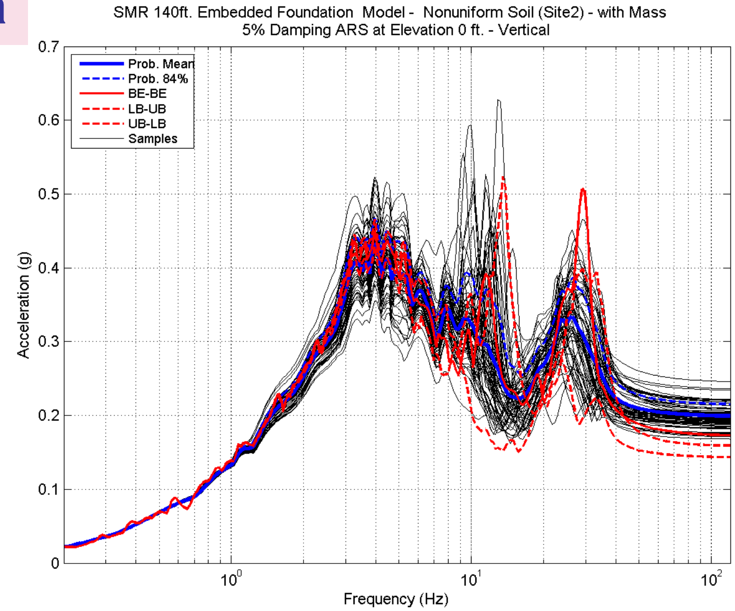




Probabilistic ISRS Simulations for 140ft Embedded SSI Model (Site 2)

Basemat

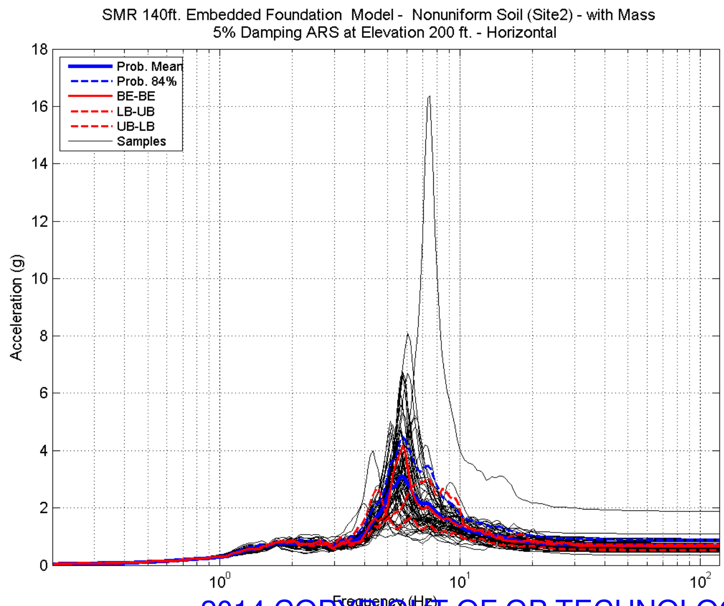


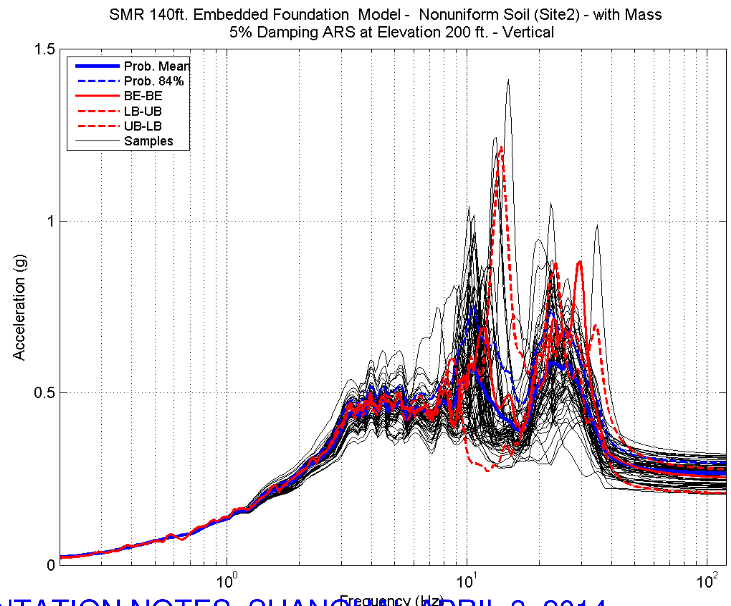


Horizontal

Vertical

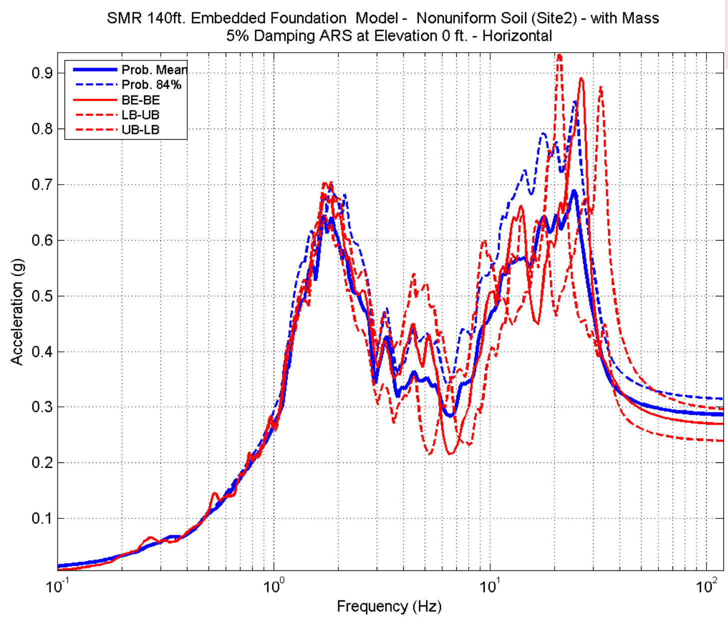
Roof

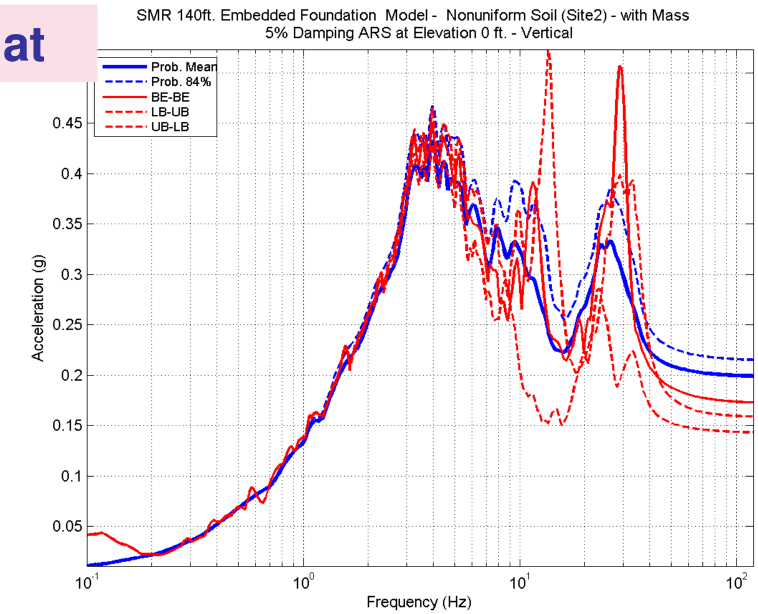




Deterministic vs. Probabilistic ISRS for 140ft Embedded Model (Site 2)

Basemat

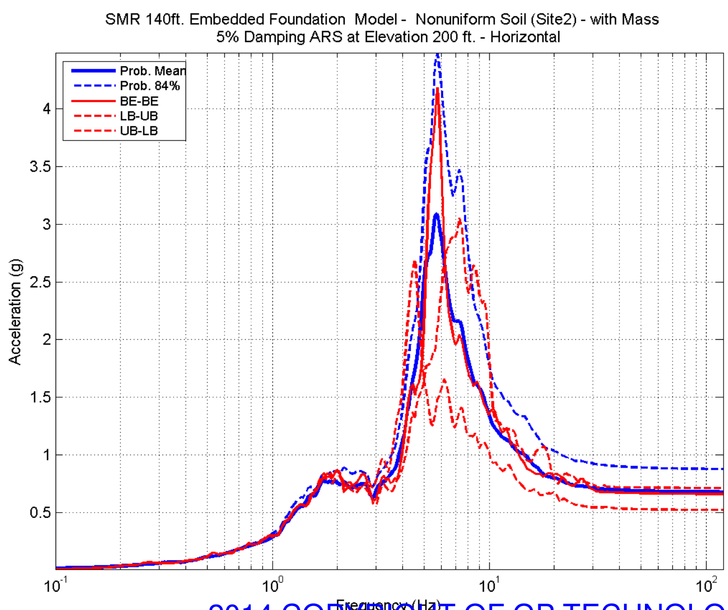


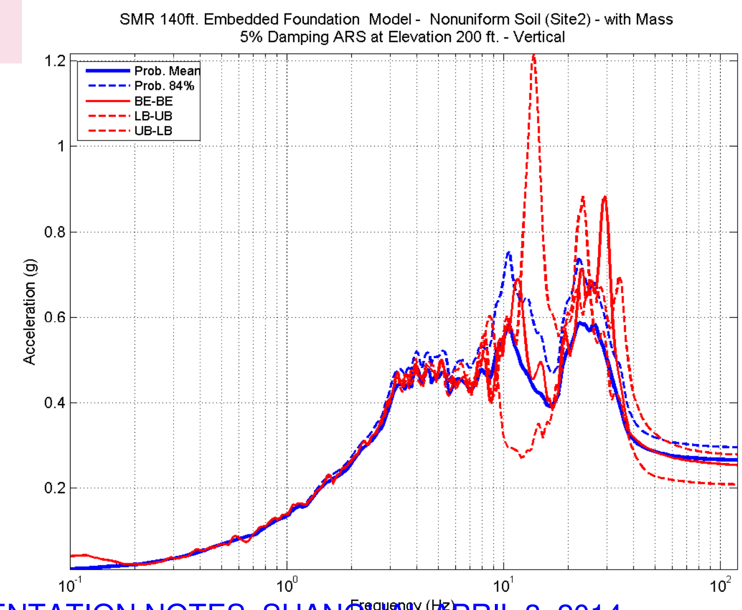


Horizontal

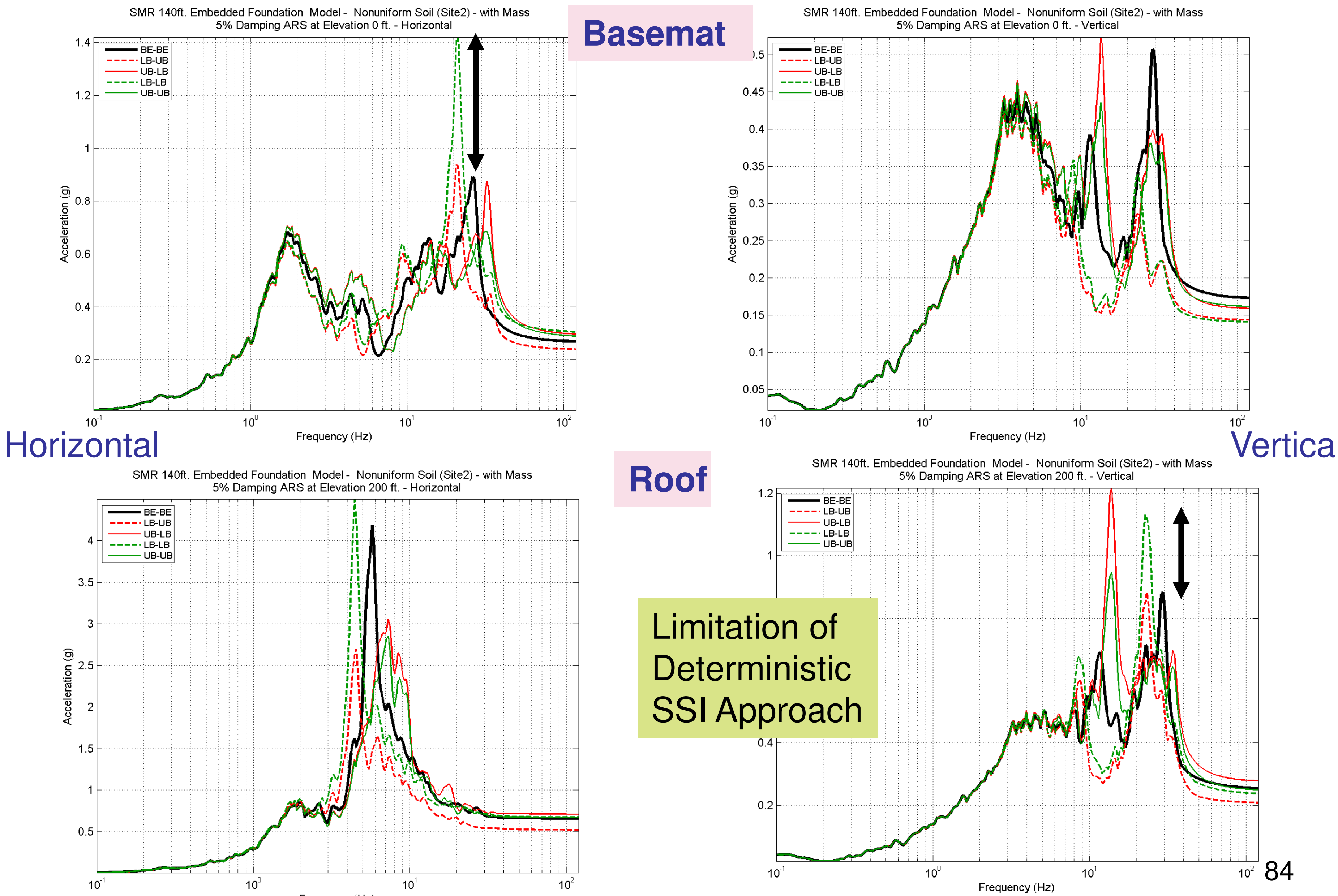
Vertical

Roof





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

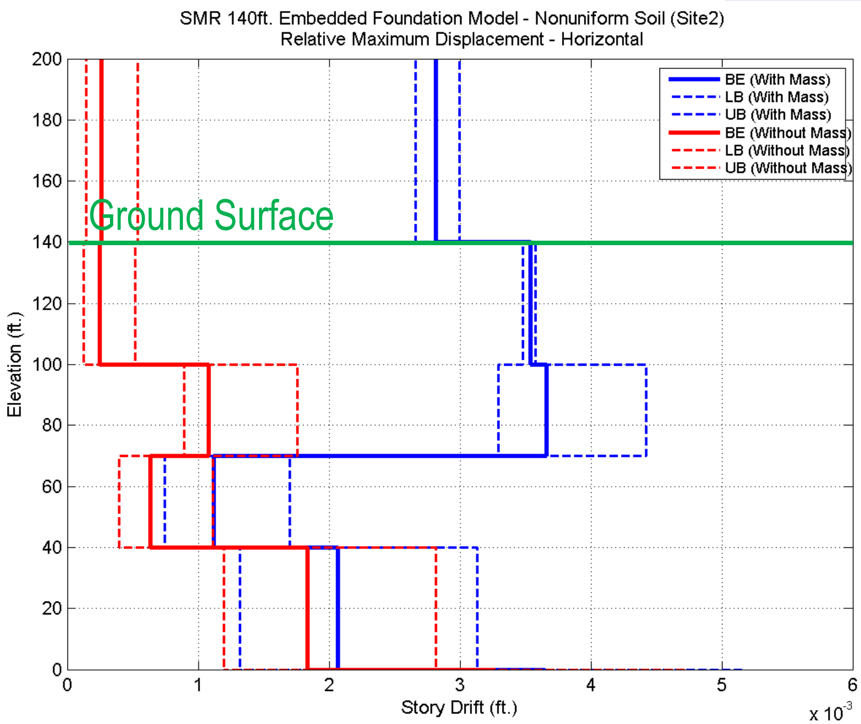


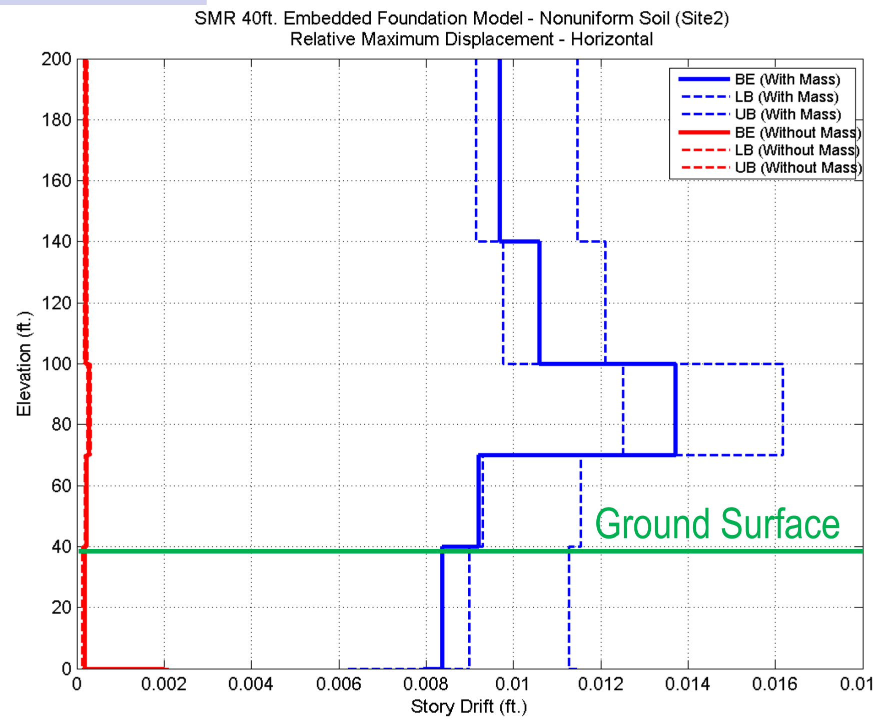
Effects of Kinematic SSI for Embedded SMRs (Site 2)

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 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*:

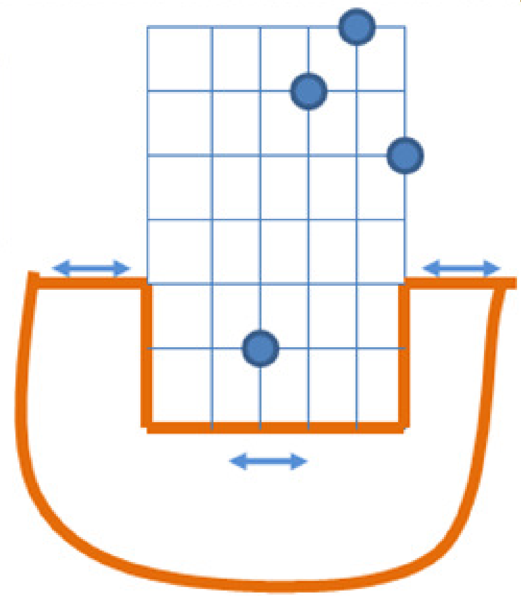
- *ANSYS Equivalent-Static Seismic SSI Analysis* Using Refined FE Models (including refined mesh, element types including local nonlinearities, nonlinear materials, contact elements, etc.)
- *ANSYS Dynamic Seismic SSI Analysis* Using More Refined FE Models (including refined mesh, element types including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

For *soil pressure computation (approximate):*

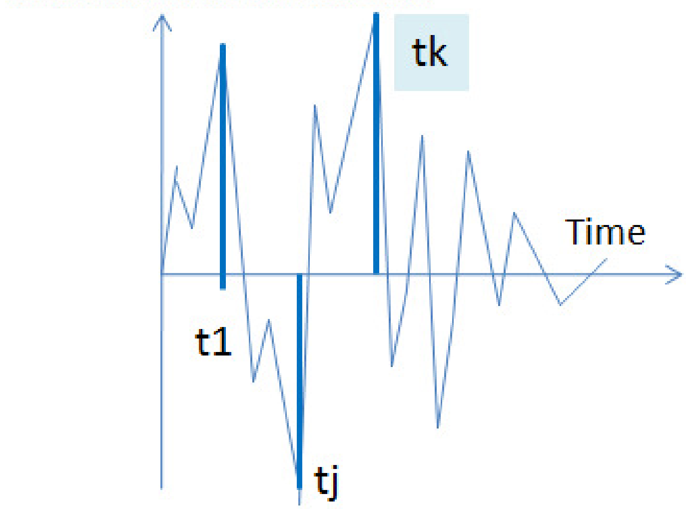
- *ANSYS Equivalent-Static Seismic Soil Pressure Computation* including Soil-Foundation Separation Effects

ACS SASSI Seismic SSI Analysis

Computing Structural Stress/Forces

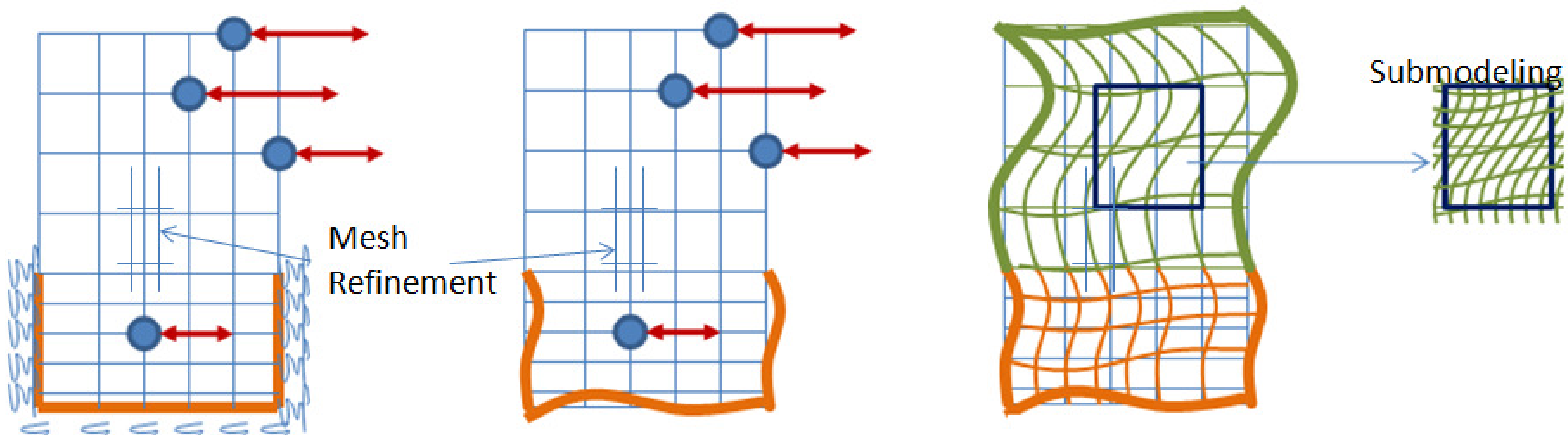


Selected Critical Time Steps for Maximum Stresses
To be Used for Equivalent Static Structural Analysis

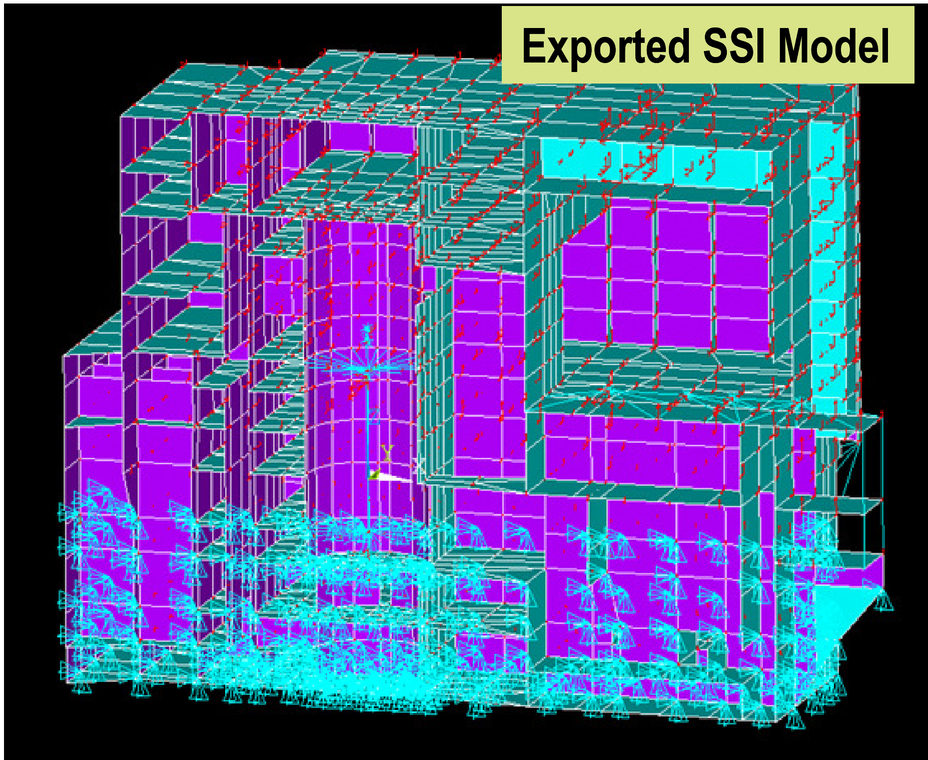


SSI Solution Time Frames As Equivalent Static Structural Loading at Critical Time Steps

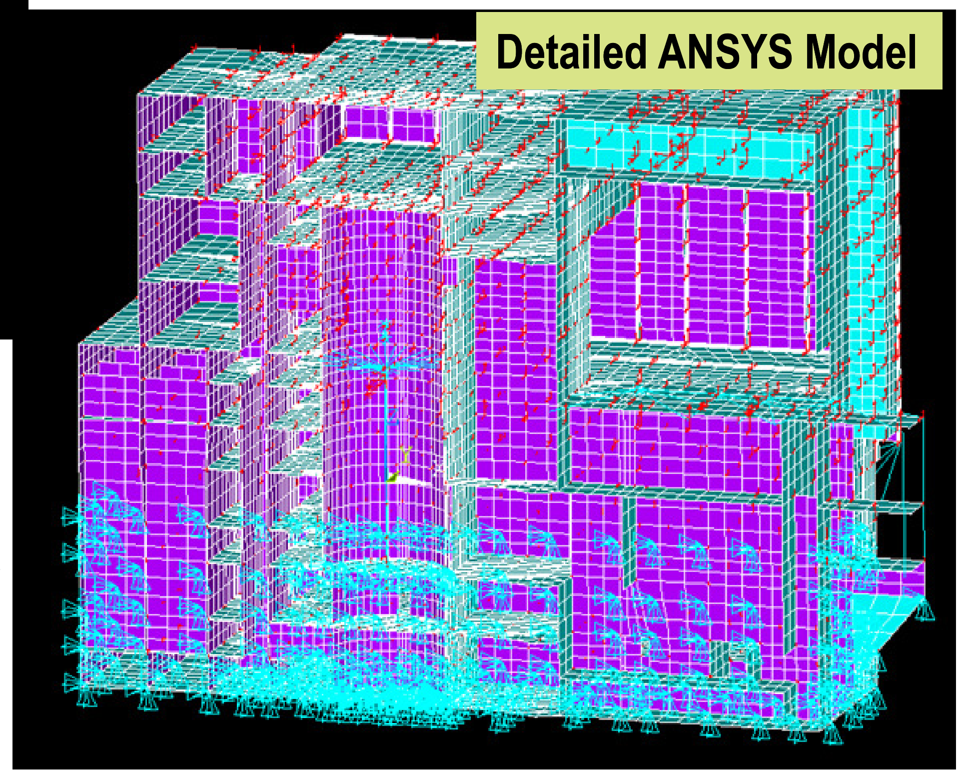
EQS Forces + BC Springs | EQS Forces + BC Displacements | EQS Relative Displacements



ACS SASSI – ANSYS Interface for Refined Seismic Stress Analysis

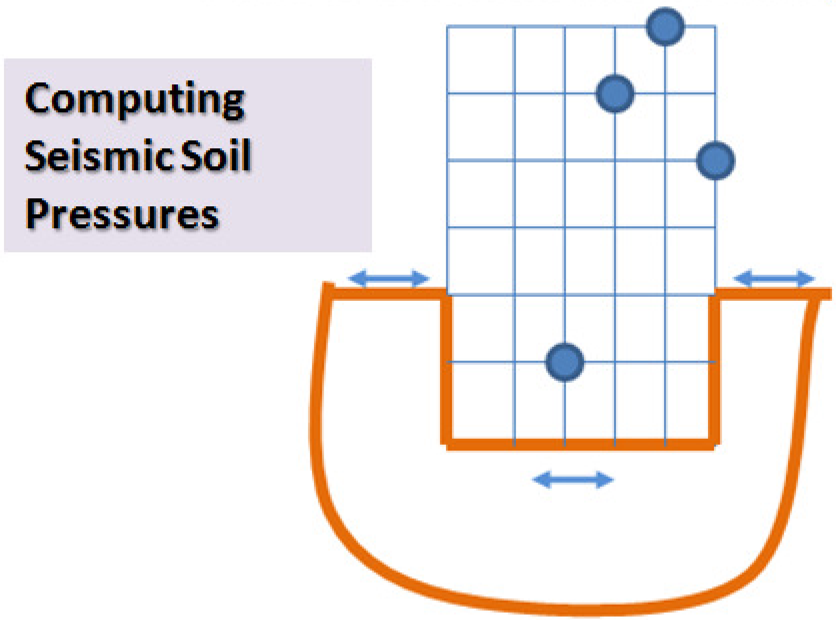


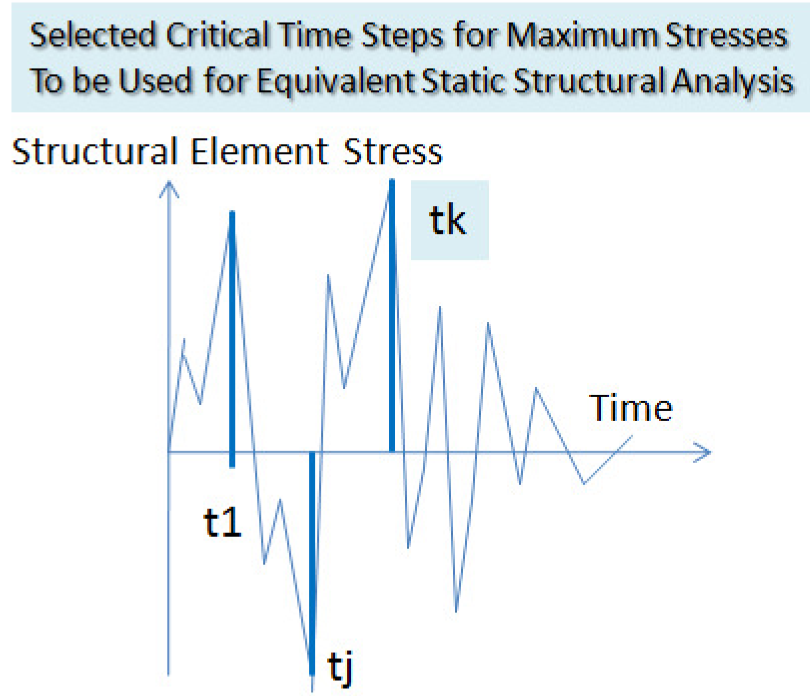
ANSYS Structural Model Automatically Converted From ACS SASSI Using PREP Module



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

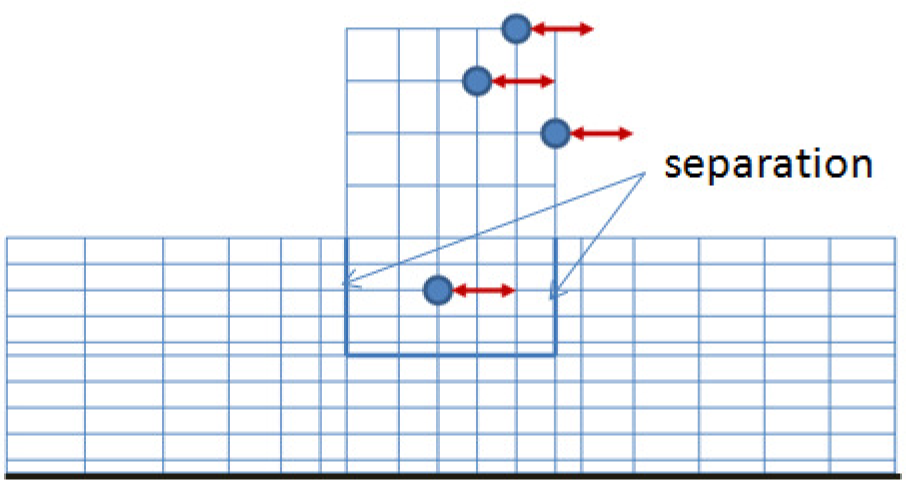
ACS SASSI Seismic SSI Analysis



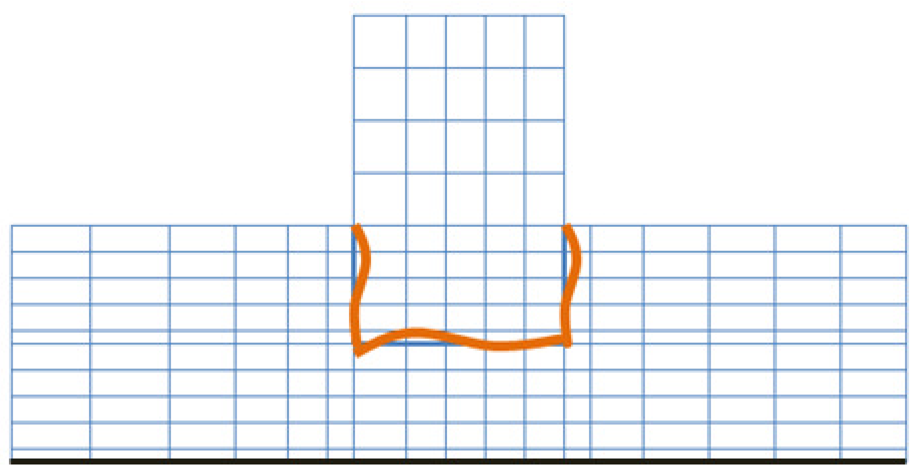


SSI Solution Time Frames As Equivalent Static Loading at Critical Time Steps

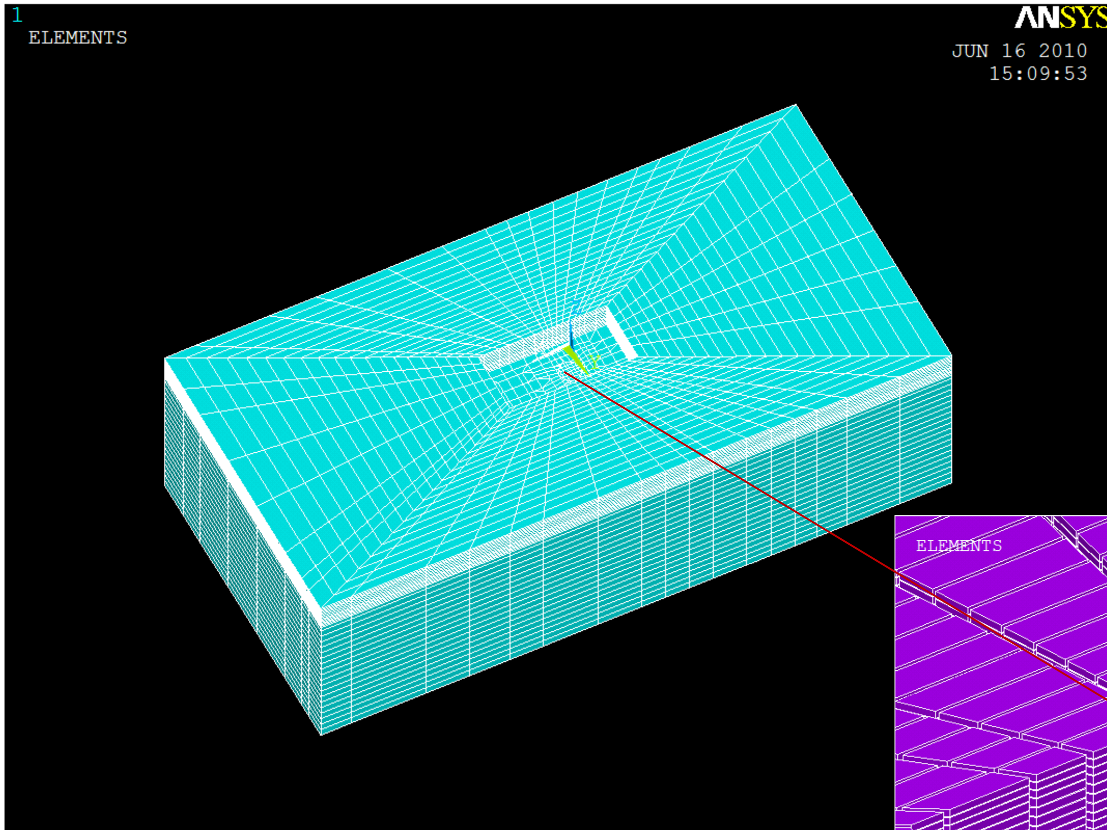
EQS Forces – Linear & Nonlinear



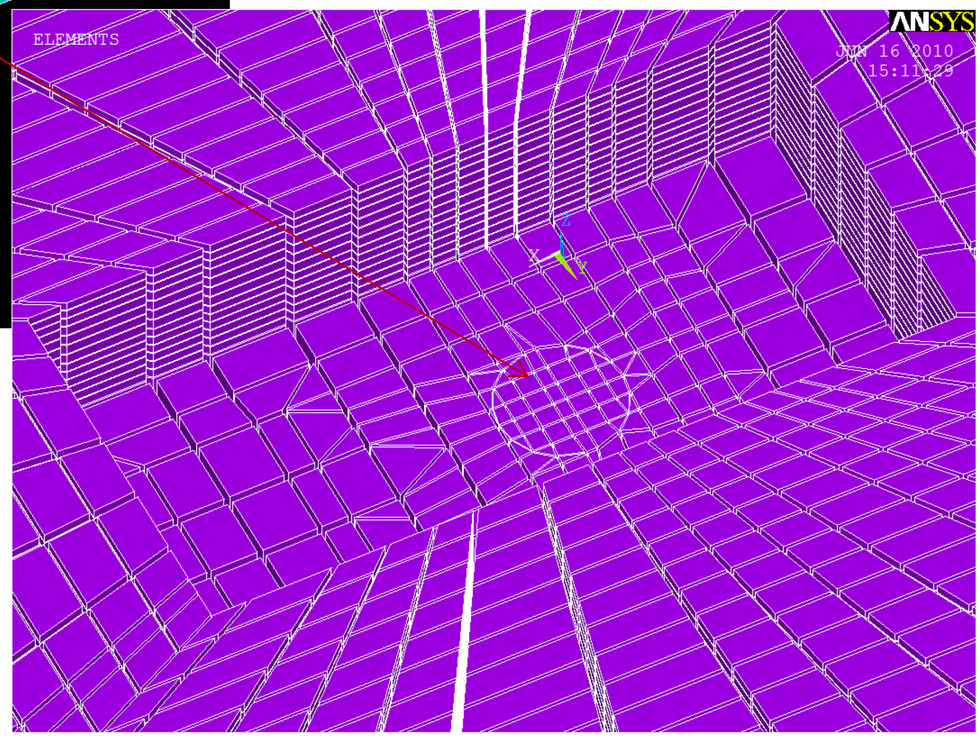
EQS Relative Displacements – Linear (Welded)



ACS SASSI – ANSYS Interface for Seismic Soil Pressure Analysis



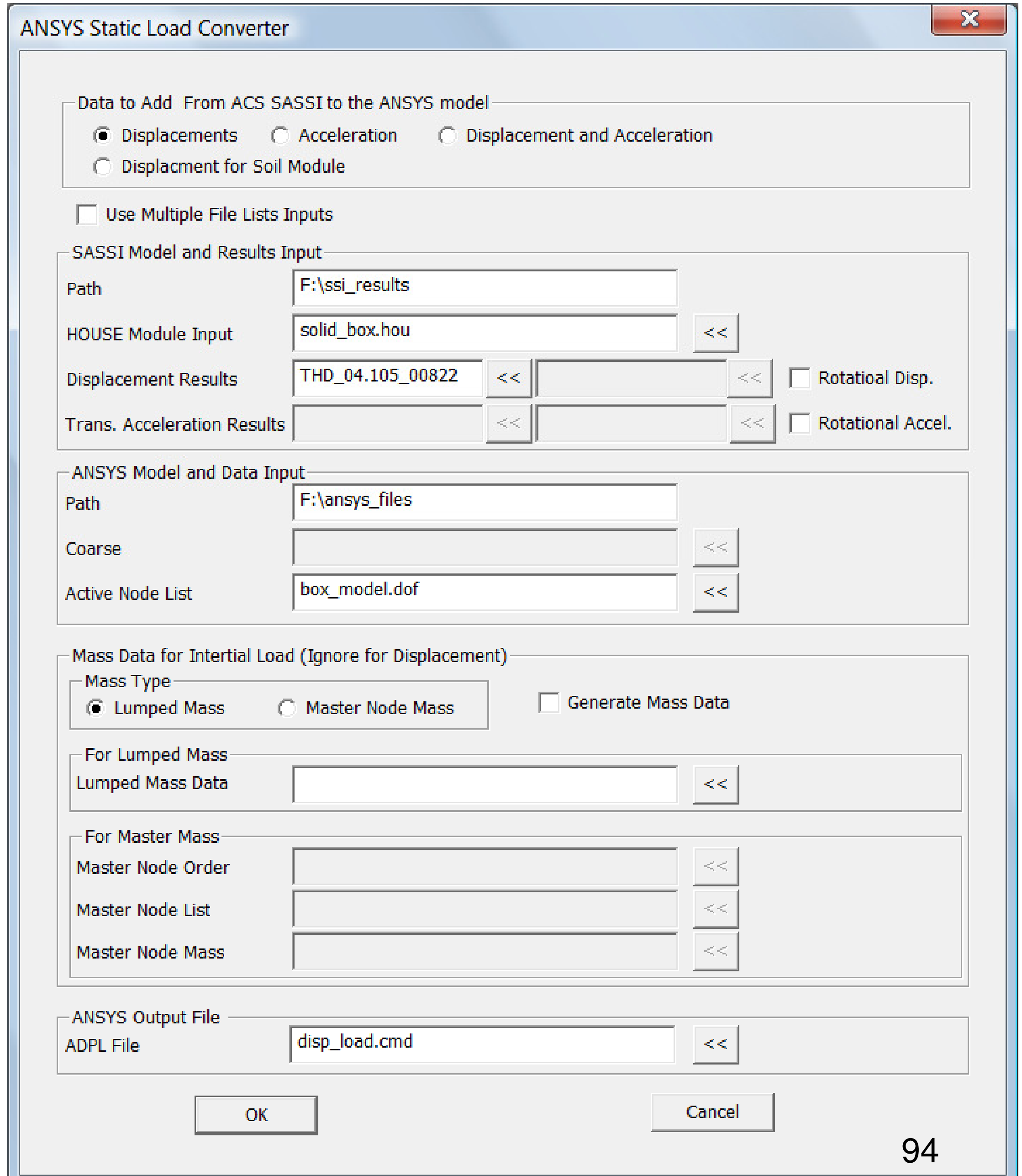
ANSYS Soil FE Model
Is Automatically Generated
by SOILMESH Module



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
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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
```
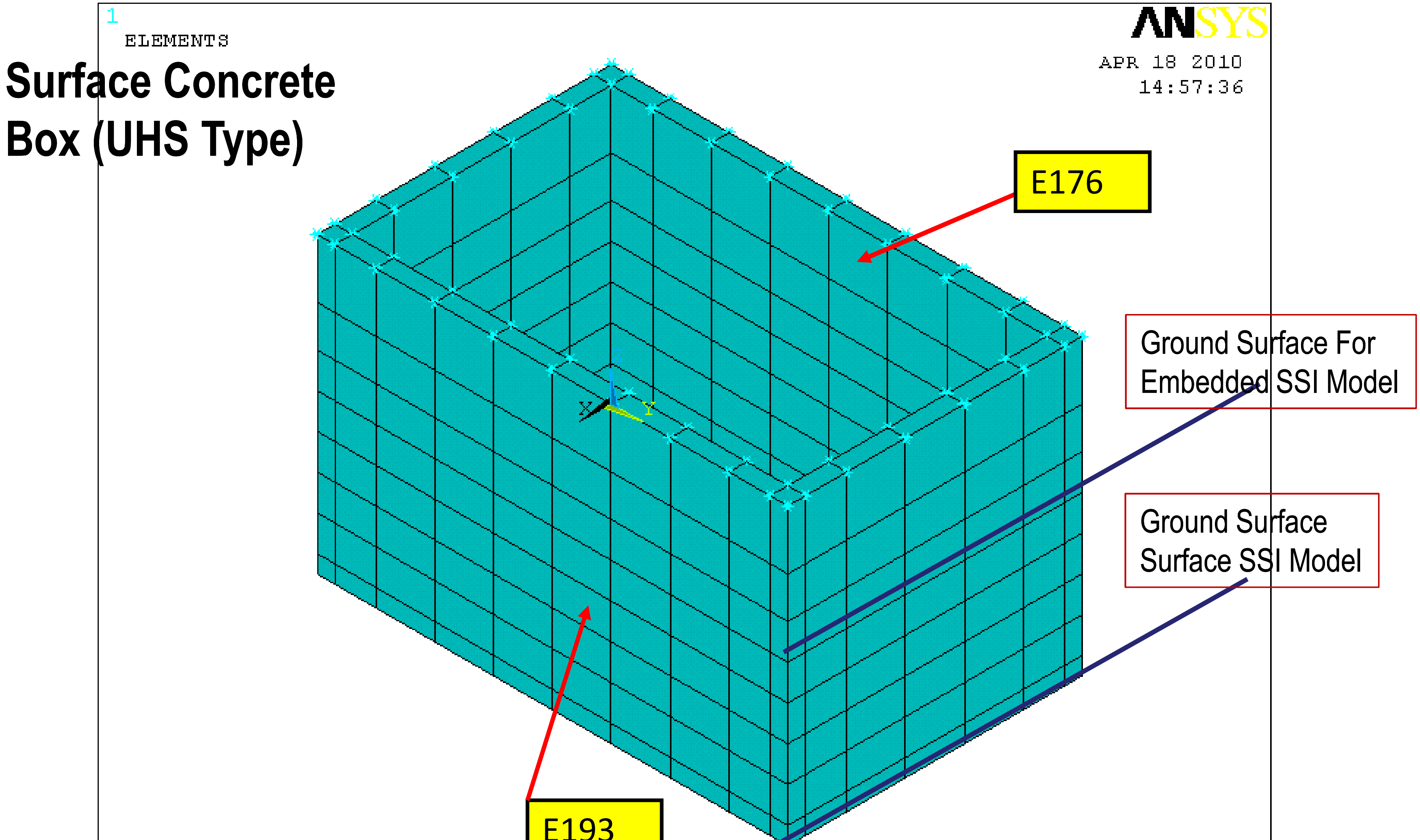

ACS SASSI-ANSYS Equivalent-Static SSI Stress Analysis for Surface and Embedded Structure



ANSYS Equivalent-Static vs. ACS SASSI

SSI Analysis

Surface Concrete Box
SOLID Elements

Soil Vs=1000fps

Flexible Base

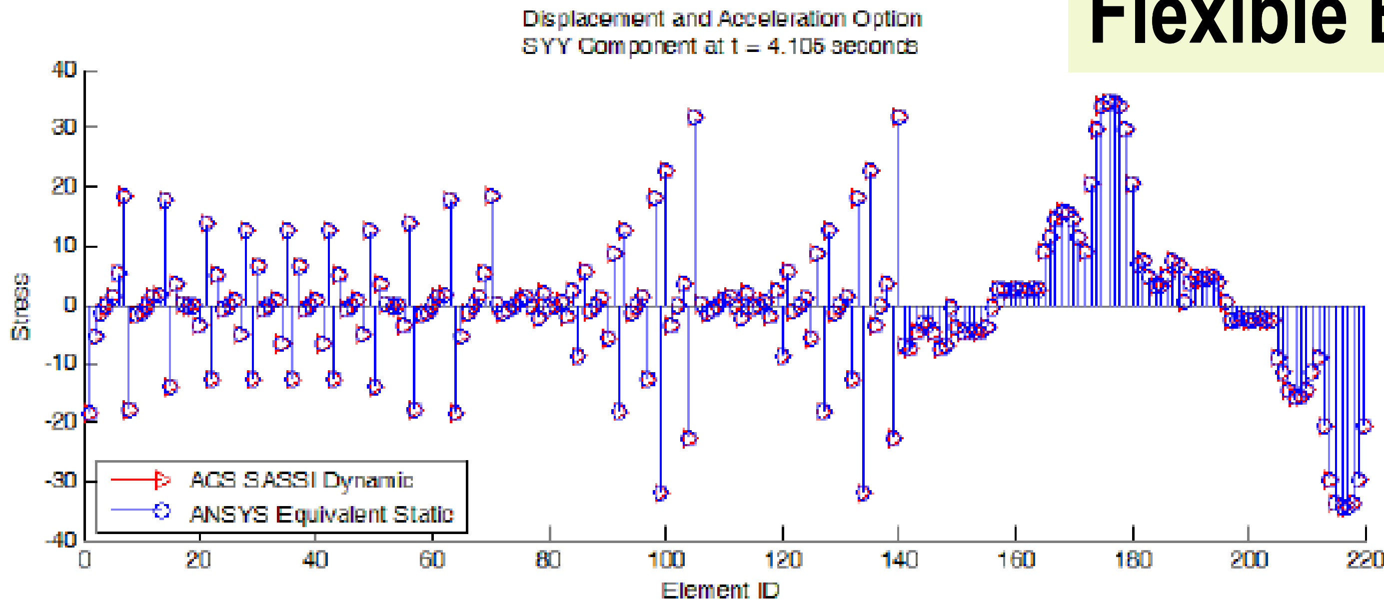


Figure 193: Case b) SYY Element Center Stresses for "Displacement and Acceleration" Option

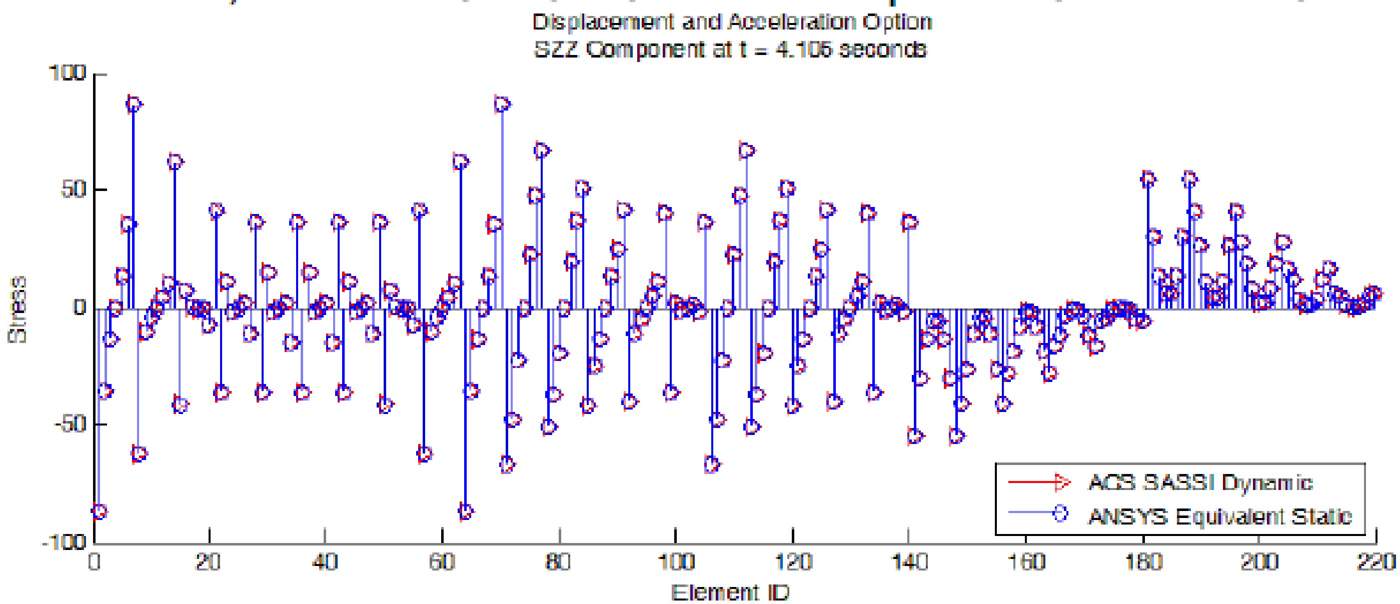


Figure 194: Case b): SZZ Element Center Stresses for "Displacement and Acceleration" Option

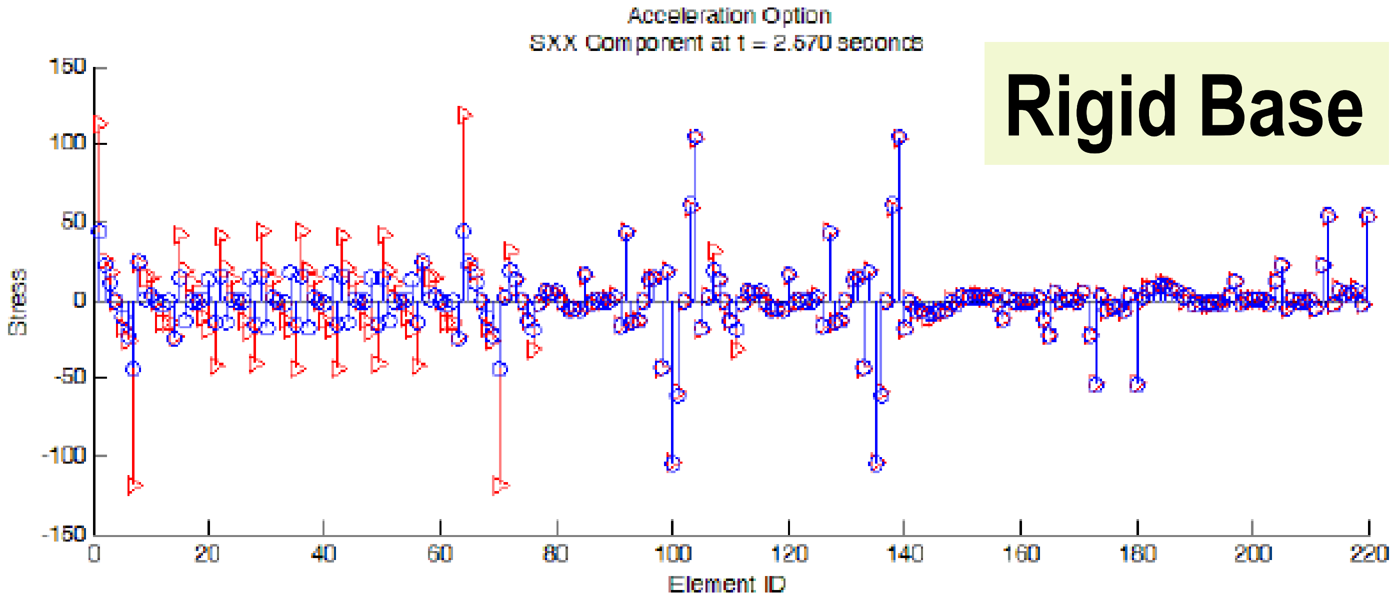


Figure 197: Case c): SXX Element Center Stresses for "Acceleration" Option

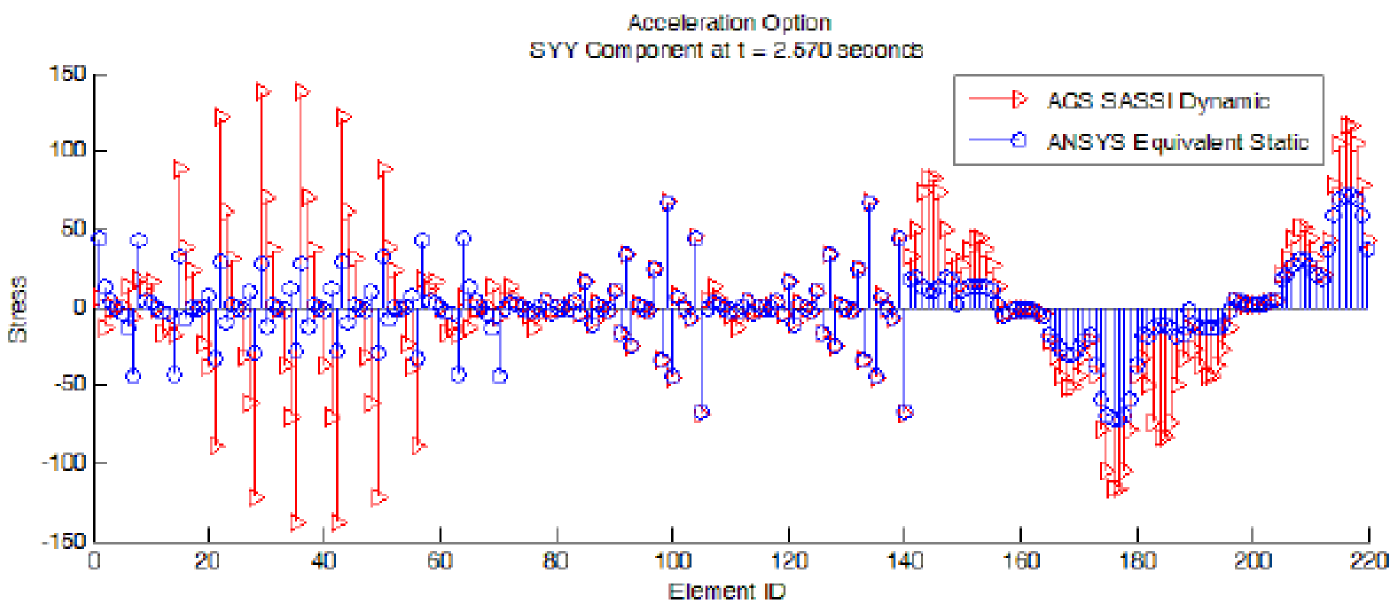


Figure 198: Case c): SYY Element Center Stresses for "Acceleration" Option

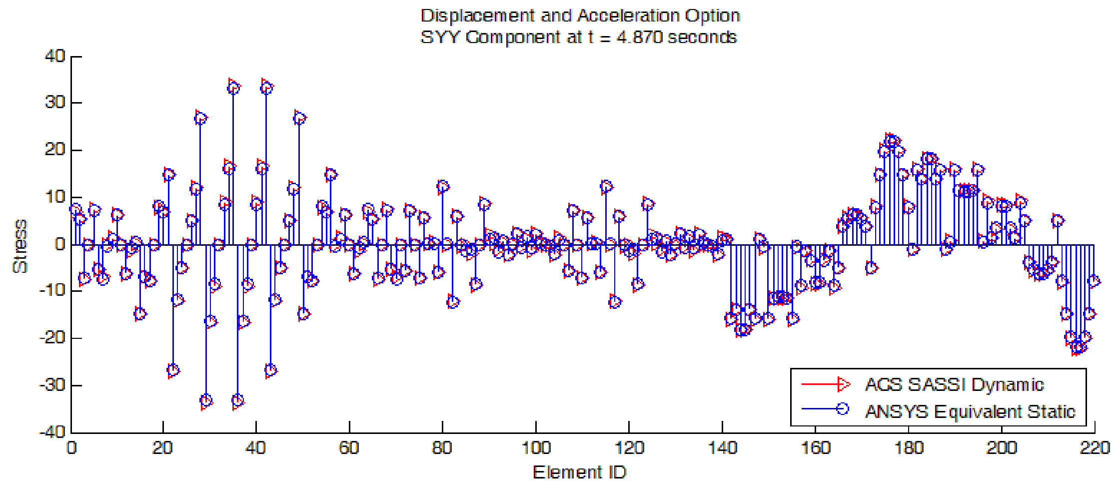
ANSYS Equivalent-Static vs. ACS SASSI

SSI Analysis

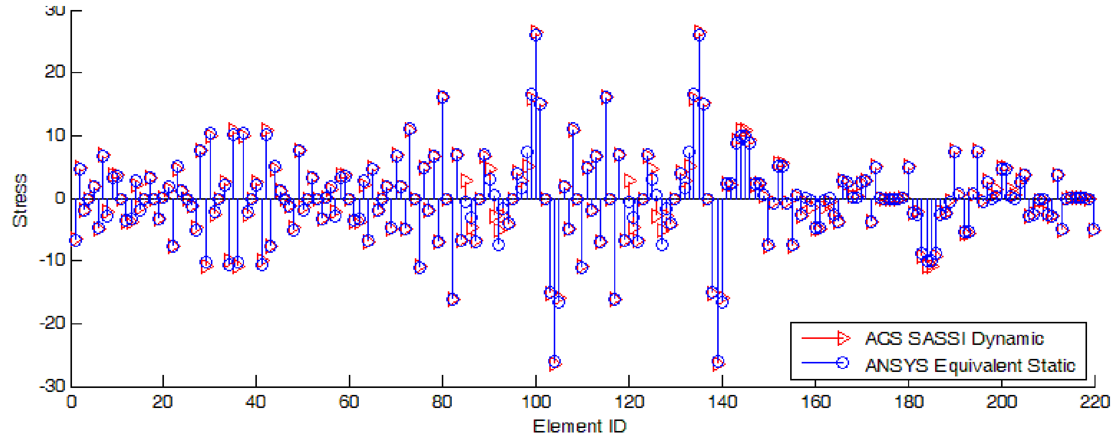
Deeply Embedded Concrete Box
SOLID Elements

Soil Vs=1,000 fps

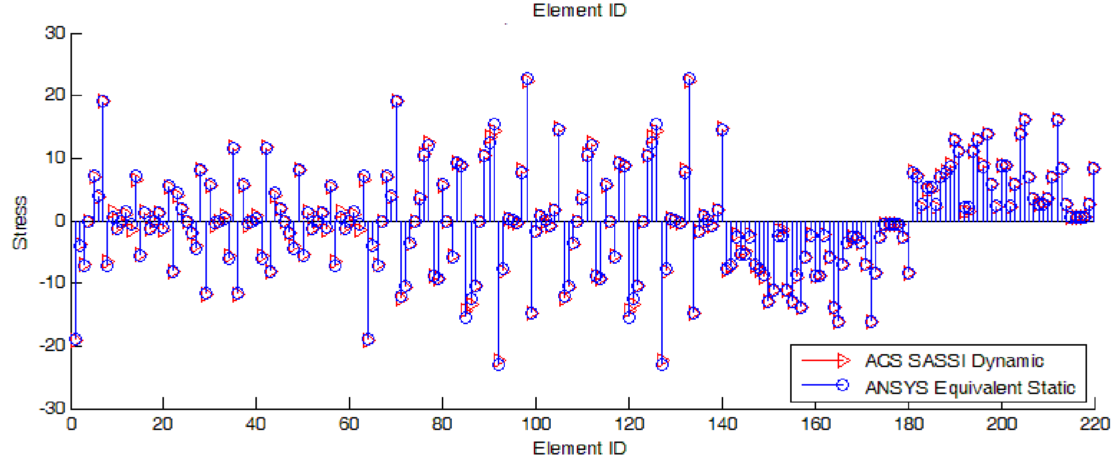
SXX


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

SYY

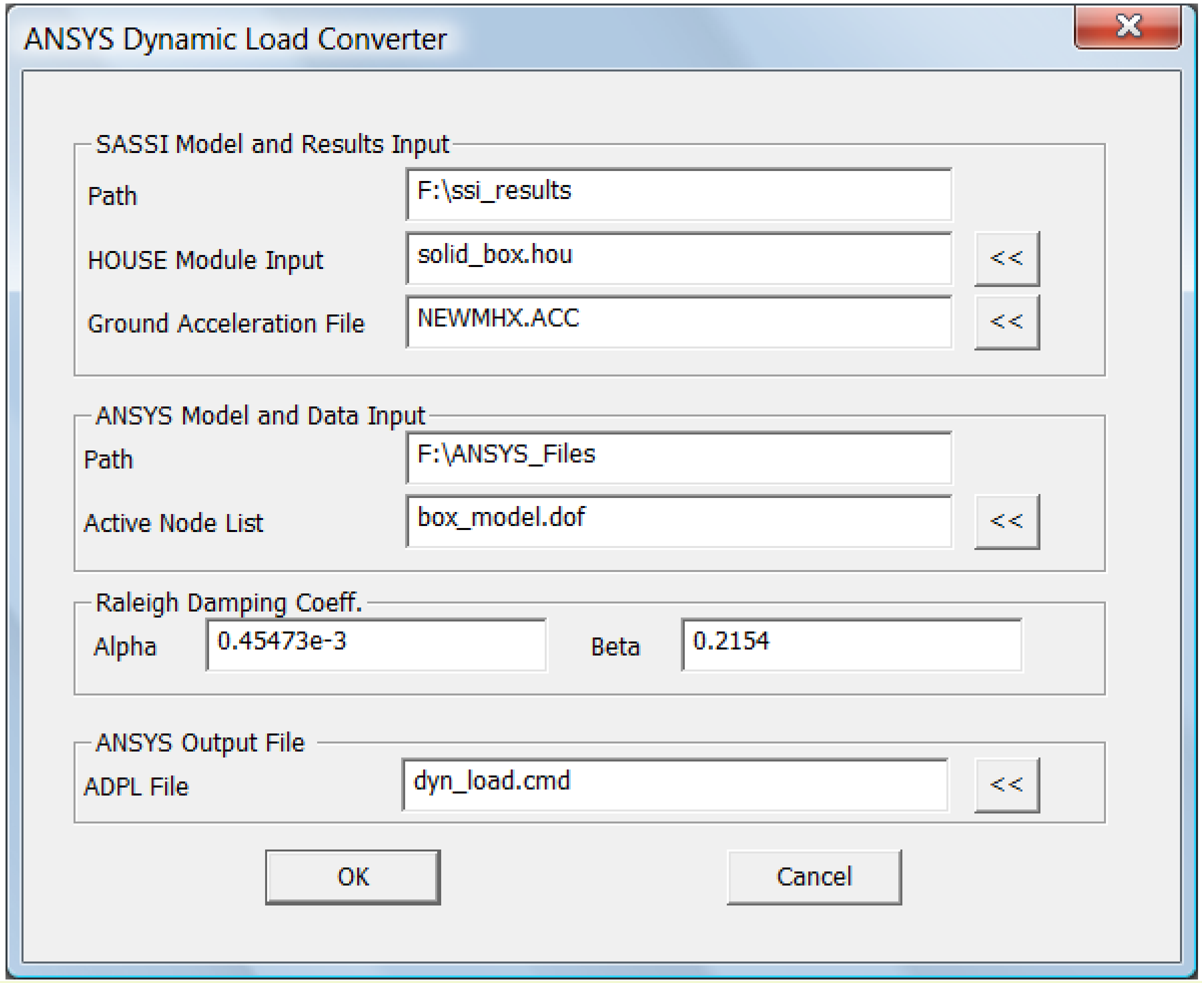

Stress
Element ID
ACS SASSI Dynamic
ANSYS Equivalent Static

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

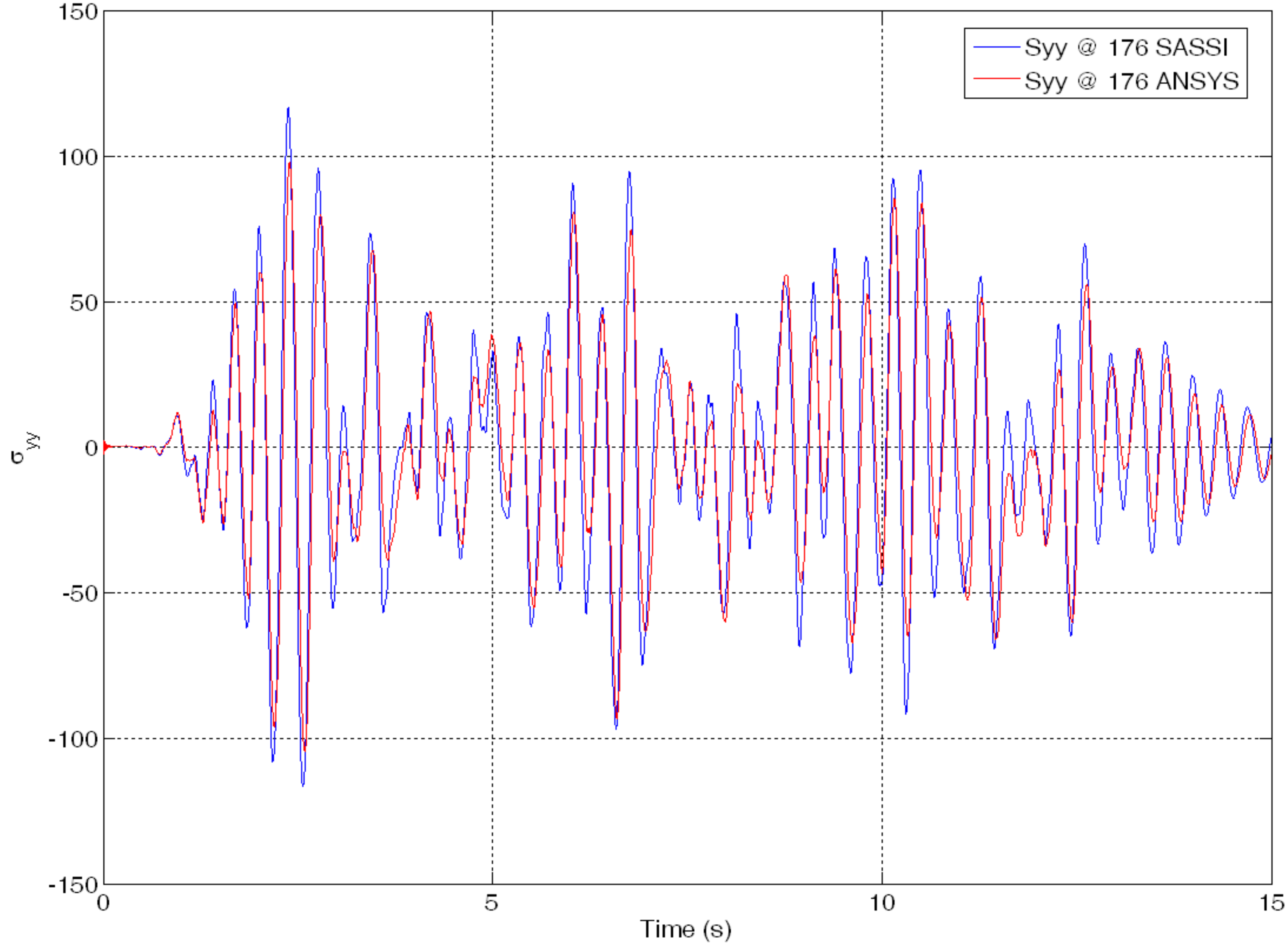
Surface Concrete Box
SOLID Elements
Soil Vs=1,000 fps

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

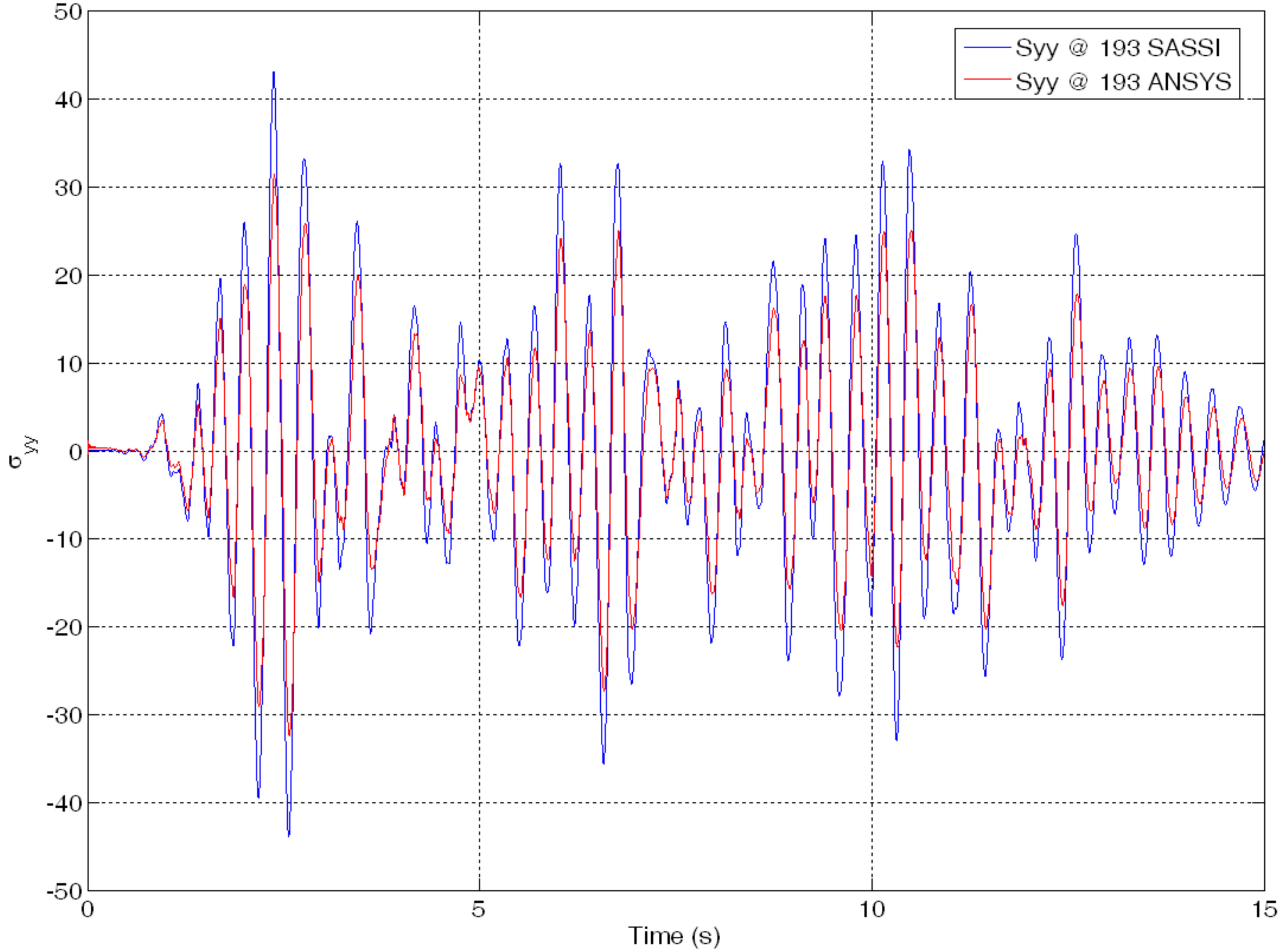
SYY



ANSYS Dynamic vs. ACS SASSI – for Surface SSI Model

Below Ground Surface

SYY



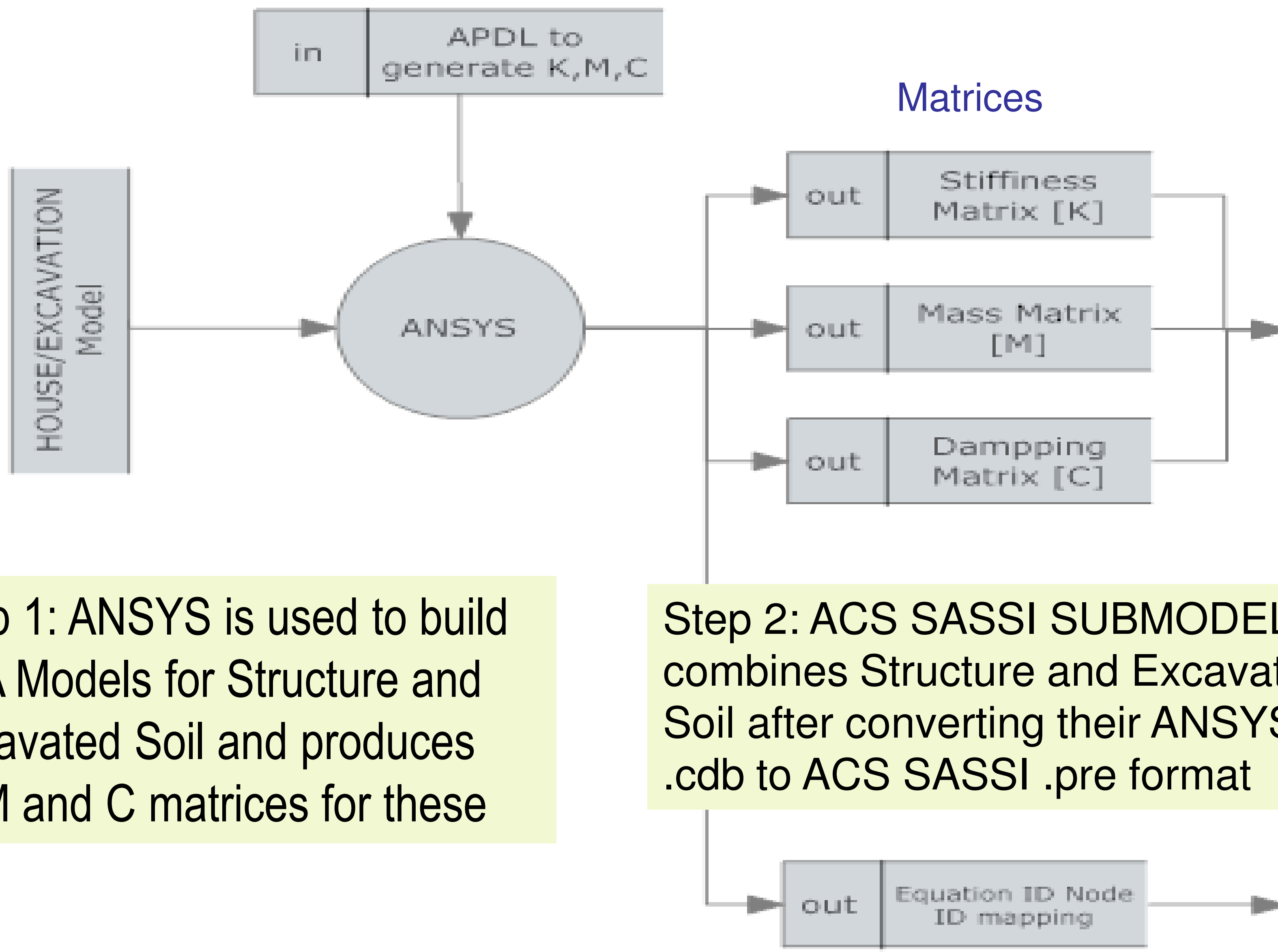
OPTION AA: ACS SASSI-ANSYS Interface for SSI Analysis Using ANSYS Models

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

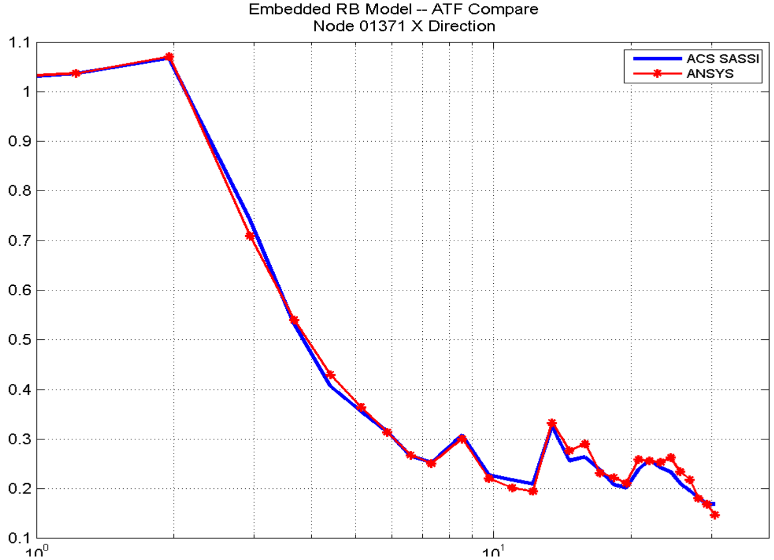
OPTION AA: Preliminary ANSYS steps for SSI analysis

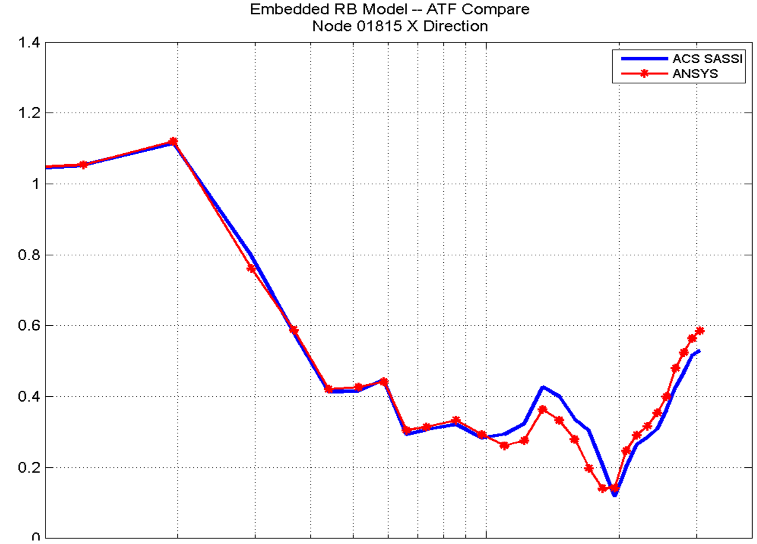


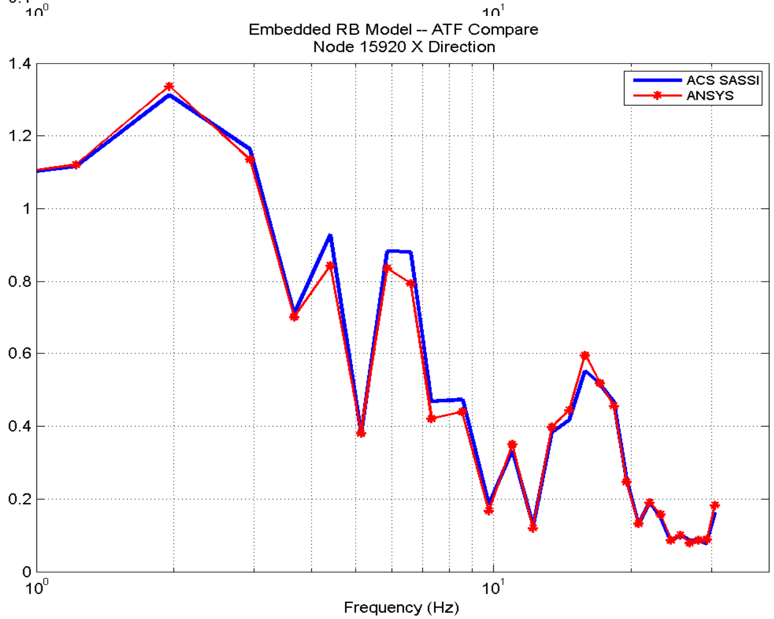
Step 1: ANSYS is used to build FEA Models for Structure and Excavated Soil and produces K, M and C matrices for these

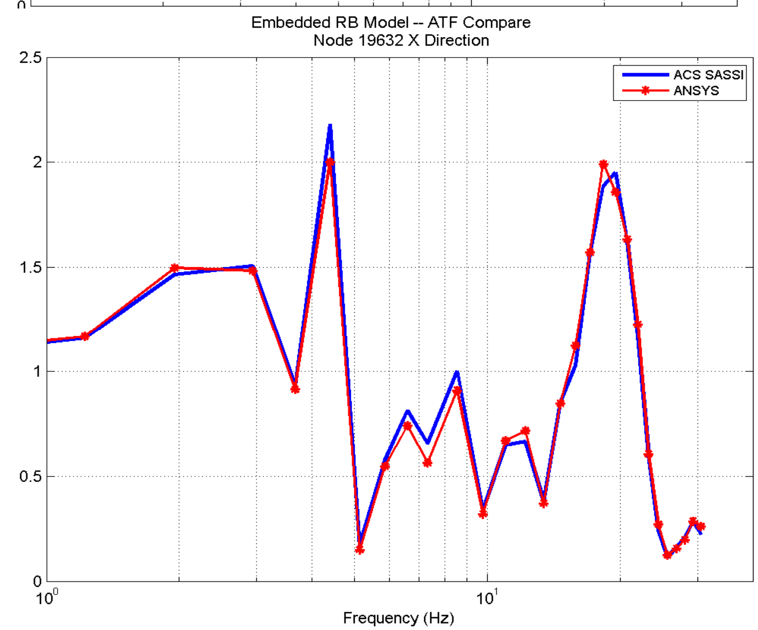
Step 2: ACS SASSI SUBMODELER combines Structure and Excavated Soil after converting their ANSYS .cdb to ACS SASSI .pre format

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

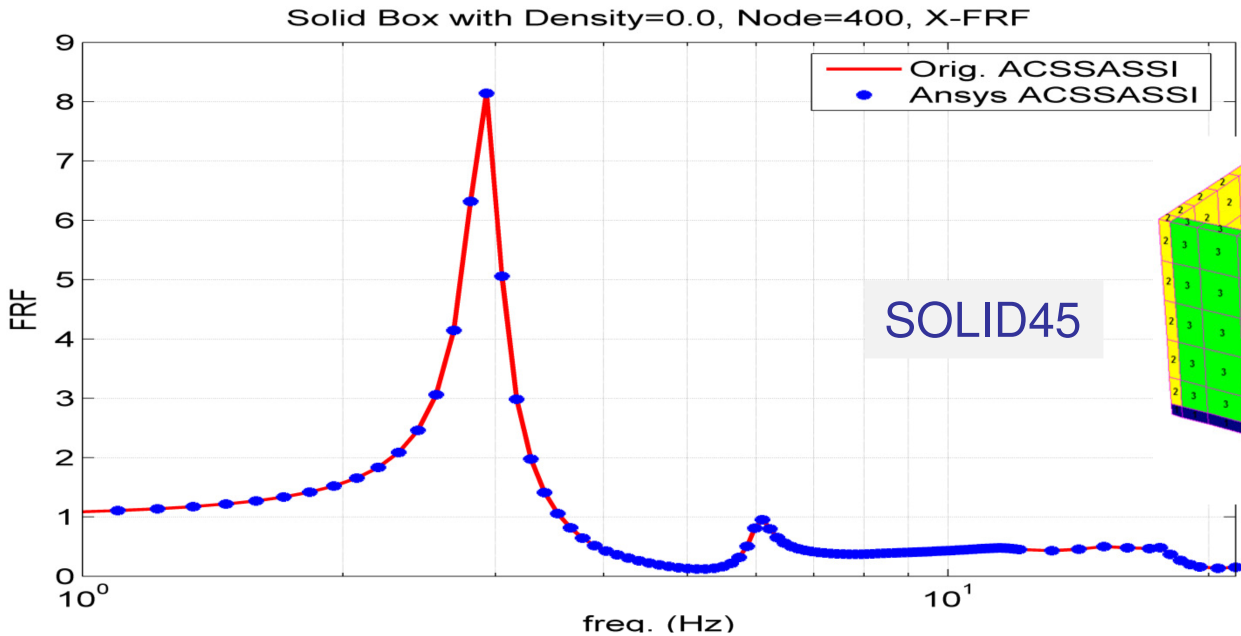


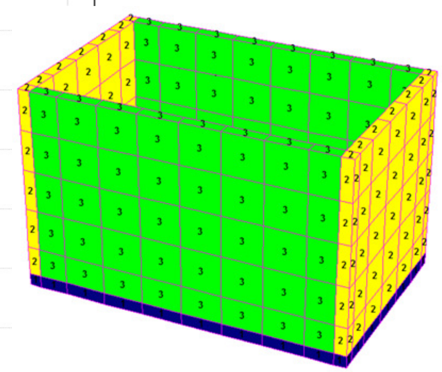




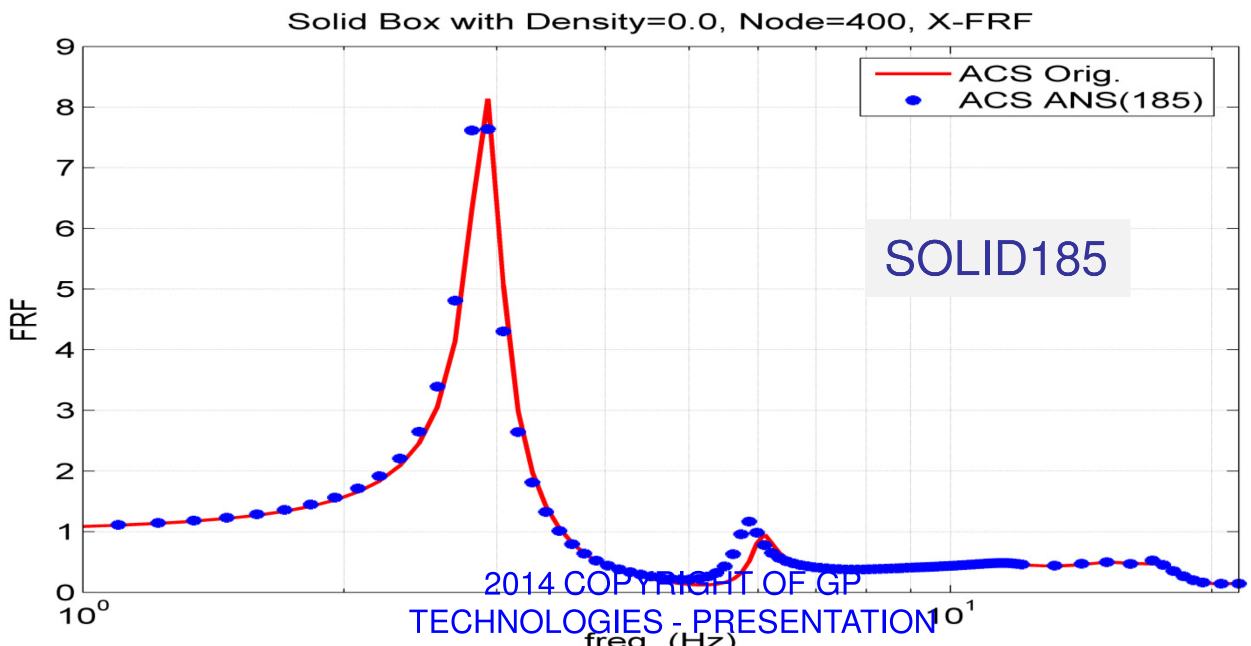


Concrete Pool ANSYS SOLID Model Example



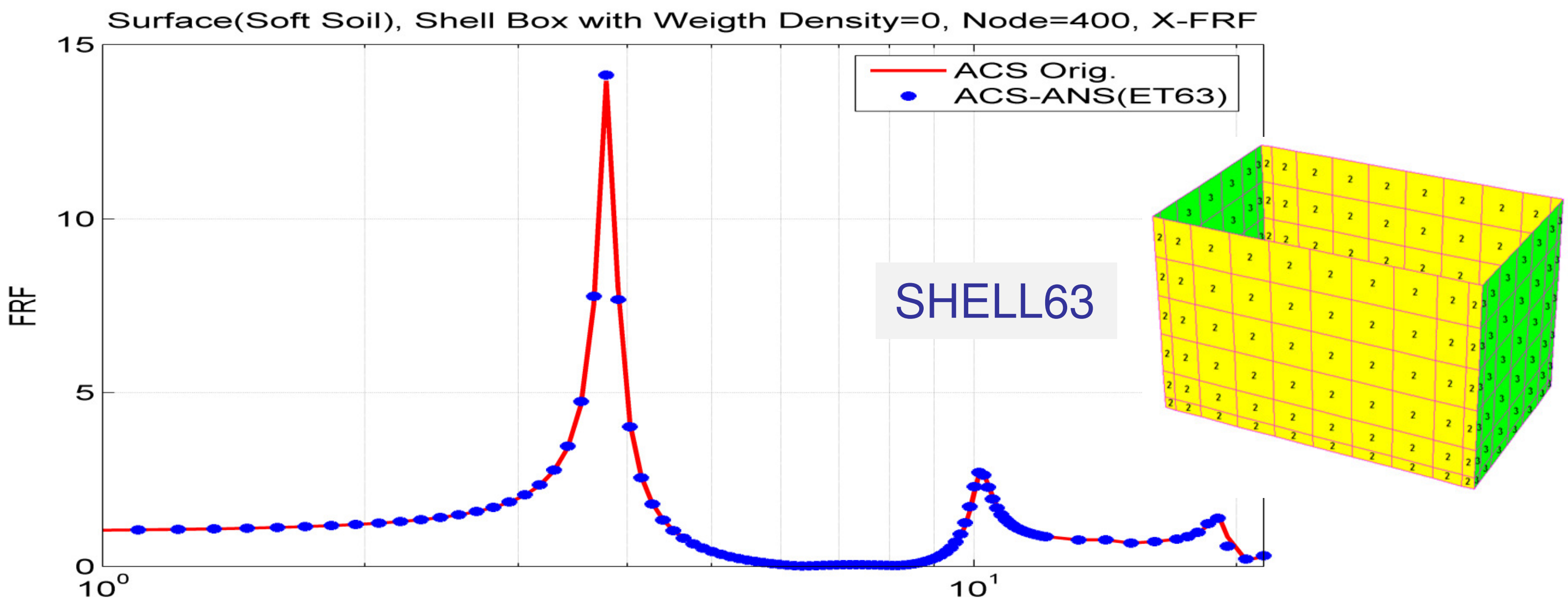


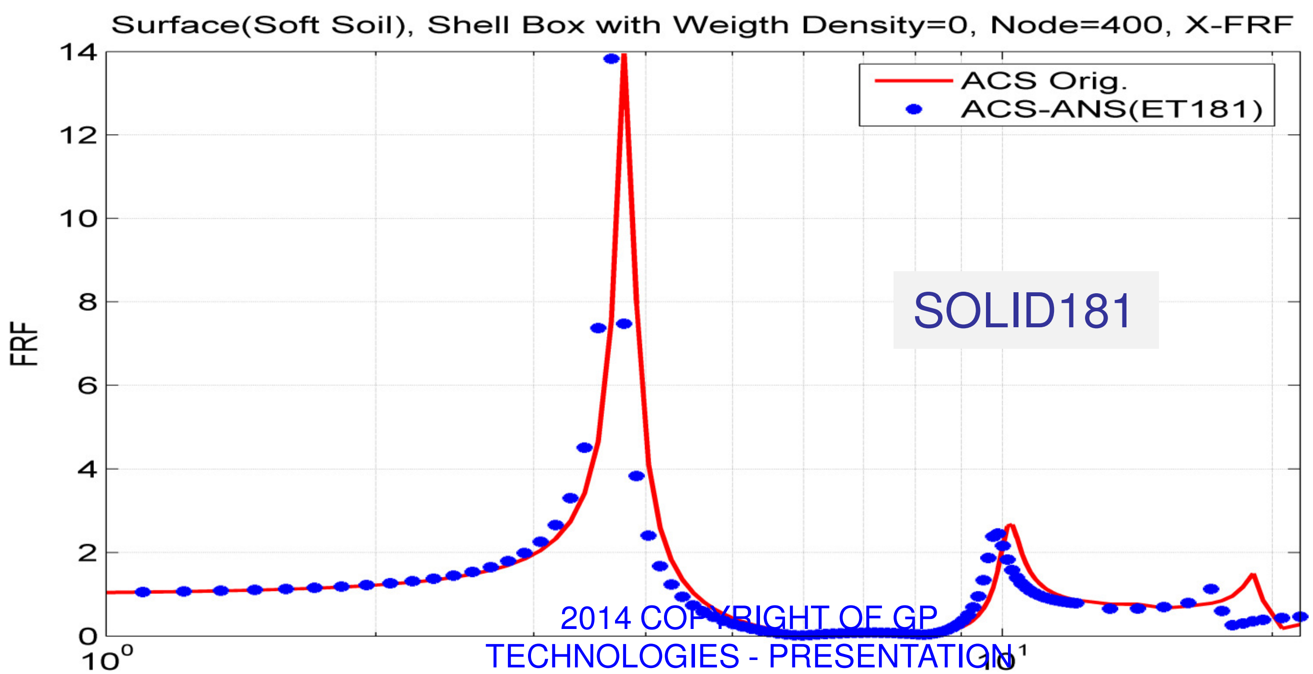
SOLID45



SOLID185

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…

Presentation Conclusions

In the last 10 years, great efforts in US, including both industry and Government, produced significant advancements in earthquake engineering with emphasis on seismic SSI analysis methodologies as described in the EPRI TR# 1015111-2007 and ASCE 04-2014 standard, as partially discussed in this presentation.

The ACS SASSI includes basically all the SSI approaches recommended by EPRI and ASCE 04-2014 and additional ones.

Recent Advances in Seismic Soil-Structure Interaction (SSI) Analysis of Special Structures Using ACS SASSI

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 2: Other Civil Engineering Structures

Shanghai Fangzhen Information Technology Co. Seminar

Shanghai, China, April 3, 2014

ACS SASSI Version 3.0 Fast Nonlinear Analysis Capability in Complex Frequency (Option Non)

This capability is a novel nonlinear SSI approach for modeling of nonlinear hysteretic behaviors of reinforced concrete structures in the complex frequency domain.

The new approach can be used to perform fast and accurate nonlinear SSI analyses, including sophisticated nonlinear hysteretic models, at a small fraction of the runtime of a time domain nonlinear SSI analysis.

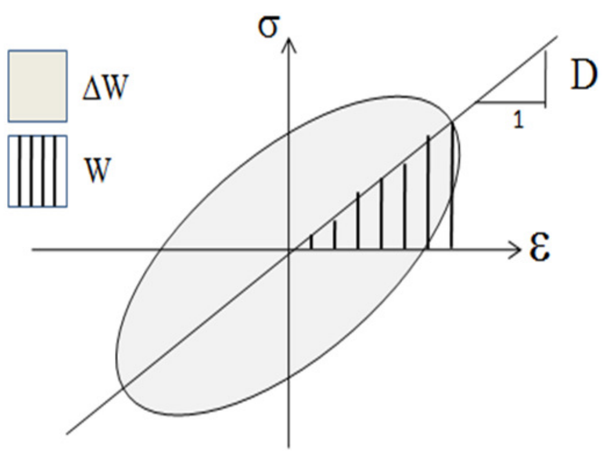
Initially the new approach will be limited to low-rise shearwall structures with planar walls (no curved walls)

Equivalent-Linear System in Complex Frequency

Based on the up-to-date literature, the nonlinear behavior of dynamic structural systems can be captured only by nonlinear time history analyses.

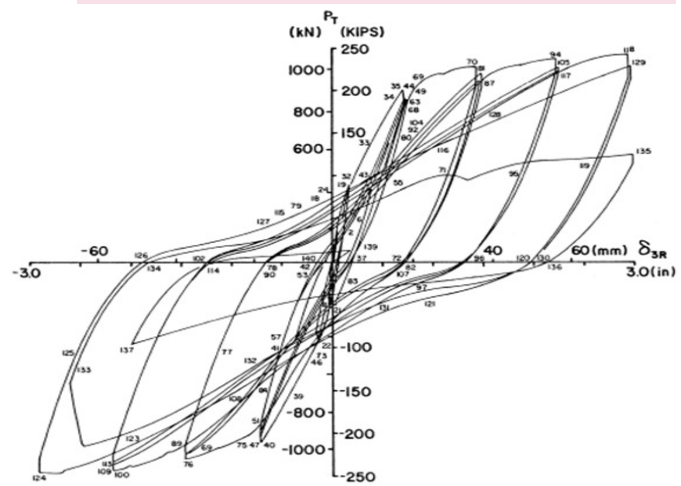
Only simple equivalent linear (EQL) approaches were applied in frequency domain. As a result of the EQL model *time invariant behavior*, the SSI response could be either over or under estimated at different time moments.

Linear Hysteretic Model



Frequency Domain
(Time-Invariant System)
(Frequency-Invariant)

Non-Linear Hysteretic Model



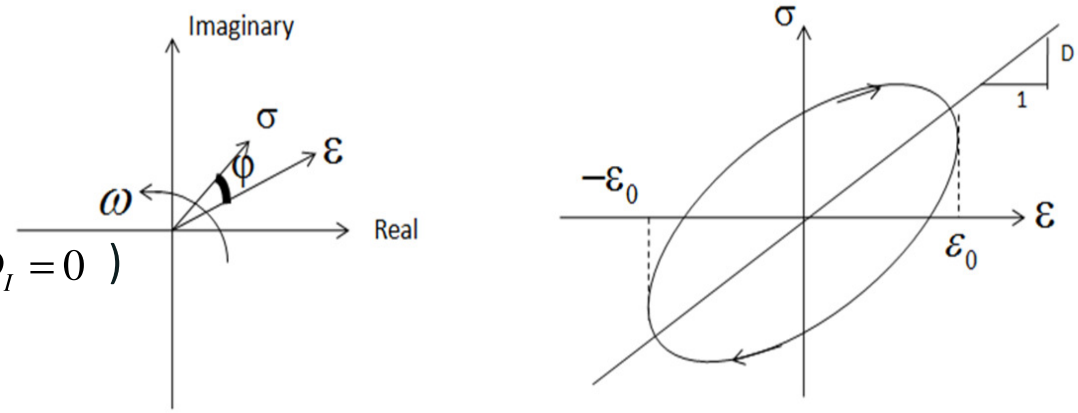
Time Domain
(Time-Dependent System)
(Frequency-Dependent)

Linear Hysteretic (Voigt) Model in Complex Frequency

In complex frequency, Hooke Law is:

$$\sigma^*(\omega) = D^*(\omega)\varepsilon^*(\omega)$$

$$D^*(\omega) = D_R + iD_I$$ (for elastic solid $D_I = 0$)



In complex frequency space

In physical space

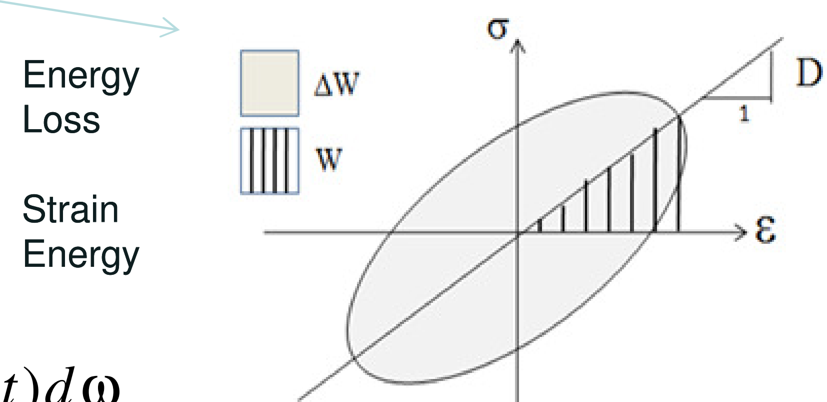
Visco-Elastic Material Model

Linear Hysteretic Model Parameters:

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

$$D^* = D_R\left(1 - 2\beta^2 + 2i\beta\sqrt{1-\beta^2}\right)$$

real part imag part



In time domain, using Fourier duality:

$$\sigma(t) = \sigma_{elast}(t) + \sigma_{diss}(t)$$

$$\sigma_{elast}(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} D_R(\omega)\varepsilon^*(\omega)\exp(-i\omega t)\,d\omega$$

$$\sigma_{diss}(t) = \frac{1}{2\pi}\int_{-\infty}^{\infty} D_I(\omega)\varepsilon^*(\omega)\exp(-i\omega t)\,d\omega$$

Using Fourier duality linear (nonlinear) time response can be mapped in a complex frequency response and vice-versa.

Nonlinear Hysteretic Models in Time and Frequency

To map a linear system response time history we need a linear (frequency-independent) hysteretic model.

To map a nonlinear system response time history we need a nonlinear (frequency-dependent) hysteretic model.

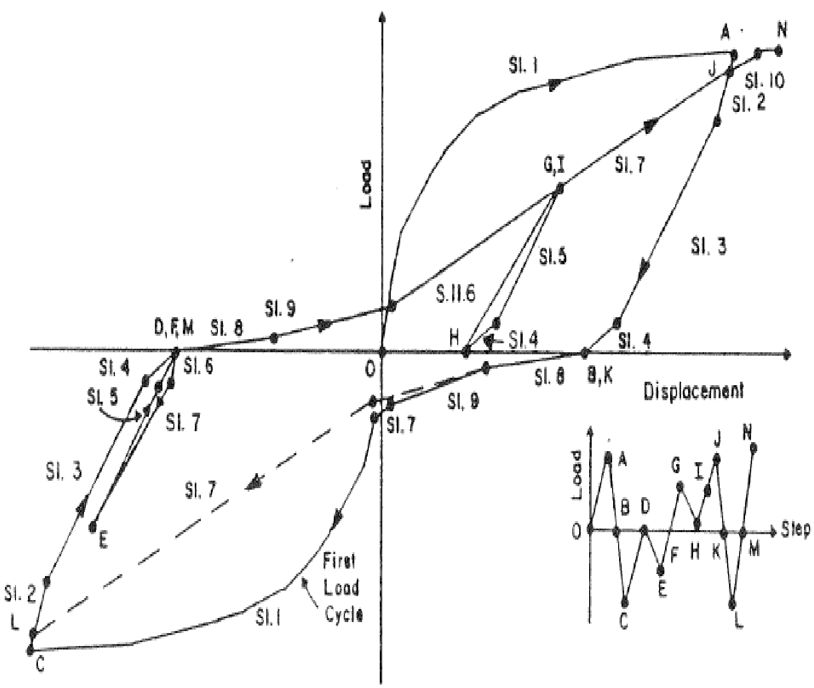
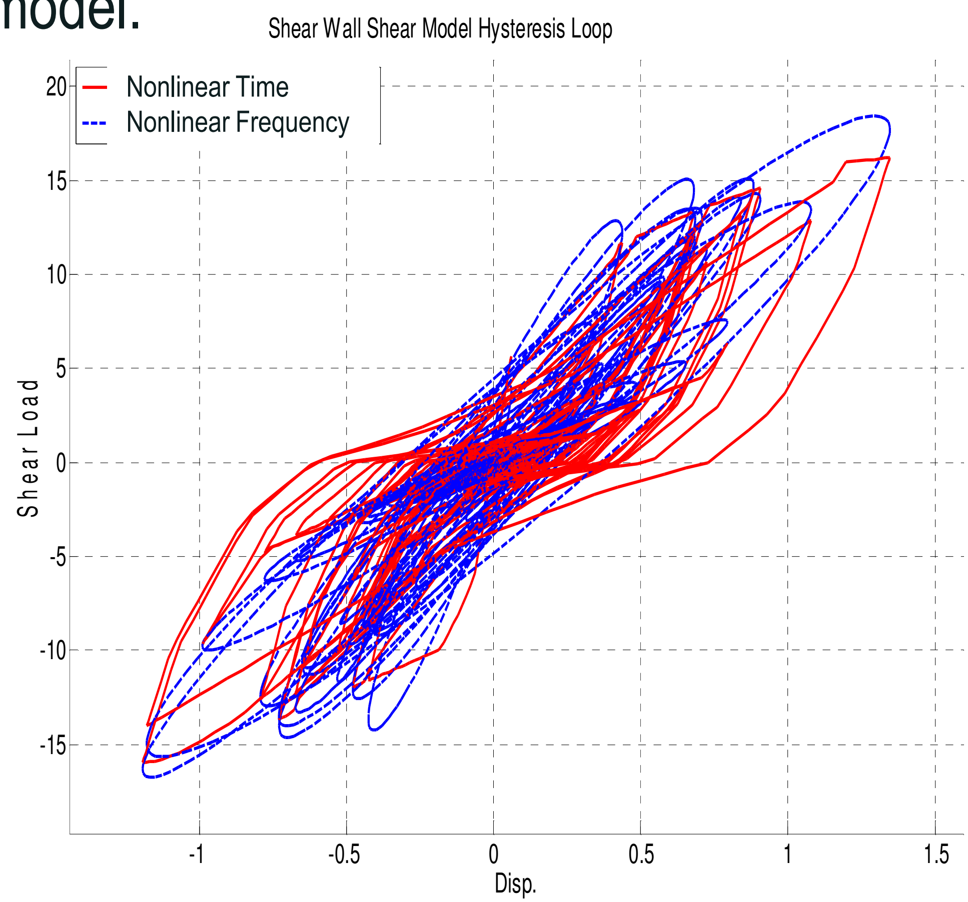
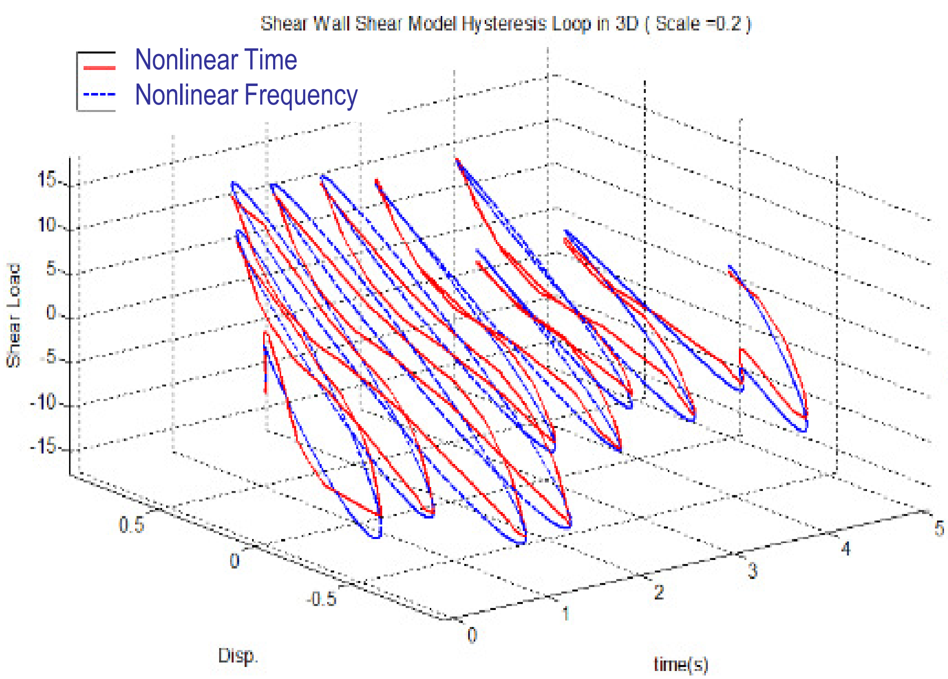


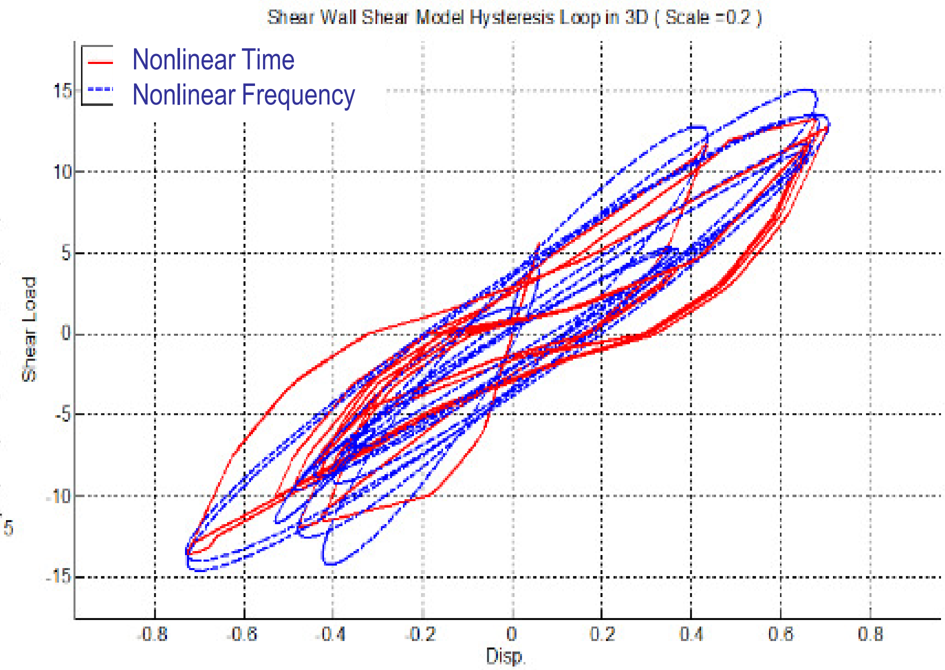
Figure 5b. Shear hysteresis model



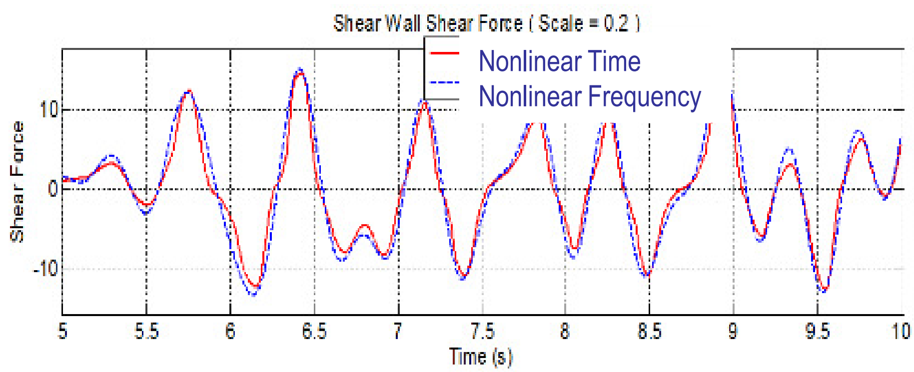
Nonlinear Hysteretic Model in Complex Frequency



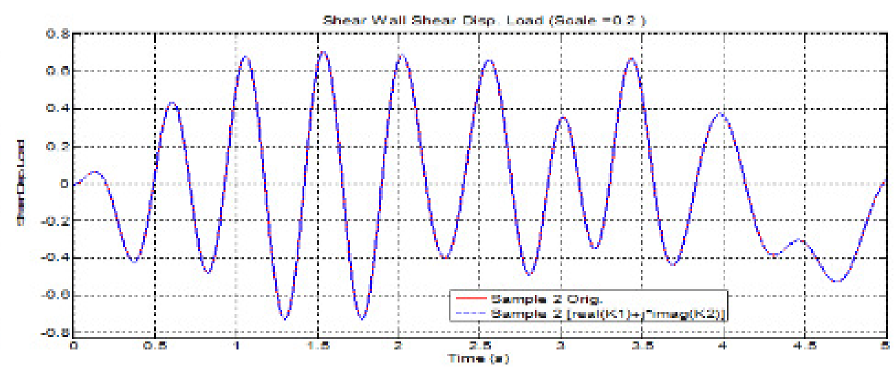
Comparison Hysteretic Loops in Time-Domain



Comparison of the Two Nonlinear Hysteretic Models



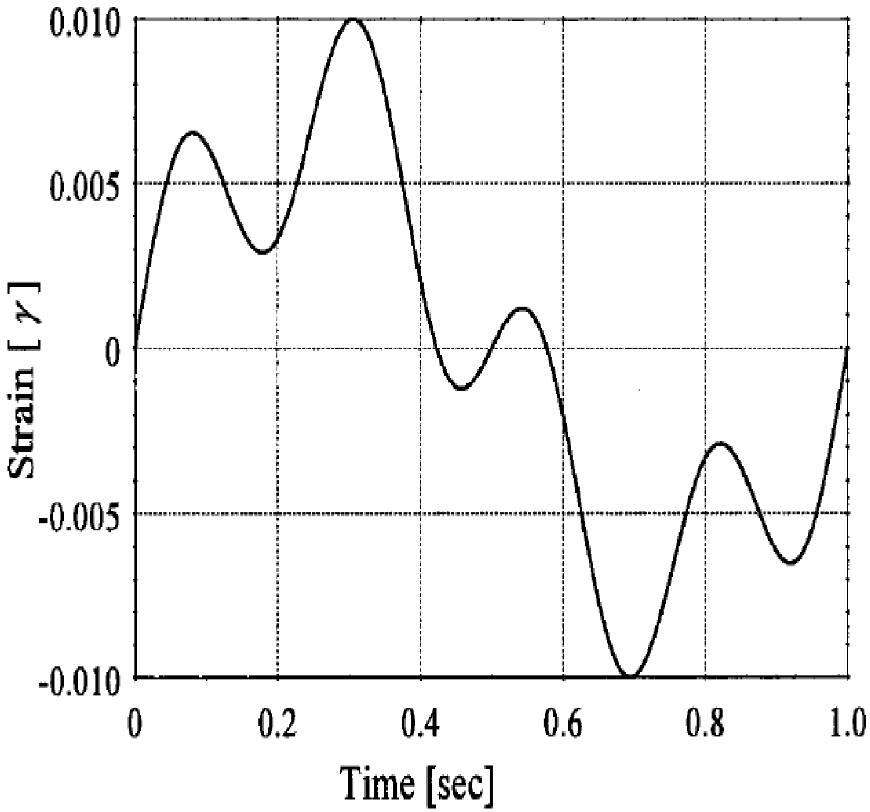
Shear force in time



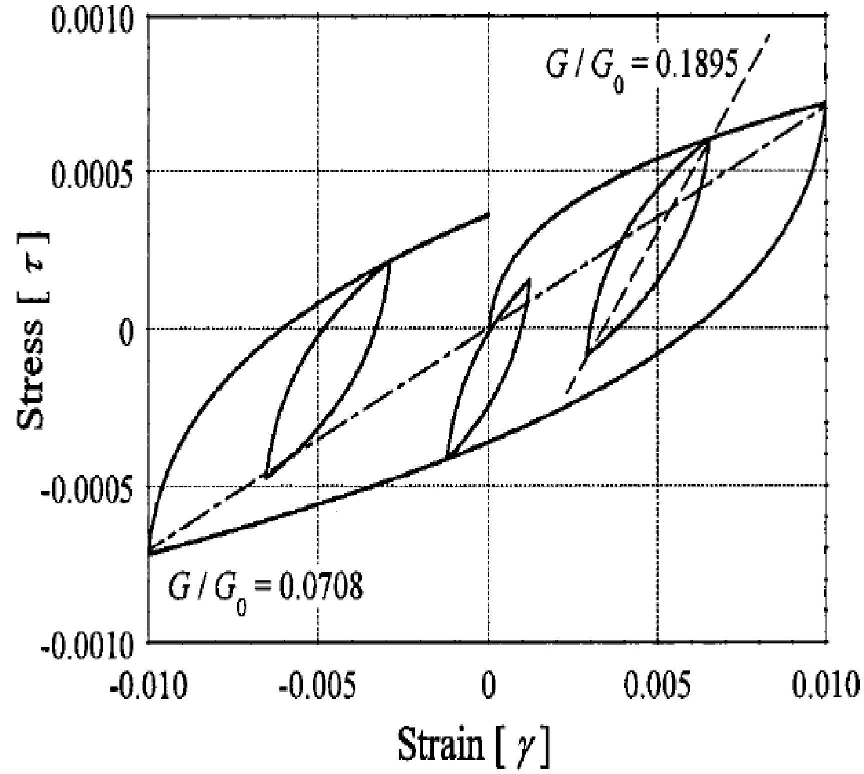
Displacement

Frequency-Dependent Linearized Hysteretic Models in Complex Frequency: Kausel-Assimaki Model

Time Response

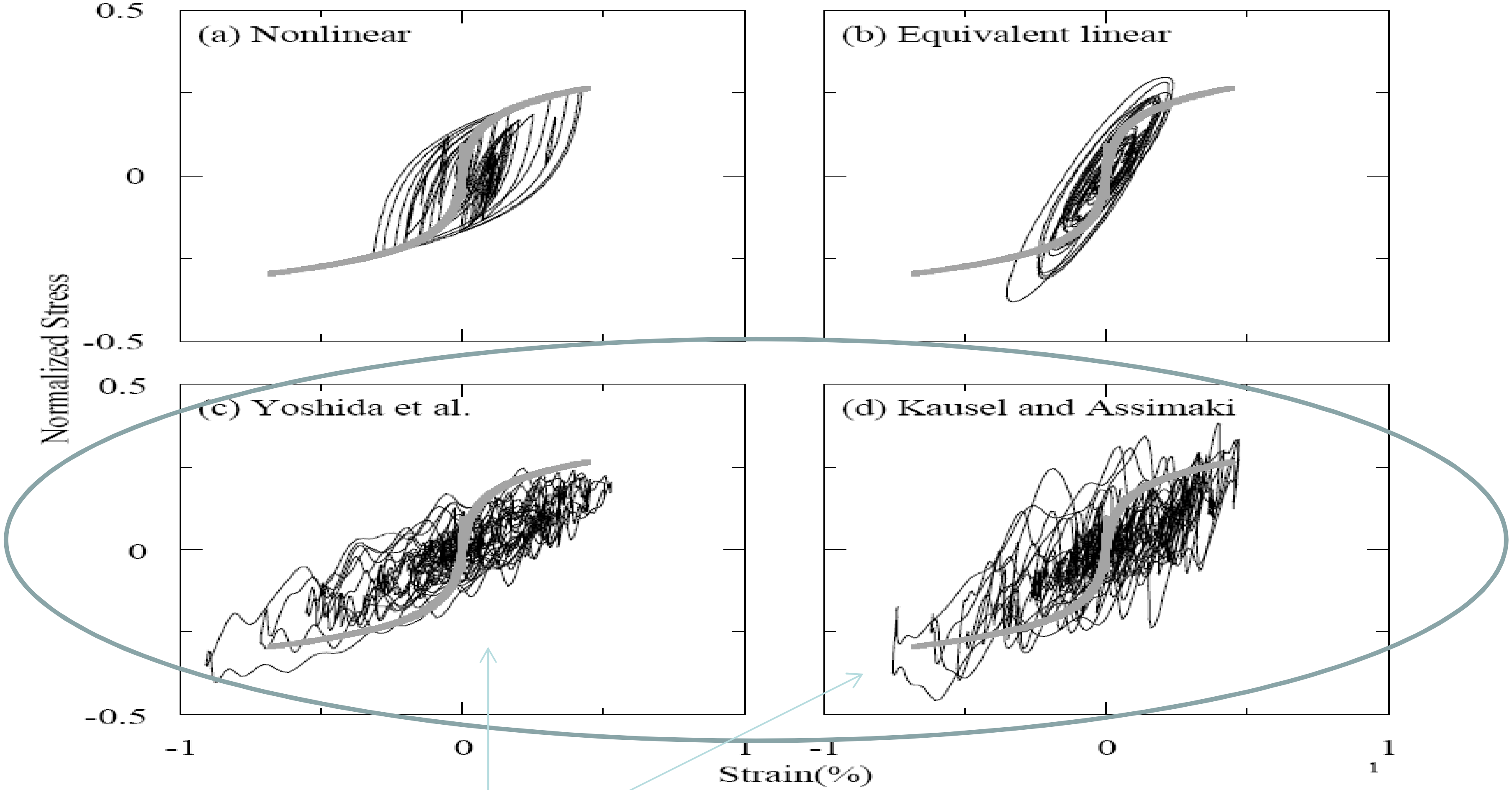


Hysteretic Loops



Kausel, E. and Assimaki, D. ,2002

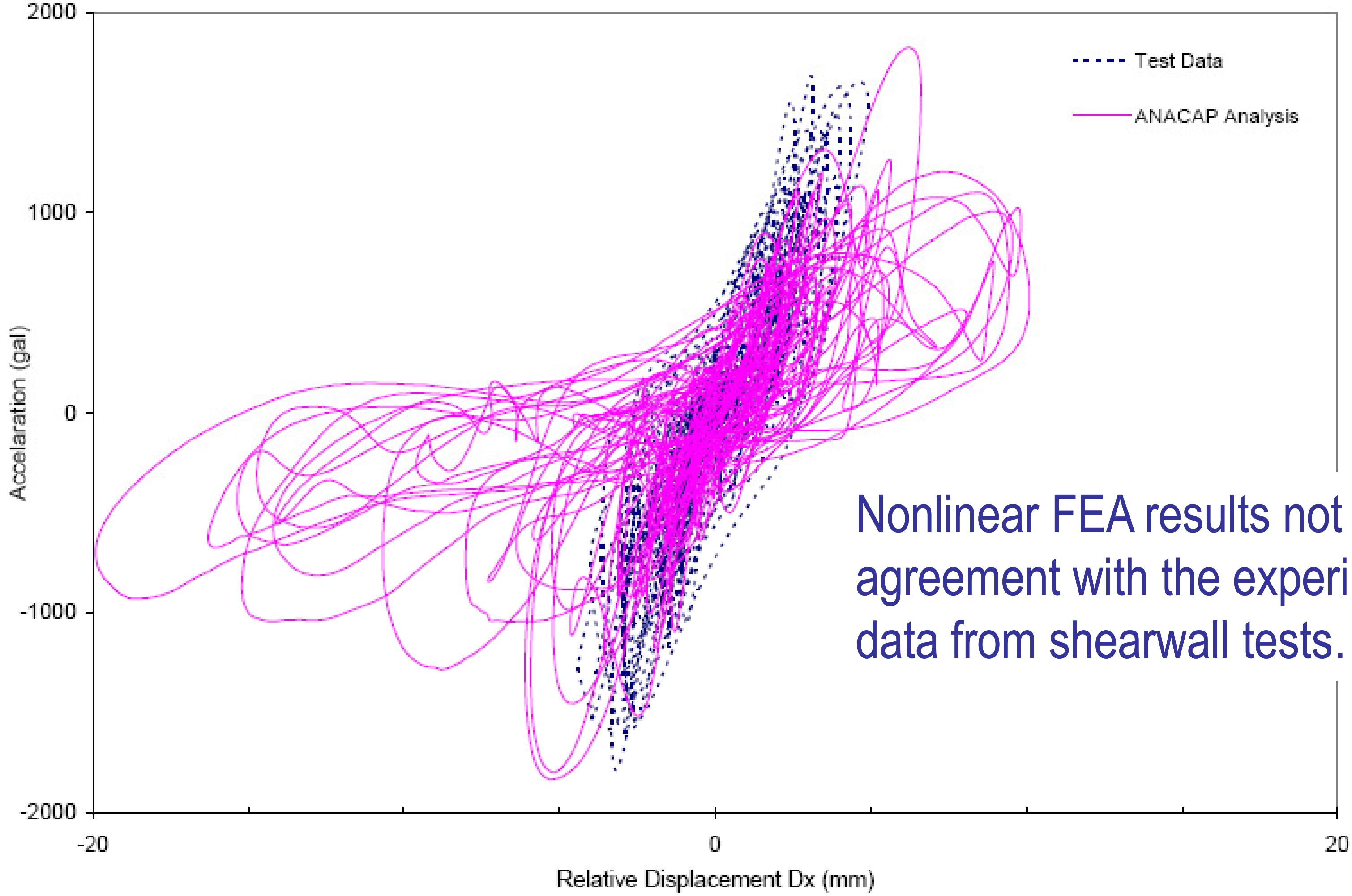
Frequency-Dependent Hysteretic Model Results



Kwak, D.Y.K., Jeong, C.G., Park, D. and Park, S. ,2008

REMARK: *Kausel and Assimaki (2002) and Yoshida et al. (2002) implementations lacked in the compatibility between the frequency and the time domain representations.*

Nonlinear Plasticity FEA Models: ANACAP Model



Nonlinear FEA results not fully in agreement with the experimental data from shearwall tests…..

Figure 5-86 Comparison of X-Direction Hysteresis from ANACAP Analysis Considering Prior Damages but with X-Input Motion only and Test Result for Run-6

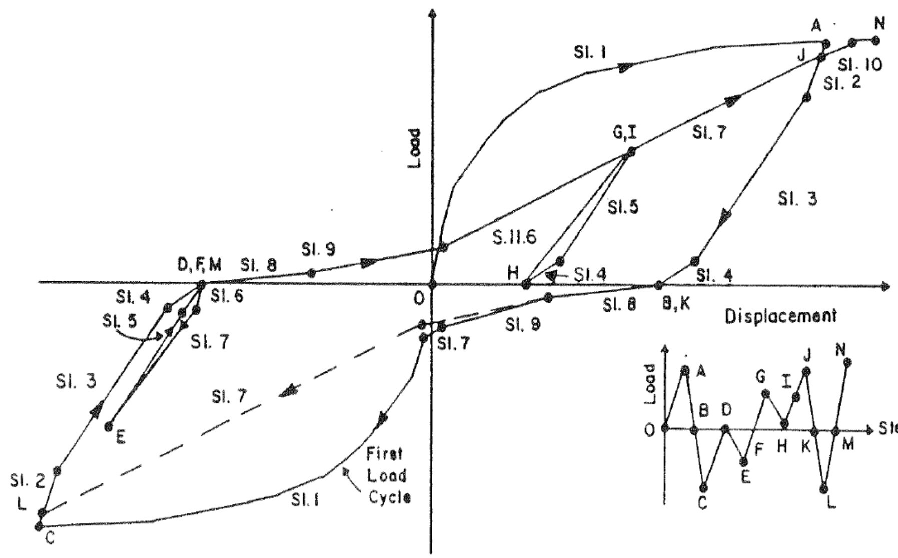
NUREG/CR-6925, BNL-NUREG-77370, 2006

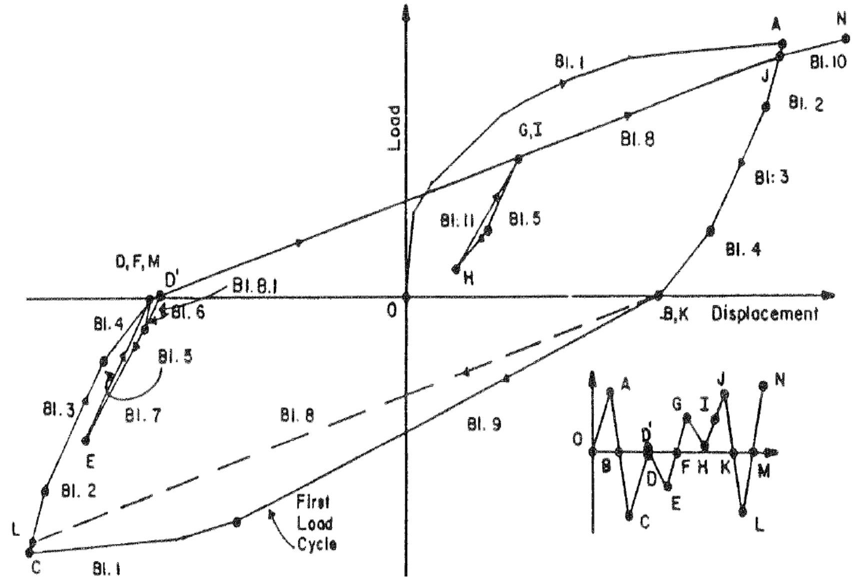
Nonlinear SSI Analysis in Complex Frequency:

Computational Steps:

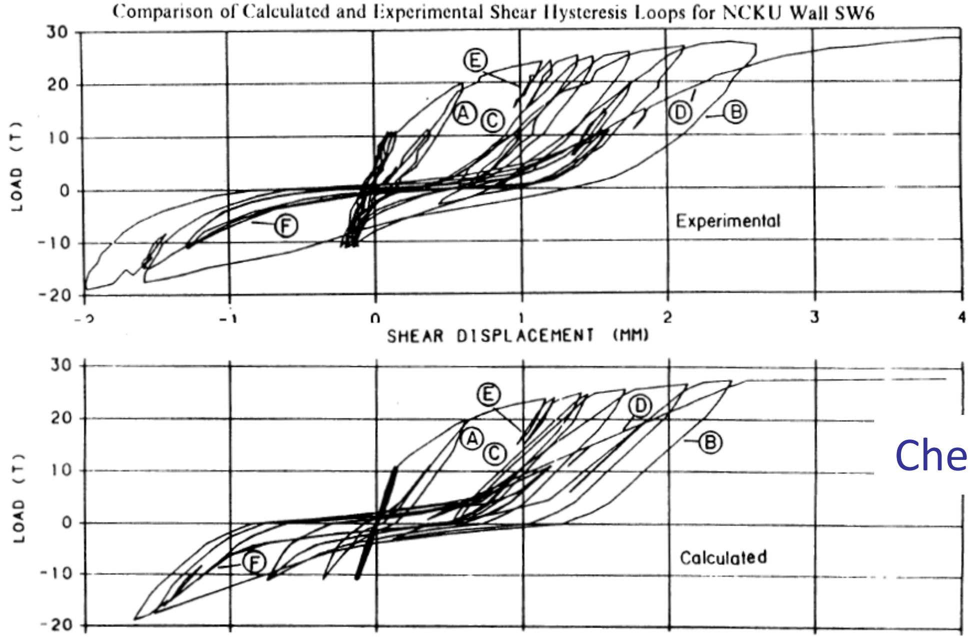
- For the initial iteration, perform a linear SSI analysis using the elastic properties for the selected shearwall panels
- Compute the reinforced concrete shearwall panel behavior in time domain and frequency domain using the hysteretic model associated to each selected panel
- Perform a new SSI analysis iteration using a fast SSI reanalysis (restart analysis) in the complex frequency domain using the hysteretic models computed in Step 2 for all selected panels
- Check convergence of the nonlinear SSI response after new SSI iteration, and go back to Step 2 if the convergence was not achieved.

Chen-Mertz Hysteretic Model for Low-Rise Shearwalls





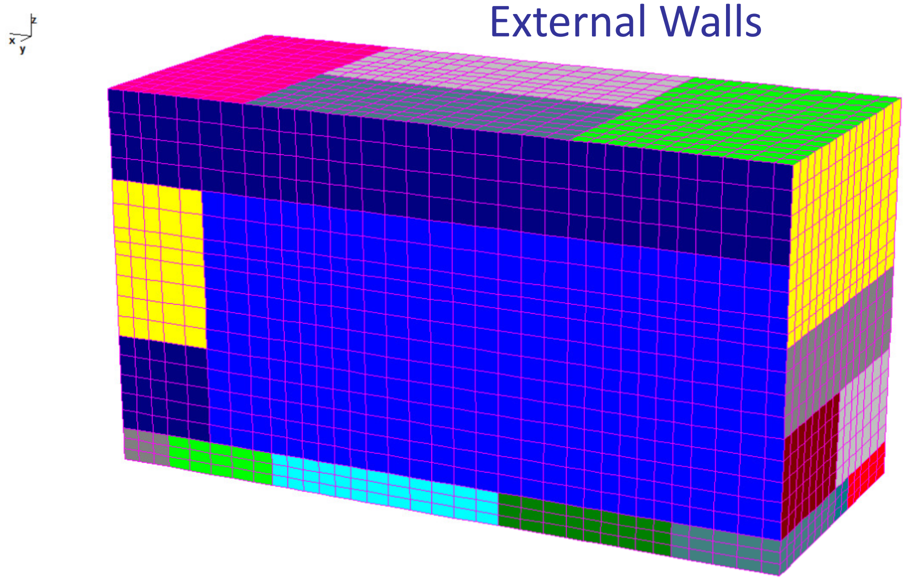
Comparison of Calculated and Experimental Shear Hysteresis Loops for NCKU Wall SW6



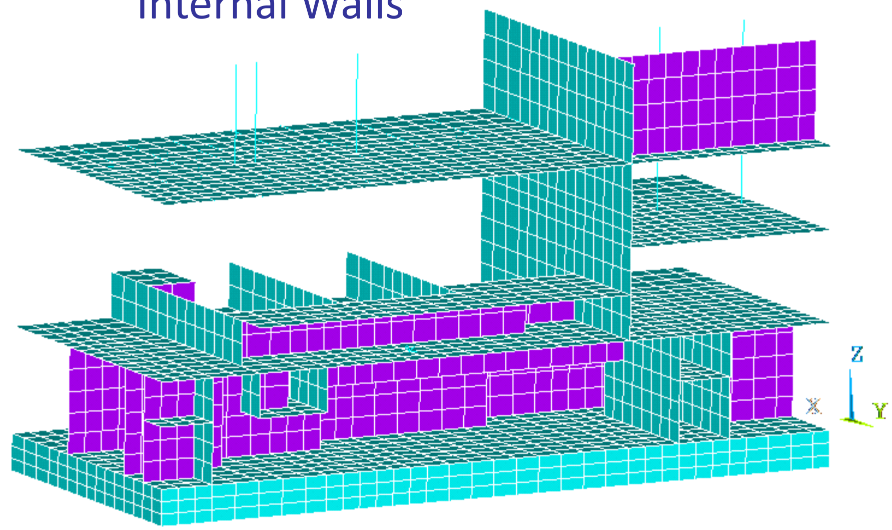
Cheng and Mertz, 1989

Low-Rise Shearwall Building on A Rock Site

External Walls

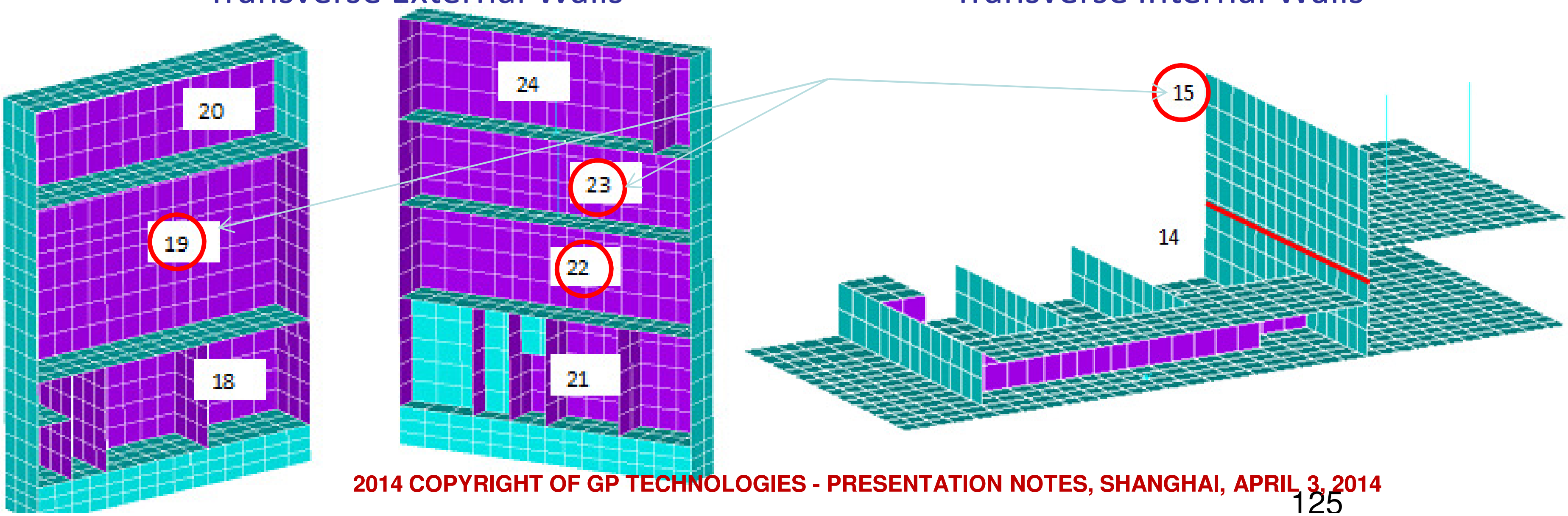


Internal Walls



Transverse External Walls

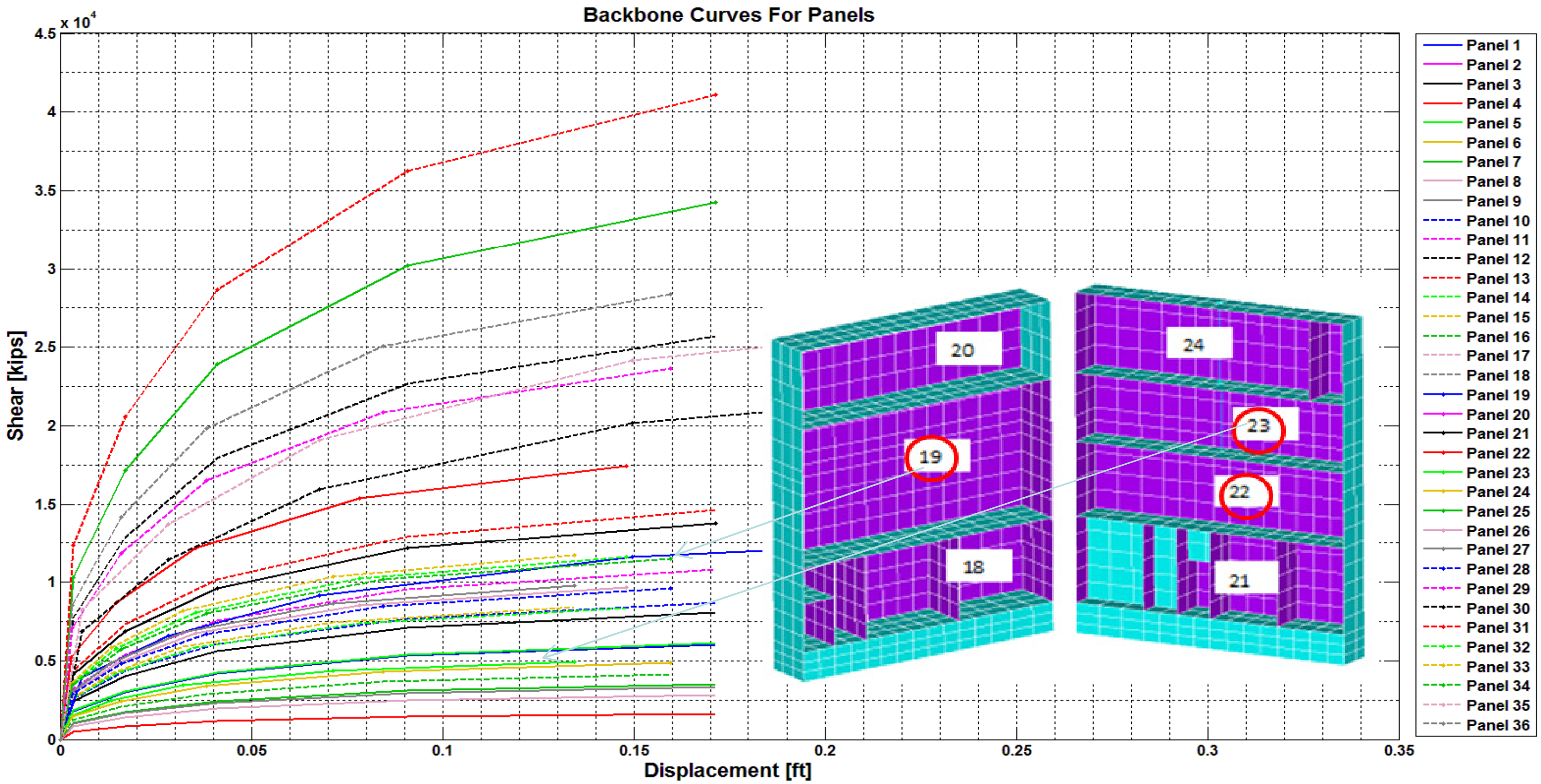
Transverse Internal Walls



Shearwall Back Bone Curves (BBC) for All Shearwalls

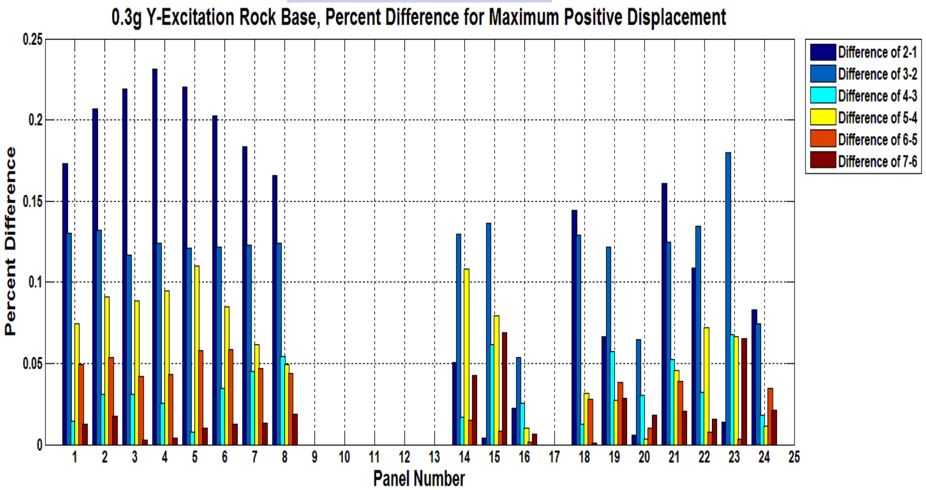
A number of 36 wall panels were modeled for nonlinear SSI analysis.
For each BBC were determined based on ASCE 41-2006 and ASCE 43-05.

Focus of the weak story (results shown for the panels #19 and 23)

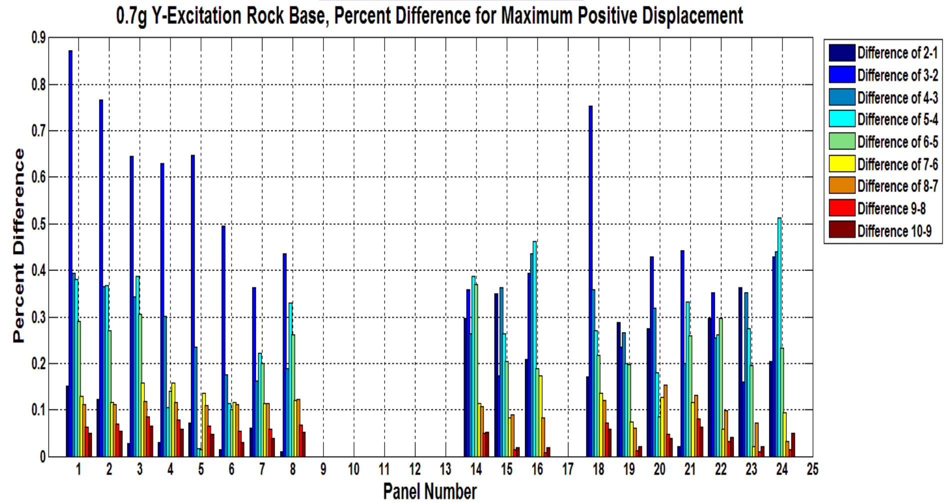


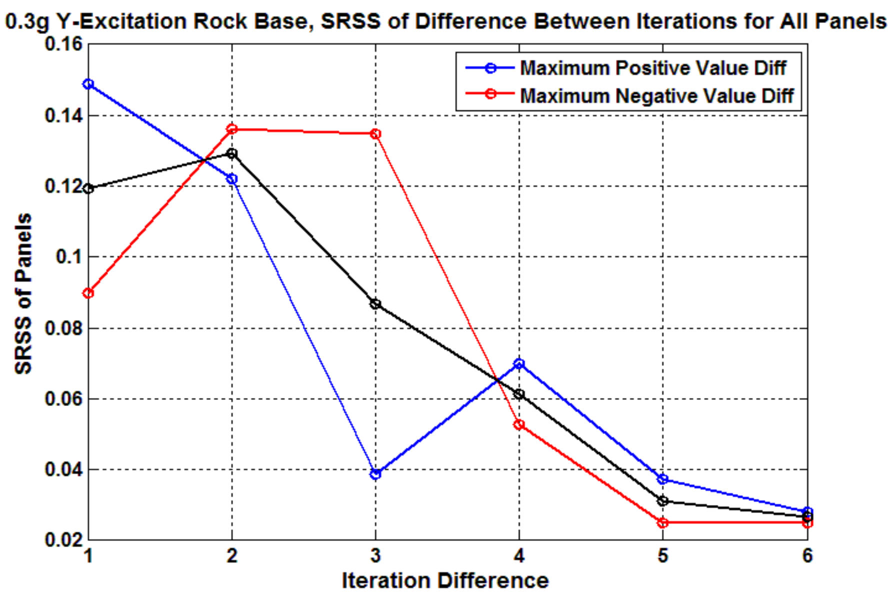
Nonlinear SSI Analysis Convergence (Per Panel and Global)

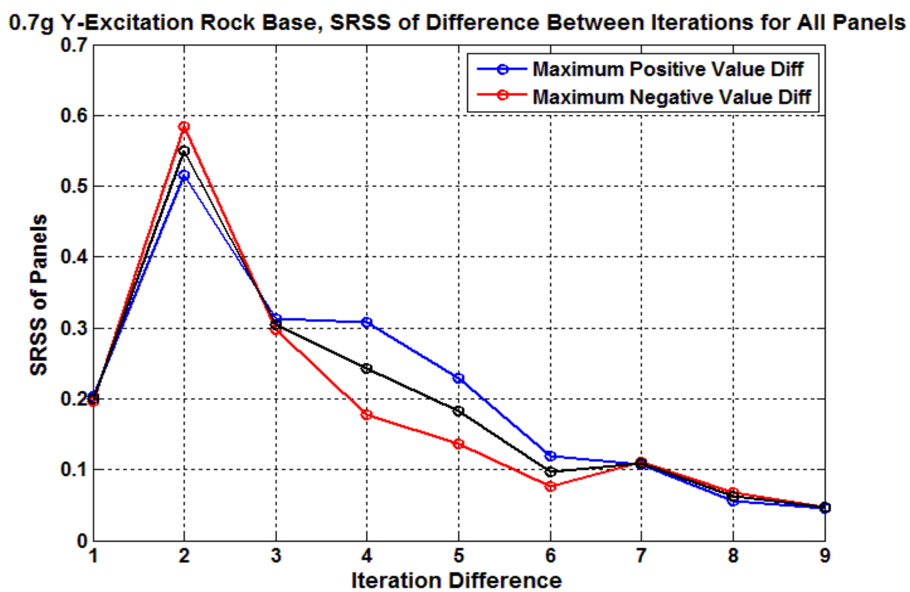
0.30g ZPGA



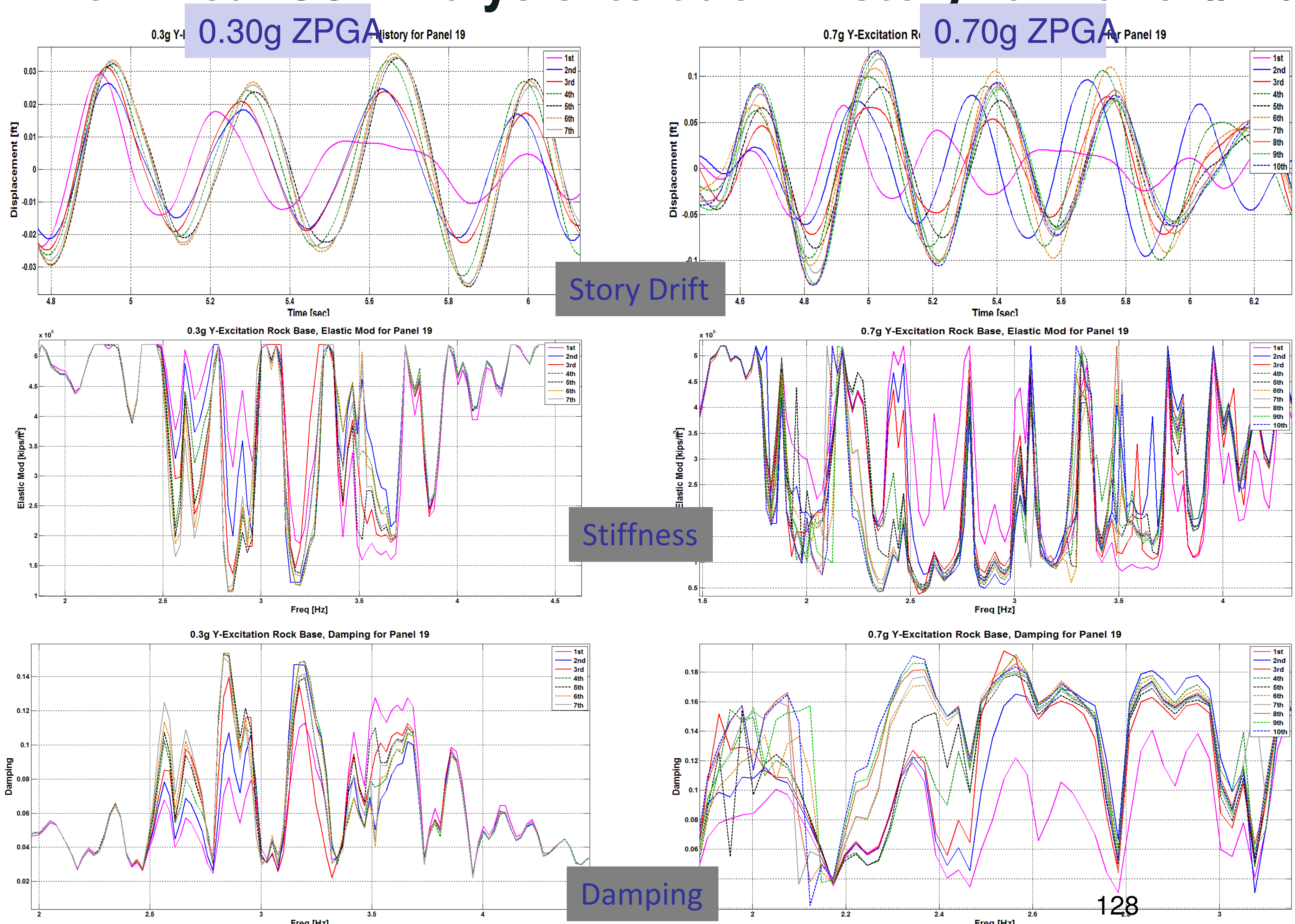
0.70g ZPGA





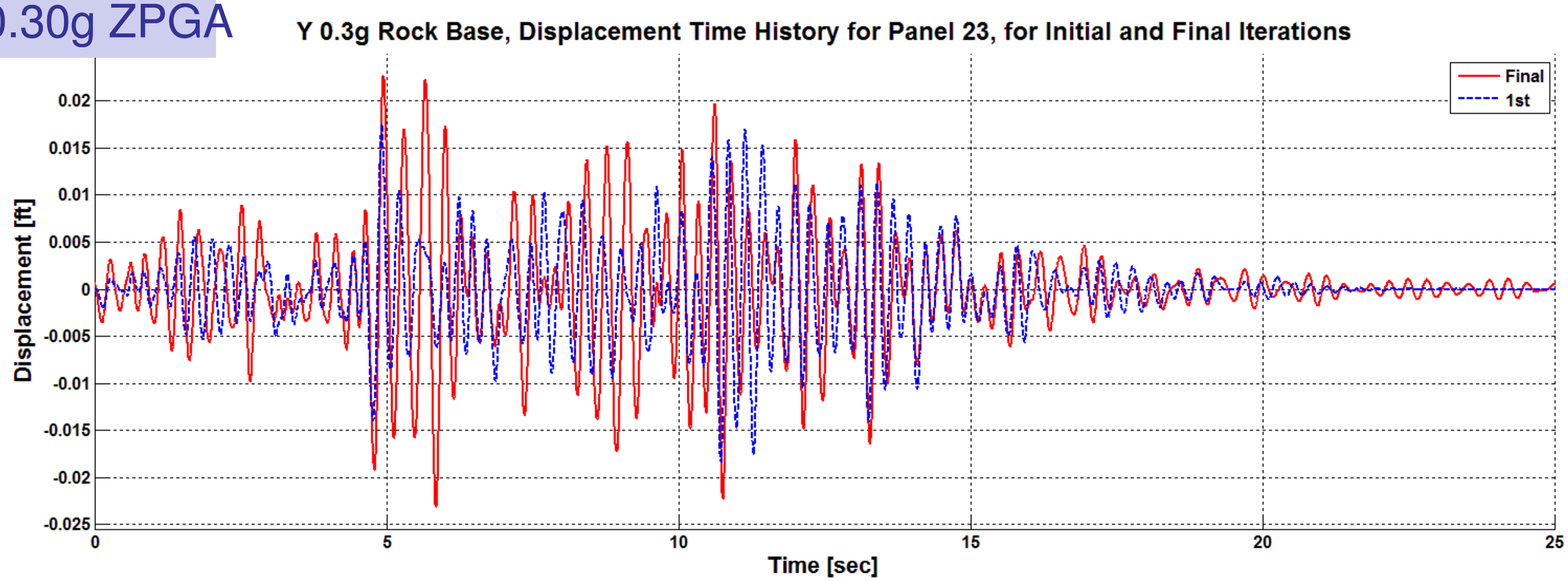


Nonlinear SSI Analysis Iteration History for Panel # 19

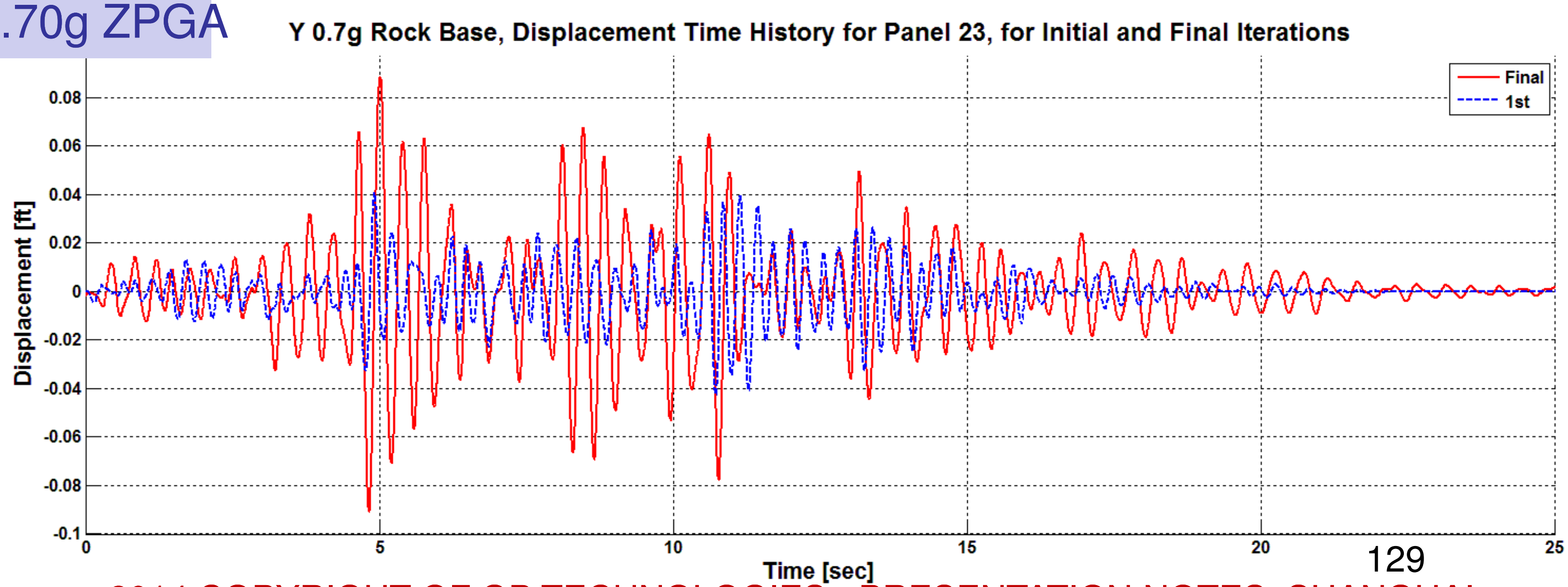


Panel #23 Comparative Linear and Nonlinear Story Drifts

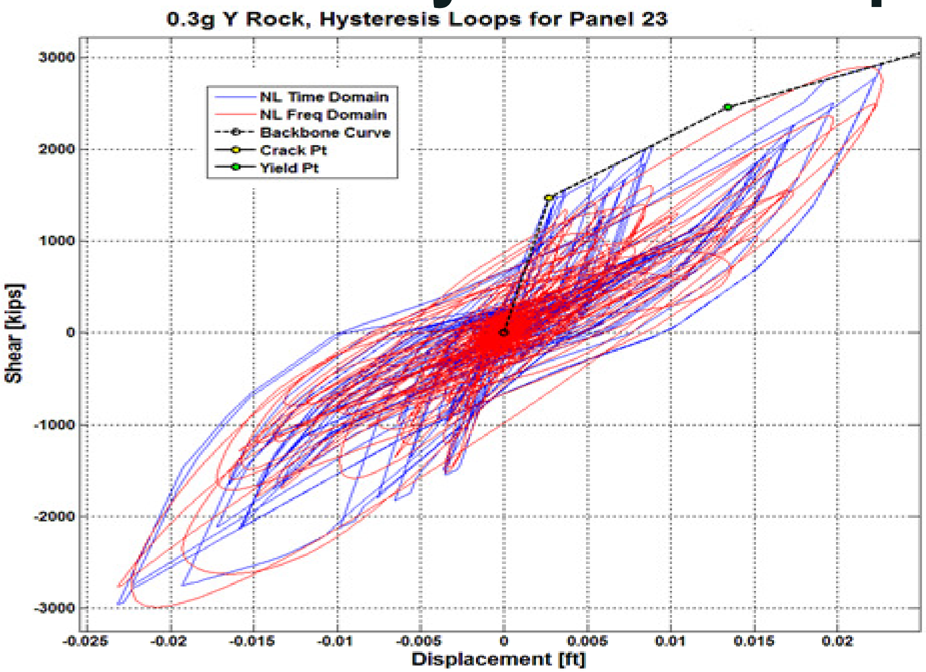
0.30g ZPGA



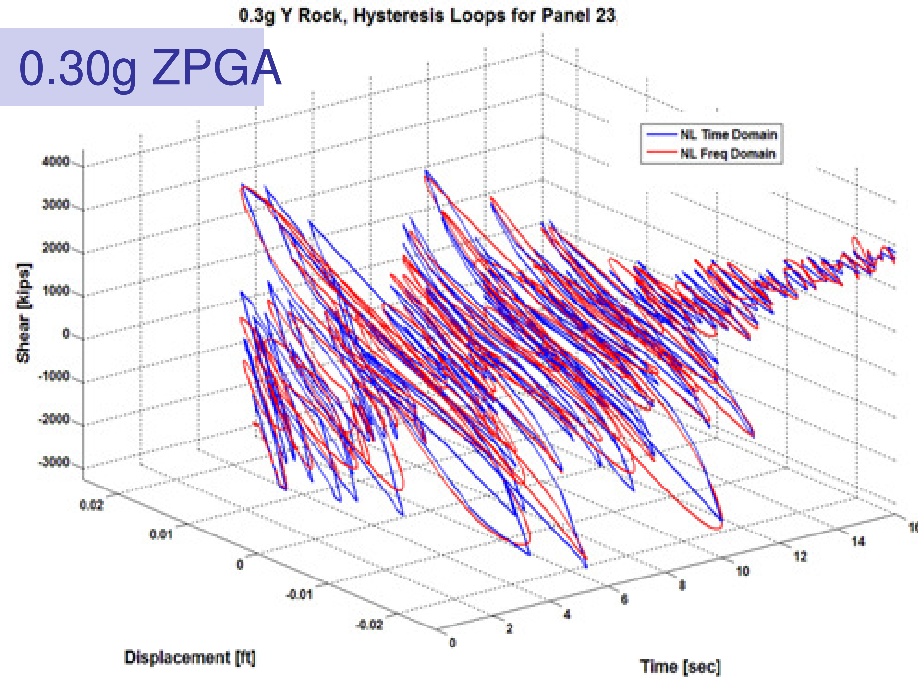
0.70g ZPGA

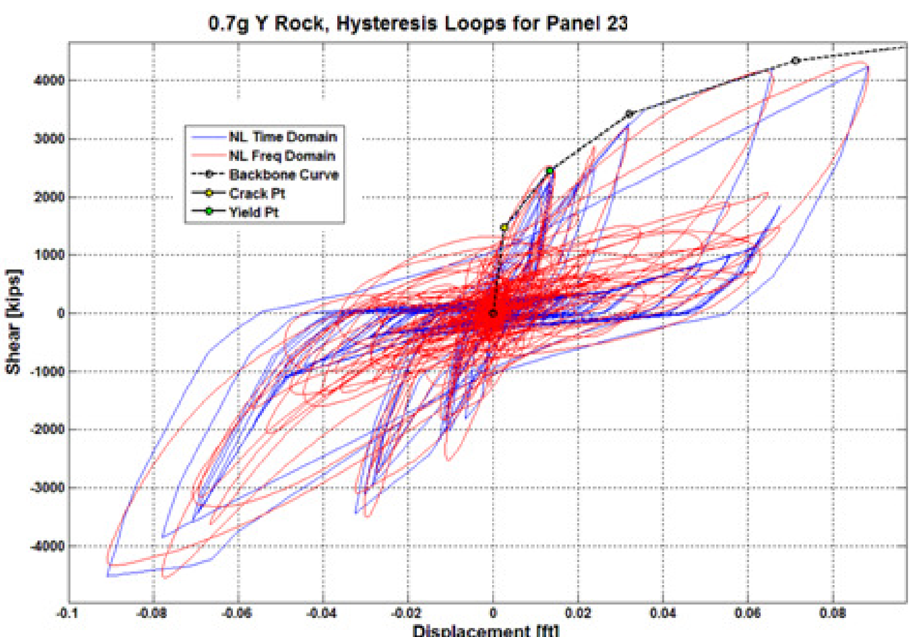


Panel #23 Hysteretic Loops for 1st and Final Iterations

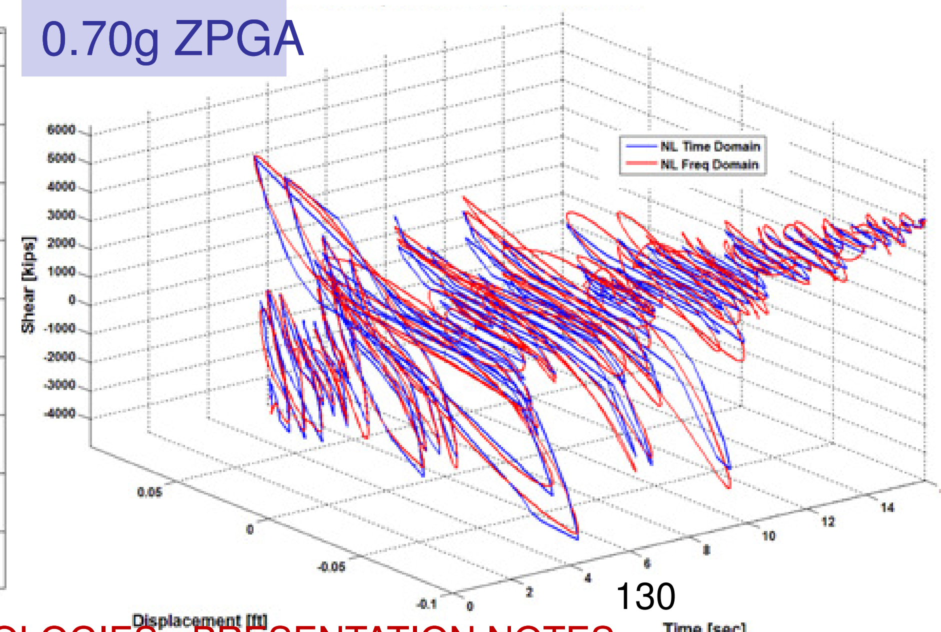


0.30g ZPGA

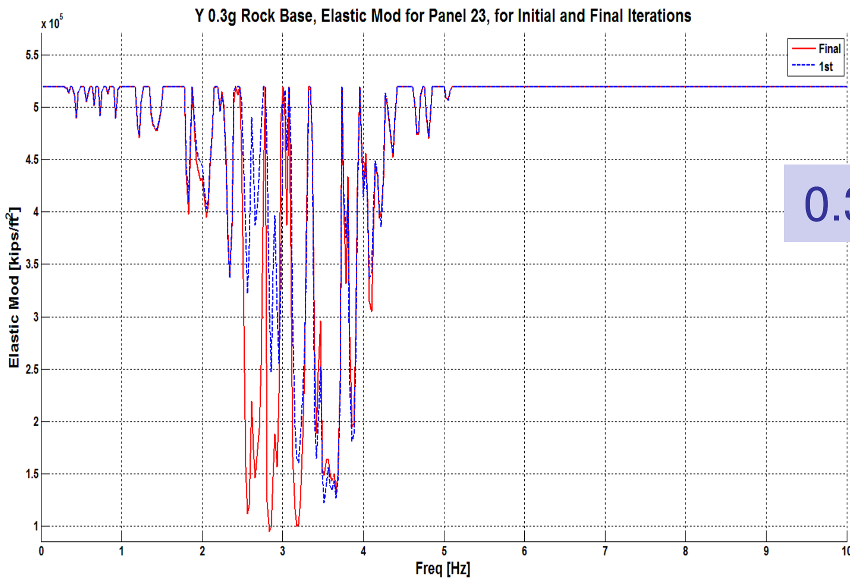




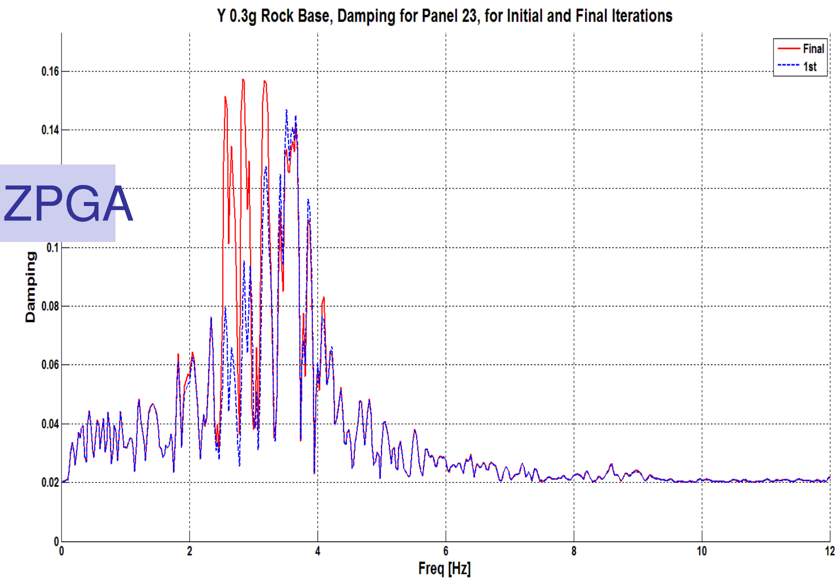
0.70g ZPGA



Panel #23: Frequency-Dependent Stiffness and Damping

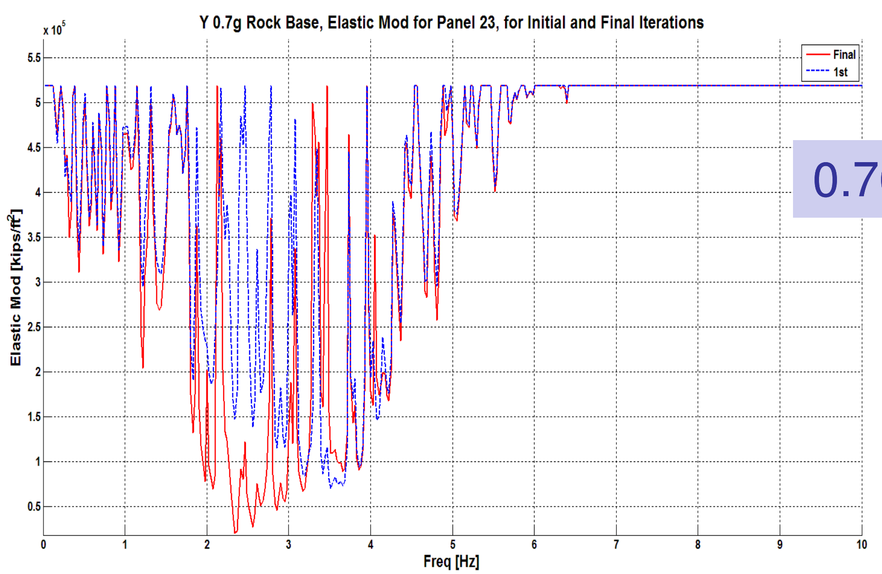


0.30g ZPGA

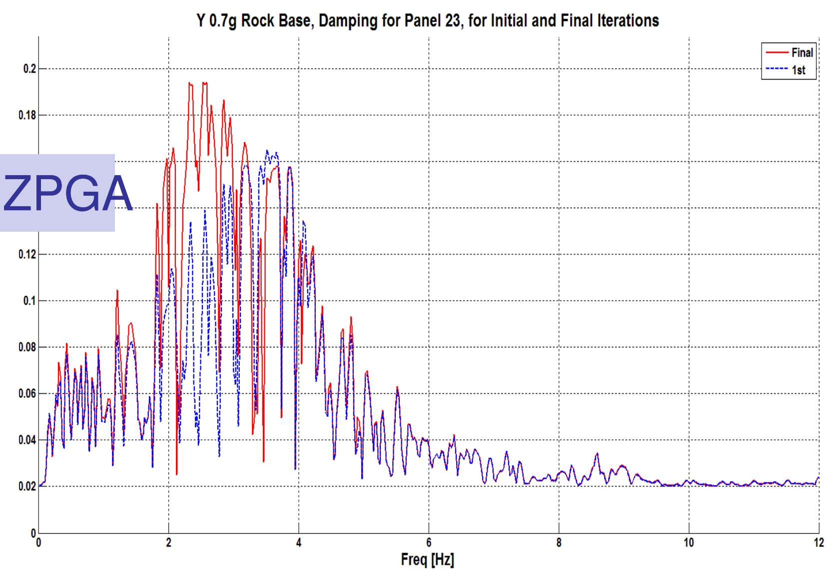


Stiffness

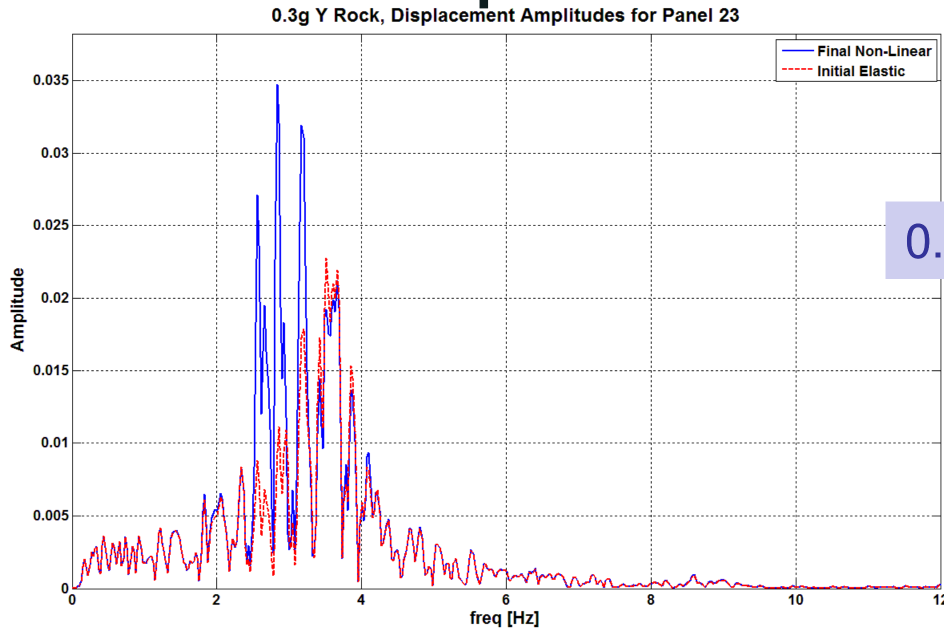
Damping

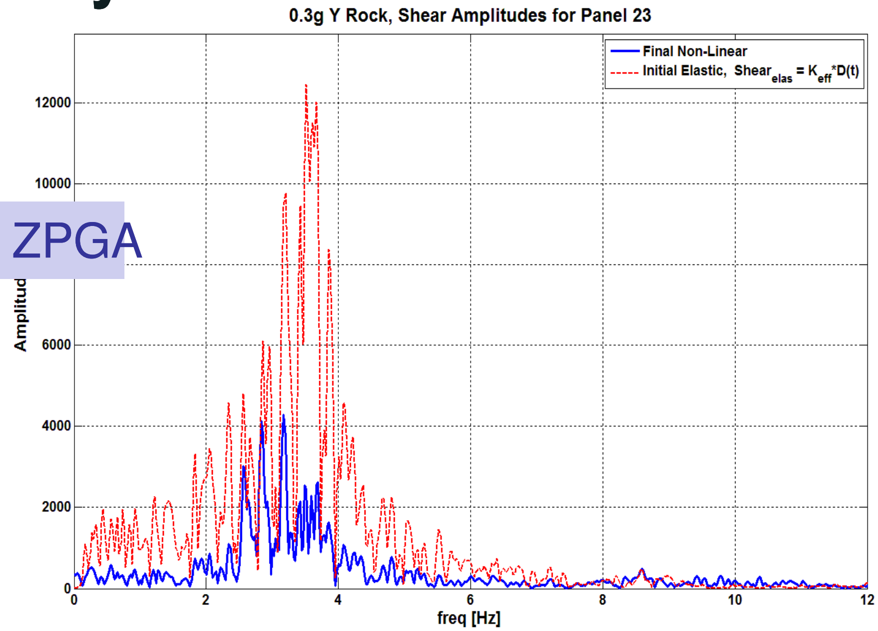


0.70g ZPGA



Panel #23: Amplitude Fourier of Story Drifts and Shear Forces

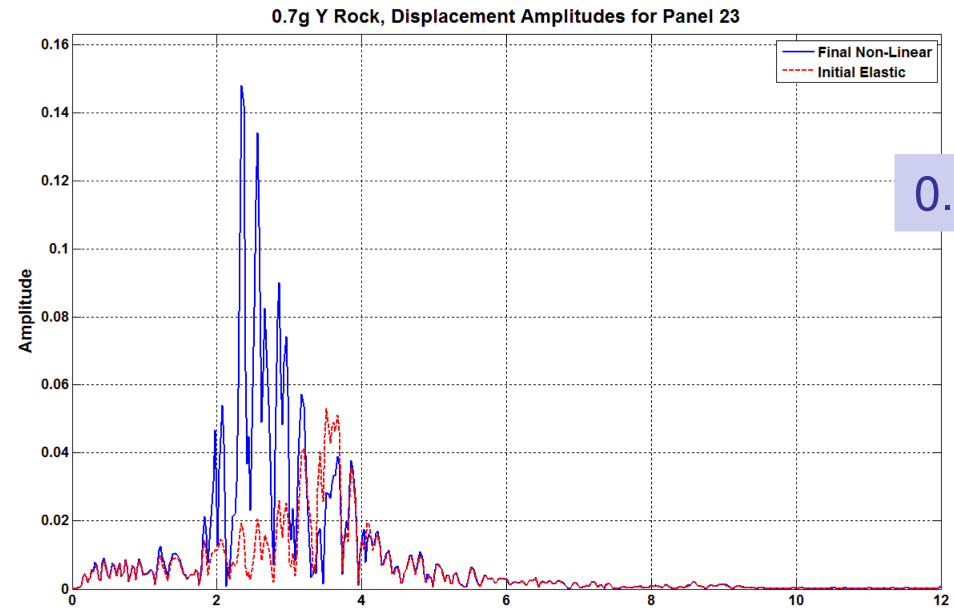


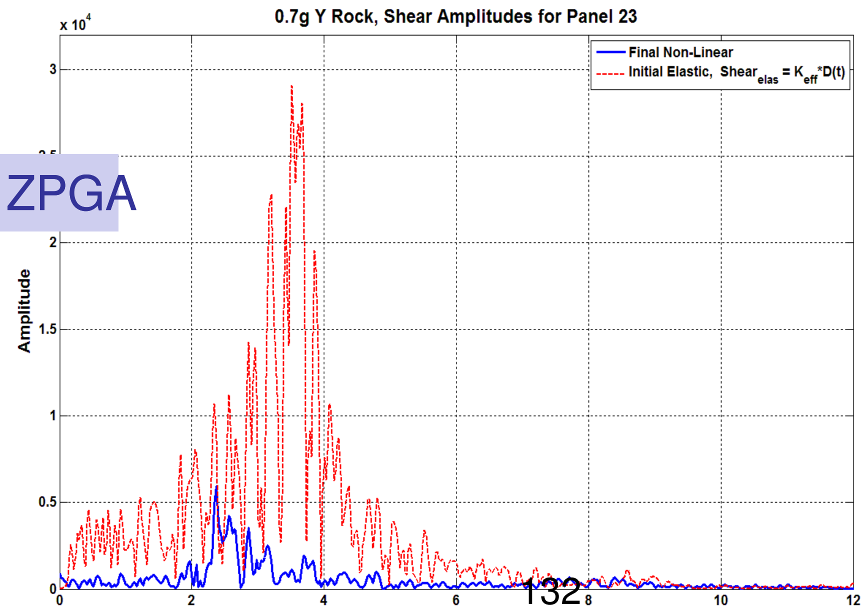


0.30g ZPGA

Story Drift Fourier Amplitude

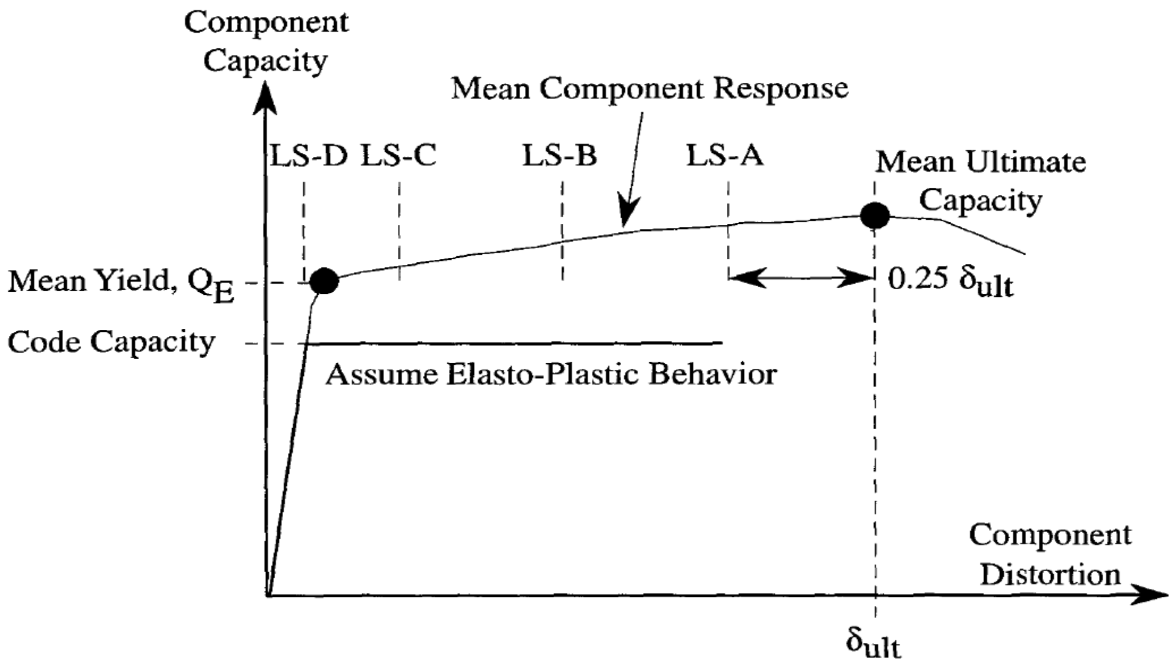
Shear Force Fourier Amplitude





0.70g ZPGA

ASCE 43-05 Inelastic Reduction Factors for Different Damage States



C5-4 Typical Load-Deformation Curve and Limit States

Limit State		Reduction Factor, F_μ	
	LS-A	LS-B	LS-C
SMRF reinforced concrete moment frames			
Beams $(15 \le \ell/h)$	5.25	4.0	2.5
Beams $(\ell/h \le 10)$	3.25	3.0	2.5
Columns**	2.0	1.75	1.5
Reinforced concrete shear wall, in plane:			
Bending controlled walls, $\frac{h_w}{\ell_w} \ge 2.0$			
$6\sqrt{f'_c} < f_v$	2.25	2.0	1.75
$f_v < 3\sqrt{f'_c}$	2.5	2.25	1.75
Shear controlled walls, $\frac{h_w}{\ell_w} < 2.0$	2.0	1.75	1.5

Nonlinear SSI and ASCE 43-05 Inelastic Reduction Factors

0.30g ZPGA Design Level (LS-D)

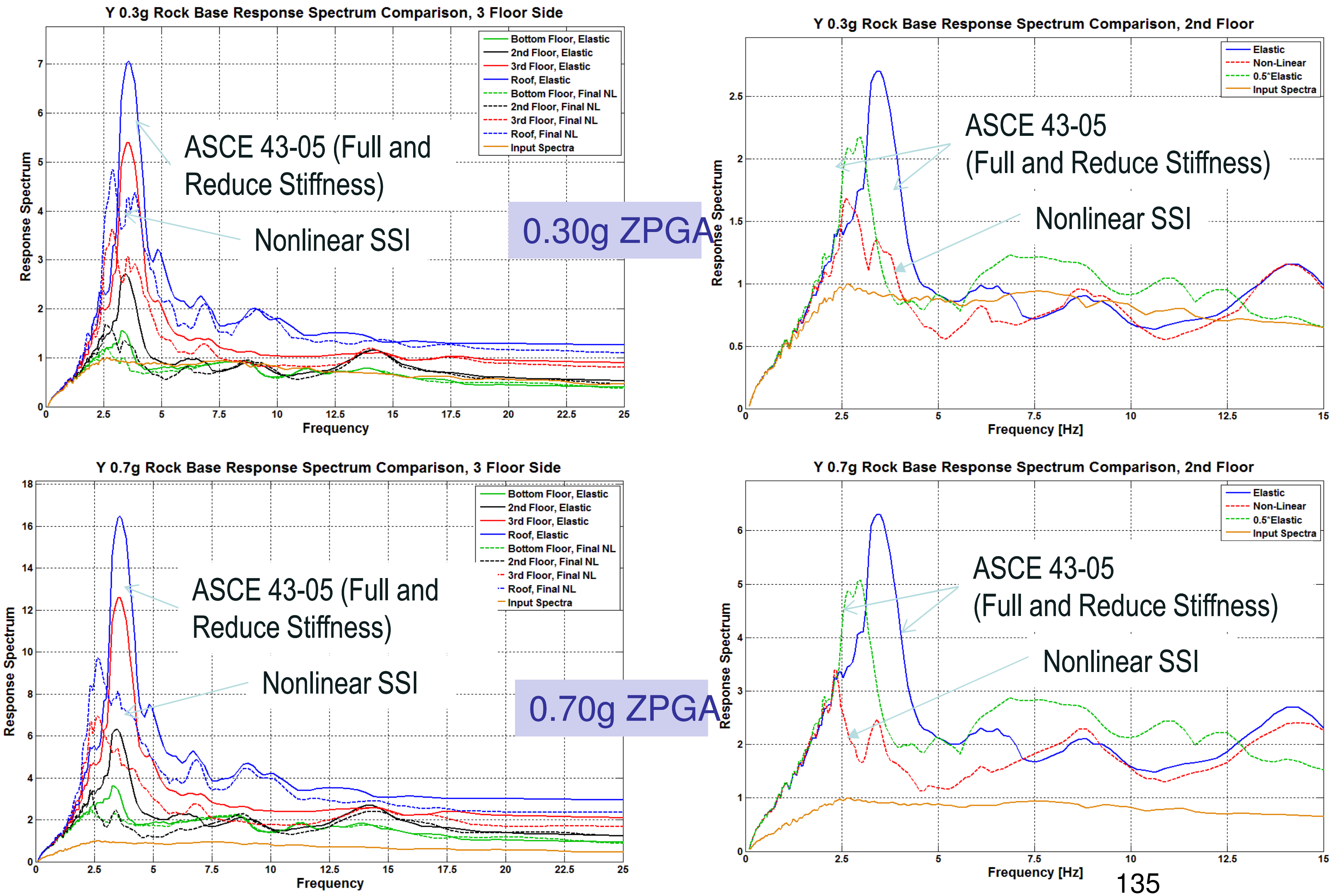
Panel Number	μ, Final Analysis	Fμ, Final Analysis (ASCE 43)	Fμ, Shear (Calcs)
1	0.716	0.657	1.042
2	0.662	0.568	1.004
3	0.664	0.573	1.029
4	0.734	0.684	1.097
5	0.776	0.743	1.153
6	0.756	0.715	1.153
7	0.708	0.645	1.093
8	0.735	0.686	1.122
14	1.373	1.321	1.315
15	1.662	1.524	1.348
16	1.230	1.208	1.358
18	0.800	0.775	1.104
19	1.238	1.215	1.222
20	1.198	1.182	1.328
21	0.732	0.681	1.112
22	1.100	1.095	1.144
23	1.721	1.562	1.339
24	1.070	1.068	1.241
Average	**0.993**	**0.939**	**1.178**
Building	**1.177**	**1.163**	**-----**

0.70g ZPGA Review Level (LS-A)

Panel Number	μ, Final Analysis	Fμ, Final Analysis (ASCE 43)	Fμ, Shear (Calcs)
1	1.811	1.619	1.697
2	1.673	1.532	1.636
3	1.615	1.493	1.703
4	1.716	1.559	1.846
5	1.720	1.562	1.985
6	1.596	1.480	2.022
7	1.515	1.425	1.901
8	1.621	1.497	1.887
14	4.500	2.828	2.040
15	6.390	3.432	2.052
16	3.810	2.573	2.143
18	2.020	1.743	1.801
19	4.523	2.836	1.819
20	4.058	2.668	2.031
21	1.648	1.515	1.855
22	3.745	2.548	1.752
23	6.764	3.539	2.046
24	3.143	2.299	1.982
Average	**2.993**	**2.119**	**1.900**
Building	**3.801**	**2.569**	**----**

Large ductility demands

Nonlinear SSI and ASCE 43-05 Inelastic Reduction Factors

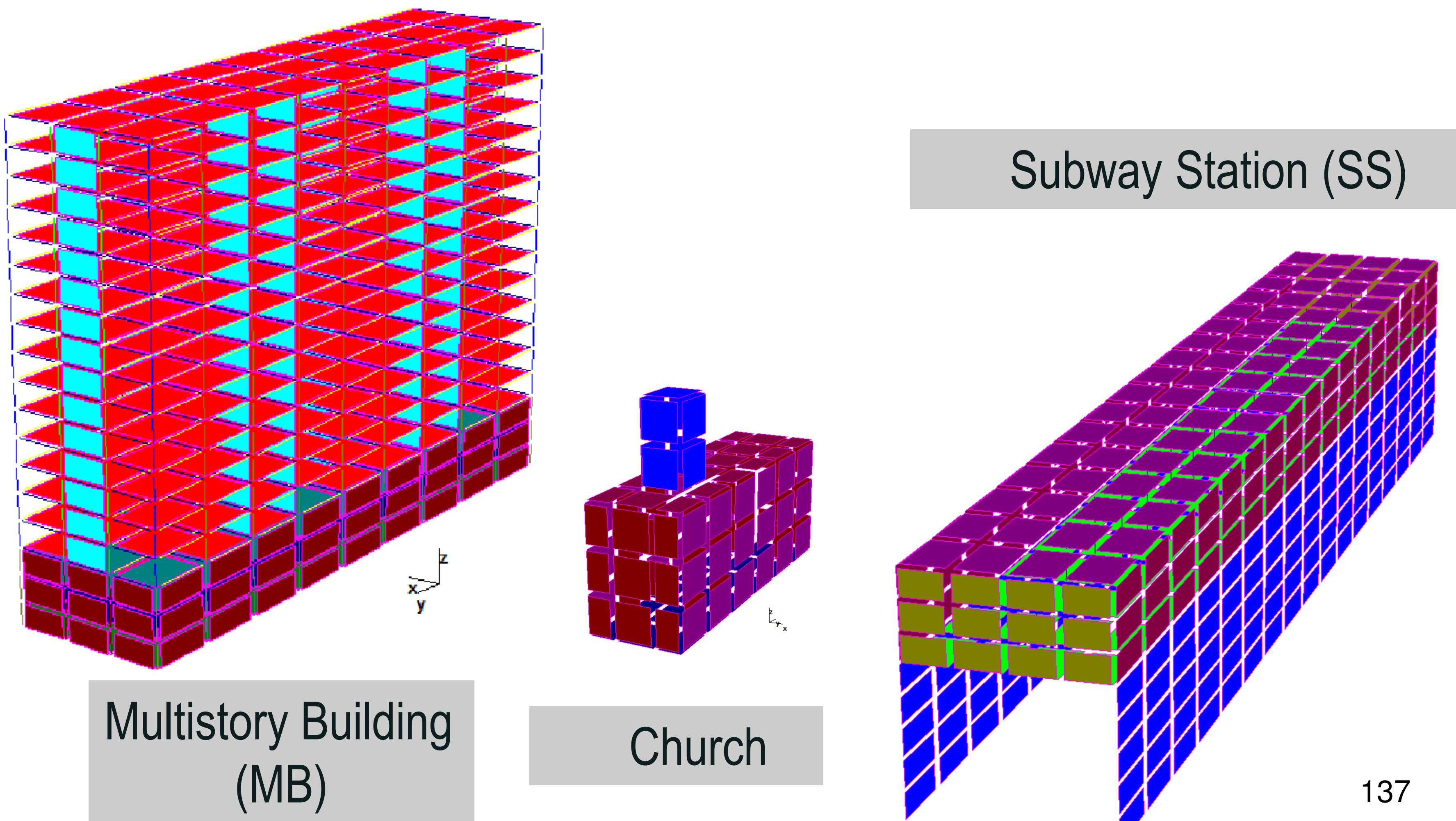


Concluding Remarks

- Nonlinear SSI analysis in complex frequency domain is a very promising engineering approach. It is at least 500 -1000 times faster than nonlinear SSI analysis in time domain.
- It provides results consistent with the ASCE 43-05 standard recommendations.
- Nonlinear SSI analysis in complex frequency is much more robust that nonlinear SSI analysis in time domain that is much more sensitive, especially for higher frequencies.

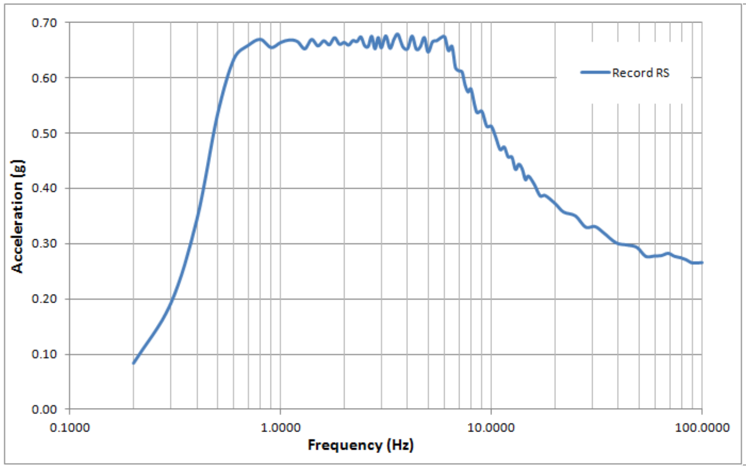
SSSI Effects for Buildings in Dense Urban Areas

Study for evaluating the SSI and SSSI effects for neighboring structures in dense urban areas including the effects of incoherency.

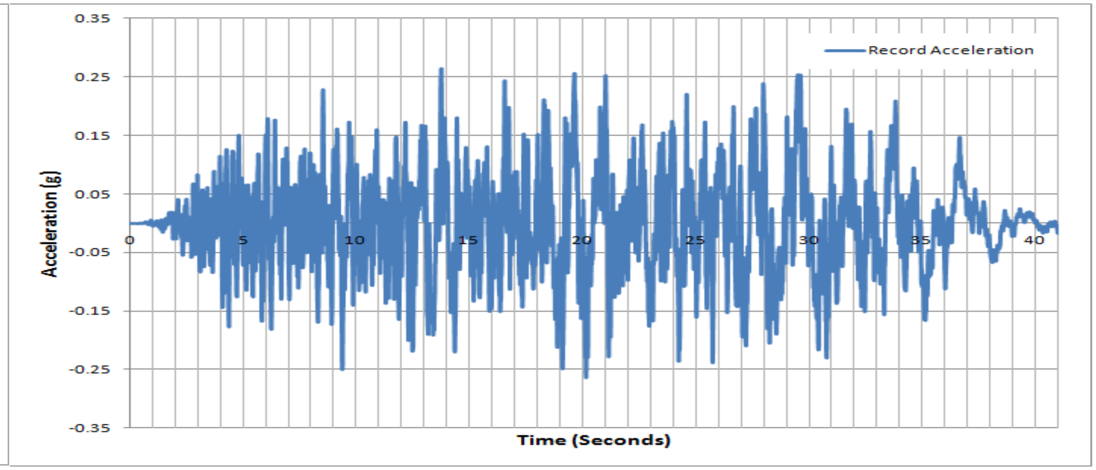


Seismic SSI Analysis Inputs

Seismic Input Motion at Ground Surface:



Design Spectrum (0.25g)

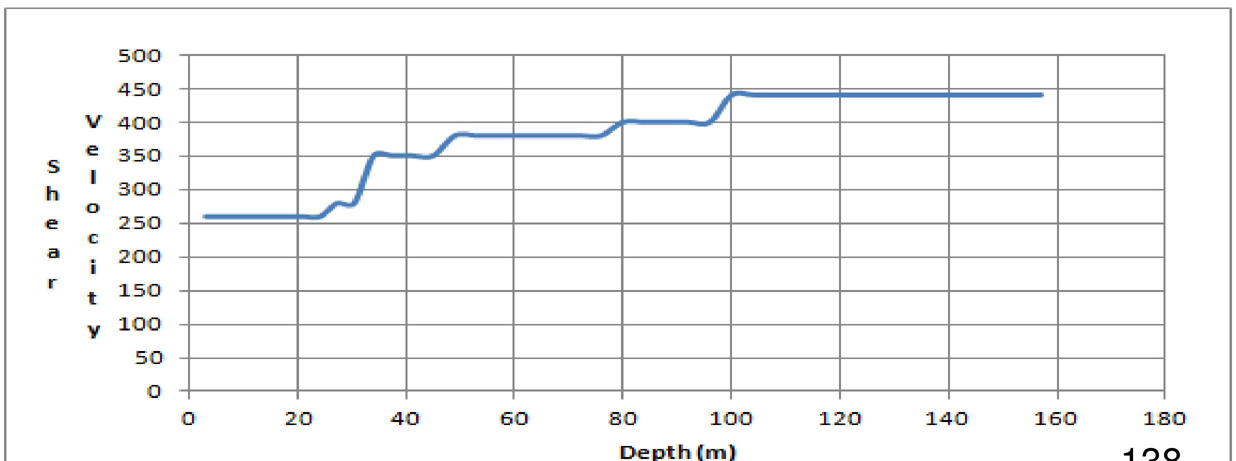


Simulated Acceleration Input (0.25g)

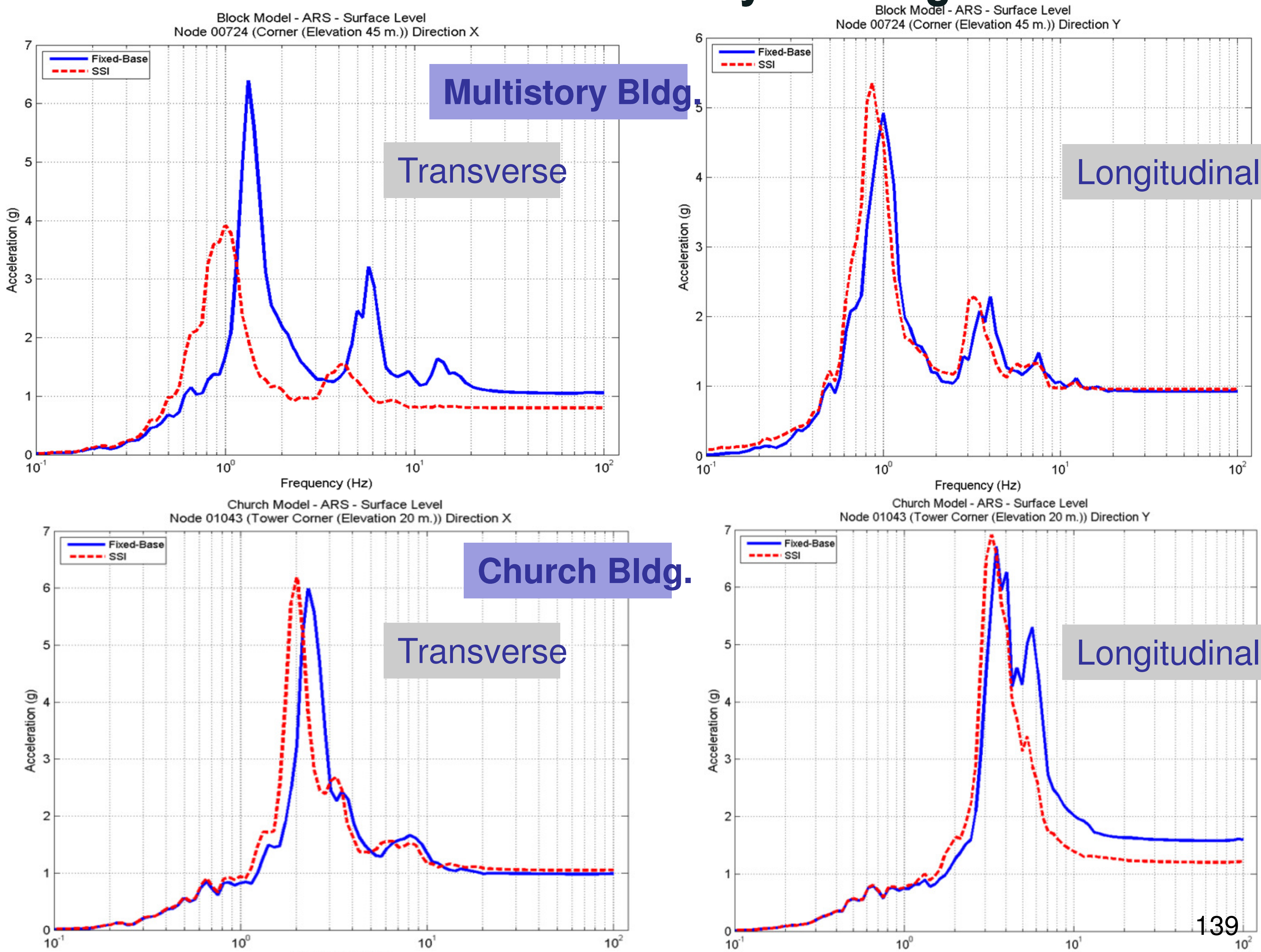
Incoherent Motion: 2005 Abrahamson coherency model, with wave passage Va=1,300m/s

Soil Layering:

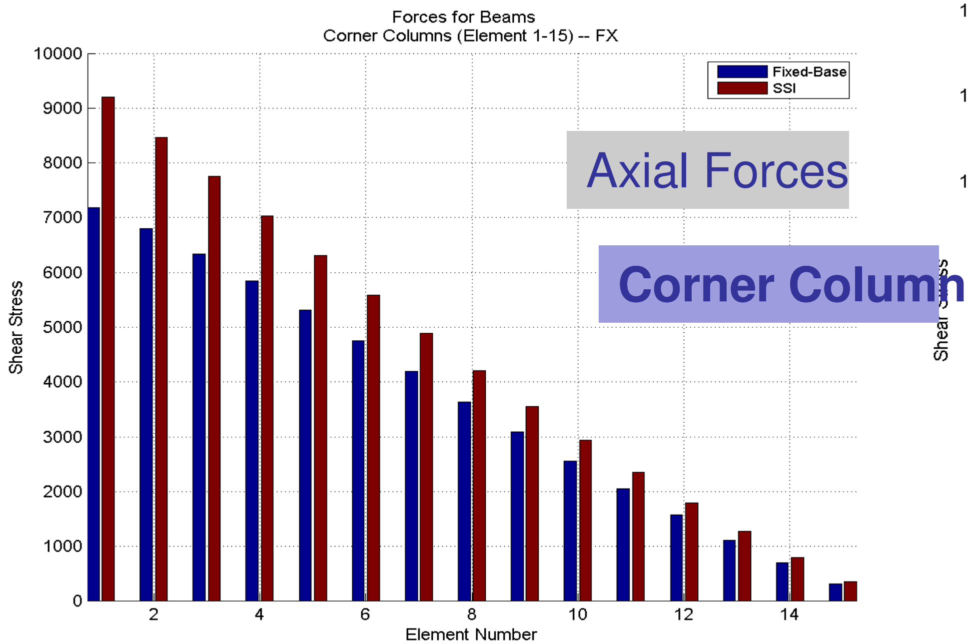
Deep soft soil deposit,
Vs = 260…..450m/s

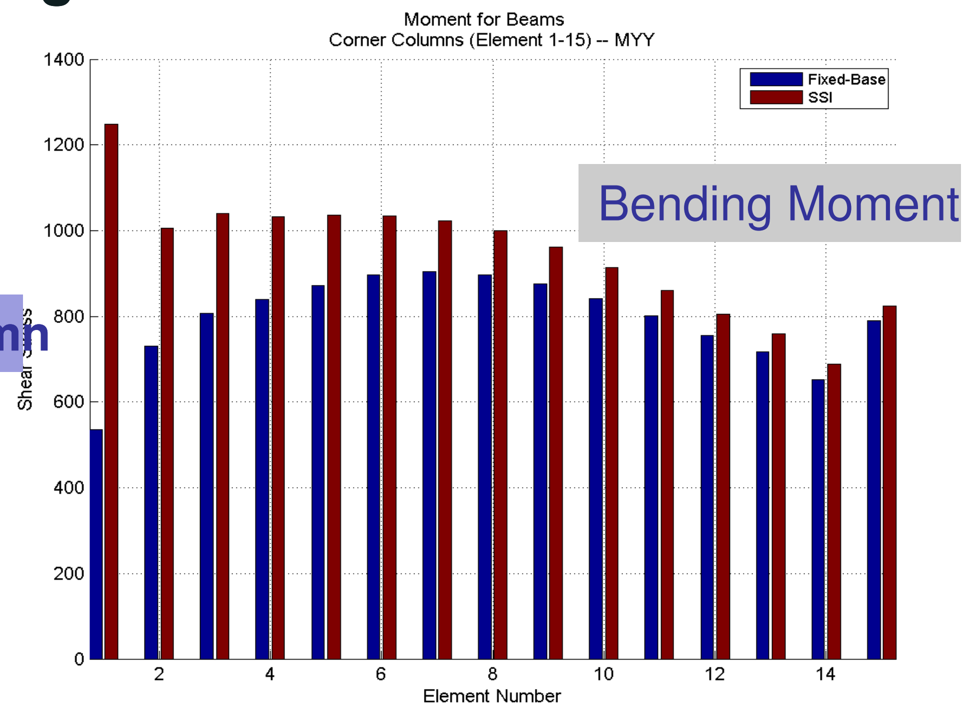


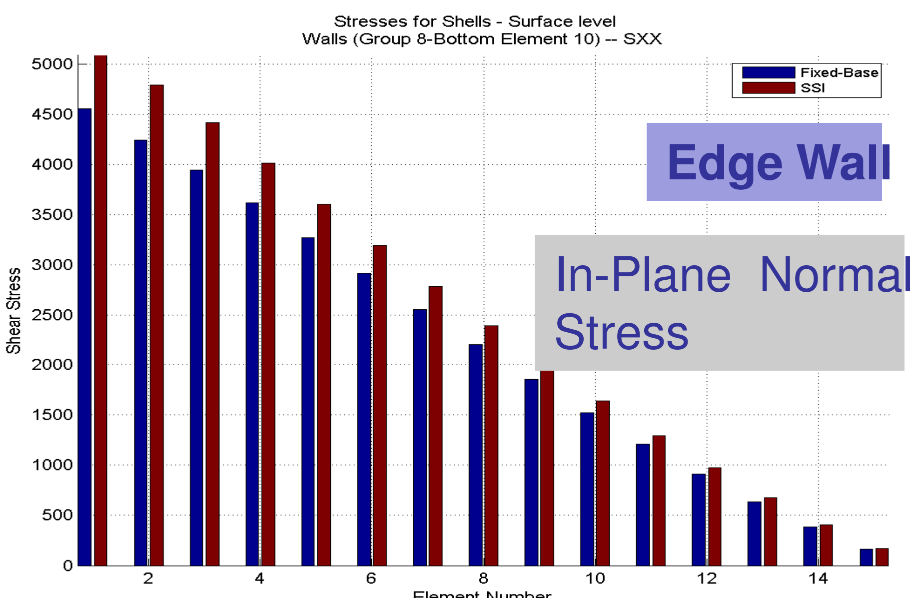
SSI Effects on ISRS for Multistory Building and Church

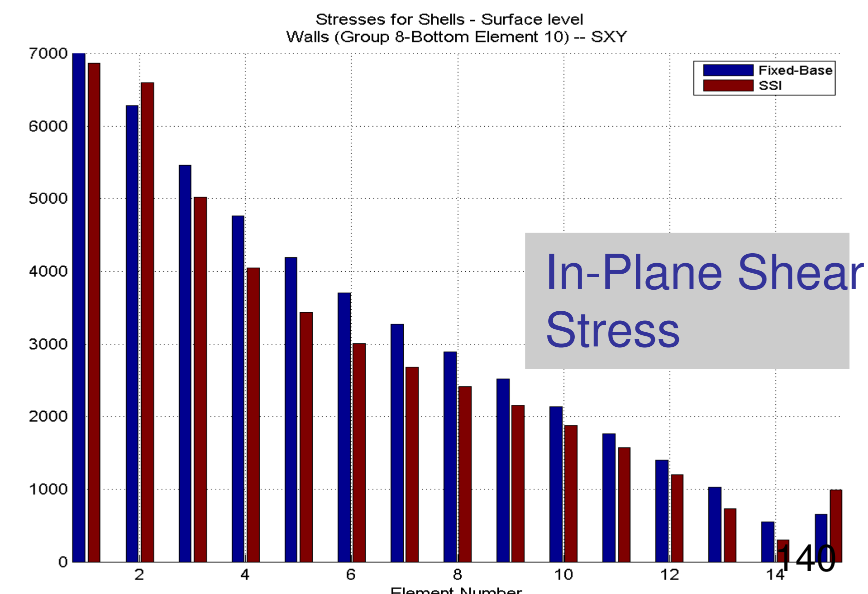


SSI Effects on Multistory Building Forces in Columns and Walls

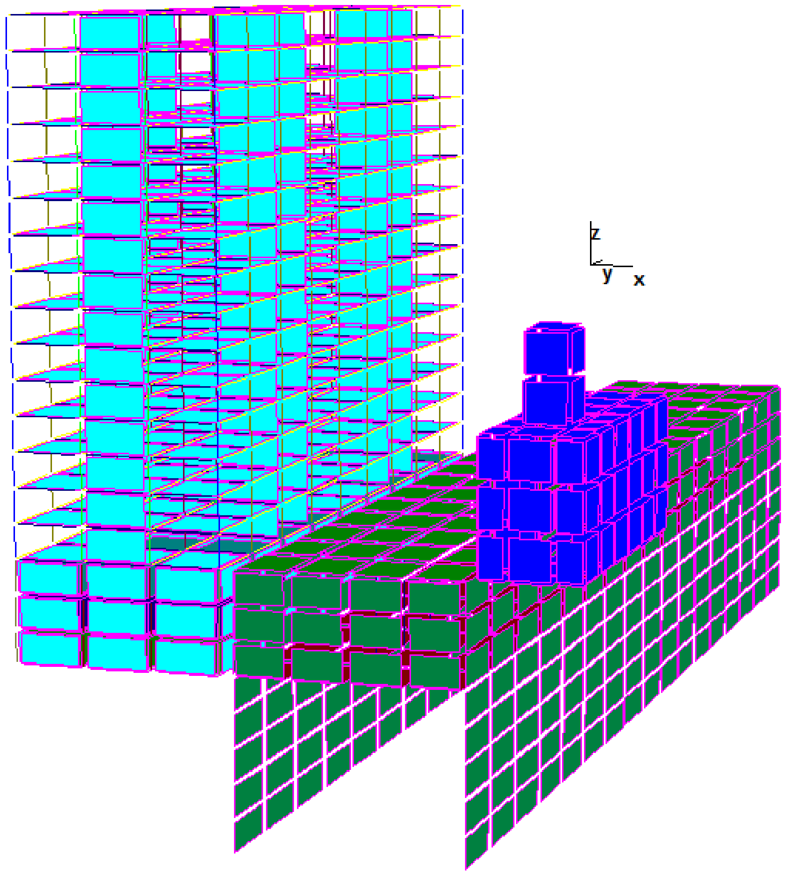




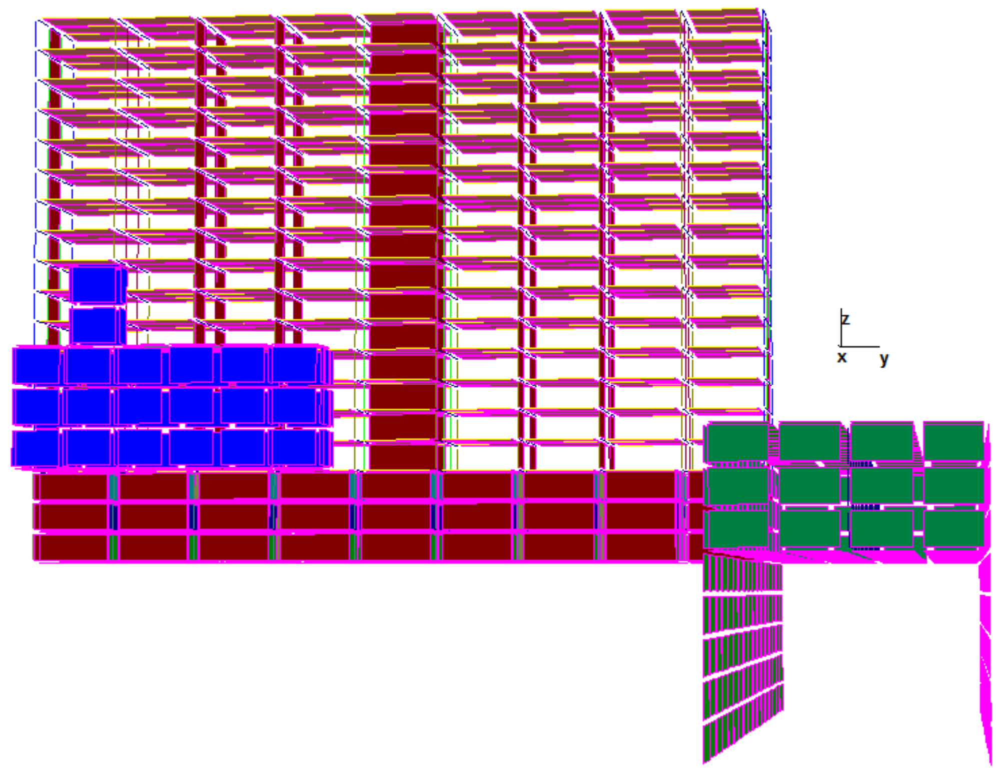




Two Different Layout Scenarios for SSSI Models

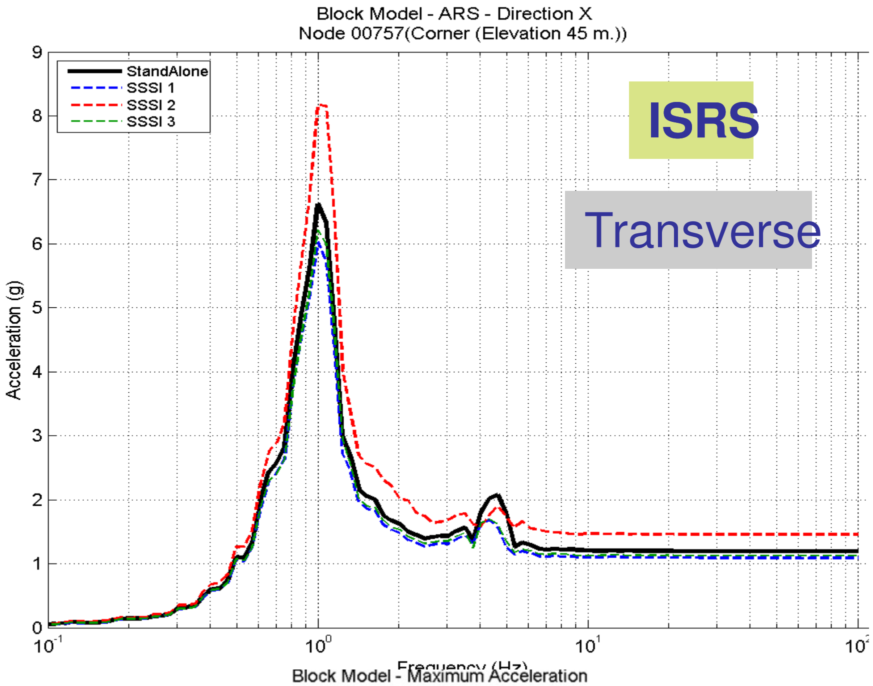


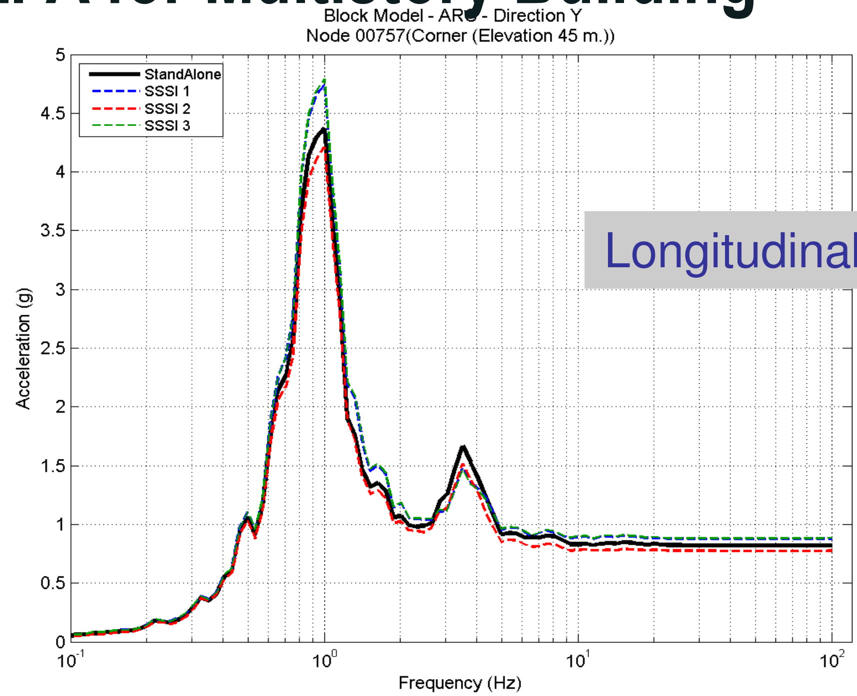
SSSI Model 2
(Parallel MB and SS)

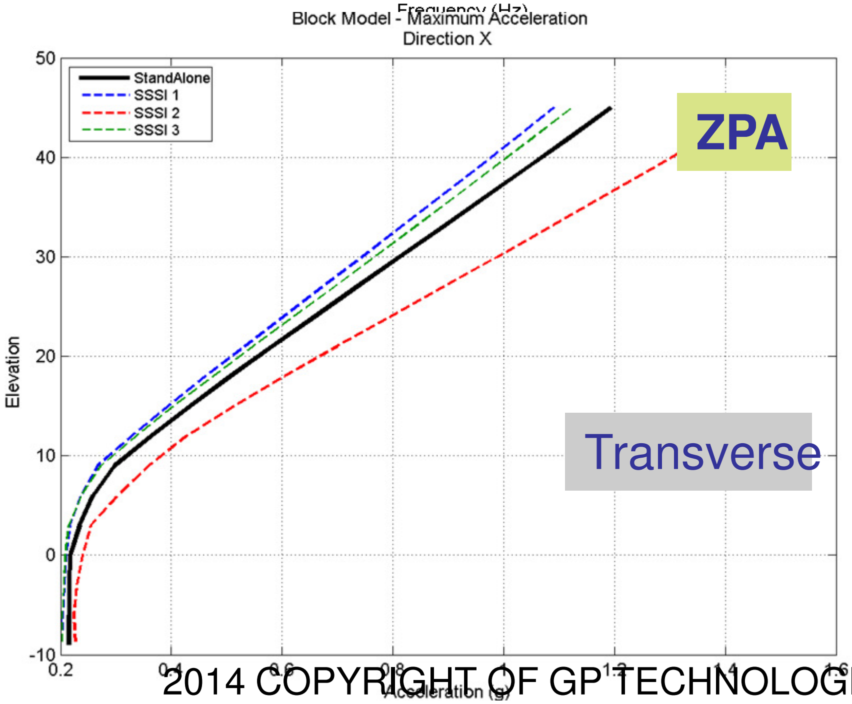


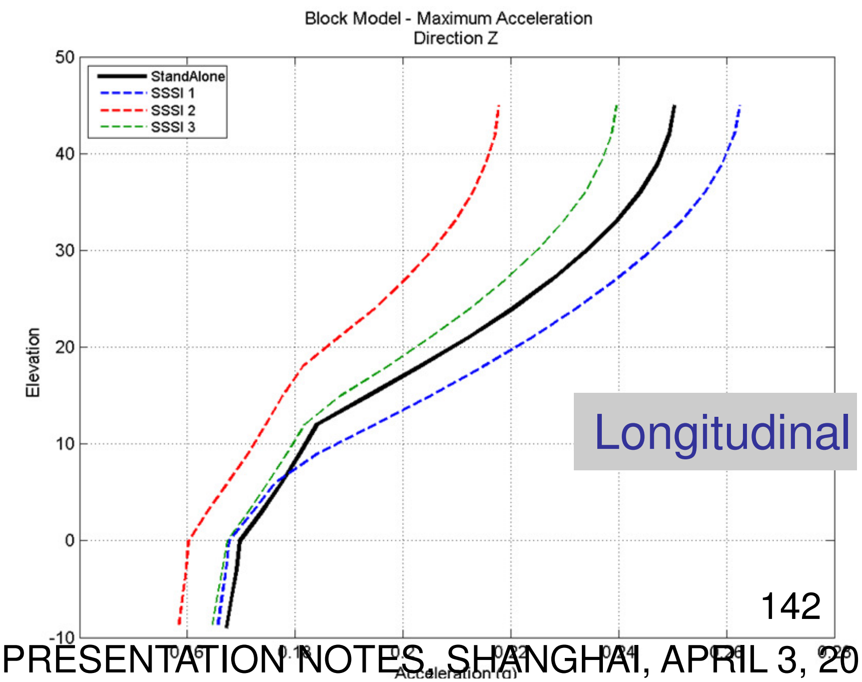
SSSI Model 3
(Perpendicular MB and SS)

SSSI Effects on ISRS and ZPA for Multistory Building

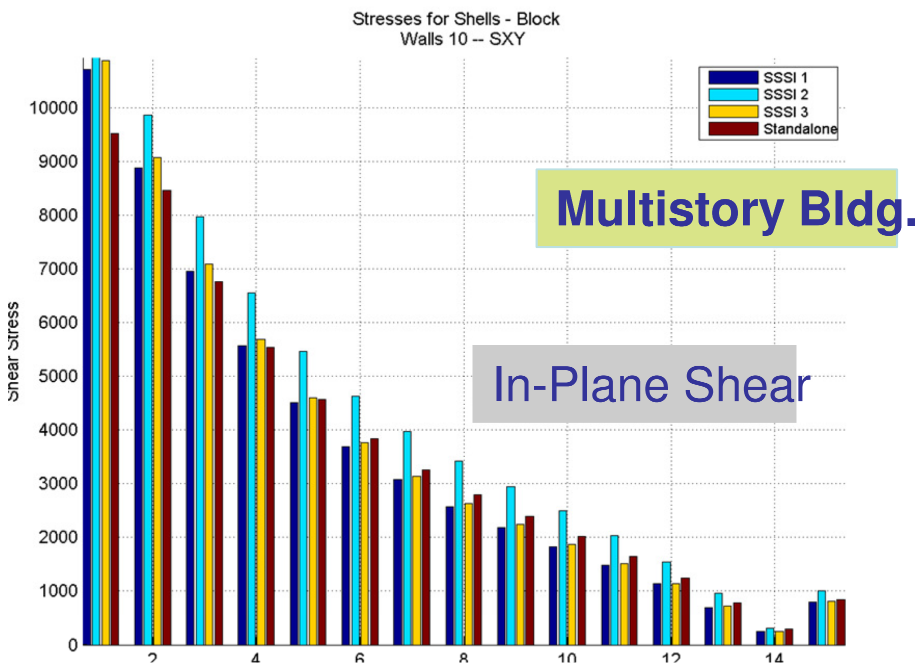


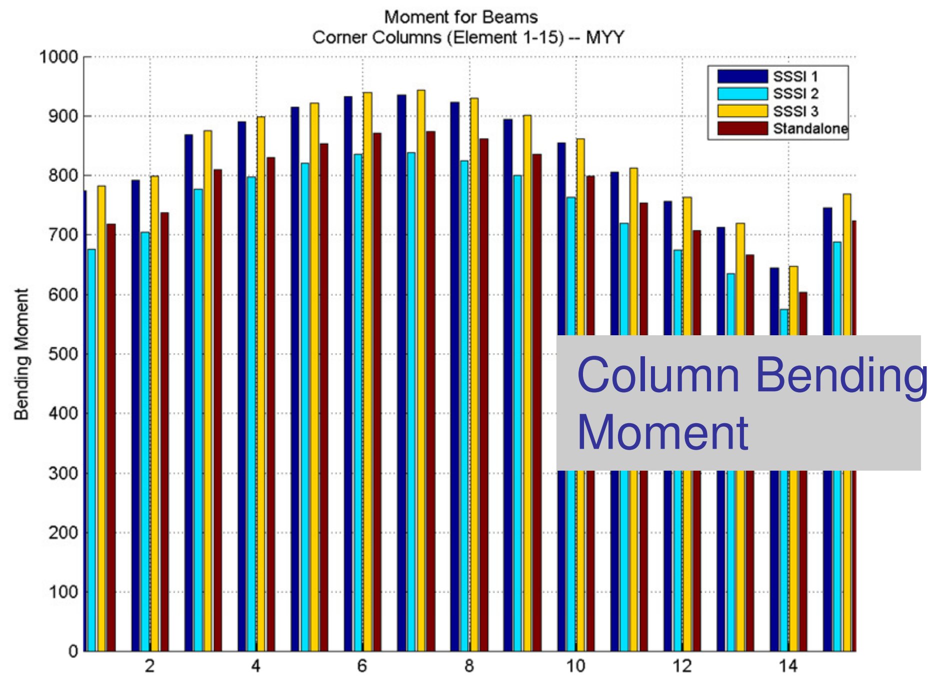


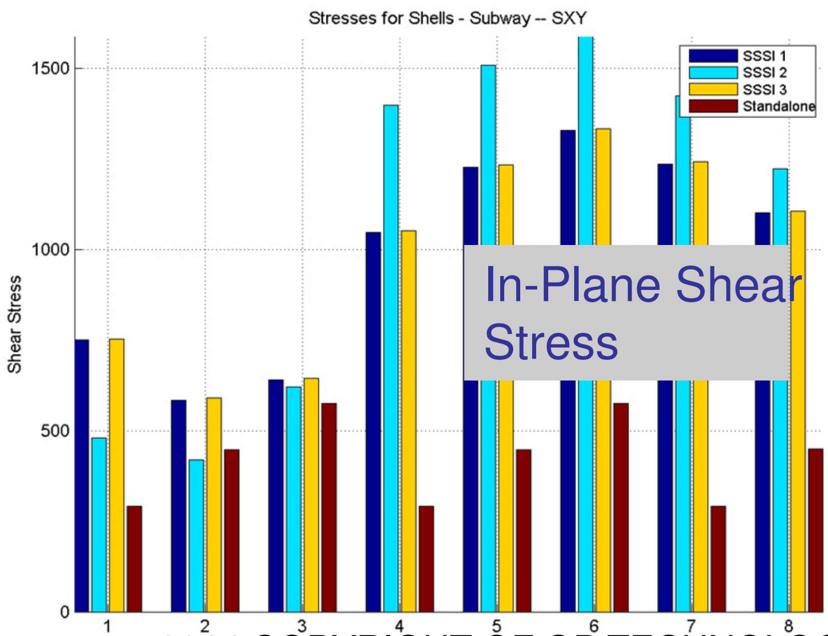


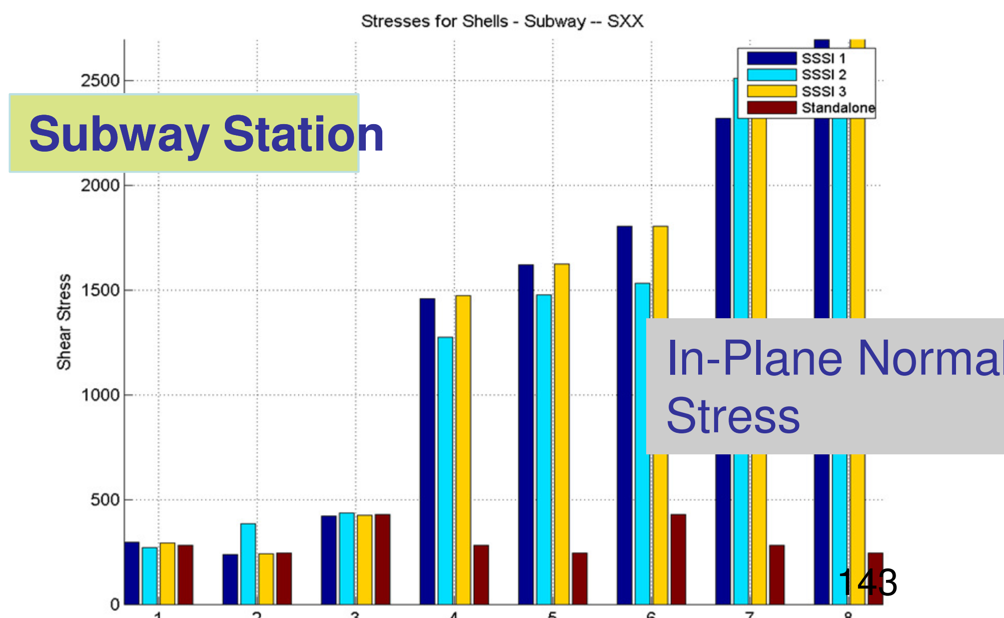


SSSI Effects on Structural Forces/Stresses in MB and SS

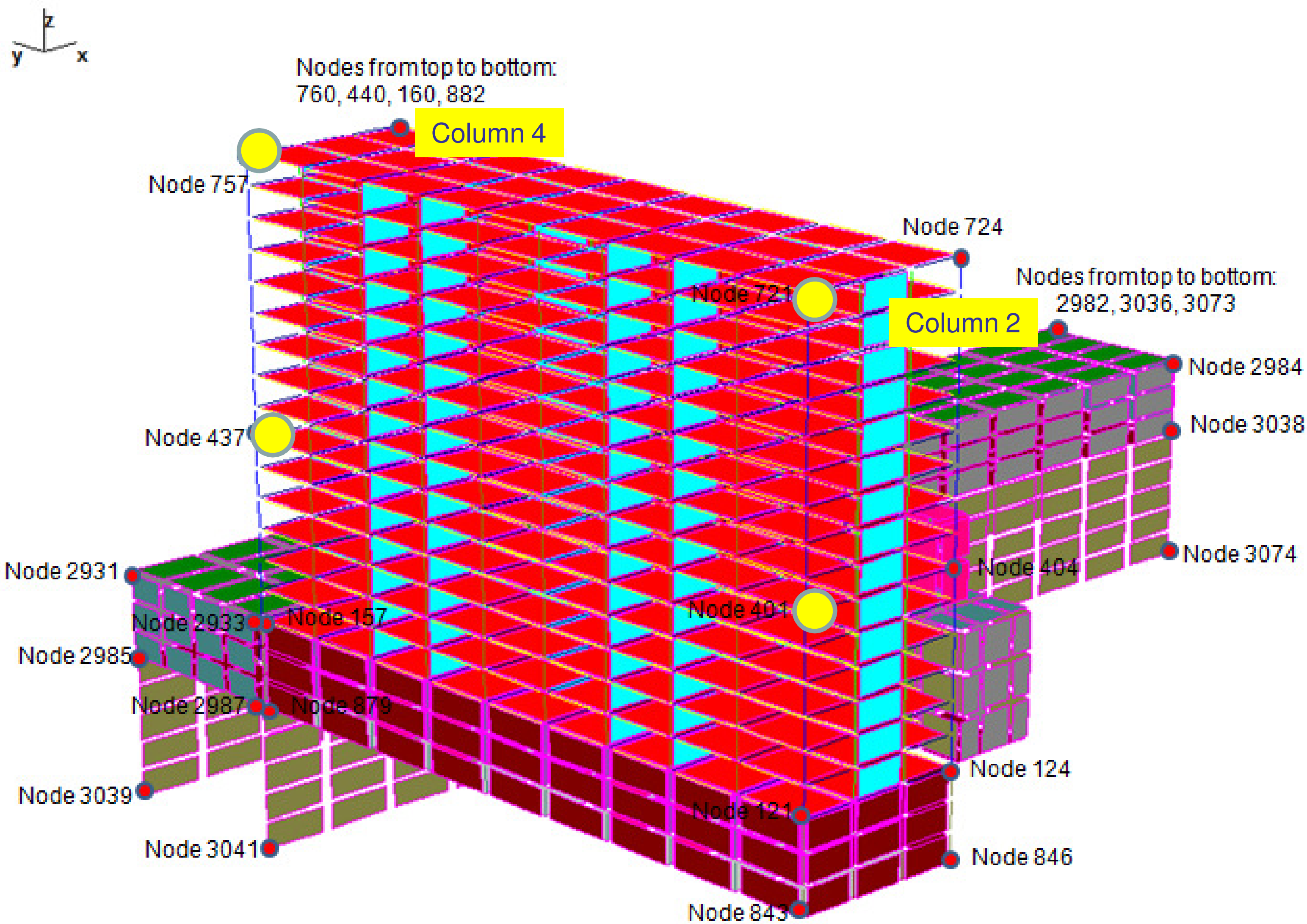




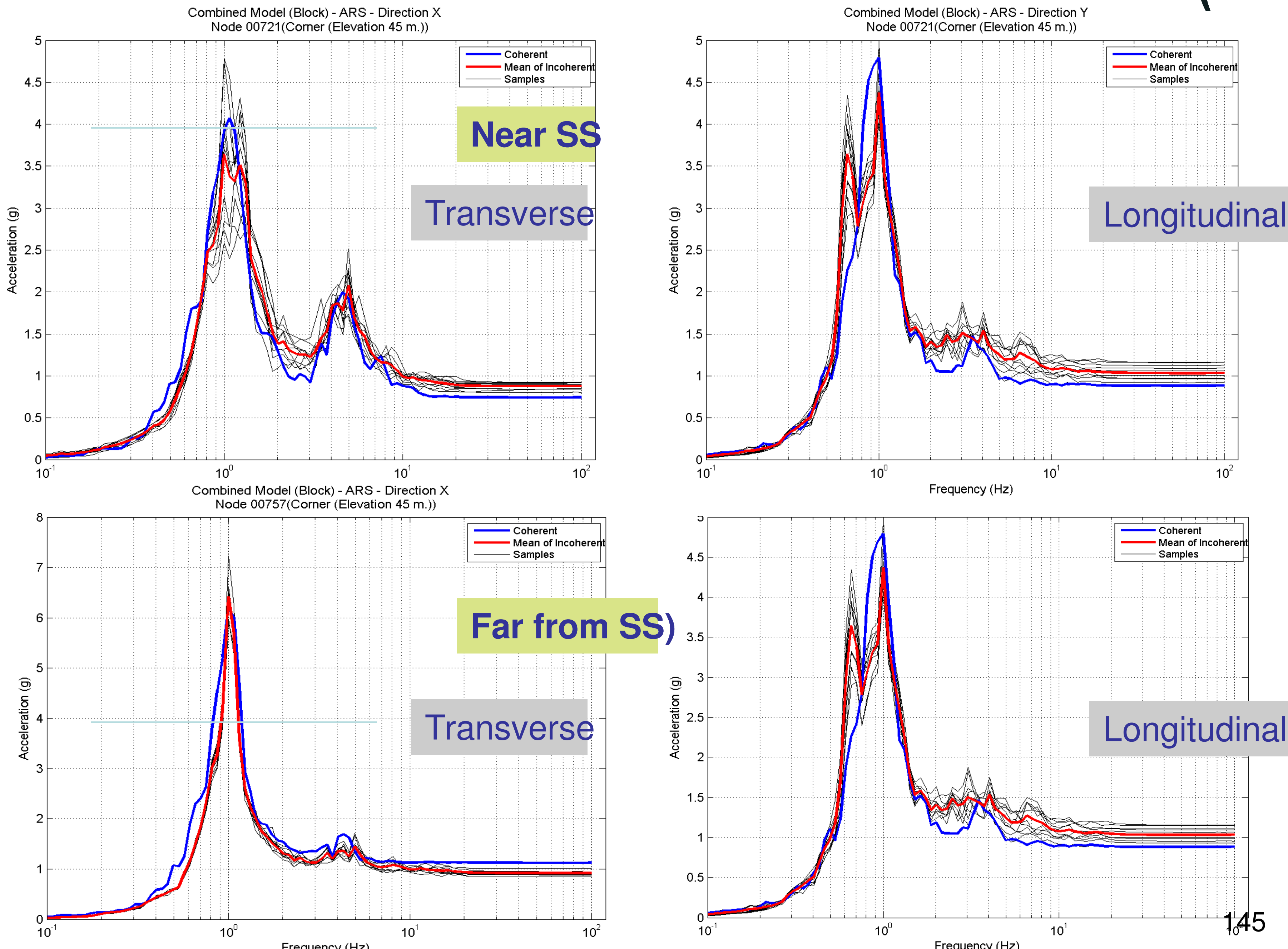




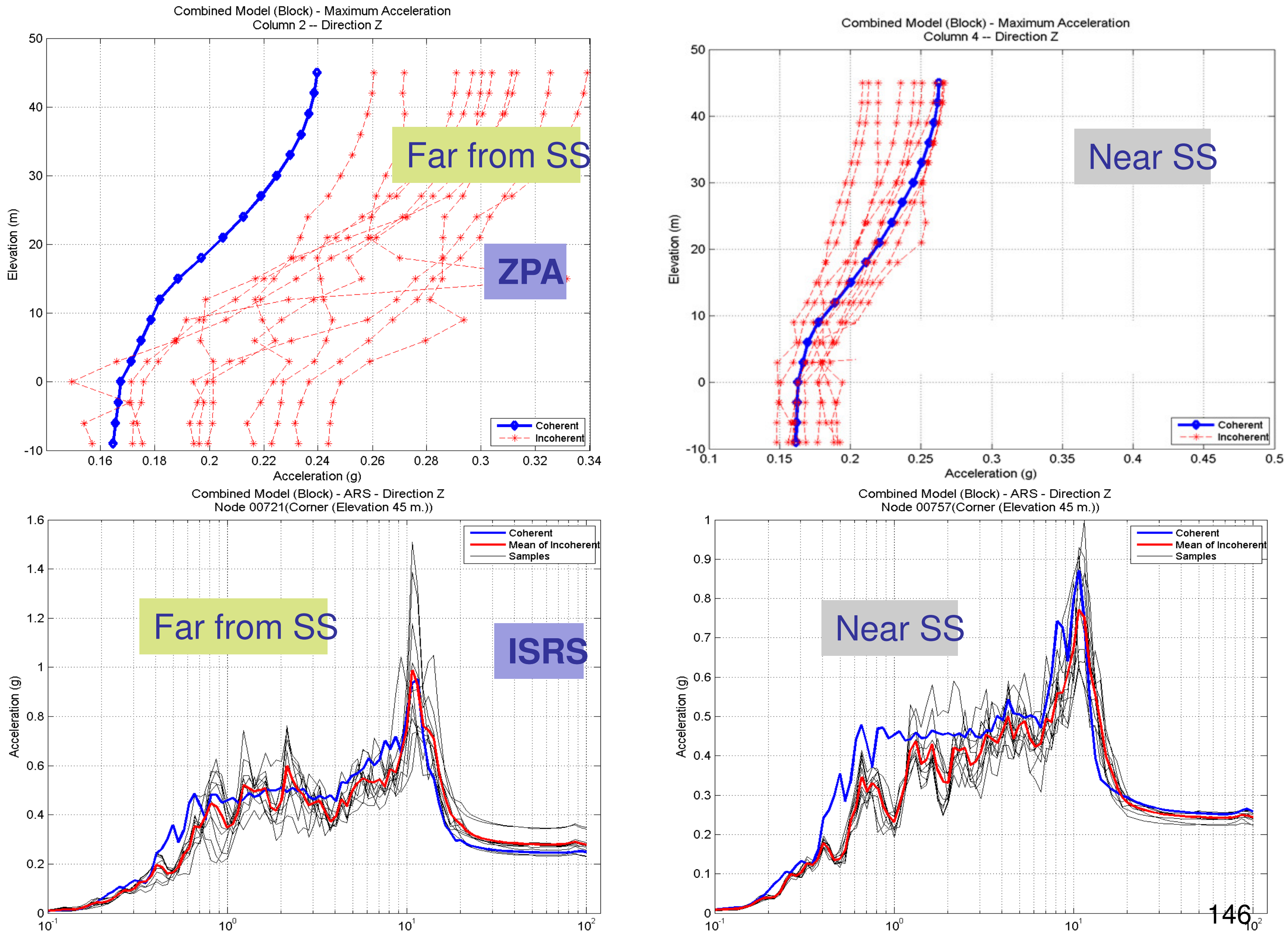
SSSI Response Locations for MB



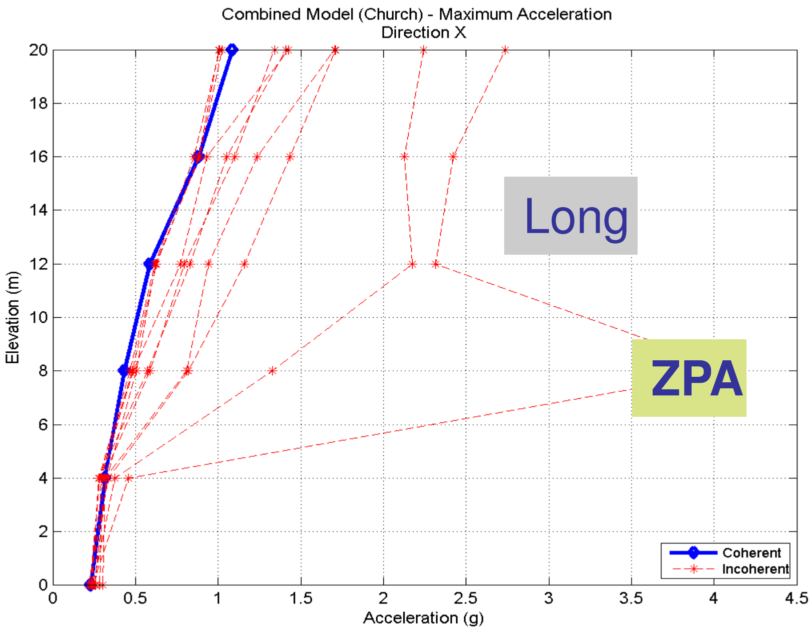
Incoherent SSSI Effects on Horizontal ISRS for MB (Roof)

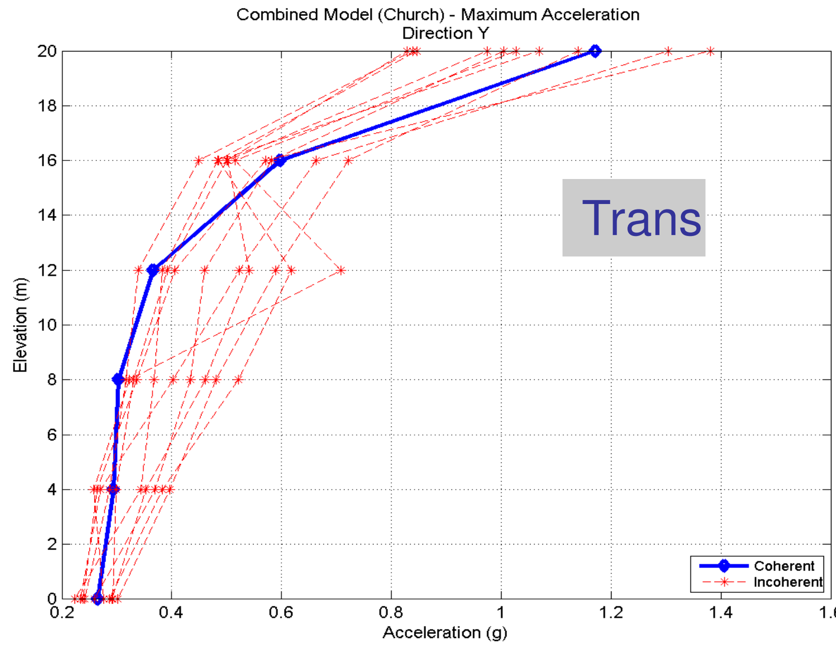


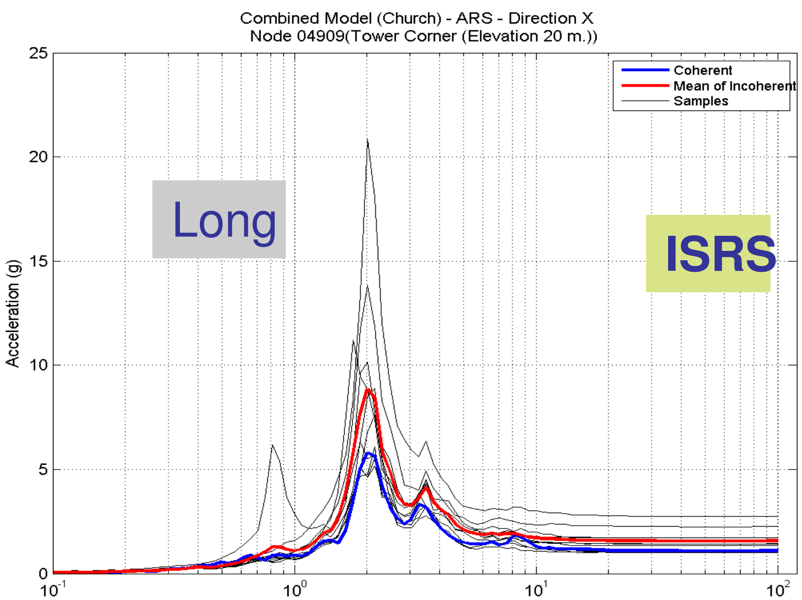
Incoherent SSSI Effects on Vertical ISRS and ZPA for MB

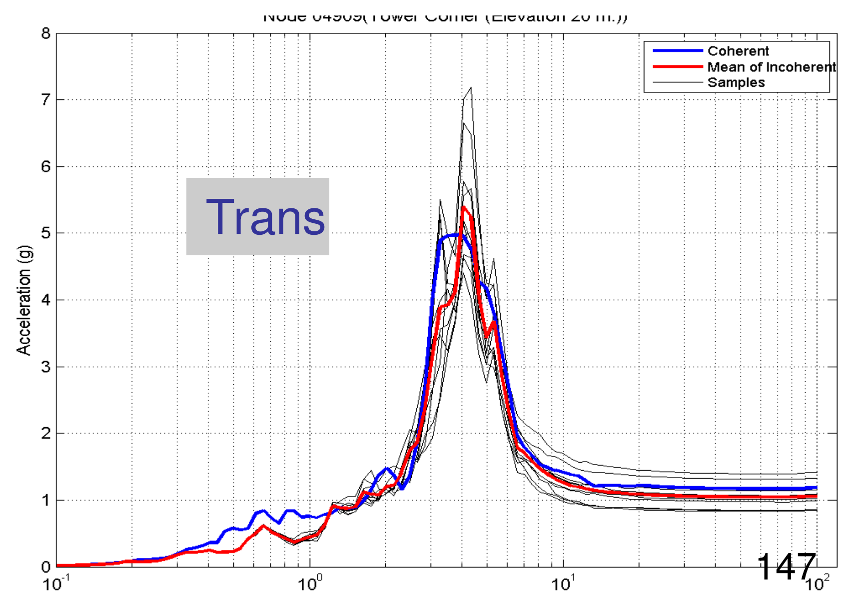


Incoherent SSSI Effects on Horizontal ISRS and ZPA for C (Roof)

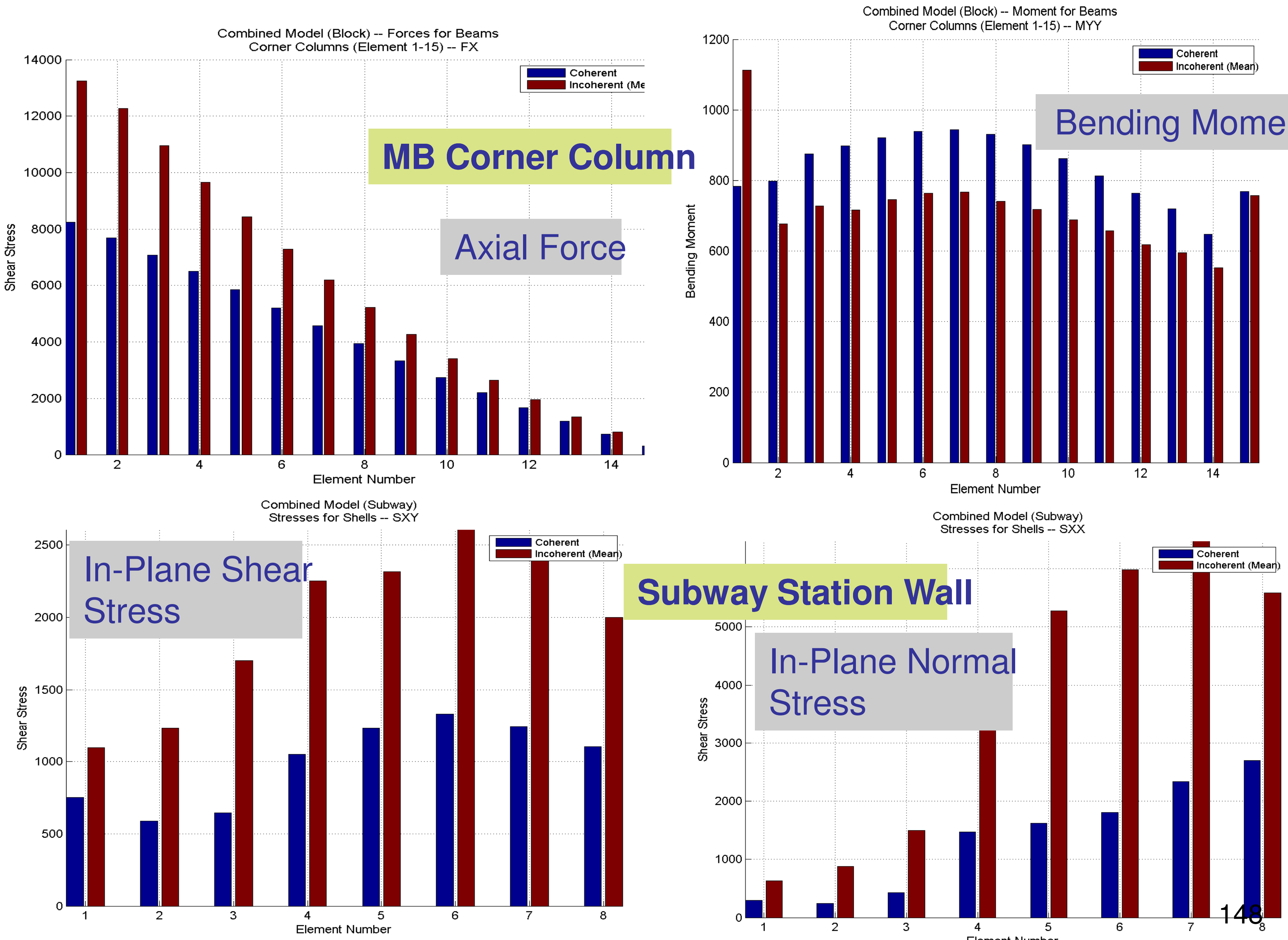








SSSI Effects on Structural Forces/Stresses in MB and SS



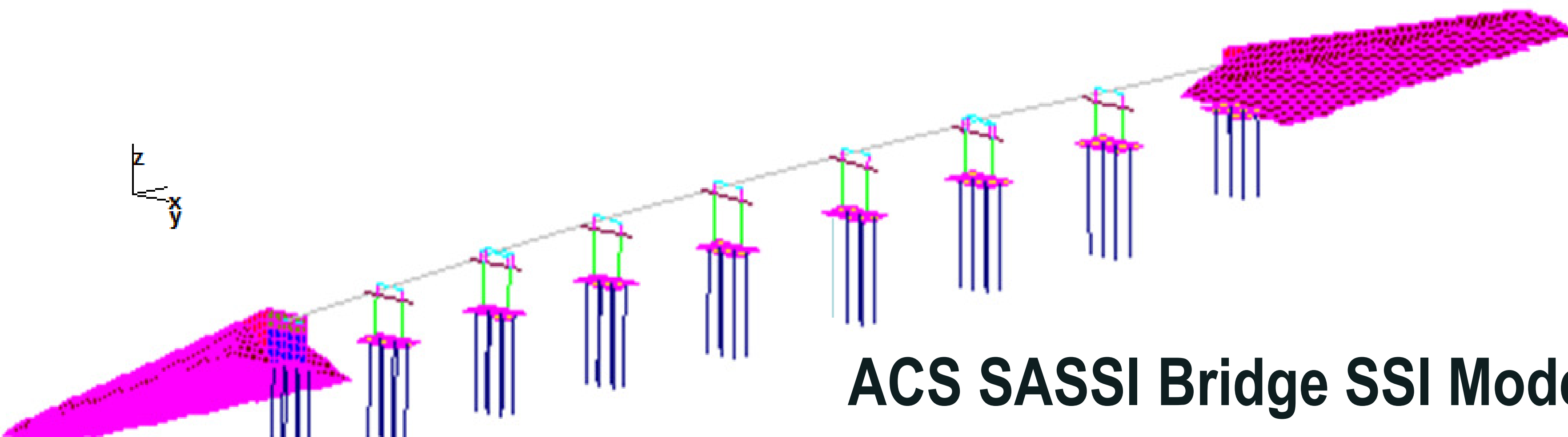
SSSI Effects for Buildings in Dense Urban Areas

This study shows that for dense urban areas where buildings are close to each other, the SSSI effects could be quite large, between 10% to 500% depending on the type of building.

It should be noted that the SSSI effects are highly amplified due to motion spatial variation in horizontal direction, i.e. motion incoherency, that creates random differential phasing between neighbor building motions.

REMARK: It shows a deficiency of the current state-of-practice of seismic SSI analysis. Need to revise the requirements for seismic analysis in design codes. Need to use ACS SASSI V3.0 to capture these important SSI-related aspects that are typically ignored.

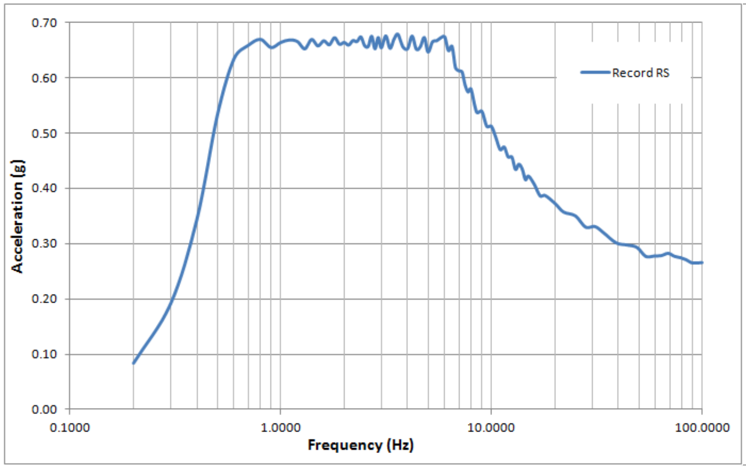
Seismic Analysis for 242m Highway Bridge



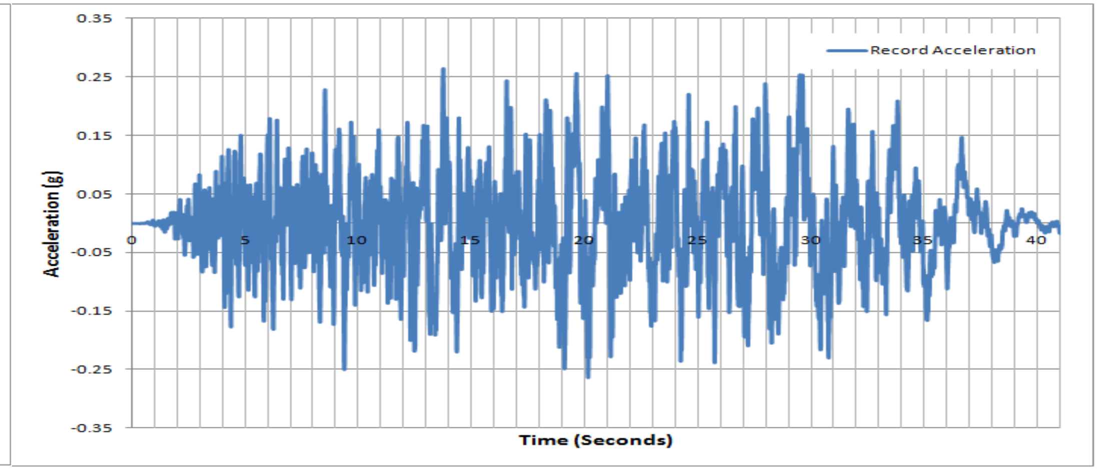
ACS SASSI Bridge SSI Model

Seismic SSI Analysis Inputs

Seismic Input Motion at Ground Surface:



Design Spectrum (0.25g)



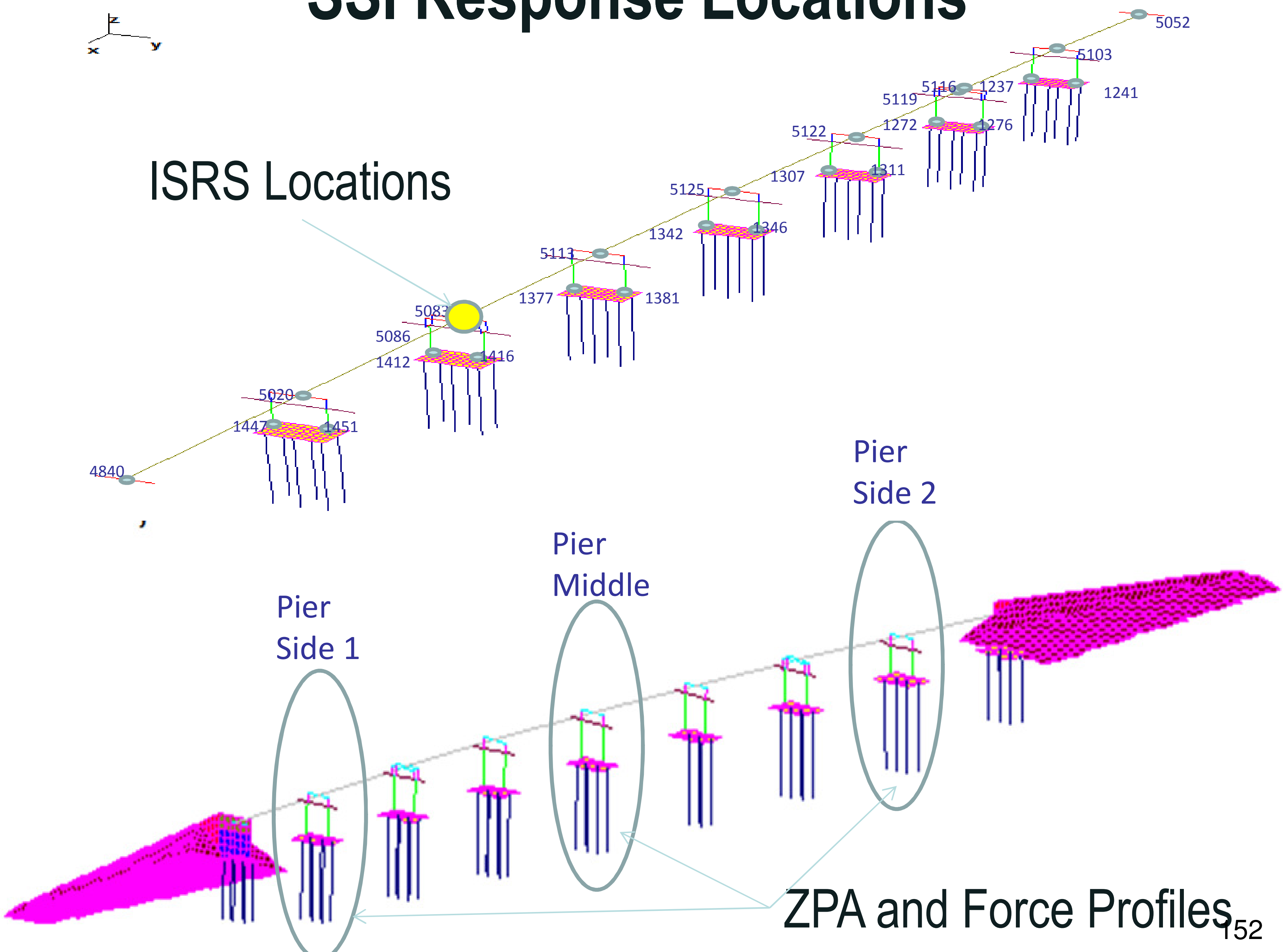
Simulated Acceleration Input (0.25g)

Incoherent Motion: 2005 Abrahamson coherency model, with wave passage Va=1,300m/s

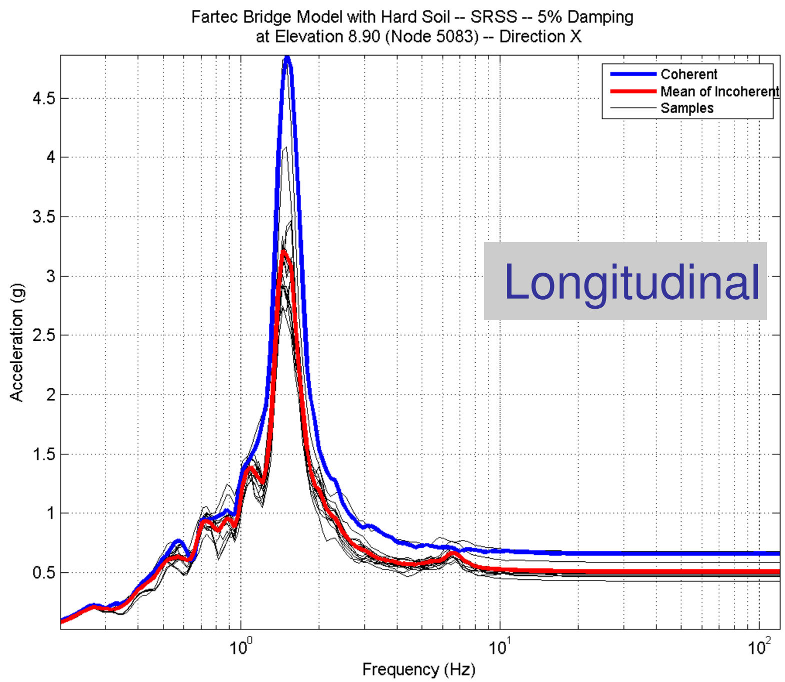
Soil Layering:

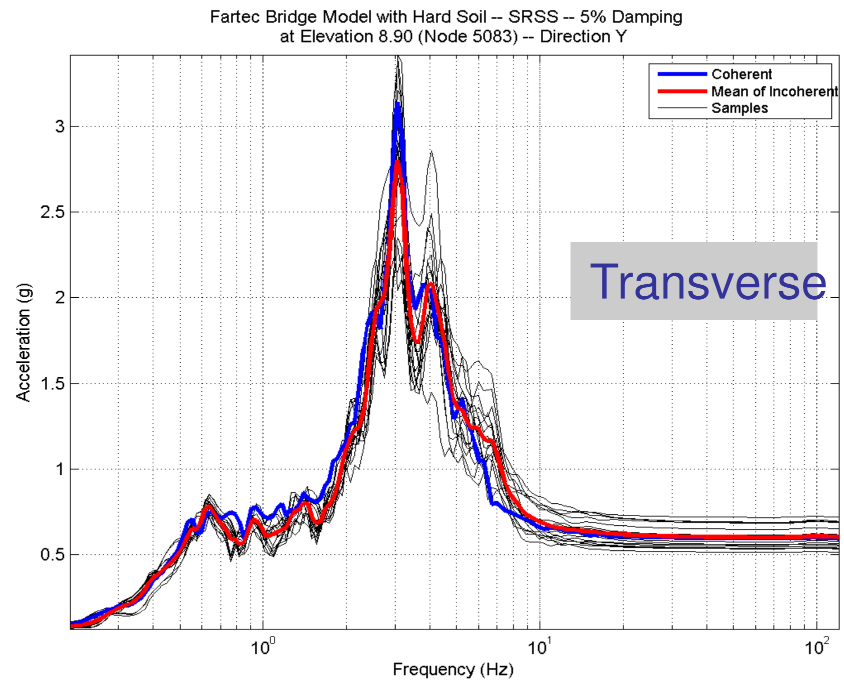
Hard Soil: Vs=1,300m/s, Uniform Profile
Soft Soil: Vs=200m/s, Uniform Profile

SSI Response Locations

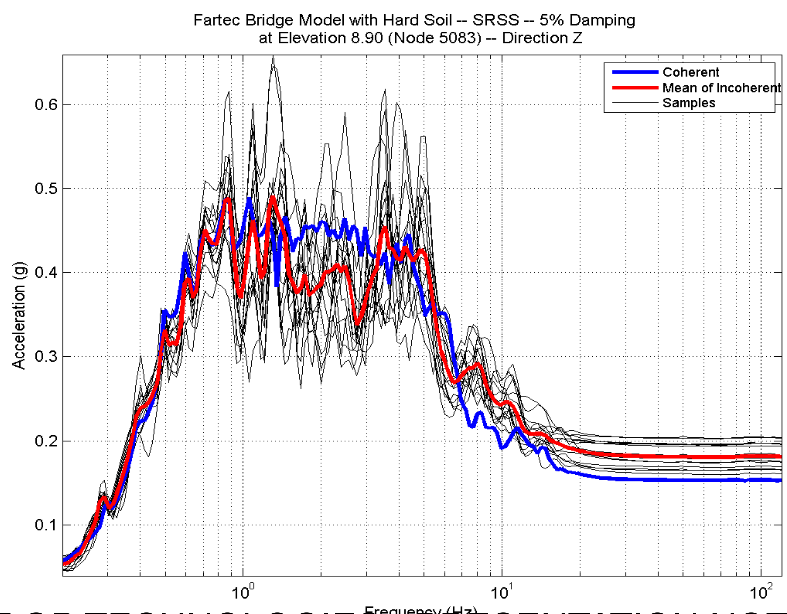


SSI Response Acceleration Response Spectra



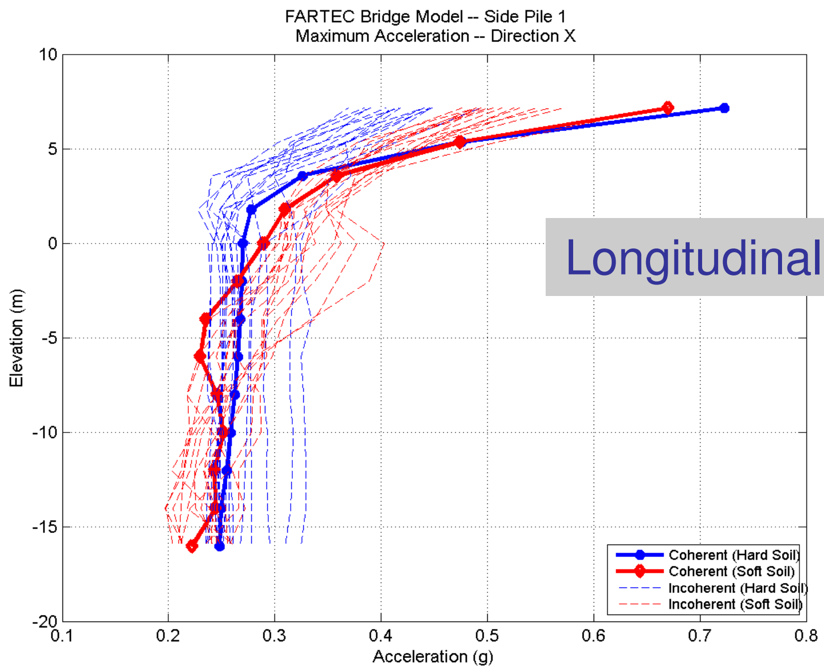


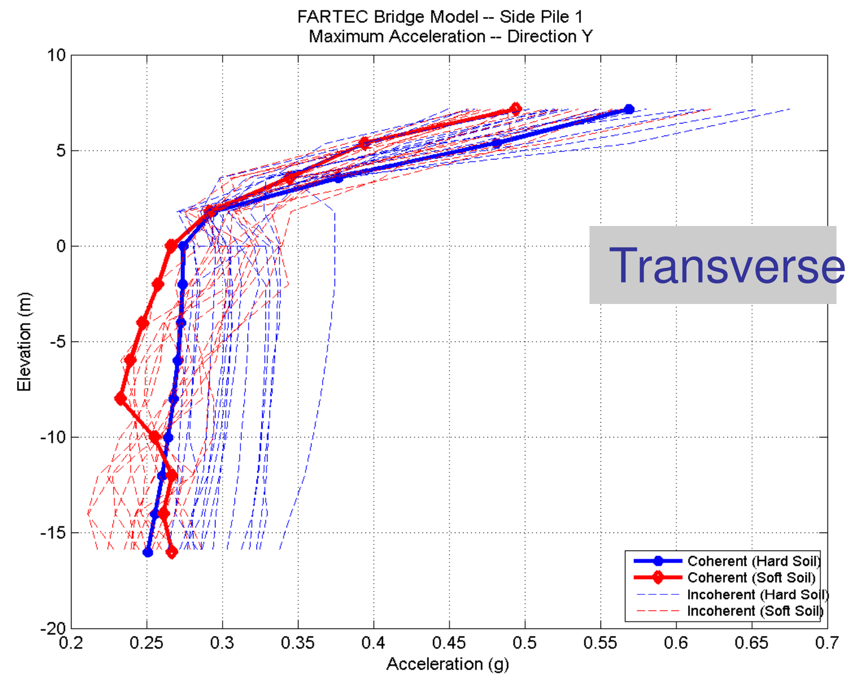
Node 5083



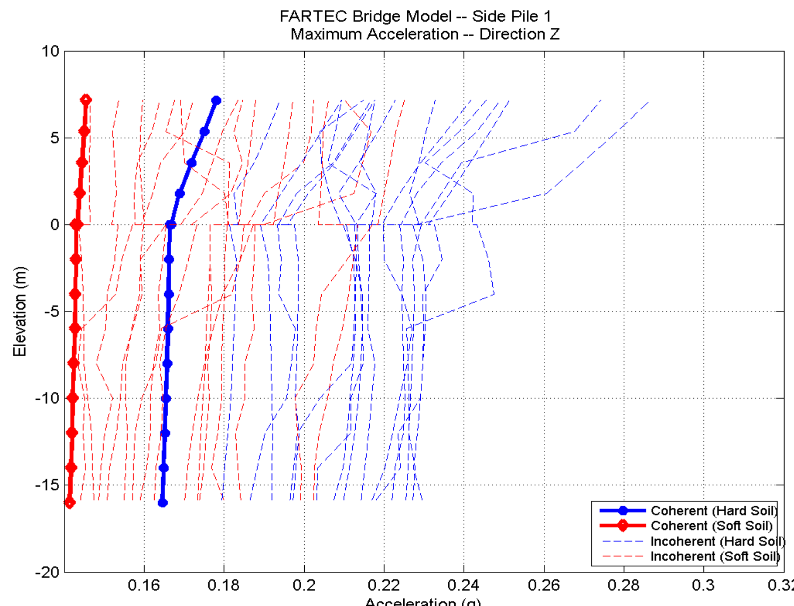
Vertical

SSI ZPA Profile at Pier Side 1



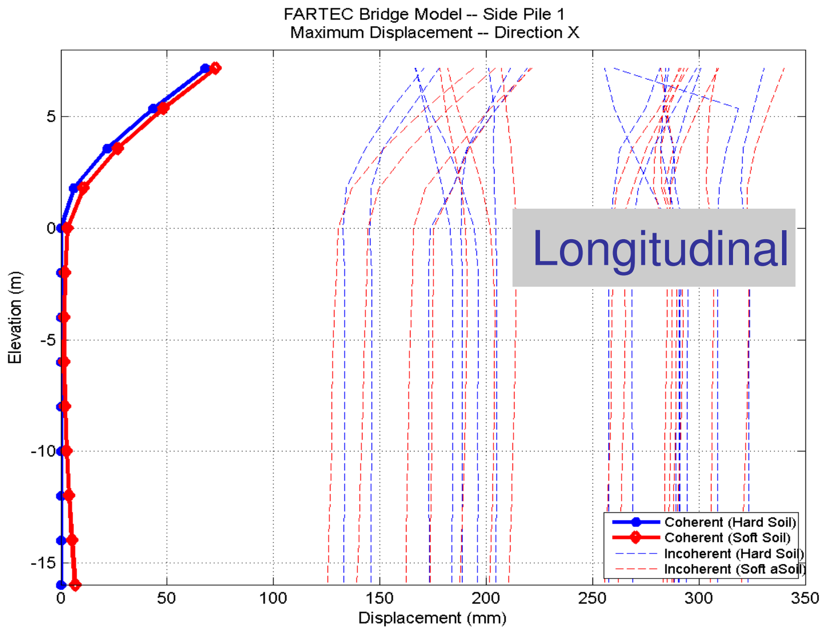


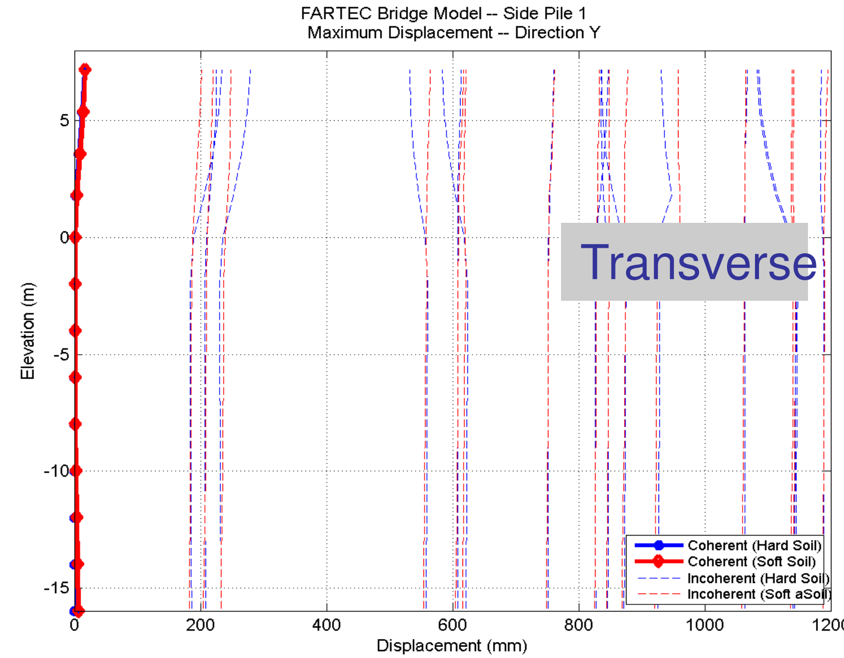
Pier Side 1



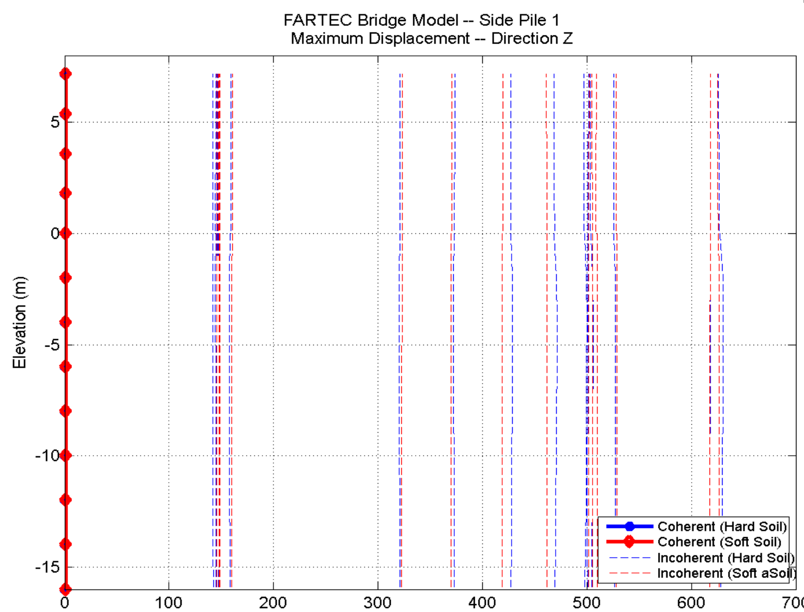
Vertical

SSI Maximum Displacement Profile at Pier Side 1

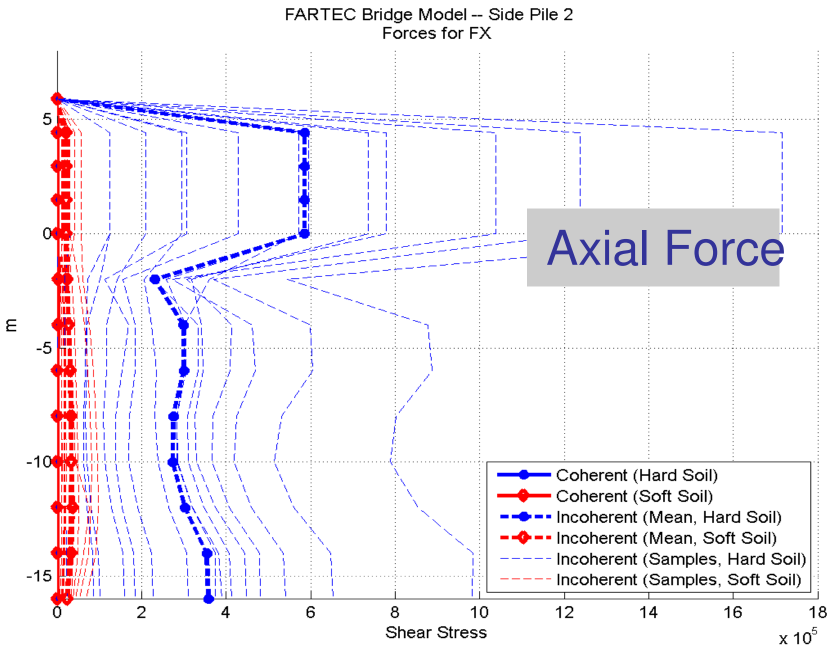


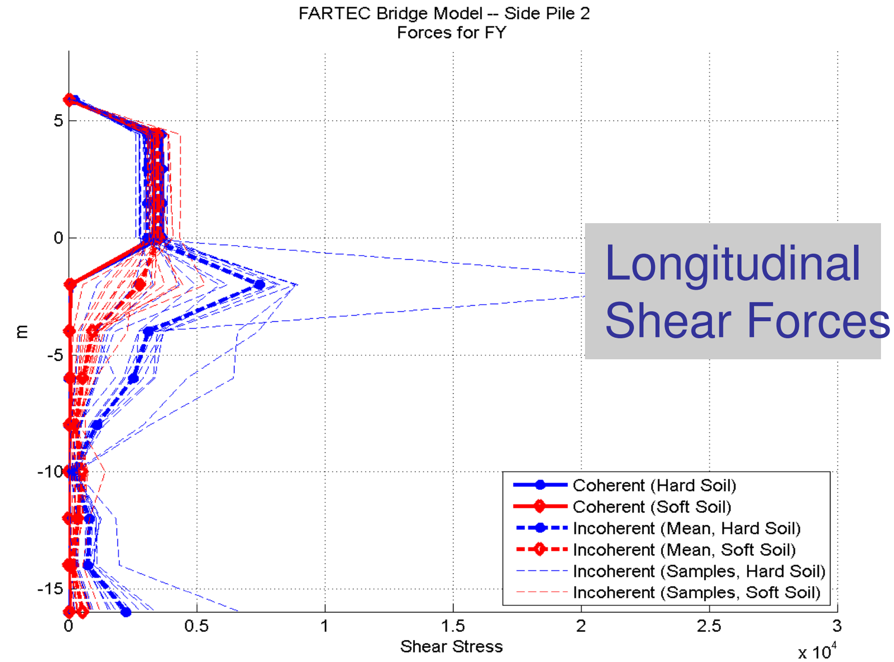


Pier Side 1

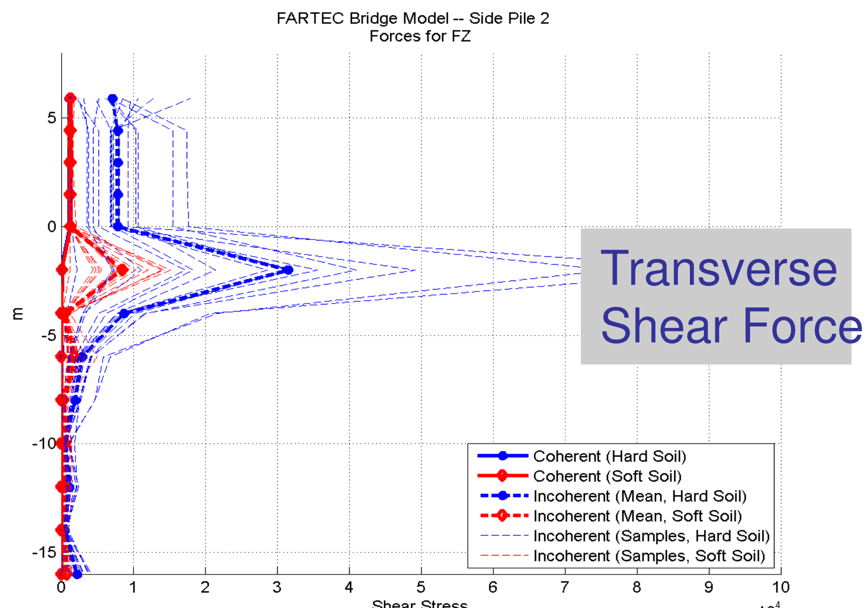


SSI Response ZPA Profile at Pier Side 2

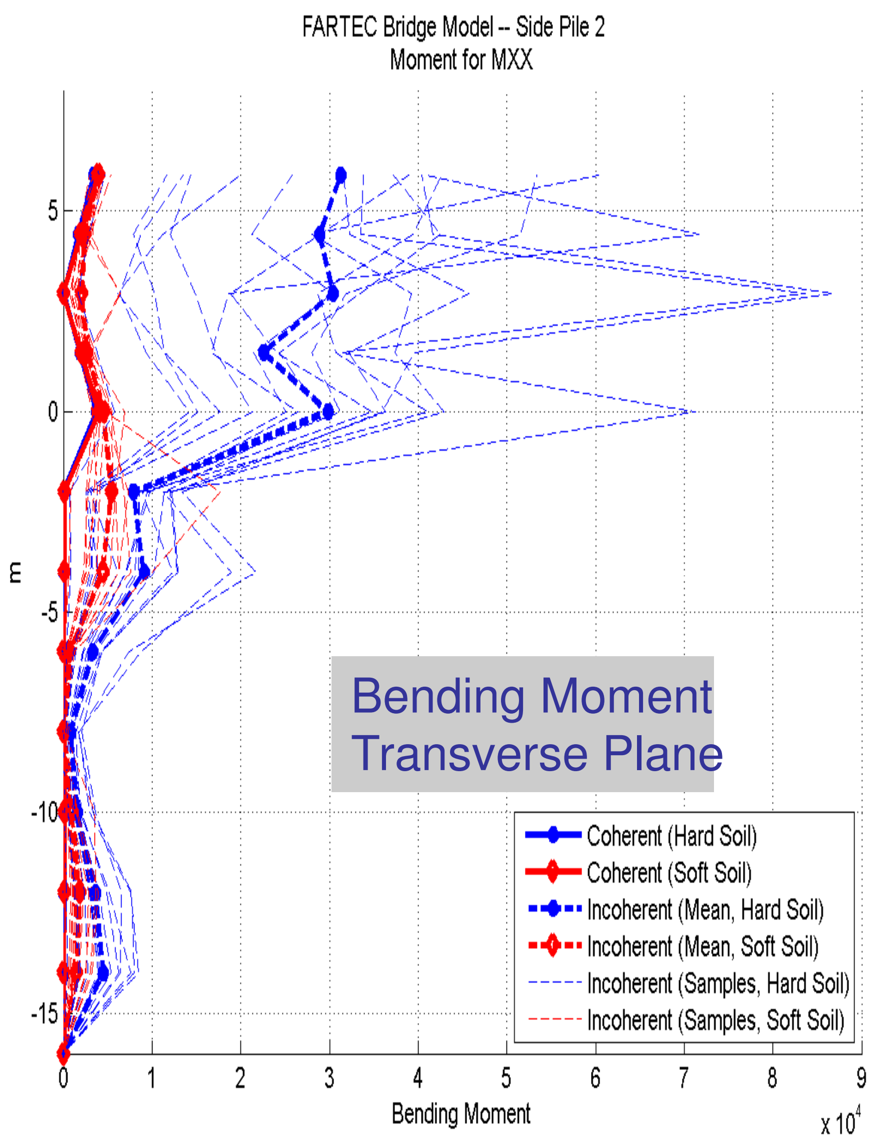


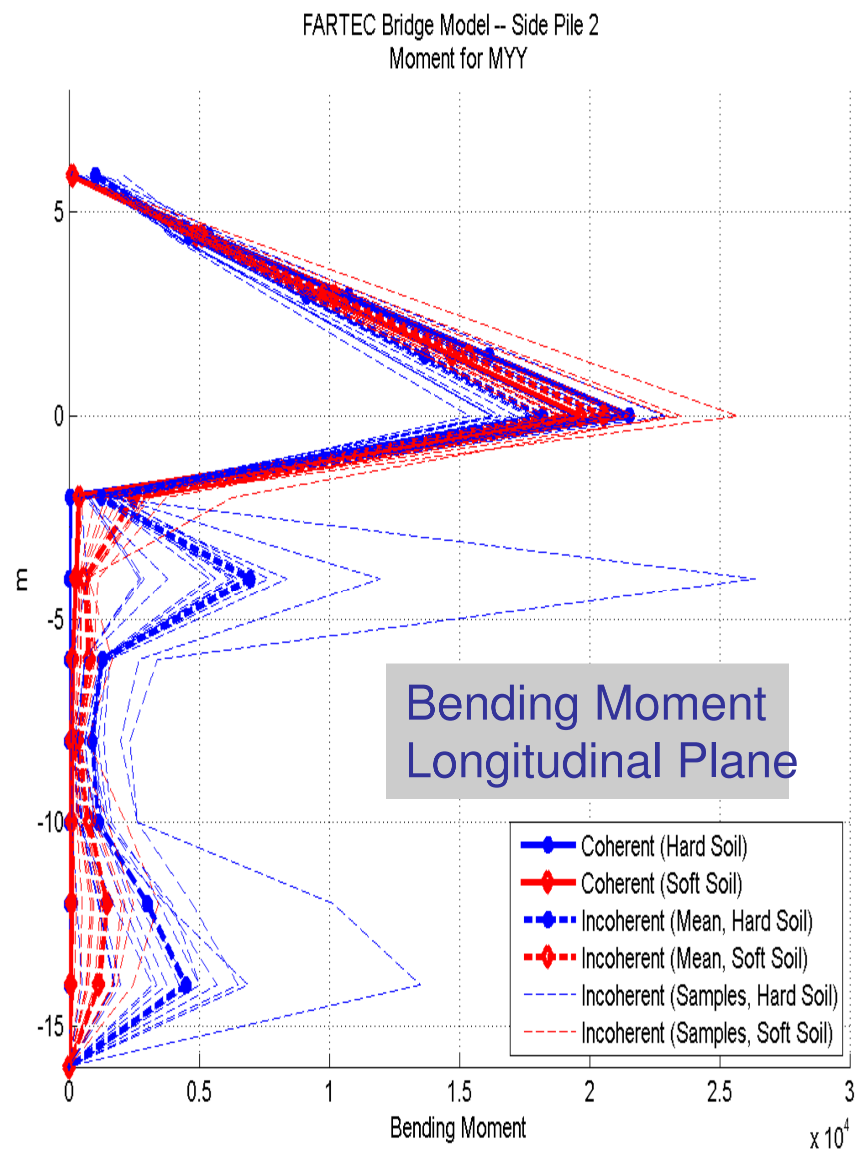


Pier Side 1



SSI Response ZPA Profile at Pier Side 2





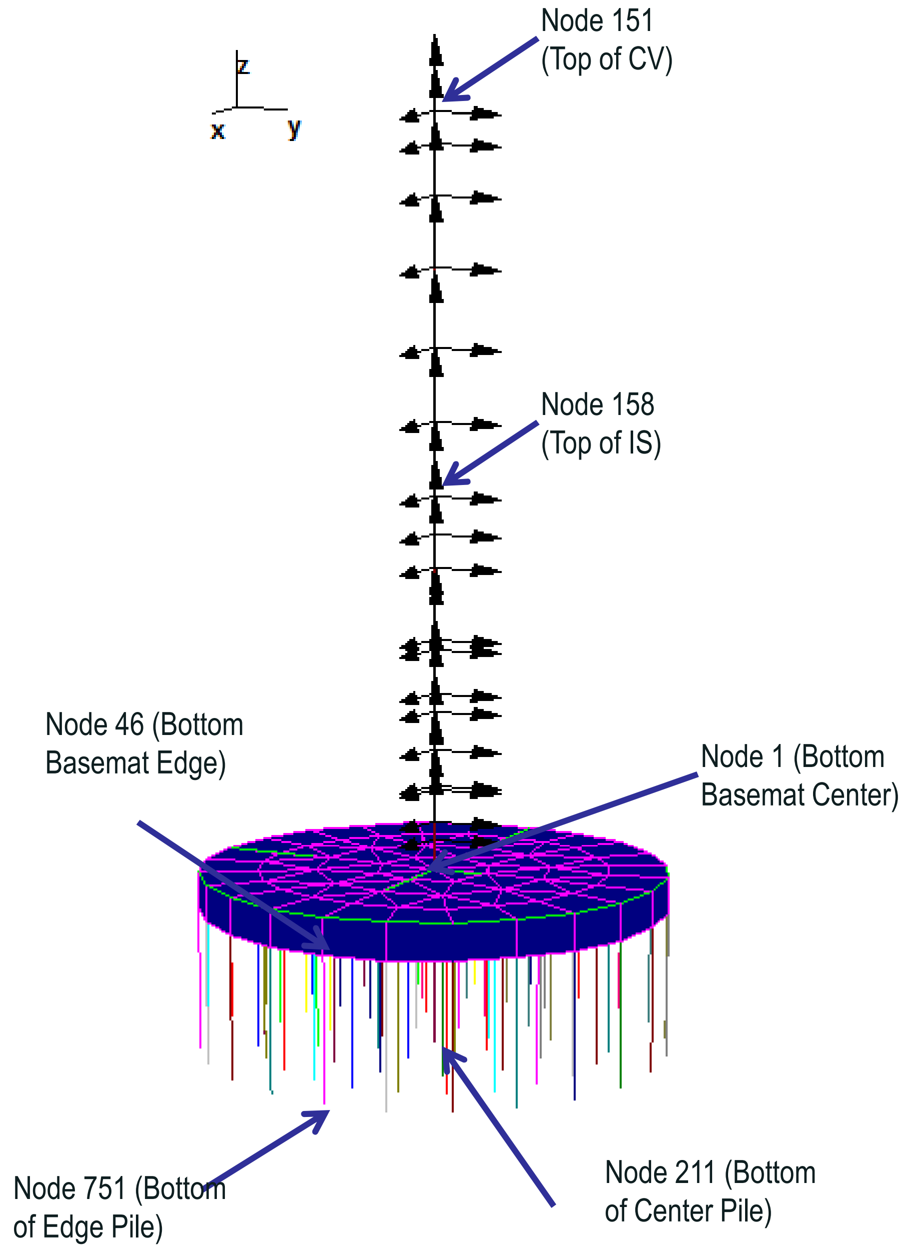
Motion Incoherency Effects on Concrete Bridges

This study shows that the effects of motion incoherency and wave passage can increase the maximum elastic structural forces and moments in the bridge pier columns and piles by up to 500%.

It should be noted that the SSSI effects are highly amplified due to motion spatial variation in horizontal direction, i.e. motion incoherency, that creates random differential phasing between neighbor building motions.

REMARK: It shows a serious deficiency of the current state-of-practice of seismic SSI analysis. Need to revise the requirements for seismic analysis in design codes. Need to use ACS SASSI to capture these important SSI-related aspects that are typically ignored.

Effects of Sand Liquefaction of RB on Piles



PWR RB Stick Model

- 69 Piles, one at each basemat node
- Pile length = 40 ft
- Pile radius = 2.5 ft
- Beams with masses used to model Containment Vessel (CV) and Internal Structure (IS)
- Foundation radius = 65 ft
- Selected output piles are attached to nodes 1 and 46 (Center basemat and edge of basemat).

Soil Liquefaction Effects on Pile Foundations

This study shows that the local soil liquefaction effects could increase the shear forces and bending moments in piles by a factor of 200-300% due to large soil deformations.

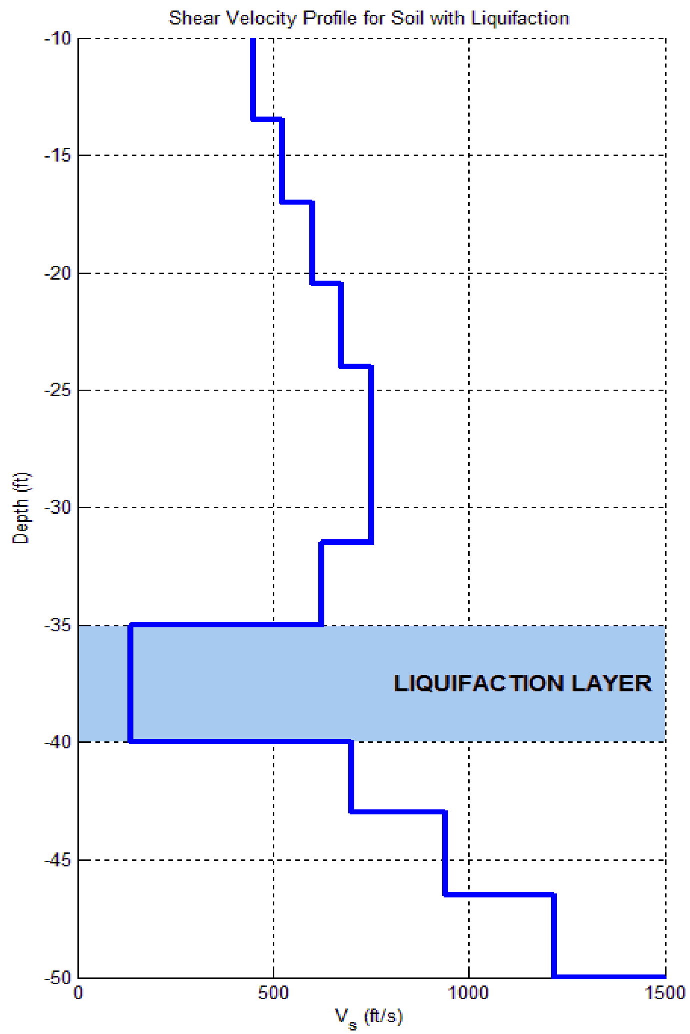
The soil liquefaction could also increase largely the structure inertial SSI effects.

REMARK:

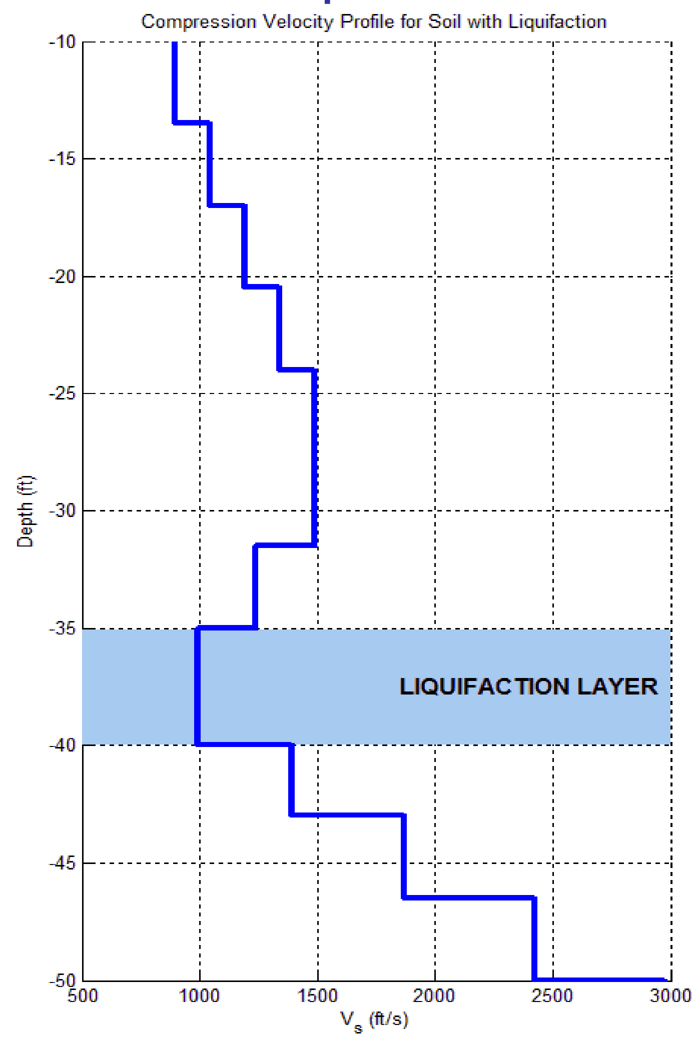
It shows a serious deficiency of the current state-of-practice of seismic SSI analysis for pile foundation. Need to use ACS SASSI V3.0 to capture these important SSI-related aspects that are typically ignored.

Soil Layering Vs and Vp Profiles

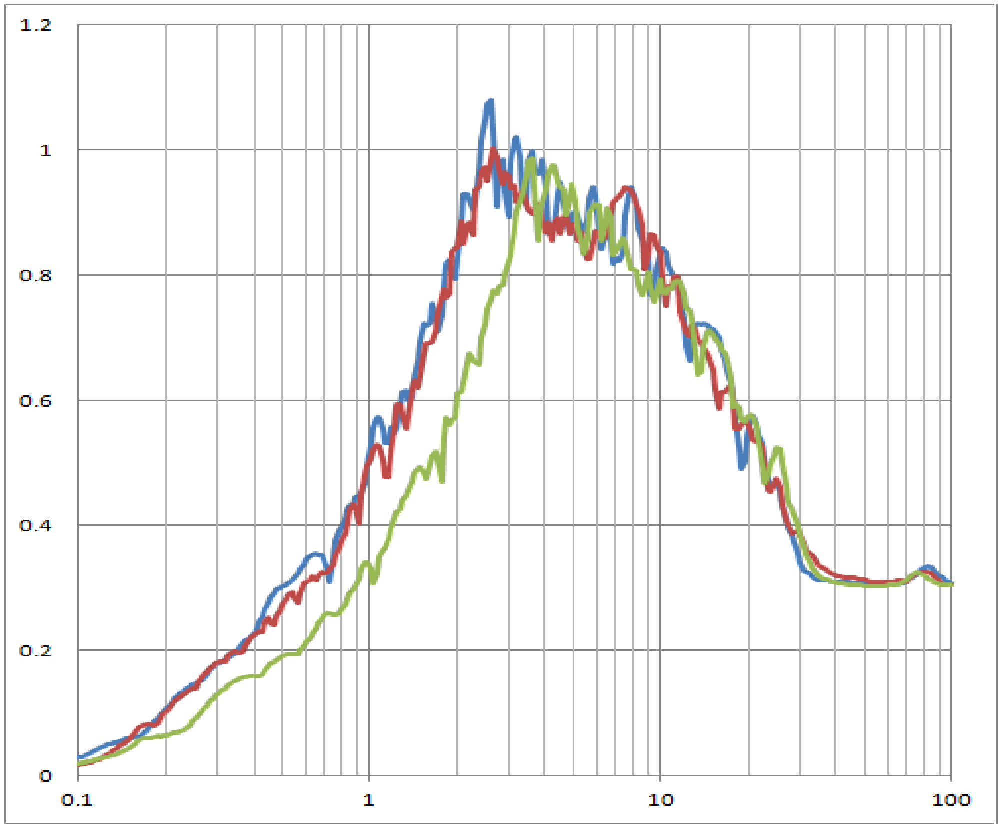
Vs

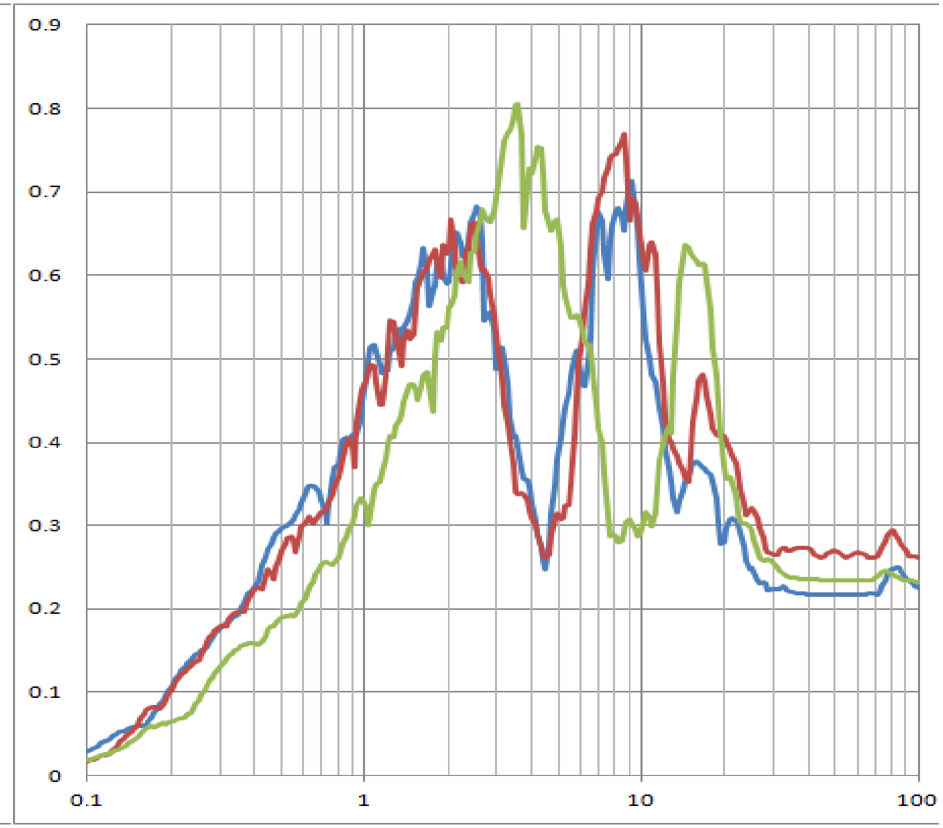


Vp



Seismic Input Ground Response Spectra (GRS)

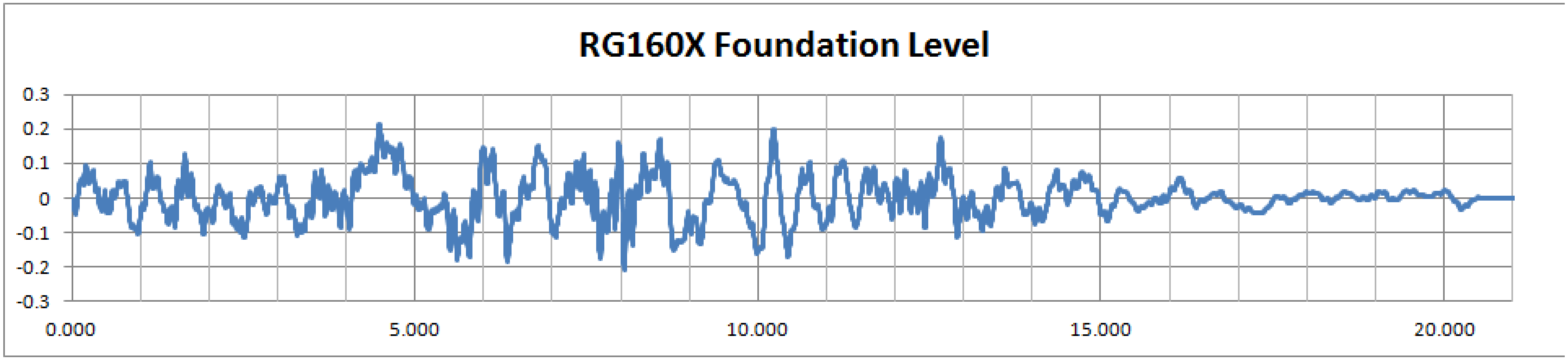


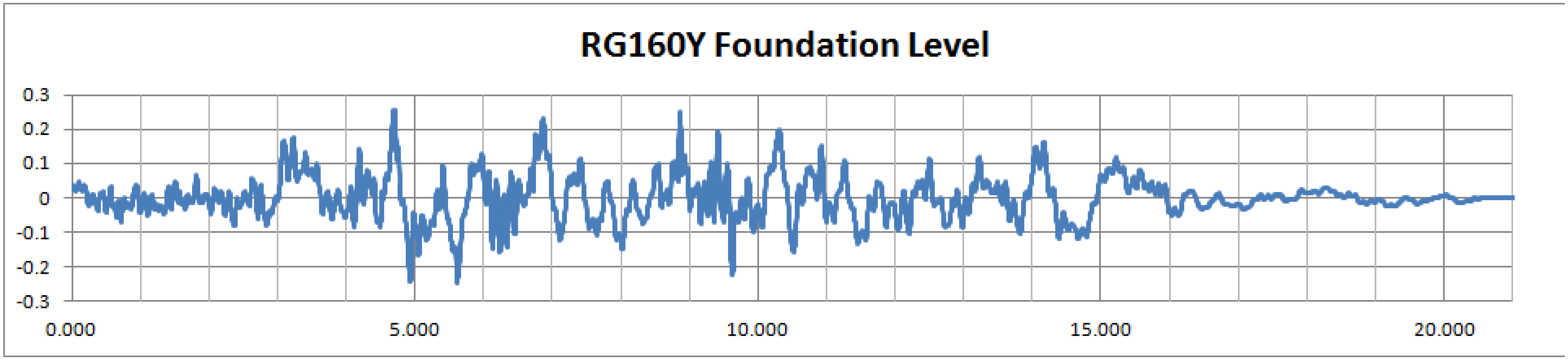


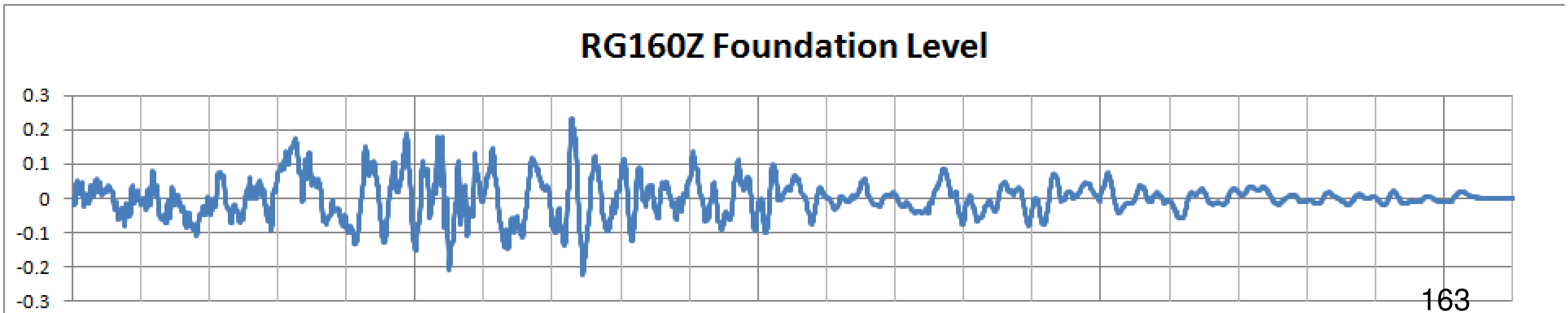
Ground Surface Spectra
RG 1.60 Shape

Foundation Level Spectra
(In-Column Motions)

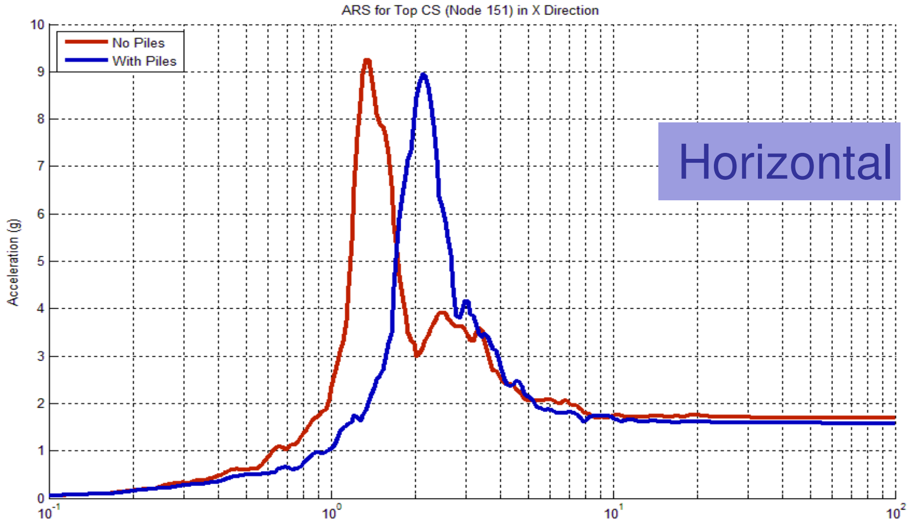
Input Acceleration Time Histories

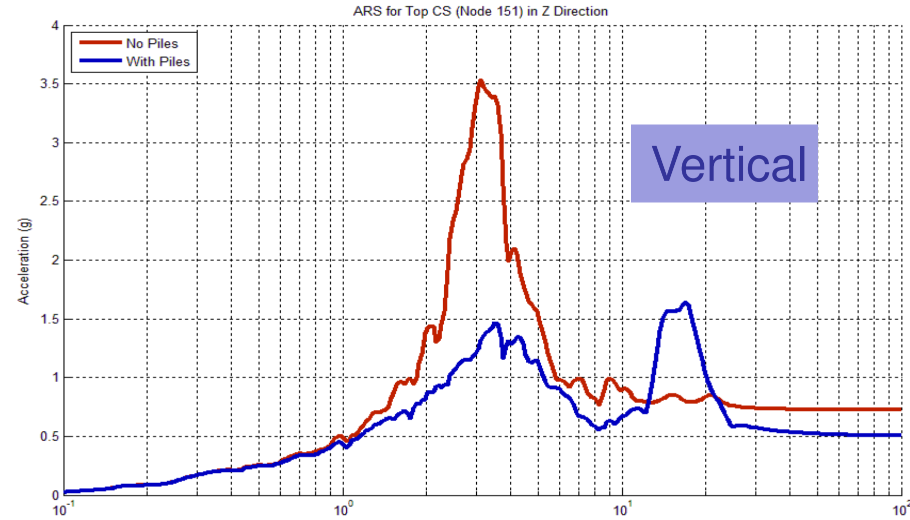




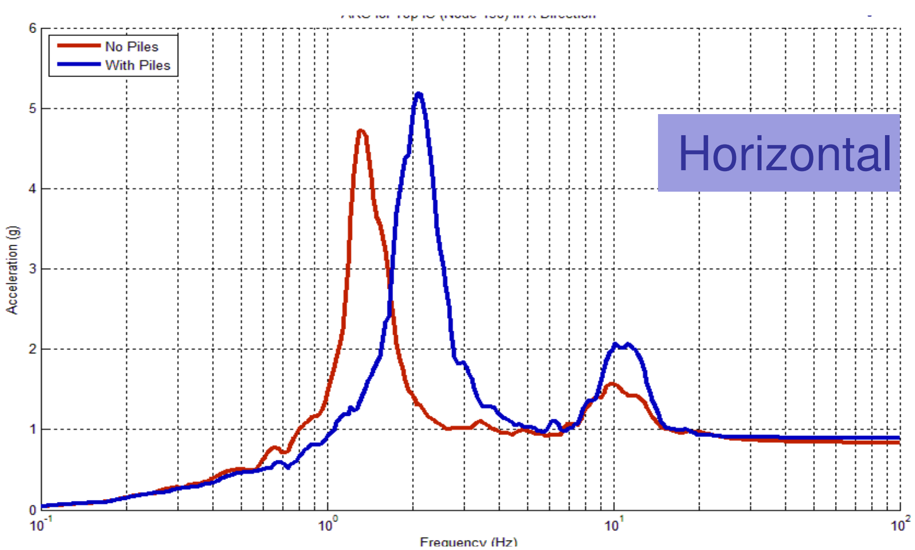


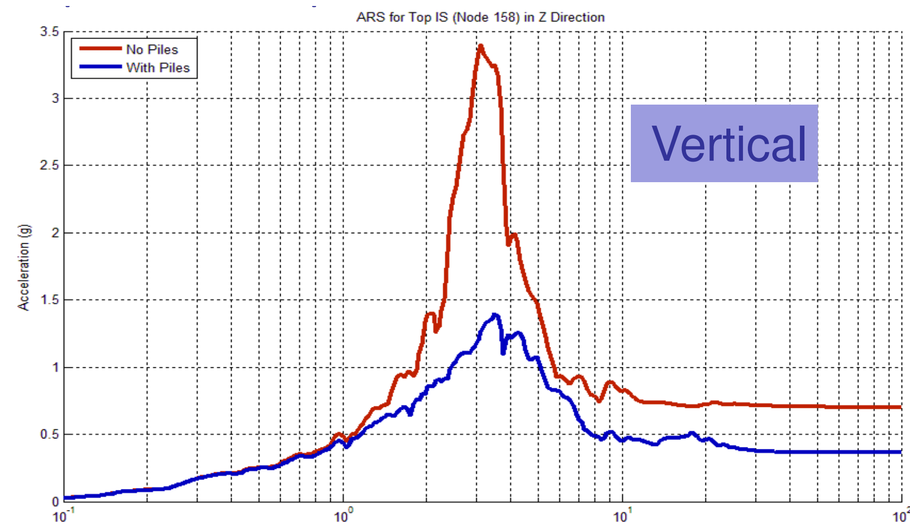
Effects of Piles on RB SSI Response





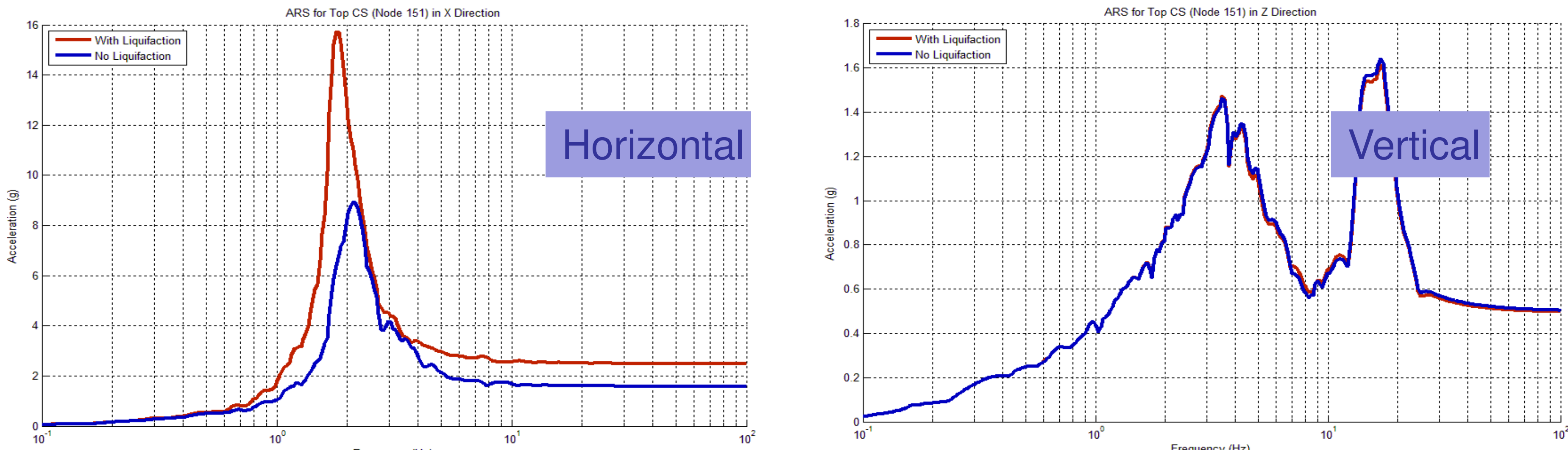
ARS at Top of CS



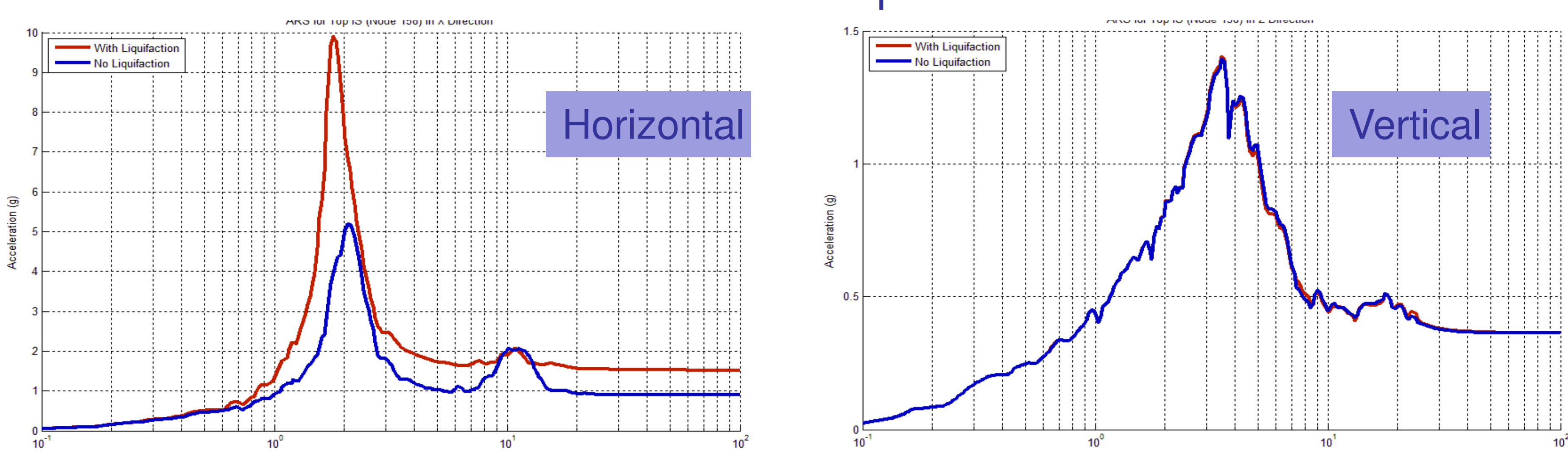


ARS at Top of IS

Effects of Liquefaction for RB on Piles



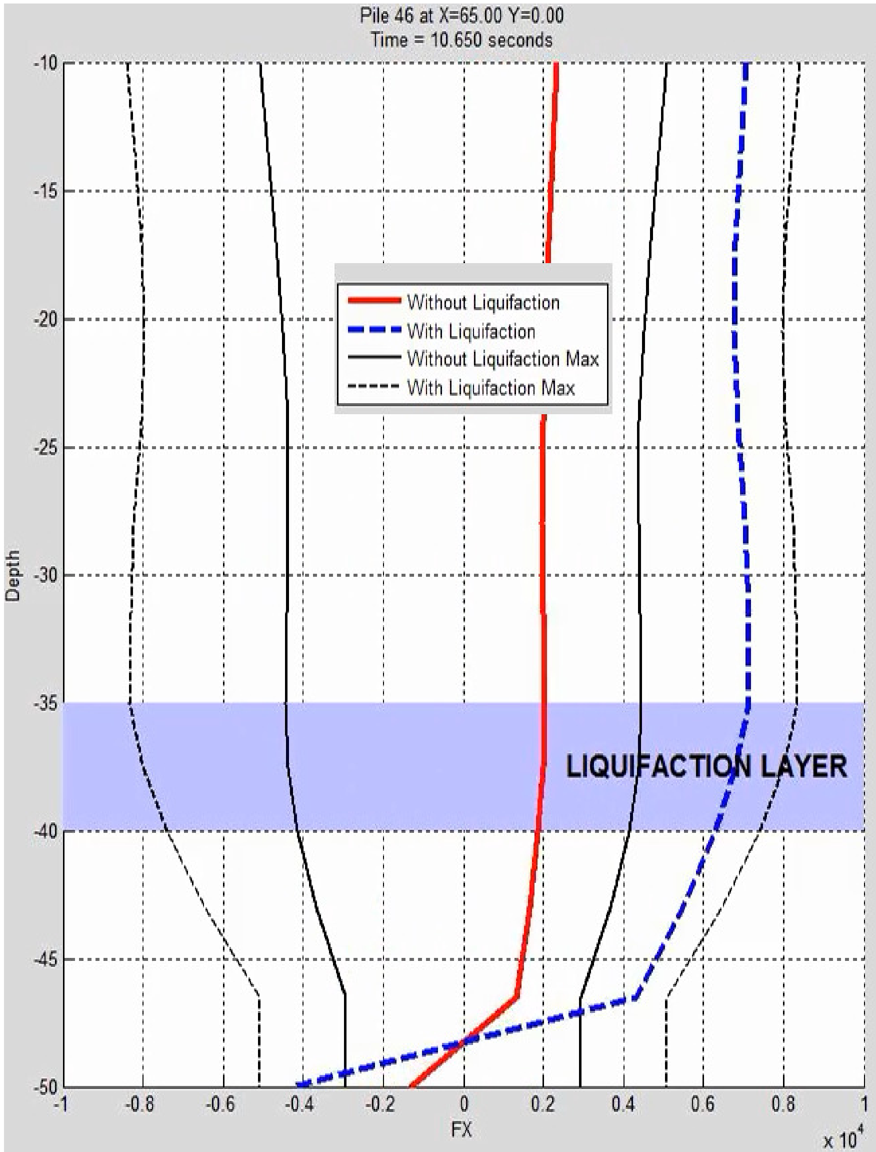
ARS at Top of CS



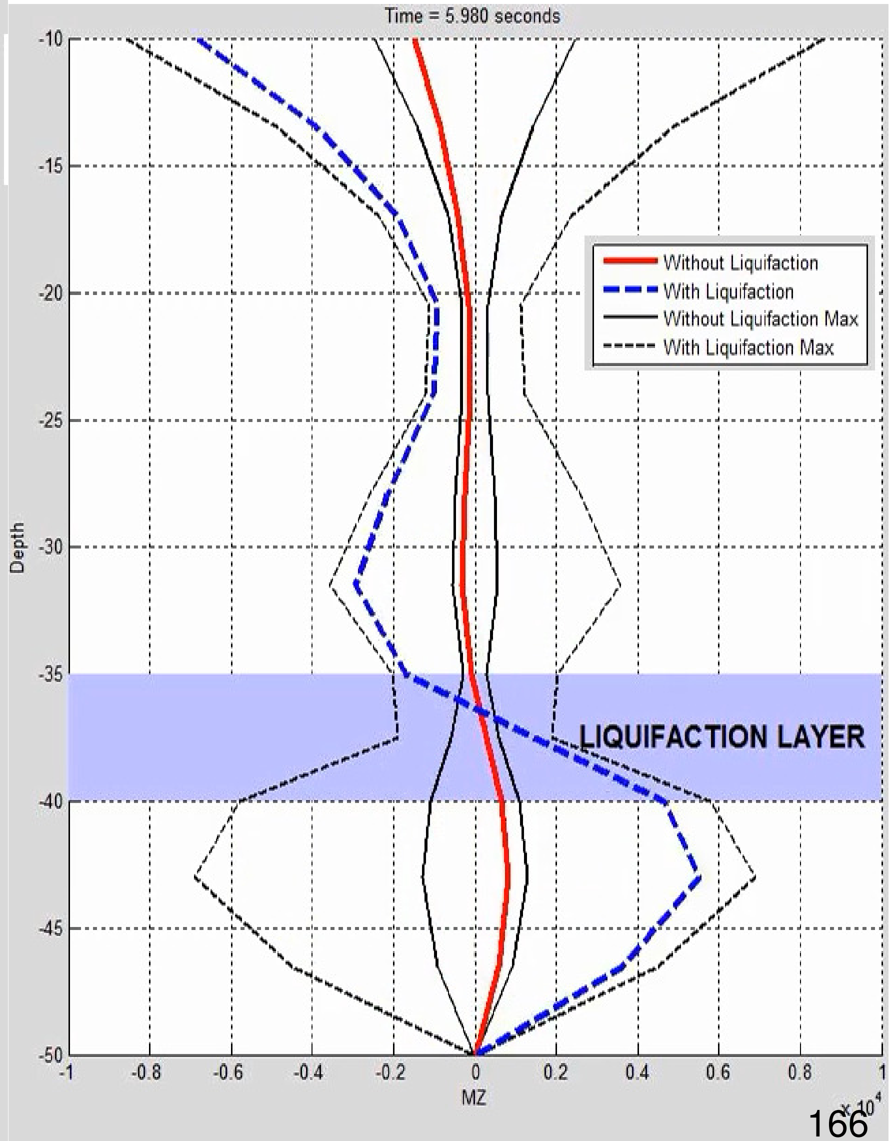
ARS at Top of IS

Liquefaction Effects on Pile Forces and Moments

Axial Force in Edge Pile



Bending Moment in Edge Pile



Thank you for your interest in ACS SASSI software!