ACS SASSI Application to Linear and Nonlinear Seismic SSI Analysis of Nuclear Structures Subjected to Coherent and Incoherent Inputs

Dr. Dan M. Ghiocel

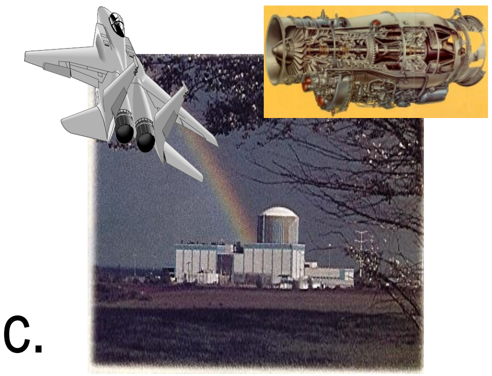
Email: dan.ghiocel@ghiocel-tech.com

Phone: 585-641-0379

Ghiocel Predictive Technologies Inc.

Ghiocel Predictive Technologies Inc.

http://www.ghiocel-tech.com



PART 1

North Marriott Convention Center, Bethesda, MD

January 25-27, 2011

Purpose of This Presentation:

To present an overview on the present state of engineering understanding and practice for evaluation of seismic soil-structure interaction (SSI) effects for nuclear facility structures.

SSI effects are of paramount importance for seismic analysis of nuclear structures.

DAY 1: January 25, 2011

Understanding Basic Seismic SSI Effects for Nuclear Facility Structures

Overview on SSI Effects
Case Studies

8:30am-5:00pm

Presentation Content:

PART 1: Overview on Seismic SSI Effects

- Application Areas
- Seismic SSI Analysis Problem
- SSI Inputs and Outputs
- Seismic Input, Soil Profiles and SSI Methods
- ACS SASSI SSI Capabilities, Incoherency and EPRI Studies

PART 2: Case Studies

- Incoherent SSI Response of RB Complex
- Different Site Conditions and Embedment Studies
- SSSI Effects for NI Complex and AB Structure

PART 1: Overview on SSI Effects

Theoretical and Implementation Aspects

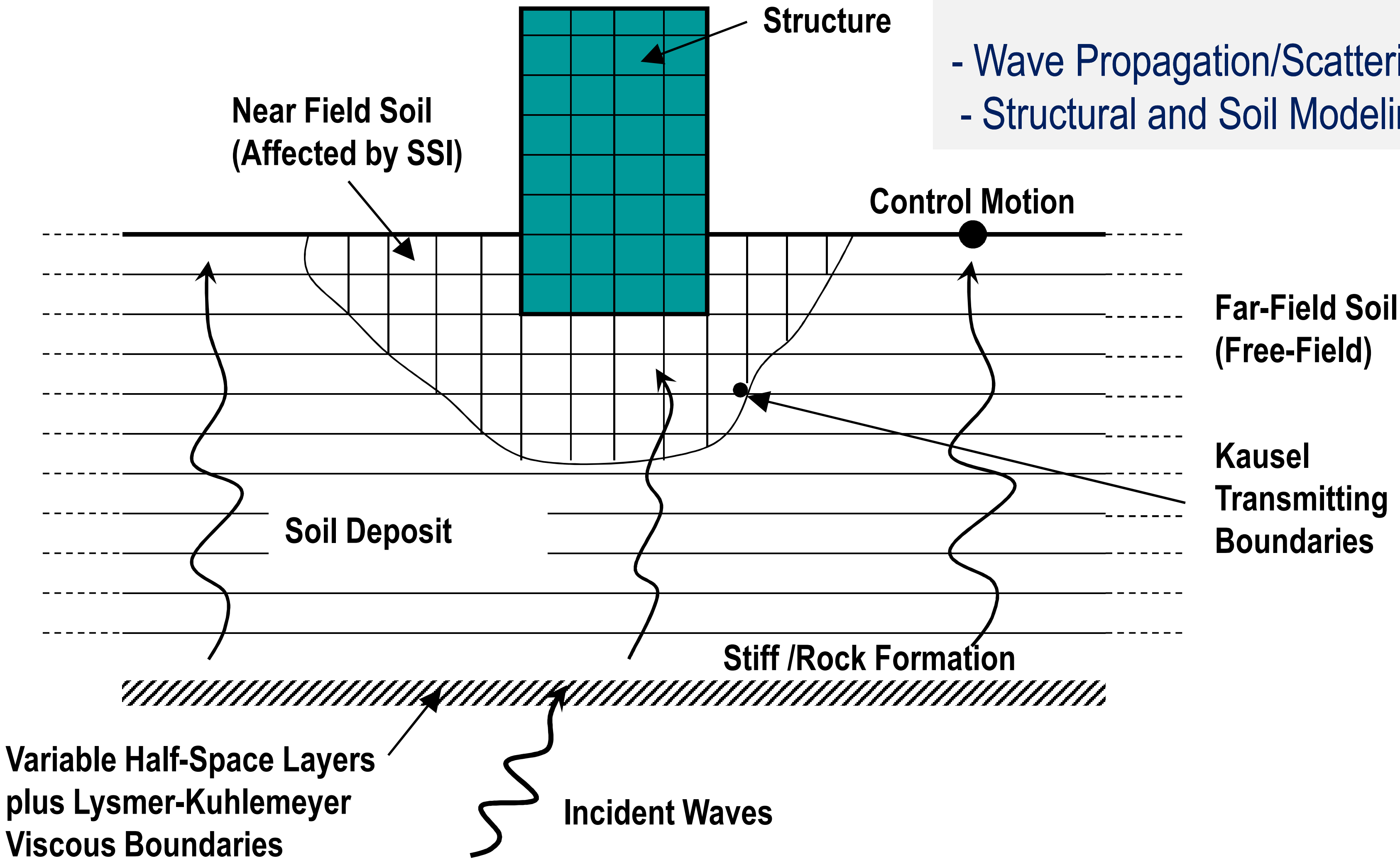
Application Areas Involving Dynamic SSI Analysis

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

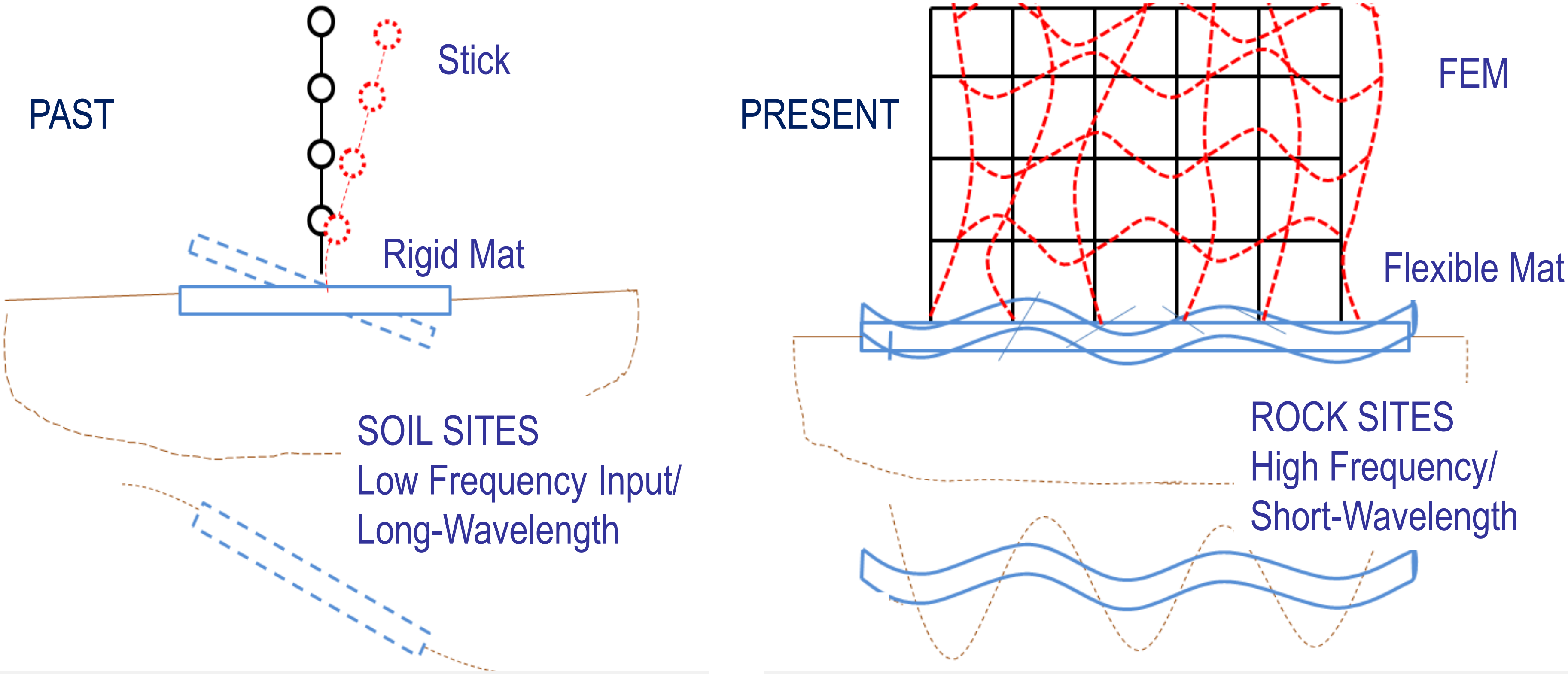
Seismic SSI Analysis Problem

Seismic SSI Analysis Aspects:

- Wave Propagation/Scattering
- Structural and Soil Modeling



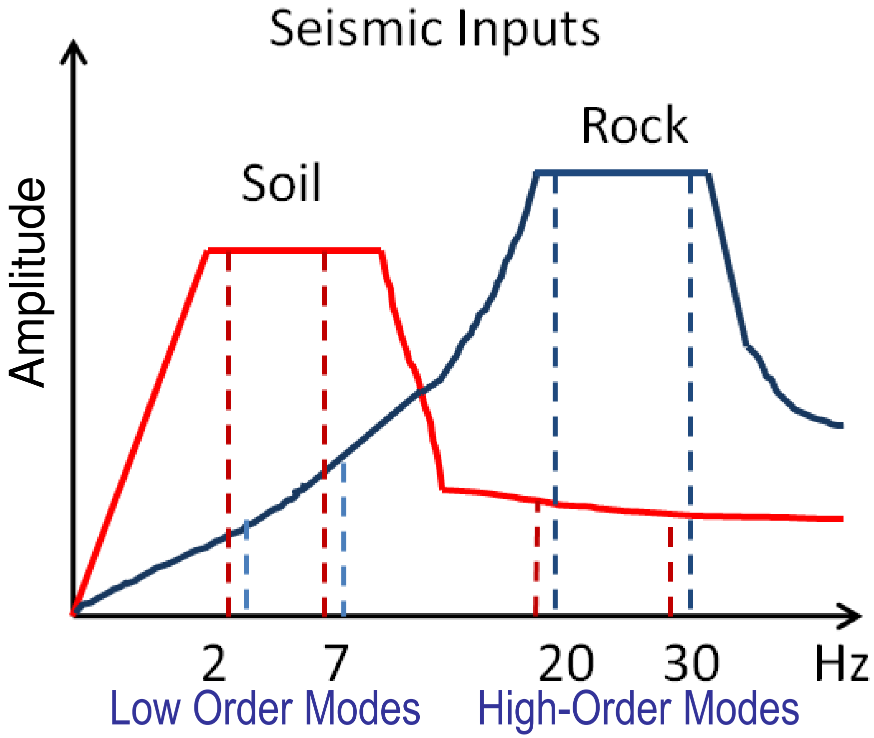
Past and Present Engineering Applications

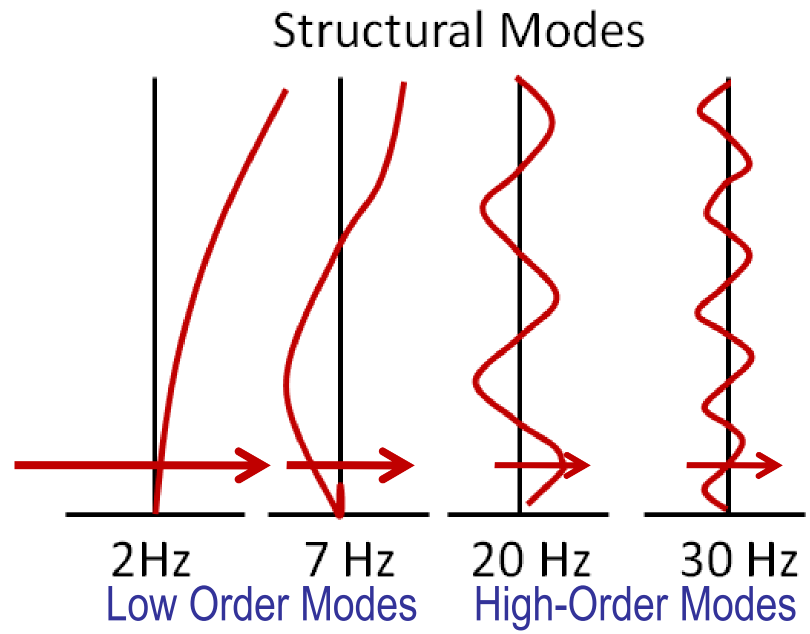


PAST EXPERIENCE:
- Low Frequency Inputs (Long-Wavelength)
- Soil Sites
- Stick Models with Rigid Mats
-Input Soil Motion as Rigid Body Motion (Coherent, 1D Propagation of S and P Waves)
Is sufficiently accurate? No…..

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

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



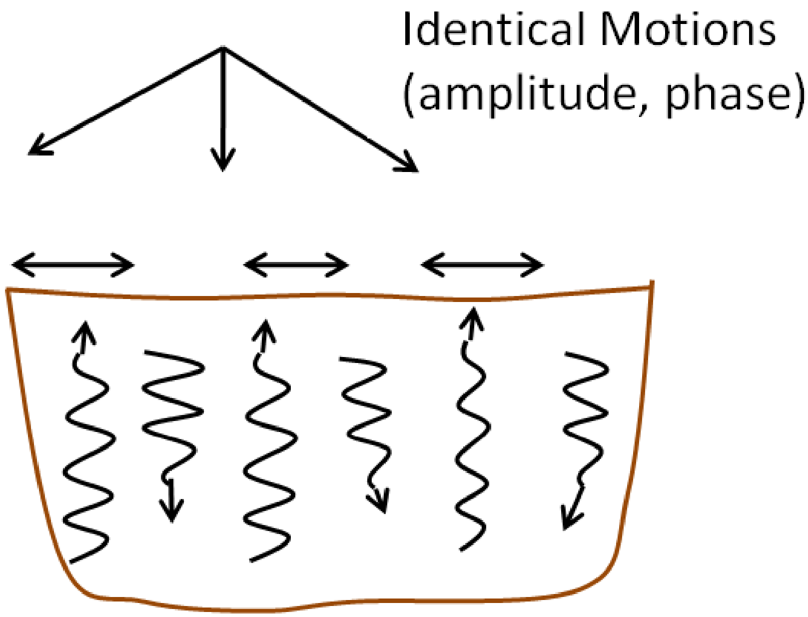


REMARKS:

- Structural forces are much larger for LF inputs than HF inputs; EQ static methods based on ZPA values fail to be consistent with the dynamics…
- ISRS will have very different shapes; if DCD (baseline design) uses LF inputs, SSI evaluation for HF inputs will show many outliers in the HF range

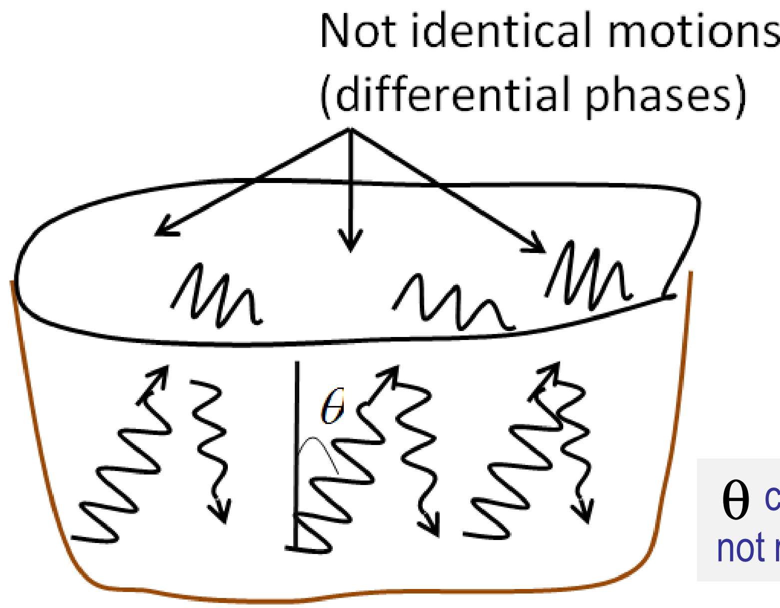
Wave Propagation Physics-Based Models

1D Wave Propagation (Idealized)



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

3D Wave Propagation (Realistic)

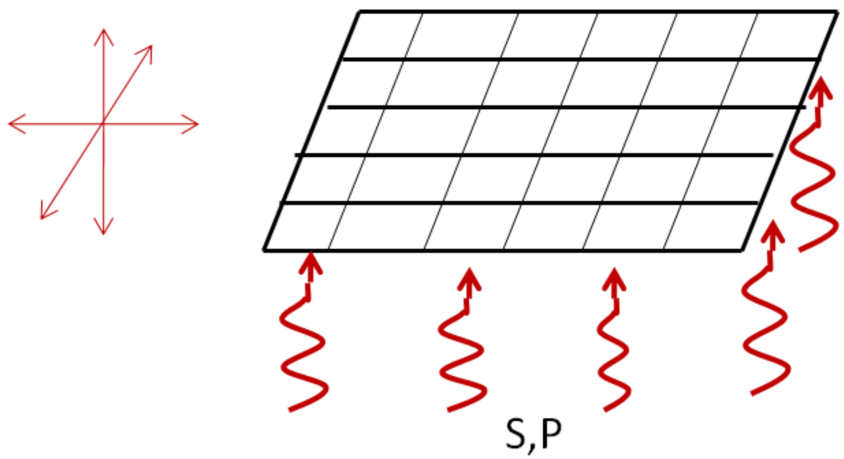


θ constant not realistic!

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

Wave Propagation Models: Coherent vs. Incoherent

3D Rigid Body Soil Motion (Idealized)

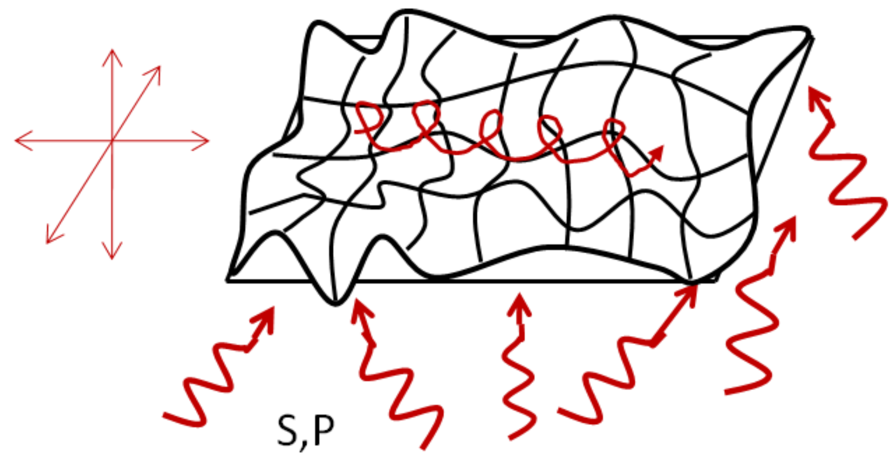


1 D Wave Propagation Analytical Model (Coherent)

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

Good for the LF inputs?

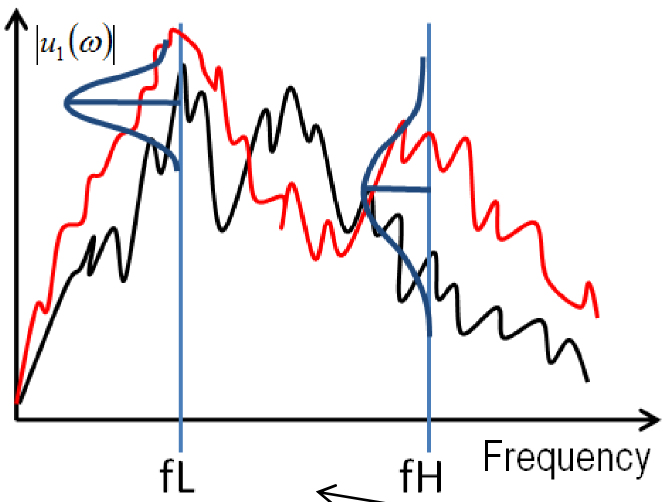
3D Random Wave Field Soil Motion (Realistic)

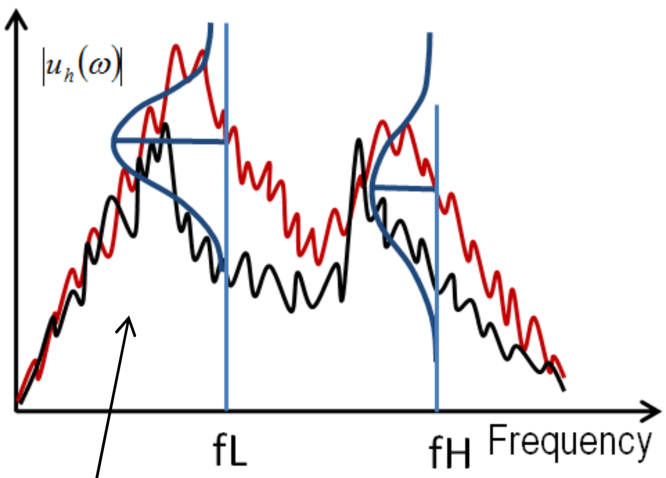


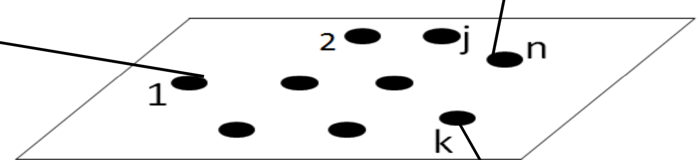
3D Wave Propagation Data-Based Model (Incoherent – Database-Driven Adjusted Coherent)
Amplitude of vertically propagating S and P wave motions are adjusted based on the statistical models derived from various field dense-arrays record databases (plane wave coherency models, plus wave passage – Abrahamson's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

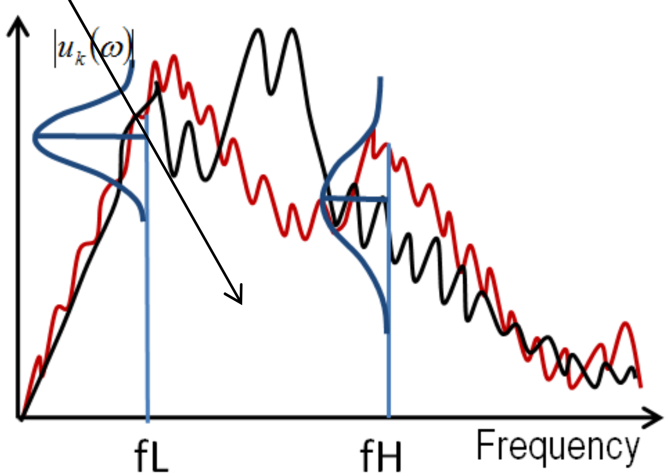
Good only for the HF inputs?

3D Stochastic Wave Model: Incoherent Motion Field









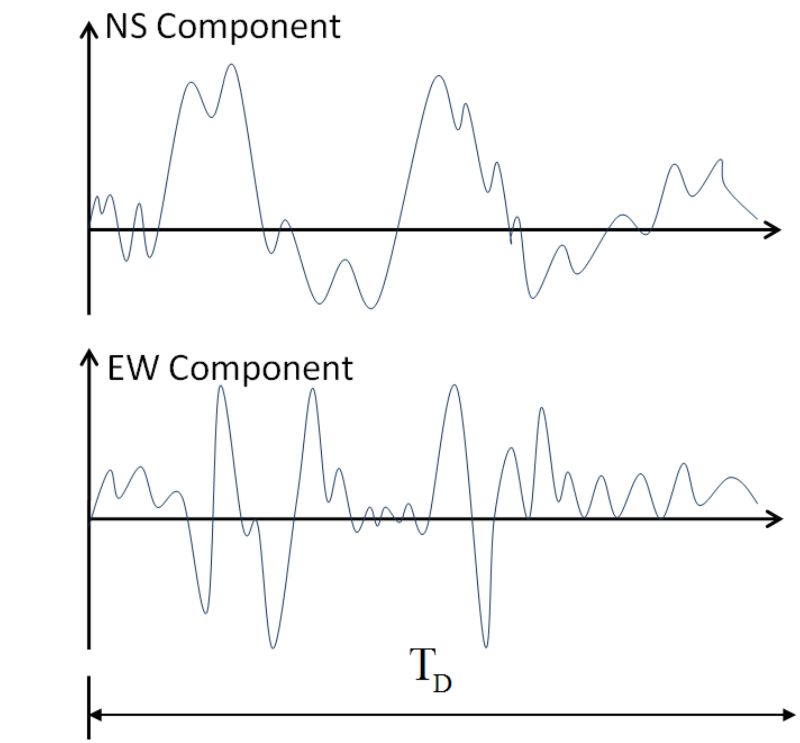
Coherent Function

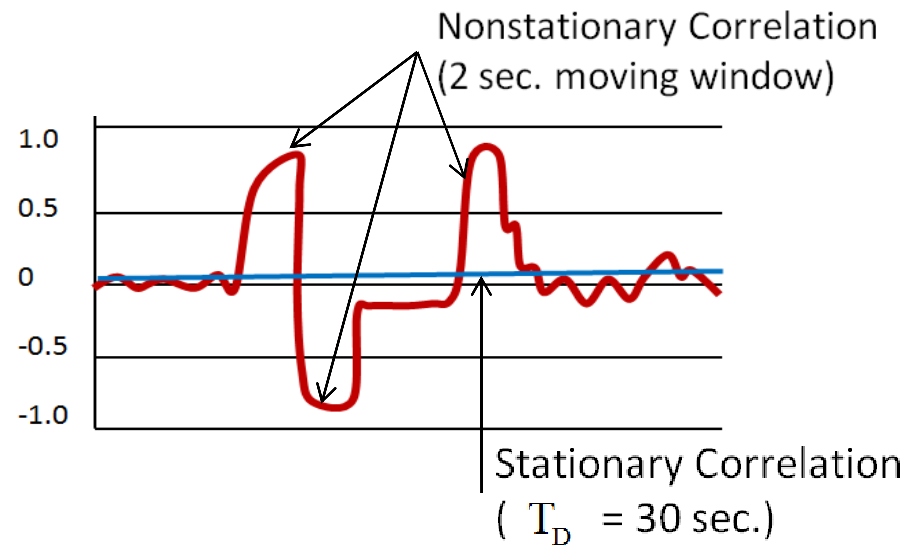
$$\Gamma_{Uj,Uk}(\omega) = \frac{S_{Uj,Uk}(\omega)}{[S_{Uj,Uj}(\omega) S_{Uk,Uk}(\omega)]^{1/2}}$$

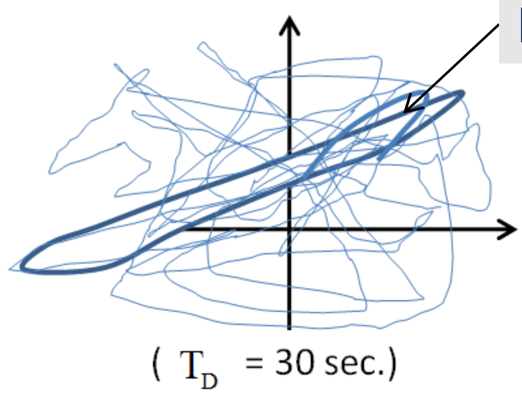
$$\Gamma_{U\ Ui,Uk}(\omega) = \Gamma_{L\ Ui,Uk}(\omega) \exp\left[i\omega (X_{D,i} - X_{D,k}) / V_D\right]$$

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

Seismic Input Directionality (Including 3D Direction Variations)



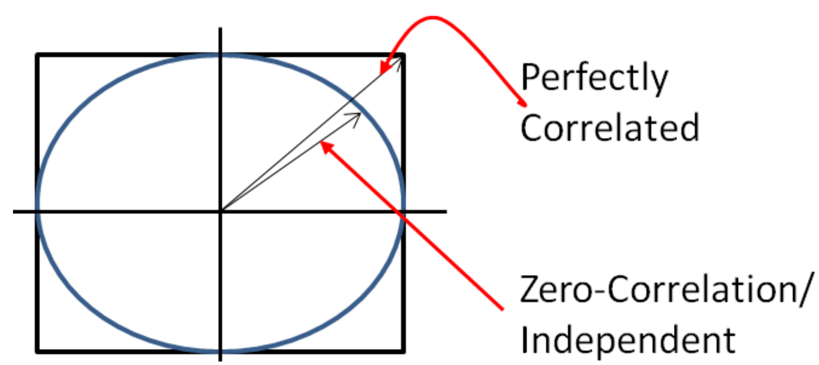




High Correlation!

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

CORNER COLUMN PROBLEM



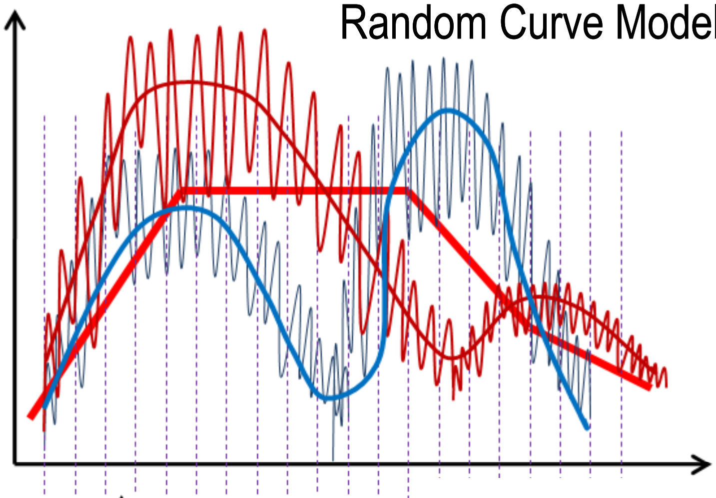
(Agnastopoulos, 1981, Der Kiureghian, 1984)

(SRSS rule neglects correlation effects)

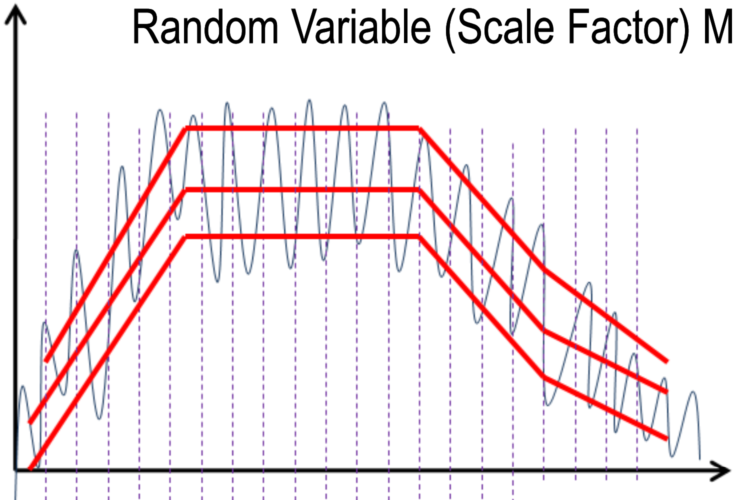
Soil Acting As A Frequency Filter on Seismic Incident Waves

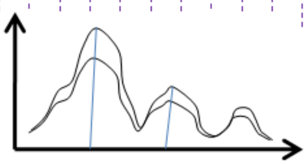
Seismic Motion Frequency Content Shows Correlation in Frequency

Random Curve Model



Random Variable (Scale Factor) Model

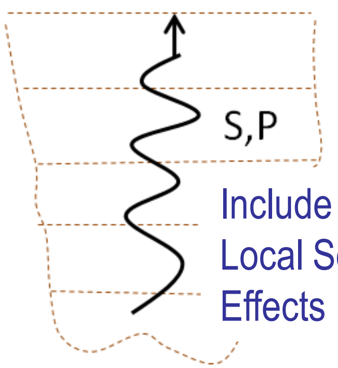




Wave Propagation Model

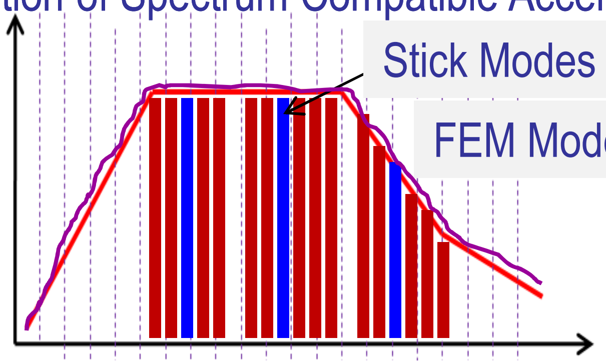
Random Variable Model

No correlation = Noise = No physics!



Include Local Soil Condition Effects

Generation of Spectrum Compatible Accelerograms



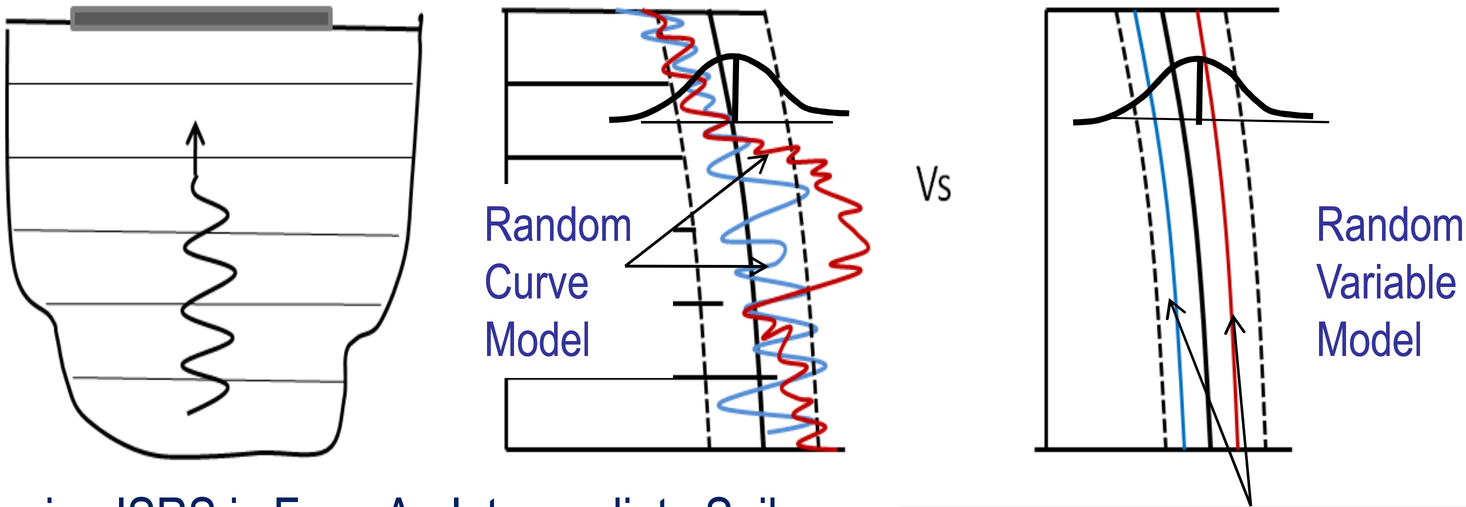
Stick Modes

FEM Modes

Neighbor frequency component phasing is important for FEM. Use appropriate phasing …Use 5 inputs – Voted recently for ASCE04 Draft 2011

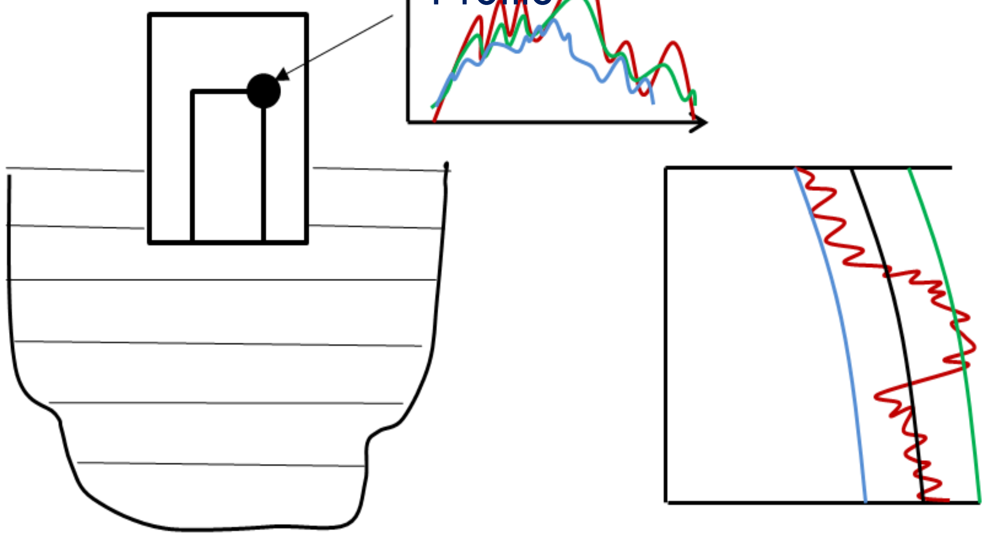
Soil Property Local and Spatial Variations (Low Strains)

Soil Layering | Real Soil Profiles | Ideal Soil Profiles



Perfect Correlation looses physics!

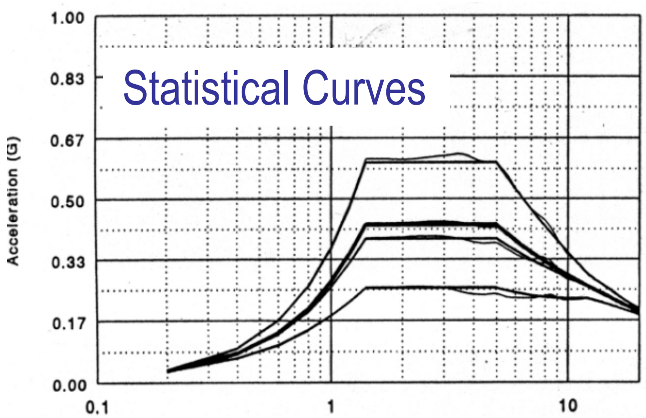
Governing ISRS is From An Intermediate Soil Profile



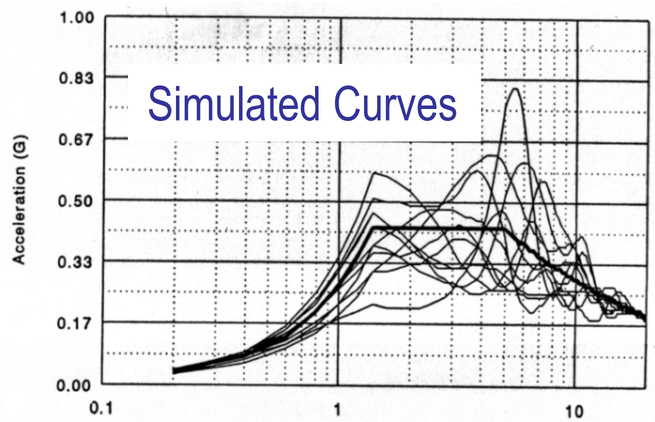
REMARK:
It could be that more than 3 soil profiles, LB, BE and UB, are needed to avoid "spectral valleys" in FIRS. Envelope of deterministic FIRS (deconvolved-down) should cover probabilistic-mean FIRS (convolved-up) – Recent discussions on ASCE04 Ch. 2 Draft 2011

Summary of Some Seismic Motion and Soil Variabilities

Statistic UHS Input for Soil Site

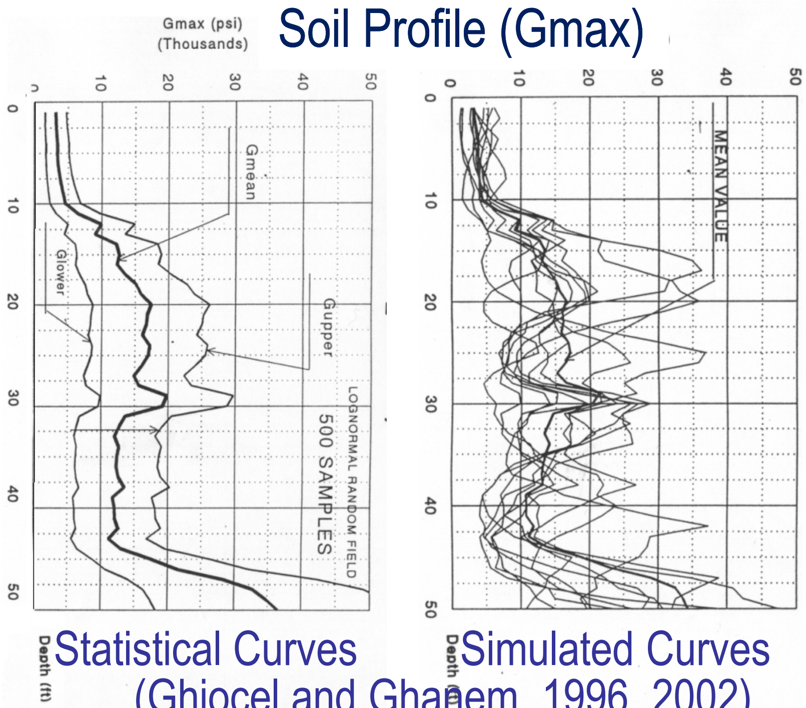


Statistical Curves



Simulated Curves

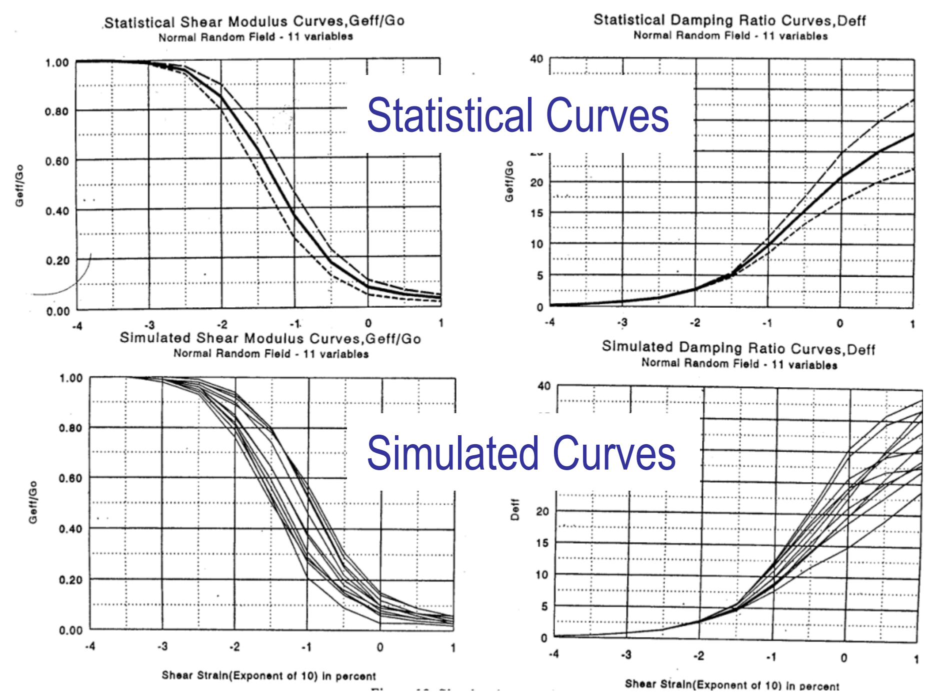
Soil Profile (Gmax)



Statistical Curves Simulated Curves

(Ghiocel and Ghanem, 1996, 2002)

Geff/Gmax and Deff Variations



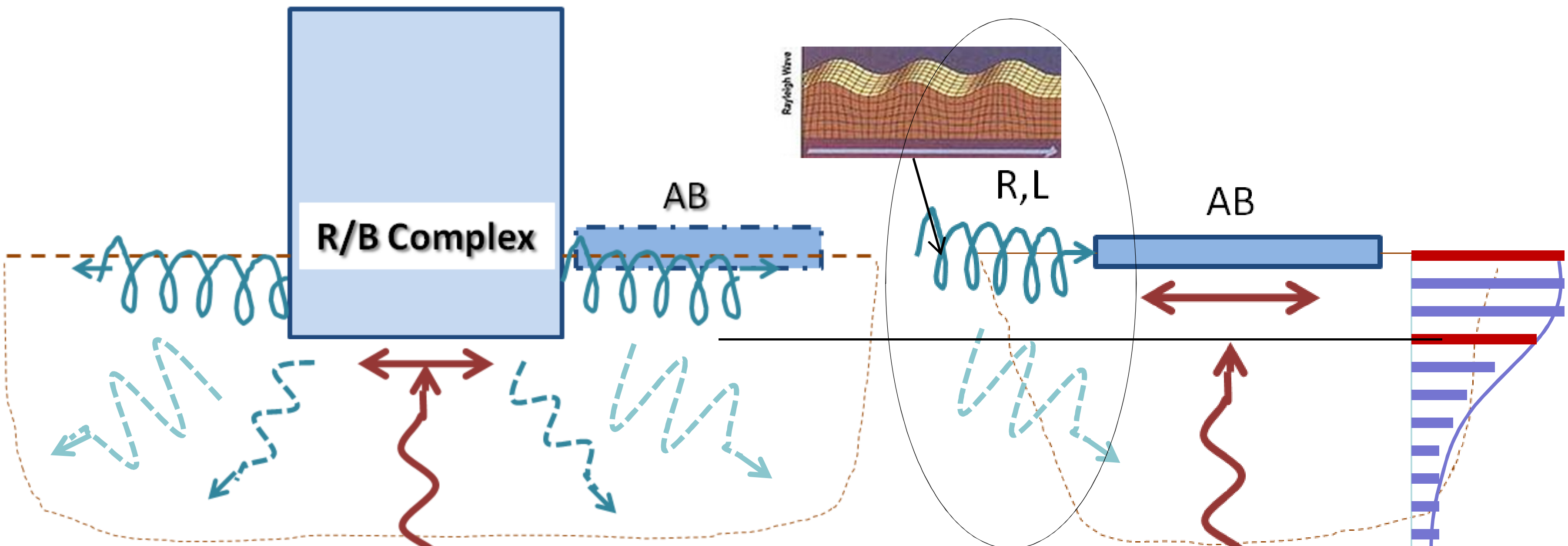
Statistical Curves

Simulated Curves

Seismic Structure-Soil-Structure Interaction (SSSI) Effects

R/B Complex – AB Interaction

SSSI Effects on AB

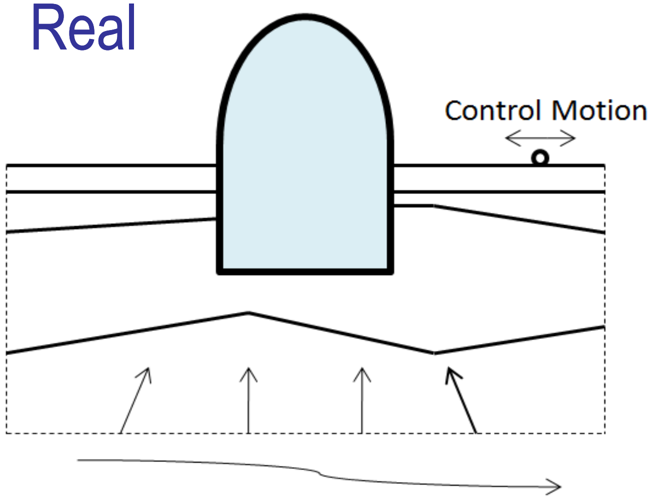


REMARKS:

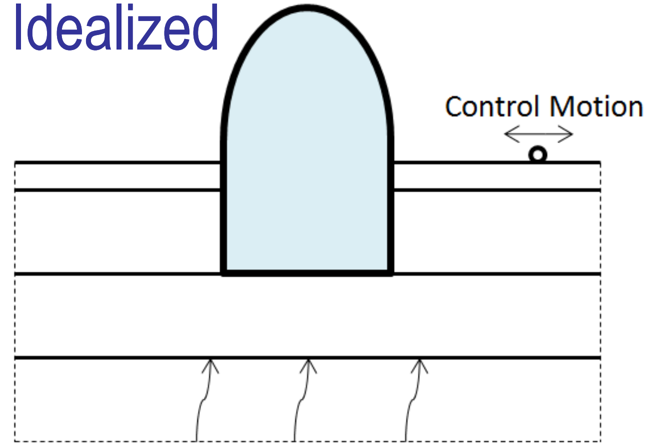
- The SSSI effects could be very significant. Both i) wave scattering and ii) inertial coupling could play significant roles. Effects show in ISRS. Usually less significant in structural forces
- Foundation levels and sizes affects the SSSI phenomena
- Light surface structures in vicinity of embedded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

SSI Analysis Methods

Real



Idealized

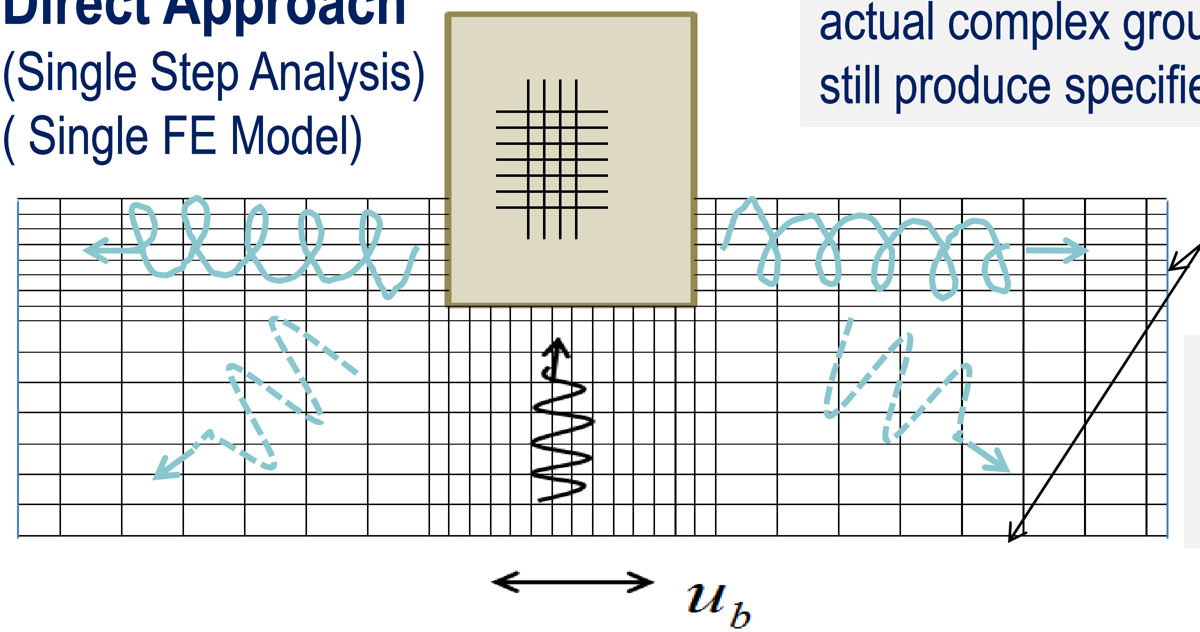


Vertical wave propagation is used to replace actual complex ground motion pattern, but still produce specified motion at control point.

Direct Approach

(Single Step Analysis)

(Single FE Model)

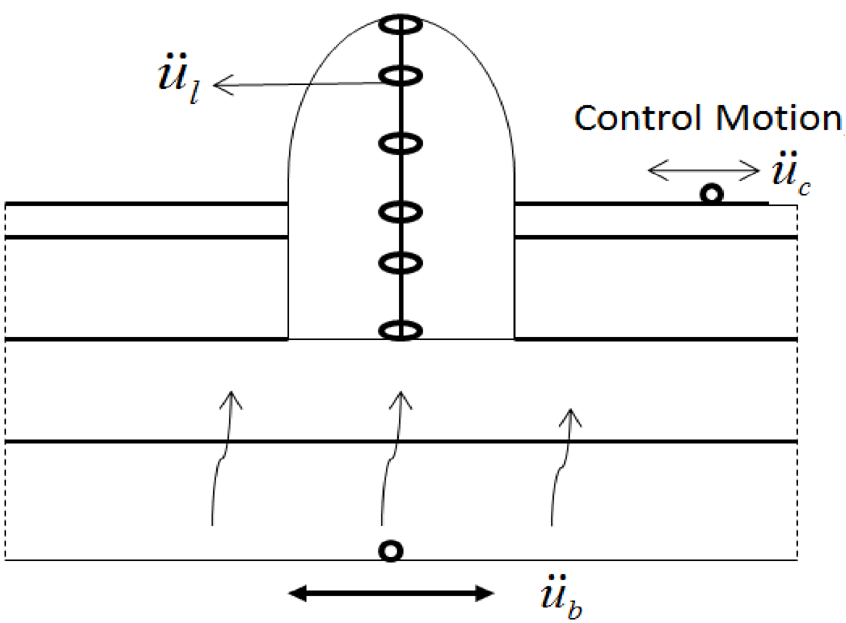


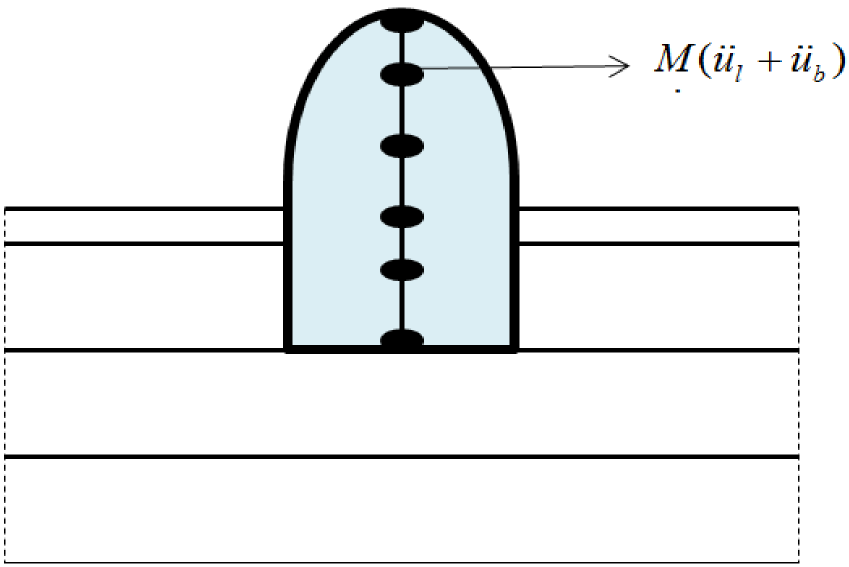
Conventional BCs

(stiffness, damping, soil motion)

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

Linear SSI Analysis Using Two Step Superposition





(a) Kinematic Interaction Analysis

Structure has stiffness but no mass.

Analysis leads to determination of motions at different points in structure relative to base control point.

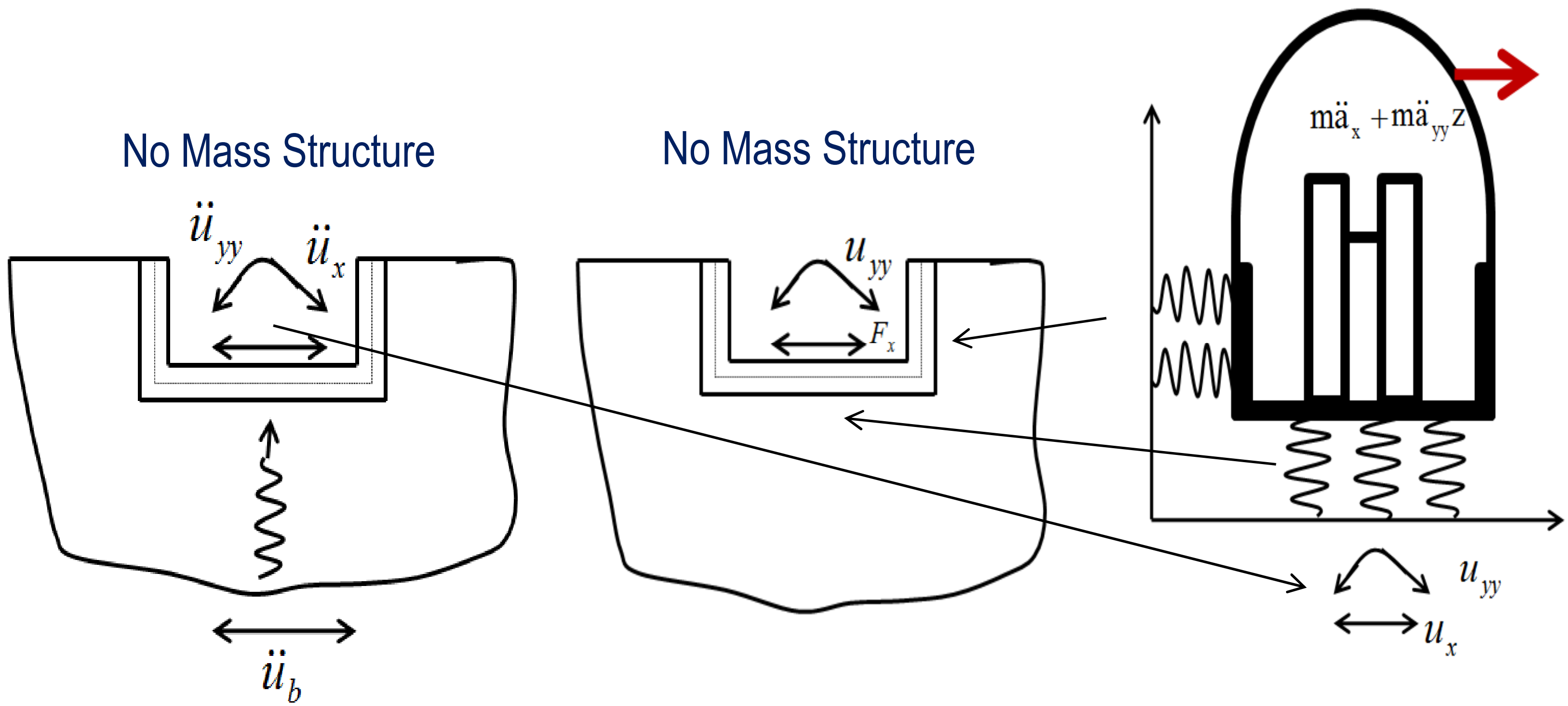
(b) Inertial Interaction Analysis

Motions computed in (a) are applied to masses in structure as shown above.

Analysis leads to computation of new motions at different points in structure.

Linear SSI Analysis Using Three Step Approach

Rigid Boundary SSI Substructuring

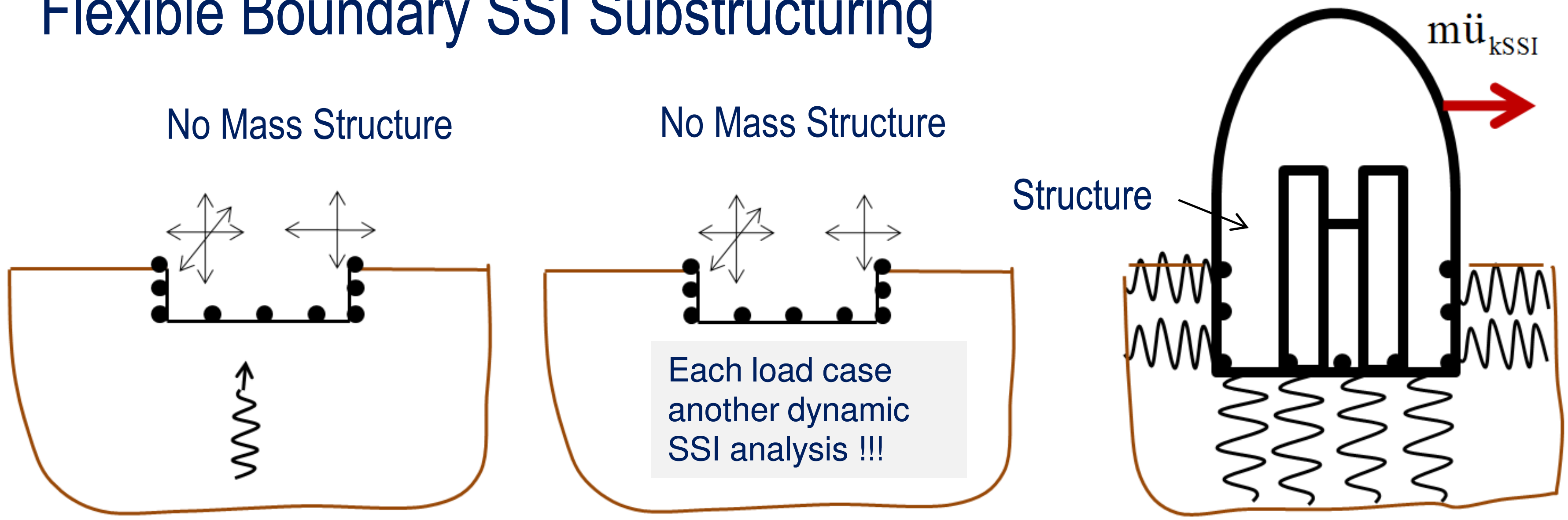


a) Wave Scattering Problem (Kinematic SSI, Wave Pb)

b) Impedance Problem (External Force Pb)

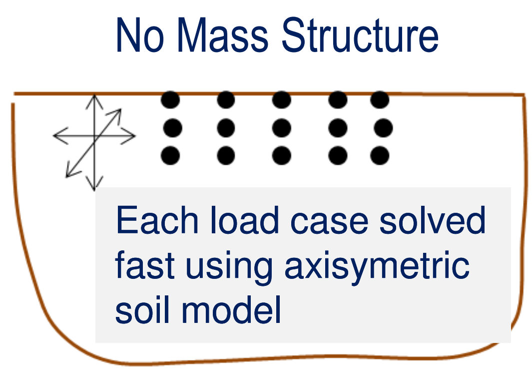
c) Structural Dynamic Analysis (Inertial SSI, External Force Pb)

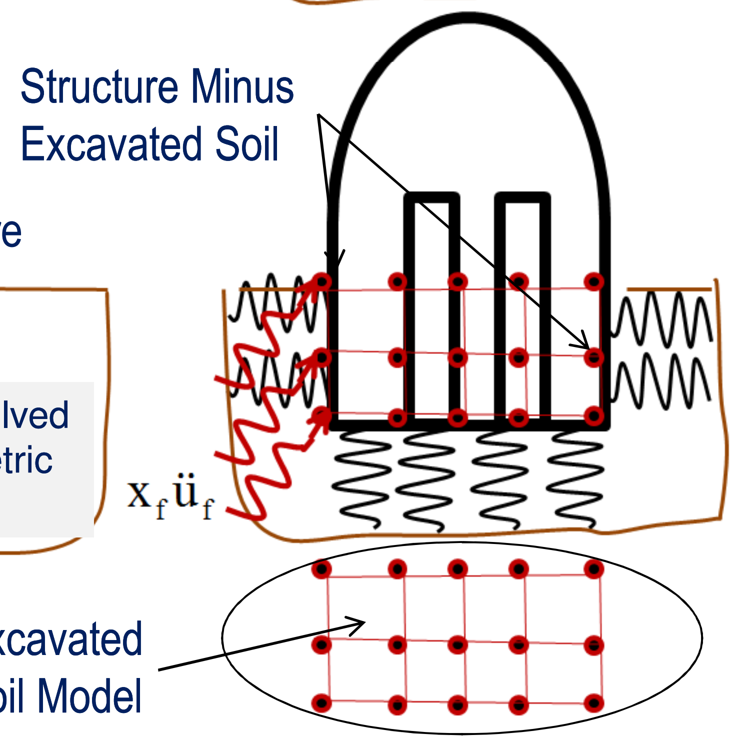
Flexible Boundary SSI Substructuring



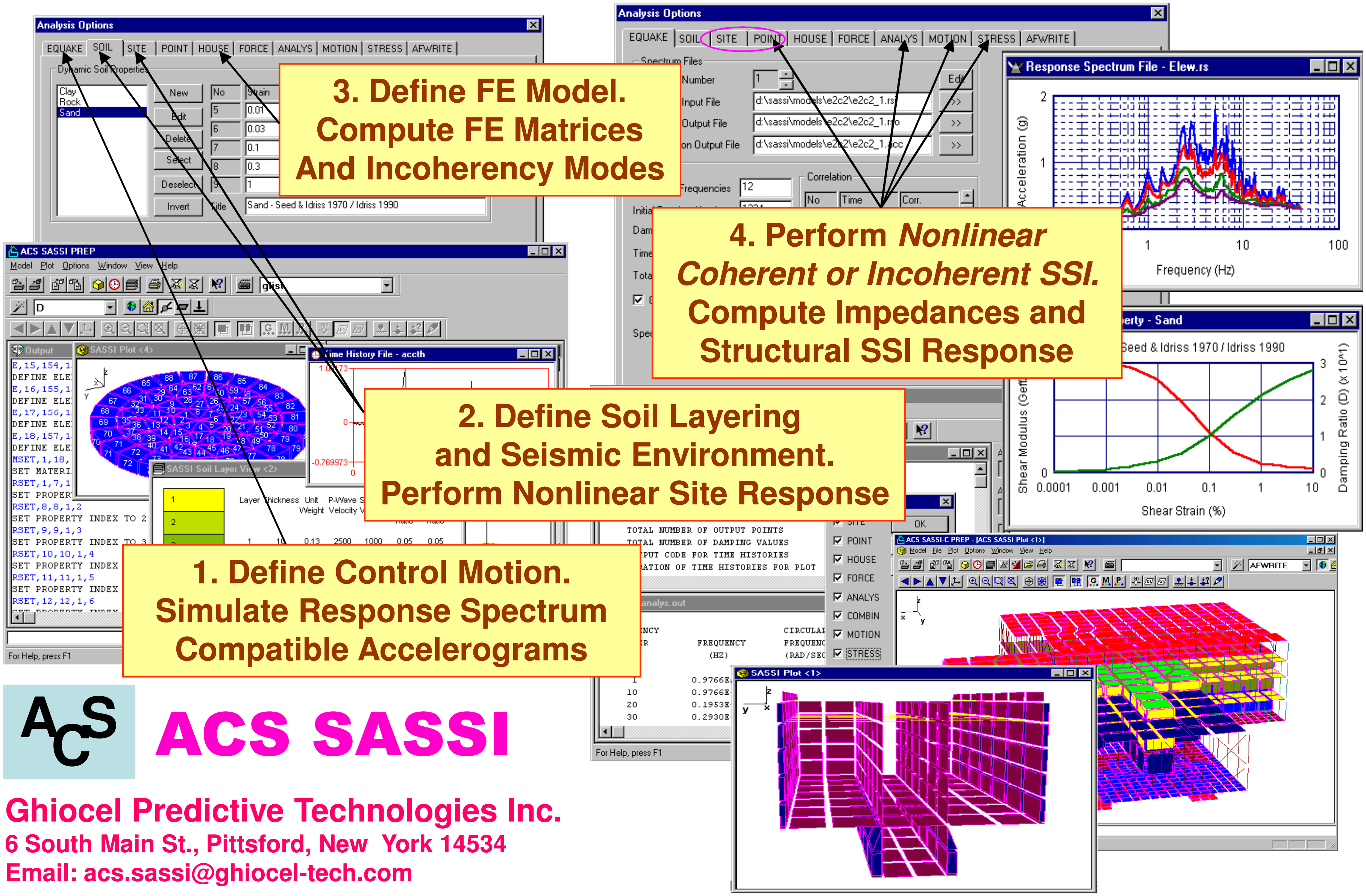
Flexible Volume SSI Substructuring

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





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



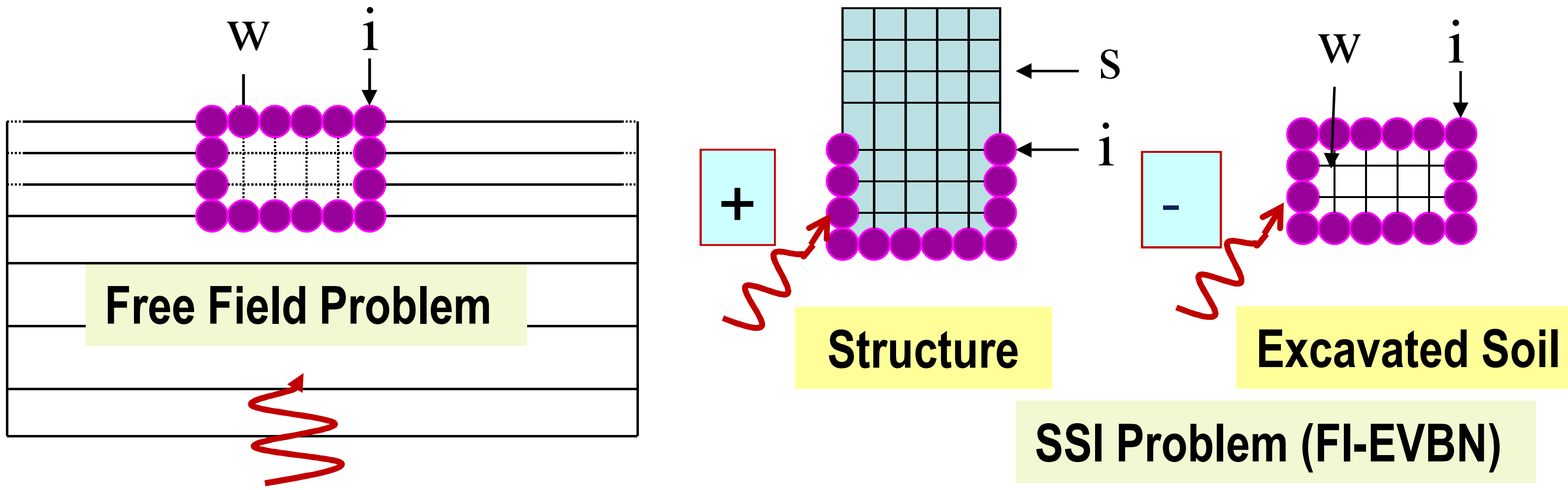
ACS SASSI

Ghiocel Predictive Technologies Inc.

6 South Main St., Pittsford, New York 14534

Email: acs.sassi@ghiocel-tech.com

Flexible Volume Methods in ACS SASSI



Flexible Volume Method (the interaction nodes are all excavated volume nodes, w and i)

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

Flexible Interface Methods (the interaction nodes are at excavated soil surface nodes, i)

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

FI-Foundation-Soil-Interface (Subtraction)
FI-Excavation-Volume-Boundary-Nodes

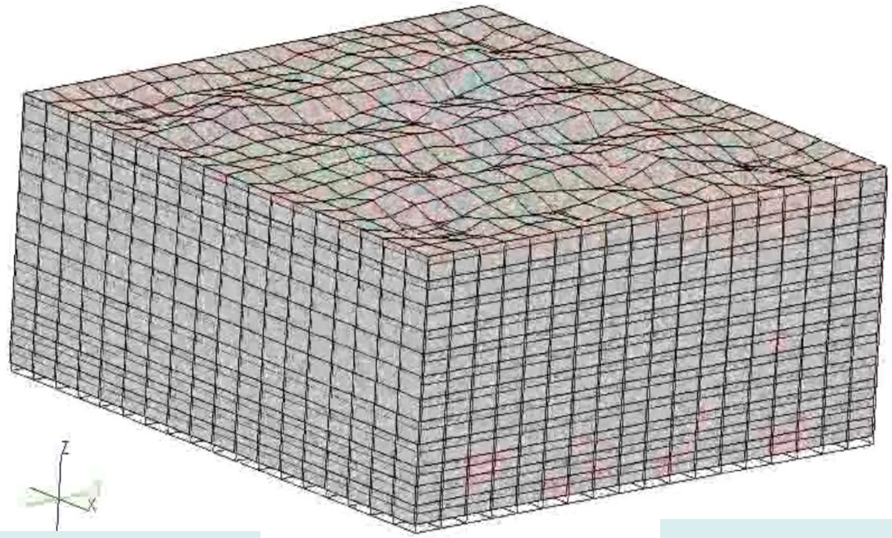
$$\mathbf{C}(\omega)\mathbf{U}(\omega) = \mathbf{Q}(\omega)$$

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

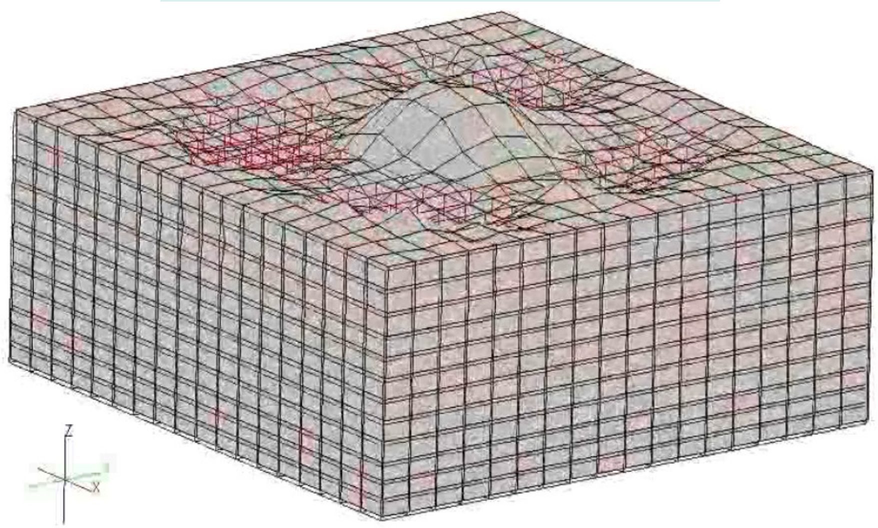
Excavated Soil Motion (Wave Scattering) Using FV Methods

SOFT SOIL
Vs=660fps

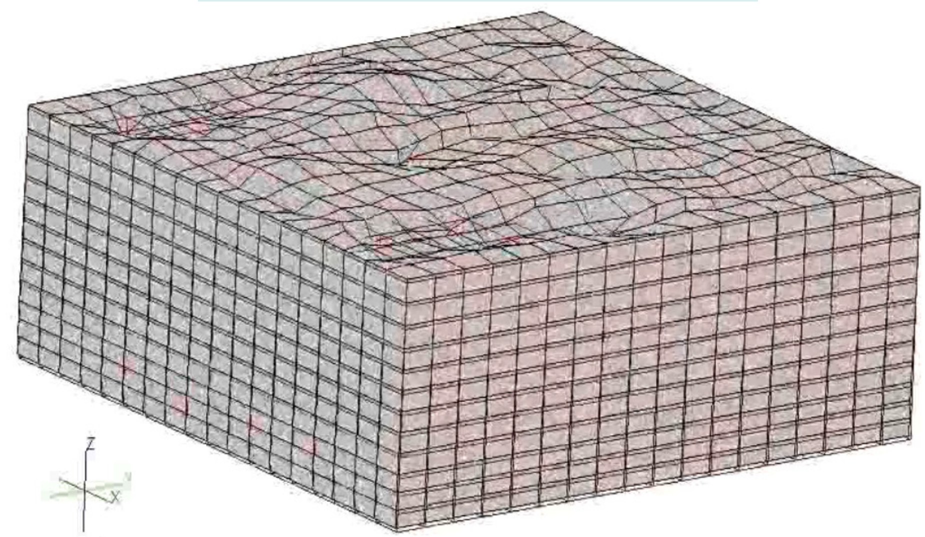
Flexible Volume



Flexible Interface - FSIN



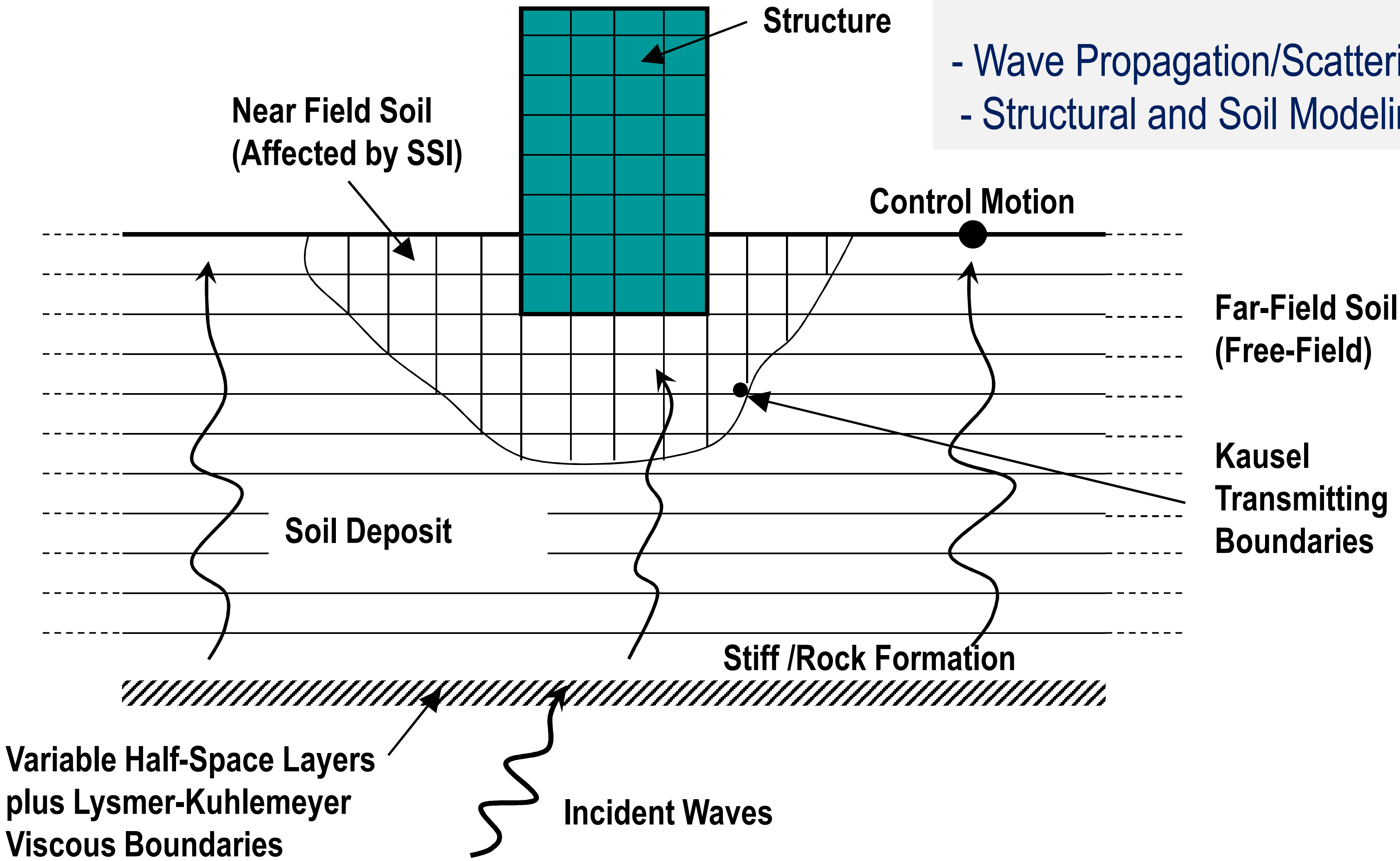
Flexible Interface - EVBN



Seismic SSI Analysis Problem

Seismic SSI Analysis Aspects:

- Wave Propagation/Scattering
- Structural and Soil Modeling



Main Computational SSI Capabilities:

1. **Simulation of Input Control Motion**

   - Generate GRS Compatible Accelerograms (Wilkison-Levy algorithm)
   - Use Correlated or Independent Horizontal Components. Include record phasing

2. **Nonlinear Site Response Analysis**

   - Compute Soil Response Under Vertically Propagating S Waves
   - Compute Equivalent Soil Properties (computed for effective shear strain)
   - Assume Horizontal Infinite Layering with Bottom Baserock (viscous boundary)

3. **Nonlinear Seismic Soil-Structure Interaction**

   - Assume Seismic Environment (S or Sand P waves, Rayleigh waves, others)
   - Compute Frequency Dependent Foundation Impedances
   - Compute Equivalent Linear SSI Solution Via Sub-Structuring (Flexible Interface)
   - Compute Nodal Motions and Stresses/Strains in Soil and Structural FE Elements
   - Compute Nodal Relative/Absolute Displacements
   - Include Motion Incoherency, Traveling Wave Effects, Multiple Excitations

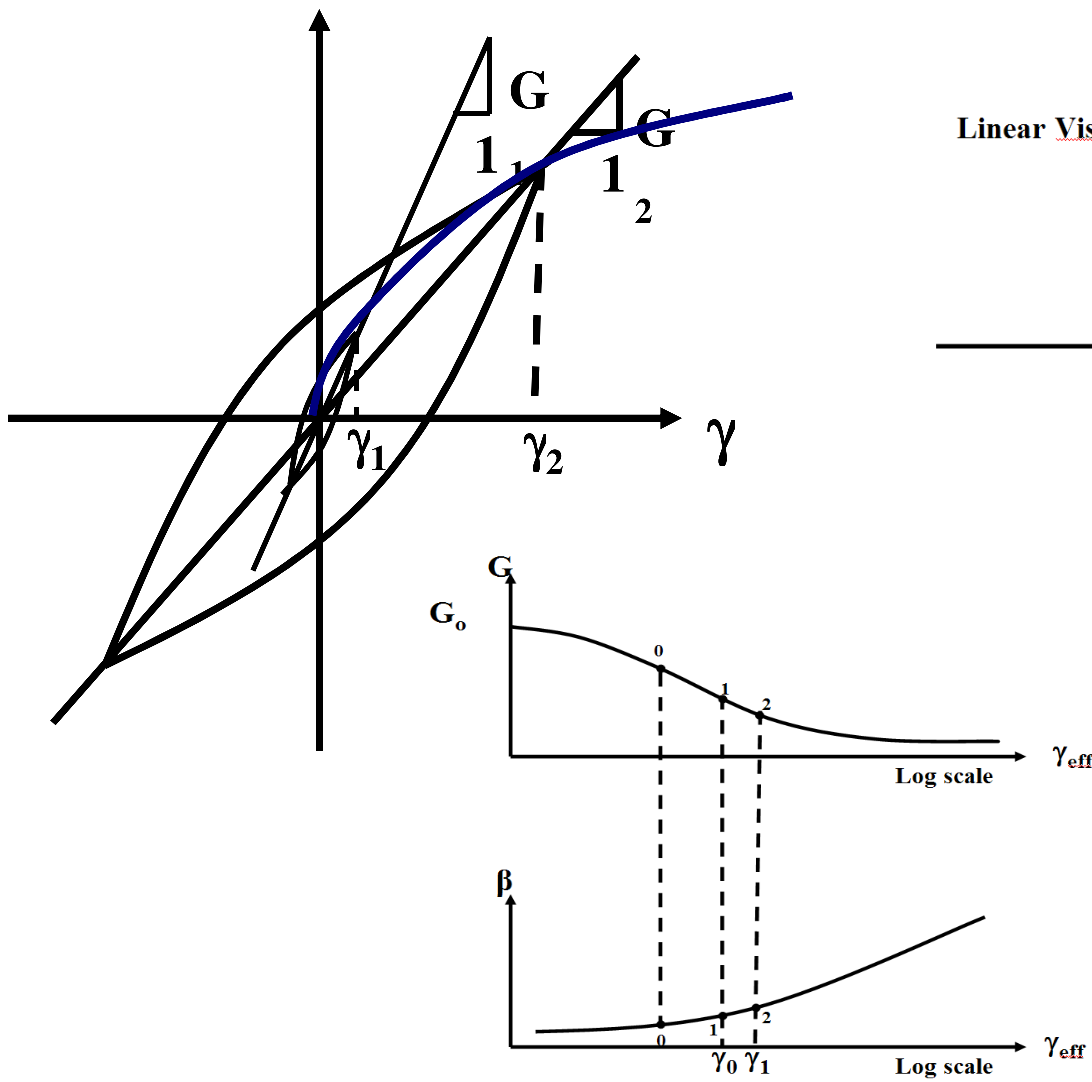
ANIMATIONS

Equivalent-Linear Model for Soil Hysteretic Behavior

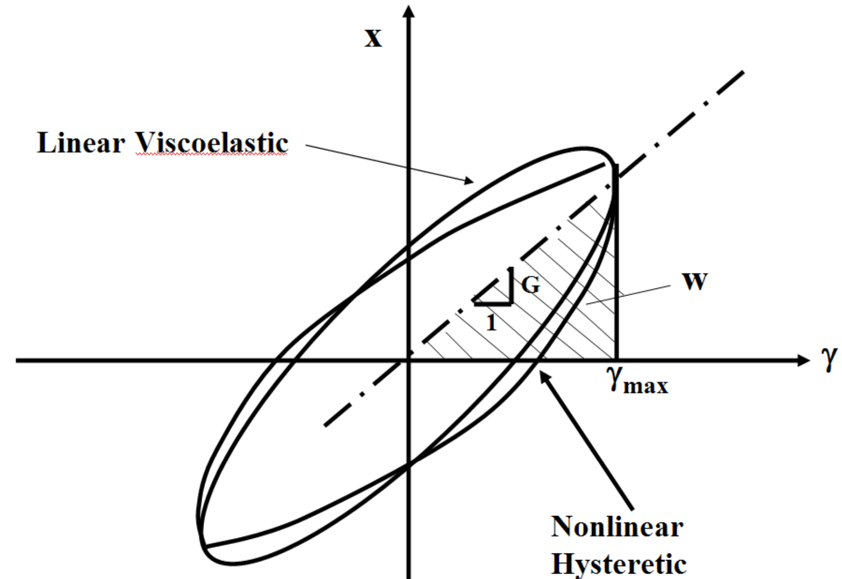
1. The nonlinear properties of the soil are approximated by equivalent linear properties consisting of the shear modulus and damping ratio for the soil which are compatible with the effective shear-strain amplitudes in soil
2. The effects of nonlinear soil behavior include two components:
   (i) The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

Seed-Idriss Equivalent Linear Iterative Method

Shear Modulus Variation



Viscous Damping Variation

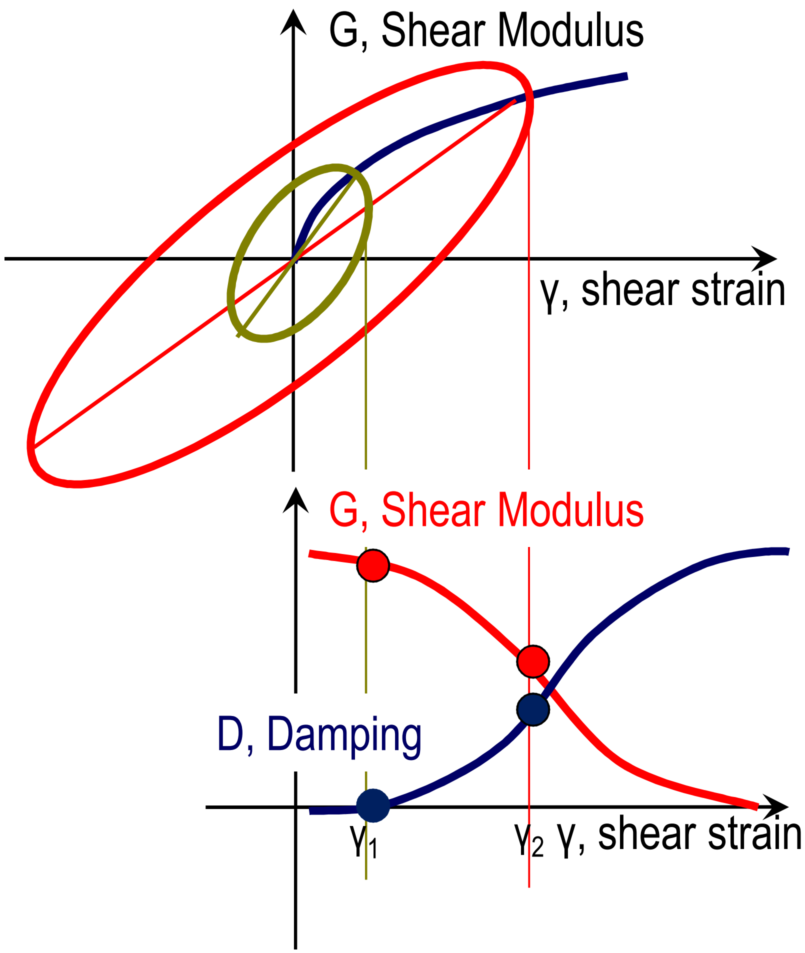


Δw = Area of hysteretic loop

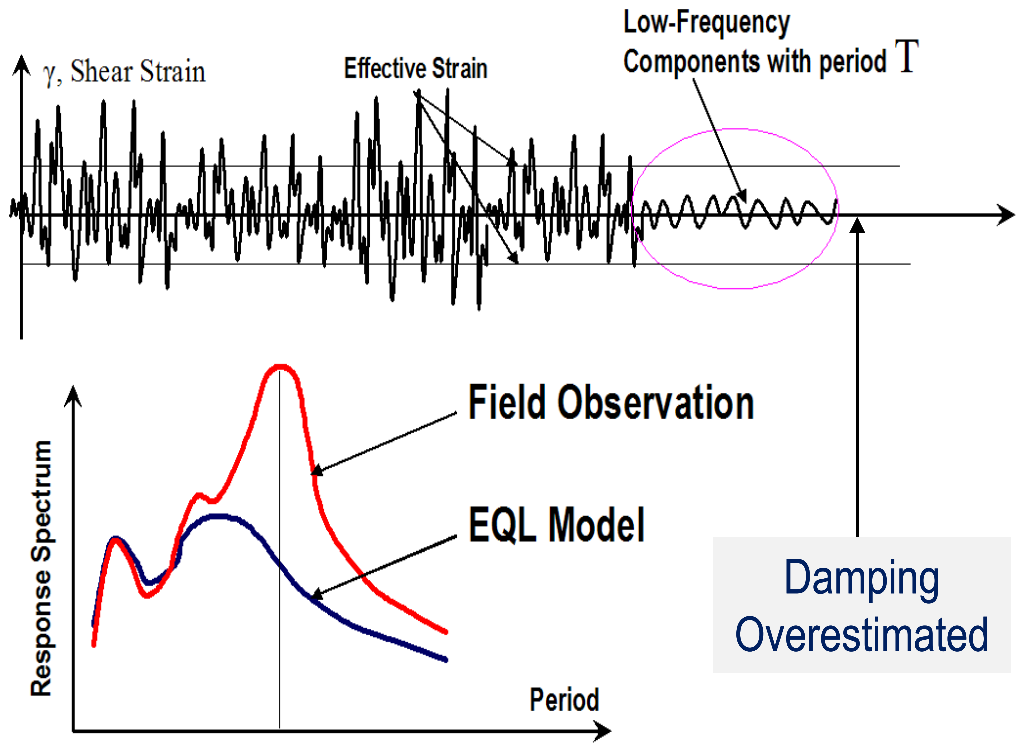
β = critical damping ratio

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

Seed-Idriss Equivalent Linear Iterative Method

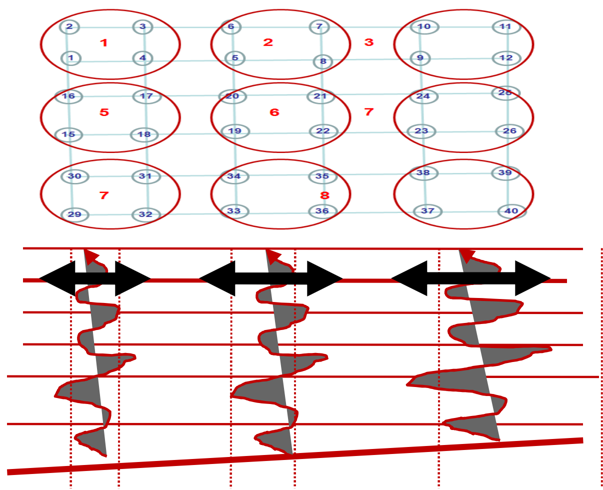


EQ Liner vs. Field Observations

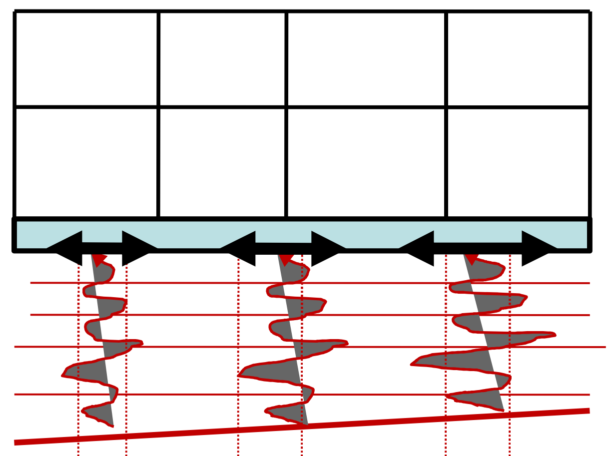


Nonuniform Seismic Input Motion in Horizontal Plane

Multiple Soil Column Response Analyses



Non-Uniform Excitation and Soil Stiffness

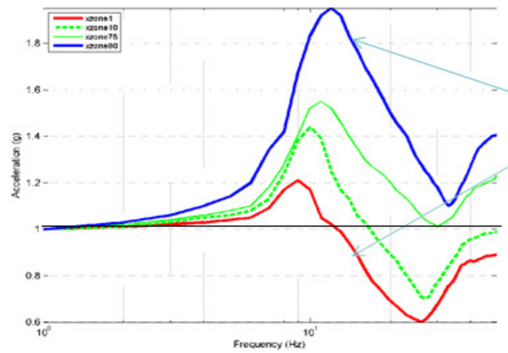


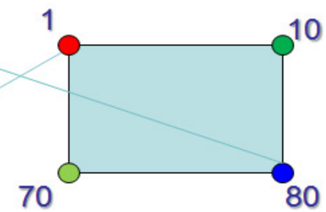
ACS SASSI Version 2.3.0 has the capability to consider deterministic spatial variation patterns for differential input motions in the horizontal plane.

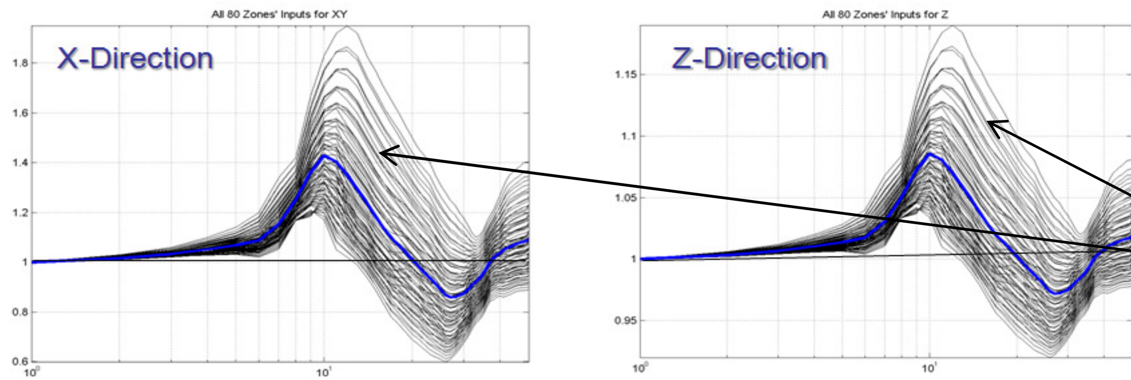
These deterministic spatial variation effects can be combined with the effects of motion incoherency and wave passage to create more realistic seismic inputs for SSI analysis of NPP structures, especially for those that have large foundation sizes.

Nonuniform Seismic Input Motion in Horizontal Plane

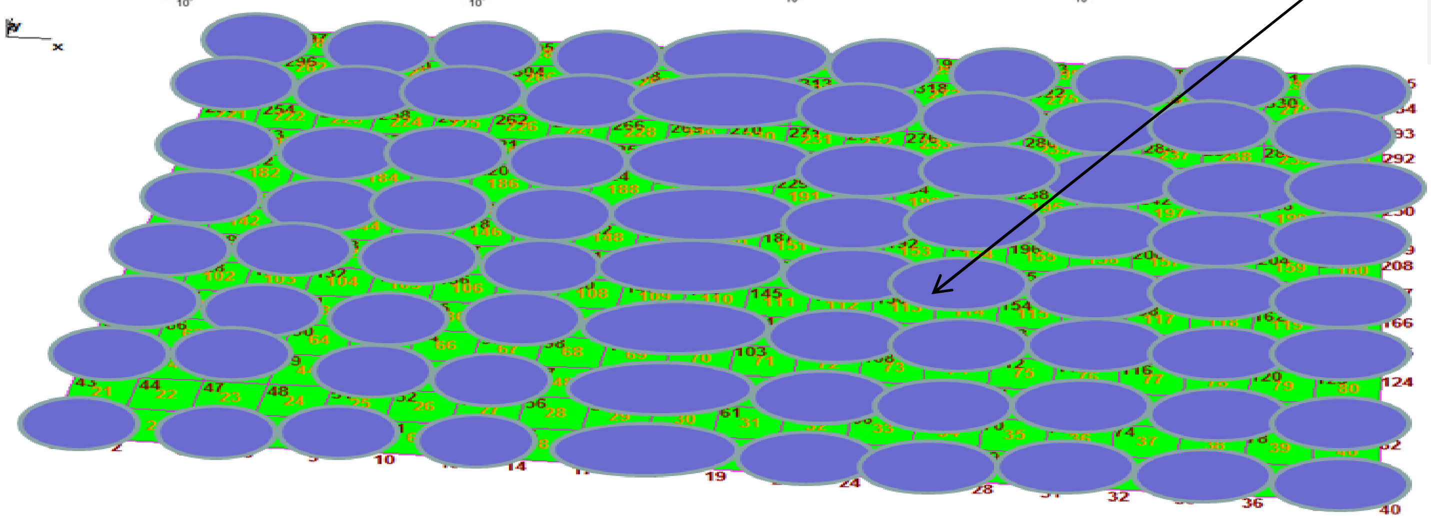
Multiple borehole soil column models







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



ACS SASSI-ANSYS Integration for Seismic Soil-Structure Interaction Analysis of Nuclear/Critical Facility Structures

ACS SASSI-ANSYS integration provides new SSI analysis capabilities:

For structural stress analysis:

- *ANSYS Equivalent-Static Seismic SSI Analysis* Using Refined Mesh FE Models

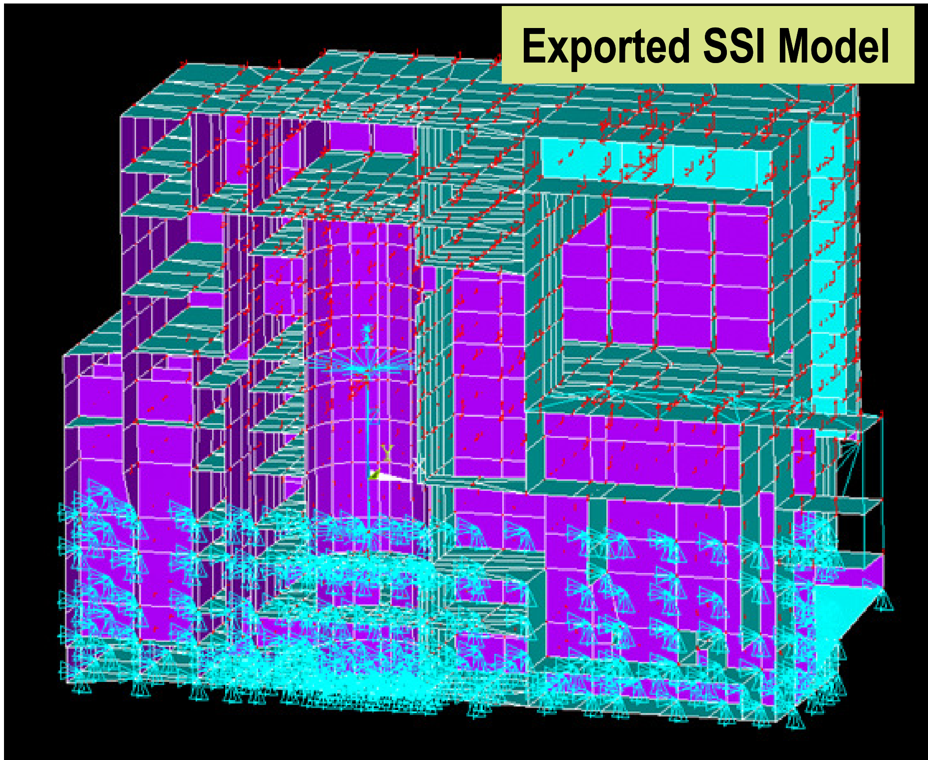
- *ANSYS Dynamic Seismic SSI Analysis* Using Nonlinear or More Refined FE Models

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

For soil pressure computation:

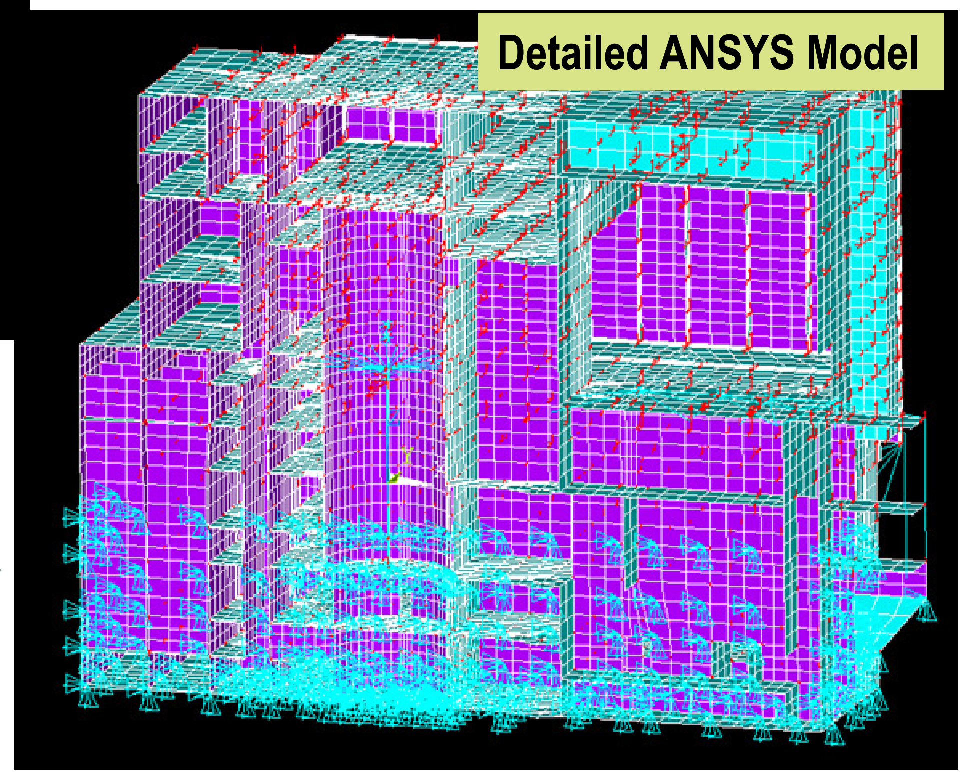
- *ANSYS Equivalent-Static Seismic Soil Pressure Computation* Including Soil-Foundation Separation Effects

ACS SASSI – ANSYS Interface for Refined Seismic Stress Analysis

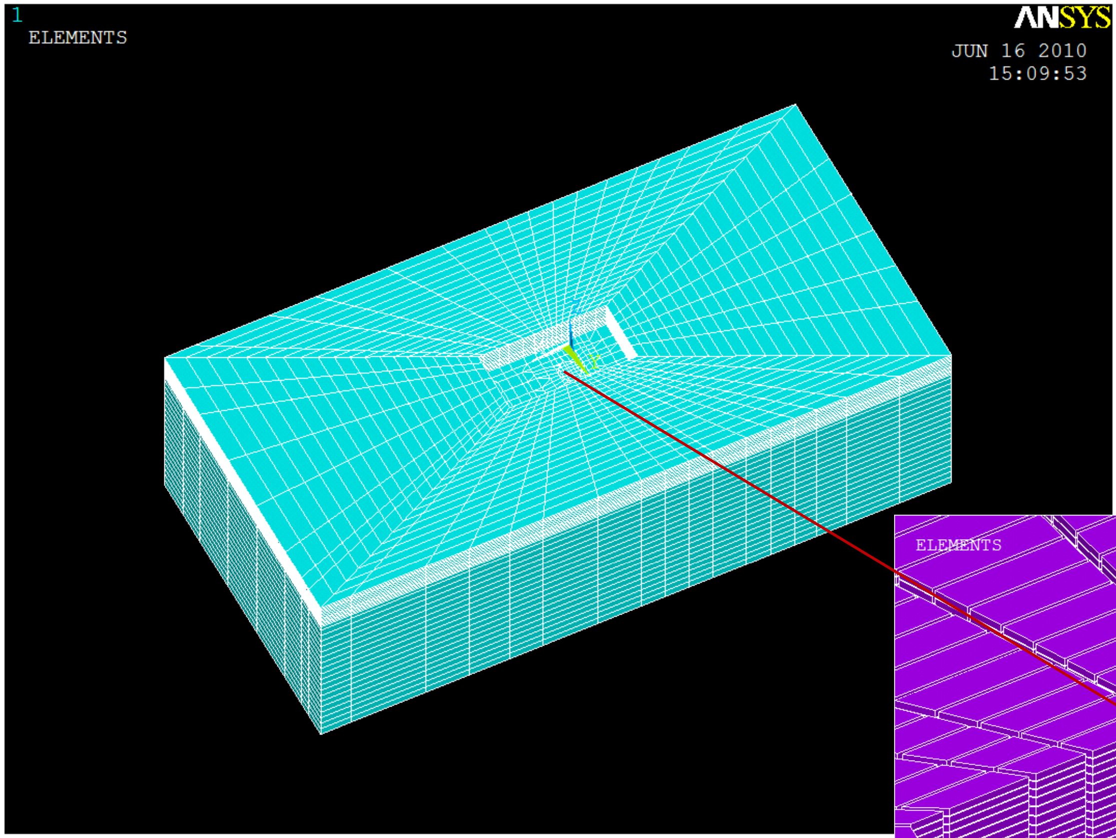


ANSYS Structural Model Automatically Converted From ACS SASSI Using PREP Module

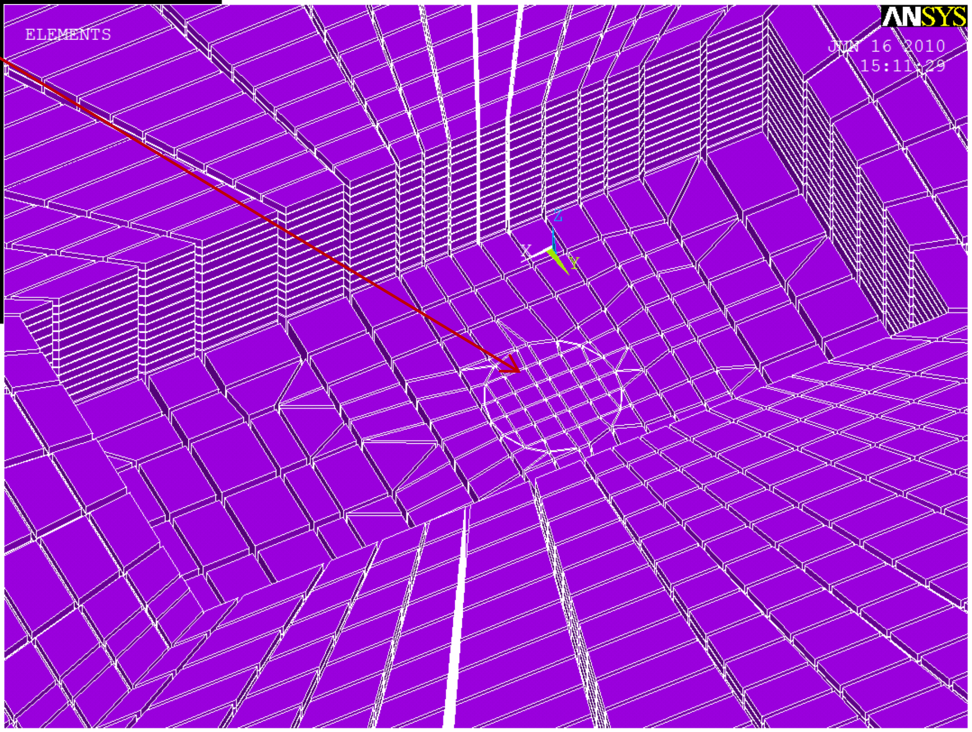
ANSYS Refined Structural Model Using EREFINE command or ANSYS GUI (rank 1-6)



ACS SASSI – ANSYS Interface for Seismic Soil Pressure Analysis



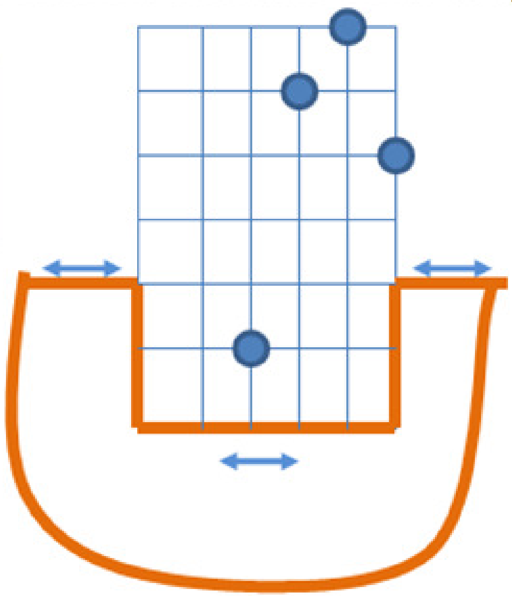
ANSYS Soil FE Model
Is Automatically Generated
by SOILMESH Module



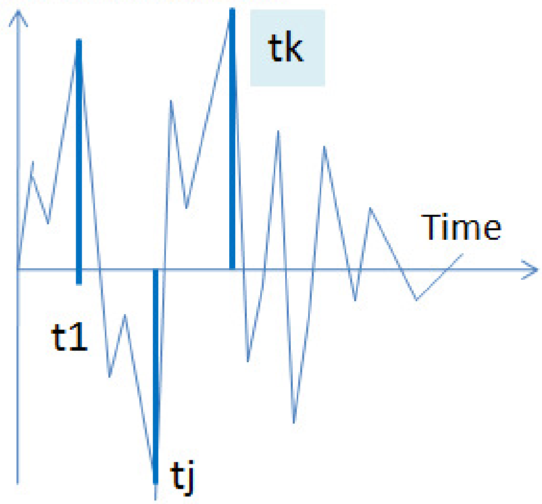
Embedment mesh is extended.
User controls extension size and
mesh density. Can use EREFINE.
Contact surfaces automatically added
By ACS SASSI SOILMESH module.

ACS SASSI Seismic SSI Analysis

Computing Structural Stress/Forces

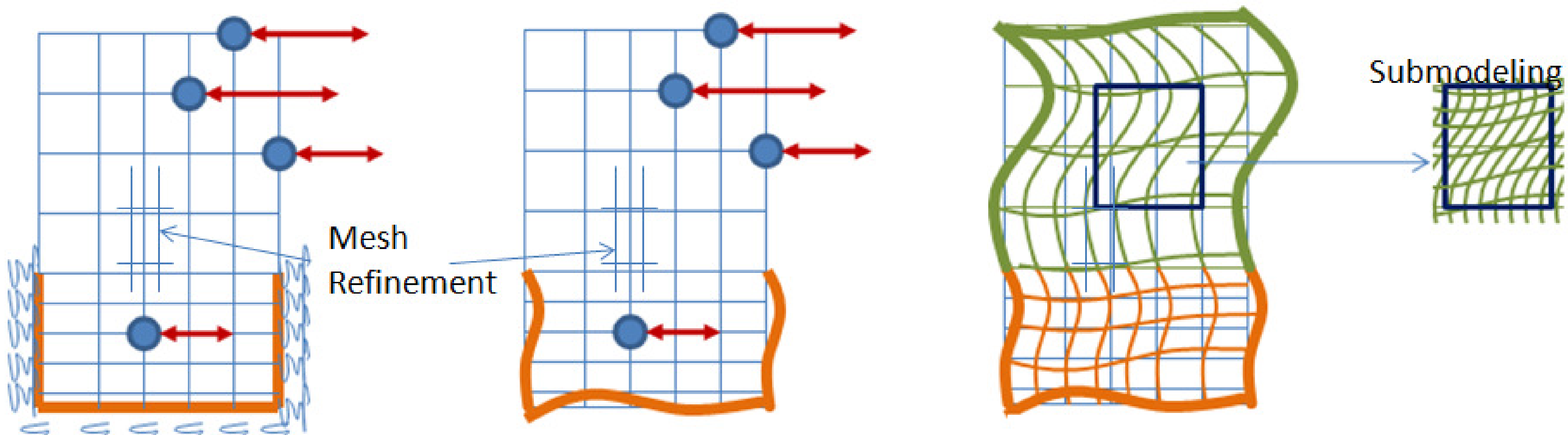


Selected Critical Time Steps for Maximum Stresses
To be Used for Equivalent Static Structural Analysis



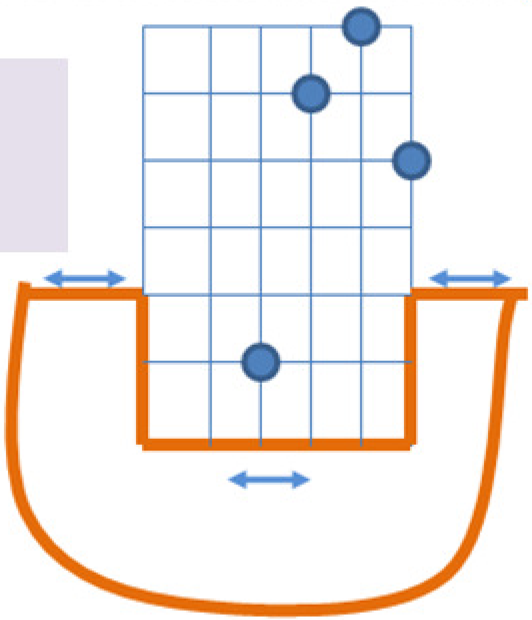
SSI Solution Time Frames As Equivalent Static Structural Loading at Critical Time Steps

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

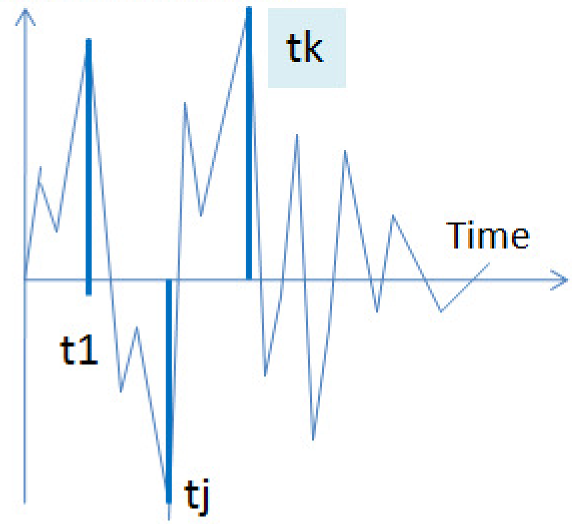


ACS SASSI Seismic SSI Analysis

Computing Seismic Soil Pressures

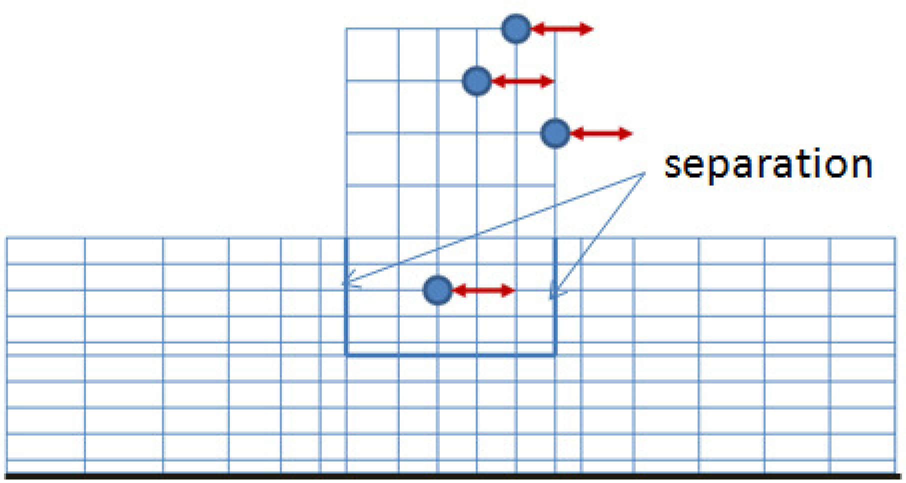


Selected Critical Time Steps for Maximum Stresses
To be Used for Equivalent Static Structural Analysis

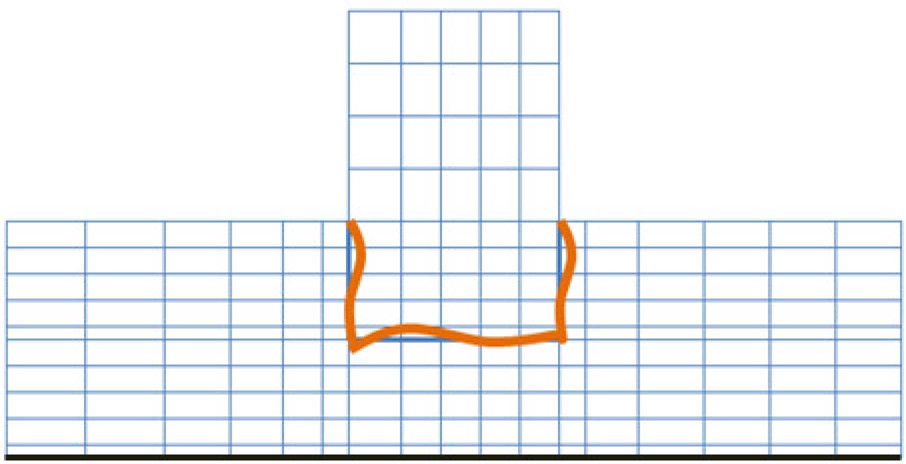


SSI Solution Time Frames As Equivalent Static Loading at Critical Time Steps

EQS Forces – Linear & Nonlinear



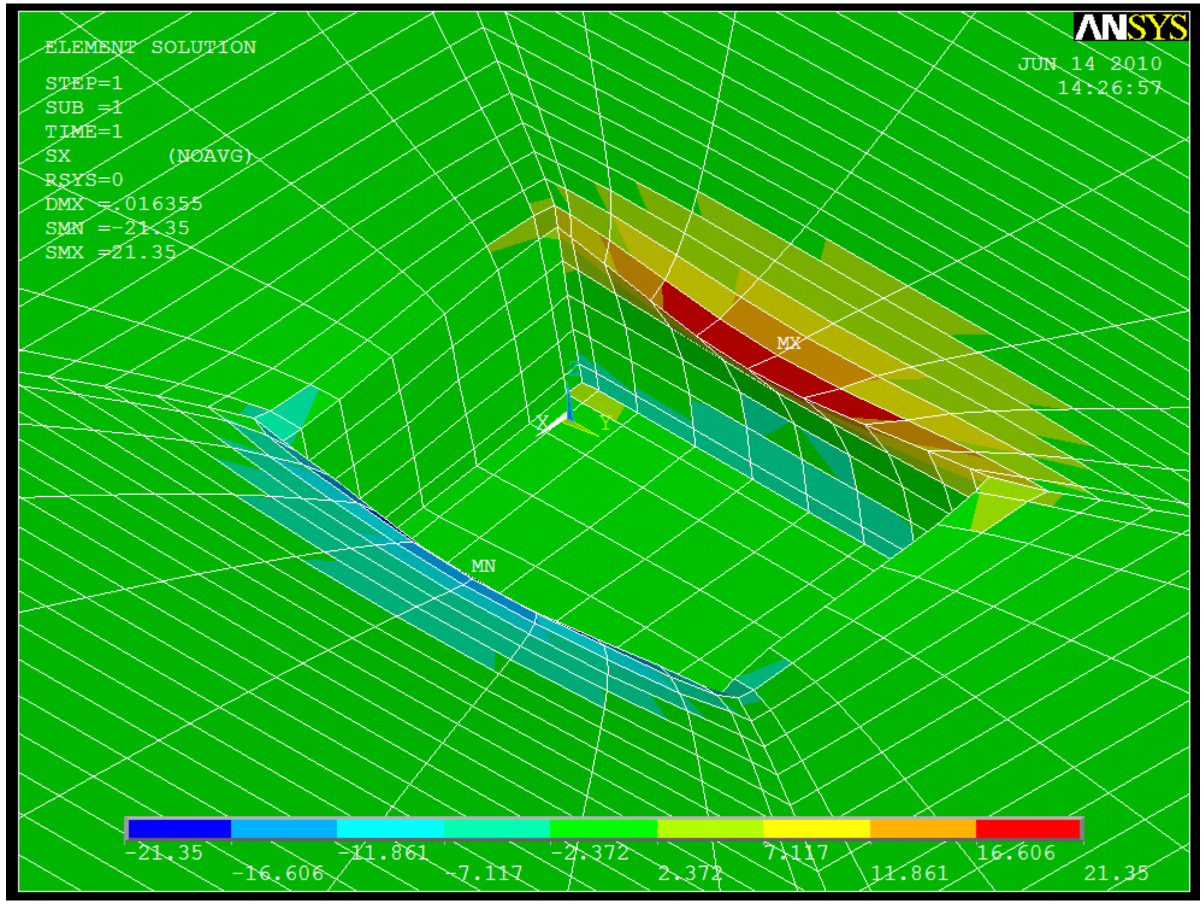
EQS Relative Displacements – Linear (Welded)



Linear Seismic Soil Pressure Analysis

LINEAR (WELDED SOIL)

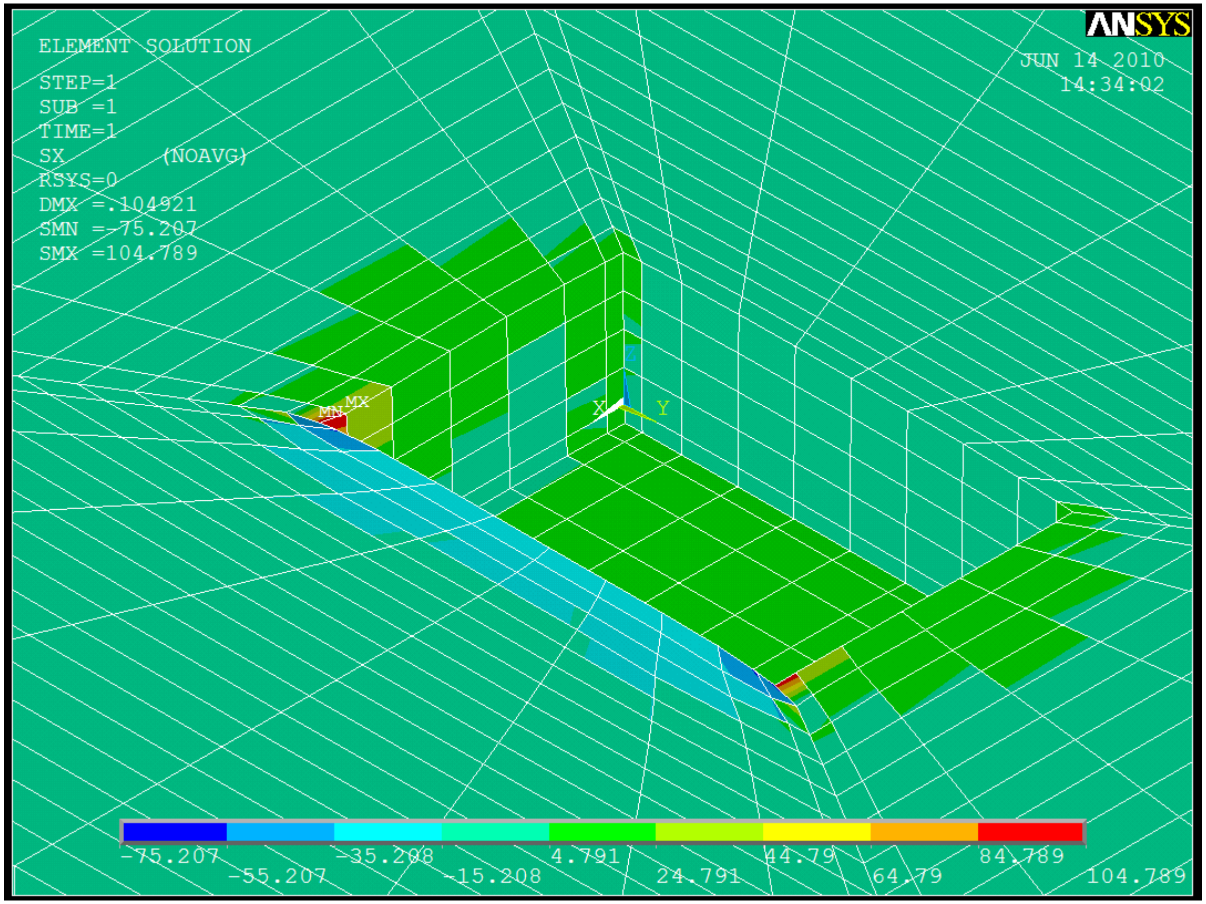
- This option provides for a basic soil pressure analysis assuming there is no separation possible between the structure and the soil
- Displacements from the interaction nodes of the structure are applied directly to the soil FE model. The structural FE model is not required for this case



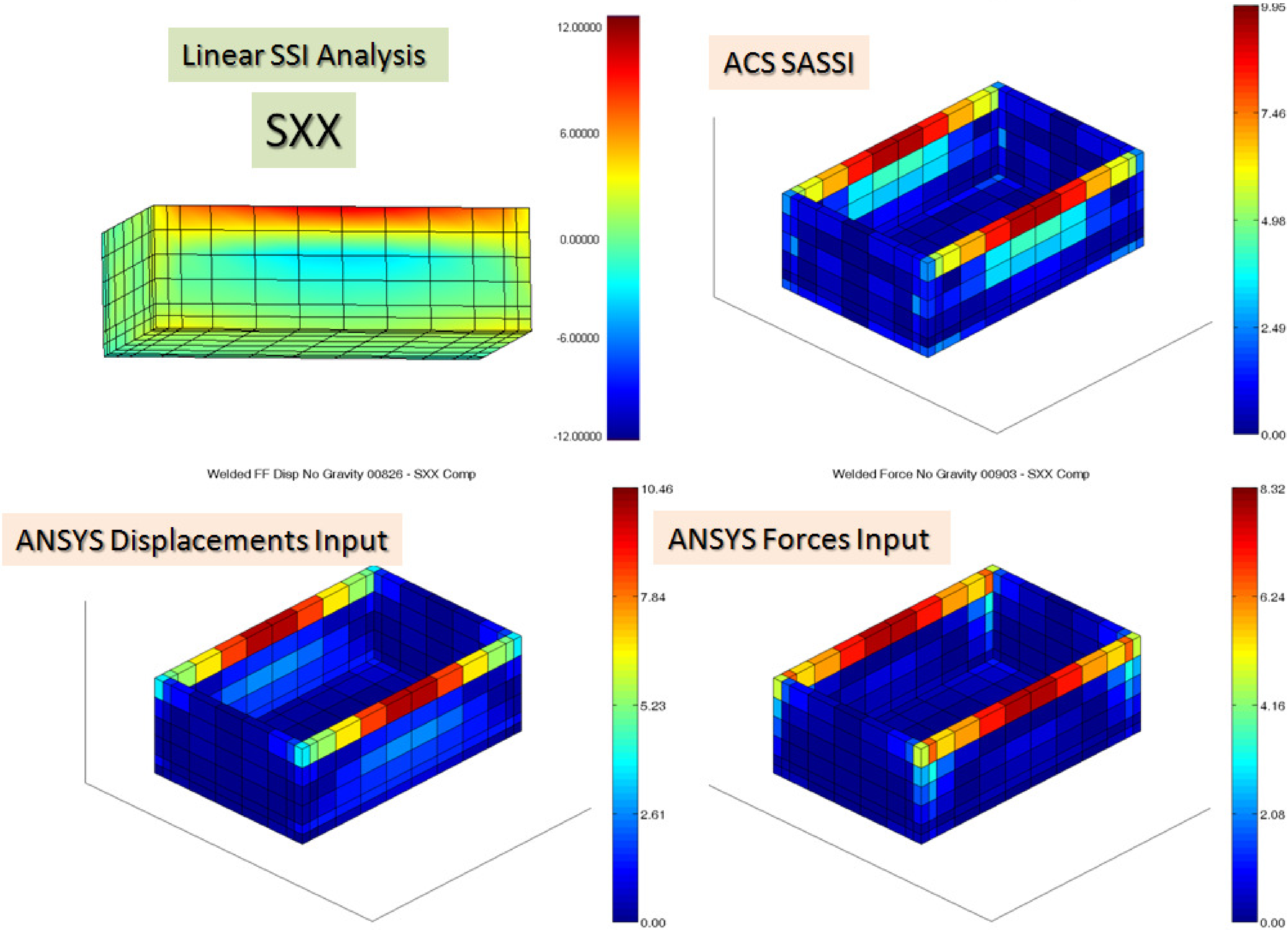
Nonlinear Seismic Soil Pressure Analysis

NONLINEAR CONTACT (FOUNDATION SEPARATION)

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



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



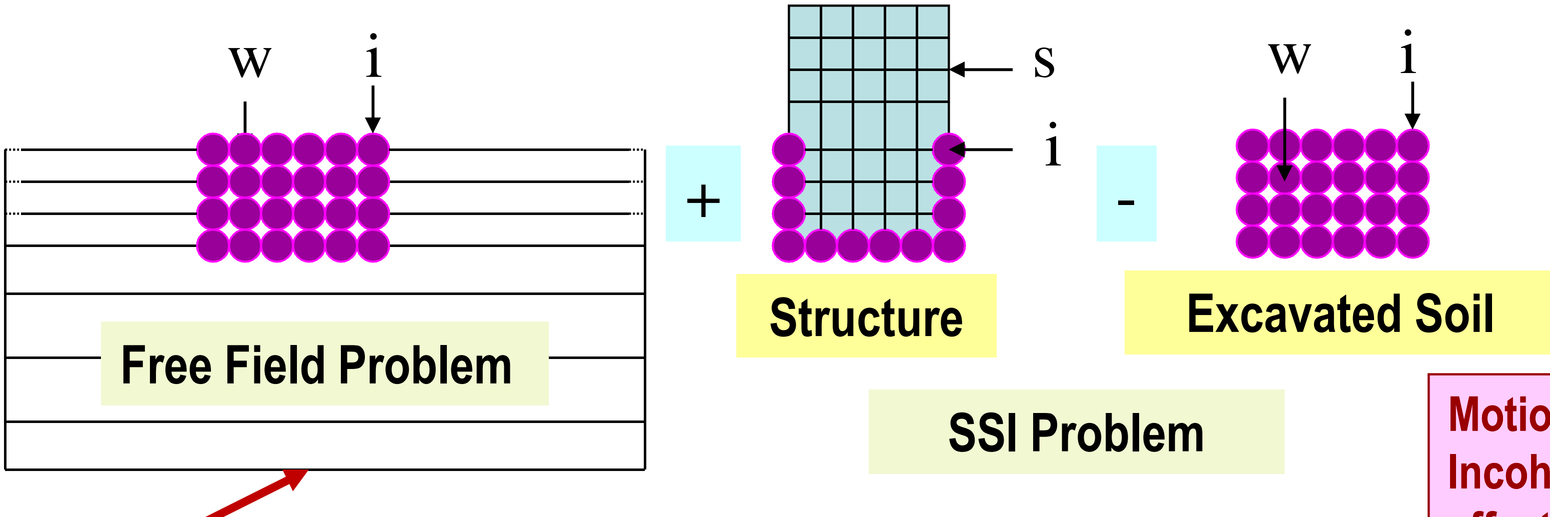
ACS SASSI NQA Version 2.3.0 Incoherent SSI Capabilities

- 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 incoherent SSI approaches validated by EPRI (2007 EPRI TR# 1015111) and endorsed by US NRC (ISG-01, May, 2008).

- It includes a stochastic approach (used as reference method in the 2007 EPRI report) and five deterministic approaches (2 used in the 2007 EPRI report and 3 others) including AS with & without phase adjustment , SRSS TF with zero-phase and coherent phase and SRSS RS (this was used in the 1997 EPRI TR# 102631, but not validated by 2007 EPRI TR# 1015111).

Incoherent SSI Analysis in ACS SASSI



Motion Incoherency affects free-field motion at interaction nodes

Flexible Volume Method (using all excavated volume nodes)

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

Flexible Interface Methods (using boundary volume nodes)

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

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

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

Seismic SSI Analysis Using ACS SASSI

The complex frequency response is computed as follows:

- Coherent SSI response:

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

Structural transfer function given input at interaction nodes

Coherent ground transfer function at interface nodes given control motion

Complex Fourier transform of control motion

•Incoherent SSI response:

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

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

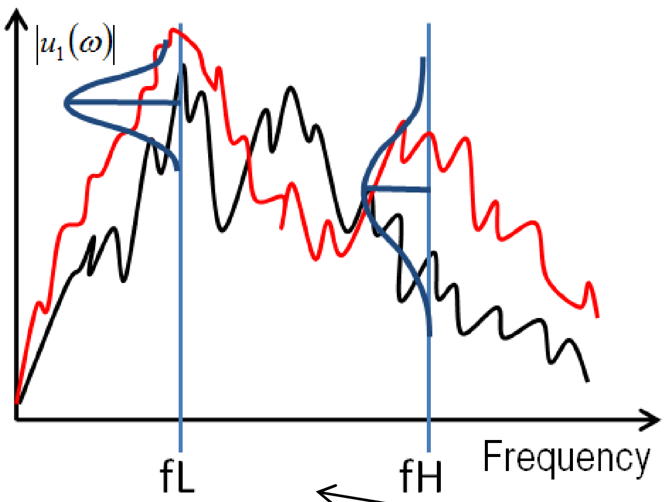
$$S_g(\omega) = [\Phi(\omega)][\lambda(\omega)]\{\eta_\theta\}$$

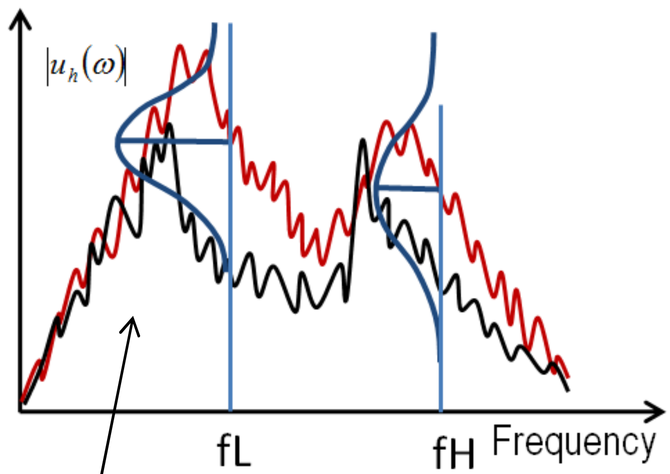
Complex Fourier transform of relative spatial variations of motion at interaction nodes that is stochastic by nature

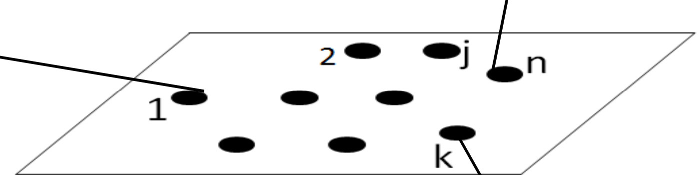
Spectral factorization of coherency kernel

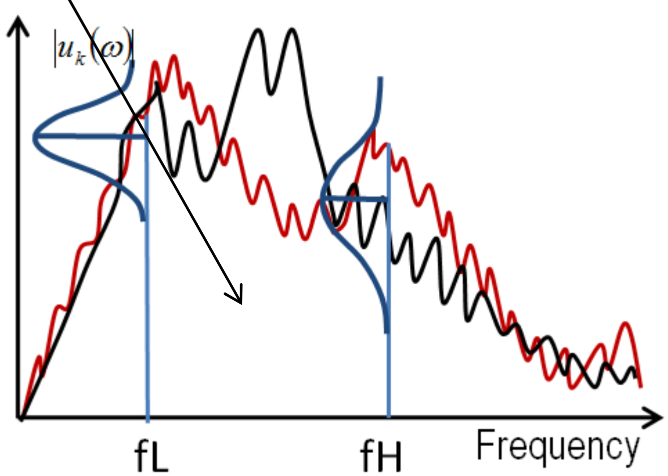
Random phases (stochastic part)

3D Stochastic Wave Model: Incoherent Motion Field









Coherent Function

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

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

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

Seismic Motion Plane-Wave Coherency Function

- Assuming that motion is a Gaussian vector process, then it is fully defined in frequency domain by

local variability

spatial correlation

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

Thus, for two arbitrary points in horizontal plane, j and k, the coherency spectrum or coherence is defined by

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

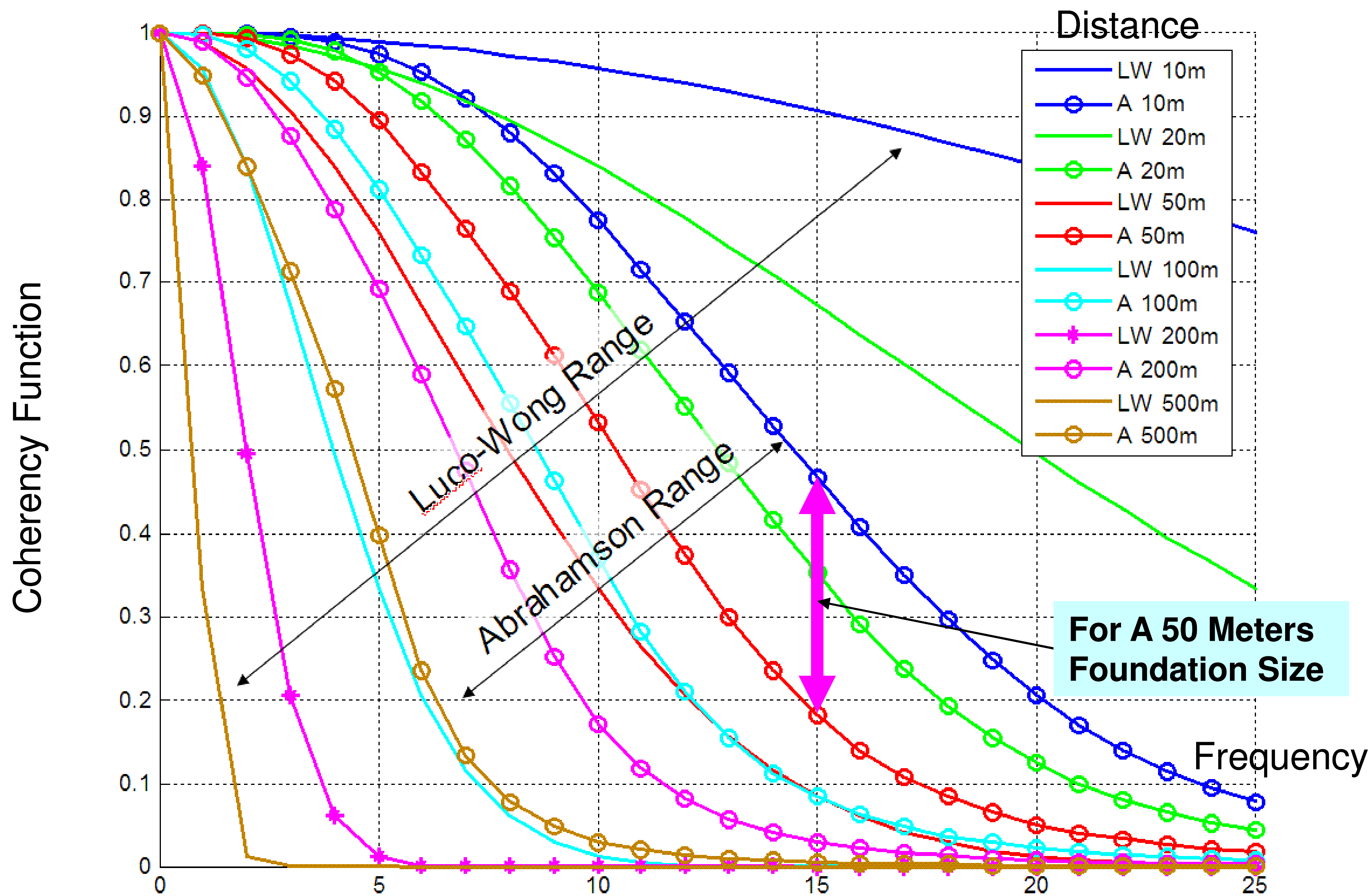
- The "plane-wave coherency" function for SSI analysis is defined as a complex function (Abrahamson, 1991-2007) including "spatial incoherency" (amplitude) and "wave passage" (phase) effects

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

amplitude variability

phase shift

Comparison of 1986 Luco-Wong and 2005 Abrahamson Plane-Wave Incoherency Models



Implemented Plane-Wave Incoherency Models

There are 6 plane-wave incoherency models (with wave passage effects):

1) For Luco-Wong model, 1986 (theoretical, unvalidated, geom anisotropic)
2) For 1993 Abrahamson model for all sites and surface foundations
3) For 2005 Abrahamson model for all sites and surface foundations
4) For 2006 Abrahamson model for all sites and embedded foundations
5) *For 2007 Abrahamson model for hard-rock sites and all foundations (NRC)*
6) *For 2007 Abrahamson model for soil sites and surface foundations*

NOTE:

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

2007 Abrahamson Coherence for Hard-Rock and Soil Sites

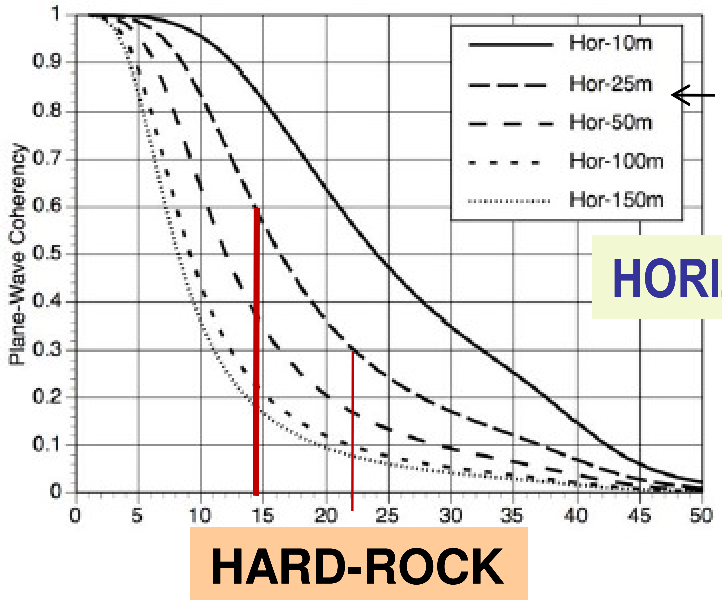


Figure 6-1
Plane-Wave Coherency for the Horizontal Component

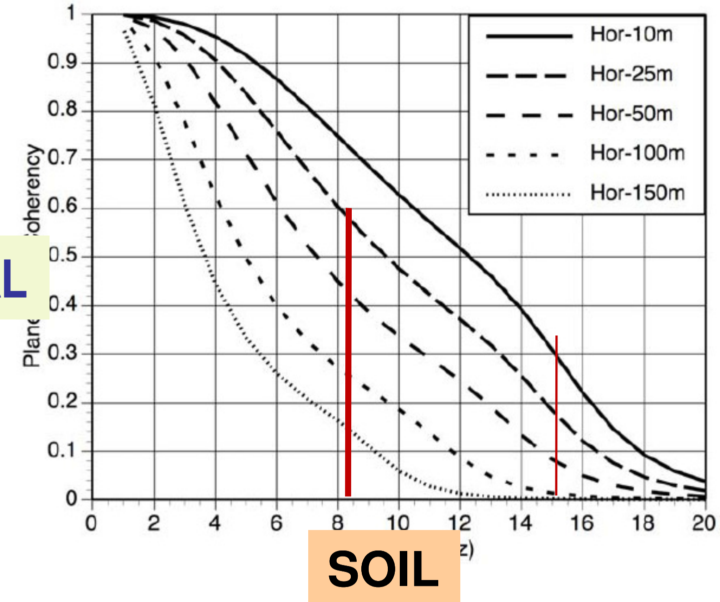


Figure 7-1
Plane-Wave Coherency for the Horizontal Component for Soil Sites

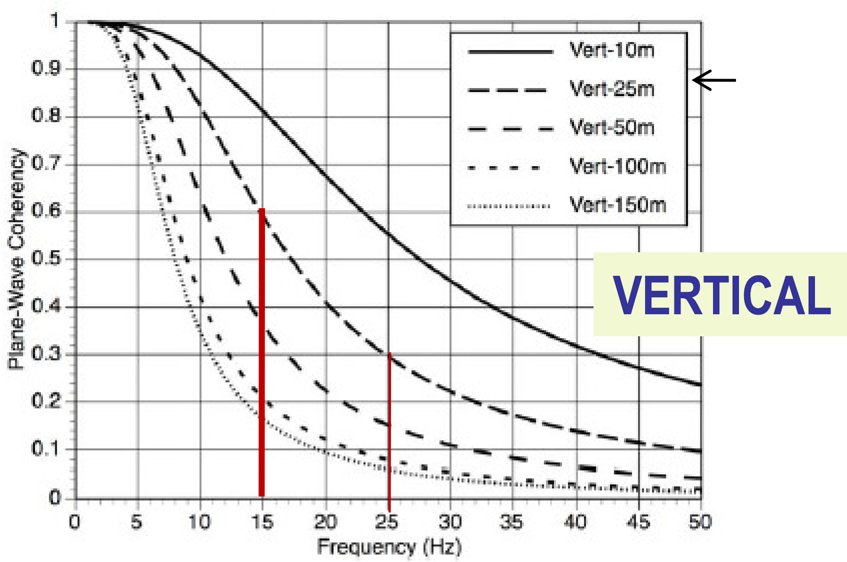


Figure 6-2
Plane-Wave Coherency for the Vertical Component

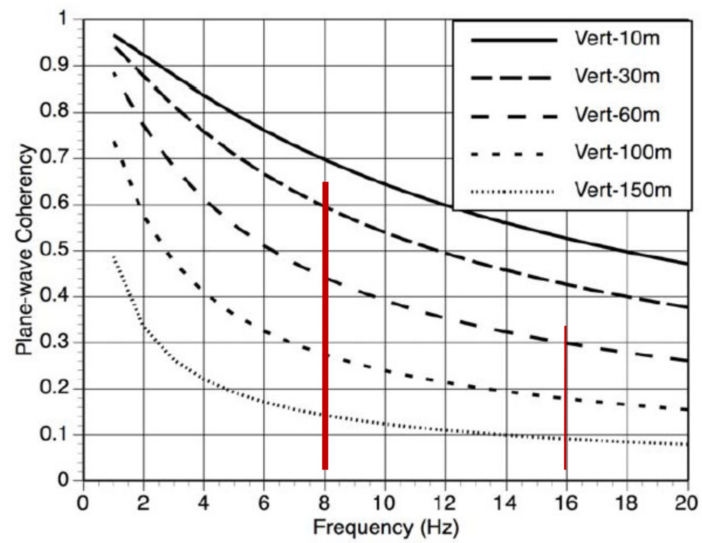
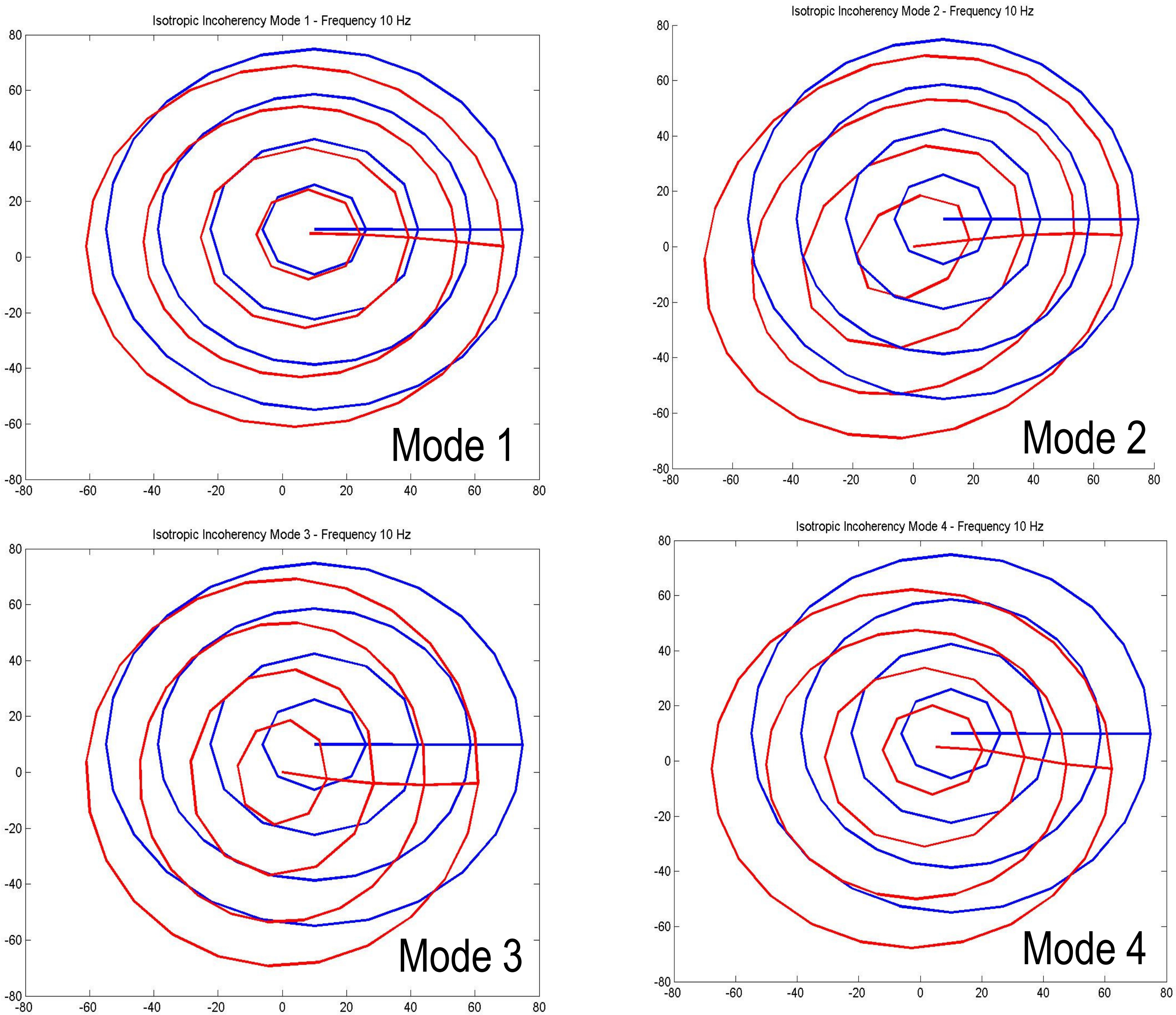


Figure 7-2
Plane-Wave Coherency for the Vertical Component for Soil Sites

(EPRI TR # 1015110, December 2007)

Motion Incoherency Modes of Basemat at 10 Hz

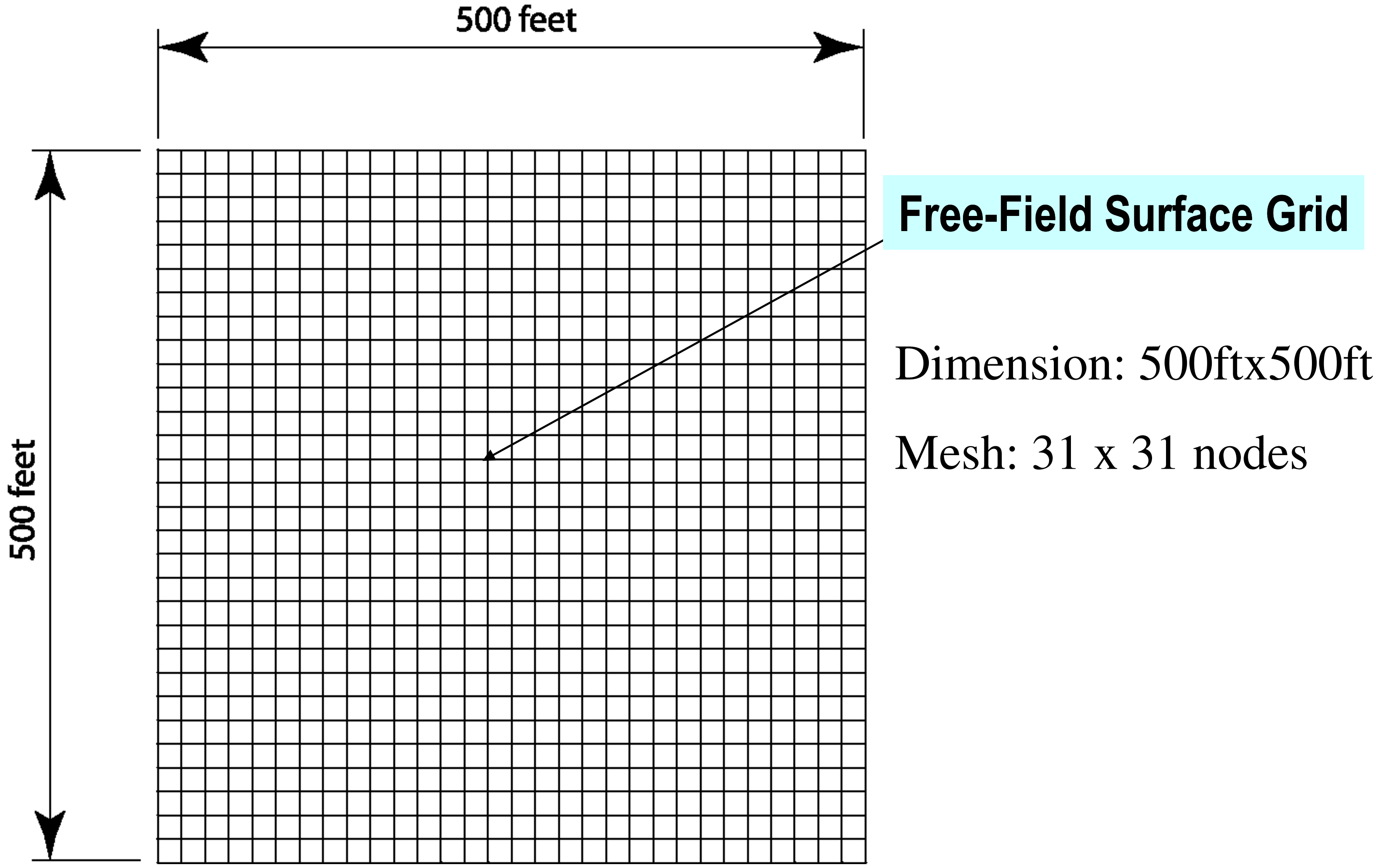


REMARKS:

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

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

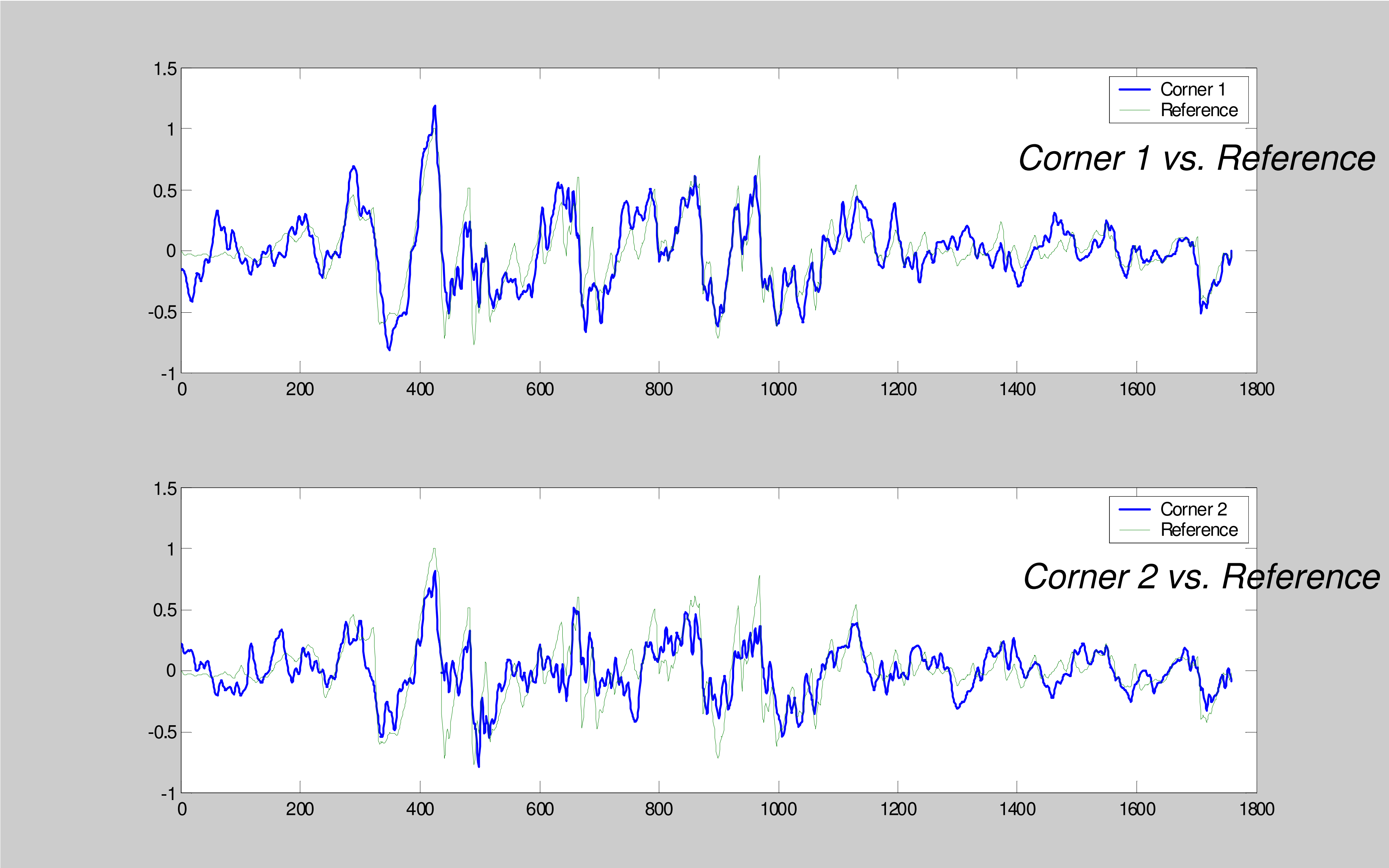
Incoherent Free-Field Motion



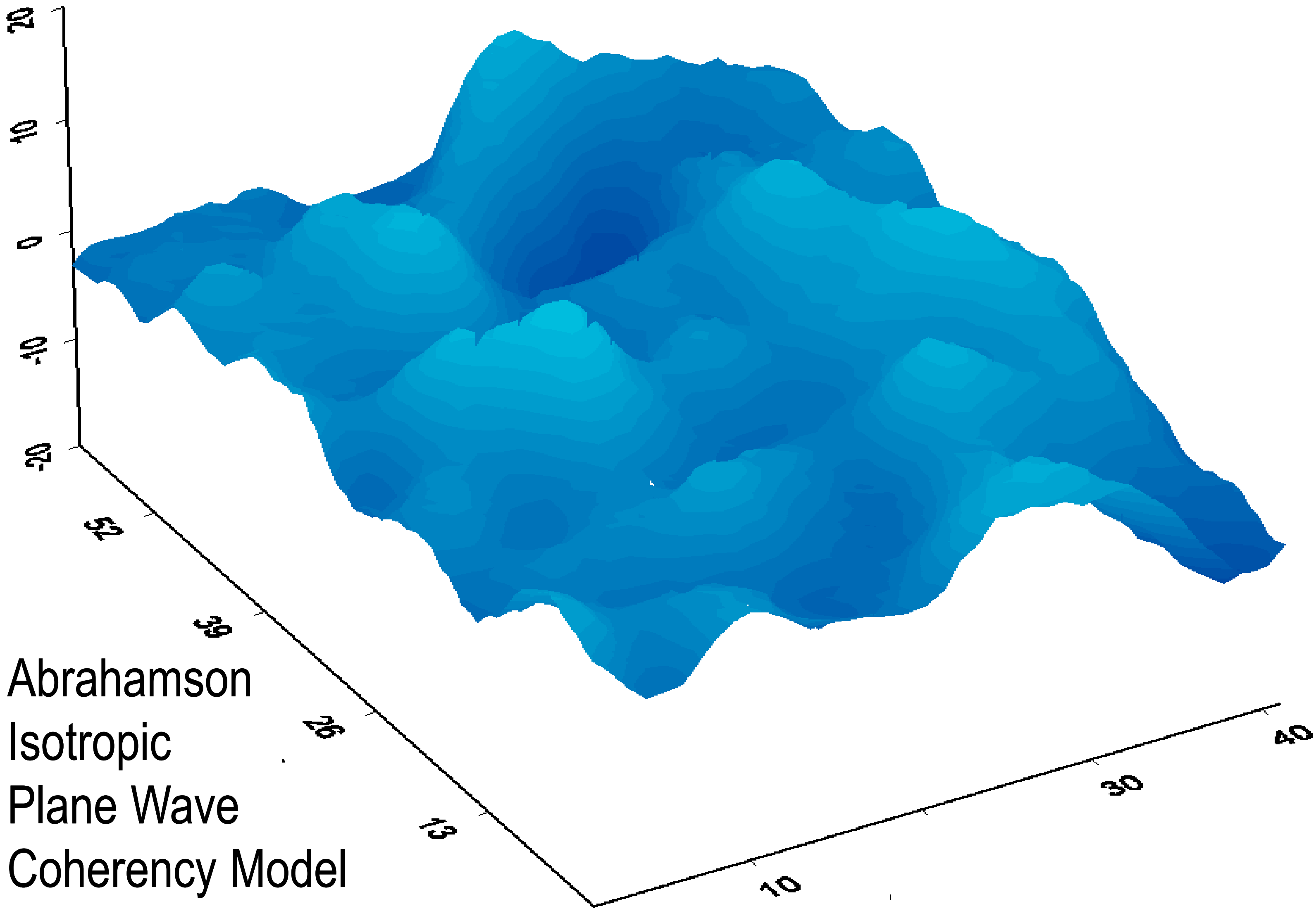
Dimension: 500ftx500ft

Mesh: 31 x 31 nodes

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

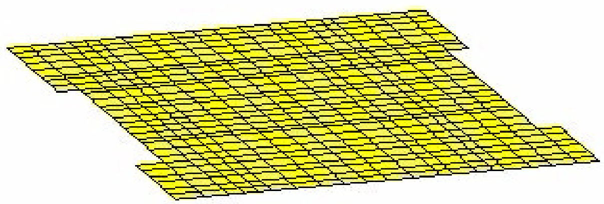


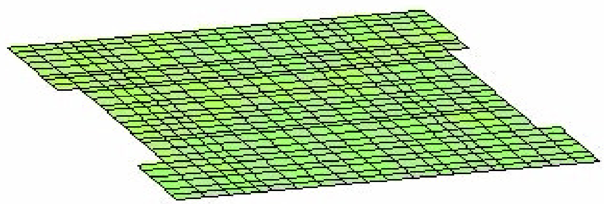
Simulated Incoherent Motion Amplitude at 10 Hz



Abrahamson
Isotropic
Plane Wave
Coherency Model

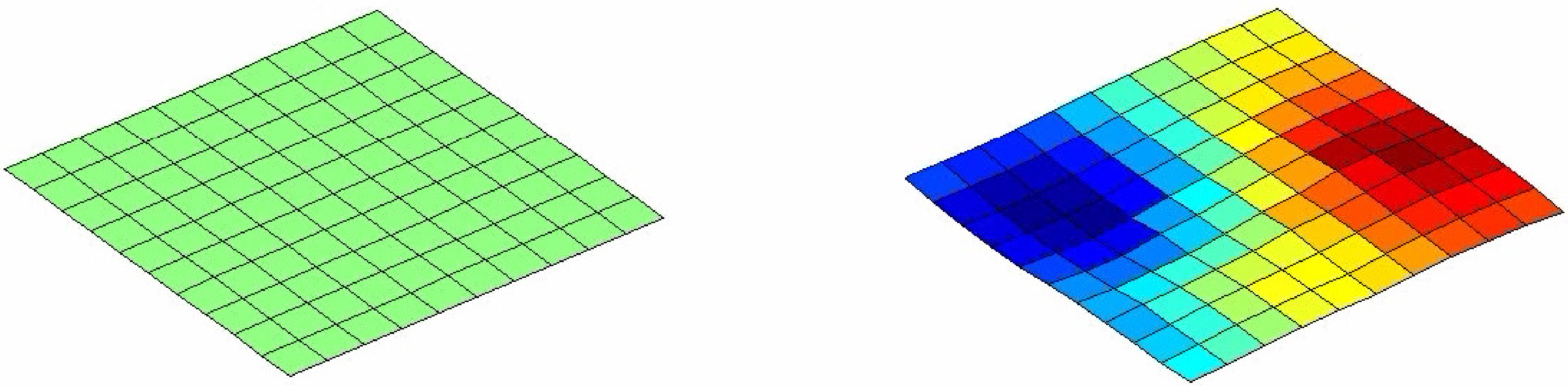
Seismic Free-Field Incoherent Motion Simulation (3-Directional Motion at Foundation-Soil Interface)





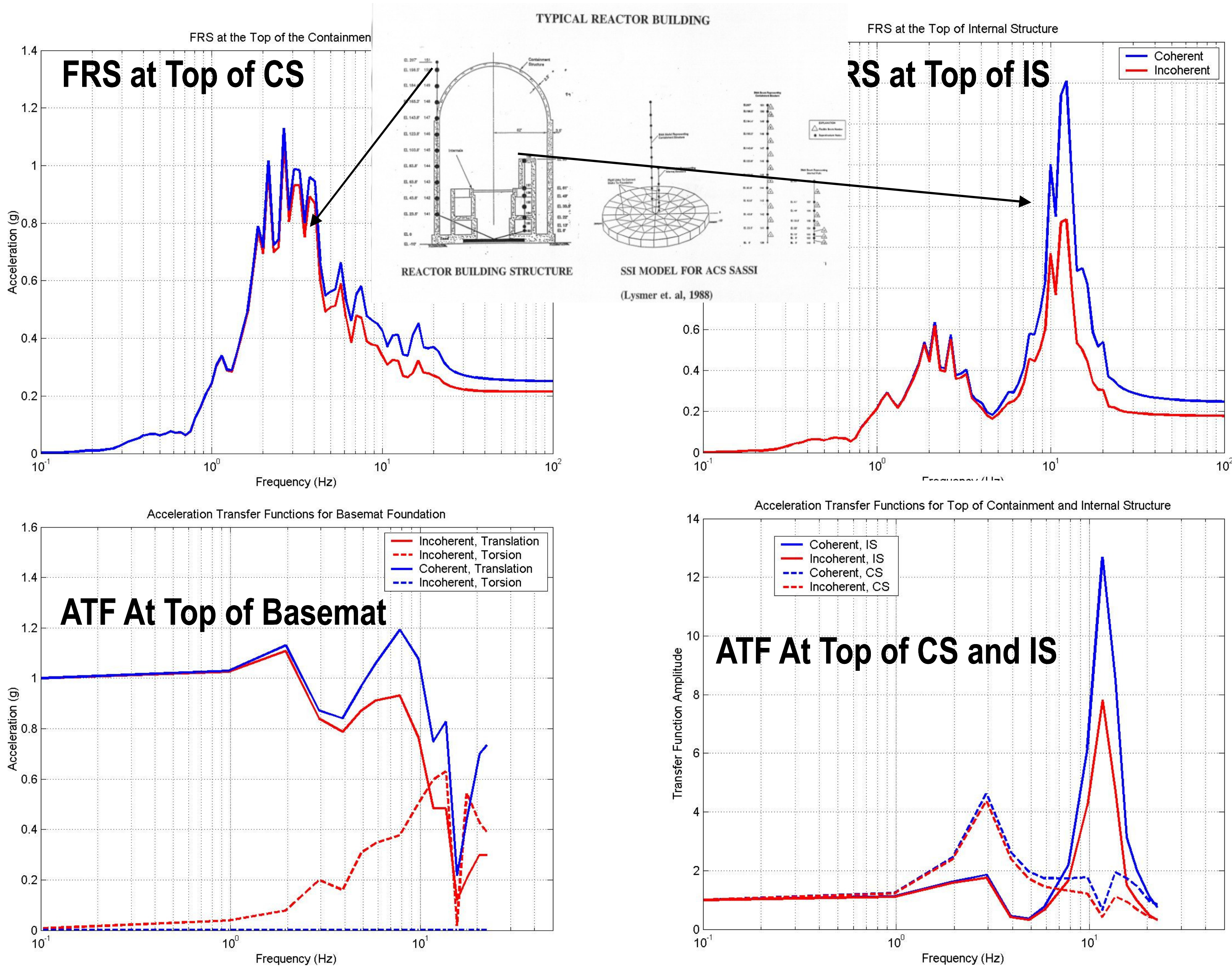
ANIMATIONS

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

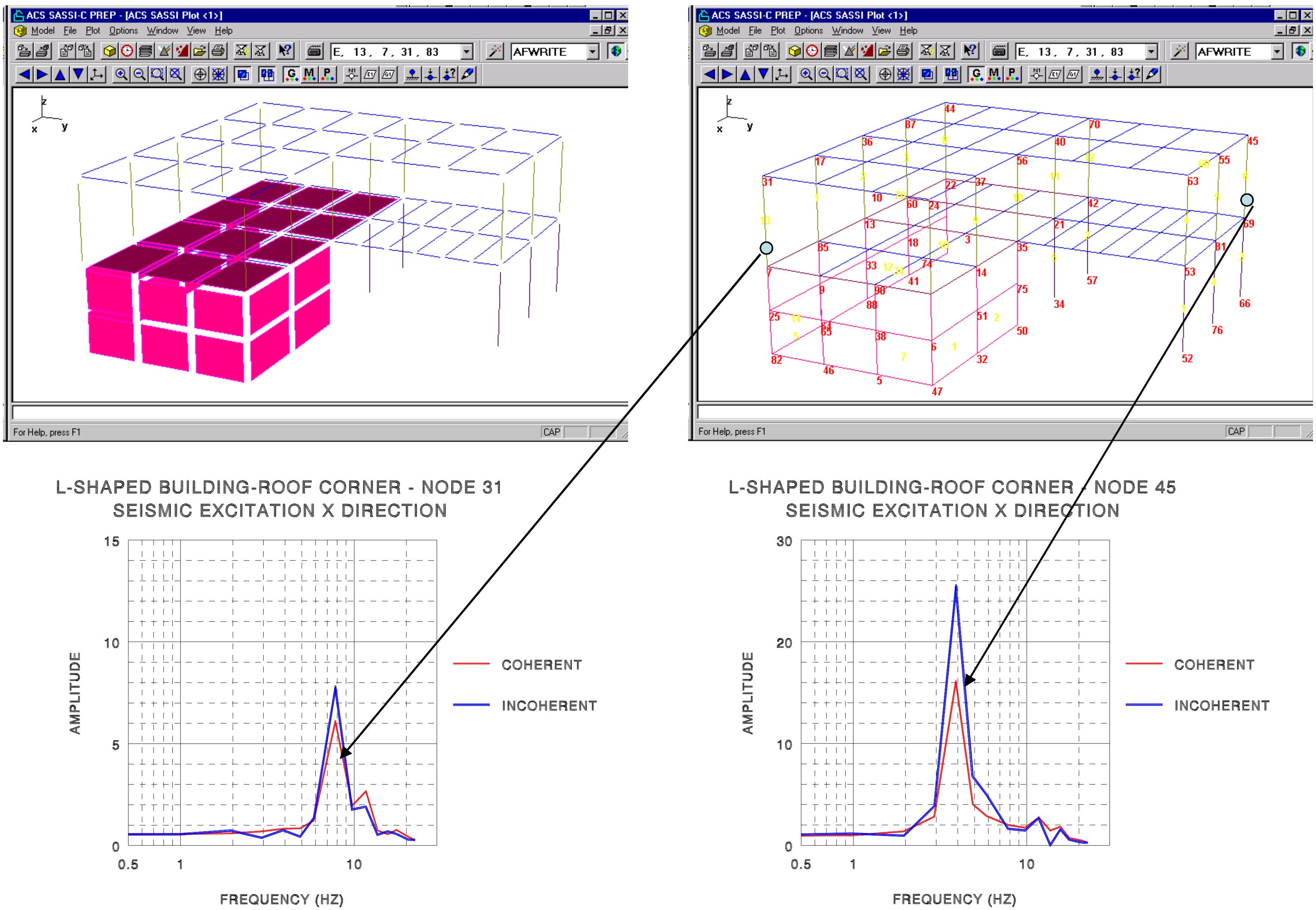


ANIMATIONS

An Axisymmetric RB Structure Founded on A Soil Site



L-Shaped Composite Auxiliary Building



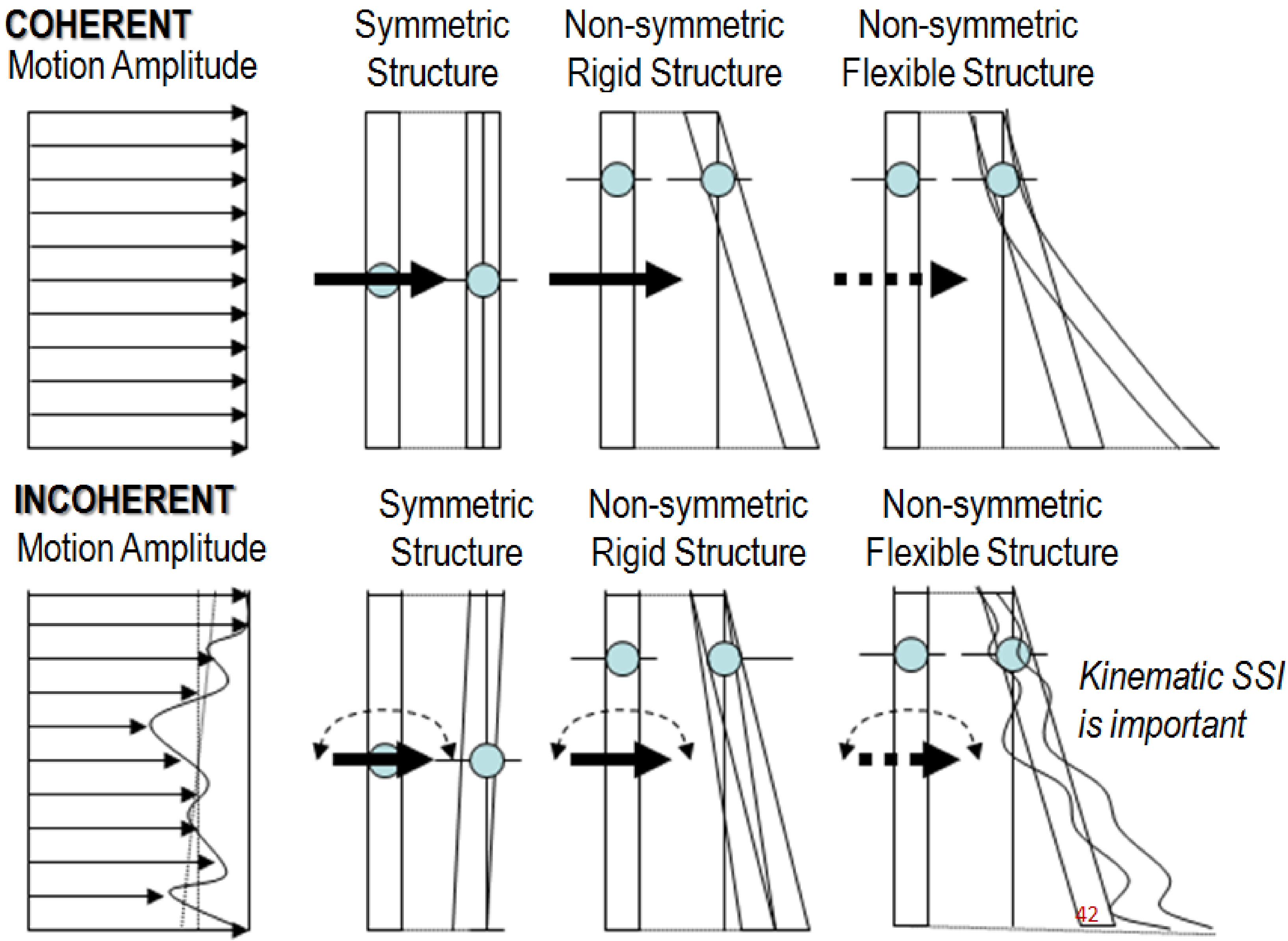
Flexible Foundations vs. Rigid Foundations

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.

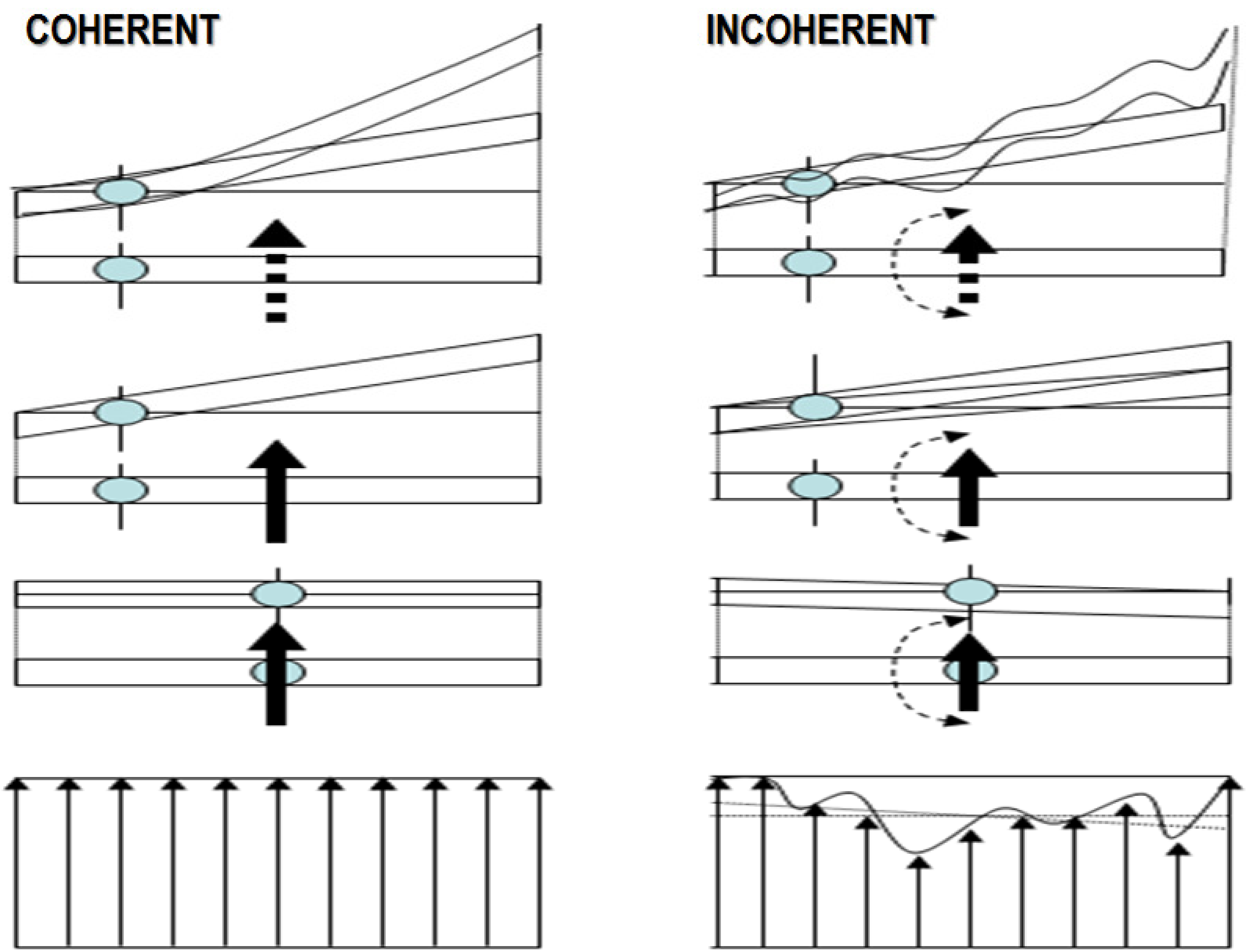
For *flexible foundations*, the incoherency-induced stochasticity of the basemat motion is driven by the local spatial variations (point variations) of free-field motion. Therefore, is much more complex and locally random, with an unsmoothed spatial variation pattern. Kinematic SSI is reduced, so that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

Coherent vs. Incoherent SSI Response - Horizontal

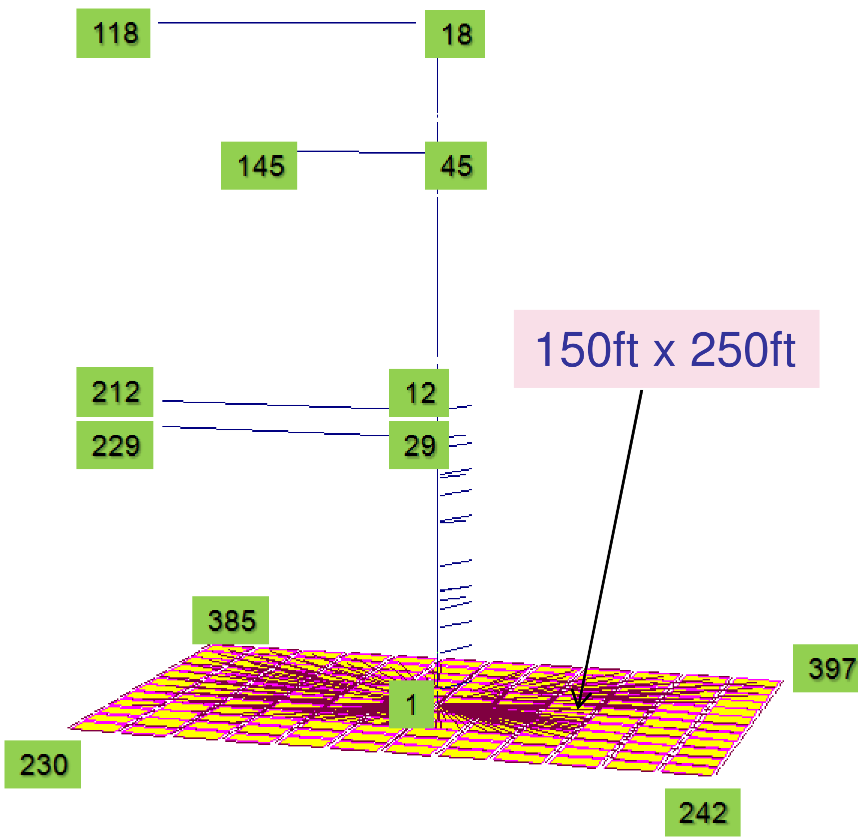


Coherent vs. Incoherent SSI Response – Vertical



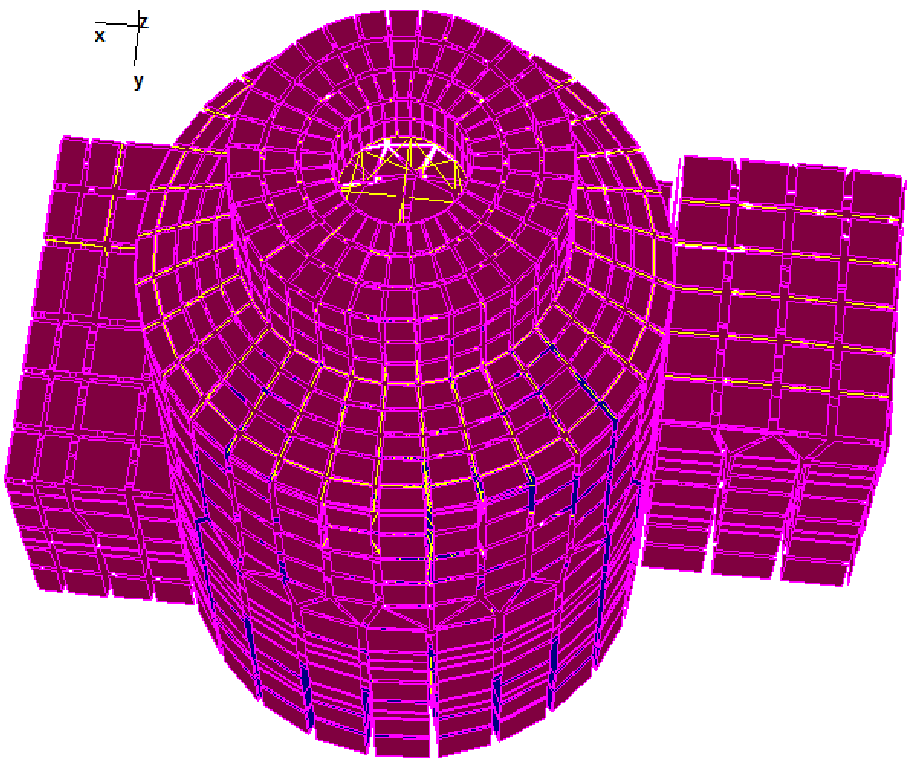
Stick with Rigid Mat vs. FE Model with Flexible Mat

Stick SSI Model



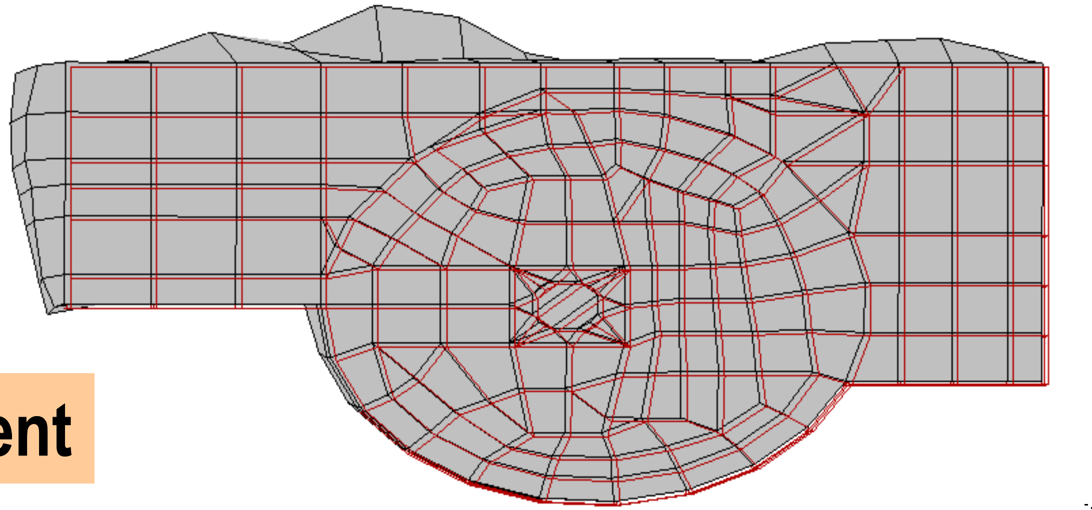
Accurate structural modeling up to 20-30 Hz

NI20 SSI Model

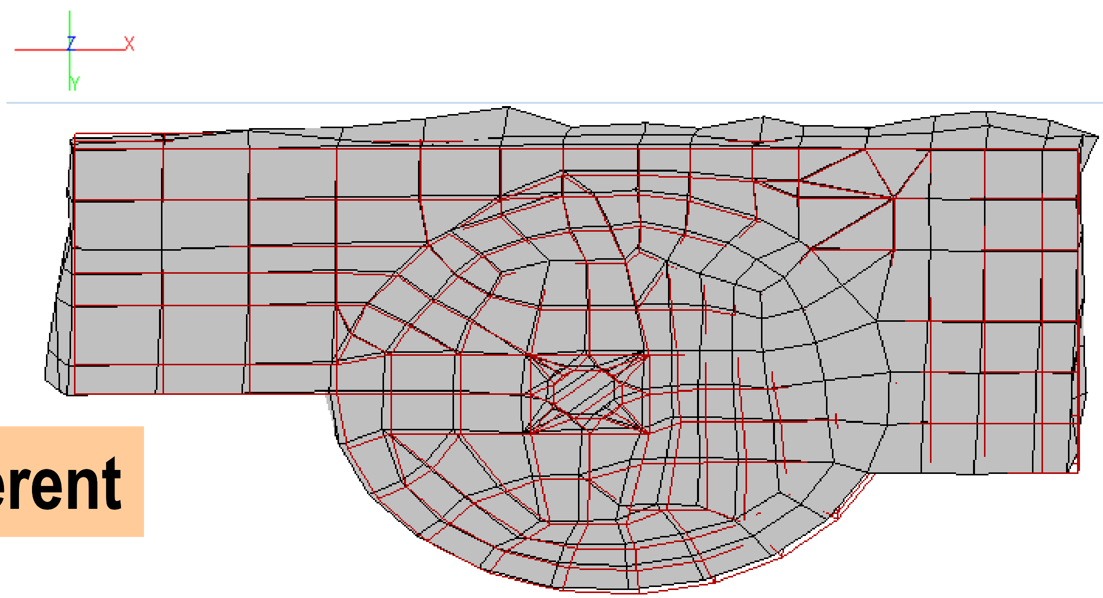


Accurate structural modeling up to 100 Hz

Coherent vs. Incoherent Basemat SSI Motion

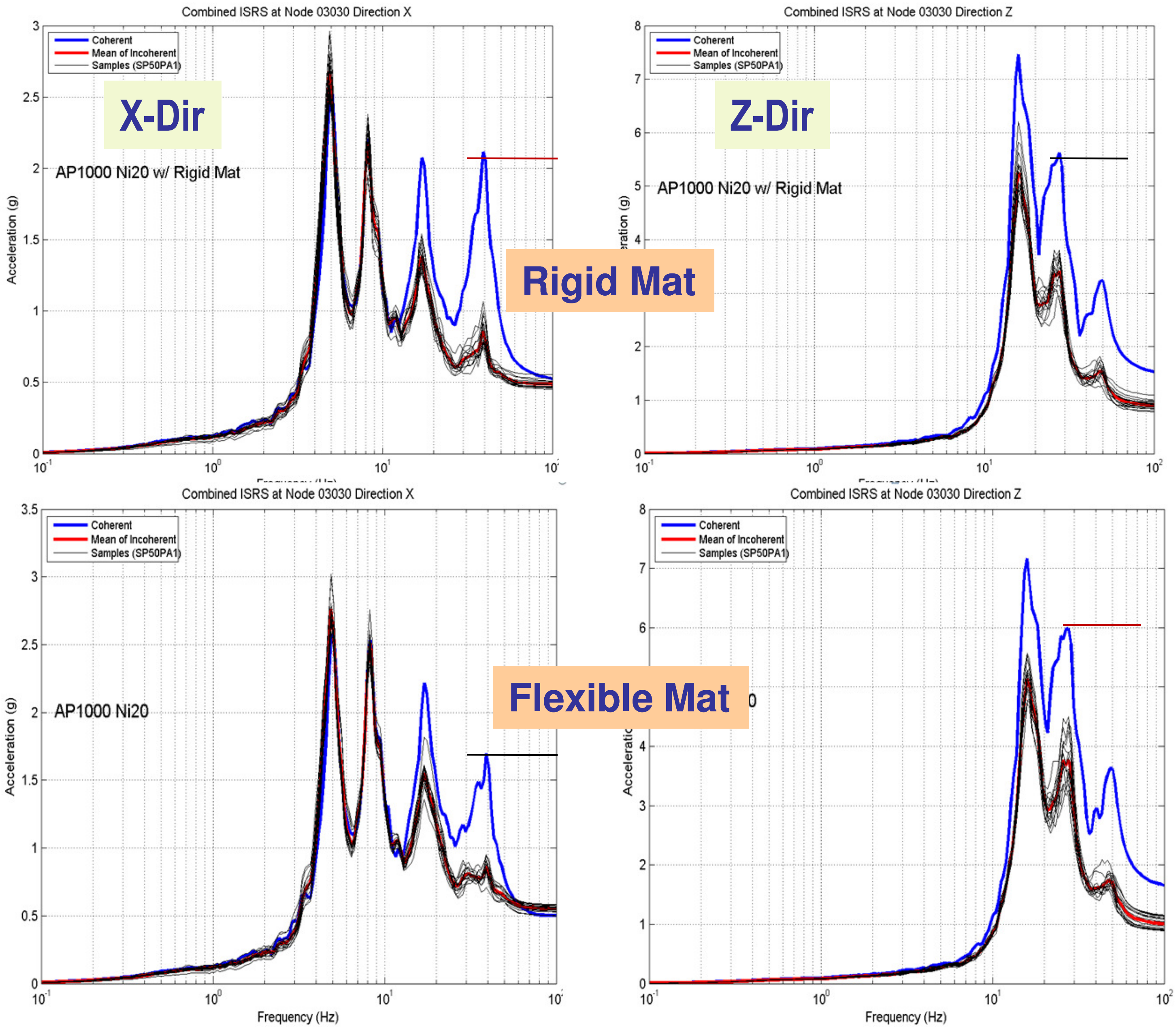


Coherent

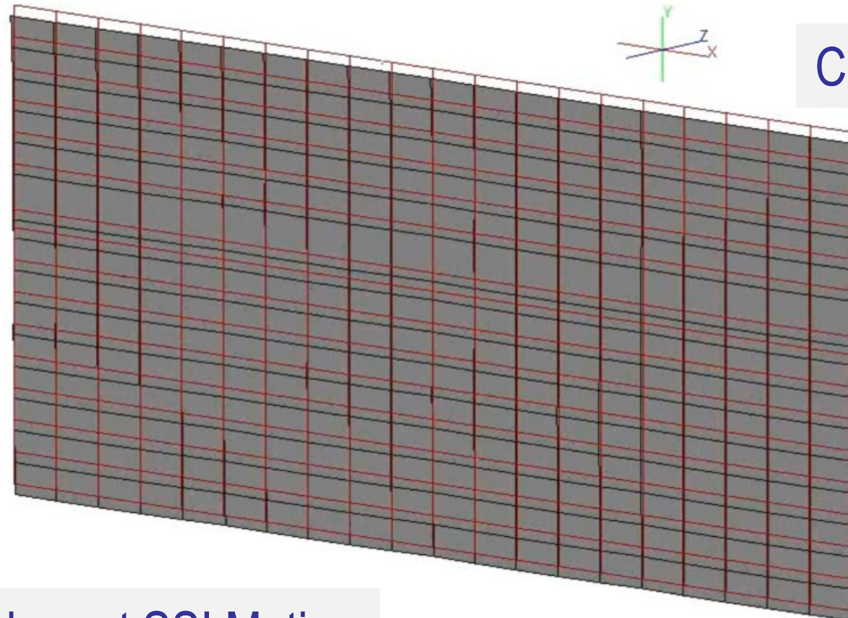


Incoherent

AP1000 NI20 Model Basemat Flexibility Study

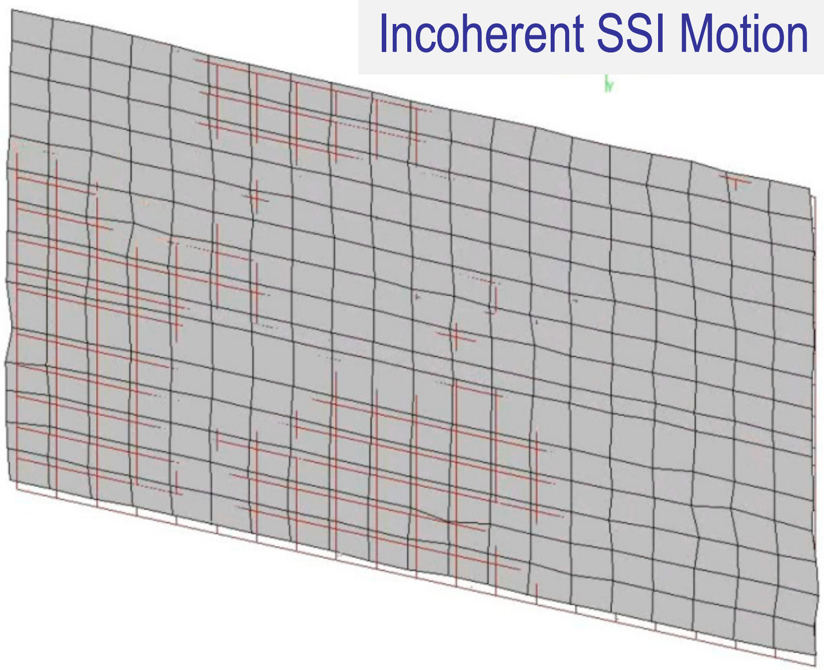


Coherent and Incoherent Basemat SSI Motion View

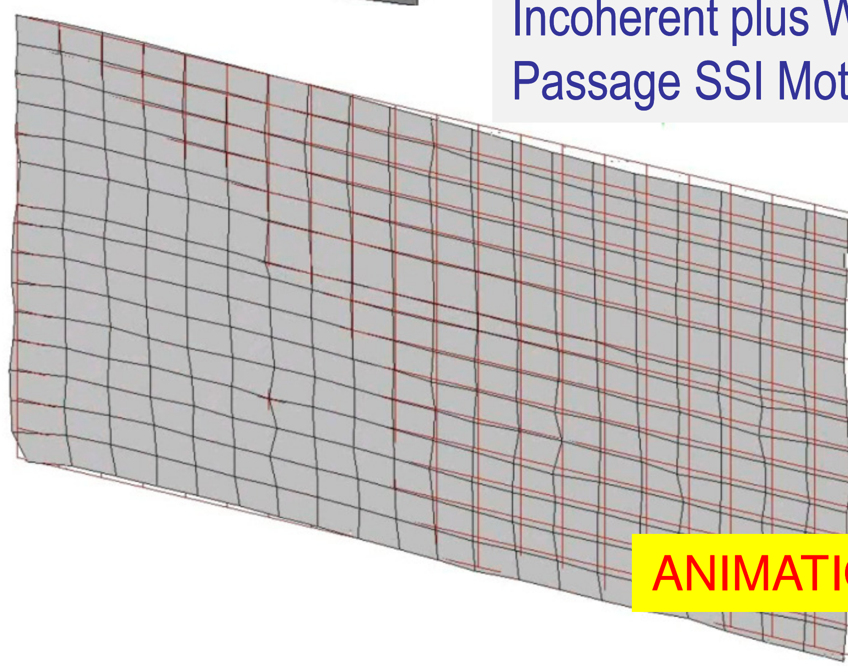


Coherent SSI Motion

Incoherent SSI Motion



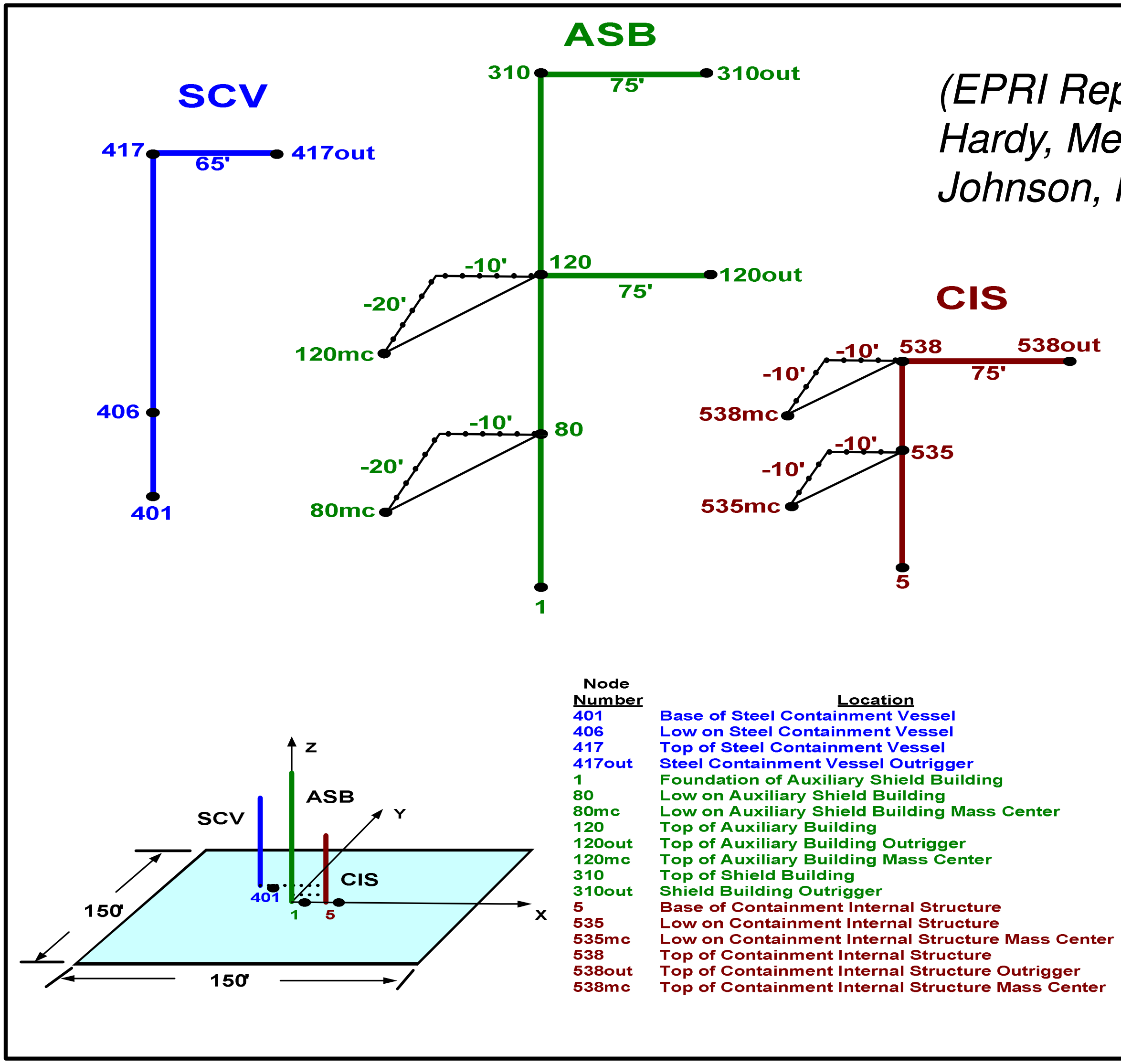
Incoherent plus Wave Passage SSI Motion



ANIMATIONS

EPRI Validation of ACS SASSI for Incoherent SSI

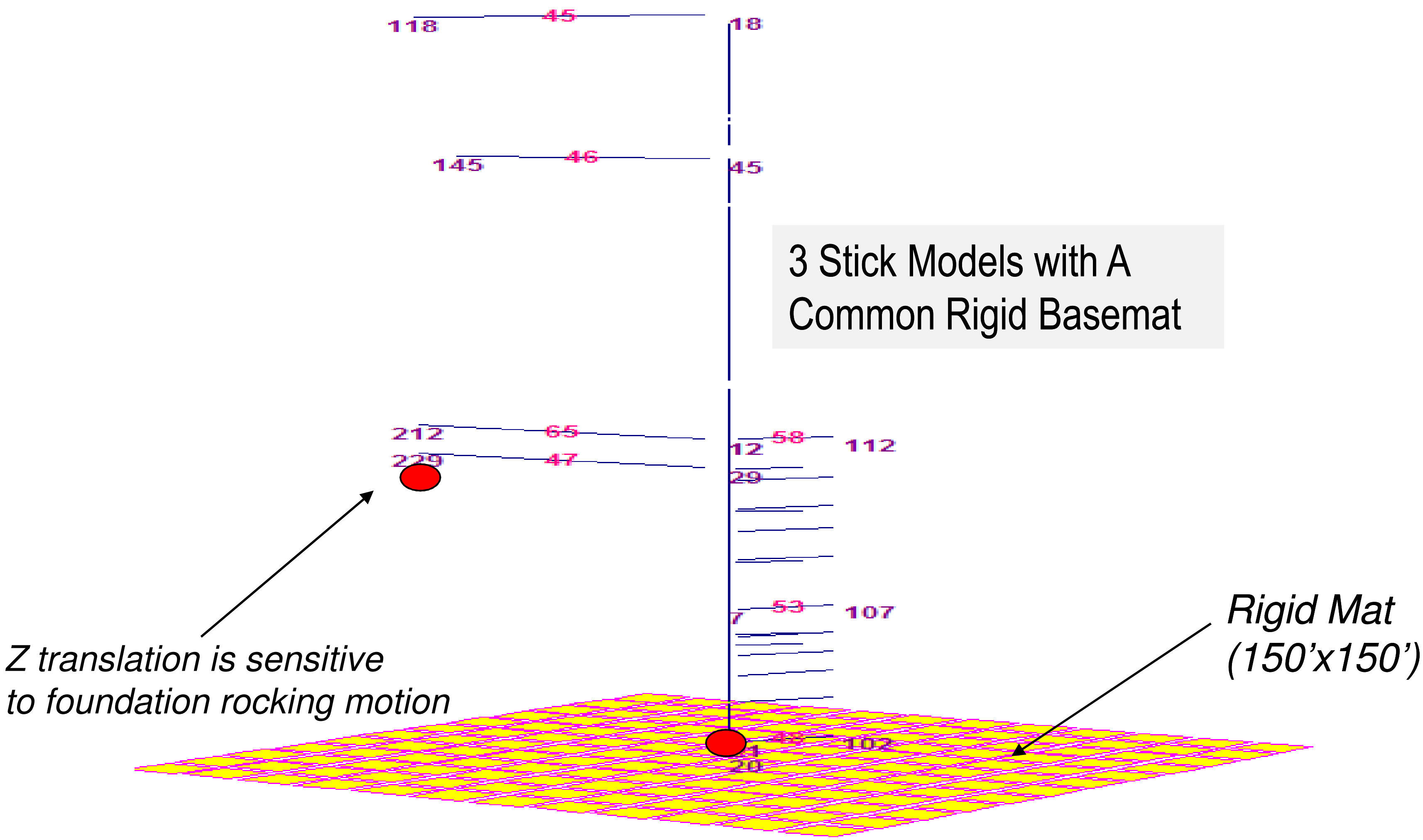
EPRI AP1000 Stick NI Model Masses (150ftx150ft)

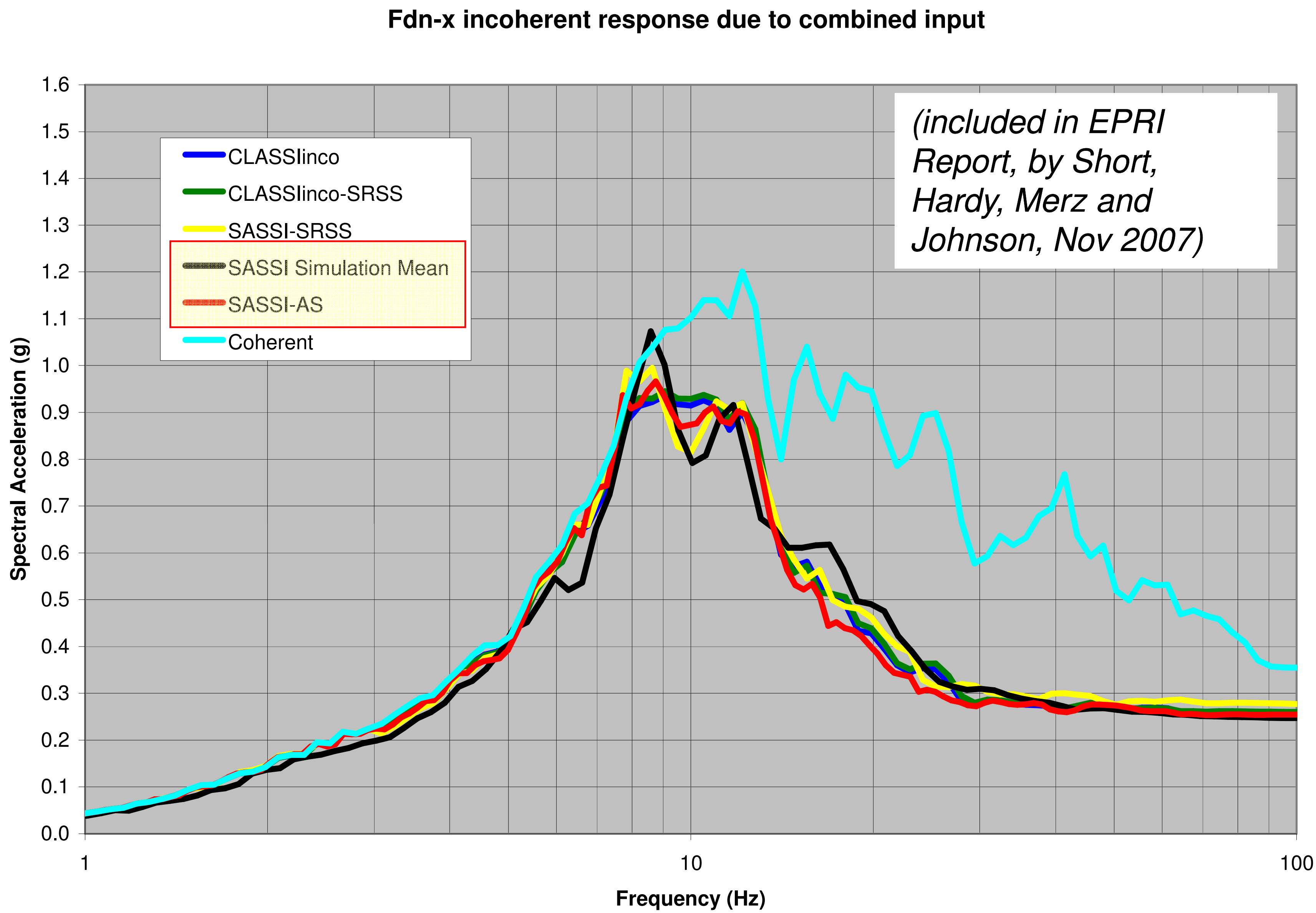


(EPRI Report, by Short, Hardy, Merz and Johnson, Nov 2007)

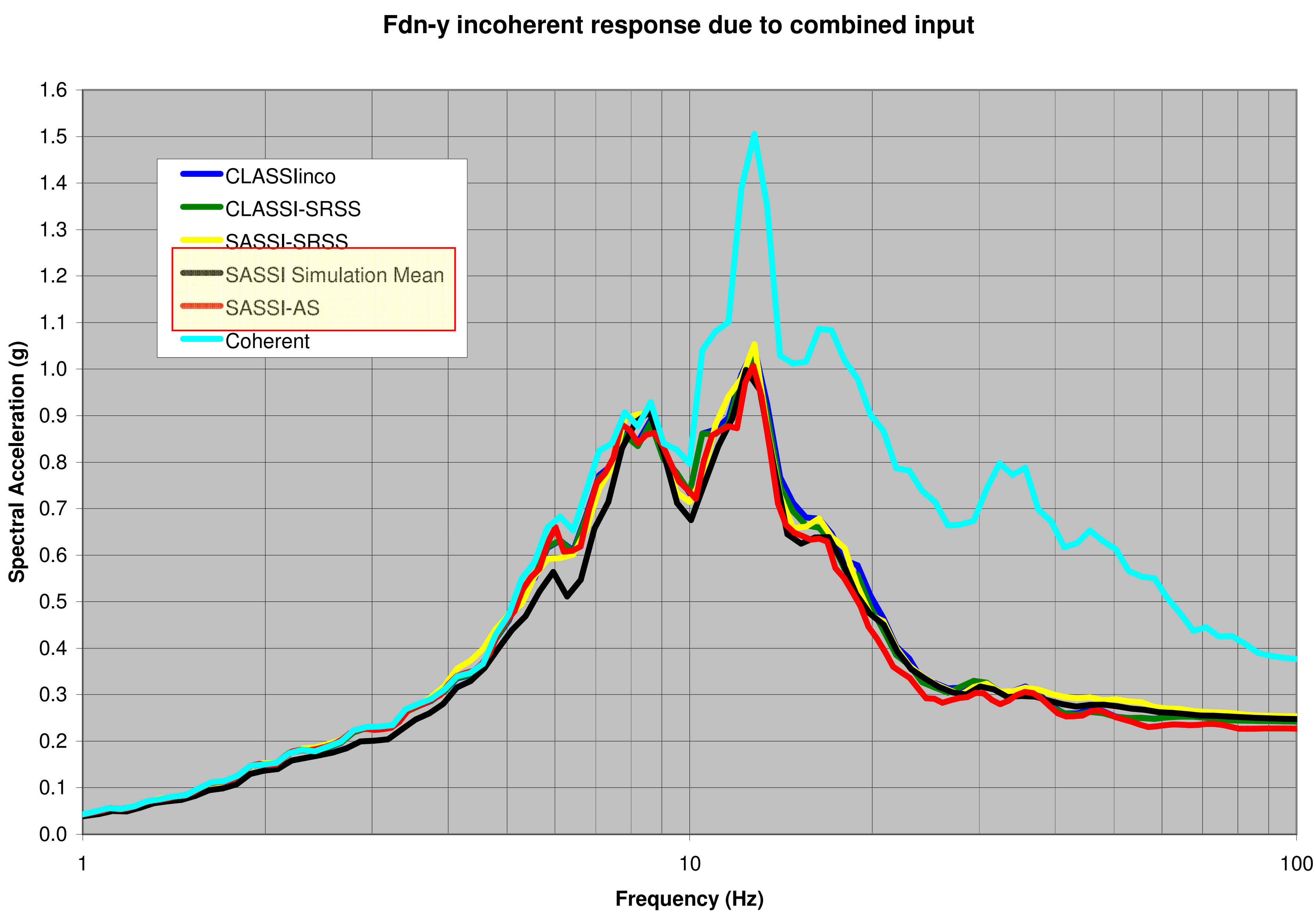
Node Number	Location
401	Base of Steel Containment Vessel
406	Low on Steel Containment Vessel
417	Top of Steel Containment Vessel
417out	Steel Containment Vessel Outrigger
1	Foundation of Auxiliary Shield Building
80	Low on Auxiliary Shield Building
80mc	Low on Auxiliary Shield Building Mass Center
120	Top of Auxiliary Building
120out	Top of Auxiliary Building Outrigger
120mc	Top of Auxiliary Building Mass Center
310	Top of Shield Building
310out	Shield Building Outrigger
5	Base of Containment Internal Structure
535	Low on Containment Internal Structure
535mc	Low on Containment Internal Structure Mass Center
538	Top of Containment Internal Structure
538out	Top of Containment Internal Structure Outrigger
538mc	Top of Containment Internal Structure Mass Center

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



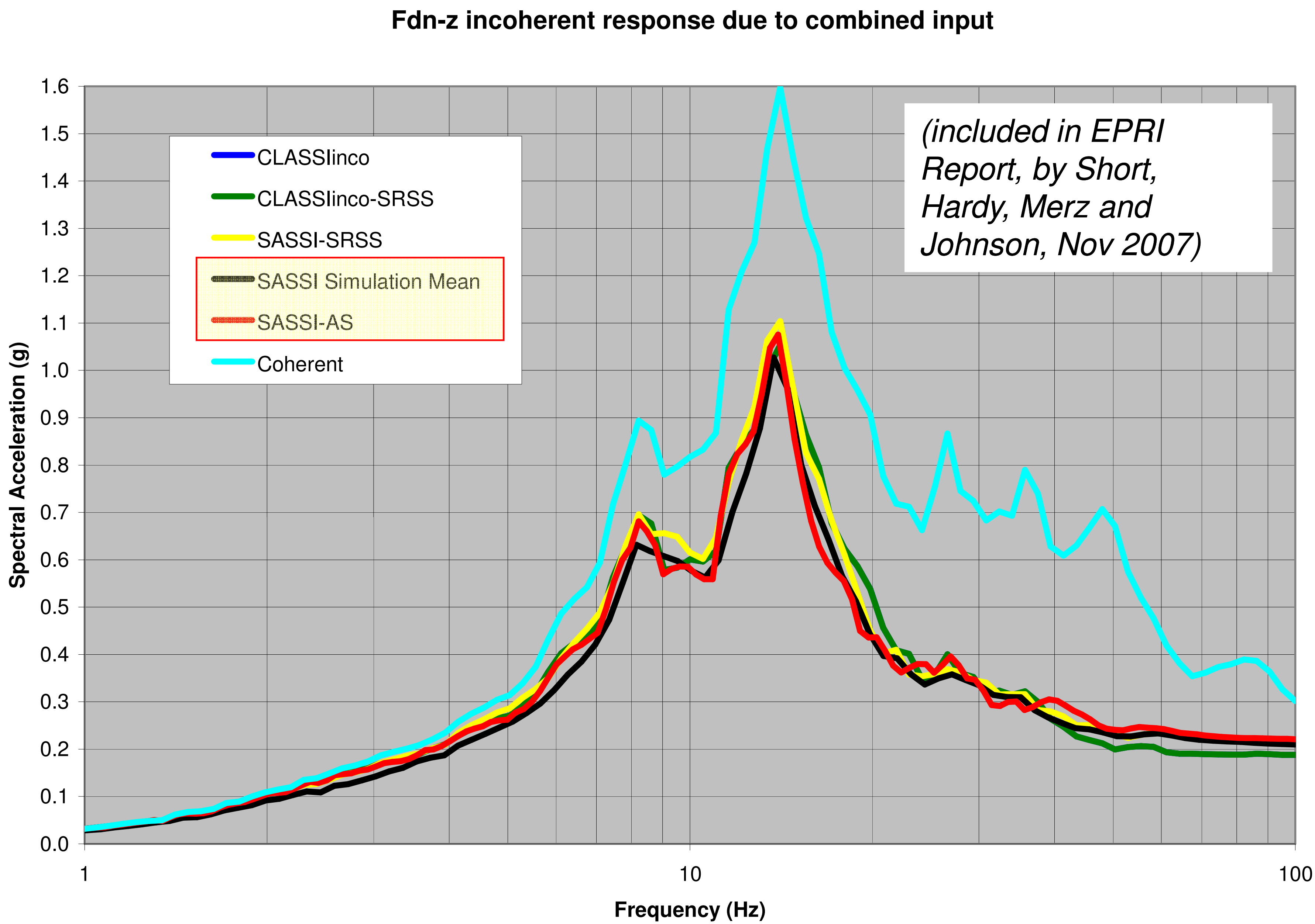


Center of Foundation (Node 1) Response Spectra – X Direction
CLASSlinco, CLASSlinco-SRSS, Bechtel SASSI-SRSS, ACS SASSI Simulation Mean and AS

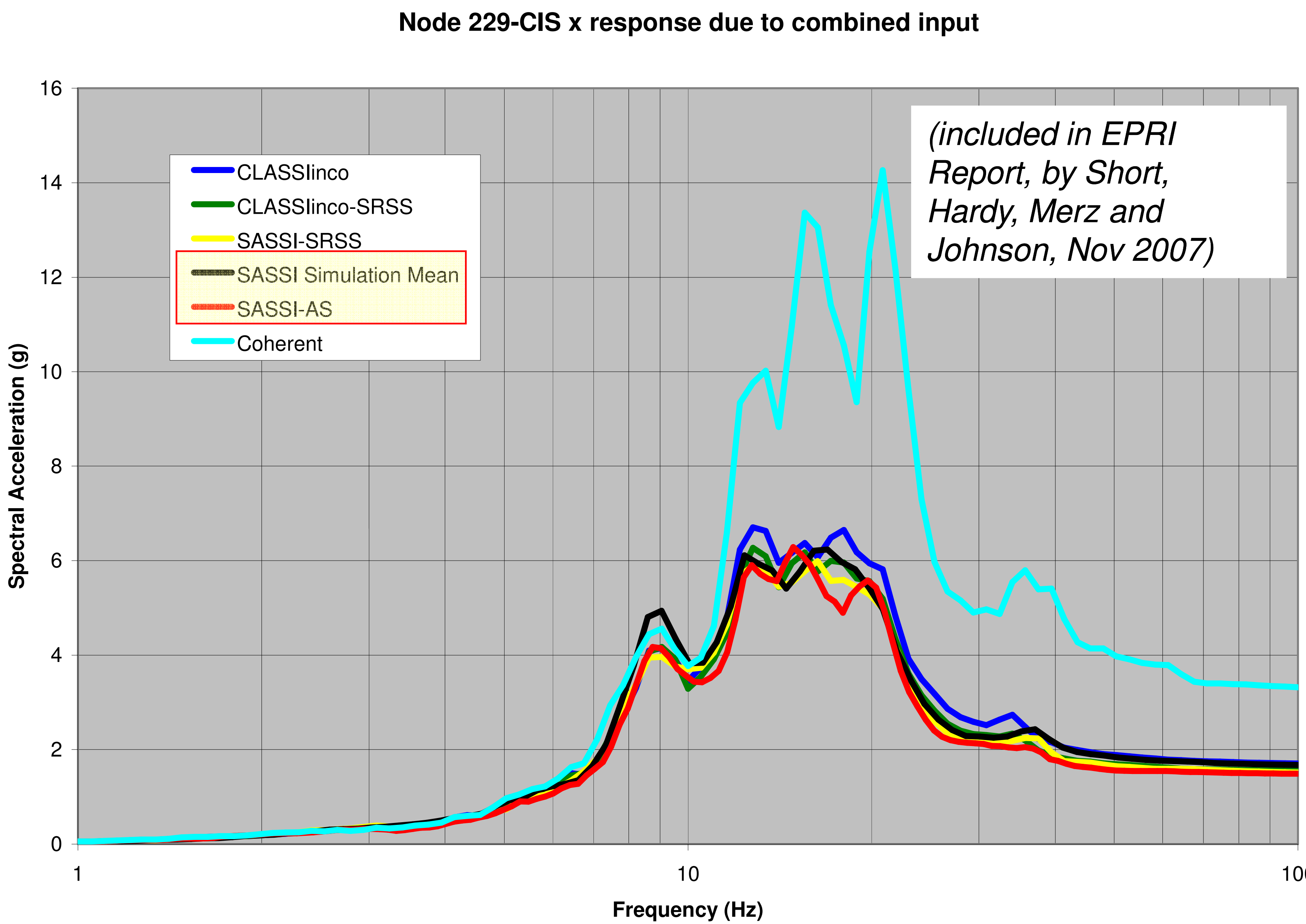


Center of Foundation (Node 1) Response Spectra – Y Direction

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

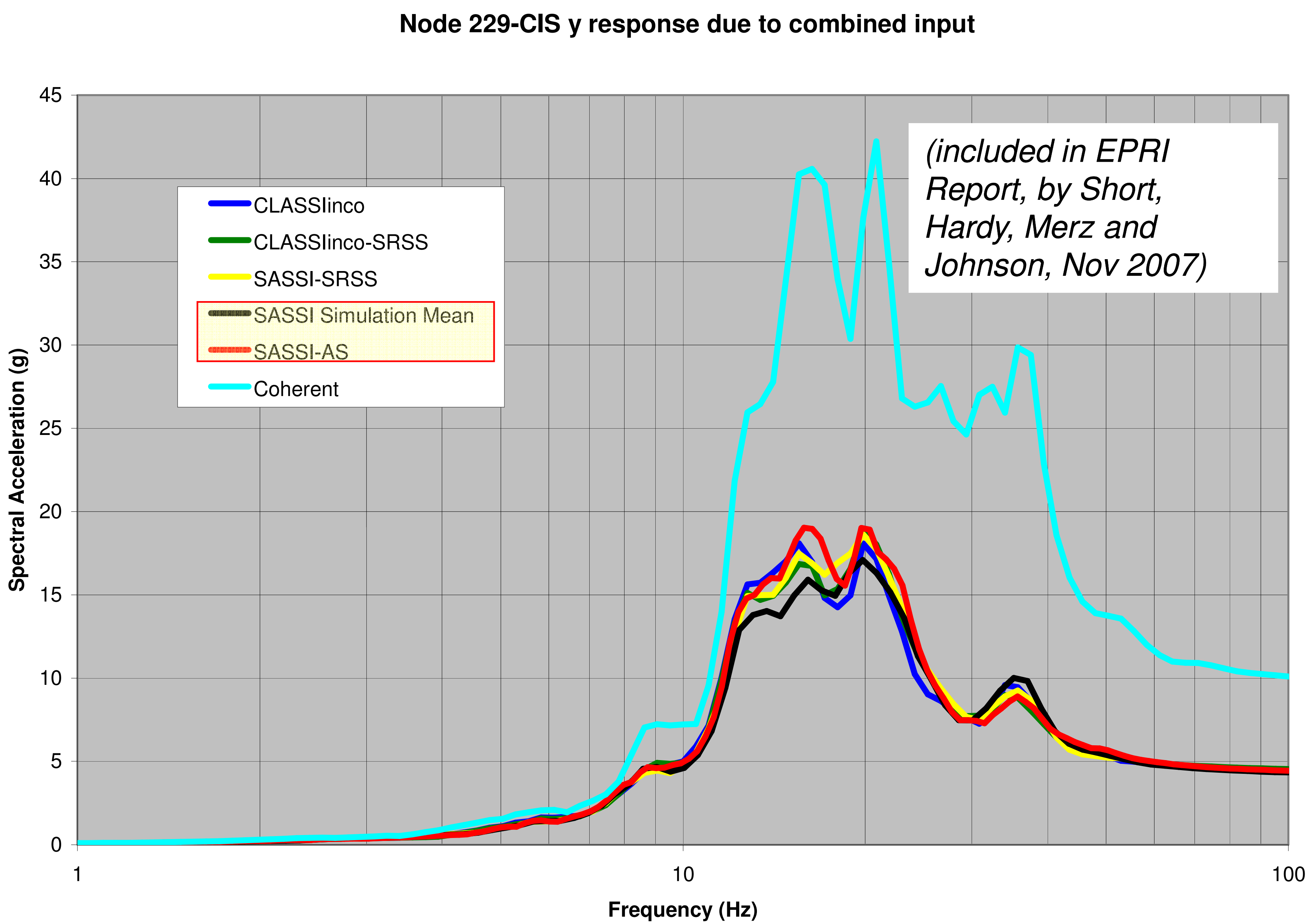


Center of Foundation (Node 1) Response Spectra – Z Direction
CLASSIinco, CLASSIinco-SRSS, Bechtel SASSI-SRSS, ACS SASSI Simulation Mean and AS



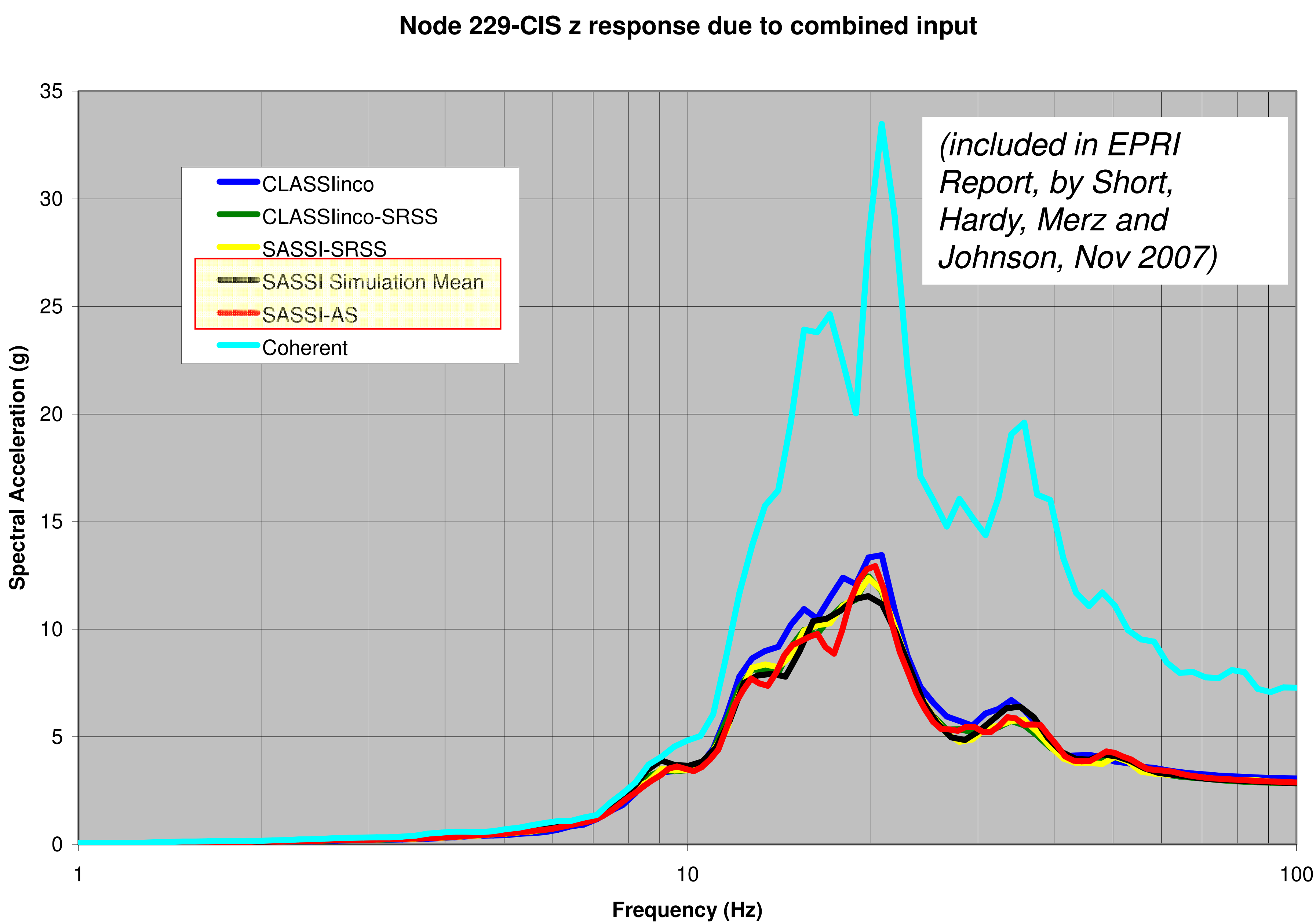
CIS Outrigger (Node 229) Response Spectra – X Direction

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



CIS Outrigger (Node 229) Response Spectra – Y Direction

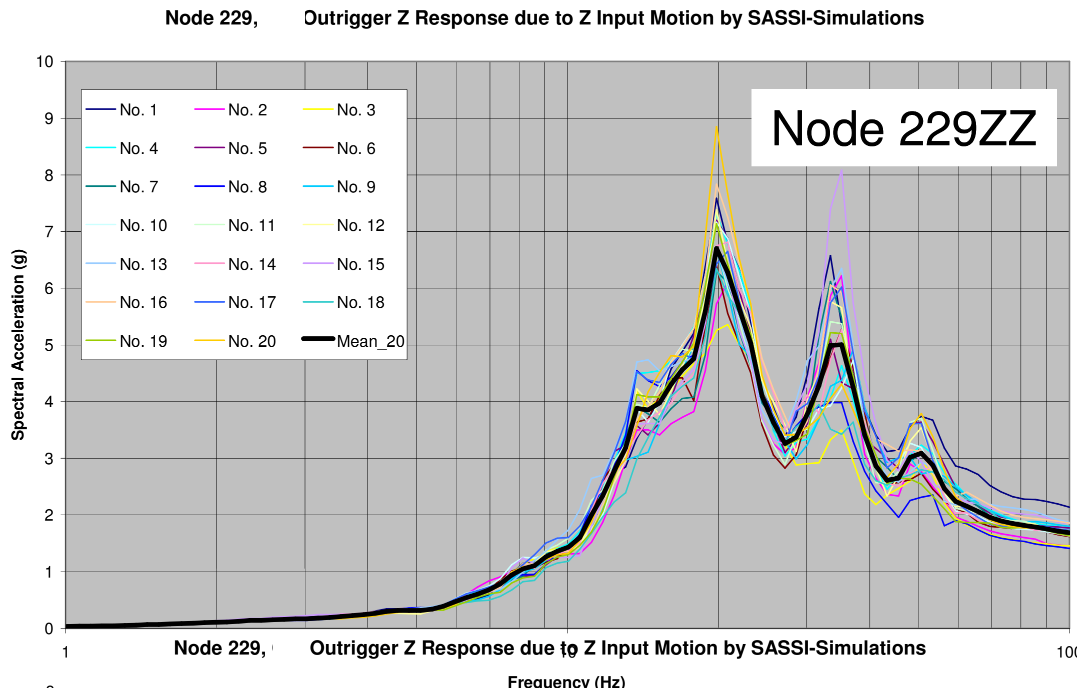
CLASSIinco, CLASSIinco-SRSS, Bechtel SASSI-SRSS, ACS SASSI Simulation Mean and AS



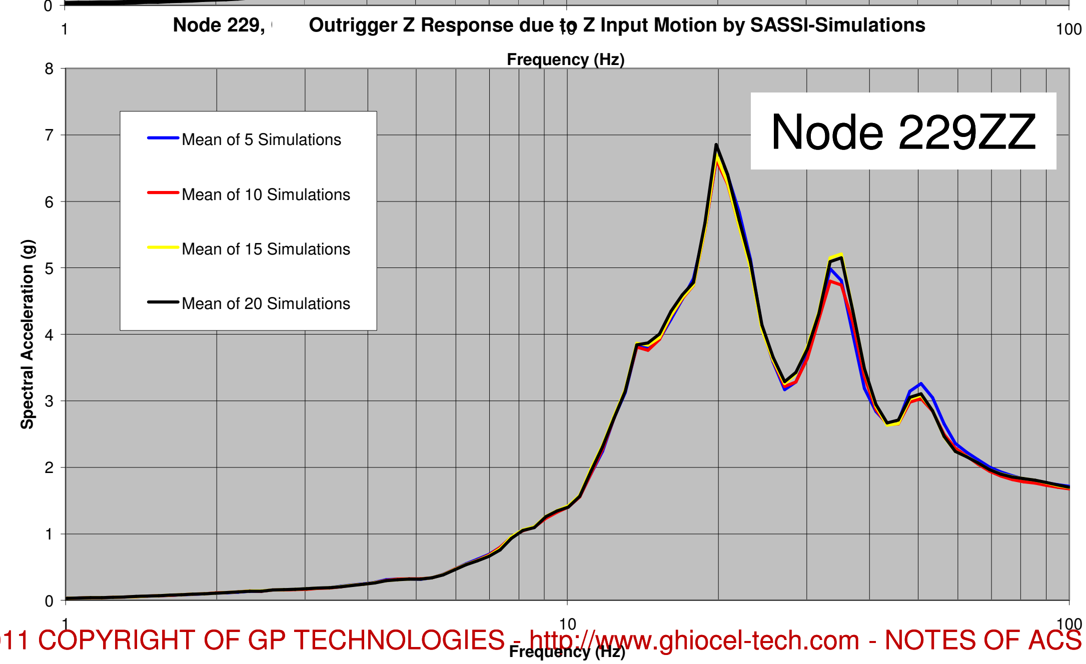
CIS Outrigger (Node 229) Response Spectra – Z Direction
CLASSIinco, CLASSIinco-SRSS, Bechtel SASSI-SRSS, ACS SASSI Simulation Mean and AS

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

Random FRS Samples



Mean FRS



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

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

ANIMATIONS

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

The qualitative effects of motion incoherency effects are:

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

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

Benchmarked SASSI-Based Approaches:

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

Other remarks:

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

PART 2: Case Studies

Seismic Incoherent SSI Response of RB Complex Structures

Dan M. Ghiocel
Ghiocel Predictive Technologies, Rochester, NY, USA

Luben Todorovski
URS Washington Division, Princeton, NJ, USA

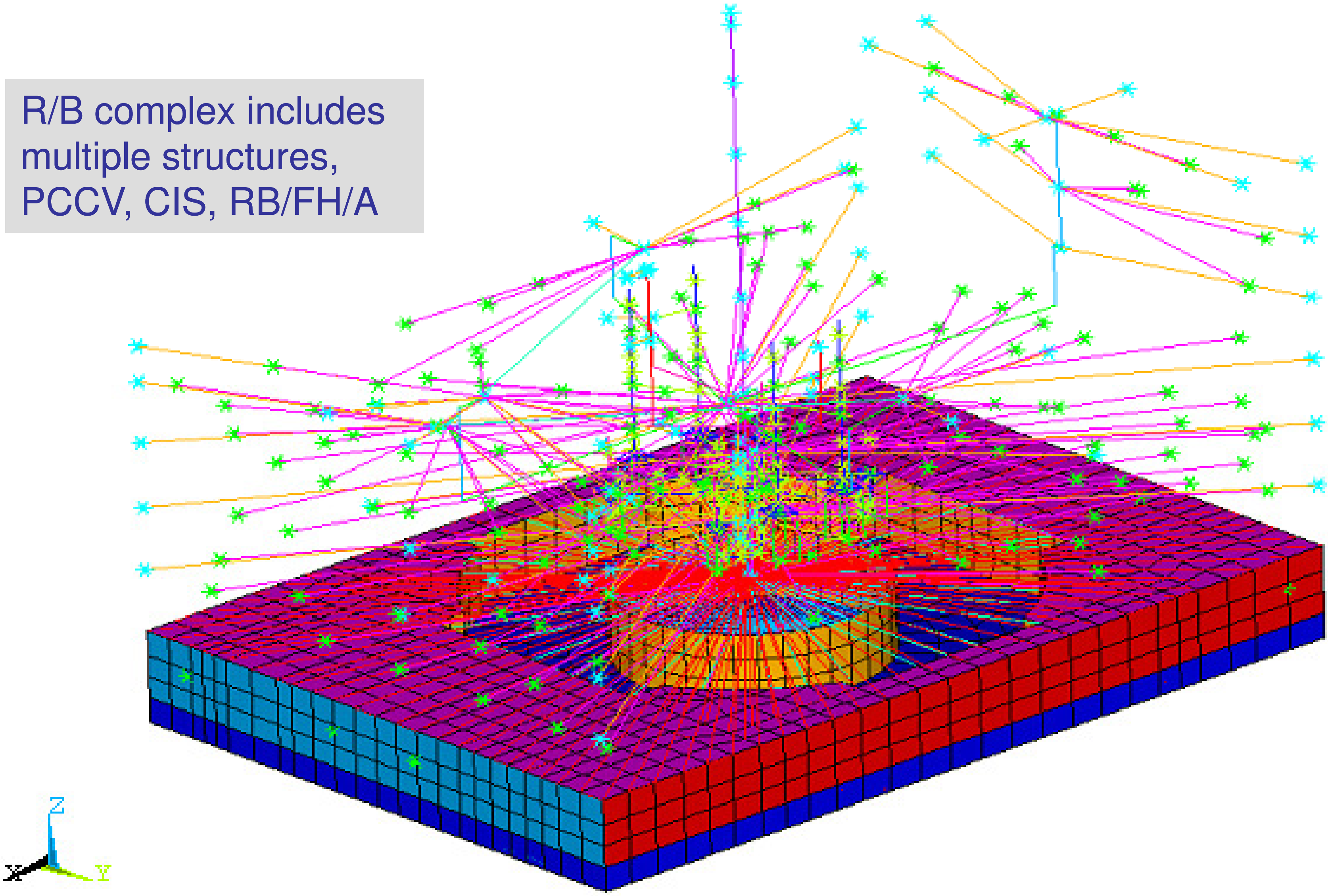
Hiroyuki Fuyama and **Daisuke Mitsuzawa**
Mitsubishi Heavy Industries, Kobe, Japan

OECD NEA/IAEA SSI Workshop

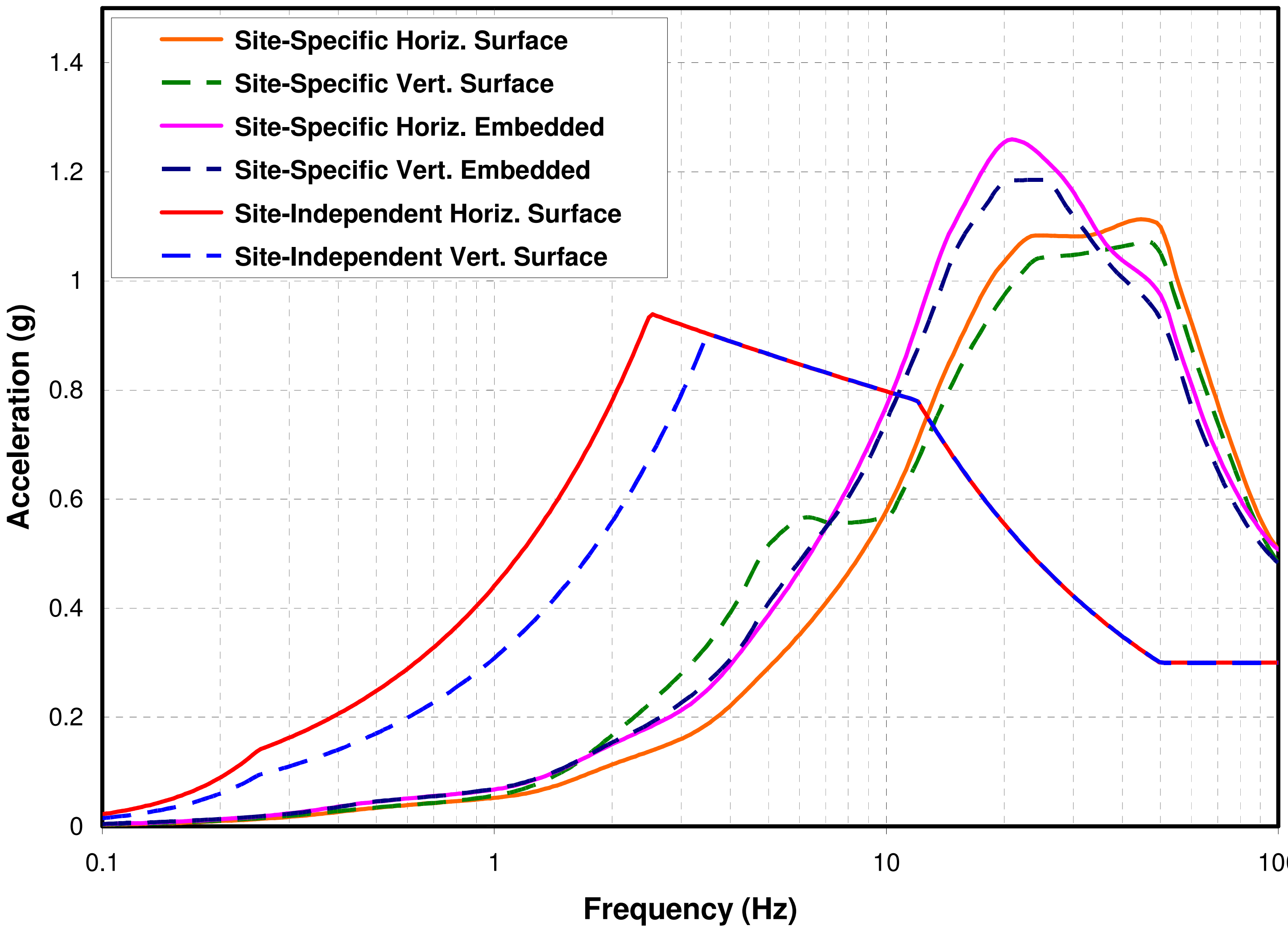
Ottawa, Canada, October 6-8, 2010

R/B Complex SSI Model

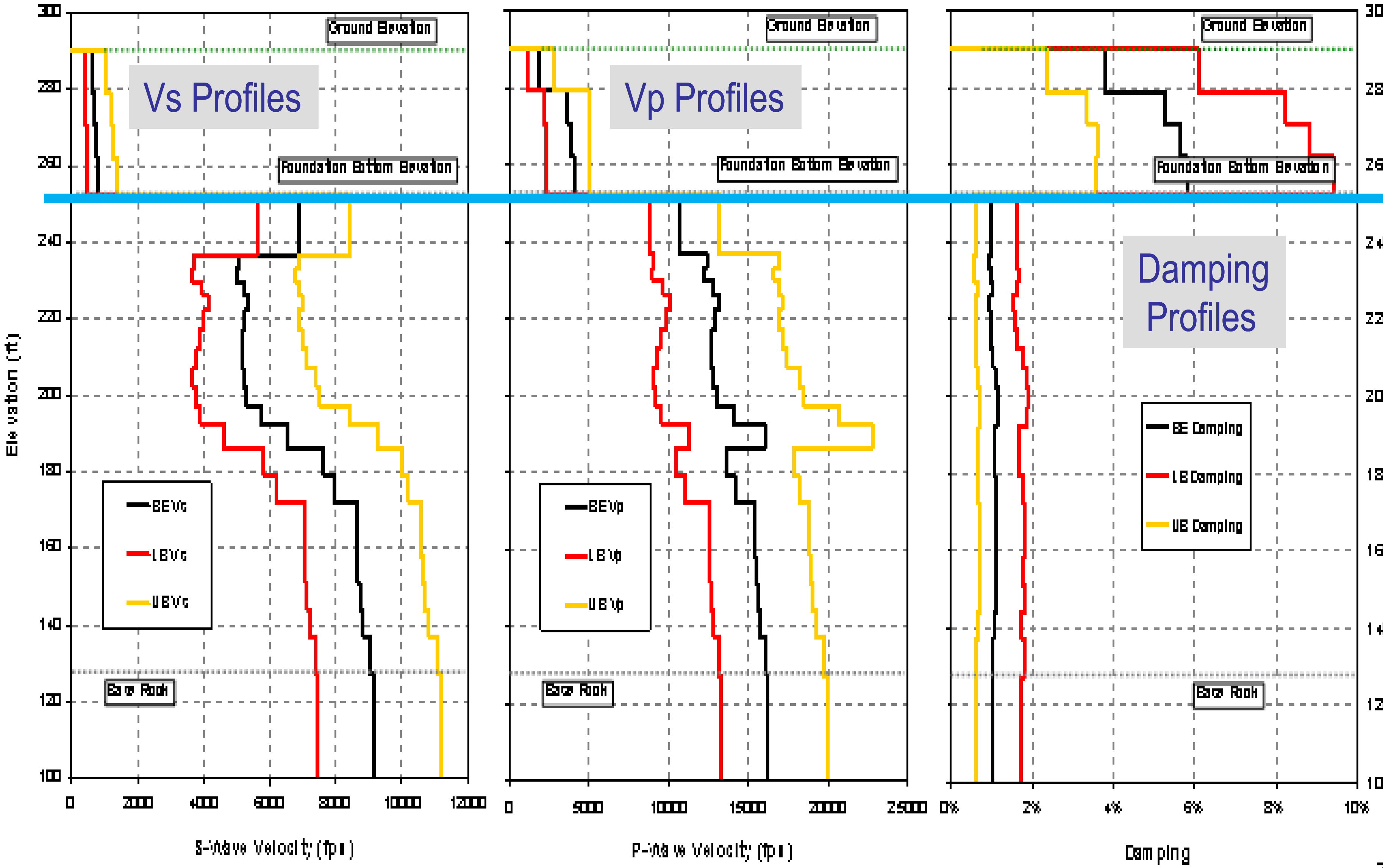
R/B complex includes multiple structures, PCCV, CIS, RB/FH/A



Site-Independent and Site-Specific Seismic Inputs



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



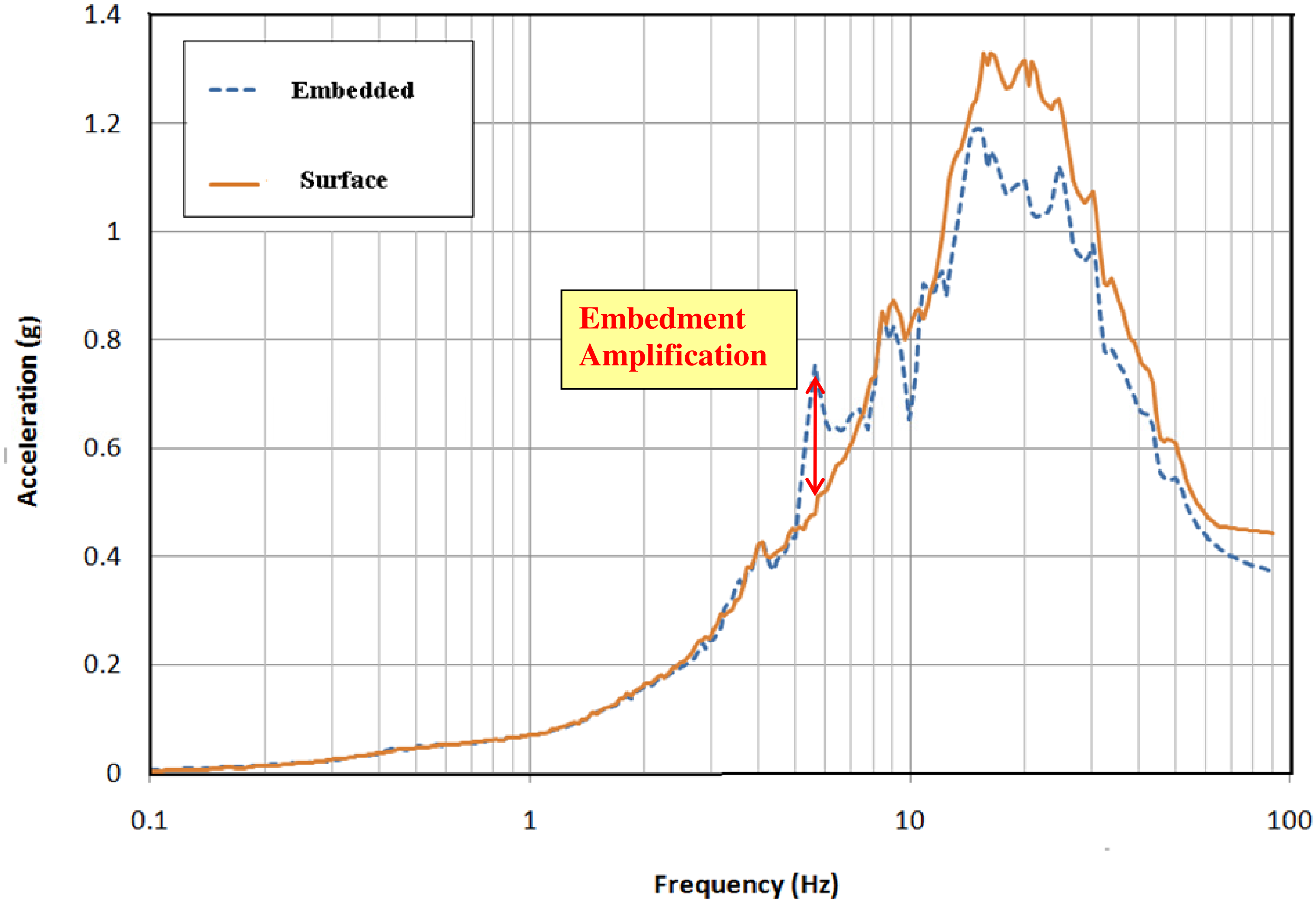
77

Backfill Soil Embedment Effects on ISRS

It should be noted that since the R/B complex sits on a rock formation, the effect of embedment is limited to the effect produced by the backfill side-soil vibration. These embedment effects that are mainly due to the ground motion amplification in the low frequency range, below 10 Hz, where the side-soil column frequencies occur.

In contrast to the embedment effects that manifest in low frequency range, the motion incoherency effects for rock sites manifest in high-frequency, being negligible below 10 Hz. This makes embedment effects decoupled from the incoherency effects.

Embedded vs. Surface RB Model ISRS at Base Level; Effects of Backfill Soil Vibration



Seismic SSI Analysis Procedure for Computing ISRS

Three types of SSI analyses were considered:

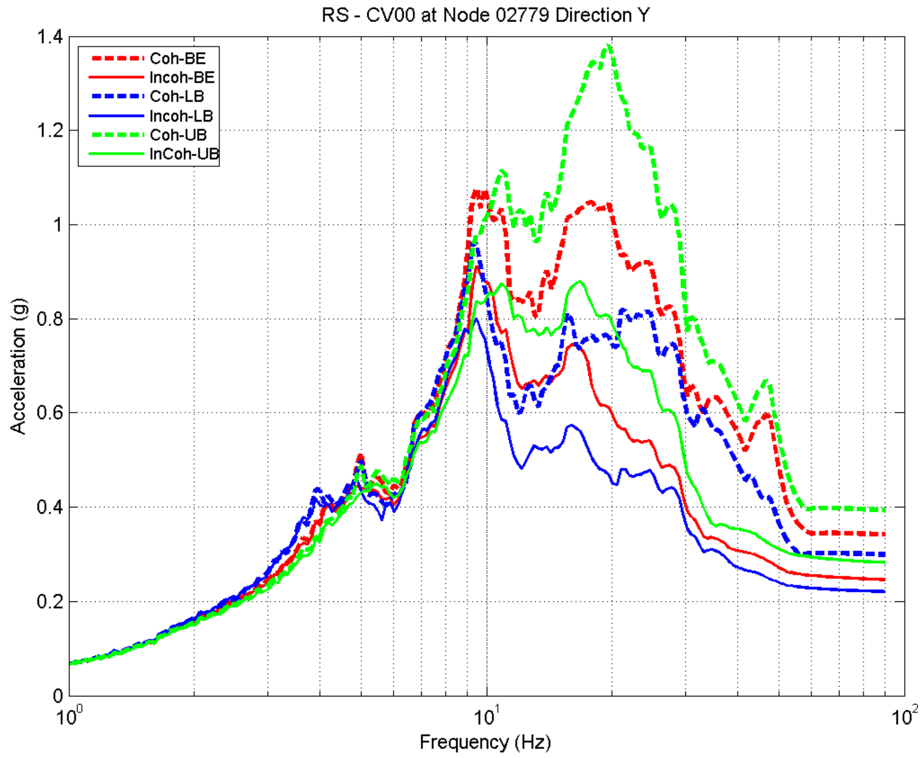
1) Surface foundation subjected to coherent input ground motion (SC)
2) Surface foundation subjected to incoherent input ground motion (SI)
3) Embedded foundation subjected to coherent ground motion (EC).

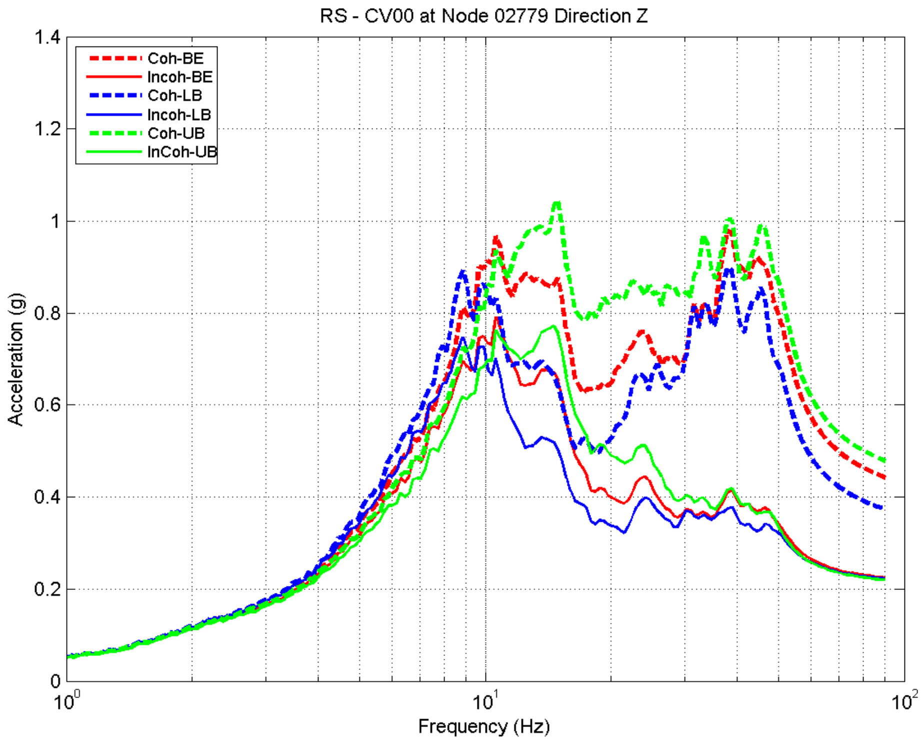
An efficient engineering approach was used to include the combined effects of embedment and incoherency on the ISRS results:

- Basic SSI analyses coherent for surface & embedded model and incoherent for surface model were performed for the three soil property sets, BE, LB, UB
-The final site-specific ISRS were obtained by multiplying the surface model incoherent ISRS by the amplification factors that were computed using the ISRS results of SSI analyses with coherent input ground motion.
-The embedment amplification factors were computed as ratio of the coherent ISRS enveloping the response of the surface and embedded models to the coherent ISRS enveloping the response of surface model.

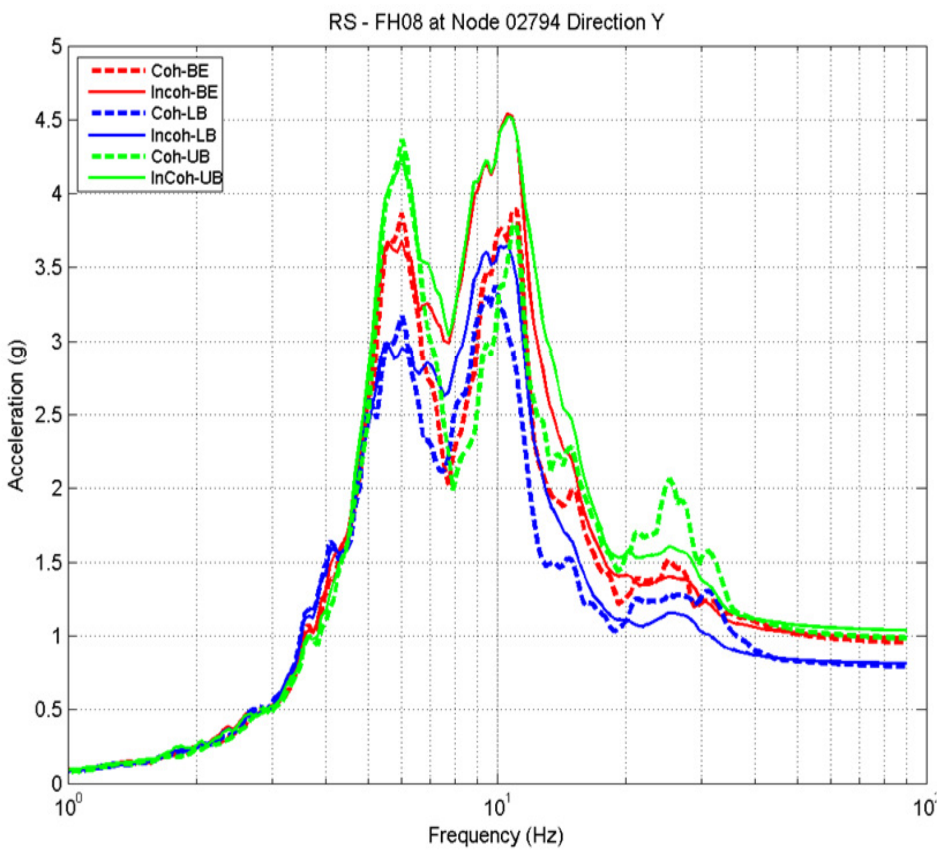
ISRS and Structural Force Results

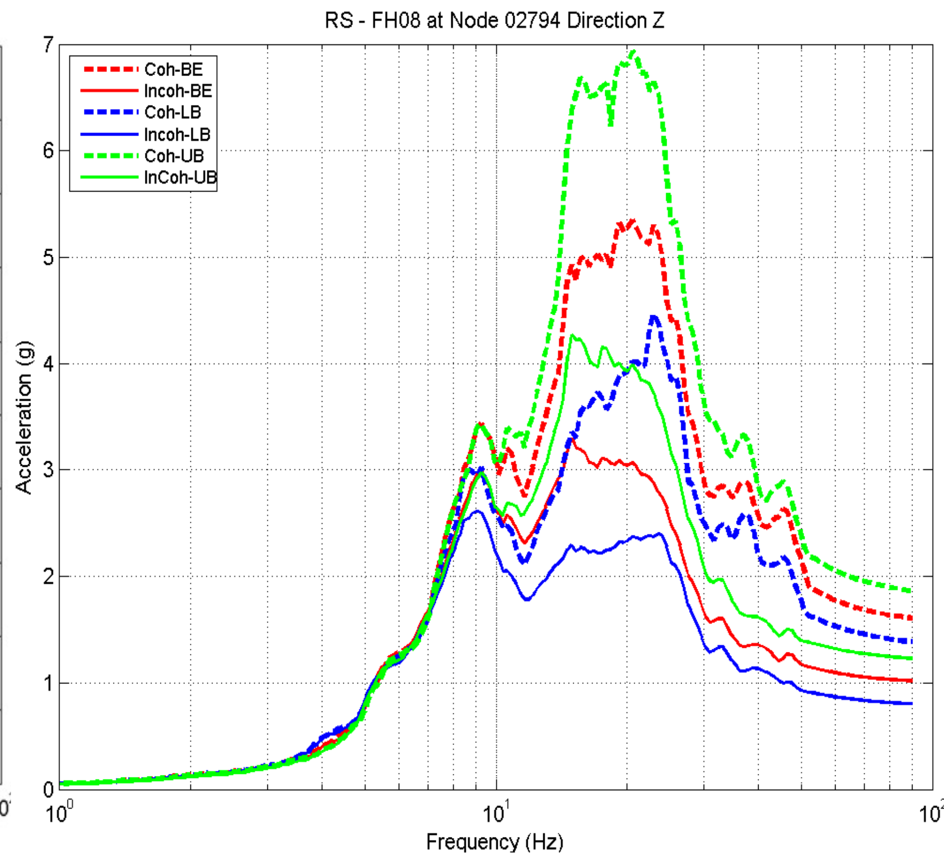
Coherent vs. Incoherent SSI Analysis Results.
5% Damp ISRS at PCCV Base-Center in Y and Z-Dir



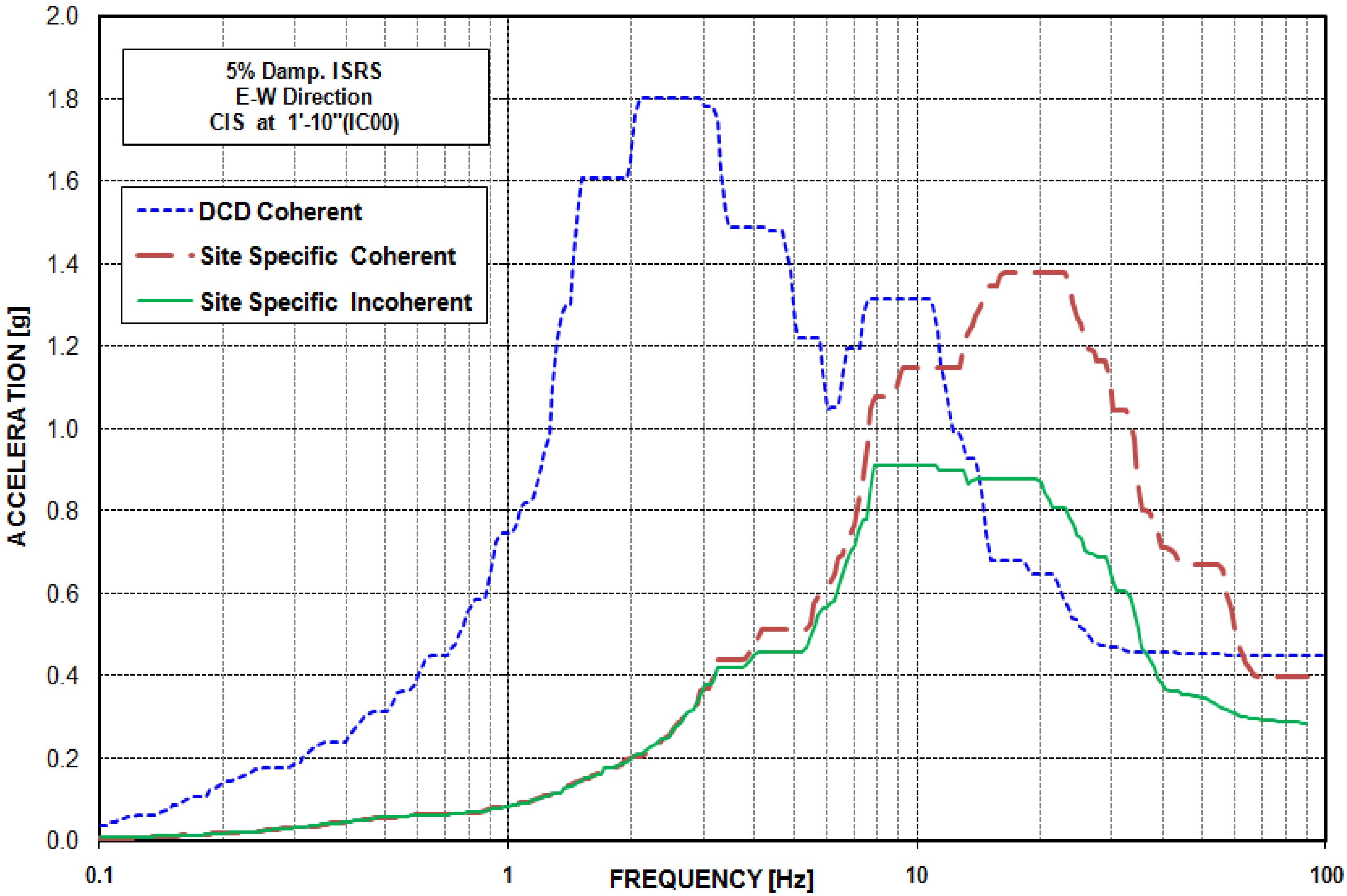


Coherent vs. Incoherent SSI Analysis Results. 5% Damp ISRS Plots at RB Top-Edge in Y and Z-Dir

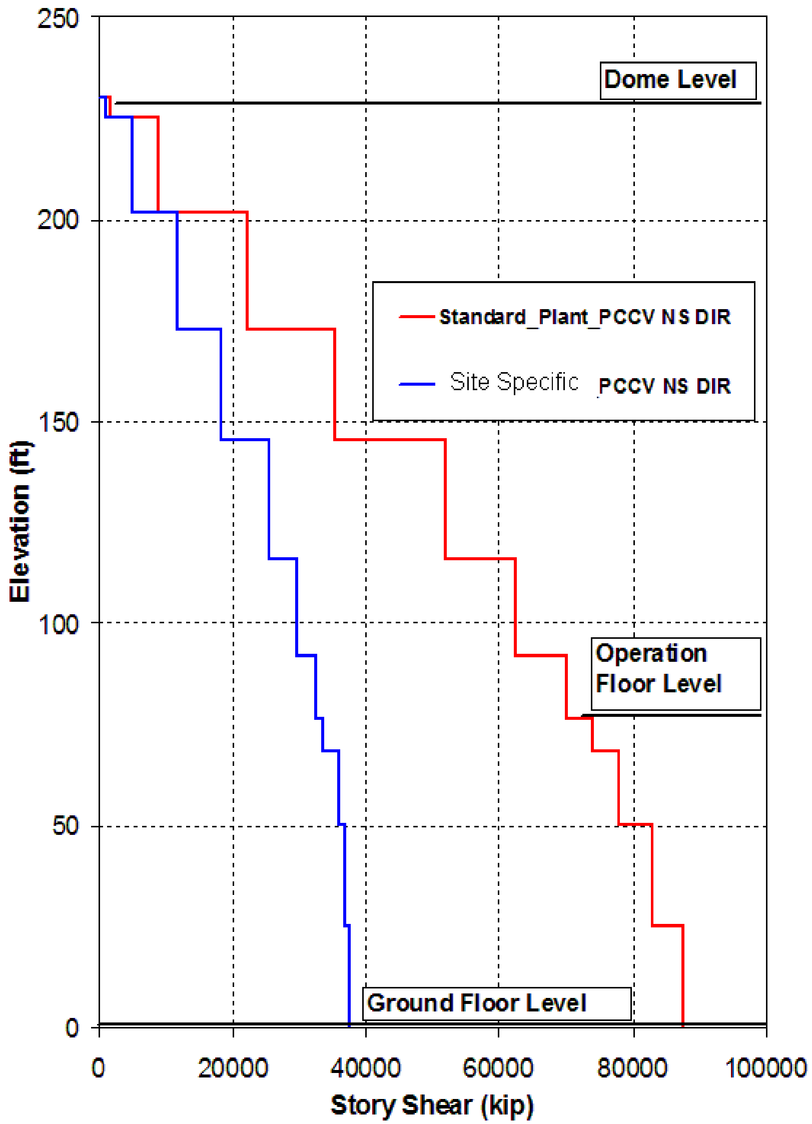


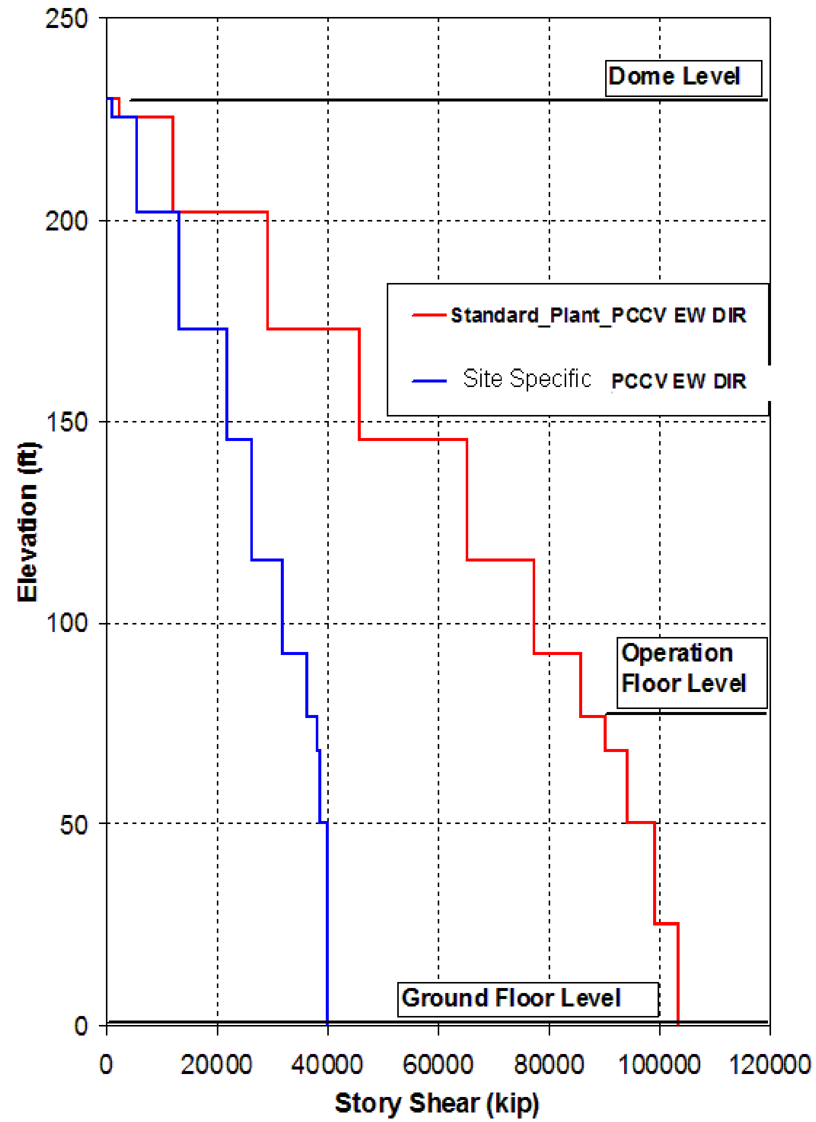


Site-Independent vs. Site-Specific Coherent and Incoherent Final ISRS Results at CIS Base in Y-Dir



Site-Independent vs. Site-Specific Structural Forces Shear Forces in PCCV Structure in X and Y Dir





Conclusions of RB Complex Case Study

Main conclusions of the SSI analysis are:

1) It was shown that these effects are decoupled since the backfill embedment effects manifests in low frequency range below 8-10 Hz, while the incoherency effects manifest.

2) The site-specific ISRS are lower than the standard design ISRS in the low and mid frequency ranges, but could be larger than standard design ISRS in the high frequency range.

3) The site-specific structural forces are significantly lower than the standard design structural forces for all of the R/B structures.

4) Since the foundation basemat of R/B structures has larger footprint dimensions, 309 ft x 210 ft, the incoherent ISRS are larger than coherent ISRS for the structures located close to the edges of the basemat in the longitudinal direction. These amplifications are for torsional motions due to horizontal inputs, and rocking motions due to vertical input.

5) The effects of basemat flexibility on the site-specific ISRS are larger for the vertical direction, for which the R/B structures behave as a multiple support excitation system. Separate local rocking motions excited by shorter wavelength motion components are visible.

Seismic Motion Incoherency Effects for Nuclear Complex Structures On Different Soil Site Conditions

Dan M. Ghiocel

Ghiocel Predictive Technologies Inc.

http://www.ghiocel-tech.com

Steve Short and Greg Hardy

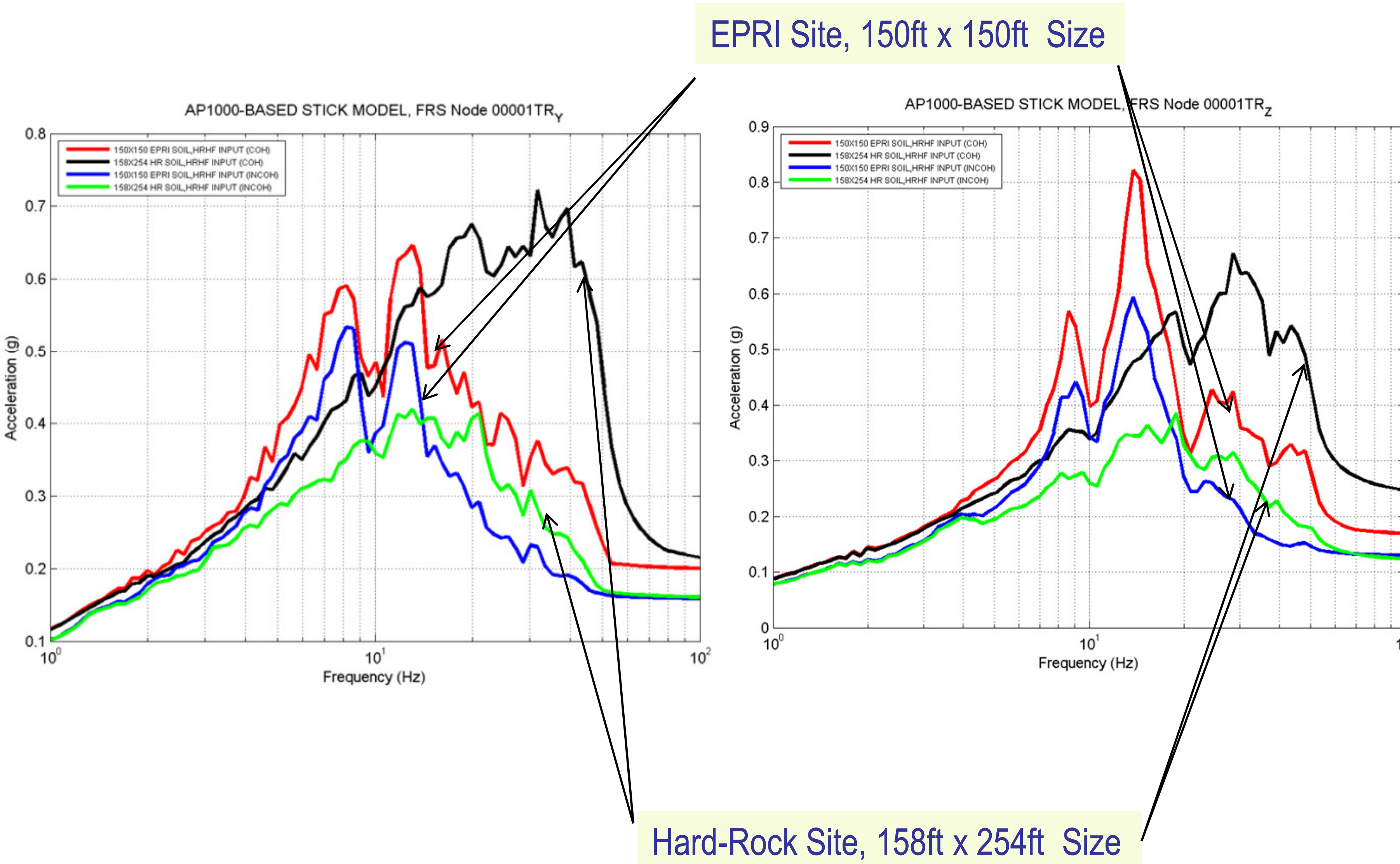
Simpson, Gumpertz and Heger

http://www.sgh.com

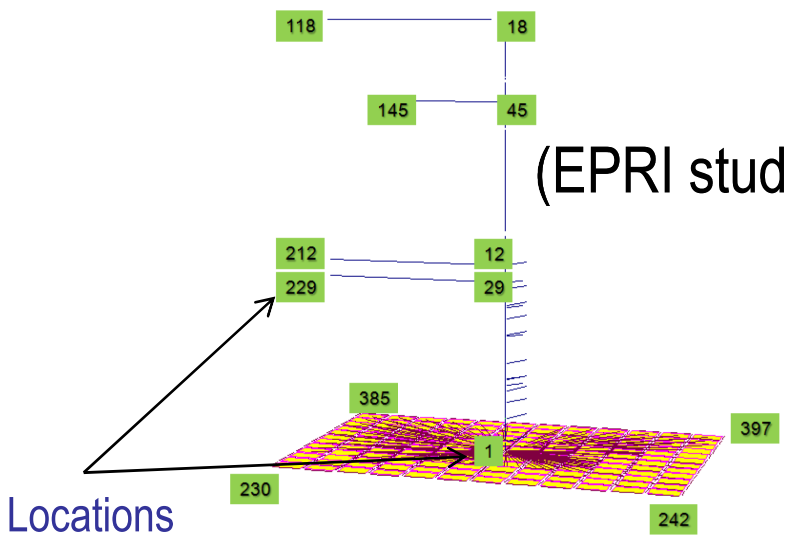
OECD NEA SSI Workshop

Ottawa, Canada, October 6-8, 2010

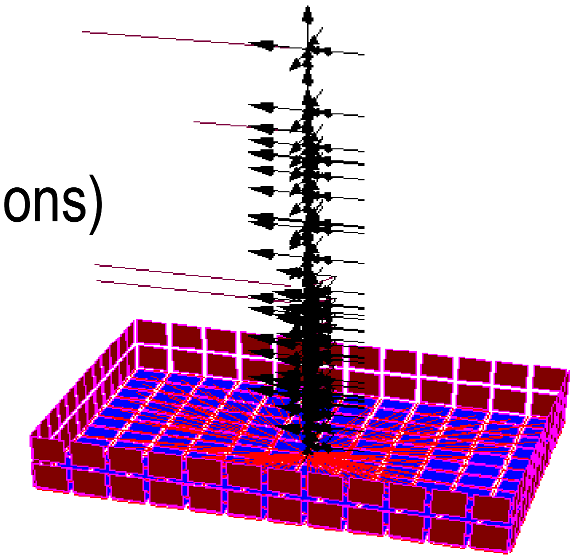
Modified AP1000 Stick Model Studies: Effects of Foundation Size and Rock Stiffness – ISRS at Basemat

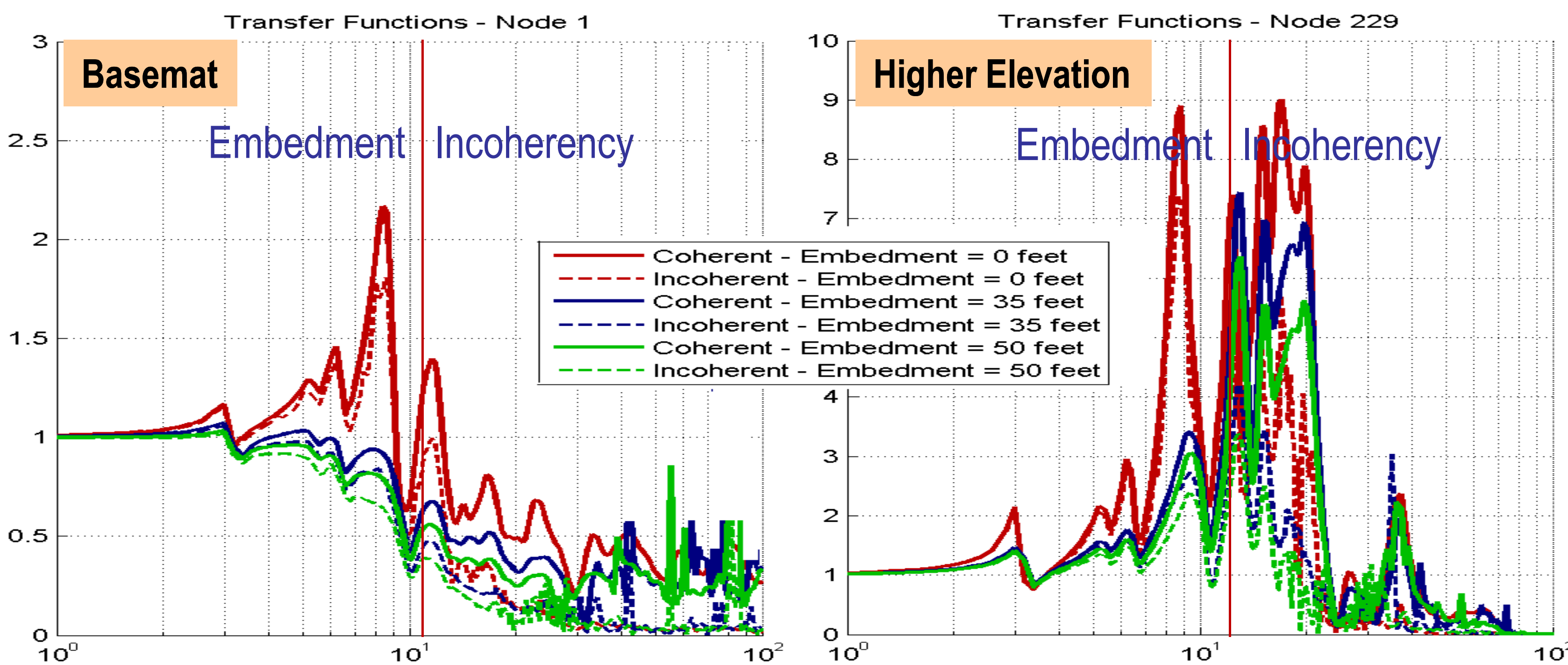


Embedded EPRI AP1000 Stick Incoherent SSI Studies



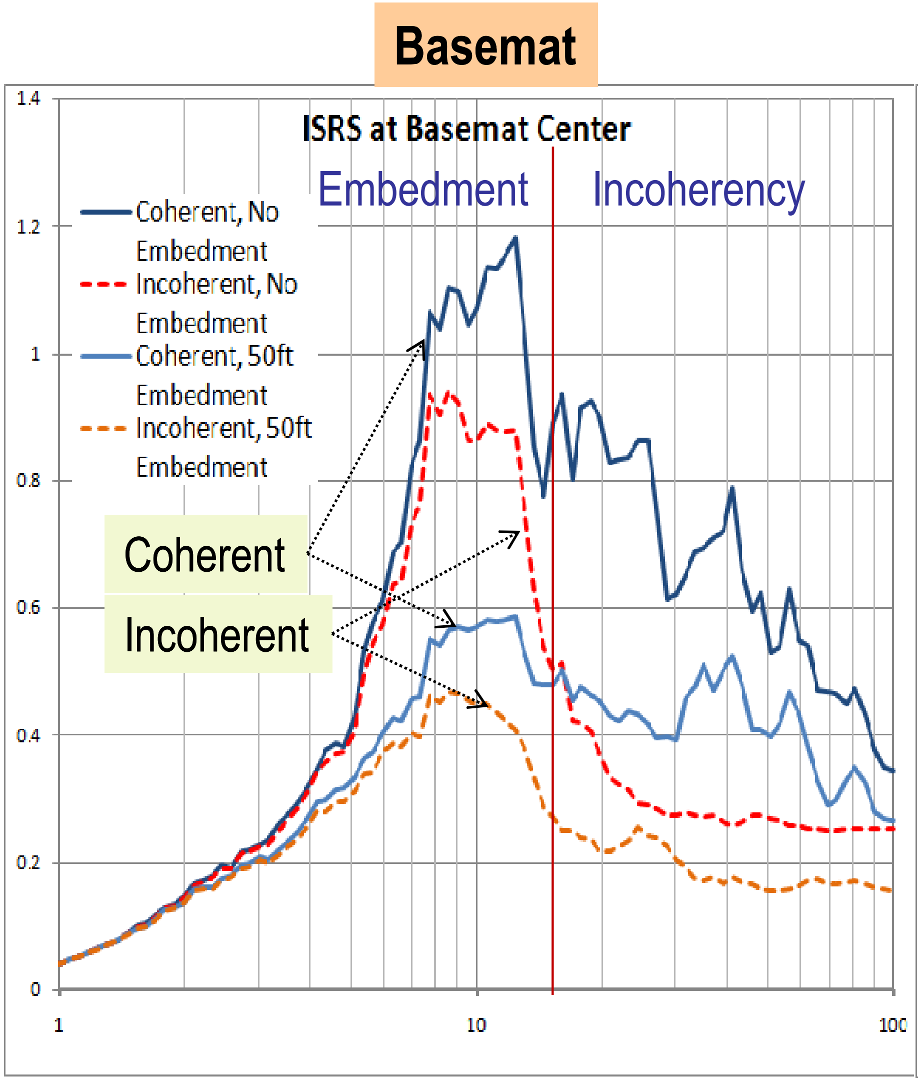
(EPRI study site conditions)

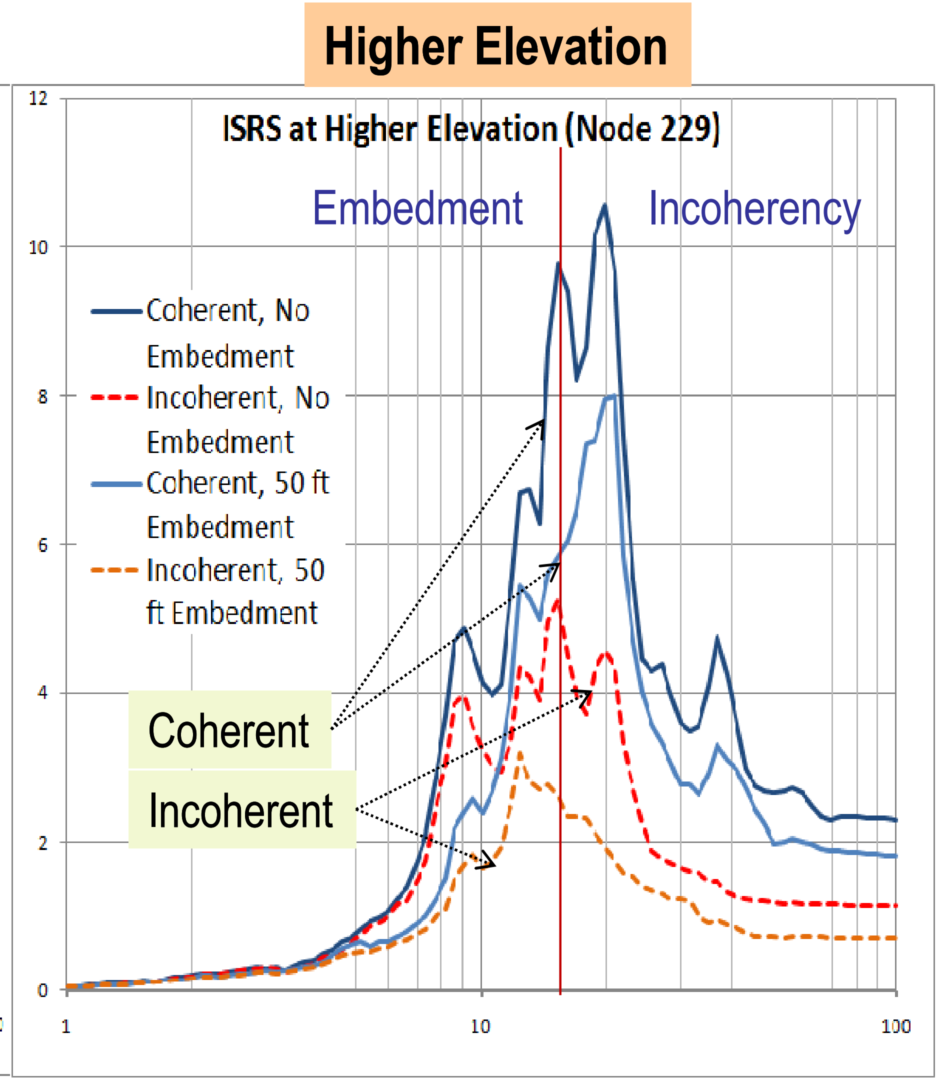




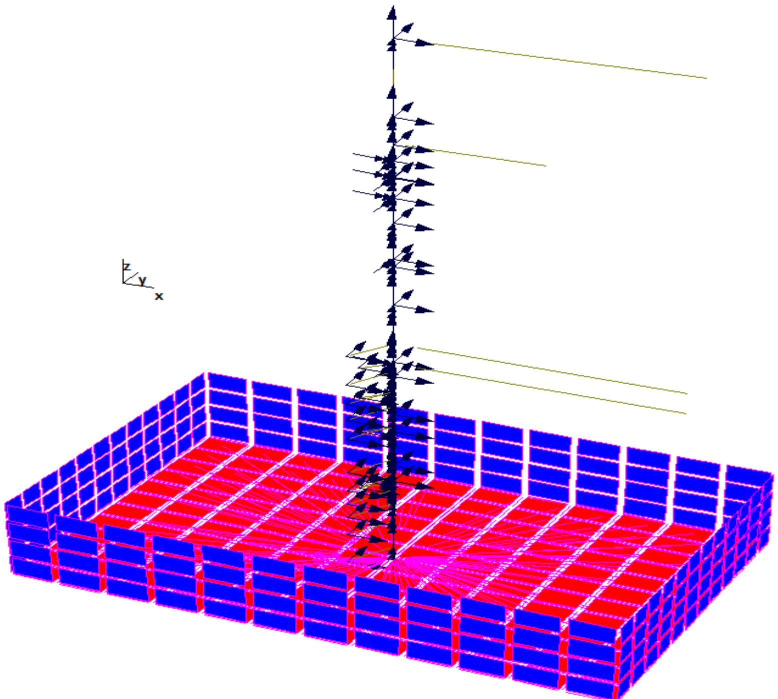
Embedded EPRI AP1000 Stick ISRS Response

(EPRI study model, input and site conditions)

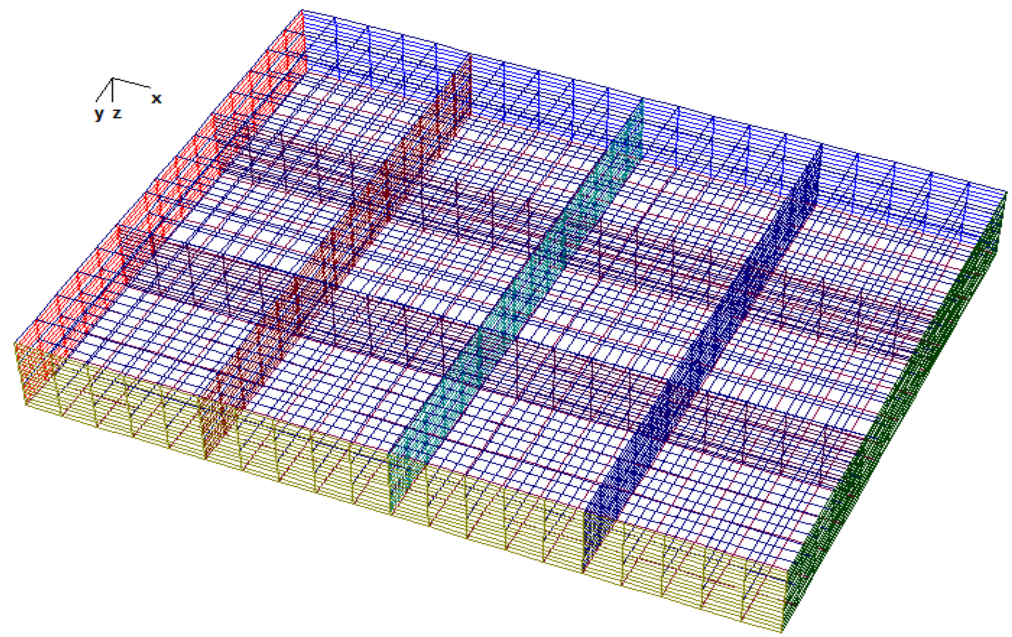




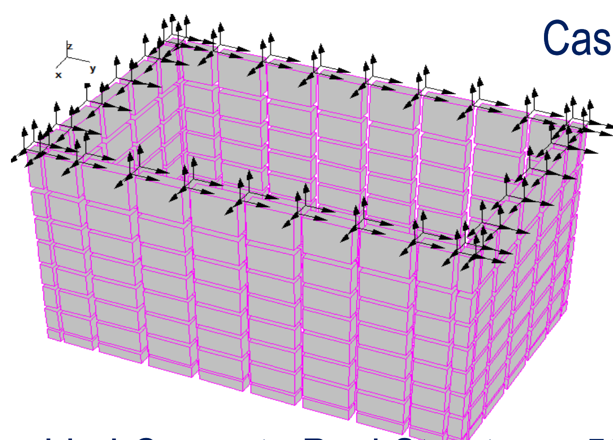
Seismic Incoherent SSI Analysis Case Studies



Case 1: 40 ft Embedded AP1000 NI
158ft x 254ft Size



Case 2: Large-Size Building
350ft x 450ft Size



Case 3: 30 ft Embedded Concrete Pool Structure . 50ft x 80ft Size

CASE 1: AP1000 Stick for Different Site Conditions

Inputs:

Hard-Rock Site:

- Structure: AP1000 Stick Model with No and 40 ft Embedment
- Soil Deposit: Uniform soil layering with Vs of about 8,000fps
- Control Motion: HRHF Input (spectral peak in 20-30 Hz range)
- Incoherency: 2007 Abrahamson Coherence Function for Hard-Rock

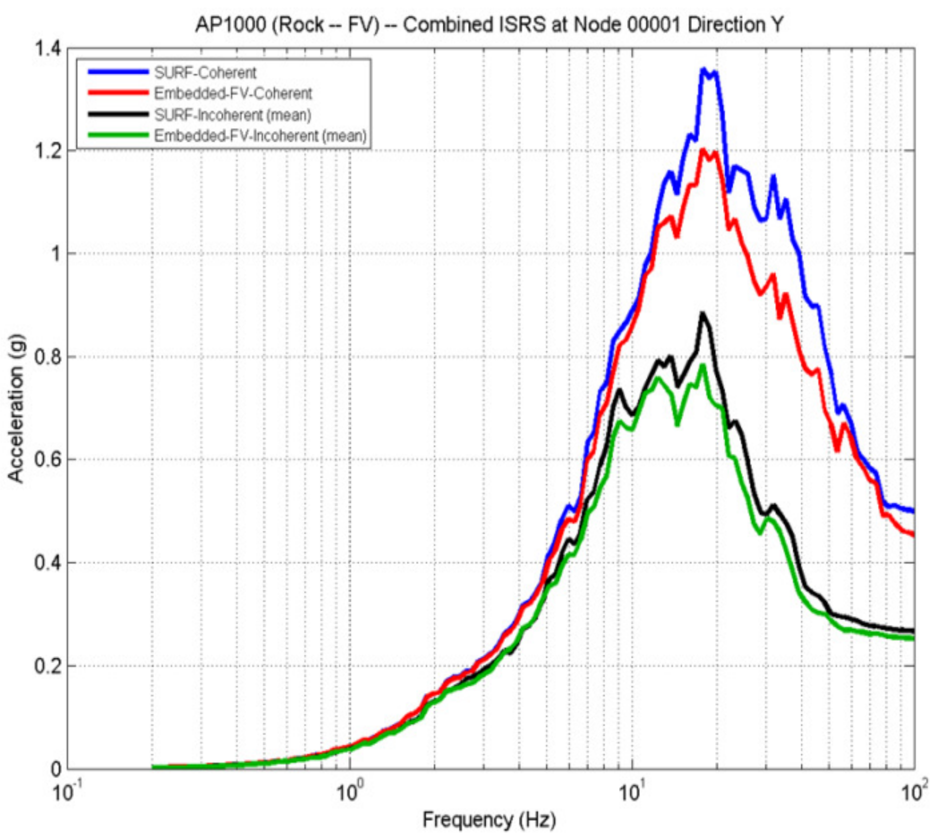
Soil Site:

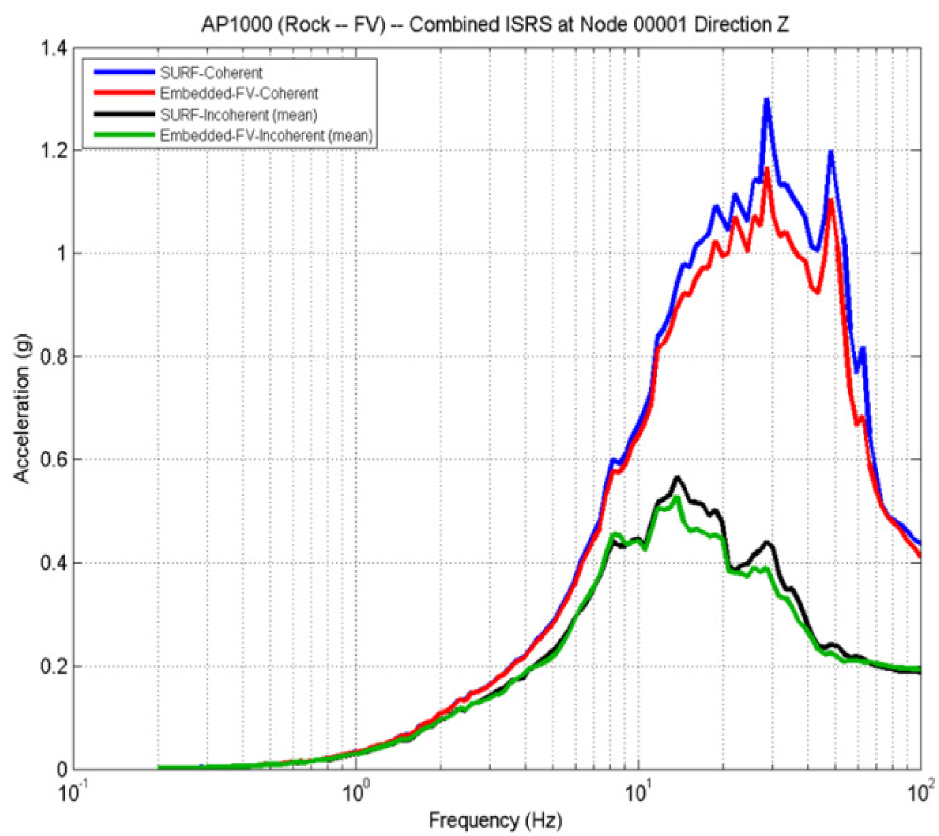
- Structure: AP1000 Stick Model with No and 40 ft Embedment
- Soil Deposit: Uniform soil layering with Vs of about 1,000fps
- Control Motion: RG 1.60 Input
- Incoherency: 2007 Abrahamson Coherence Function for Soil

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

Modified AP1000 NI Founded on Rock; Effects of Incoherency and Embedment – ISRS at Basemat

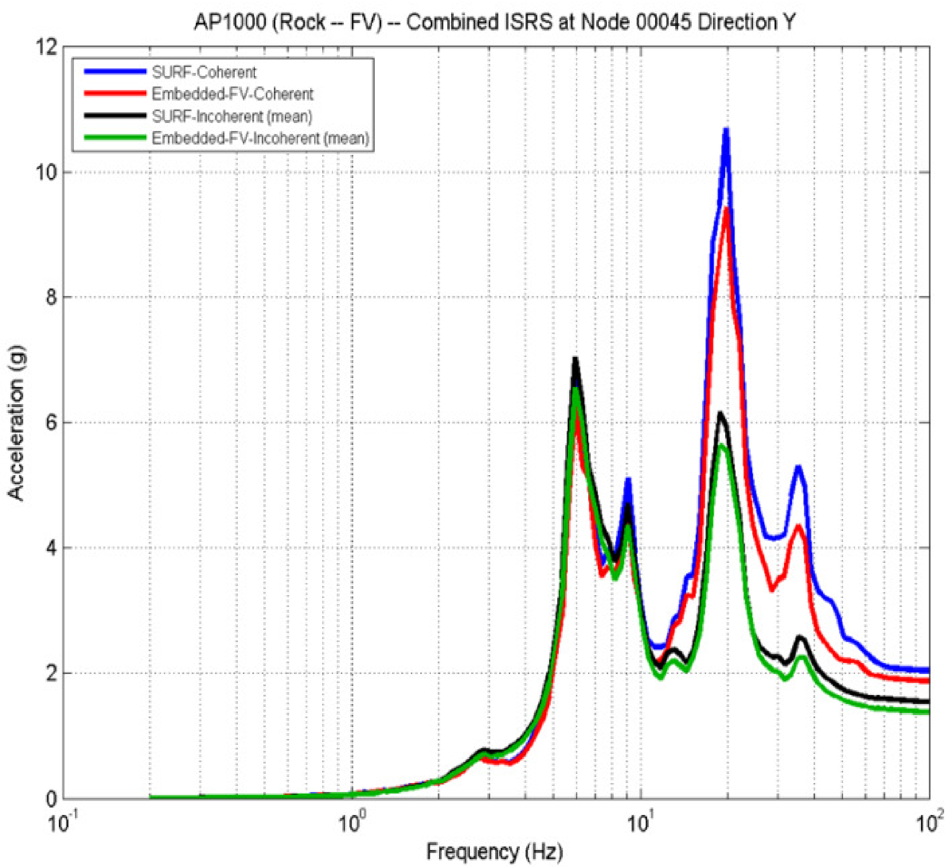
Y-Direction	Z-Direction



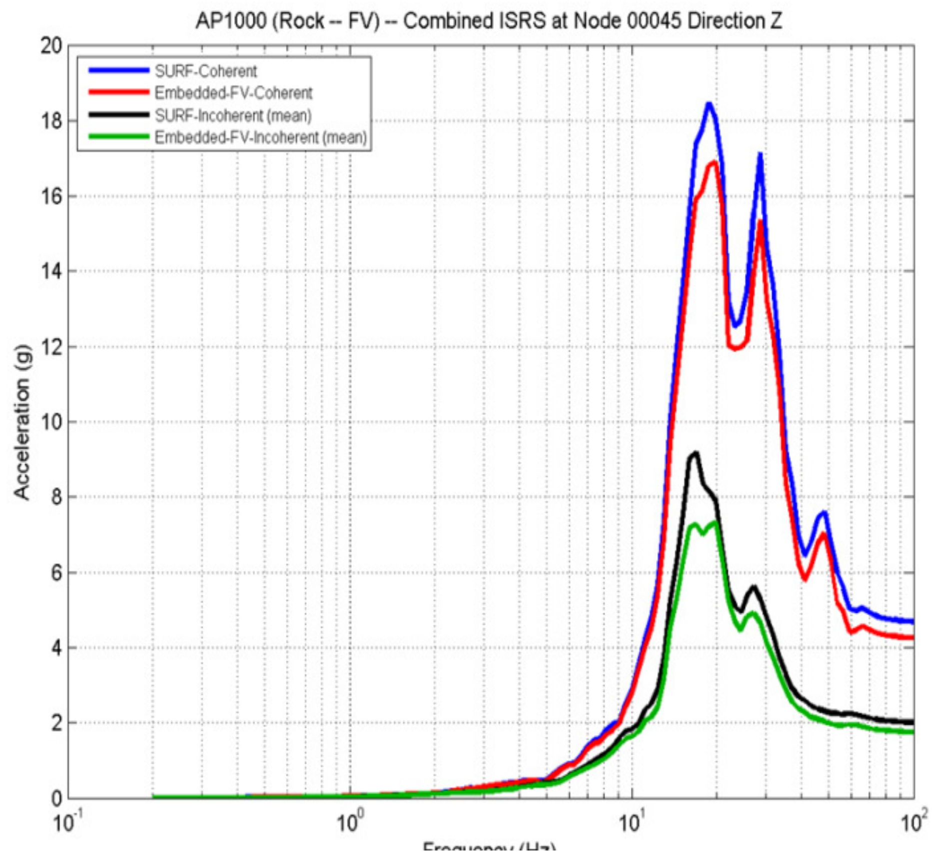


Modified AP1000 NI Founded on Rock; Effects of Incoherency and Embedment – ISRS at Top of SCV

Y-Direction

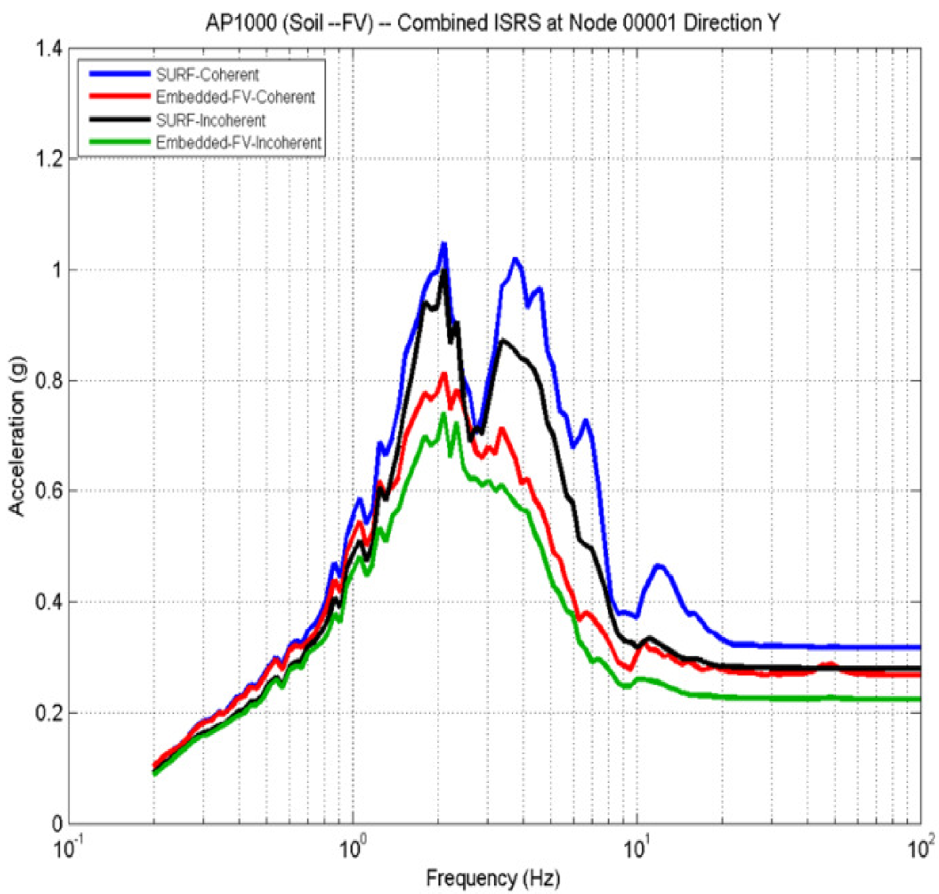


Z-Direction

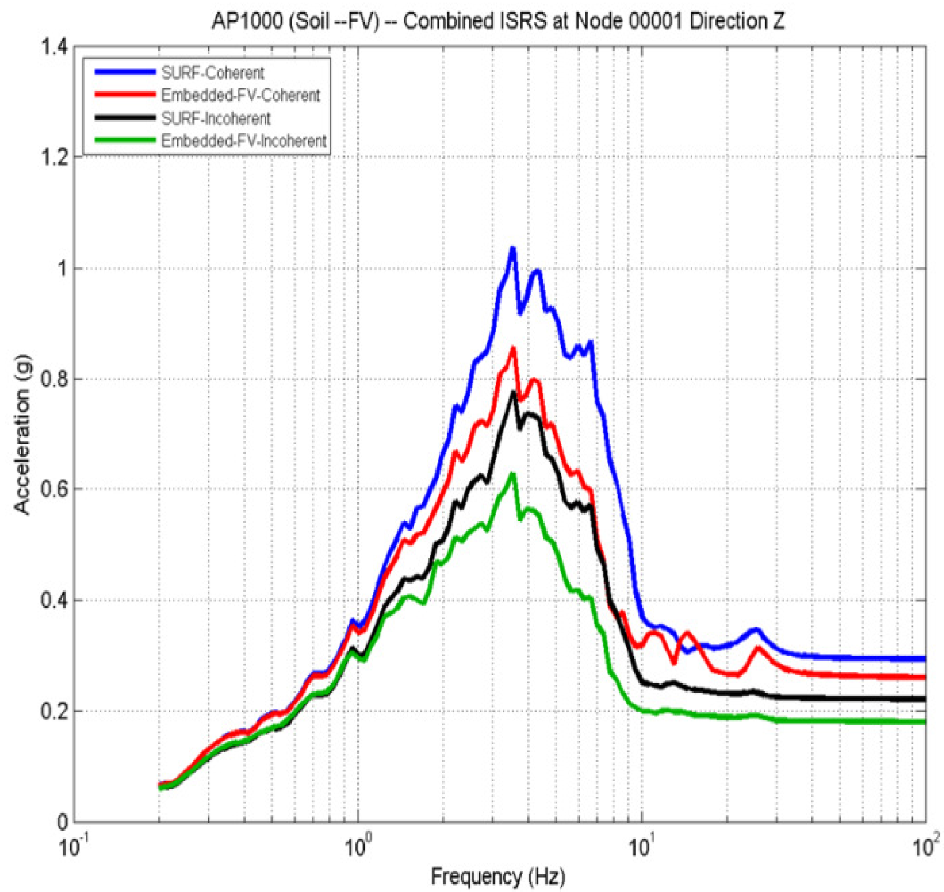


Modified AP1000 NI Founded on Soil; Effects of Incoherency and Embedment – ISRS at Basemat

Y-Direction

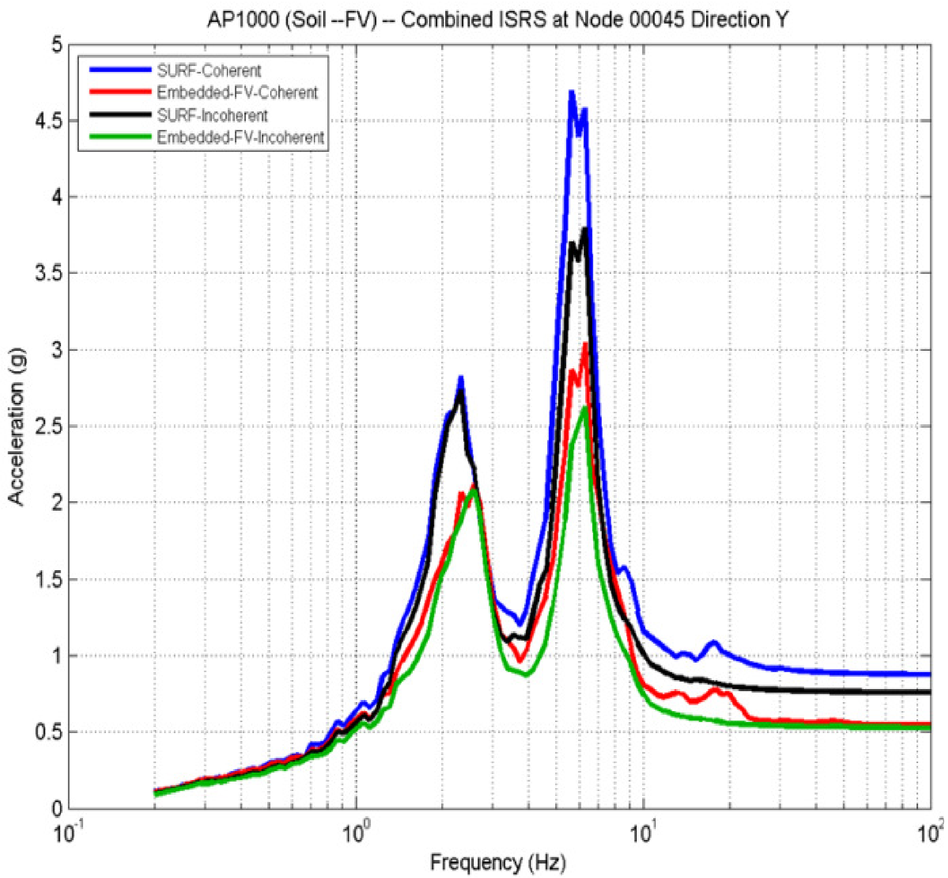


Z-Direction

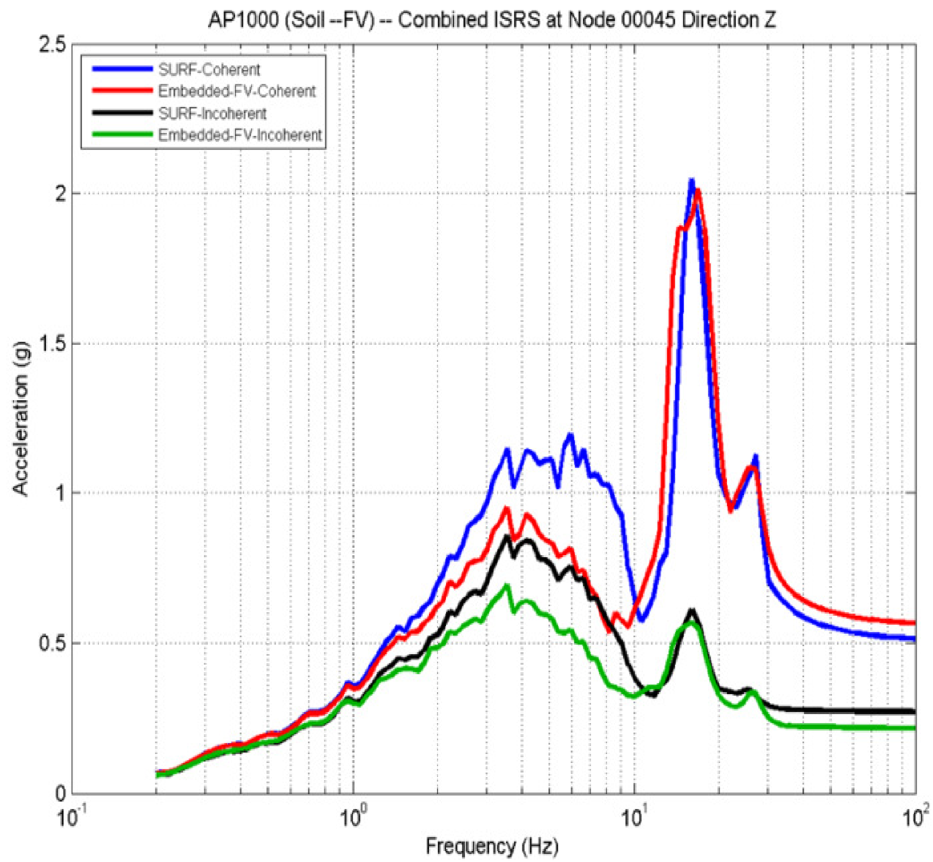


Modified AP1000 NI Founded on Soil; Effects of Incoherency and Embedment – ISRS at Top of SCV

Y-Direction

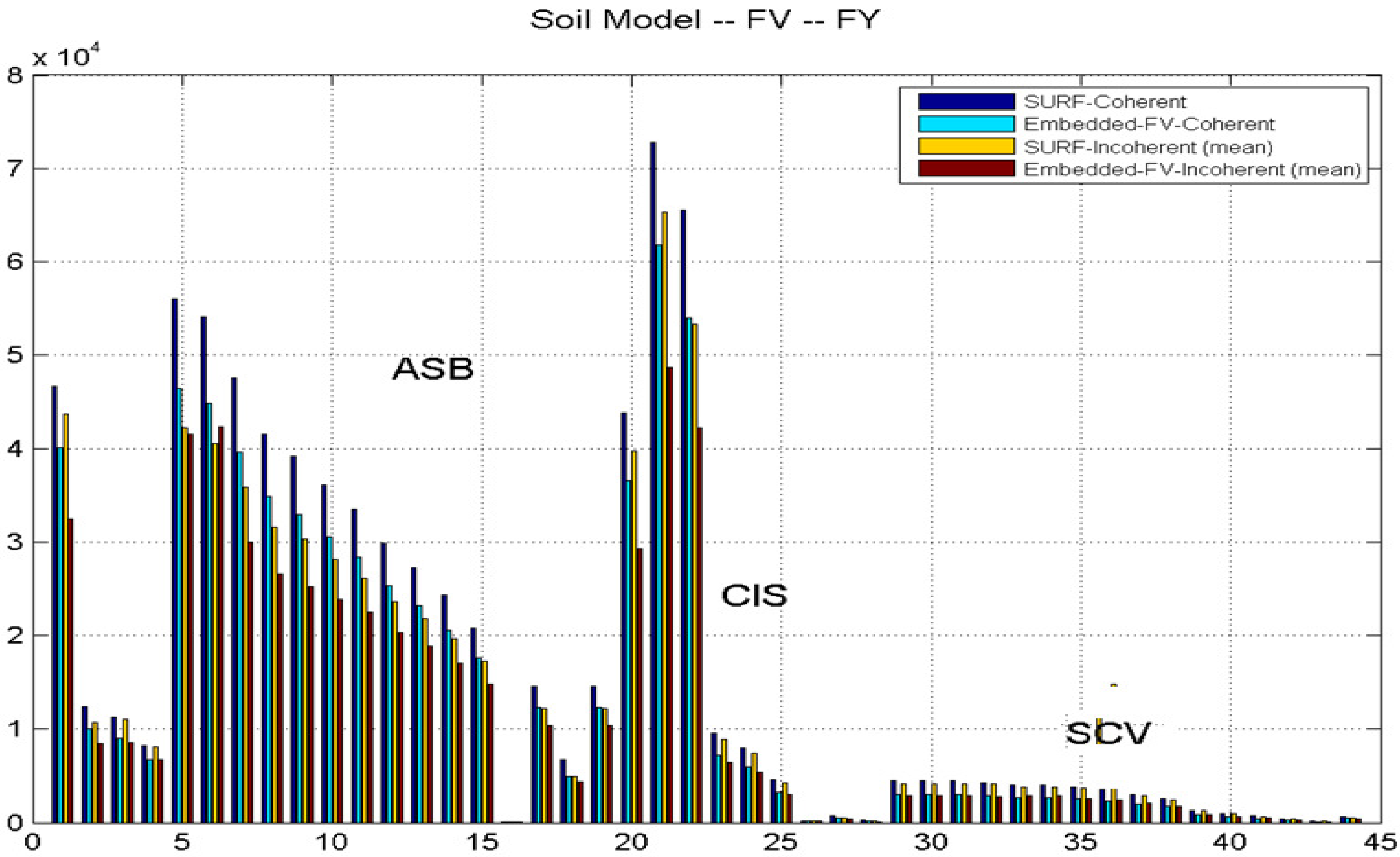


Z-Direction

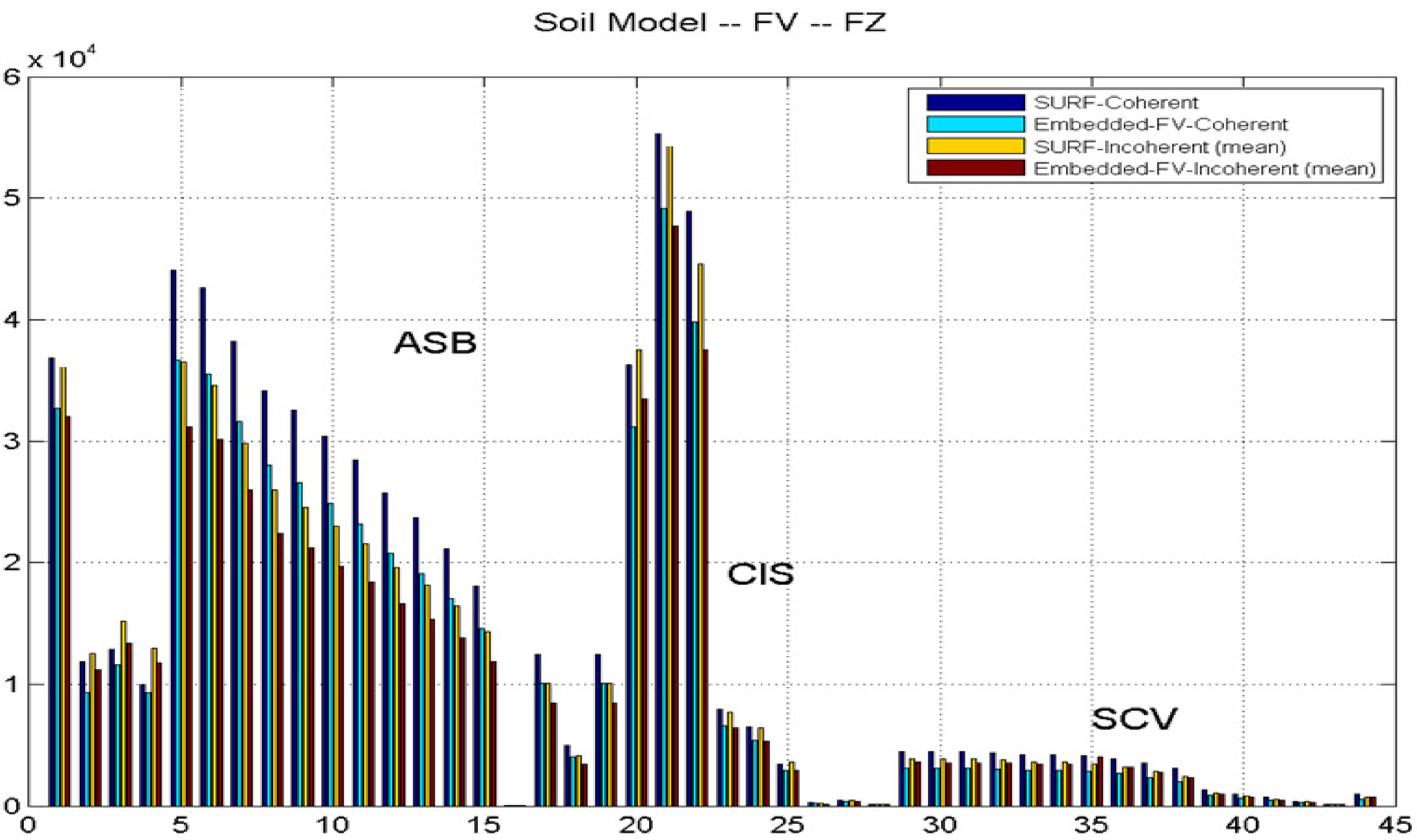


ANIMATIONS 2-7

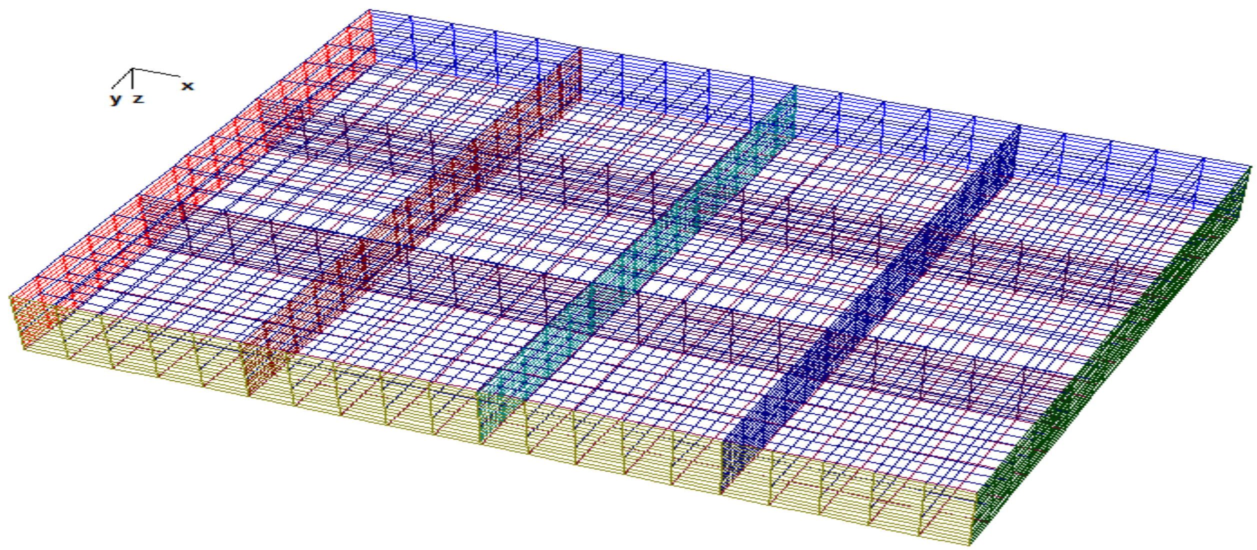
Coherent and Incoherent SSI for Surface and Embedded AP1000 Model. Shear Forces in NI Structures for X-Dir



Coherent and Incoherent SSI for Surface and Embedded AP1000 Model. Shear Forces in NI Structures for Y-Dir



CASE 2: Large-Size Shear Wall Structure



SSI Analysis Inputs:

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

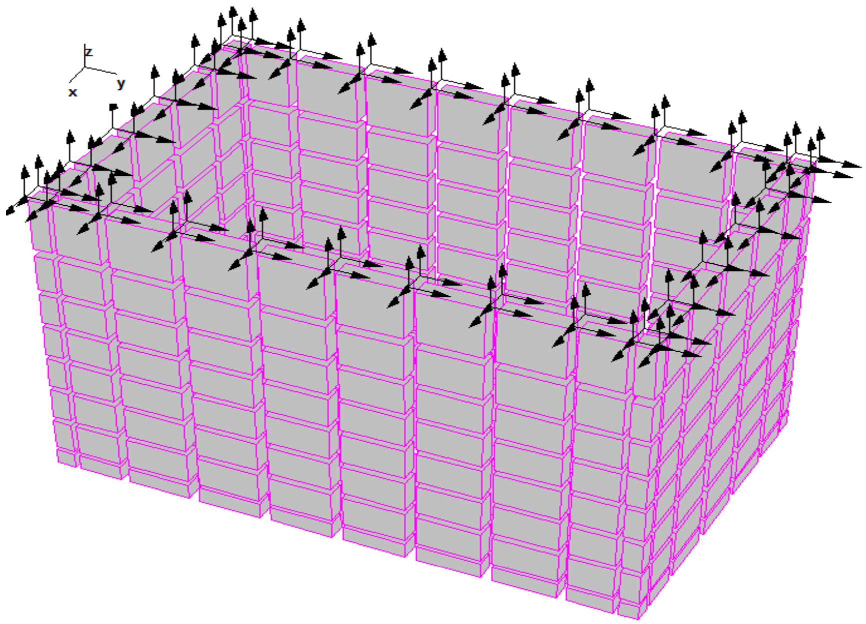
NOTE: It should be noted that at this time only the 2007 Abrahamson for hard-rock site conditions is permitted by US NRC.

ANIMATIONS

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

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

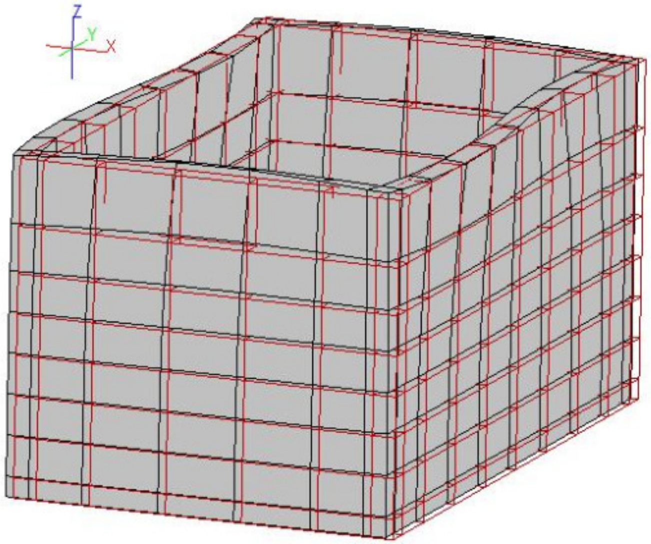
30 ft Embedded Concrete Pool Structure



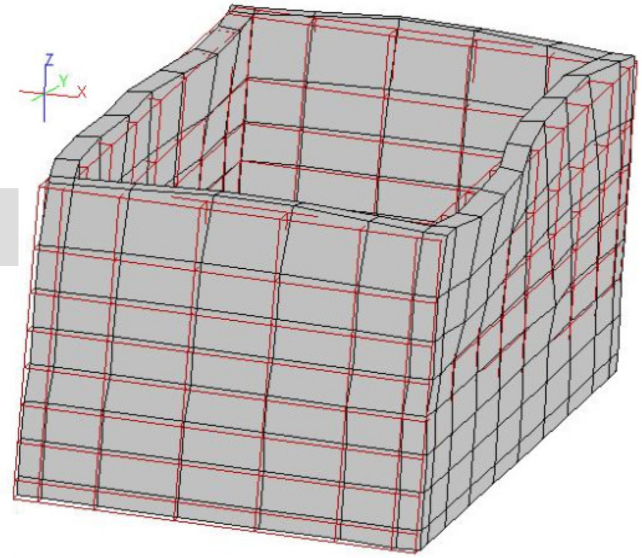
ACS SASSI SSI Analysis Inputs:

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

Coherent and Incoherent SSI Motions and Stresses



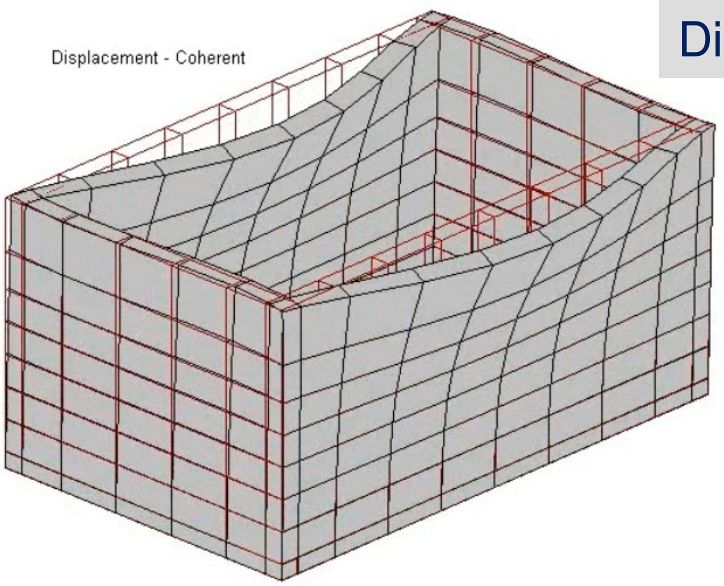
Accelerations

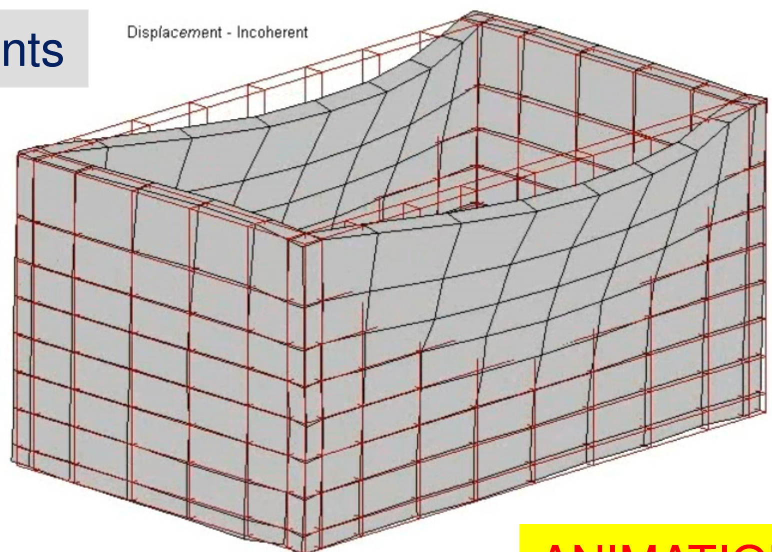


Coherent

Incoherent

Displacements

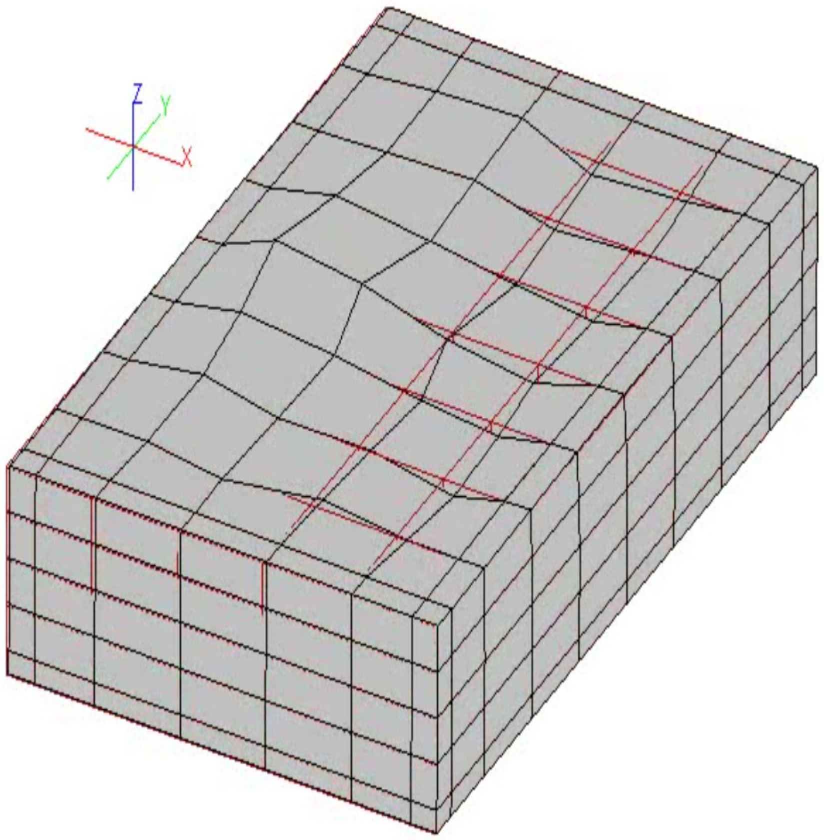




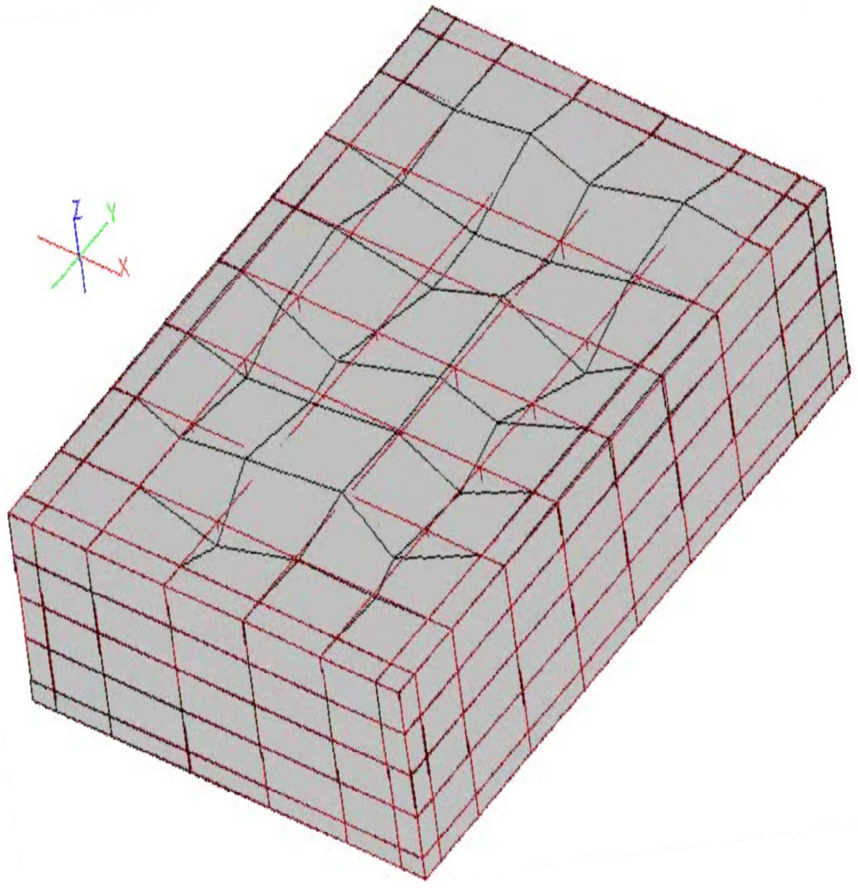
ANIMATIONS

Incoherent vs. Coherent Excavated Soil Motion

COHERENT



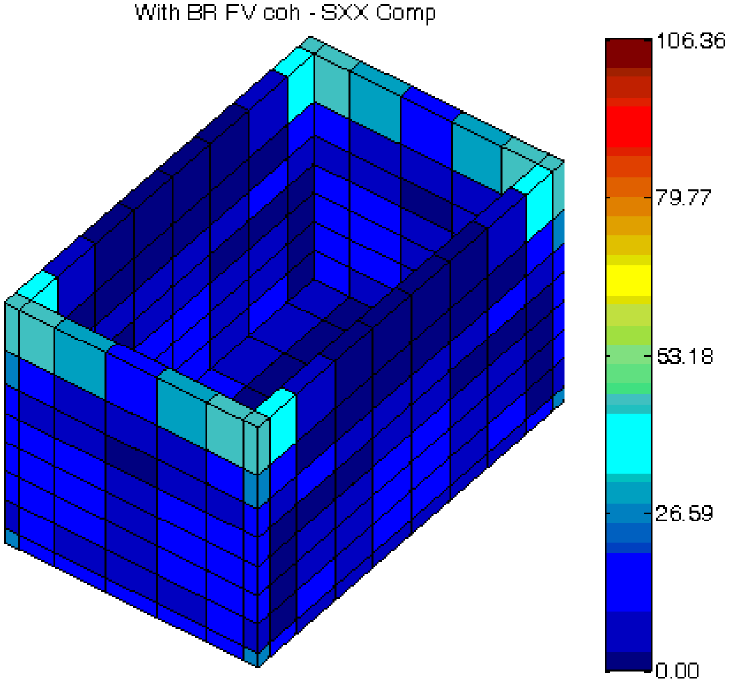
INCOHERENT

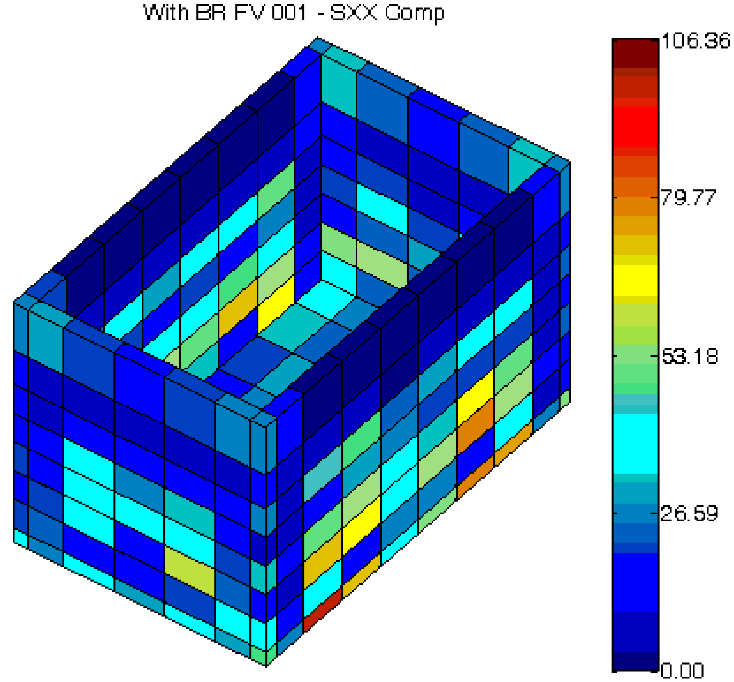


Seismic Coherent vs. Incoherent Stresses for X-Input

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

Element Center Stresses SXX

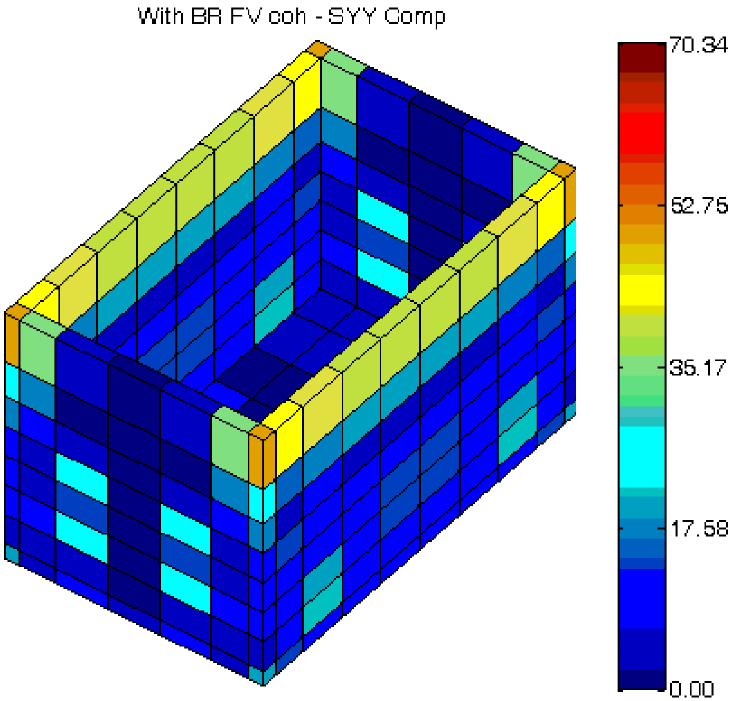


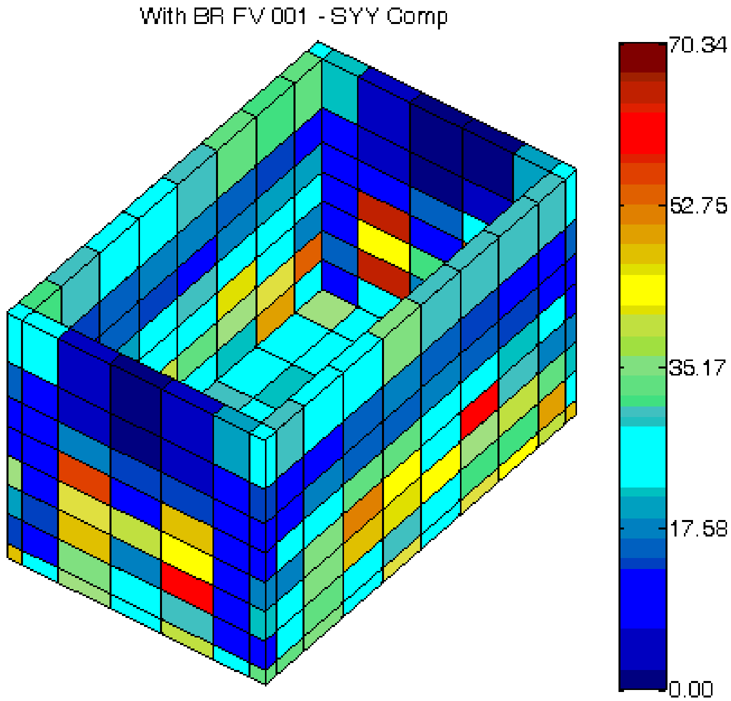


Seismic Coherent vs. Incoherent Stresses for X-Input

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

Element Center Stresses SYY

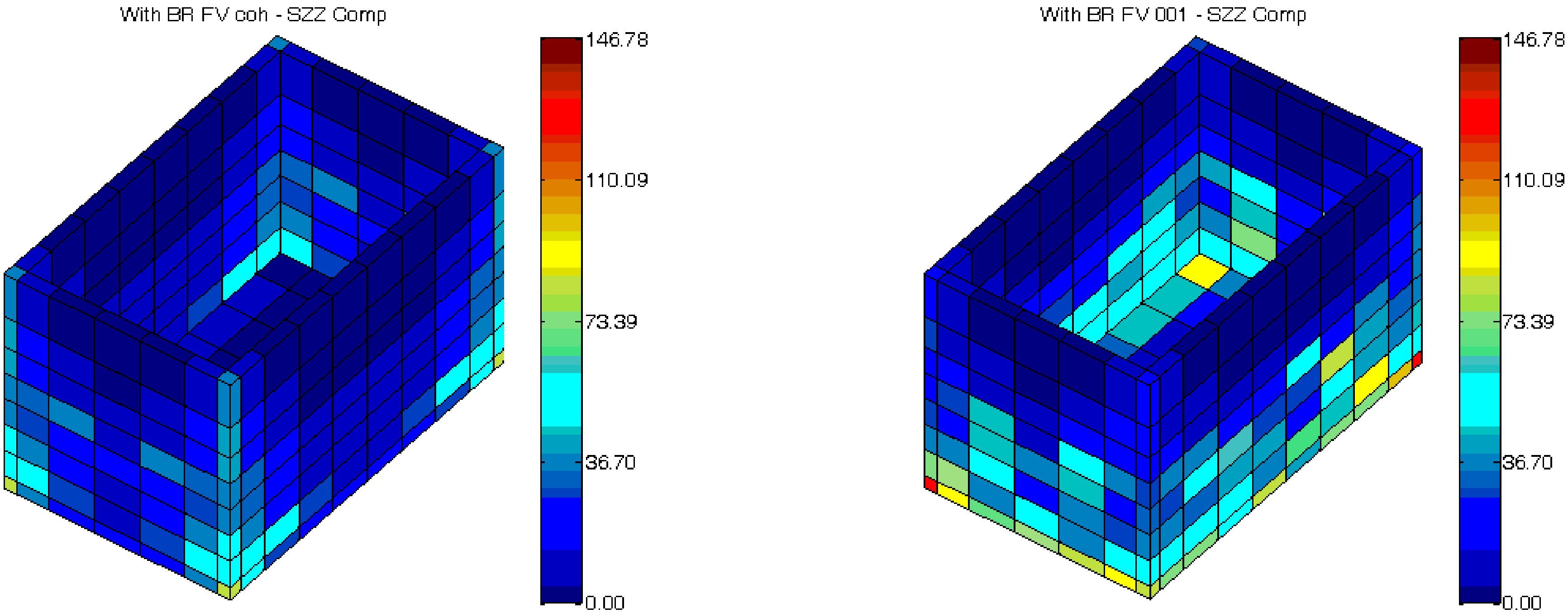




Seismic Coherent vs. Incoherent Stresses for X-Input

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

Element Center Stresses SZZ



ANIMATIONS

Conclusions for Case Studies

The effects of motion incoherency are:

1) Reduce the ISRS amplitudes in high–frequency range. For rock sites, large ISRS amplitude reductions of 2-3 times are possible.

2) Could increase in some locations the bending moments in base slabs and embedded walls

3) For large foundation sizes, increase the shear wall forces in external walls placed at the far end edges

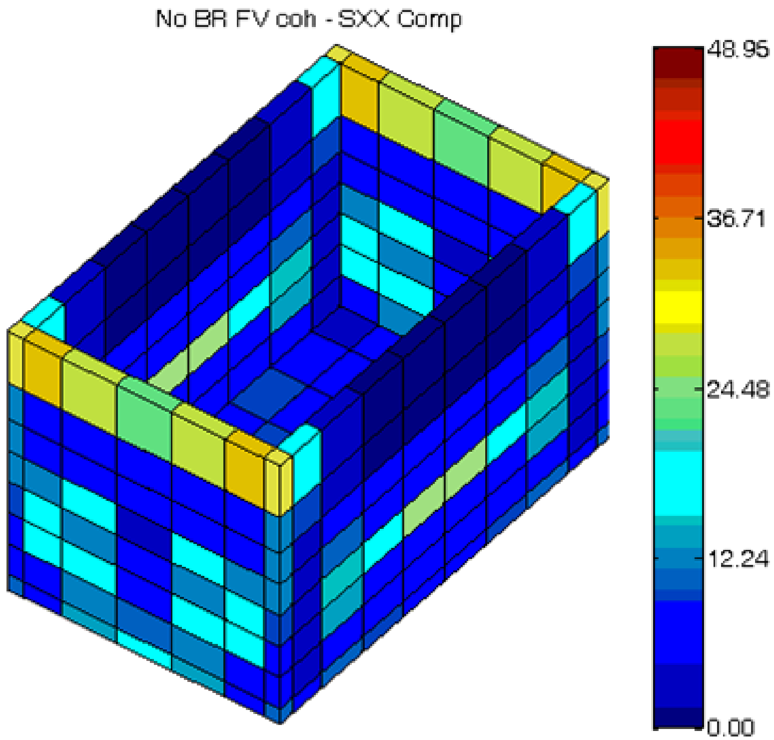
4) The inclusion of wave passage effects could be favorable for interior shear walls and detrimental for external walls located at the longitudinal edges. *More in-depth research is needed.*

5) For deeply embedded structures, the incoherency effects are to reduce the global resultant of the local soil pressures, but locally might produce *"hot spot*" pressures due to short wavelength soil motion components. Wave scattering effects around deeply embedded structures are sensitive to motion incoherency*. More in-depth research is needed.*

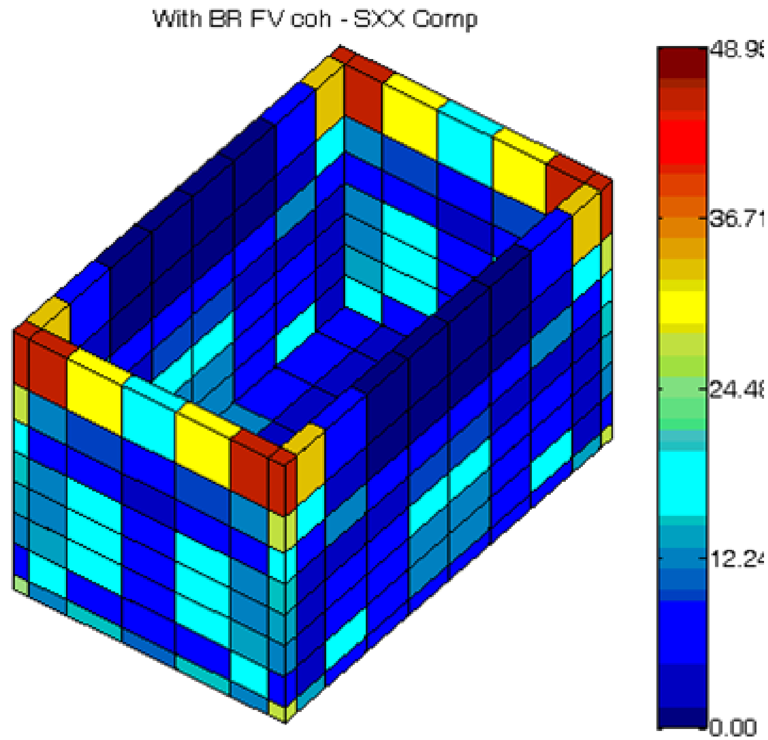
Seismic Stresses for X-Input (Frame 903) Using FV method

Half-space Soil vs. Backfill Soil Layer with Vs = 1.000 on Rock Vs = 5,500fps

Element Center Stresses SXX



Half-space

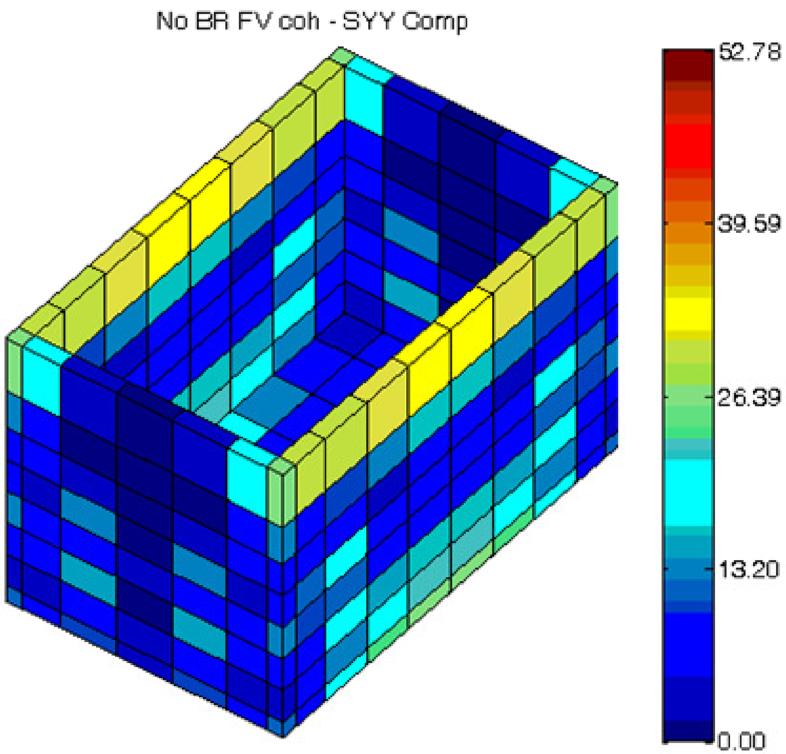


Baserock

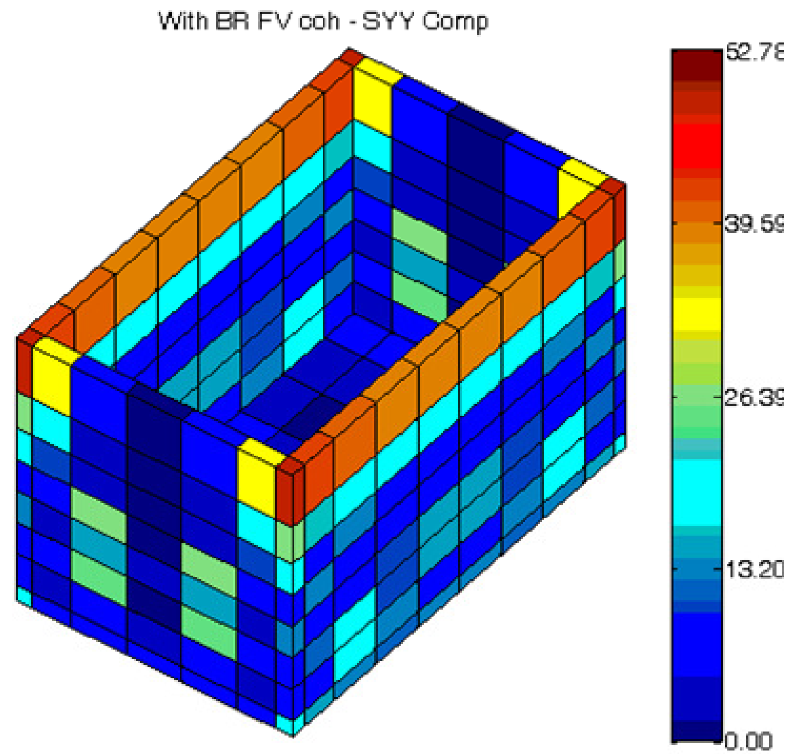
Seismic Stresses for X-Input (Frame 903) Using FV method

Half-space Soil vs. Backfill Soil Layer with Vs = 1.000 on Rock Vs = 5,500fps

Element Center Stresses SYY



Half-space

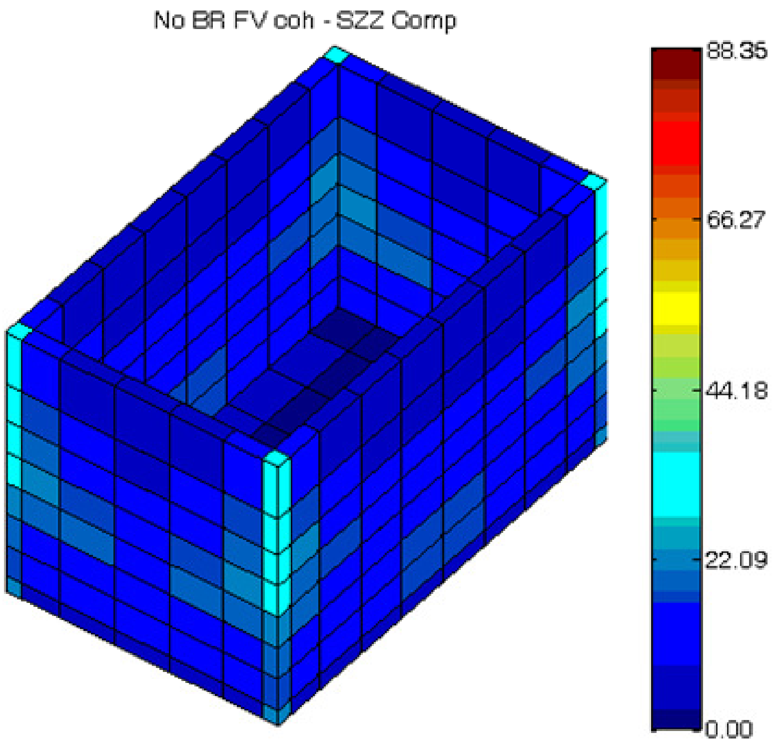


Baserock

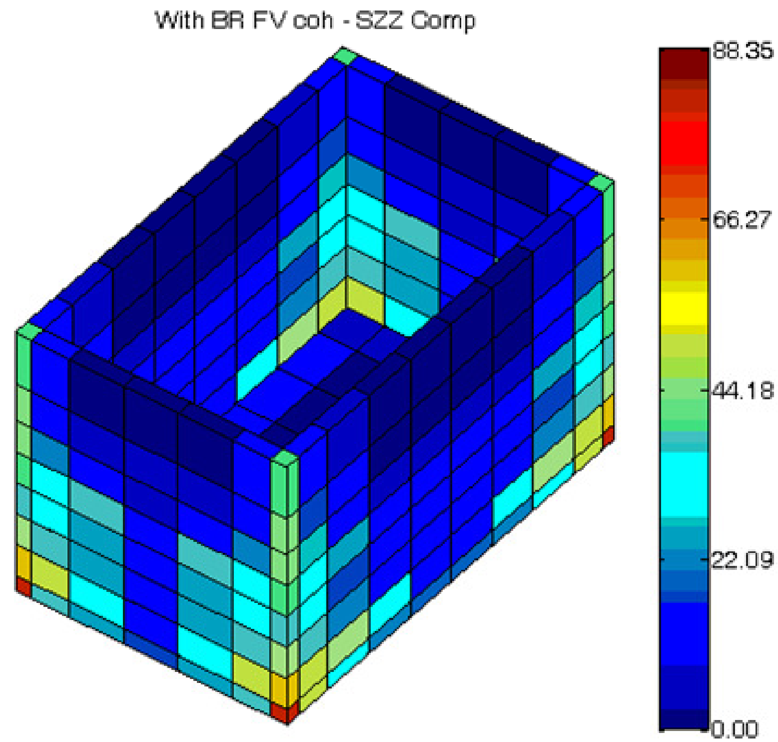
Seismic Stresses for X-Input (Frame 903) Using FV method

Half-space Soil vs. Backfill Soil Layer with Vs = 1.000 on Rock Vs = 5,500fps

Element Center Stresses SZZ



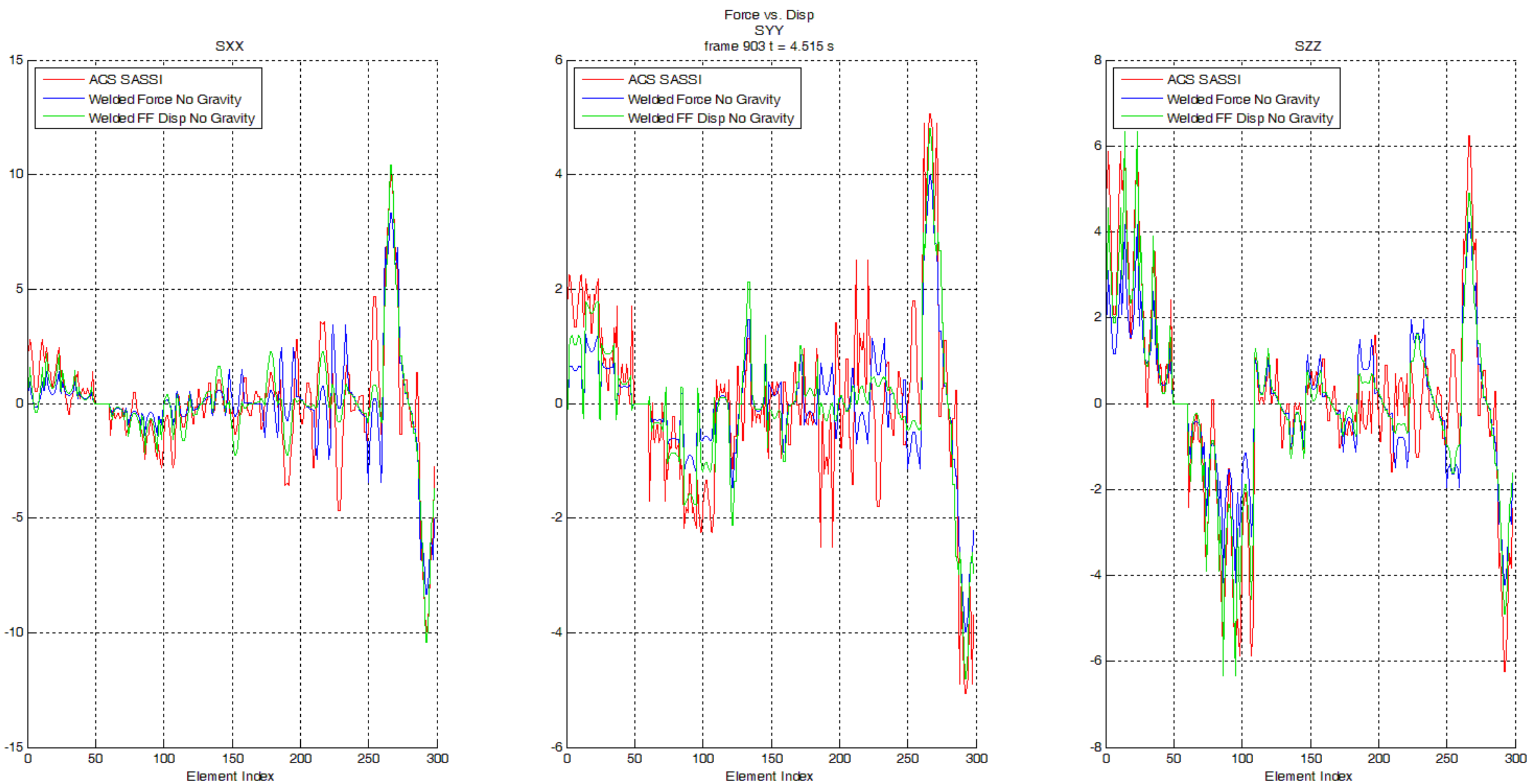
Half-space



Baserock

ACS SASSI Seismic Pressures for X-Input (Frame 903)

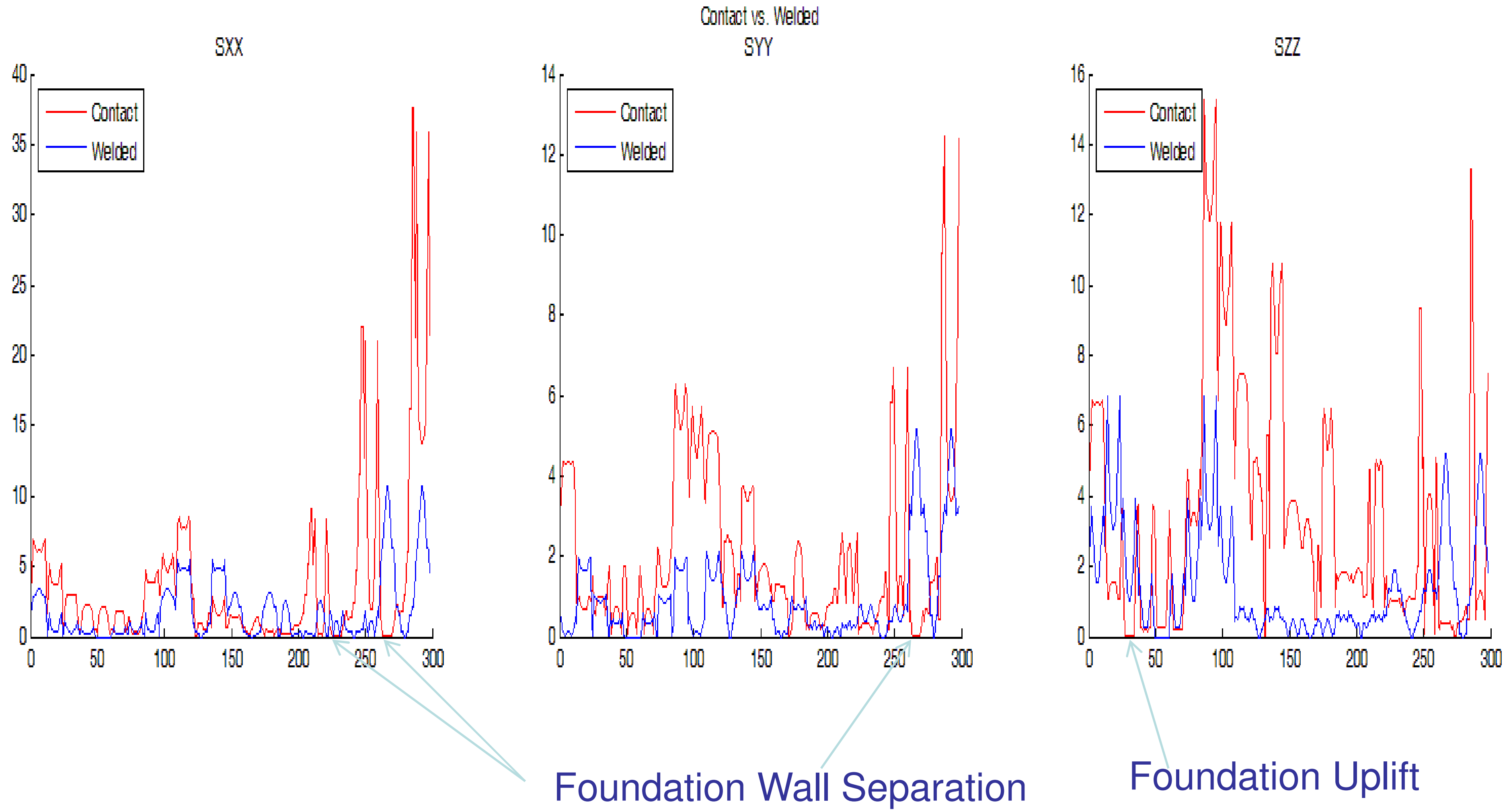
ACS SASSI vs. ANSYS Equiv. Static Displacements with Free-Field and Seismic Forces
Element Center Stresses SXX, SYY, SZZ



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

ANSYS Equivalent-Static Seismic Force Loading Option

Absolute Values of Element Center Stresses SXX, SYY, SZZ



EPRI AP1000 NI Model Studies on Seismic SSSI Effects For Hypothetical Site Condition That Includes 40 ft Backfill Soil Over A Hard Rock Formation

Dan M. Ghiocel

Ghiocel Predictive Technologies Inc.

http://www.ghiocel-tech.com

Dali Li, Nicholas T. Brown

and Jennifer J. Zhang

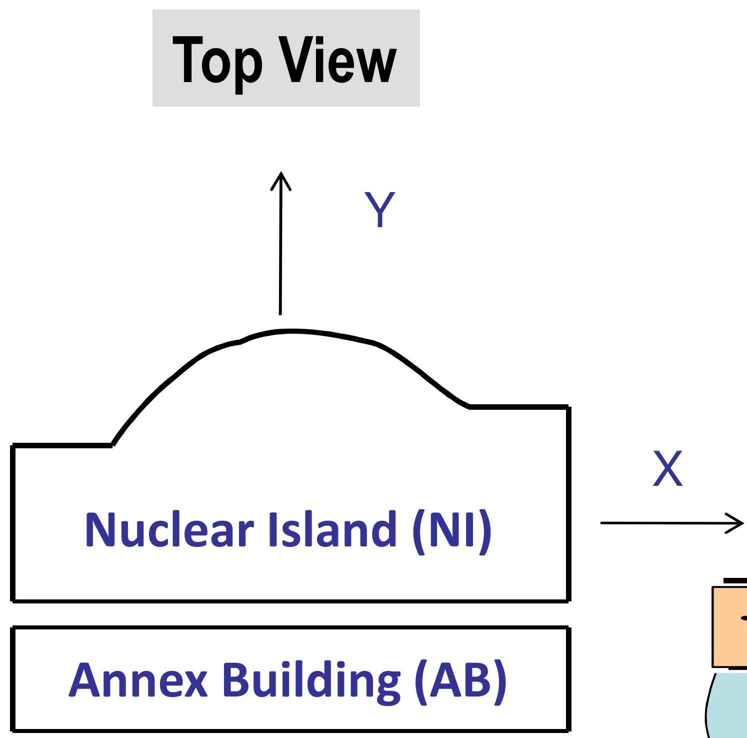
Westinghouse Co.

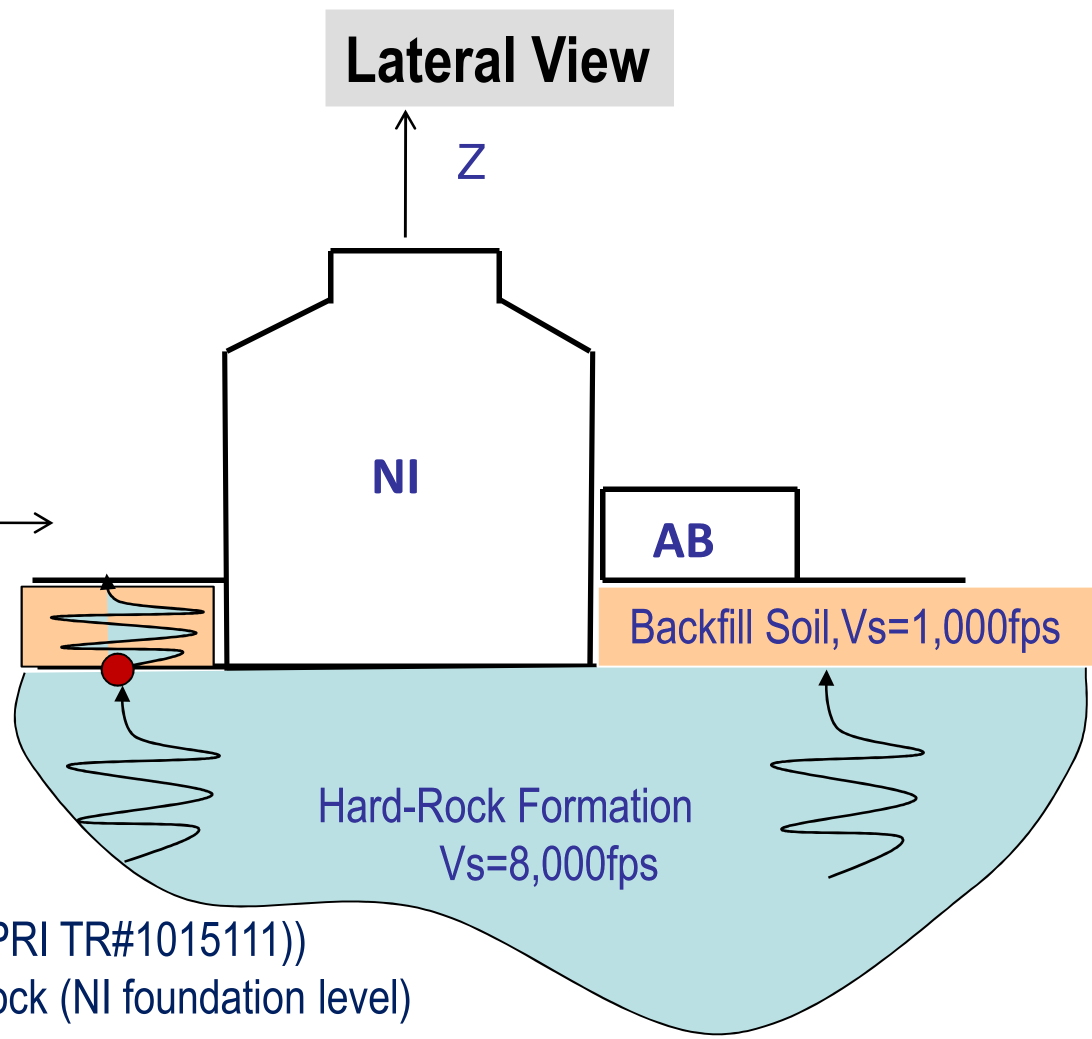
http://www.westinghouse.com

OECD NEA SSI Workshop

Ottawa, Canada, October 6-8, 2010

AP1000 NI Complex and Annex Bldg Configurations





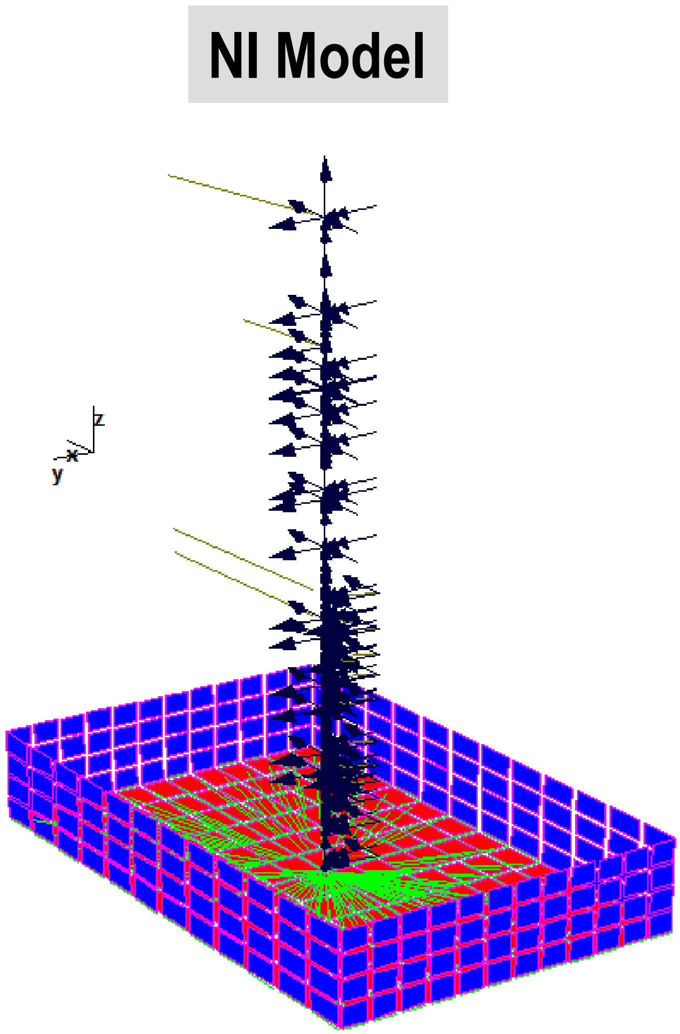
Coherent SSI Analysis:

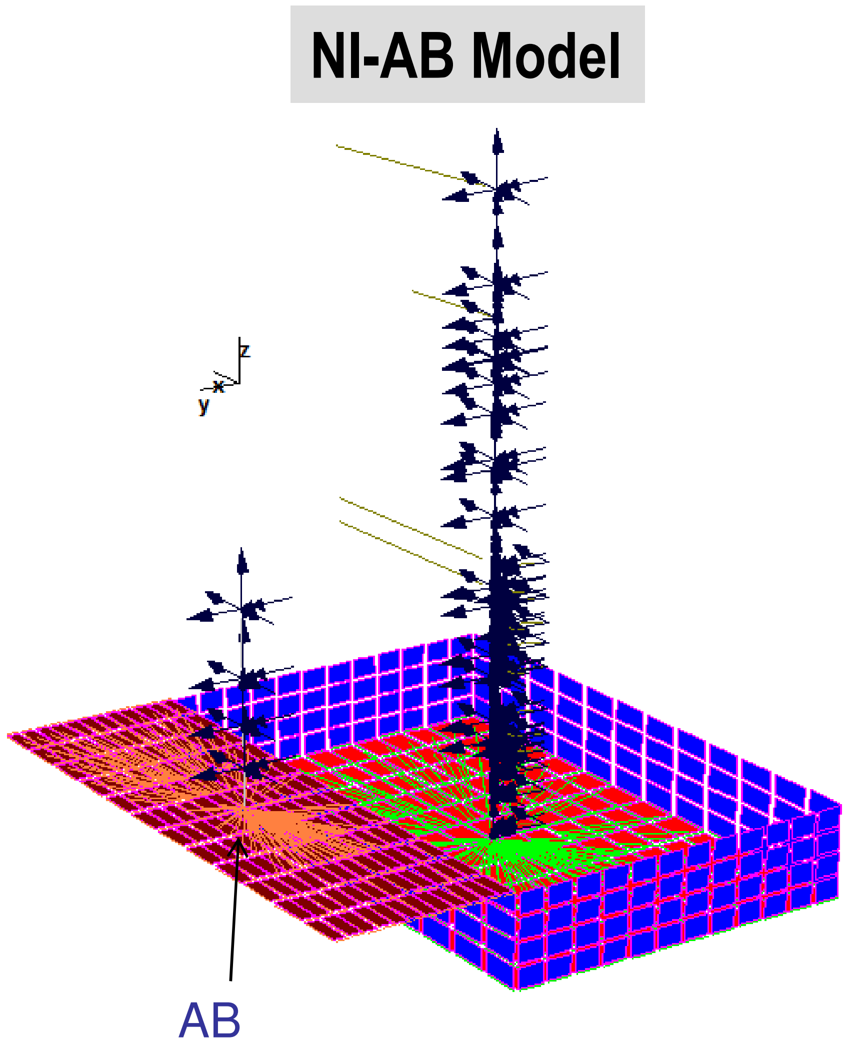
- Seismic input defined HRHF input ((EPRI TR#1015111))
- Control motion at the top of the hard-rock (NI foundation level)

Incoherent SSI Analysis:

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

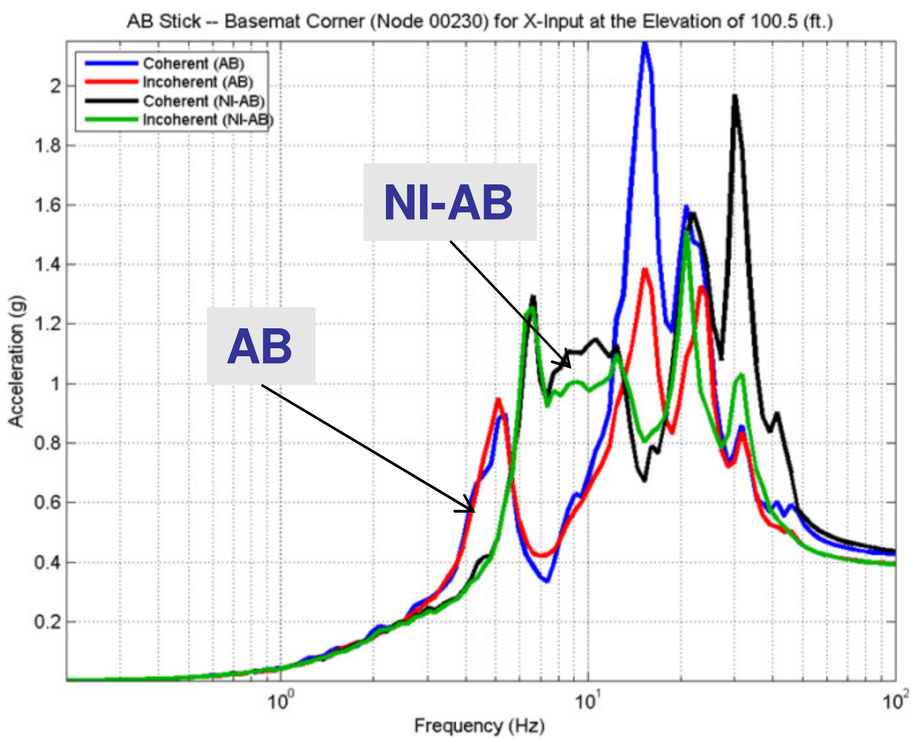
Isolated NI and Coupled NI-AB SSI Models



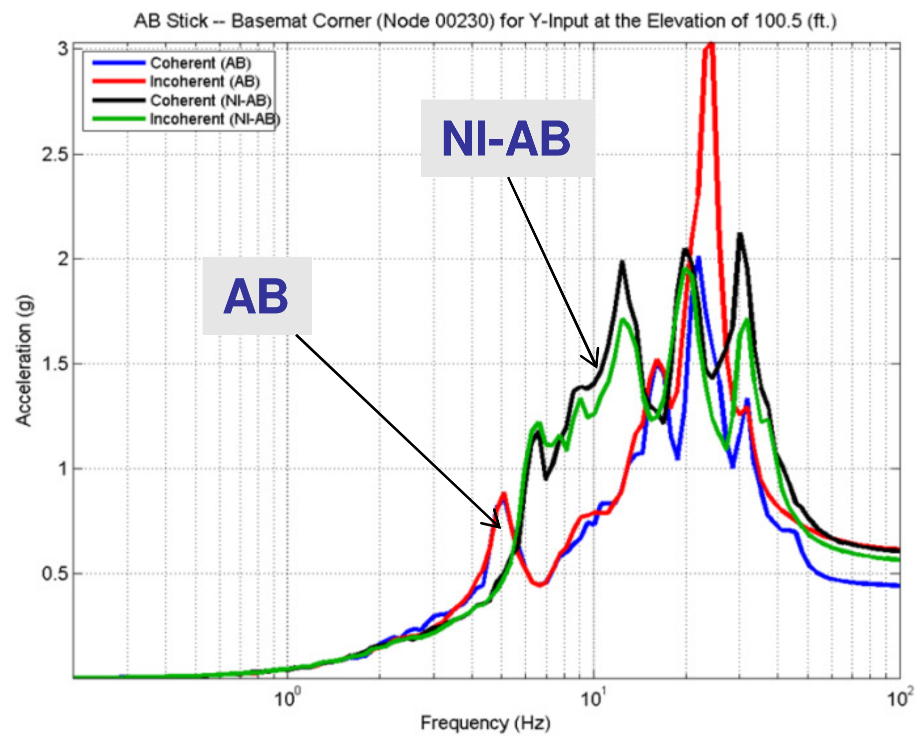


AB and Coupled NI-AB Coherent and Incoherent SSI. 5% Damp ISRS Y-Dir at AB Basemat Corner (El. 100ft)

X-Direction

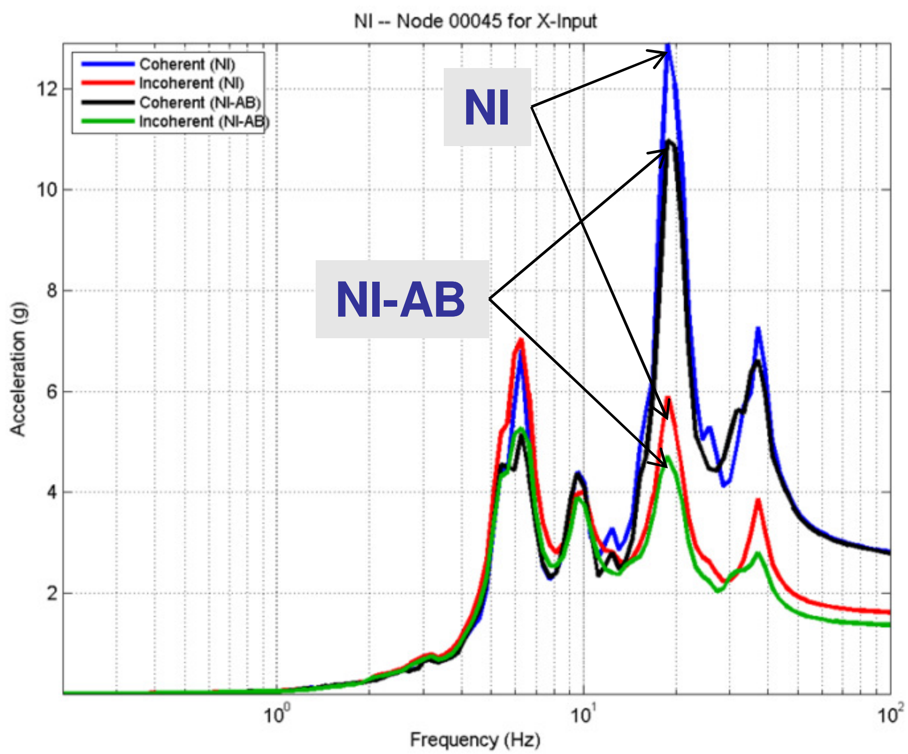


Y-Direction

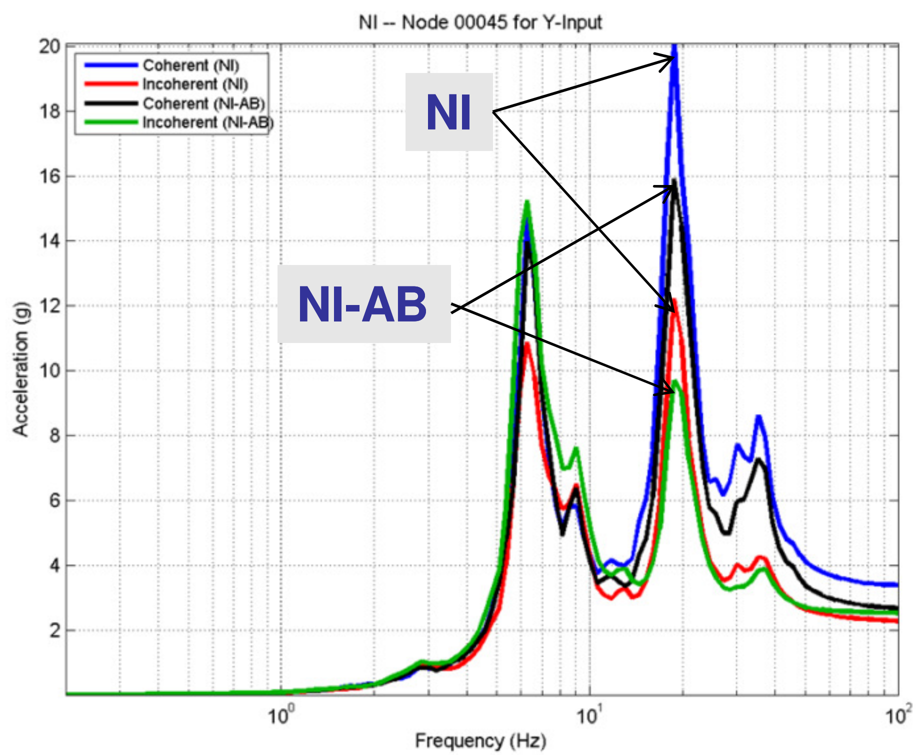


NI and Coupled NI-AB Coherent and Incoherent SSI. 5% Damp ISRS at NI Complex - Top of SCV (282 ft)

X-Direction

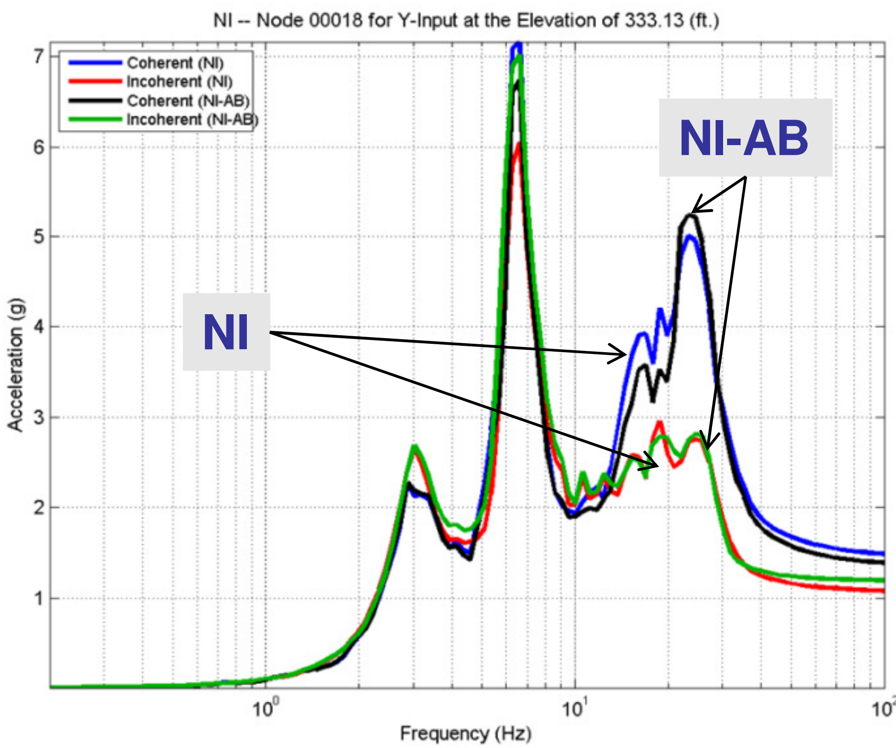


Y-Direction

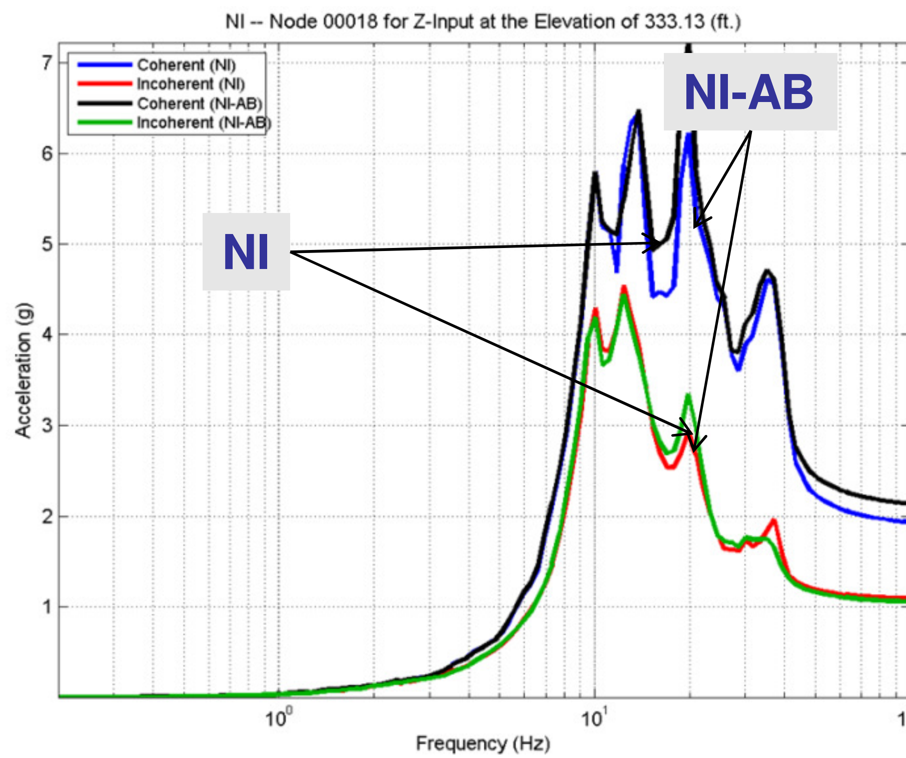


NI and Coupled NI-AB Coherent and Incoherent SSI. 5% Damp ISRS at NI Complex - Top of ASB (333 ft)

Y-Direction



Z-Direction



Conclusions on SSSI Study

For the particular case investigated herein that assumed that NI complex is founded on a bedrock and embedded in a soft backfill layer and the neighbor AB is founded on the backfill soil (with no soil improvement or lean concrete underneath), the effects of SSSI for the coupled NI-AB model indicate

- Relatively minor effects, mostly favorable, for the NI complex structures on ISRS and structural forces

- Significant effects for the AB ISRS. The SSSI effects significantly affect the the ISRS frequency content.

ANIMATIONS

Seismic SSI Incoherency Effects for CANDU Reactor Building Structure

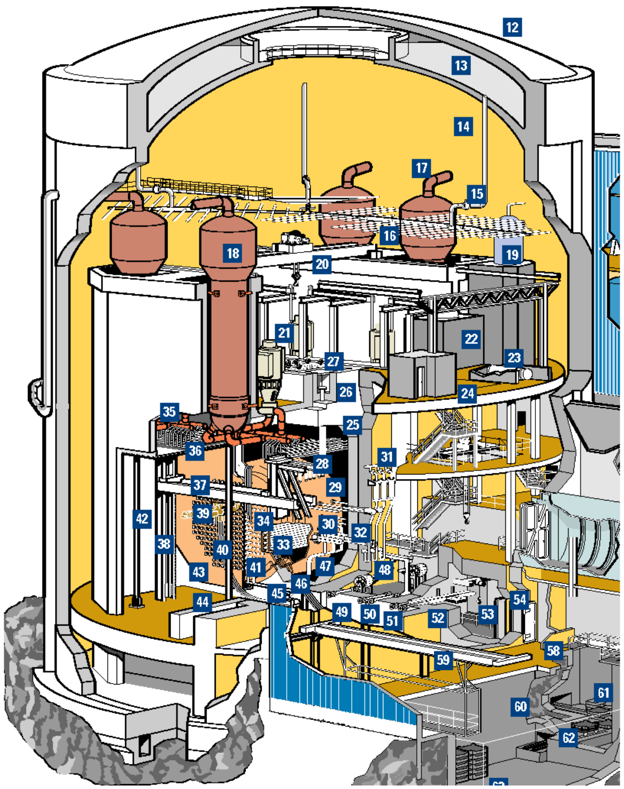
Dan M. Ghiocel
Ghiocel Predictive Technologies Inc., USA
http://www.ghiocel-tech.com

George Stoyanov, Sudip Adhikari
Tarek Aziz
AECL Ltd., Canada
http://aecl.com

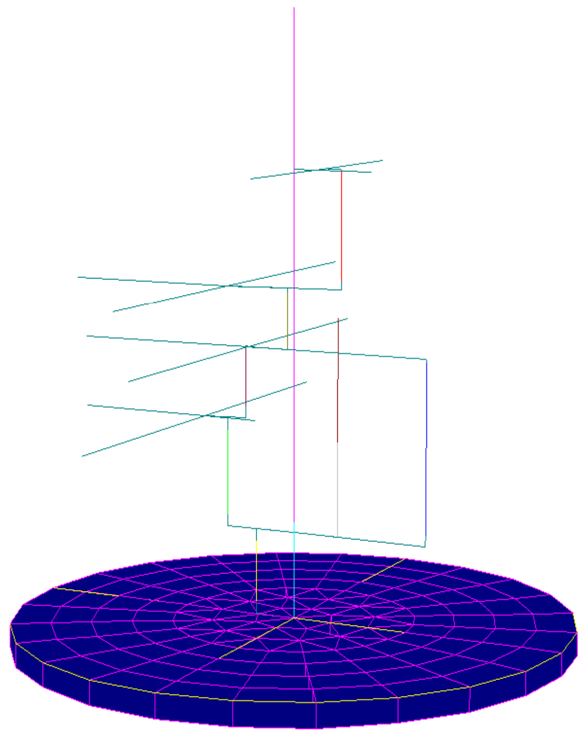
OECD NEA SSI Workshop

Ottawa, Canada, October 6-8, 2010

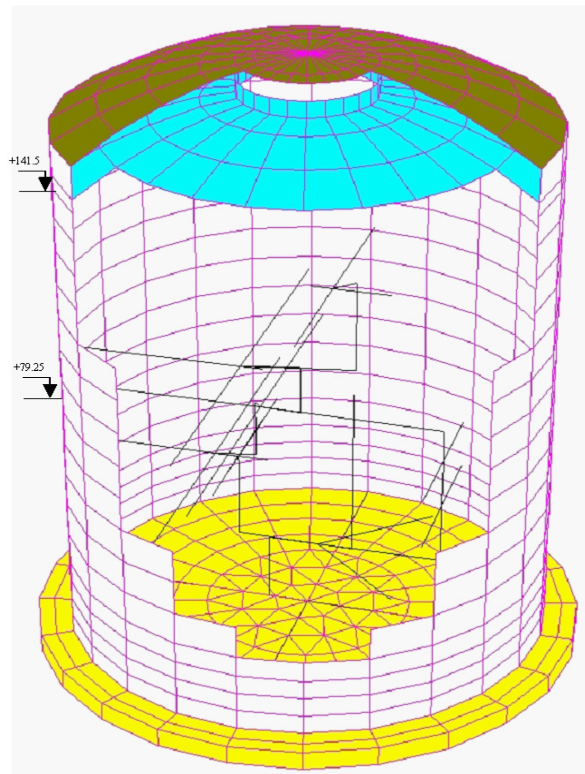
CANDU 6 Reactor Building (RB)
Incoherent SSI Case Studies



CANDU 6 RB Structure



SSI Stick Model



SSI Shell Model

CANDU 6 Study for Incoherent SSI Response On Two Different Soil Conditions

Rock Site:

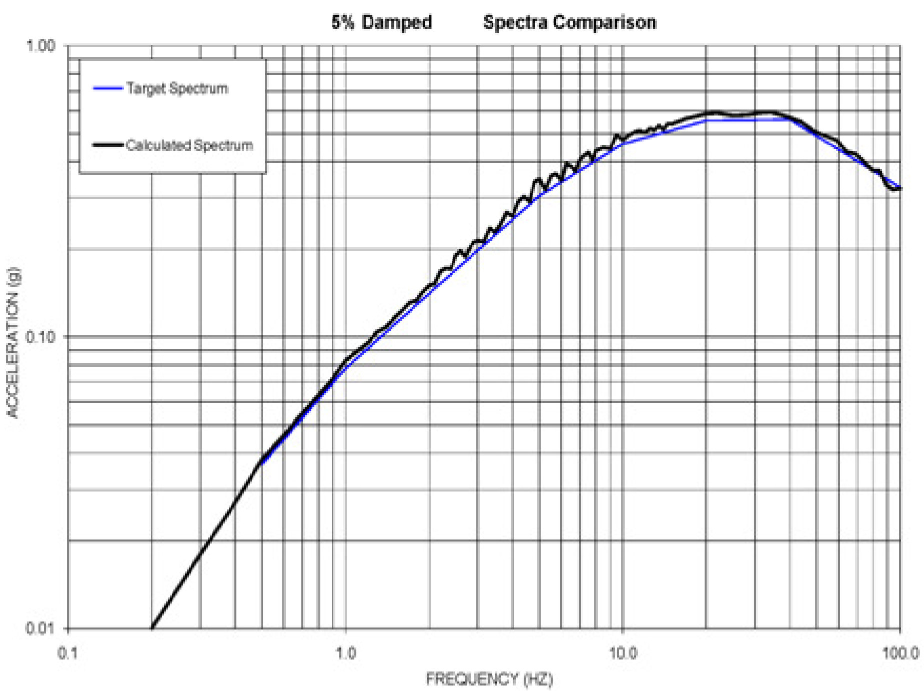
- Structure: Stick Model and Shell Model (HF Model)
- Soil Deposit: Uniform soil layering with Vs of about 5,500fps
- Control Motion: UHRS (max. in 20-40Hz range) with 0.32 ZPGA
- Incoherency: 2007 Abrahamson Coherence Function for Soil
- Wave Passage in X-Direction: Va = 10,000 fps

Stiff Soil Site:

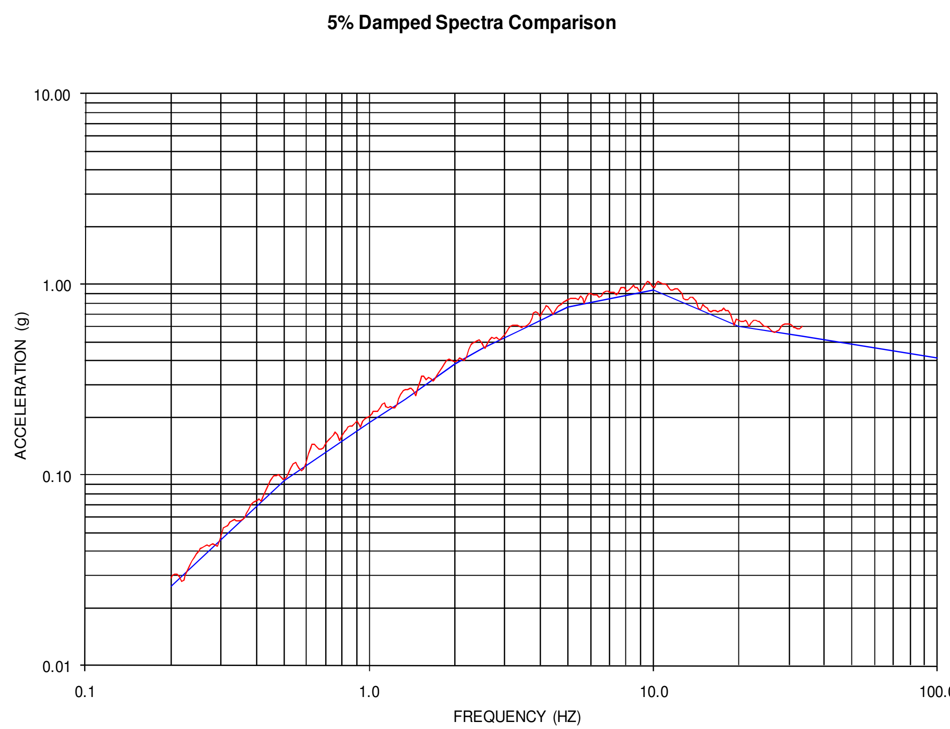
- Structure: Stick Model and Shell Model (HF Model)
- Soil Deposit: Uniform soil layering with Vs of about 3,000fps
- Control Motion: UHRS Input (spectral peak in 10 Hz) with 0.41g
- Incoherency: 2007 Abrahamson Coherence Function for Soil Sites
- Wave Passage in X-Direction: Va = 7,000 fps

Seismic Site-Specific Inputs Defined by 5% Damping UHRS

UHSRS for Rock Site
(max. in 20-40 Hz range)

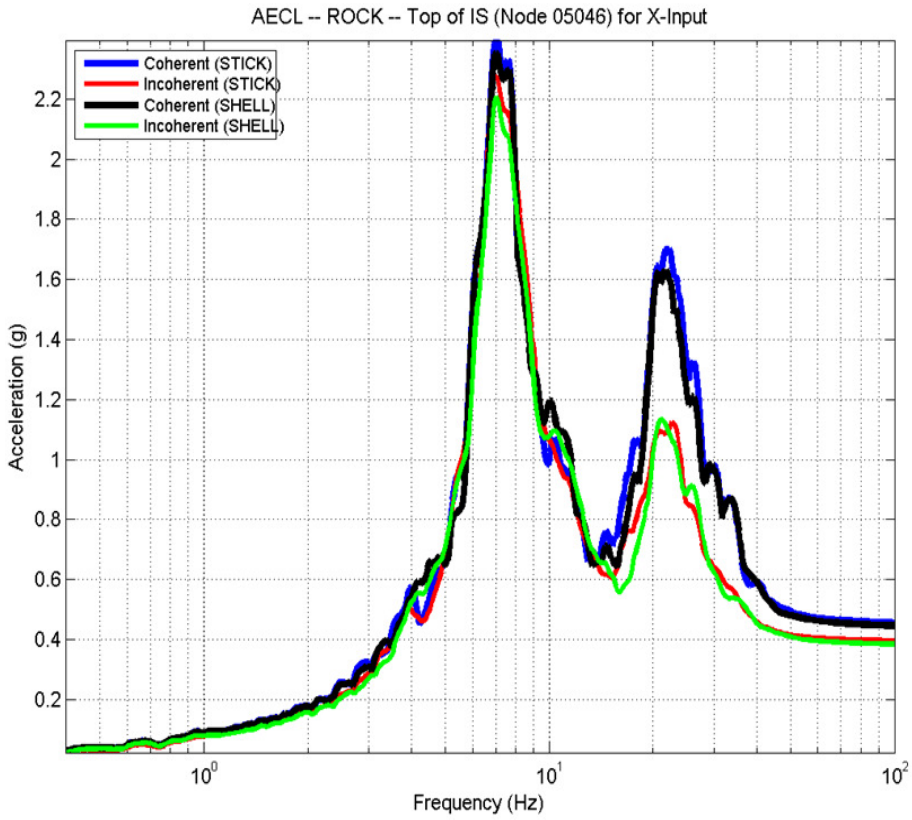


UHSRS for Soil Site
(max. at 10 Hz)

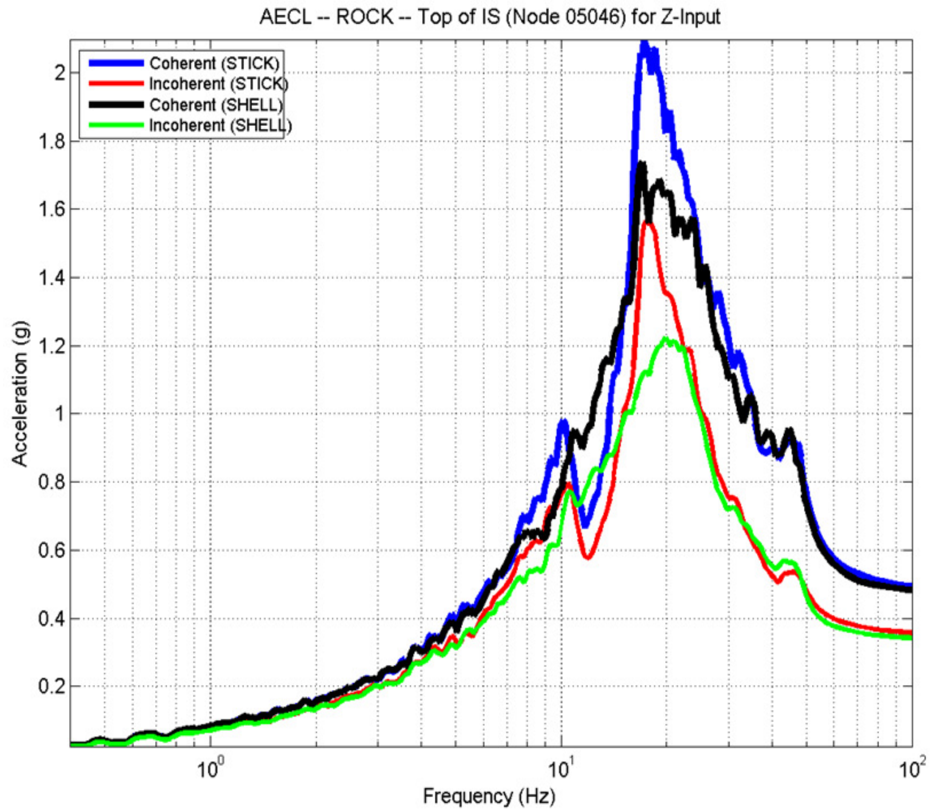


Top of Internal Structure (IS) ISRS. Rock Site

X-Direction

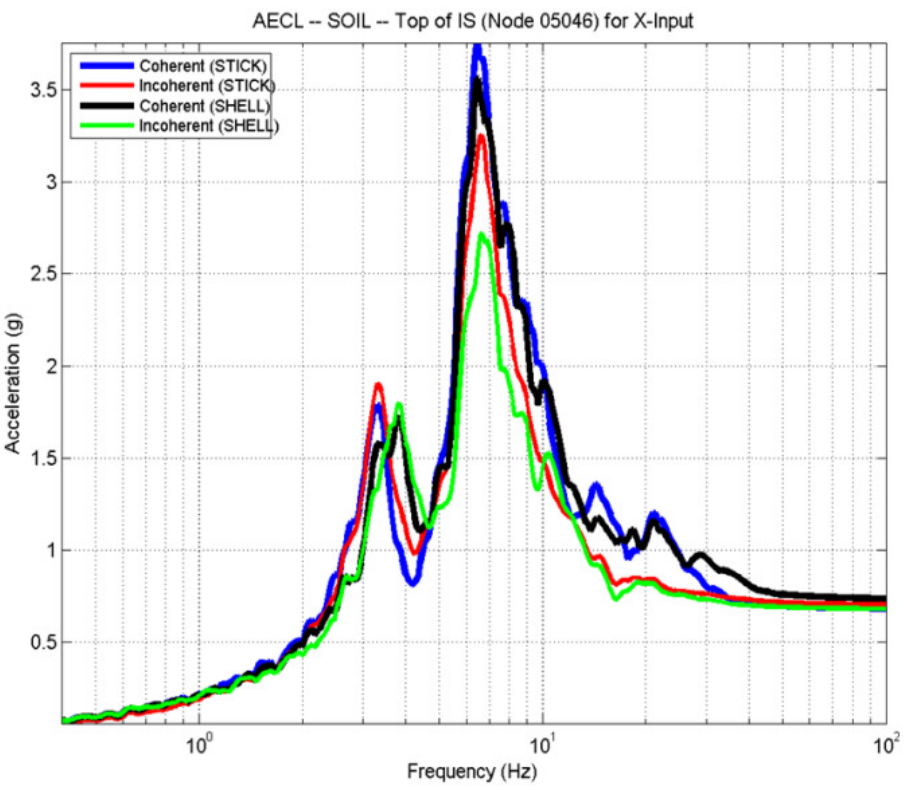


Z-Direction

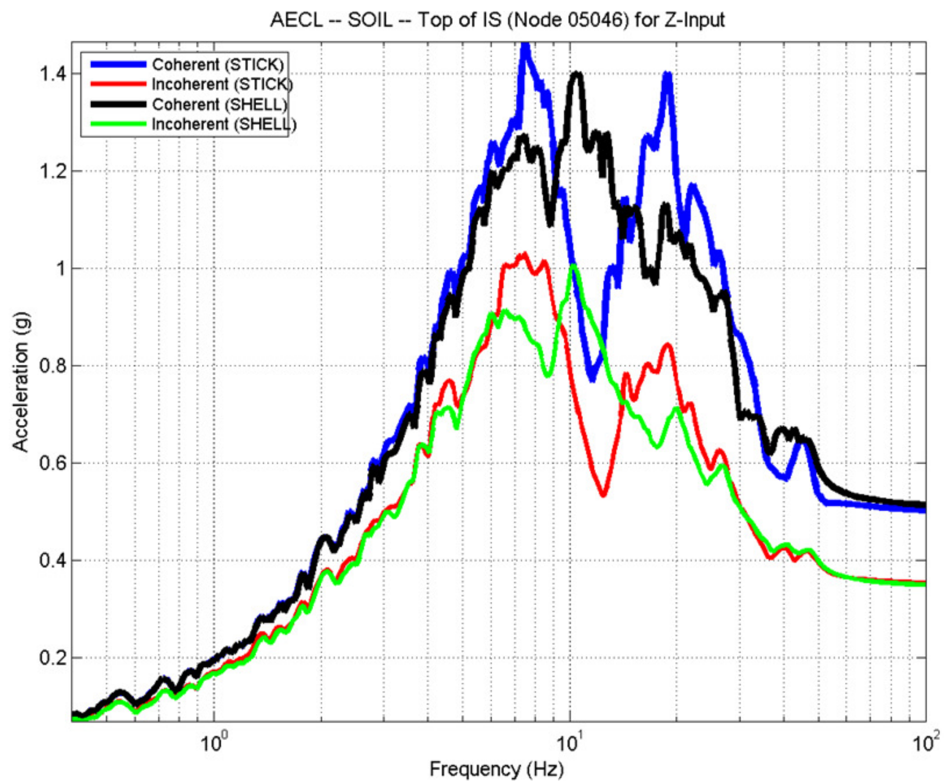


Top of Internal Structure (IS) ISRS.
Soil Site

X-Direction

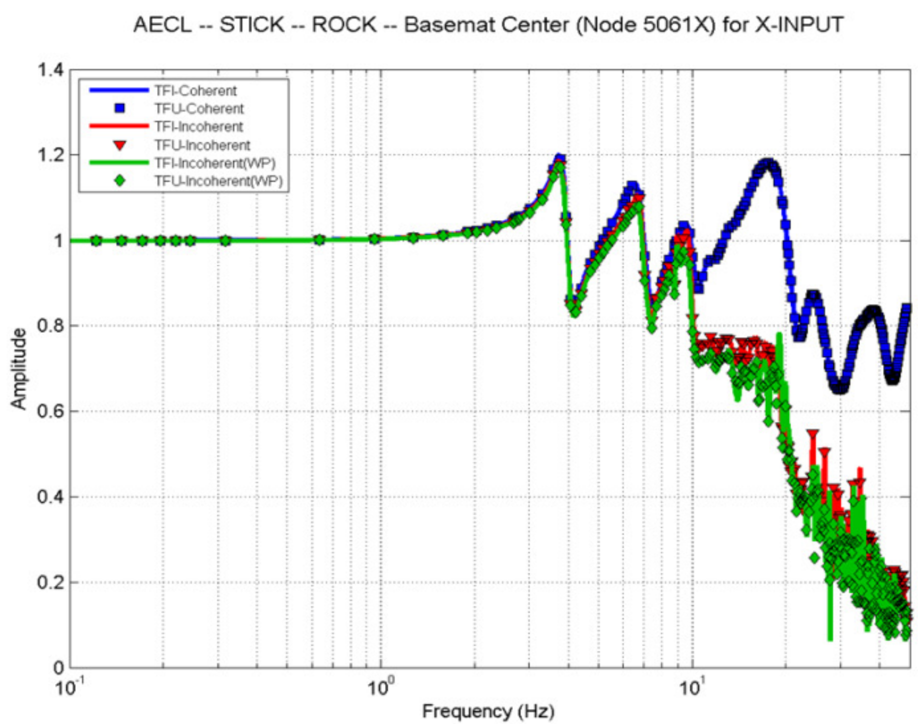


Z-Direction

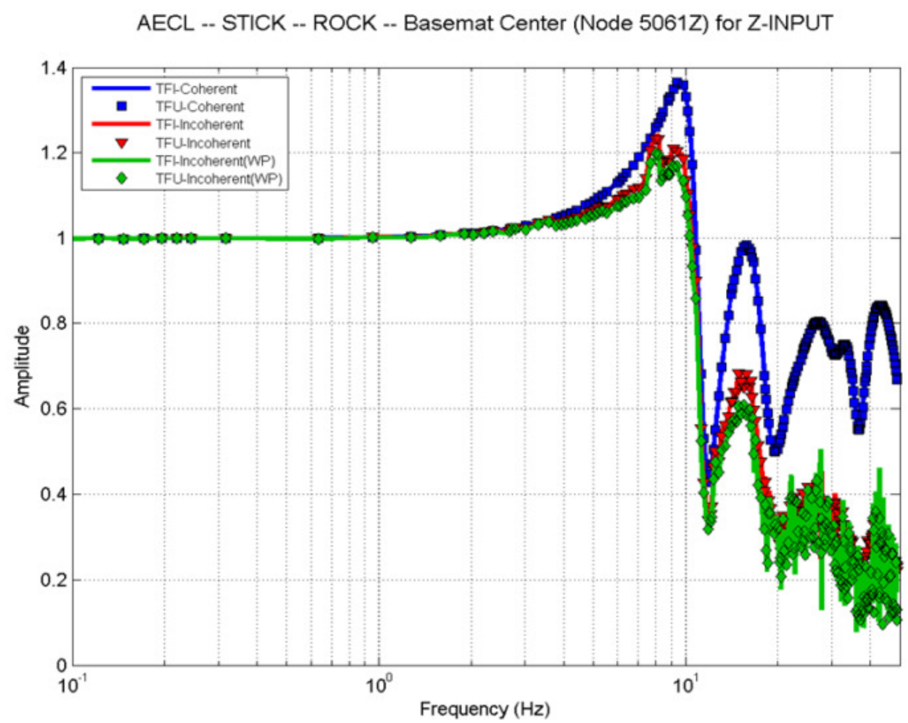


Coherent & Incoherent (Including Wave Passage) ATF at Base Center for X and Z Dir for Rock Site

X-Direction

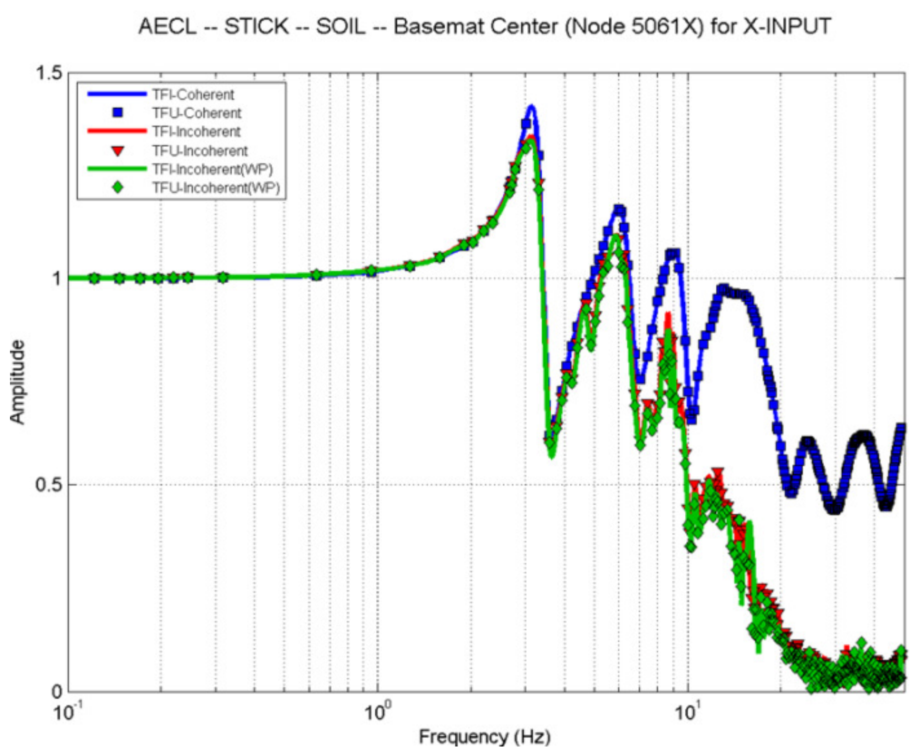


Z-Direction

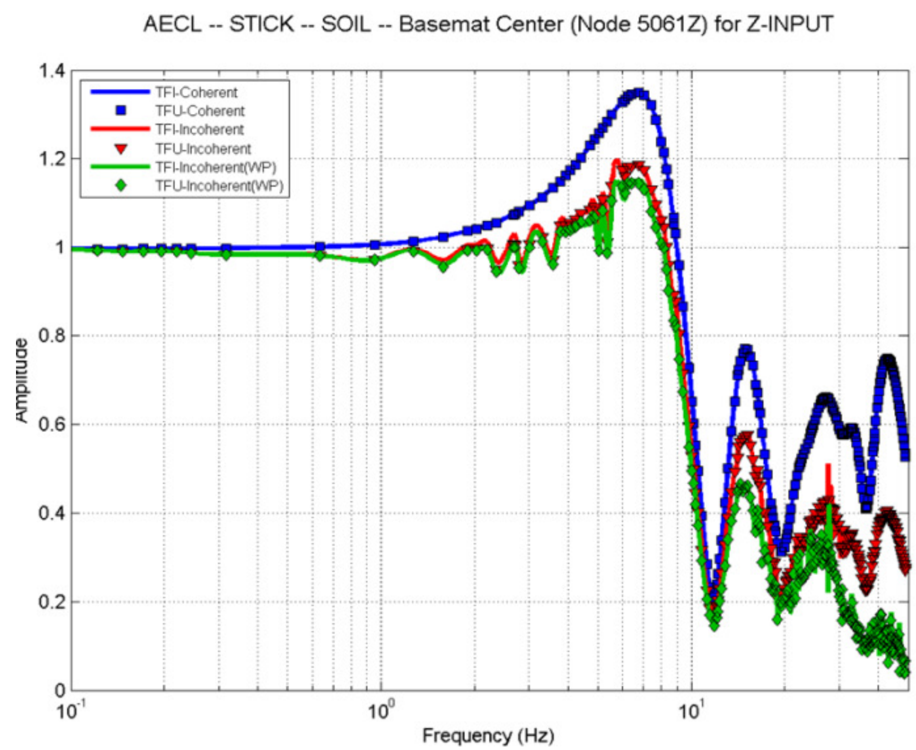


Coherent & Incoherent (Including Wave Passage) ATF at Base Center for X and Z Dir for Soil Site

X-Direction



Z-Direction



ANIMATIONS

Conclusions of RB CANDU 6 Case Studies

1) The incoherency effects are significant for the two case studies, the stiff soil site case and the rock site case.

2) The effects of wave passage appear to be insignificant for the two cases studies.

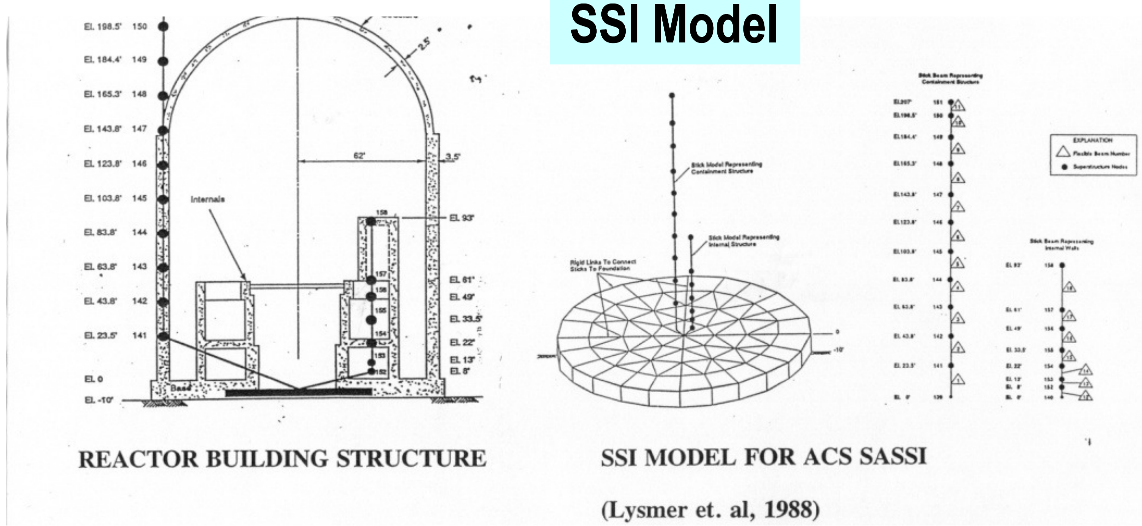
3) The effect of structural modeling the CS by shell elements rather than by a simple stick changes quite visibly the ISRS at the top of IS, especially in Z-direction.

4) The CS-IS dynamic coupling is affected by the structural modeling of the CS, although the IS stick is the same in both models.
   The CS-IS dynamic coupling effects appear to be larger for the Shell model, and for incoherent motions.

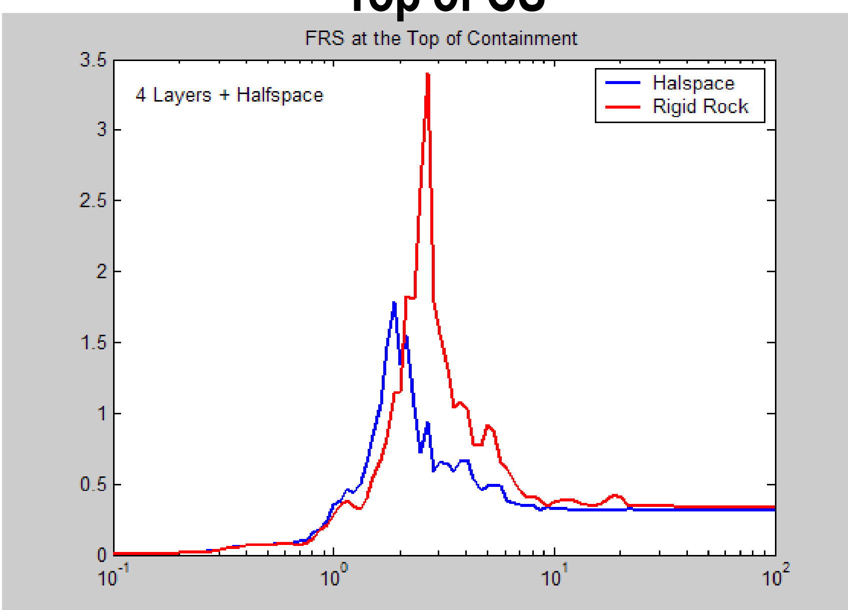
RB Complex ISRS Sensitivity Due to Baserock Location

a) Founded on Halfspace
b) Baserock at 40ft Depth

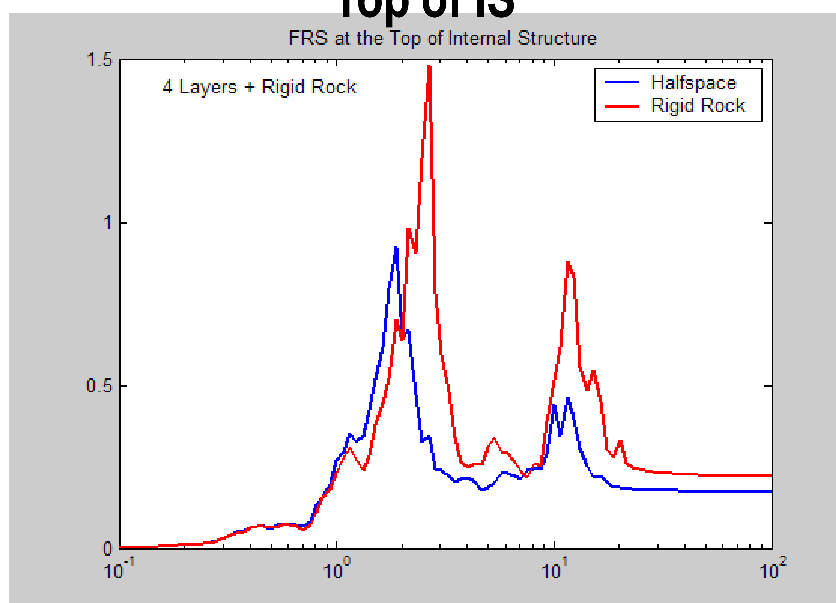
SSI Model



Top of CS



Top of IS

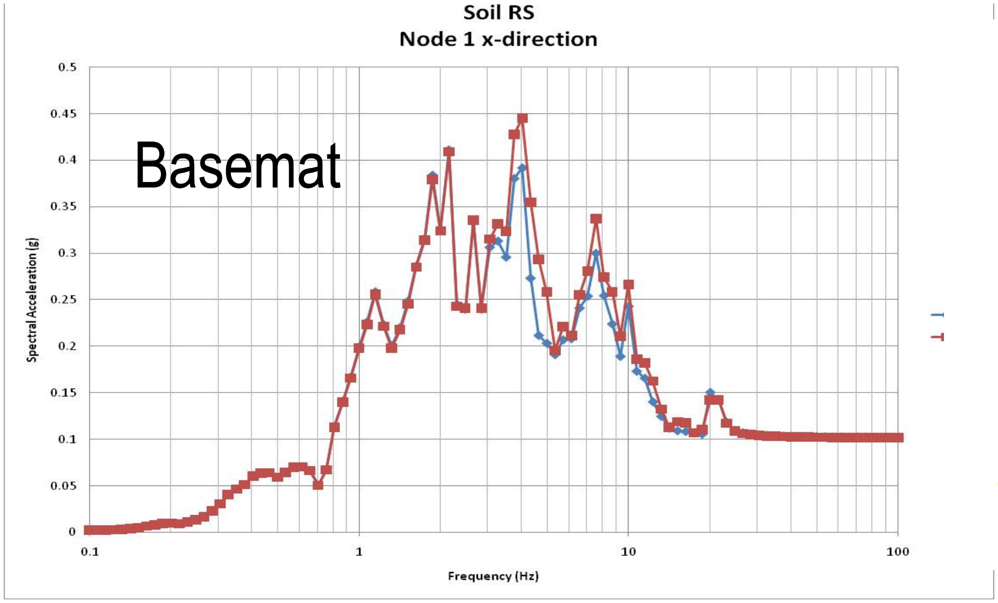


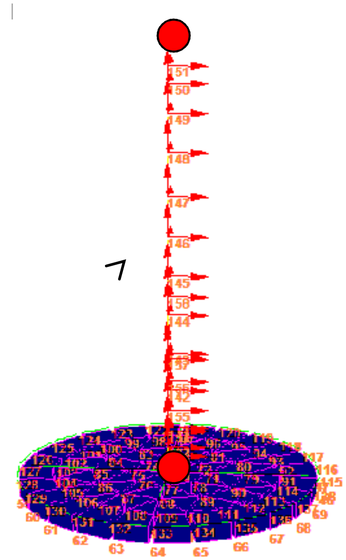
2D SSI Model vs. 3D SSI Model for RB Complex

REMARKS:

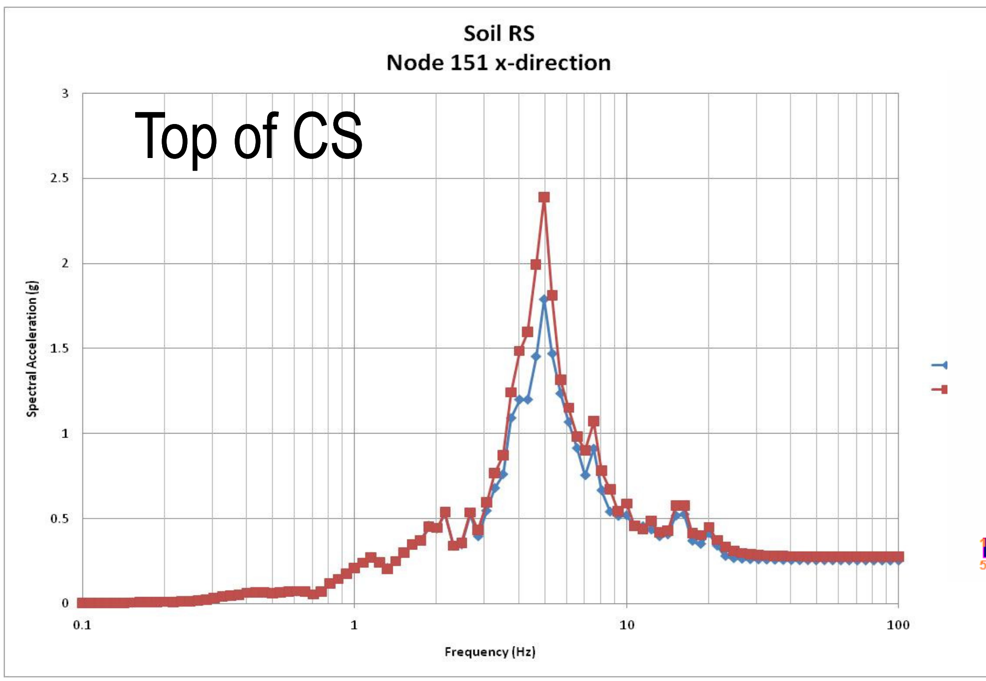
2D SSI models could exaggerate radiated energy. Surface wave decay faster in 2D space.

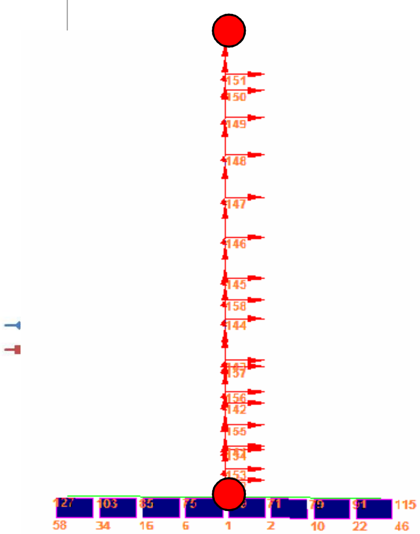
2D SSI models need calibration against 3D SSI models





3D SSI Model





2D SSI Model

New ASCE 04 Standard Draft 2011 – Progress Version

1) Improves the seismic input definition for FIRS
2) Recognize the significance of seismic input phasing – 5 input histories
3) Improves selection of deterministic soil profiles, LB, BE, UB and others
4) Recognizes the spatial correlations between soil layers
5) Provides many details for incoherent SSI analysis
6) Recognizes the basemat flexibility effects for incoherent inputs
7) Introduces probabilistic SSI methodologies
8) Limits incoherency effects for rock sites
9) It might include a recommendation for considering incoherency effects for SSSI evaluations.
10) Does not provide guidelines yet on the incoherent SSSI effects on ISRS, structural forces and relative displacements
11) No recommendation yet for incoherency effects on deeply embedded structures, including effects on seismic soil pressures on flexible walls

ACS SASSI Application to Linear and Nonlinear Seismic SSI Analysis of Nuclear Structures Subjected to Coherent and Incoherent Inputs

Dr. Dan M. Ghiocel

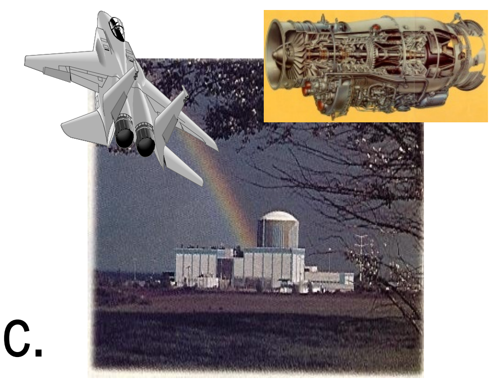
Email: dan.ghiocel@ghiocel-tech.com

Phone: 585-641-0379

Ghiocel Predictive Technologies Inc.

Ghiocel Predictive Technologies Inc.

http://www.ghiocel-tech.com



PART 2

North Marriott Convention Center, Bethesda, MD

January 25-27, 2011

ACS SASSI-ANSYS* Integration for Refined Seismic Structural Stress Analysis and Soil Pressure Computations

*** ANSYS is a trademark of ANSYS, Inc.**

ACS SASSI-ANSYS Interface for Seismic Soil-Structure Interaction Analysis of Nuclear/Critical Facility Structures

ACS SASSI-ANSYS Interface provides new SSI analysis capabilities through ANSYS:

For structural stress analysis:

- *ANSYS Equivalent-Static Seismic SSI Analysis* Using Refined Mesh FE Models

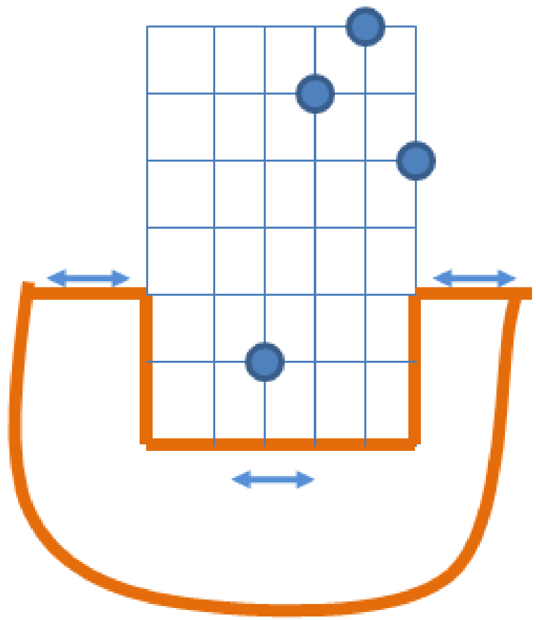
- *ANSYS Dynamic Seismic SSI Analysis* Using Nonlinear or More Refined FE Models (including refined mesh, element types including local nonlinearities, nonlinear materials, contact elements, etc.)

For soil pressure computation:

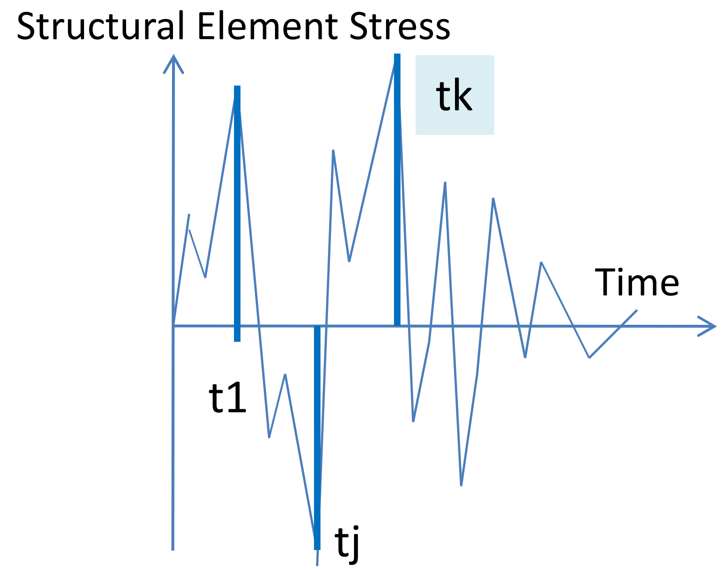
- *ANSYS Equivalent-Static Seismic Soil Pressure Computation* Including Soil-Foundation Separation Effects

ACS SASSI Seismic SSI Analysis

Computing Structural Stress/Forces

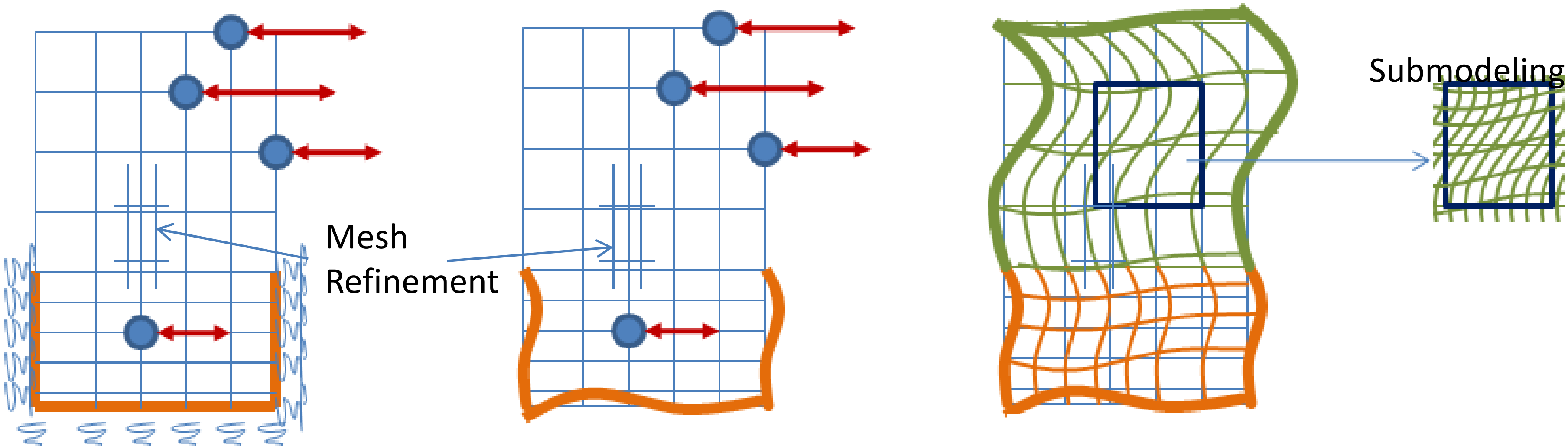


Selected Critical Time Steps for Maximum Stresses
To be Used for Equivalent Static Structural Analysis



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

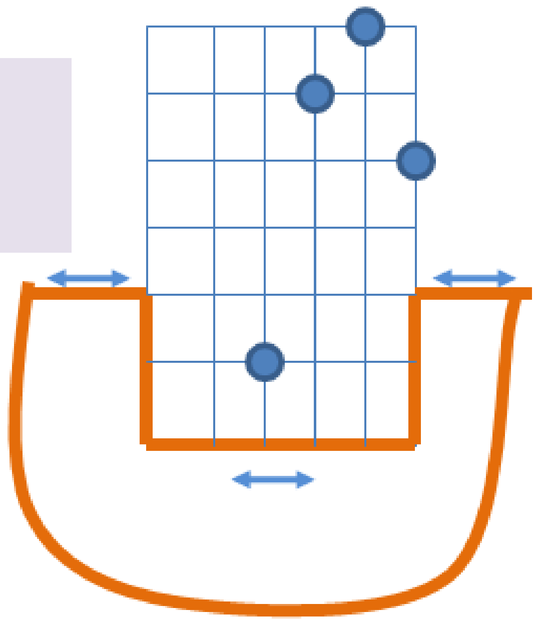
EQS Forces + BC Springs | EQS Forces + BC Displacements | EQS Relative Displacements



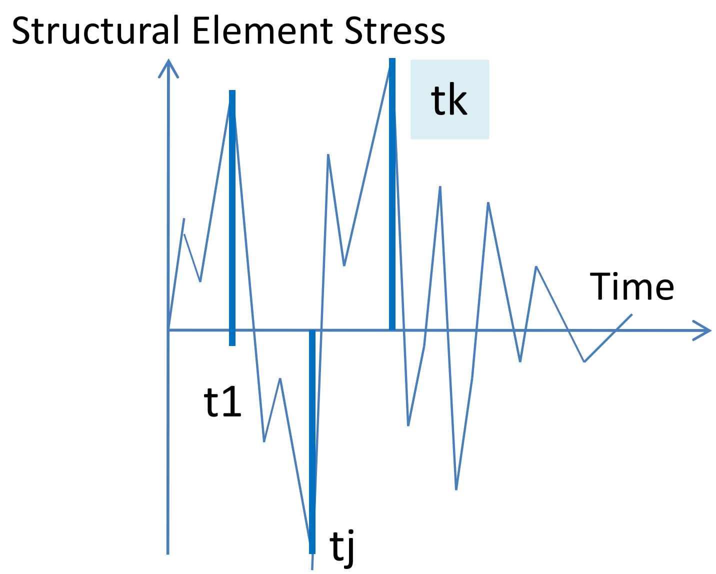
Variable Accuracy C-by-C | “Exact” | “Exact”

ACS SASSI Seismic SSI Analysis

Computing Seismic Soil Pressures

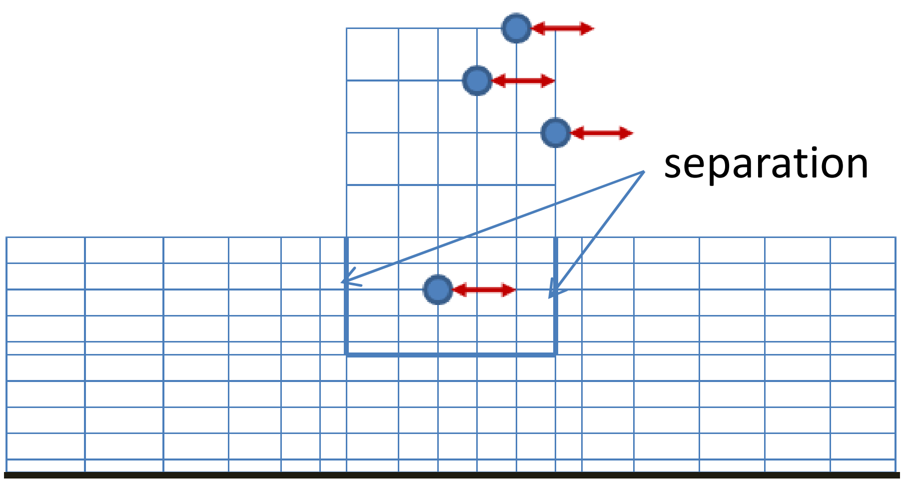


Selected Critical Time Steps for Maximum Stresses
To be Used for Equivalent Static Structural Analysis

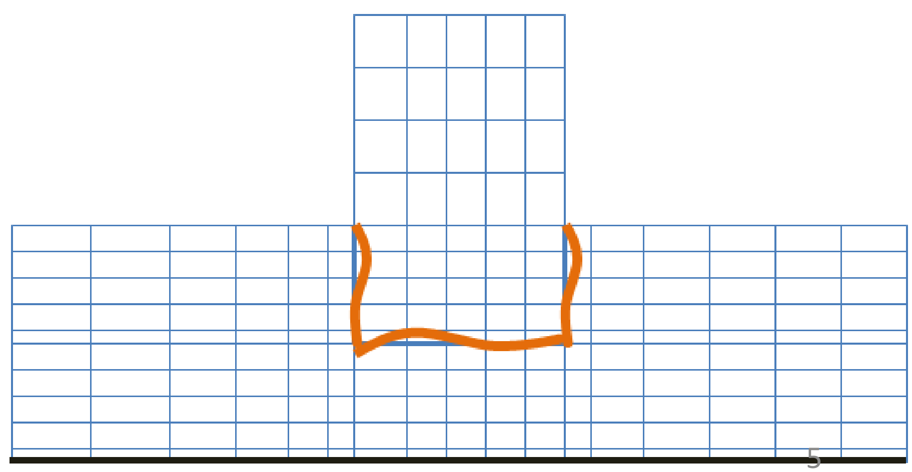


SSI Solution Time Frames As Equivalent Static Loading at Critical Time Steps

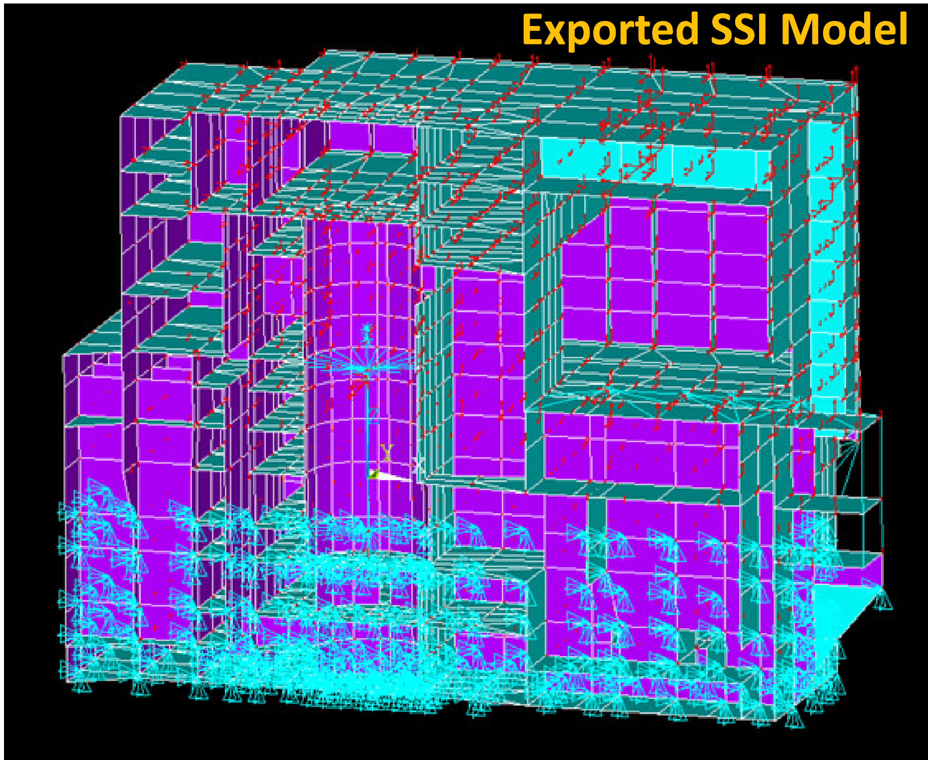
EQS Forces – Linear & Nonlinear



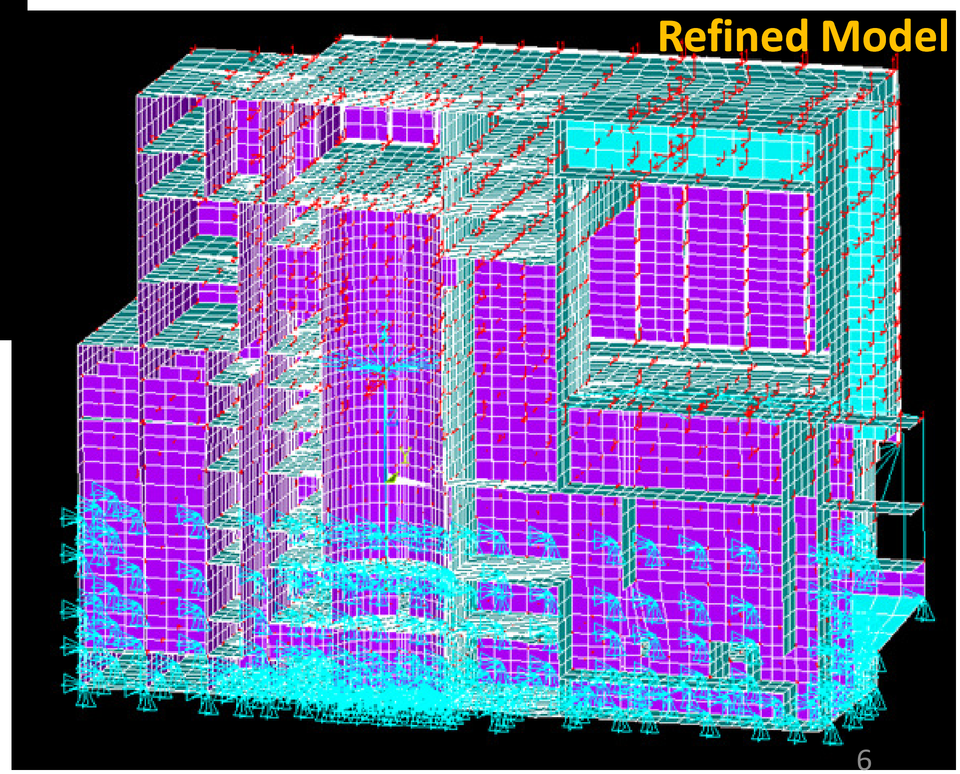
EQS Relative Displacements – Linear (Welded)



ACS SASSI – ANSYS Interface for Refined Seismic Stress Analysis

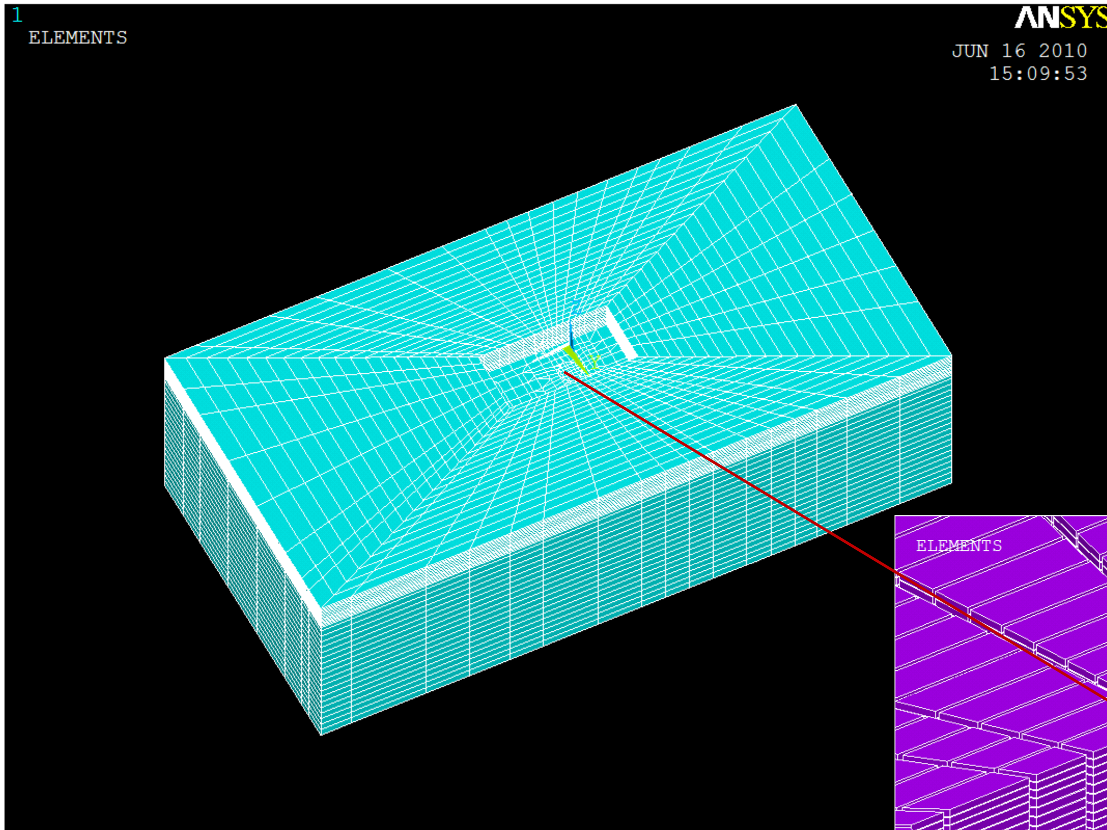


ANSYS Structural Model Automatically Converted From ACS SASSI Using PREP Module

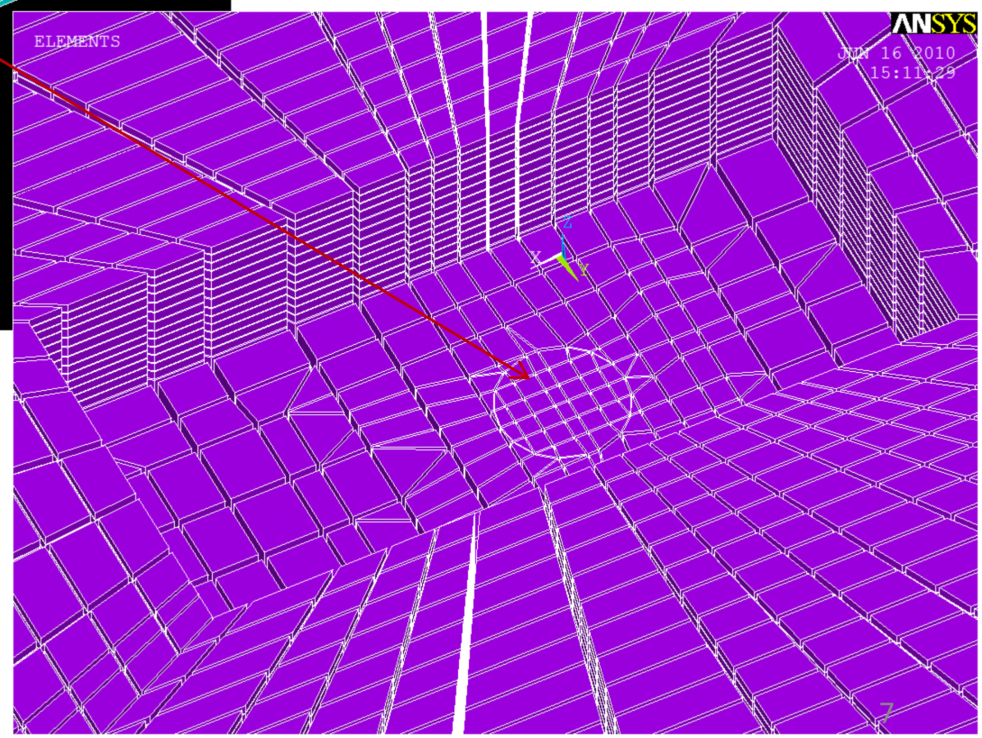


ANSYS Refined Structural Model Using EREFINE command or ANSYS GUI (rank 1-6)

ACS SASSI – ANSYS Interface for Seismic Soil Pressure Analysis

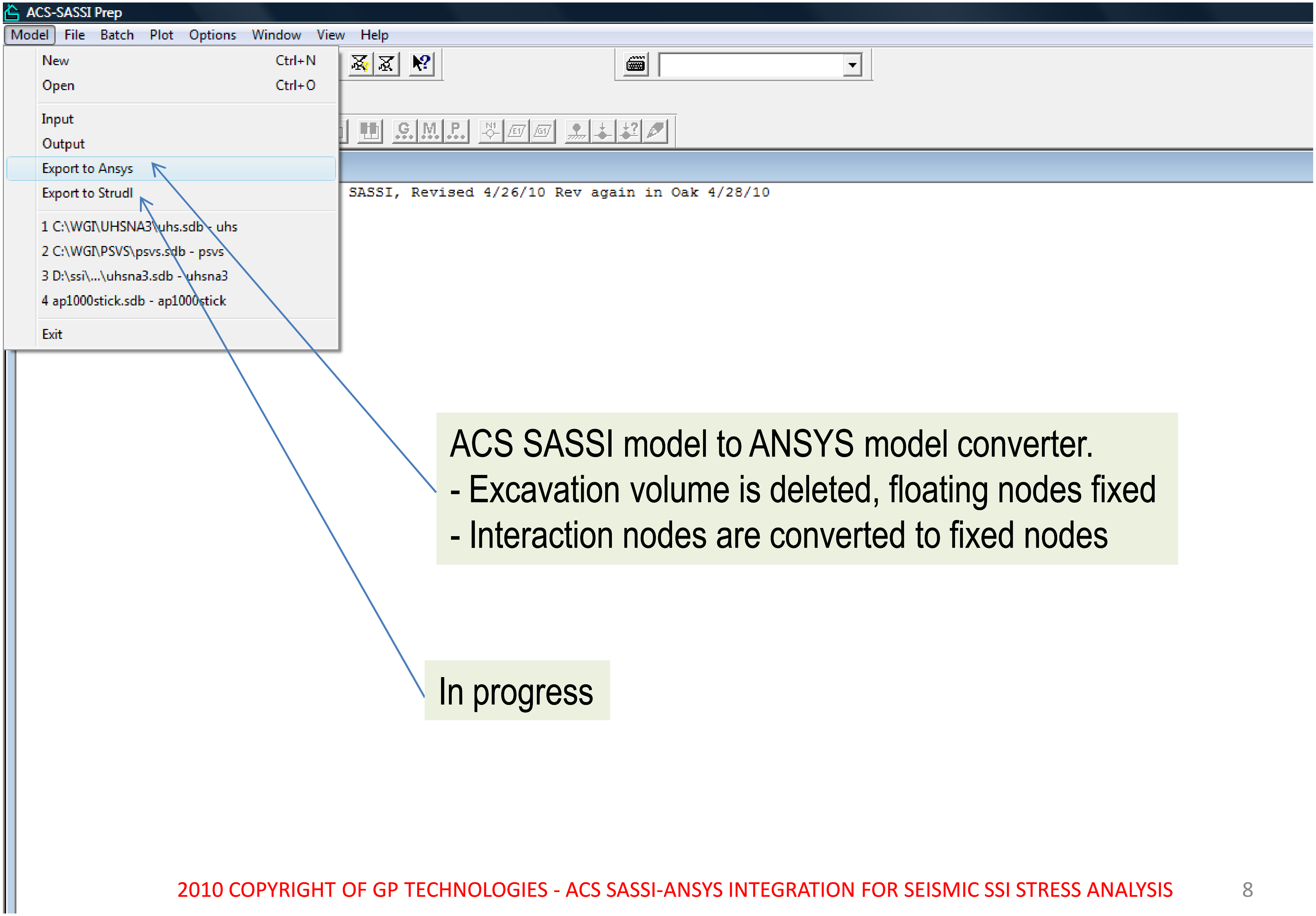


ANSYS Soil FE Model
Is Automatically Generated
by SOILMESH Module



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

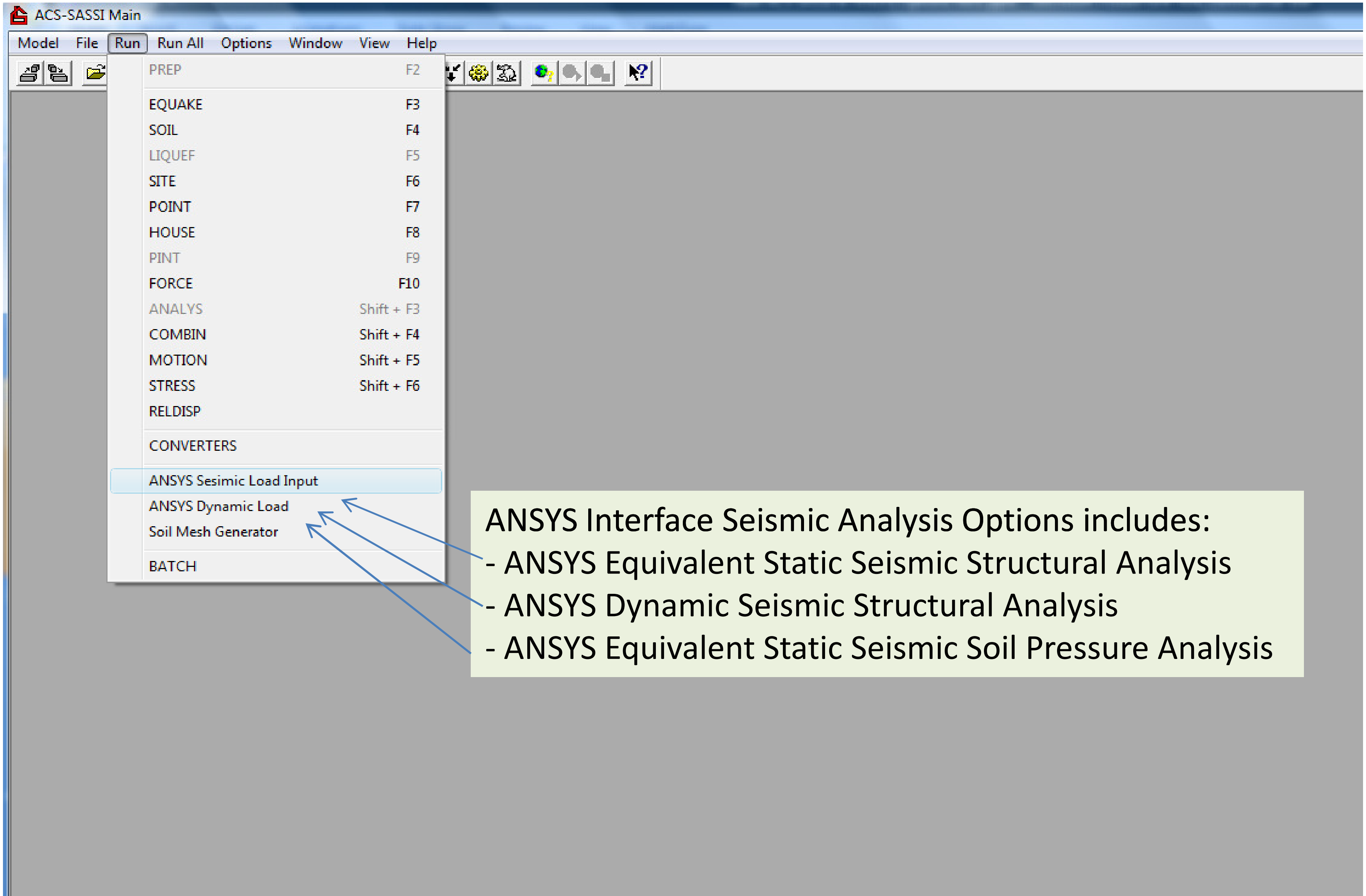
New Structural Model Converter from ACS SASSI to ANSYS



ACS SASSI model to ANSYS model converter.
- Excavation volume is deleted, floating nodes fixed
- Interaction nodes are converted to fixed nodes

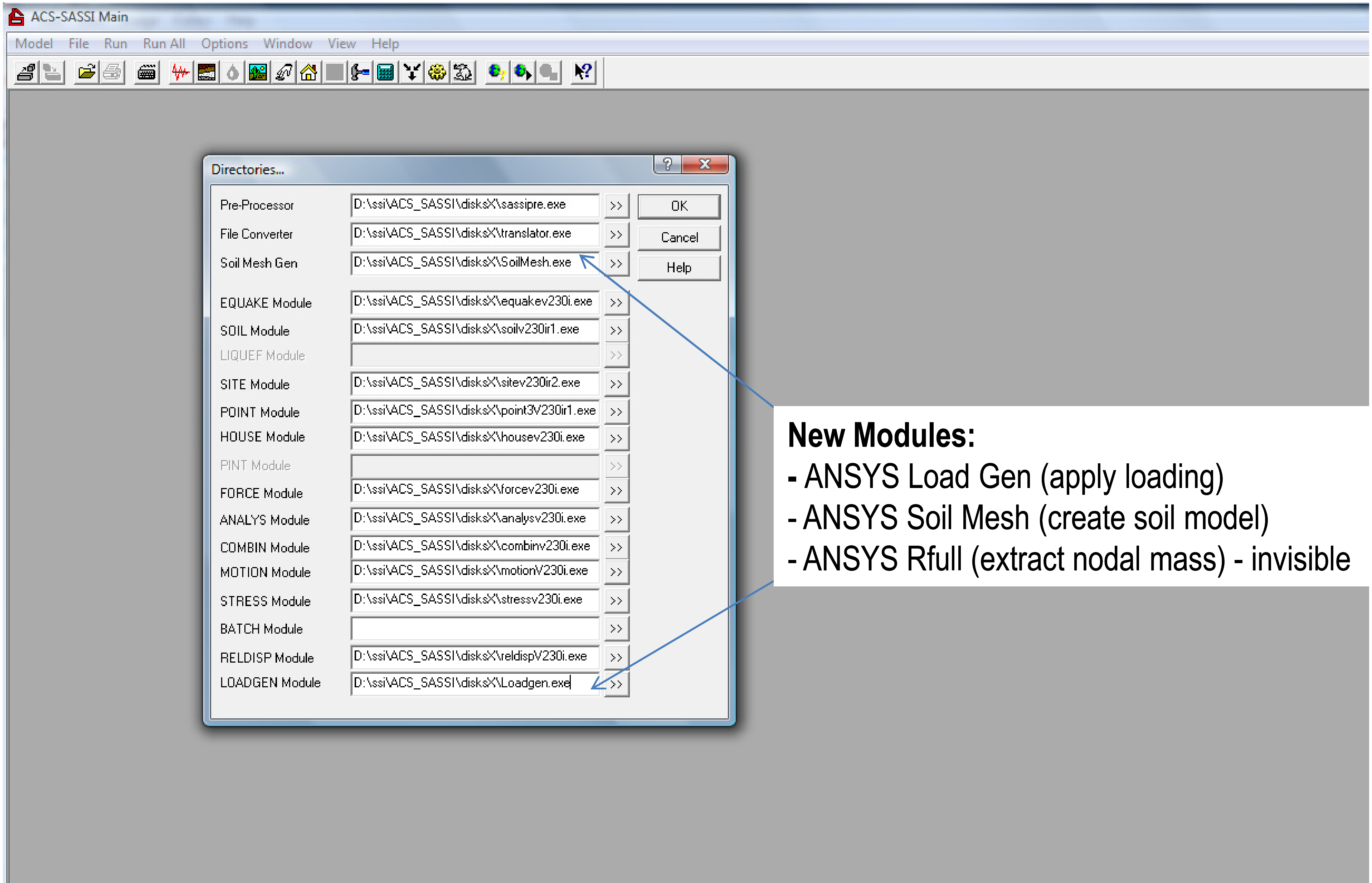
In progress

ACS SASSI – ANSYS Interface for Refined Seismic Stress Analysis



ANSYS Interface Seismic Analysis Options includes:
- ANSYS Equivalent Static Seismic Structural Analysis
- ANSYS Dynamic Seismic Structural Analysis
- ANSYS Equivalent Static Seismic Soil Pressure Analysis

New ACS SASSI Modules for ANSYS Interface – for Structure & Soil



New Modules:
- ANSYS Load Gen (apply loading)
- ANSYS Soil Mesh (create soil model)
- ANSYS Rfull (extract nodal mass) - invisible

ACS SASSI-ANSYS Interface Structure

STEP 1

Perform ACS SASSI analysis with full post-processing to create acceleration and displacement frames

STEP 2

Use the *"ANSYS Seismic Load Input"* or "ANSYS Dynamic Load" option in ACS SASSI-MAIN to generate loading for ANSYS

STEP 3

Use the new SOILMESH module to create a mesh of soil elements for soil pressure analysis.

STEP 4

Export finite element model to an ANSYS input file.

This can be done for the structural model, the soil mesh, or both.

STEP 5

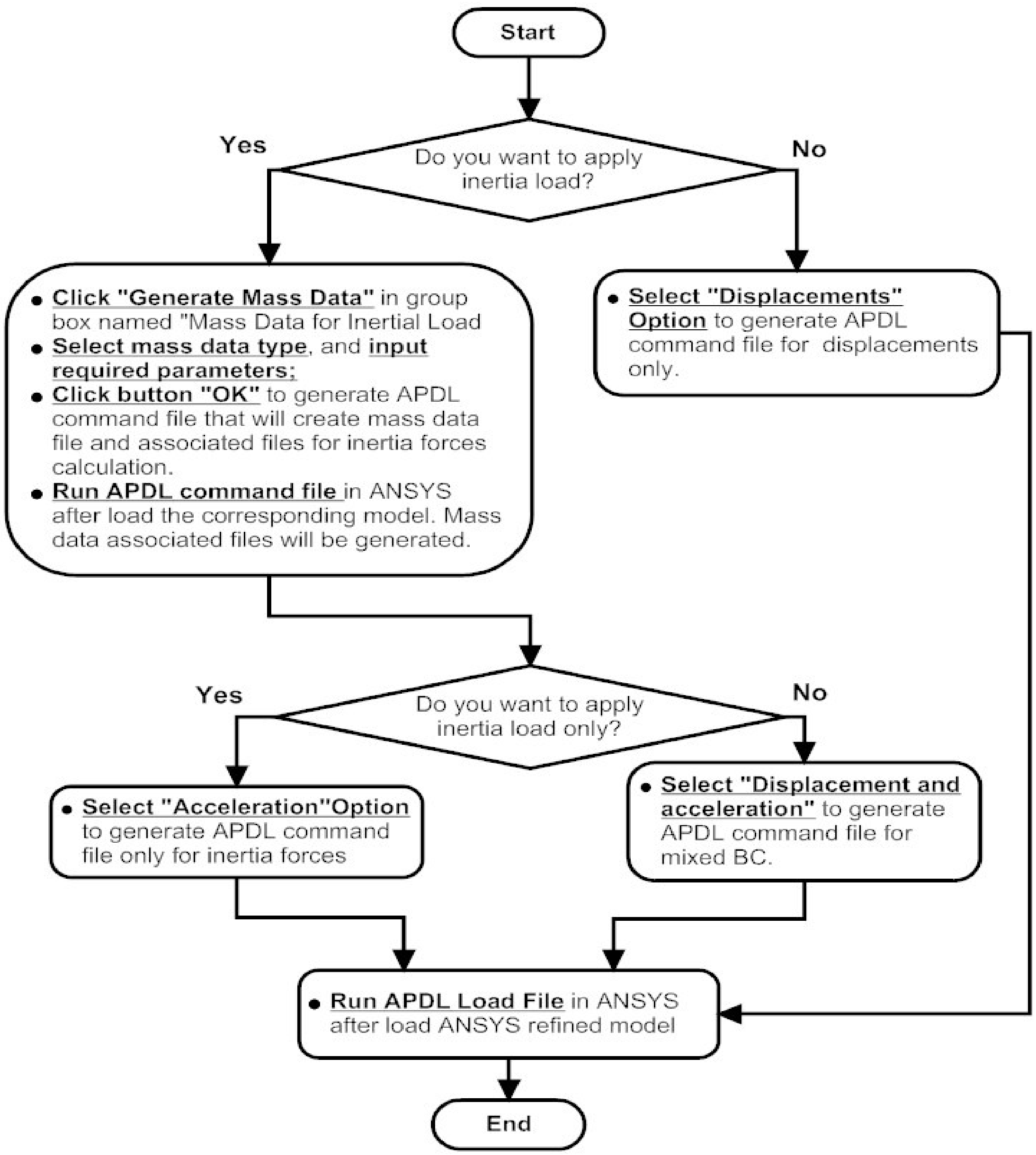
Load finite element model into ANSYS

STEP 6

Load the seismic load input file created from step 2 to apply the loading to the ANSYS model.

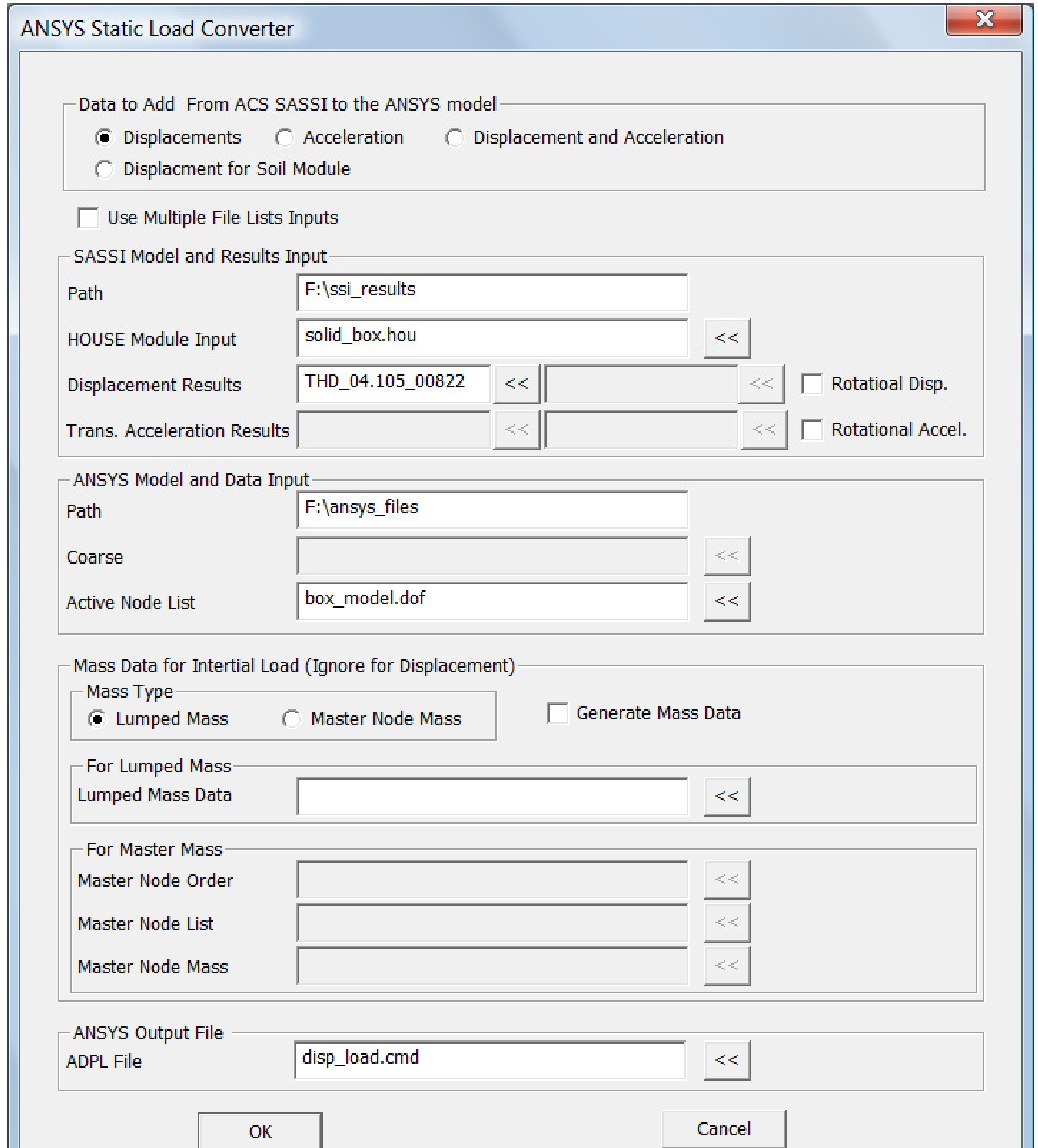
Perform ANSYS run

ANSYS Equiv. Static Load Generation from ACS SASSI Frames

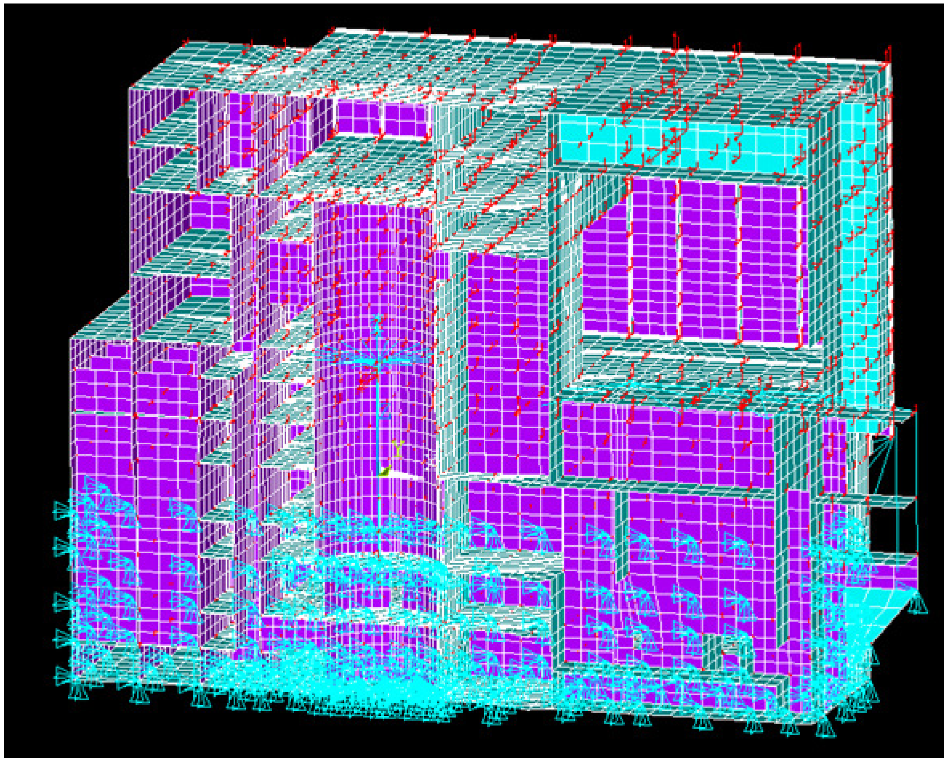


Exporting Equivalent Static Loads to ANSYS

- 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”

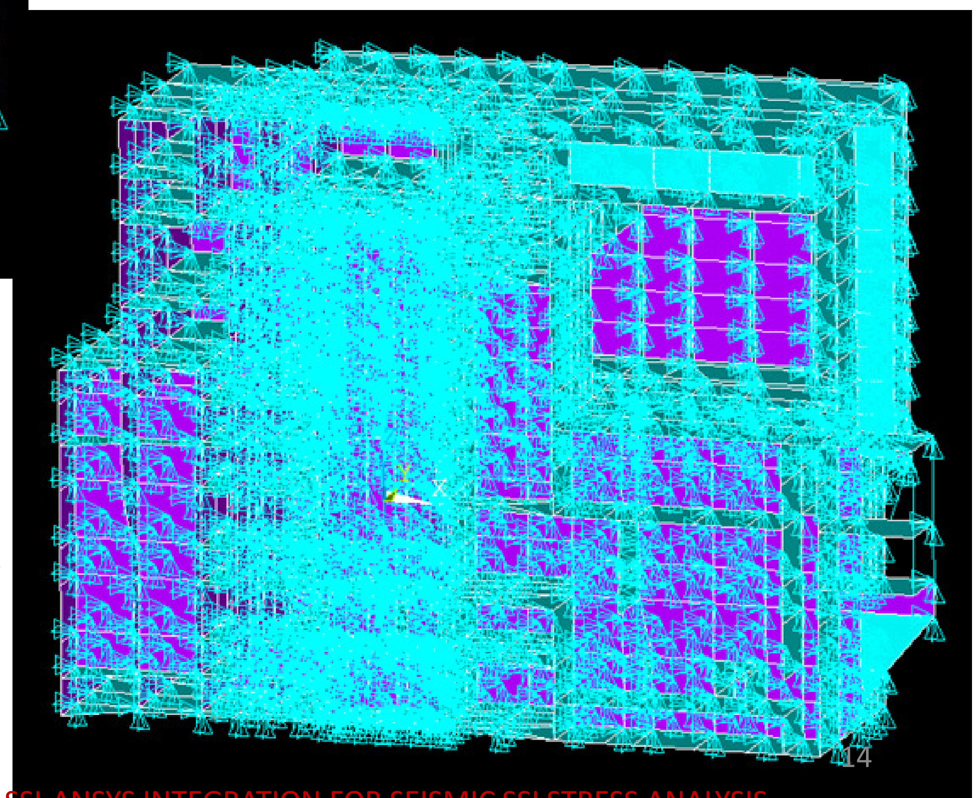


Exporting Equivalent Static Loads to ANSYS

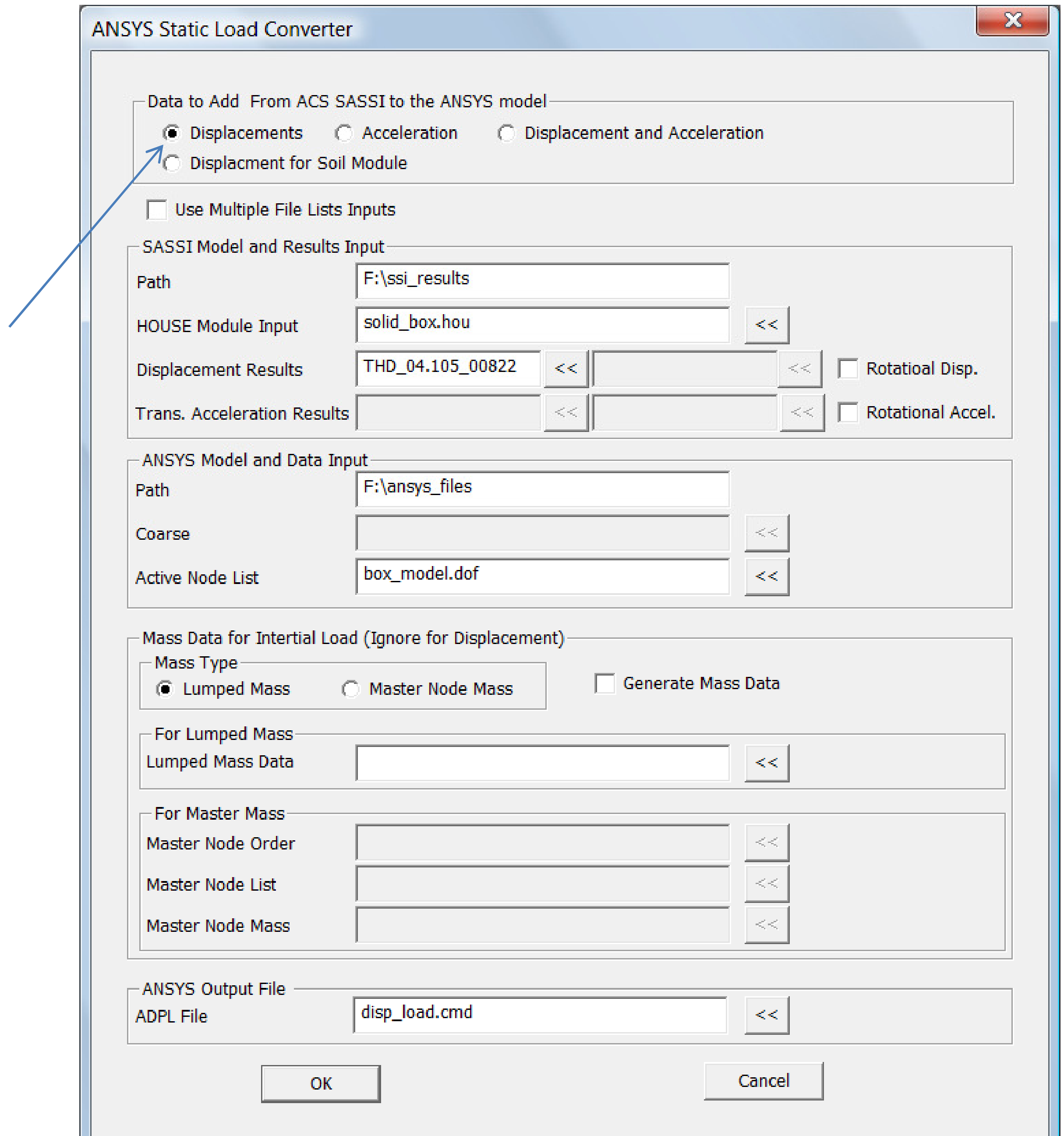


Acceleration & Displacements BC
(Uses ANSYS Refined Model Solution)
- Accurate for Refined Stress Analysis

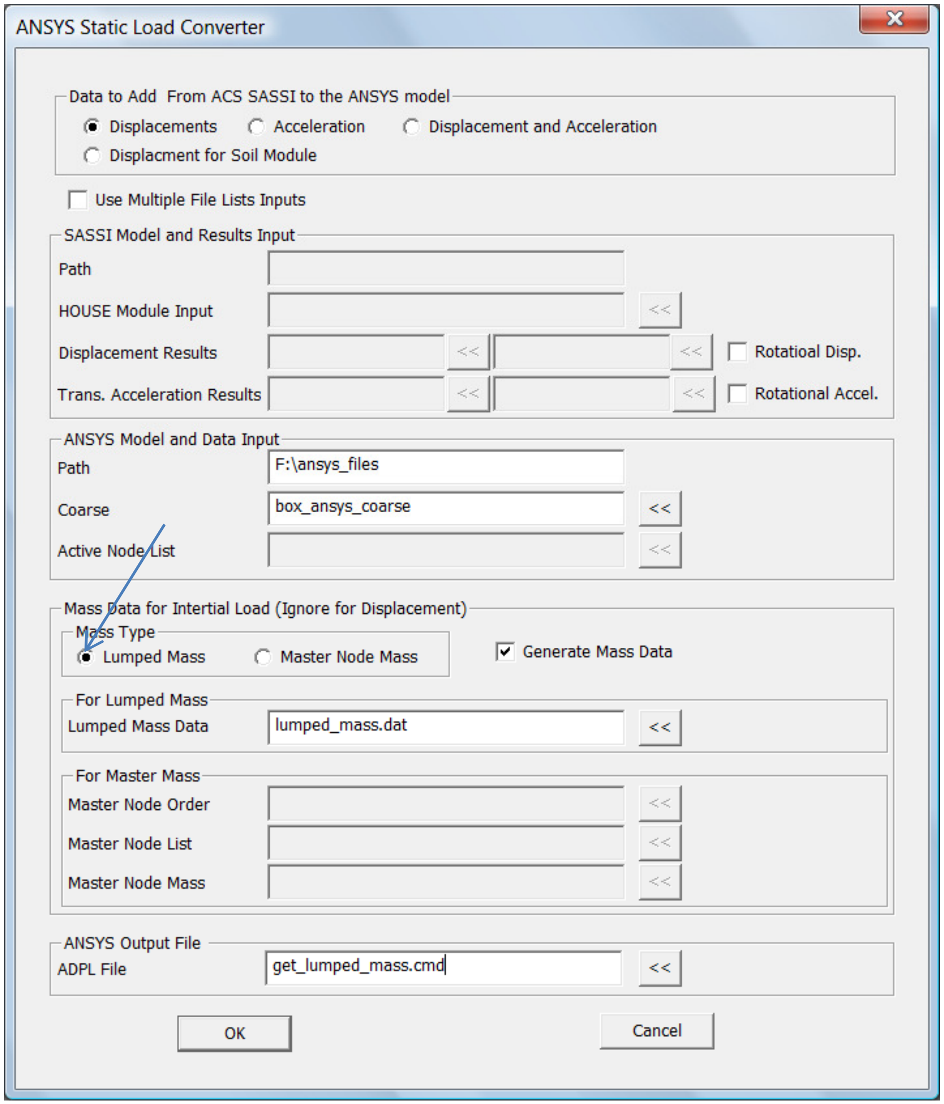
ANSYS Displacement BC
(Uses ACS SASSI Model Solution)
- Less Accurate for Refined Models
- Useful for subsystem input BC

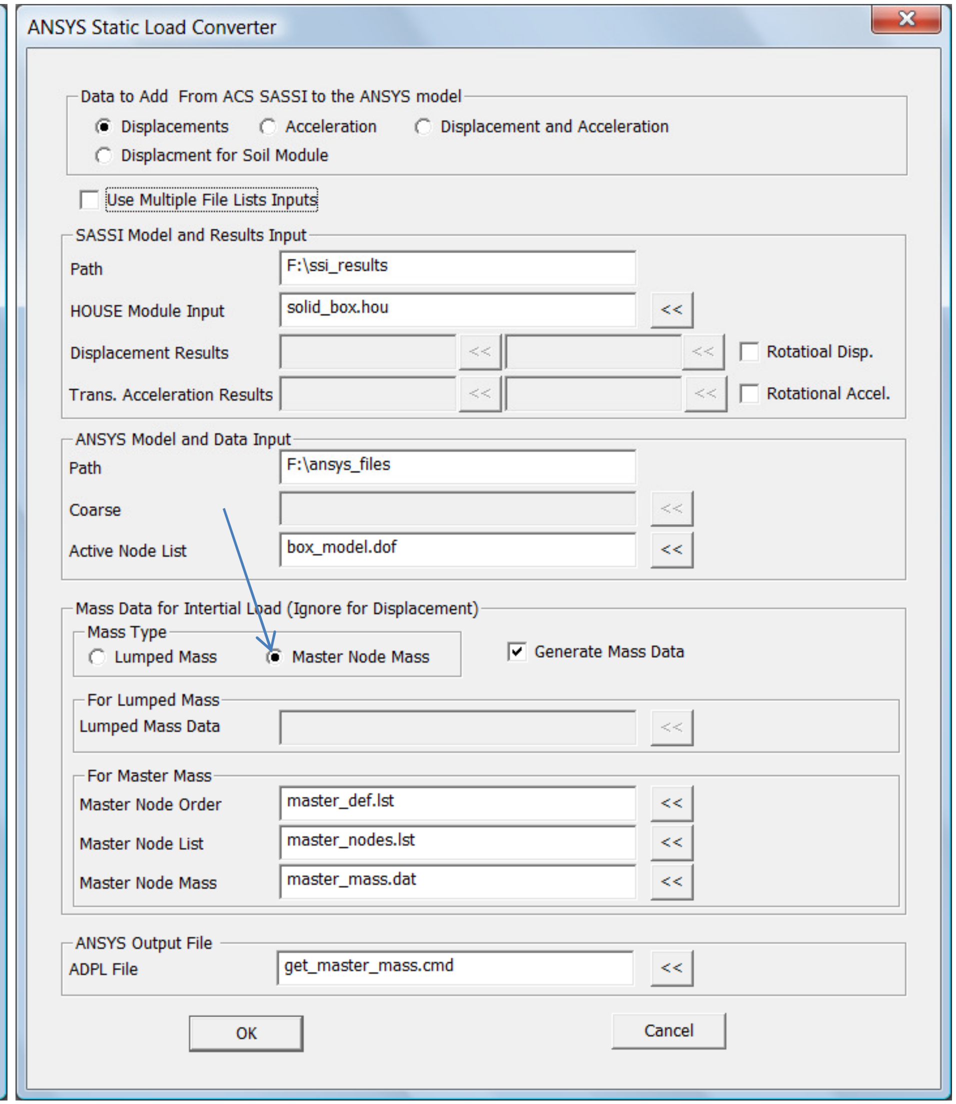


Displacement Option – Use SSI Model Solution



Acceleration Option – Select Nodal Mass Type

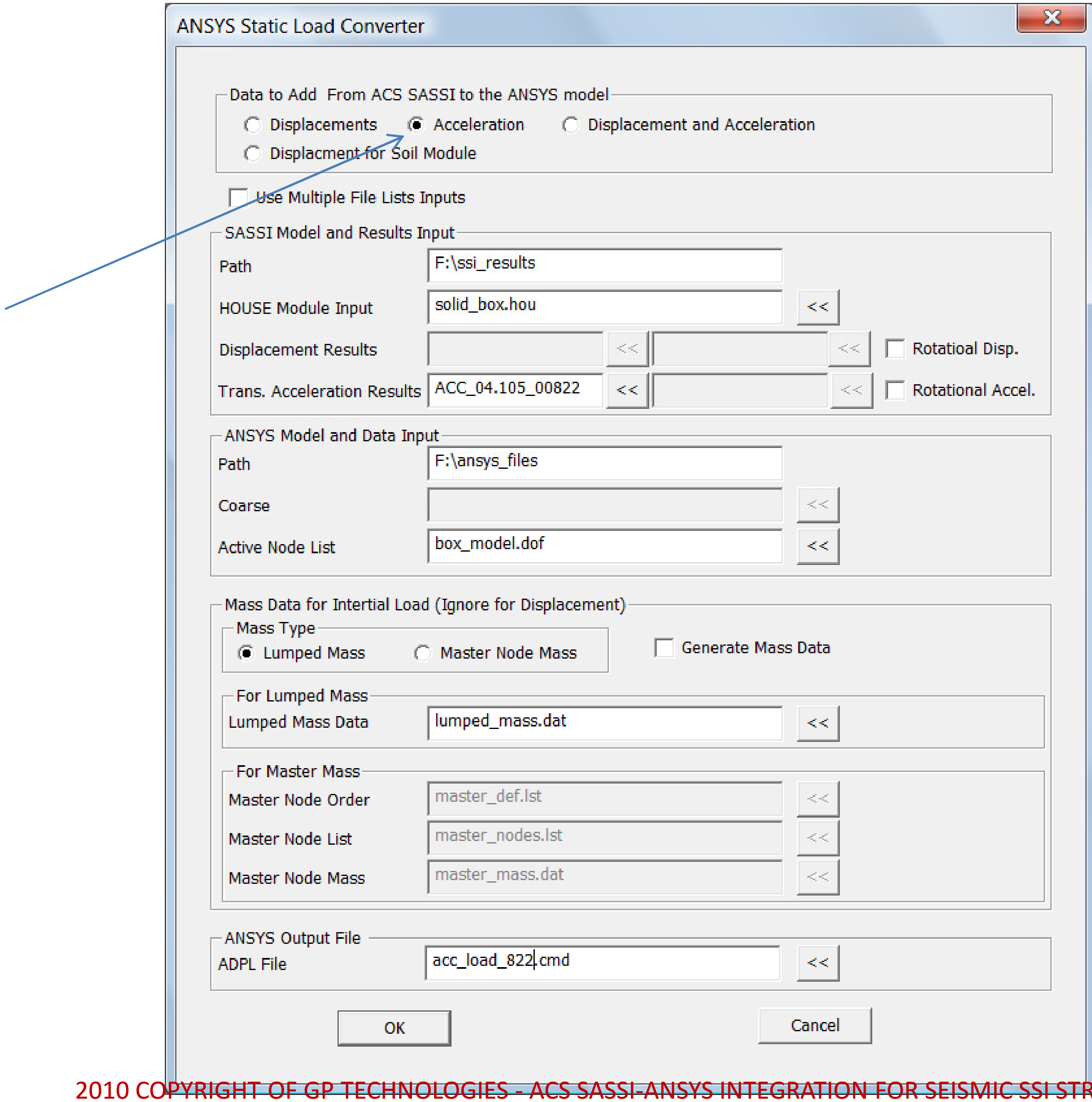




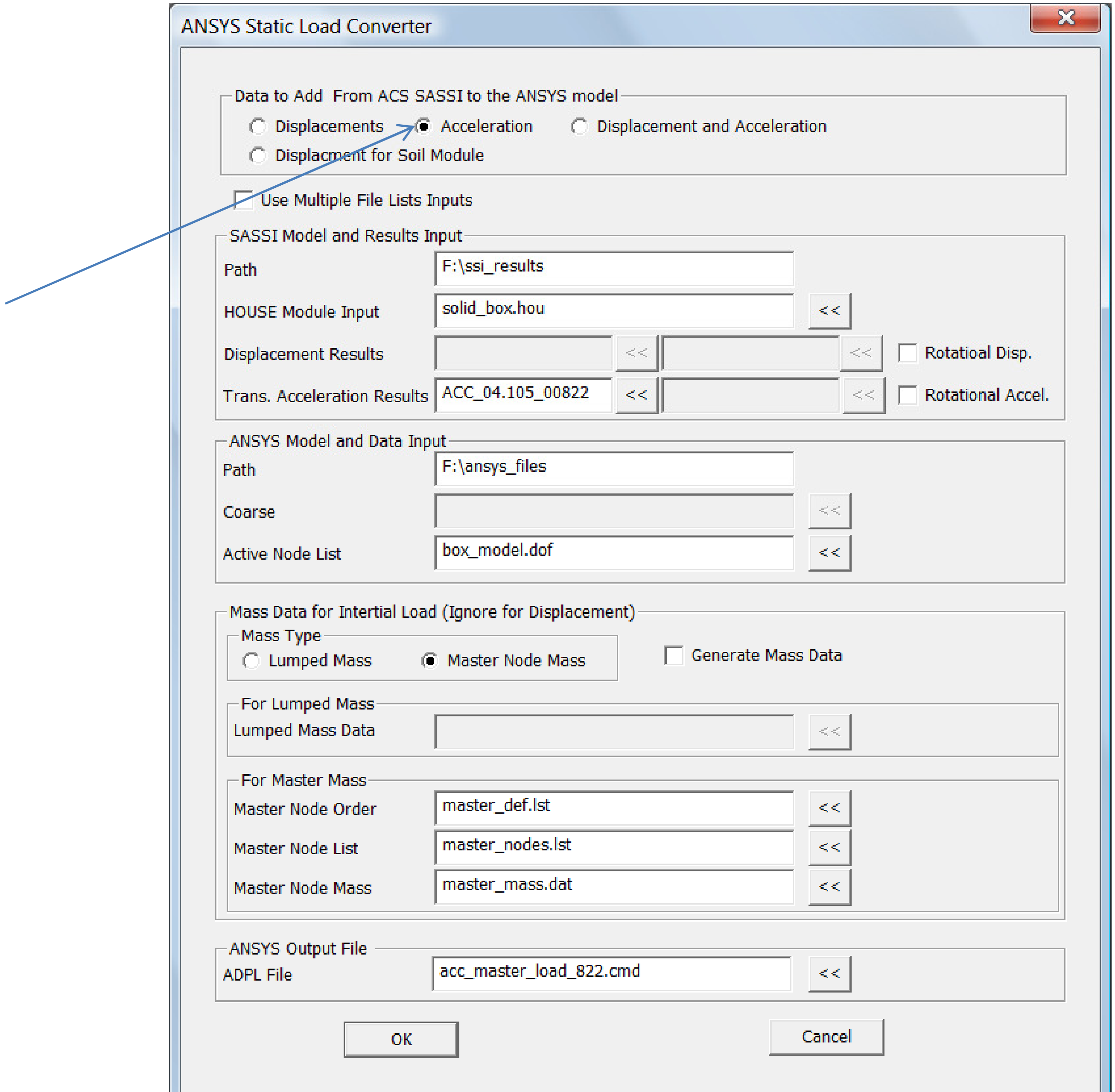
Lumped Masses/Coarse

Master DOF Masses/Refined

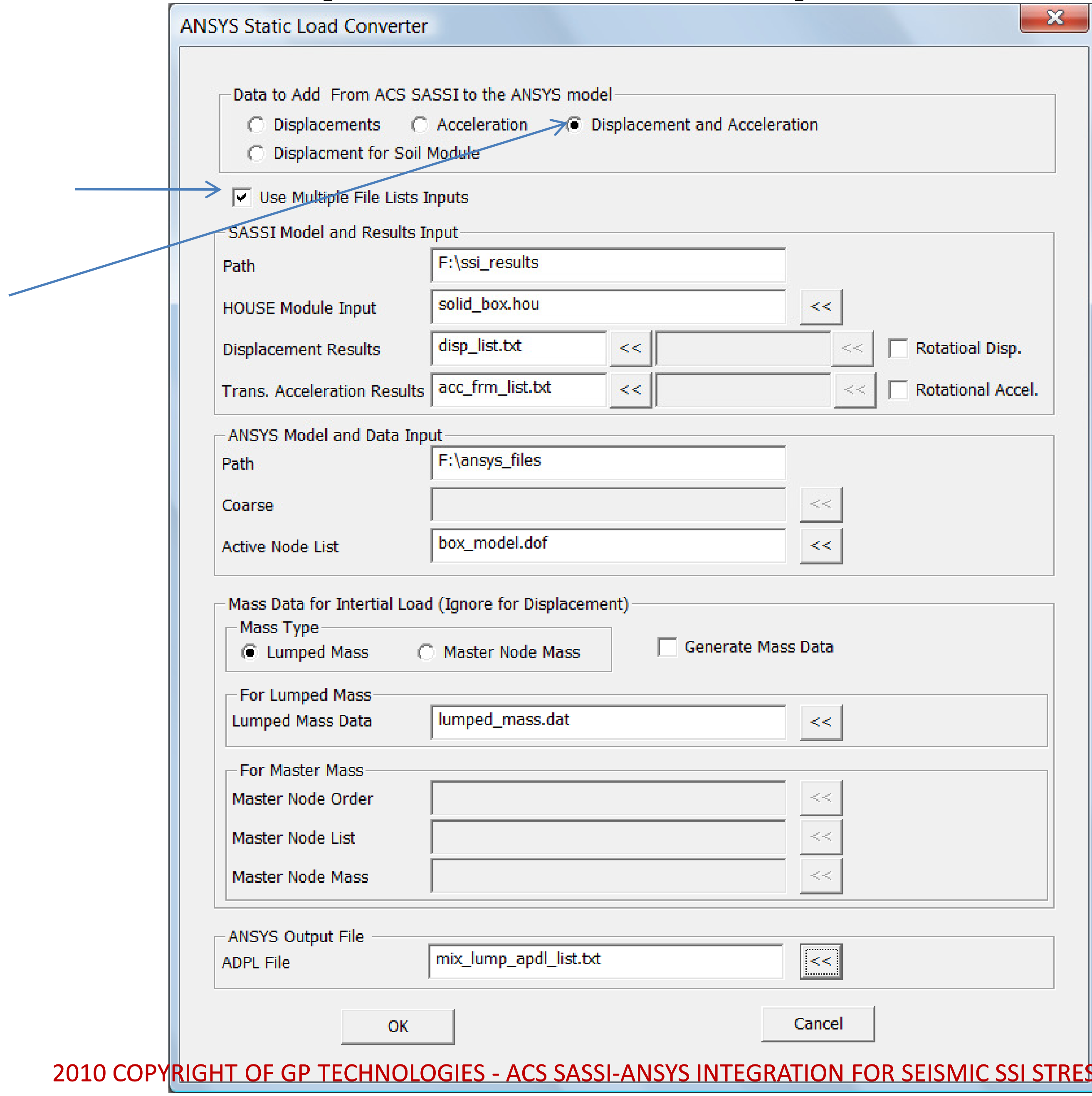
Acceleration Option – With Nodal Lumped Masses



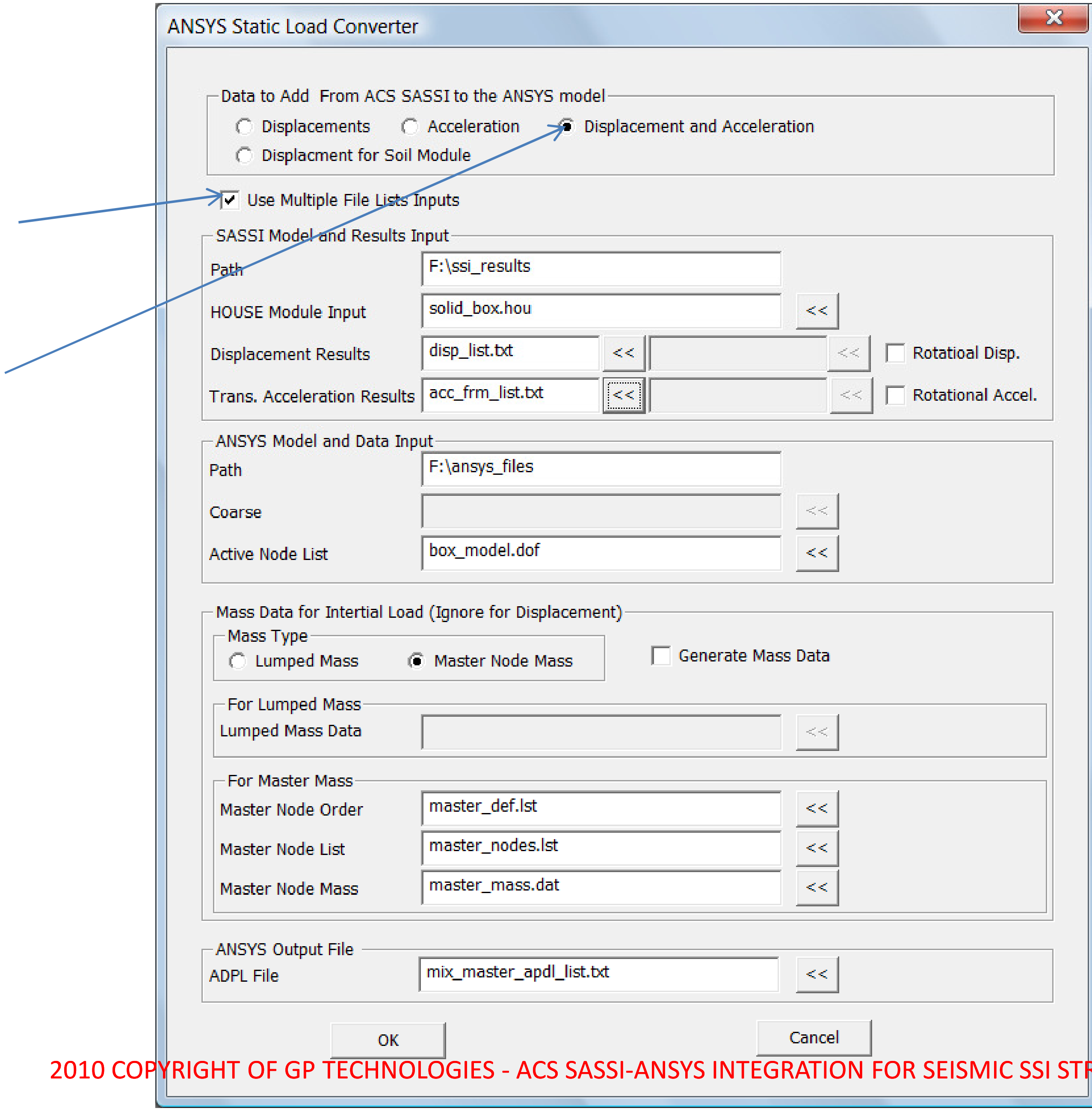
Acceleration Option – With Nodal Master DOF Masses



Mixed Option – With Lumped Masses



Mixed Option – With Master DOF Masses



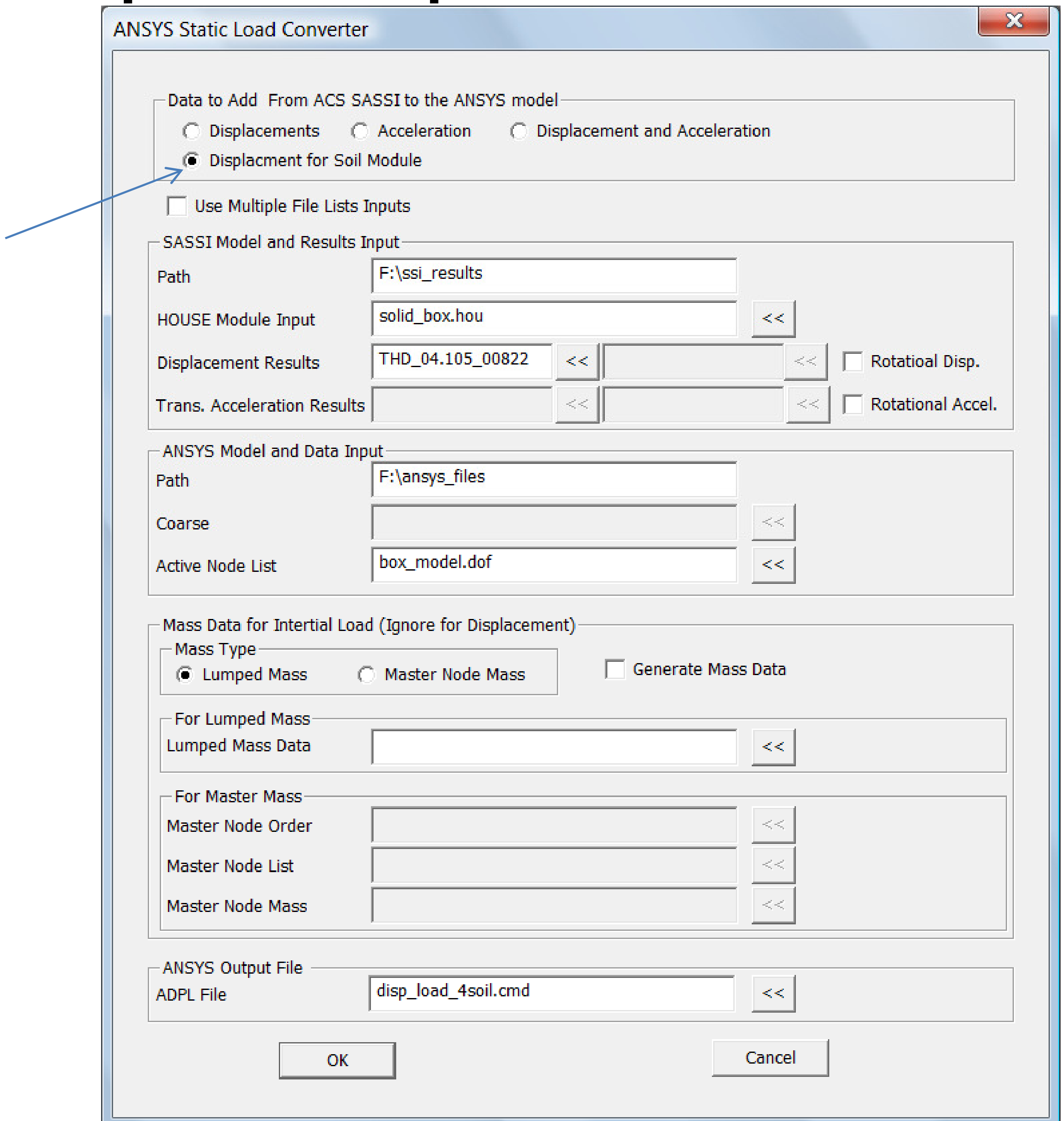
Example of Equivalent Static APDL File Created

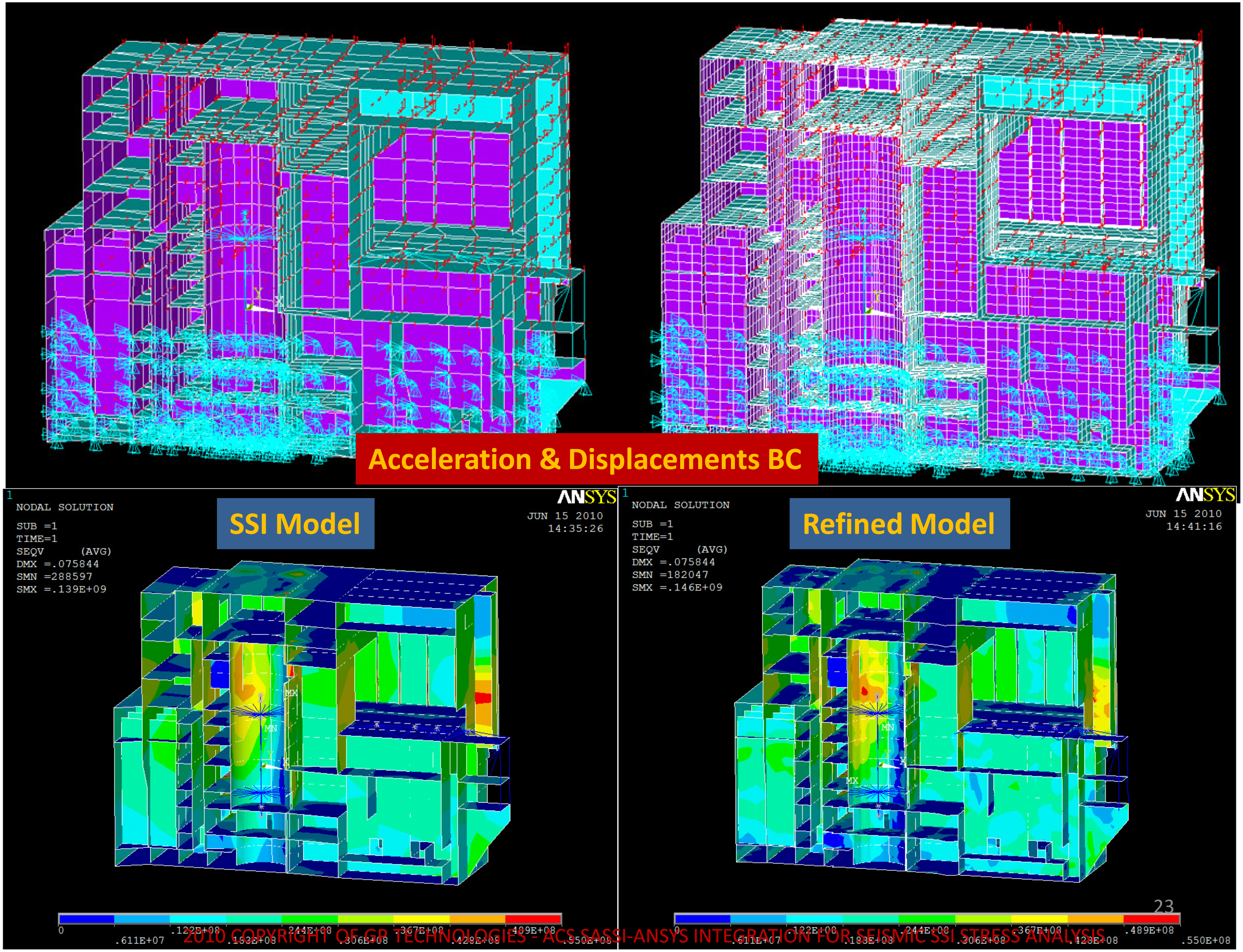
forces.inp - Notepad

File Edit Format View Help

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

Soil Model Option – Displacements at Interaction Nodes

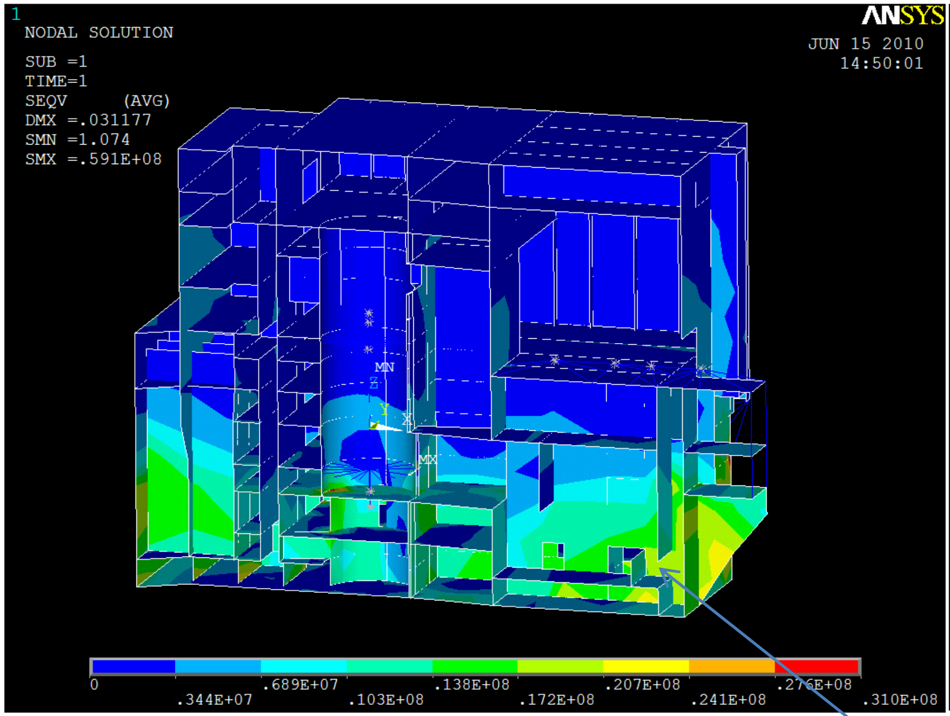


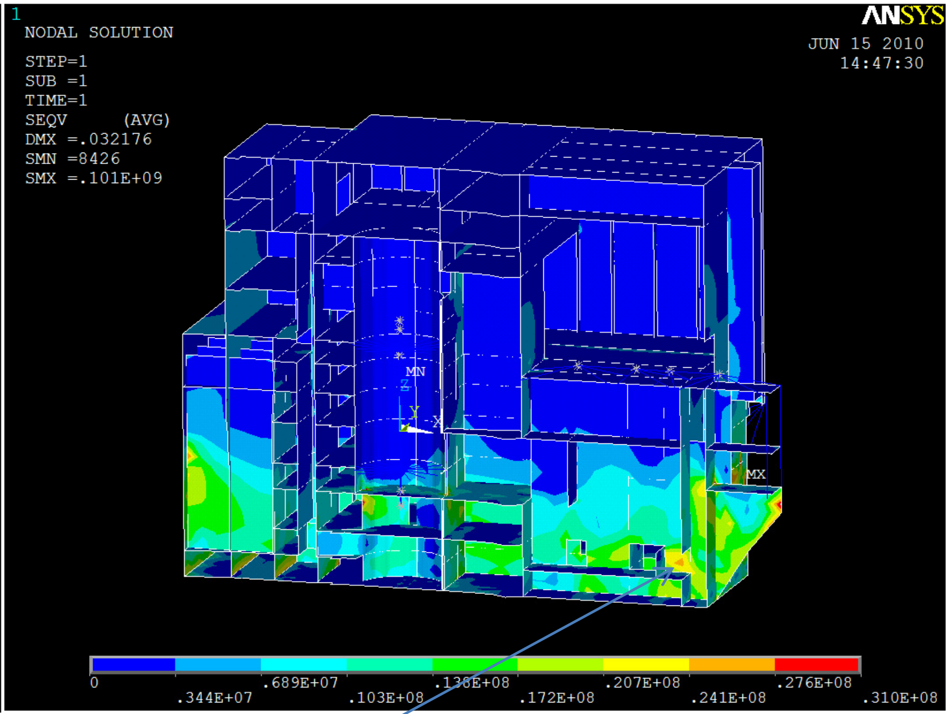

Acceleration & Displacements BC
SSI Model
Refined Model
ANSYS
NODAL SOLUTION
SUB =1
TIME=1
SEQV (AVG)
DMX =.075844
SMN =288597
SMX =.139E+09
JUN 15 2010
14:35:26
ANSYS
NODAL SOLUTION
SUB =1
TIME=1
SEQV (AVG)
DMX =.075844
SMN =182047
SMX =.146E+09
JUN 15 2010
14:41:16
0 .611E+07 .122E+08 .183E+08 .244E+08 .306E+08 .367E+08 .428E+08 .489E+08 .550E+08

Support Displacements BC

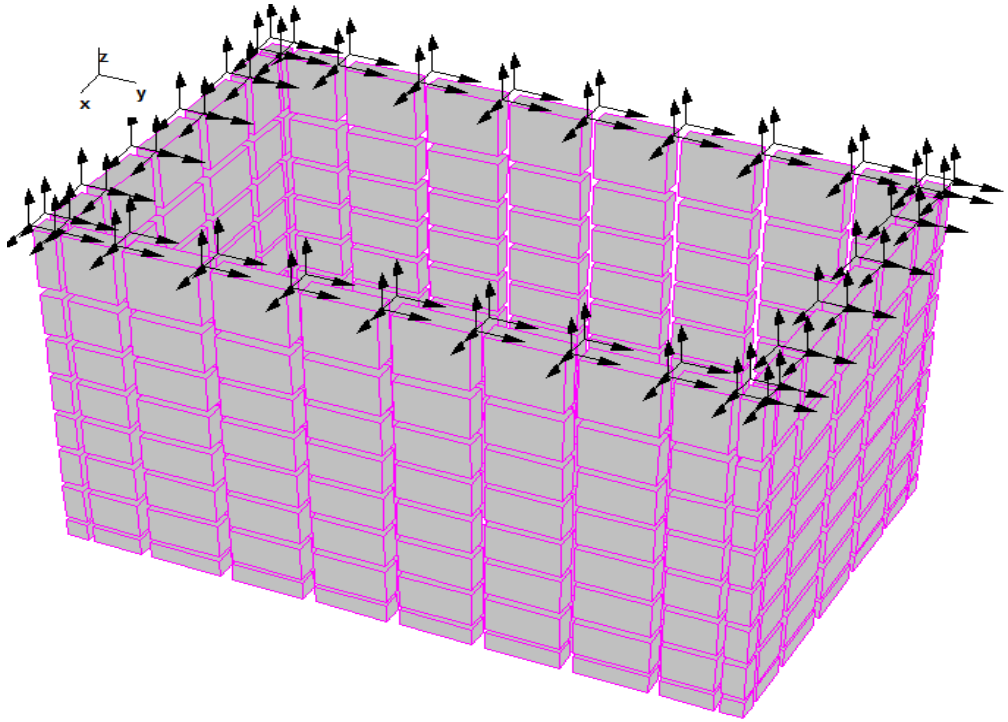
SSI Model

Refined Model



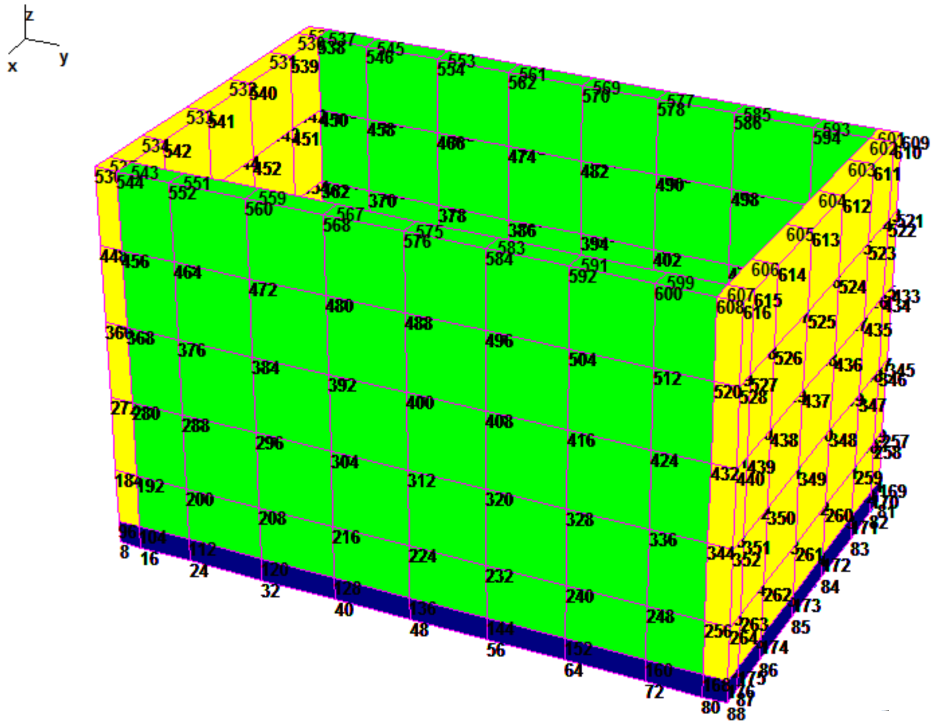


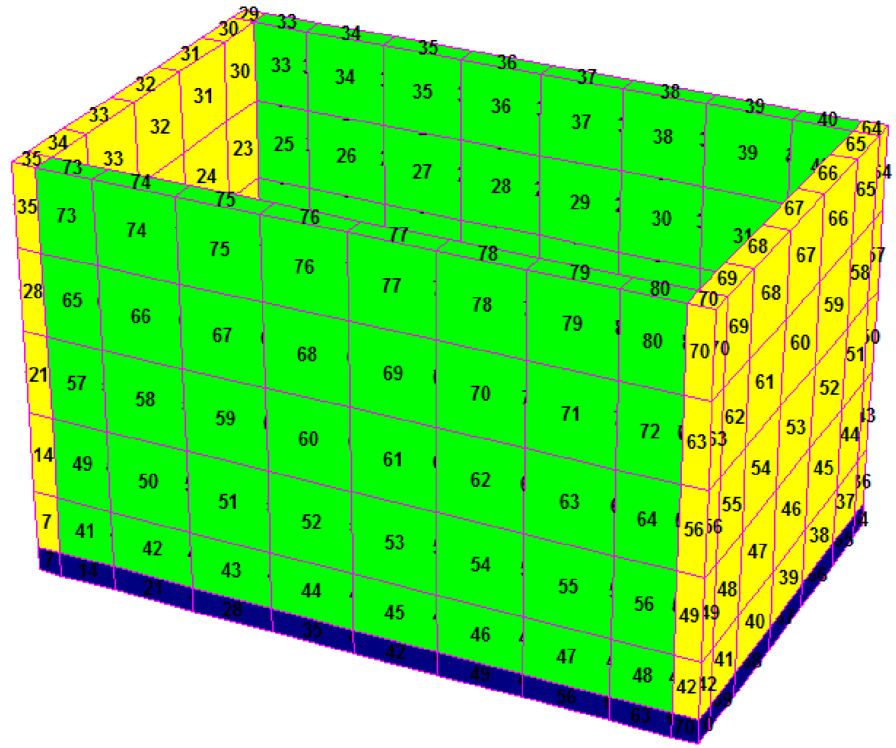
30 ft Embedded Concrete Pool Structure



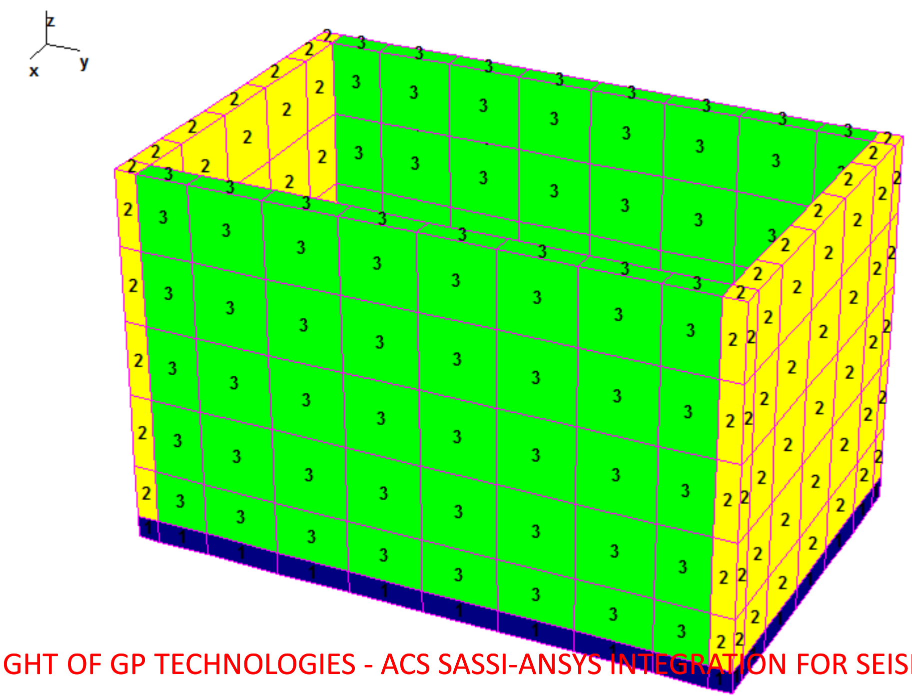
SSI Analysis Inputs:

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

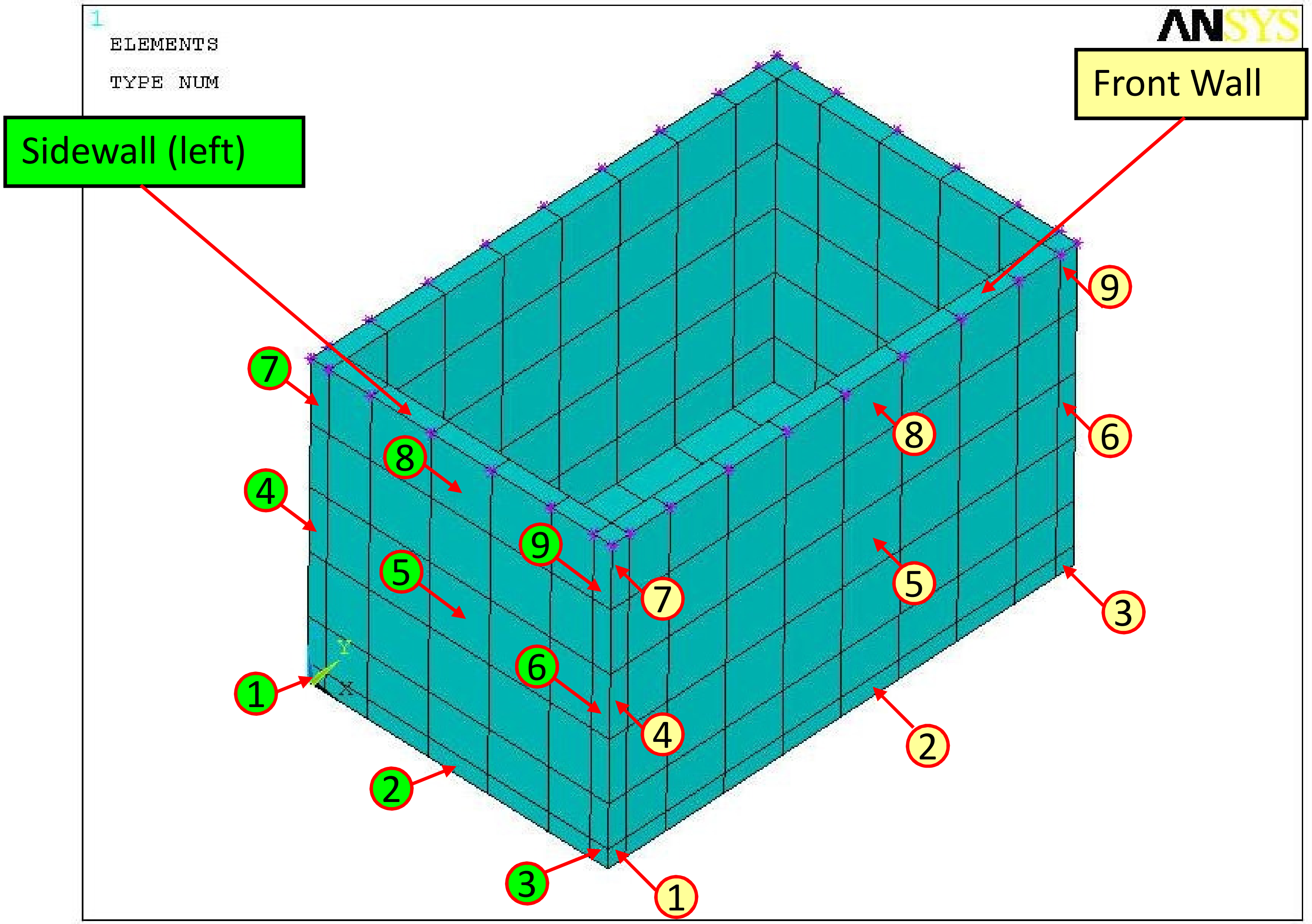




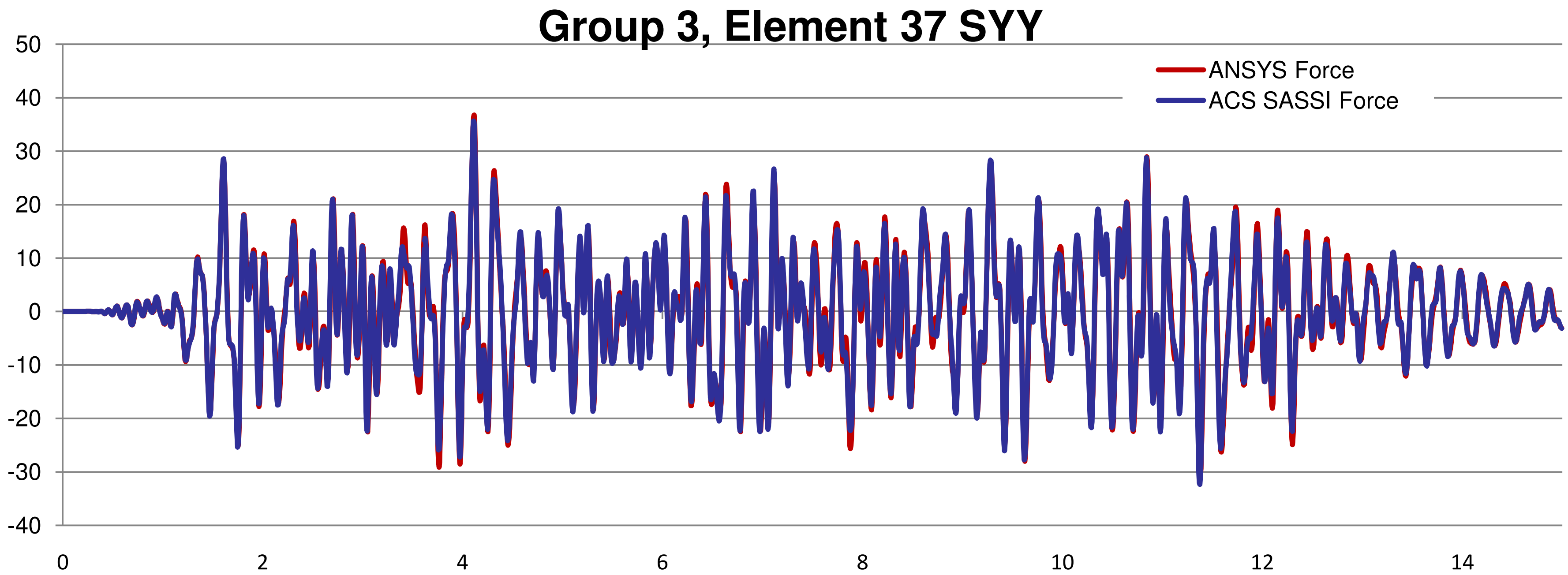
SOLID ELEMENT BOX MODEL

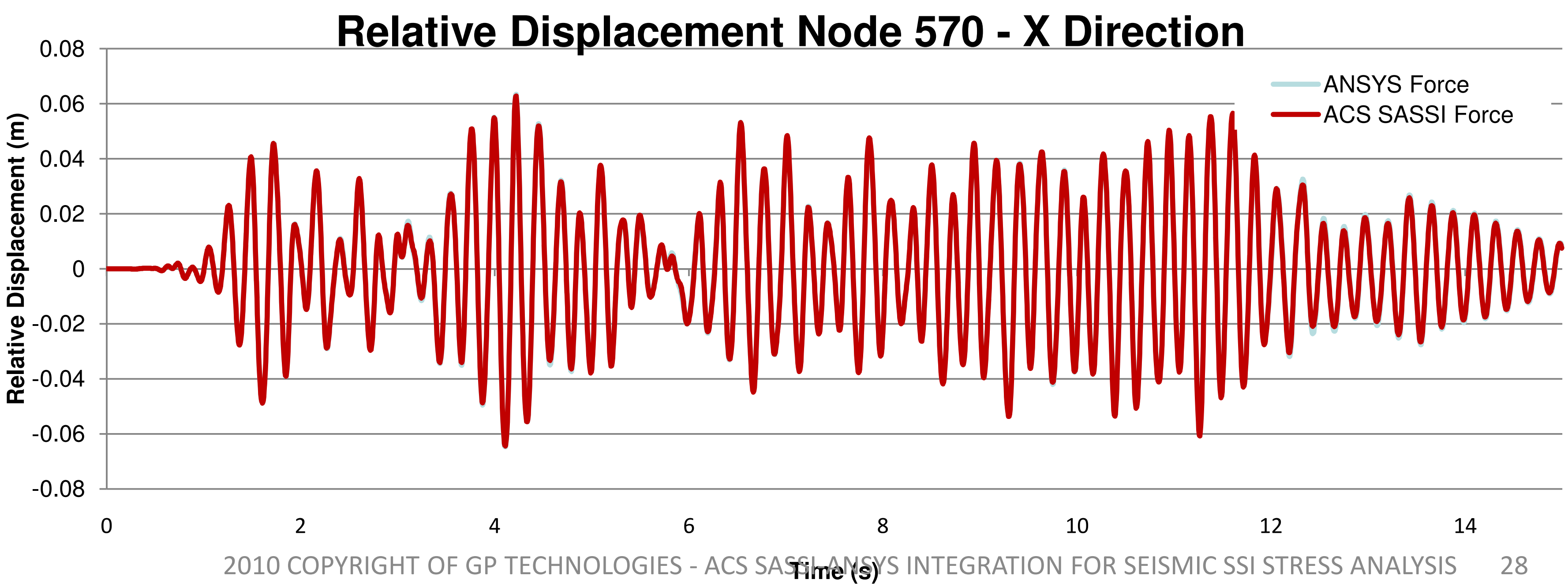


Element Numbering

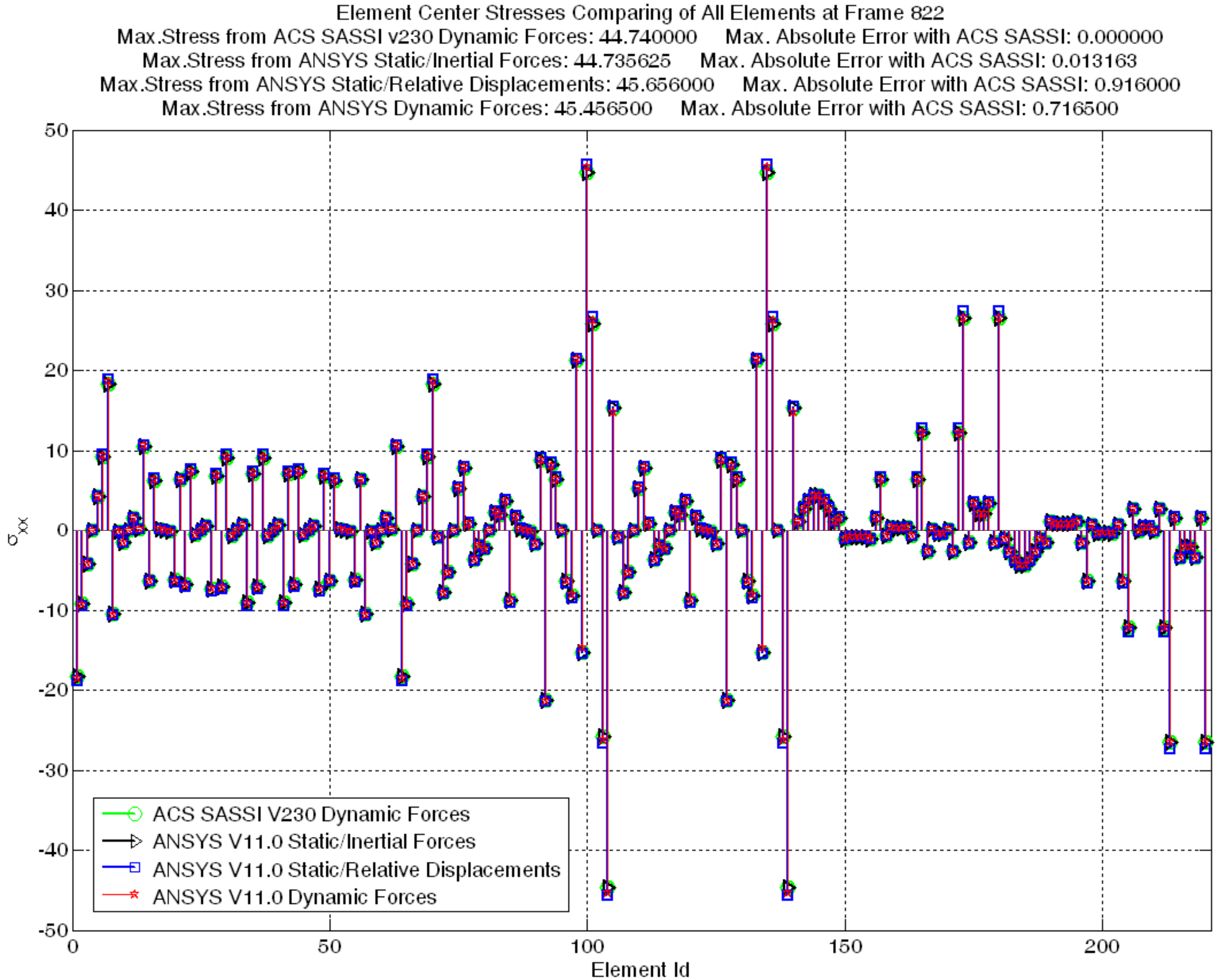


ANSYS Dynamic vs. ACS SASSI – Fixed Base Model

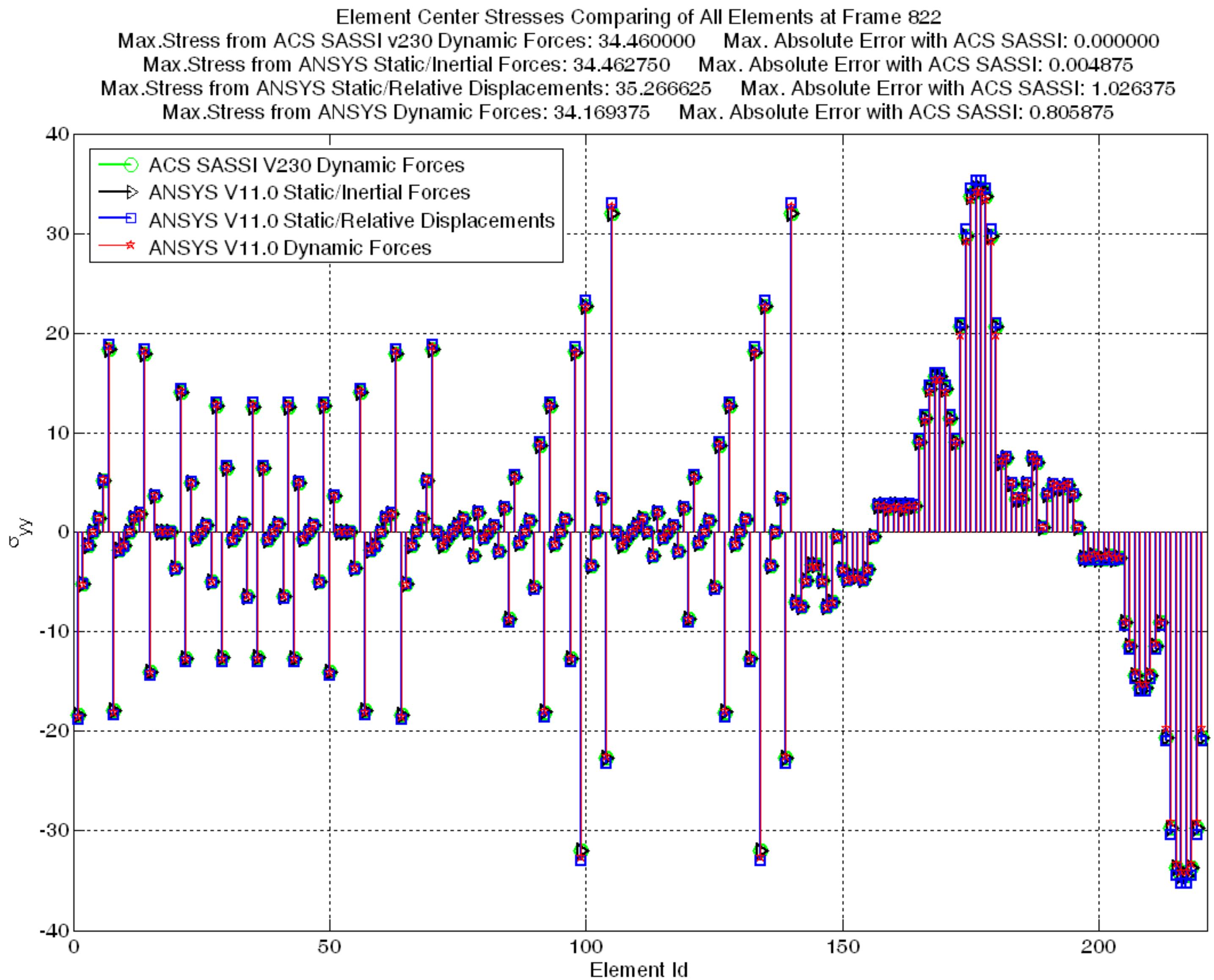




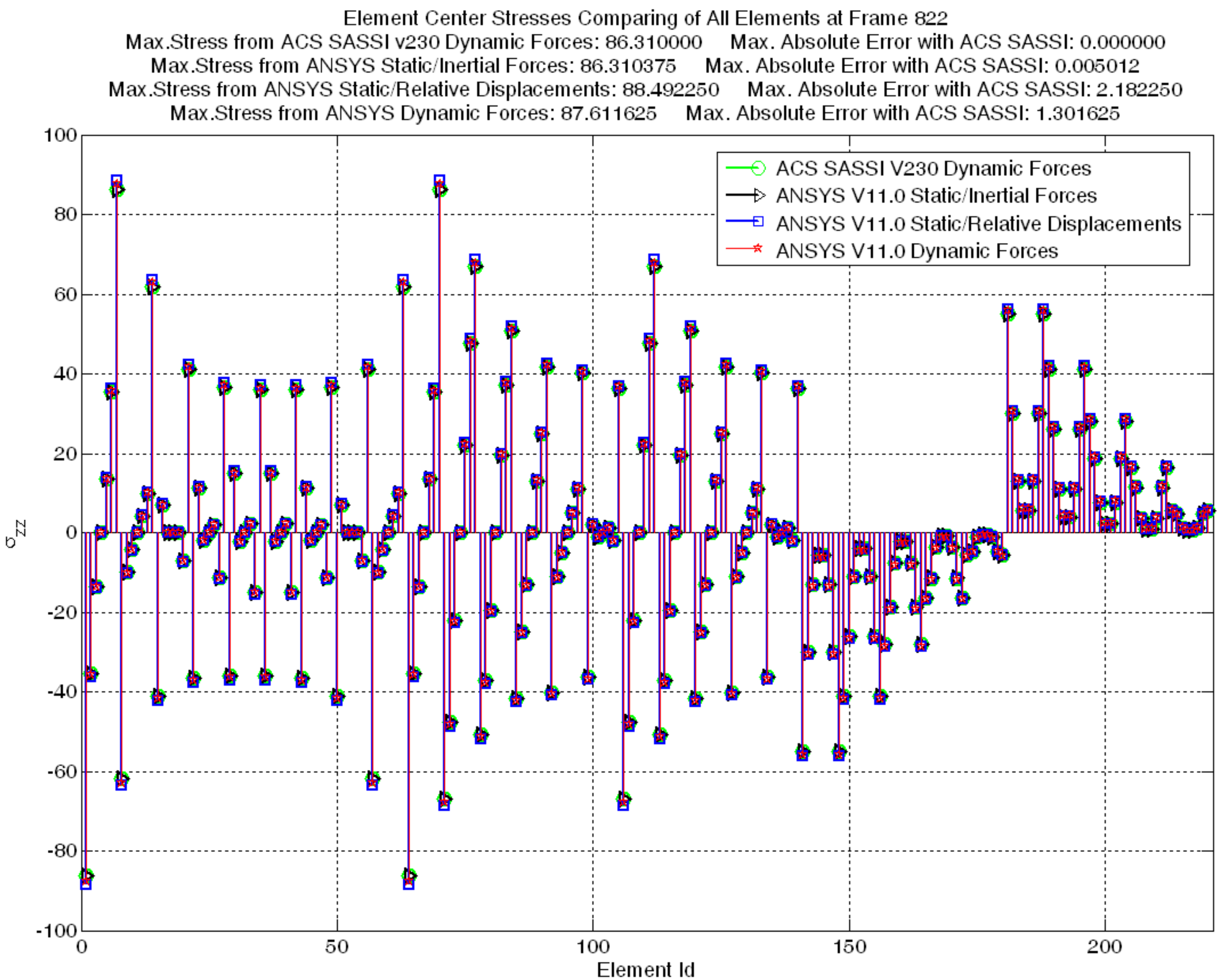
ANSYS Equivalent-Static vs. ACS SASSI – Fixed Base Model

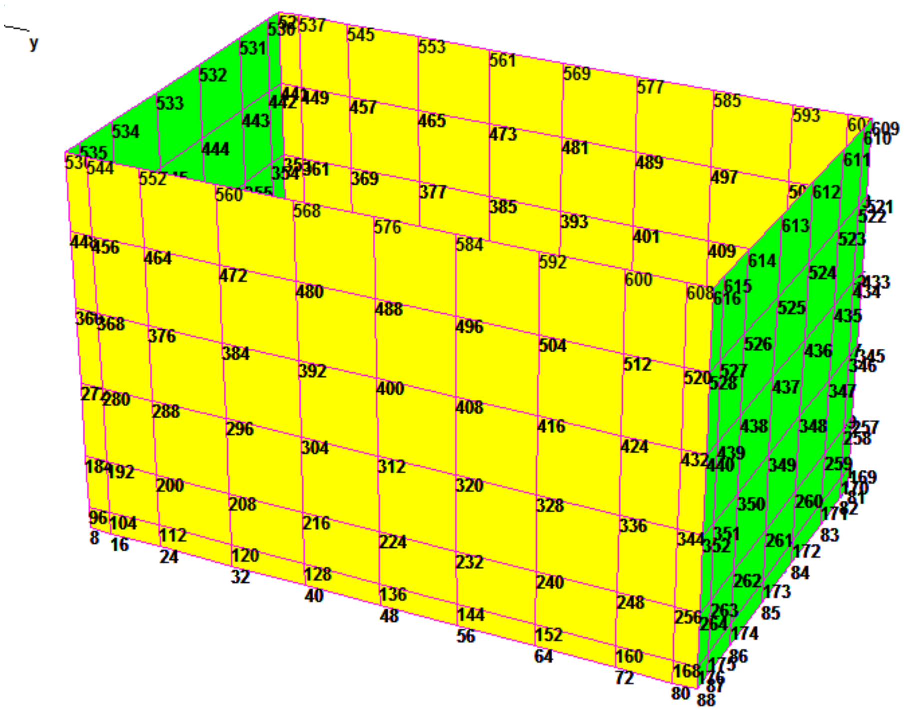


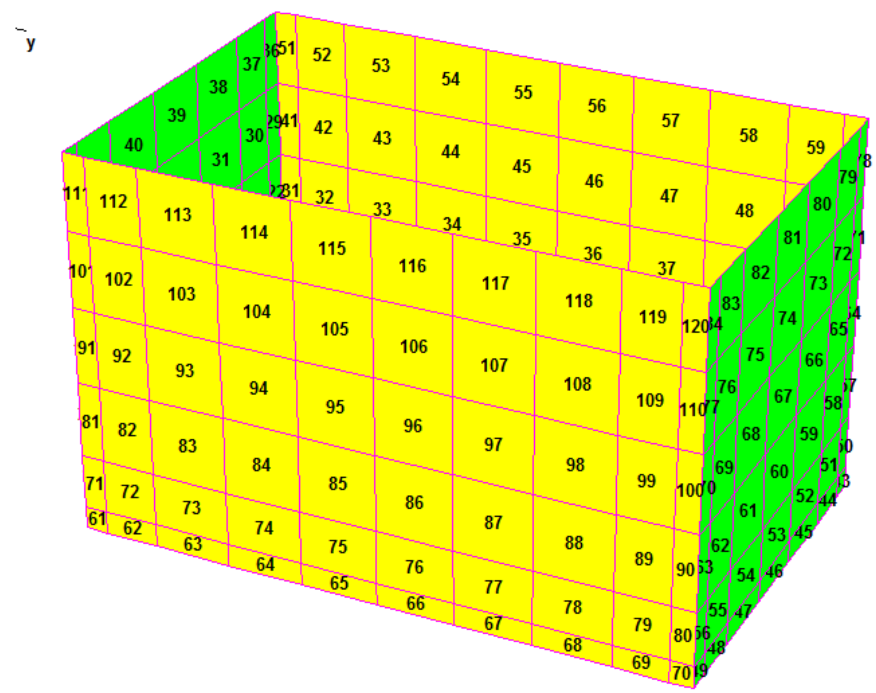
ANSYS Equivalent-Static vs. ACS SASSI – Fixed Base Model



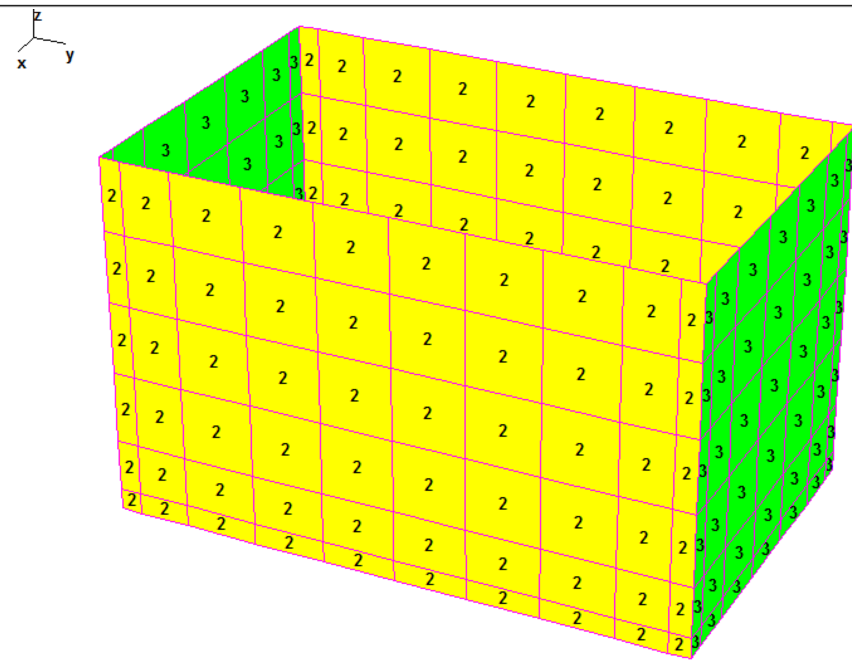
ANSYS Equivalent-Static vs. ACS SASSI – Fixed Base Model



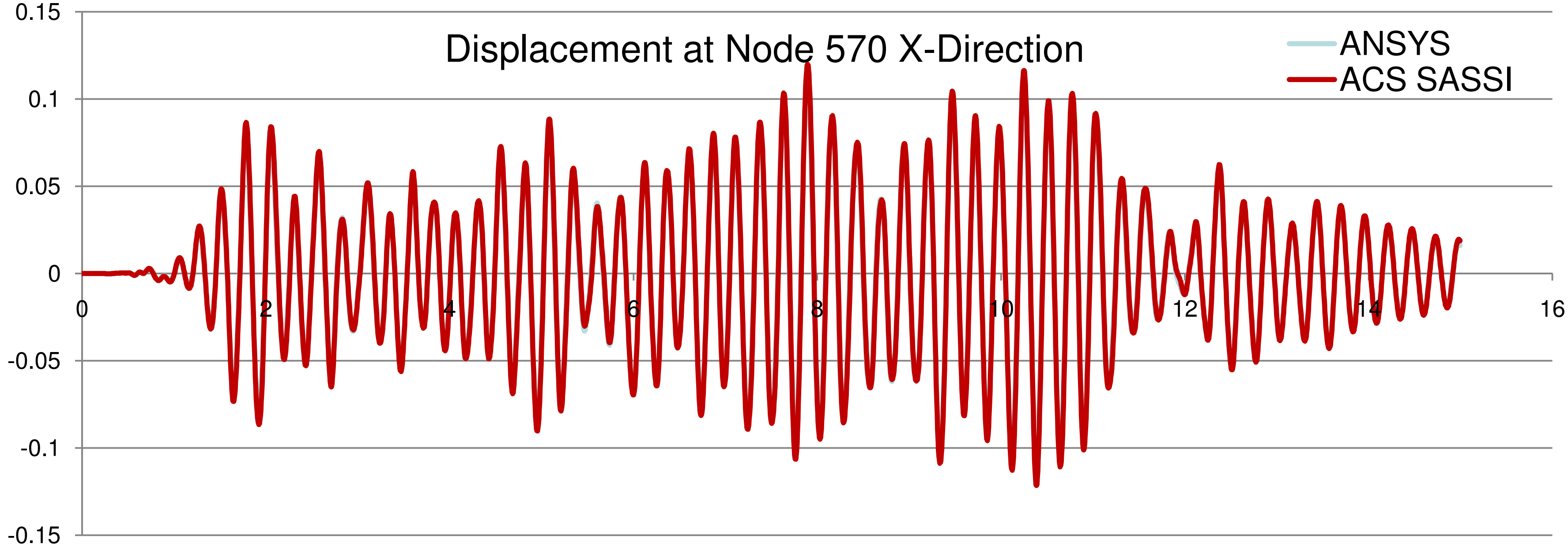


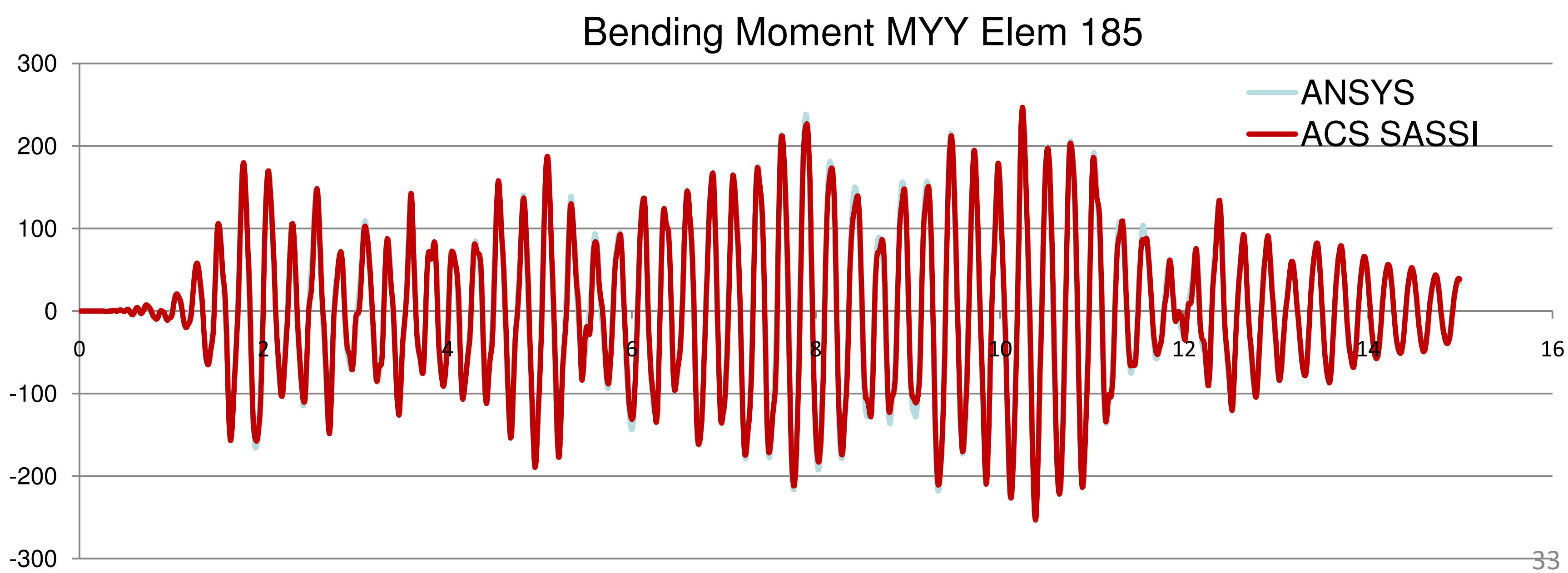


SHELL ELEMENT BOX MODEL

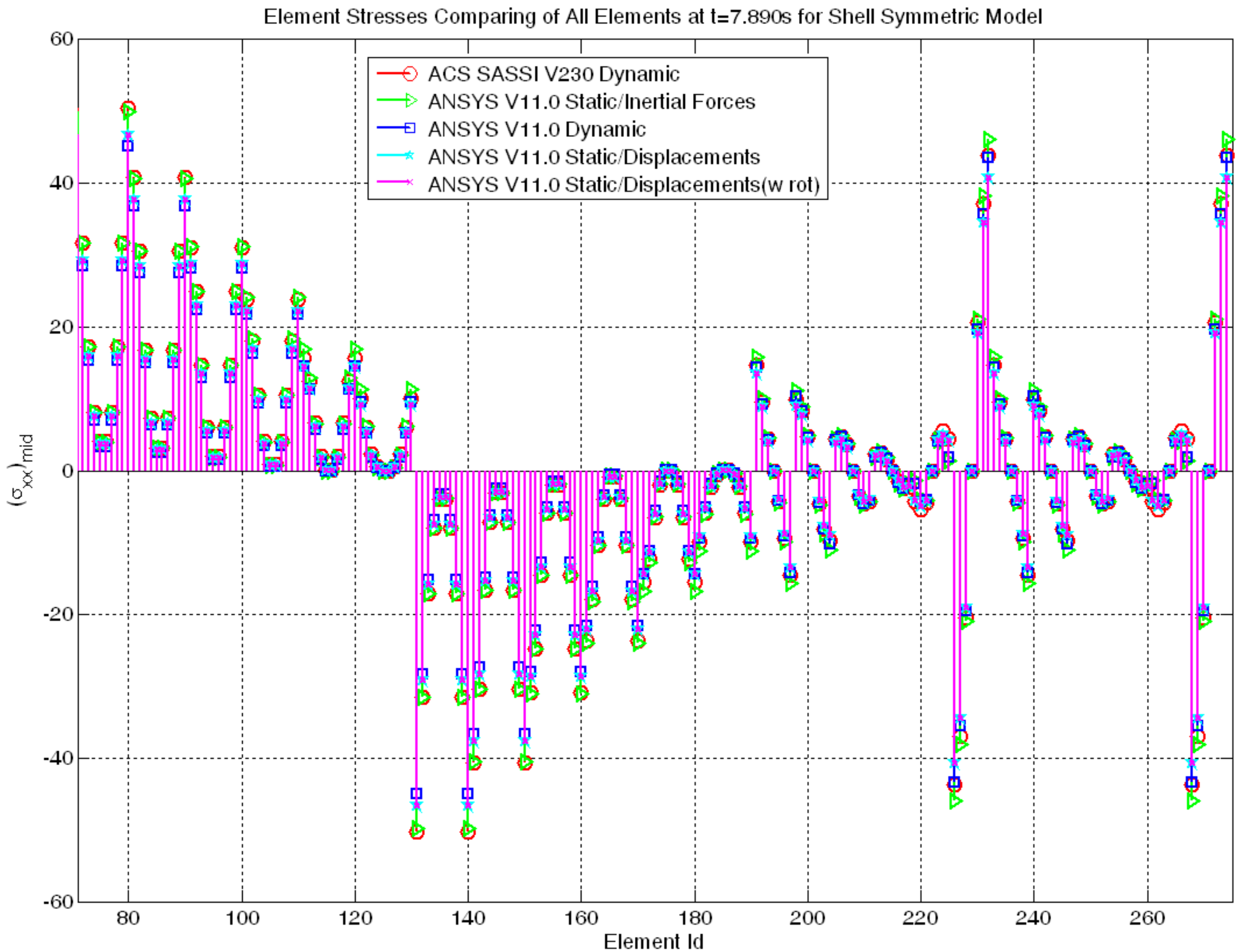


ANSYS Dynamic vs. ACS SASSI – Fixed Base Model

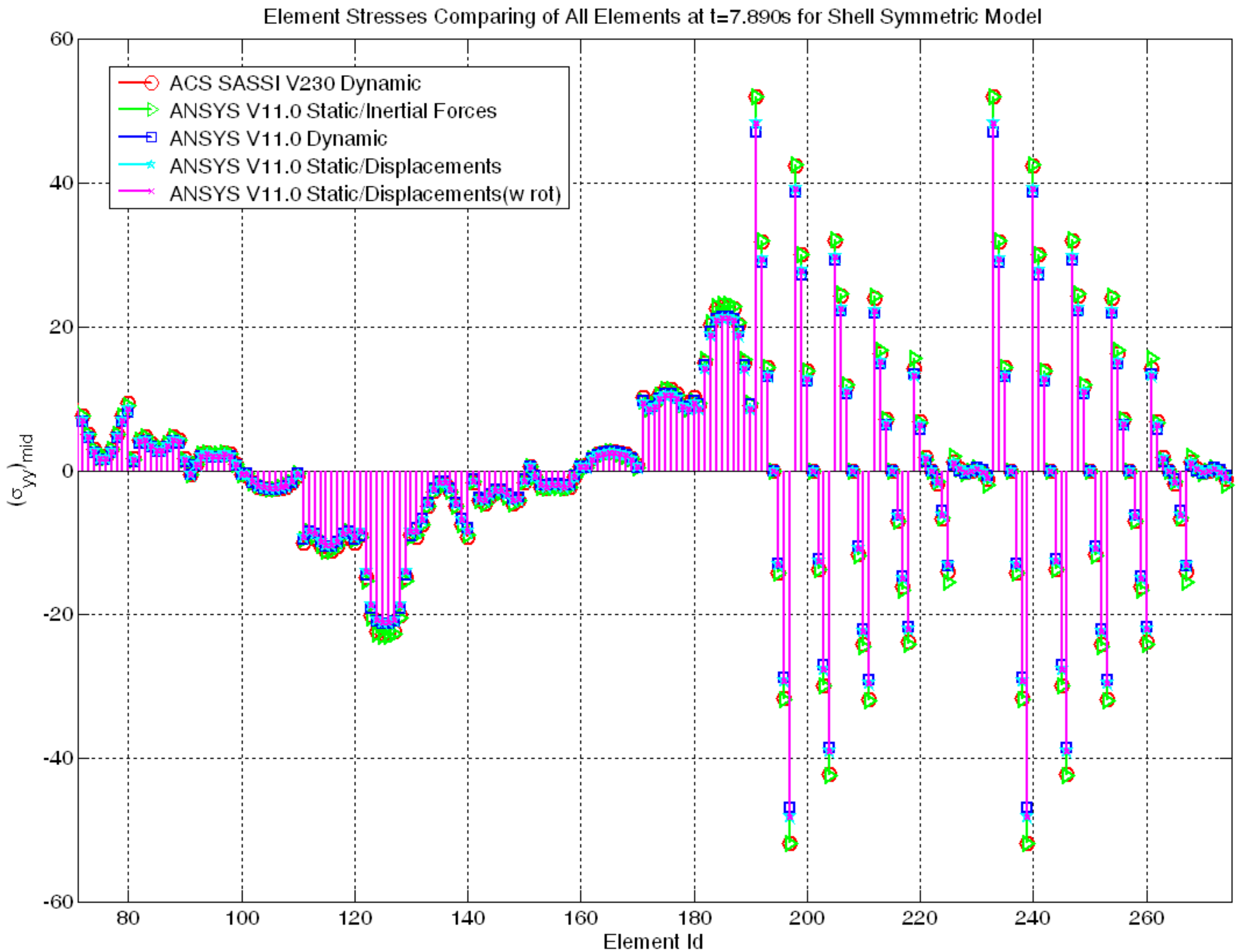




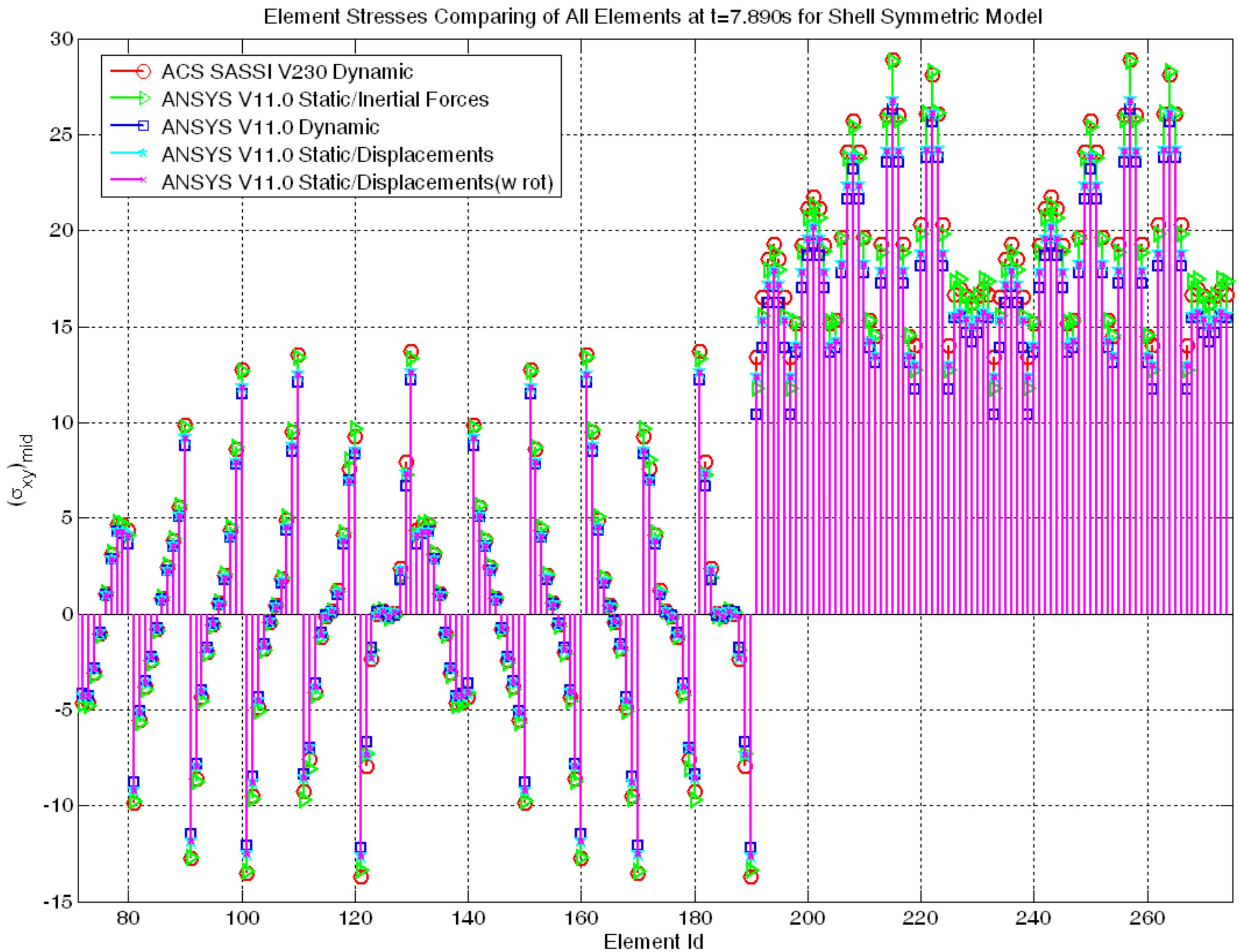
ANSYS Equivalent-Static vs. ACS SASSI – Fixed Base Model



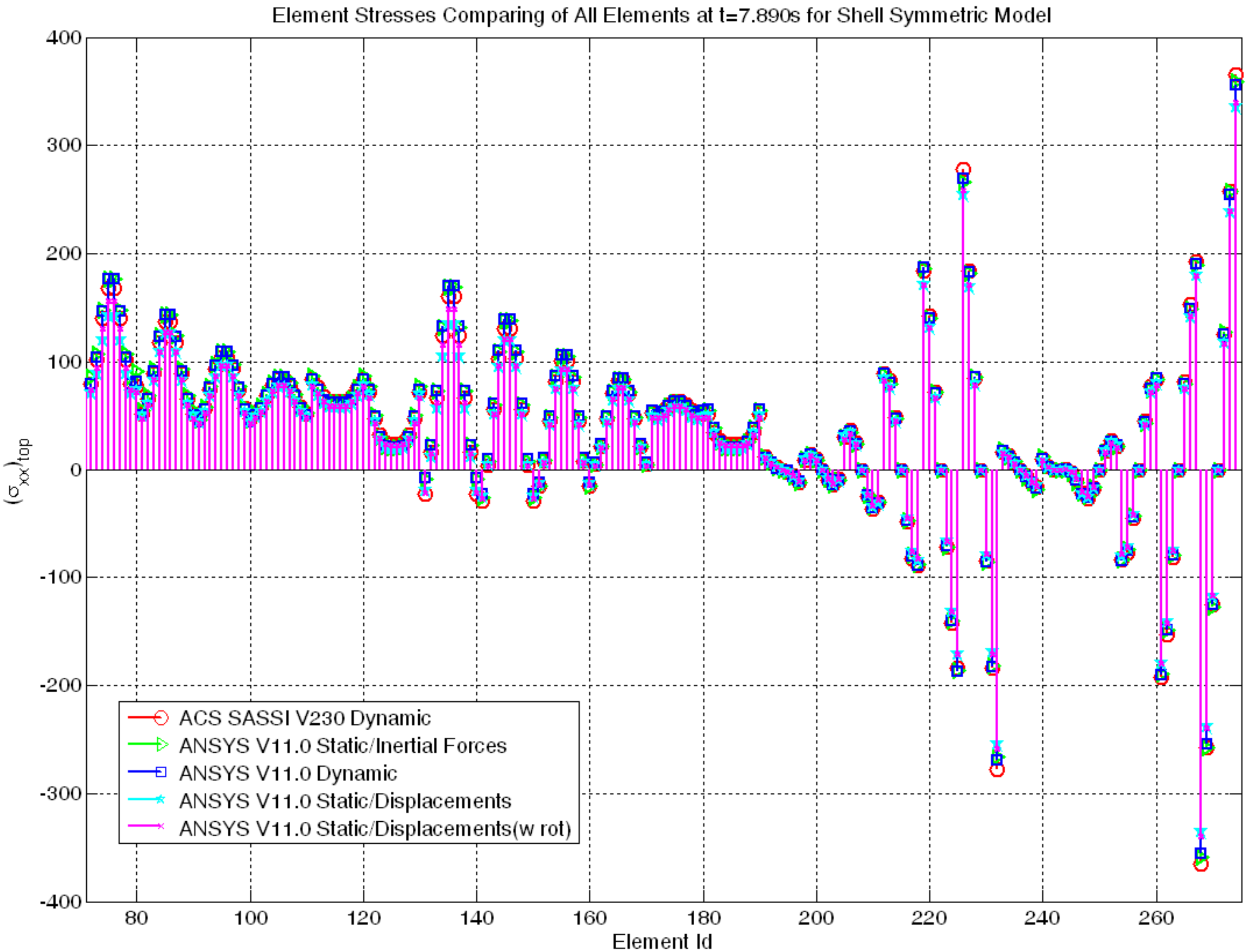
ANSYS Equivalent-Static vs. ACS SASSI – Fixed Base Model



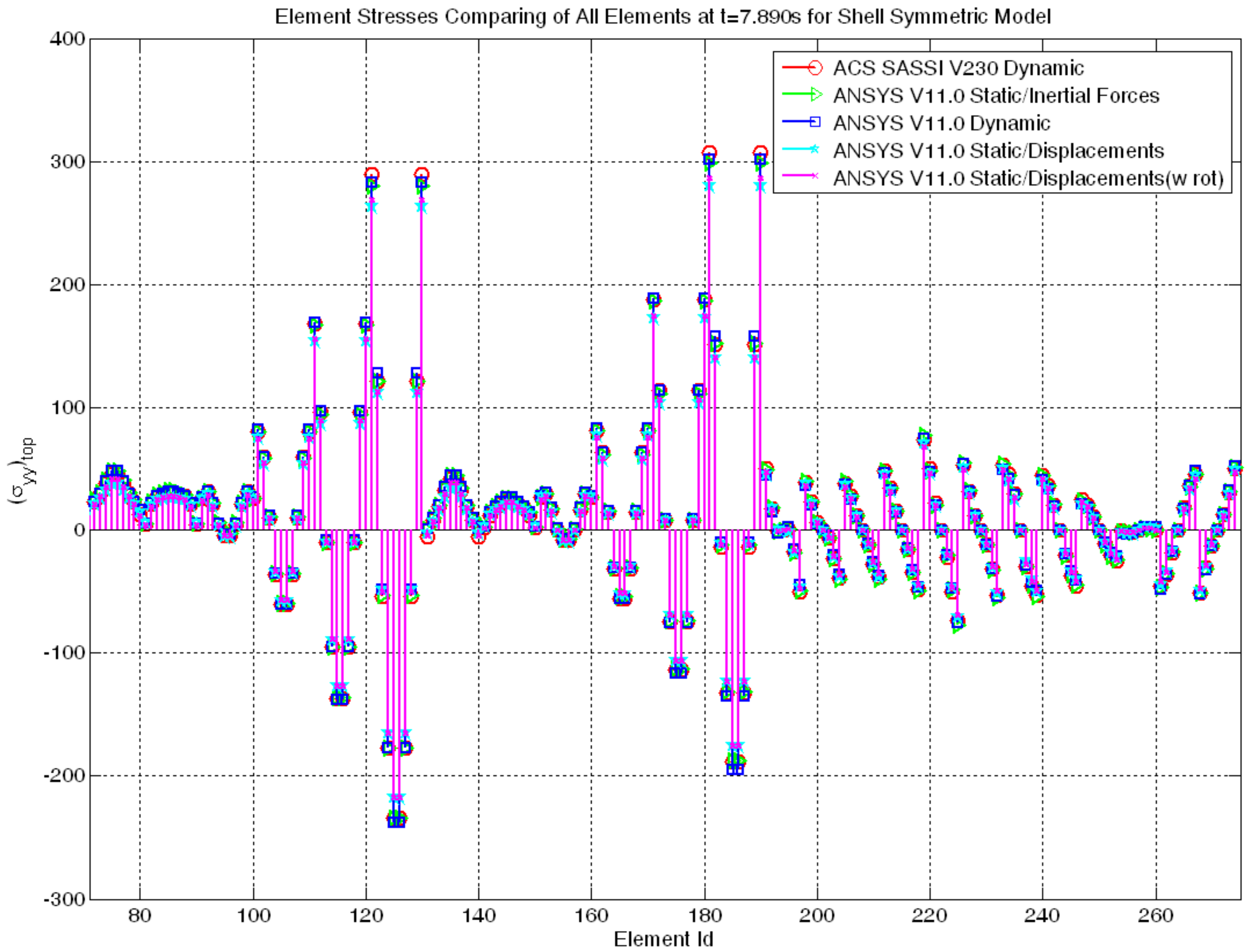
ANSYS Equivalent-Static vs. ACS SASSI – Fixed Base Model



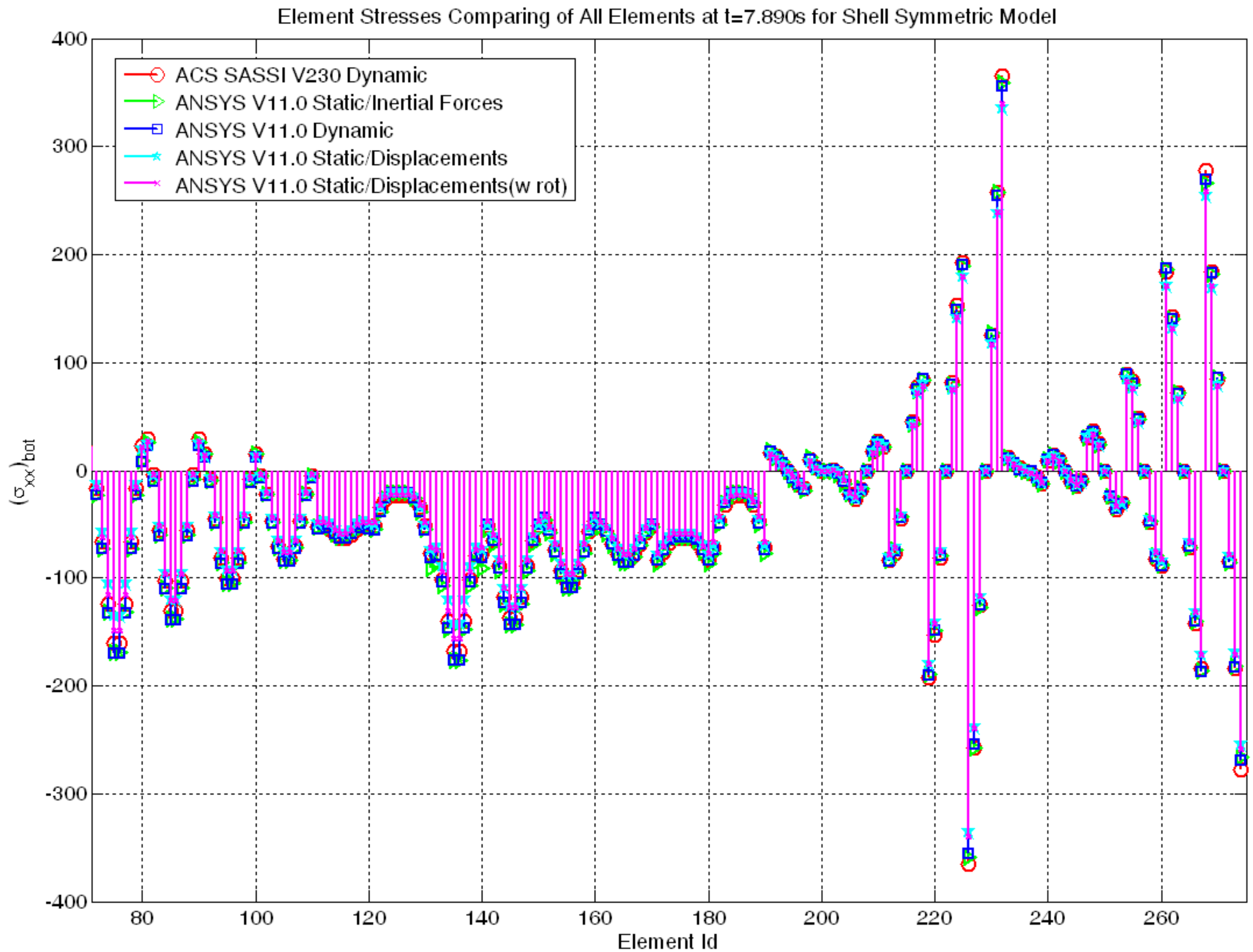
ANSYS Equivalent-Static vs. ACS SASSI – Fixed Base Model



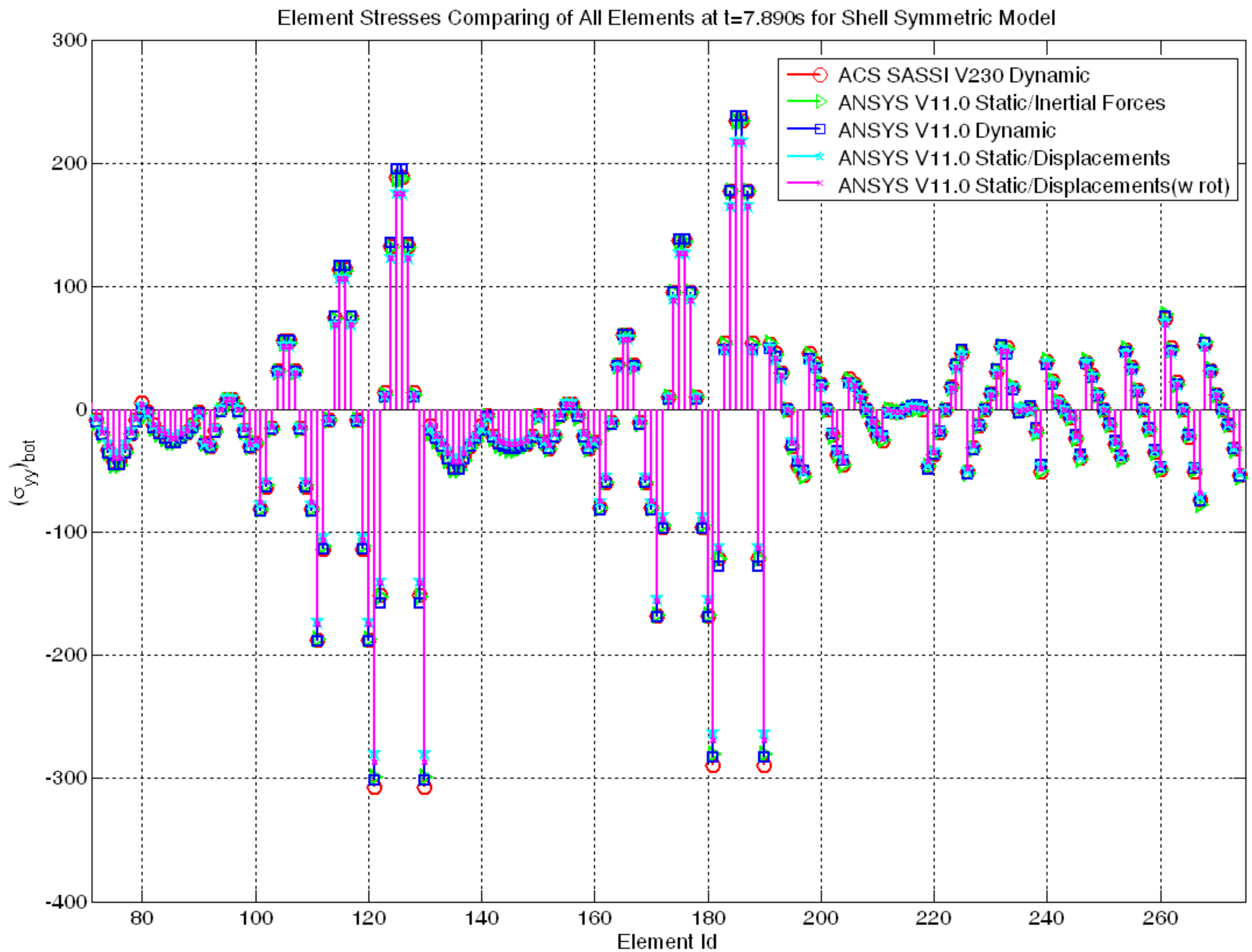
ANSYS Equivalent-Static vs. ACS SASSI – Fixed Base Model



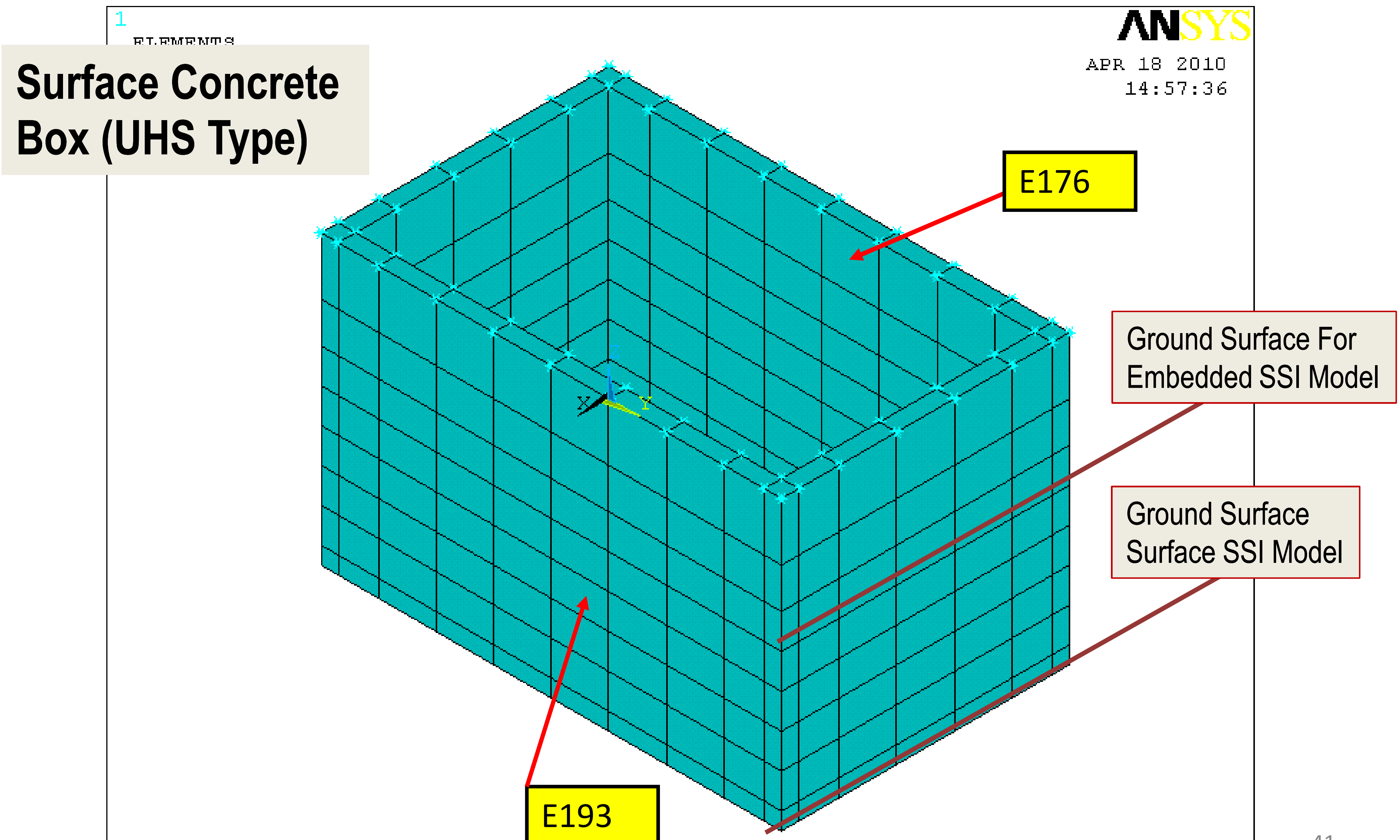
ANSYS Equivalent-Static vs. ACS SASSI – Fixed Base Model



ANSYS Equivalent-Static vs. ACS SASSI – Fixed Base Model



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



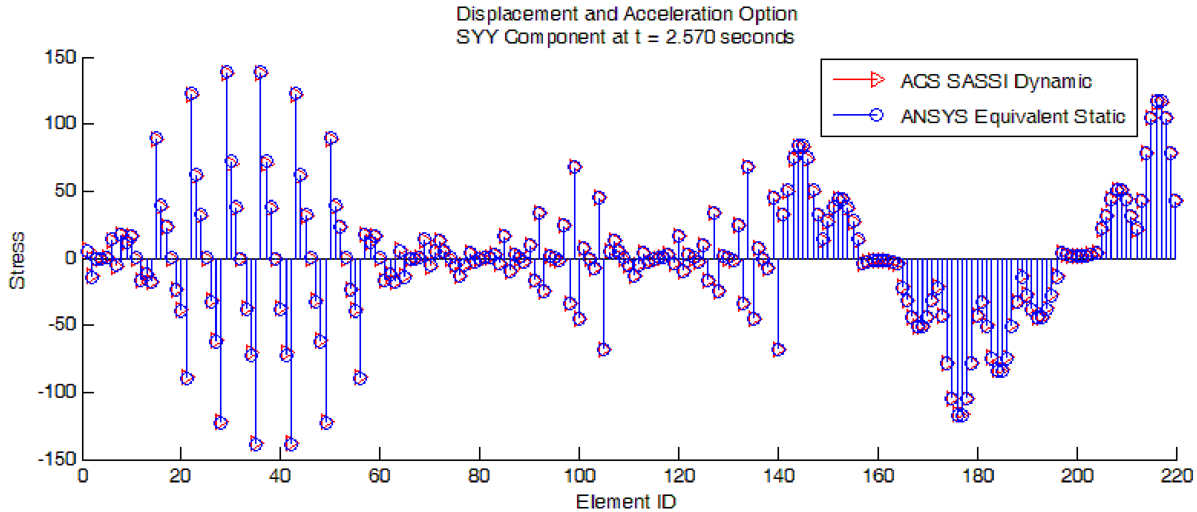
ANSYS Equivalent-Static vs. ACS SASSI

SSI Analysis

Surface Concrete Box
SOLID Elements

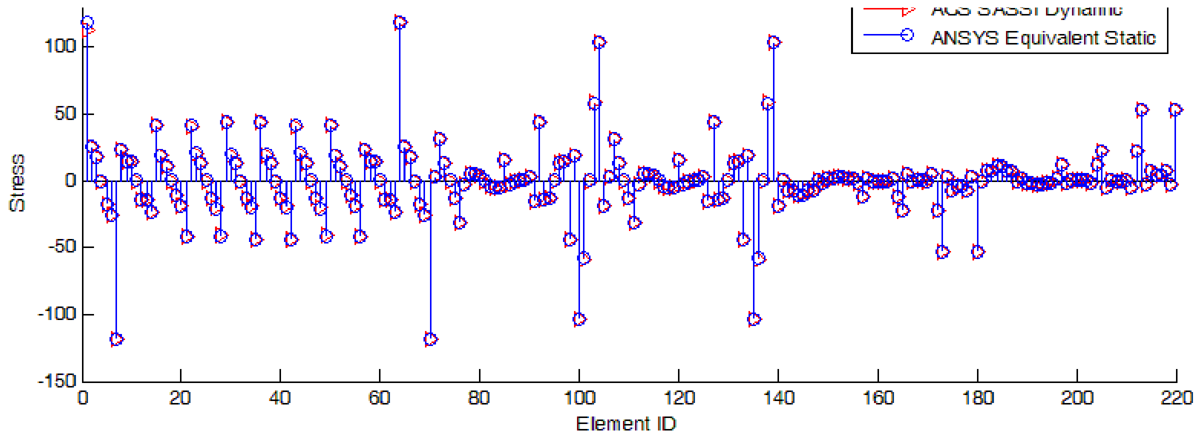
Soil Vs=1000fps

SXX



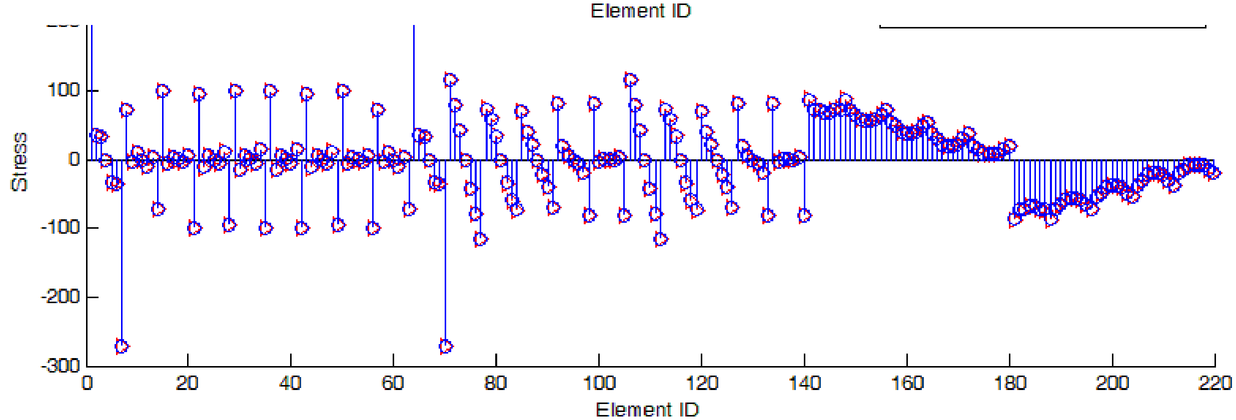
Displacement and Acceleration Option
SYY Component at t = 2.570 seconds
ACS SASSI Dynamic
ANSYS Equivalent Static
Stress
Element ID

SYY



ANSYS Equivalent Static
Stress
Element ID

SZZ



Stress
Element ID

ANSYS Equivalent-Static vs. ACS SASSI

SSI Analysis

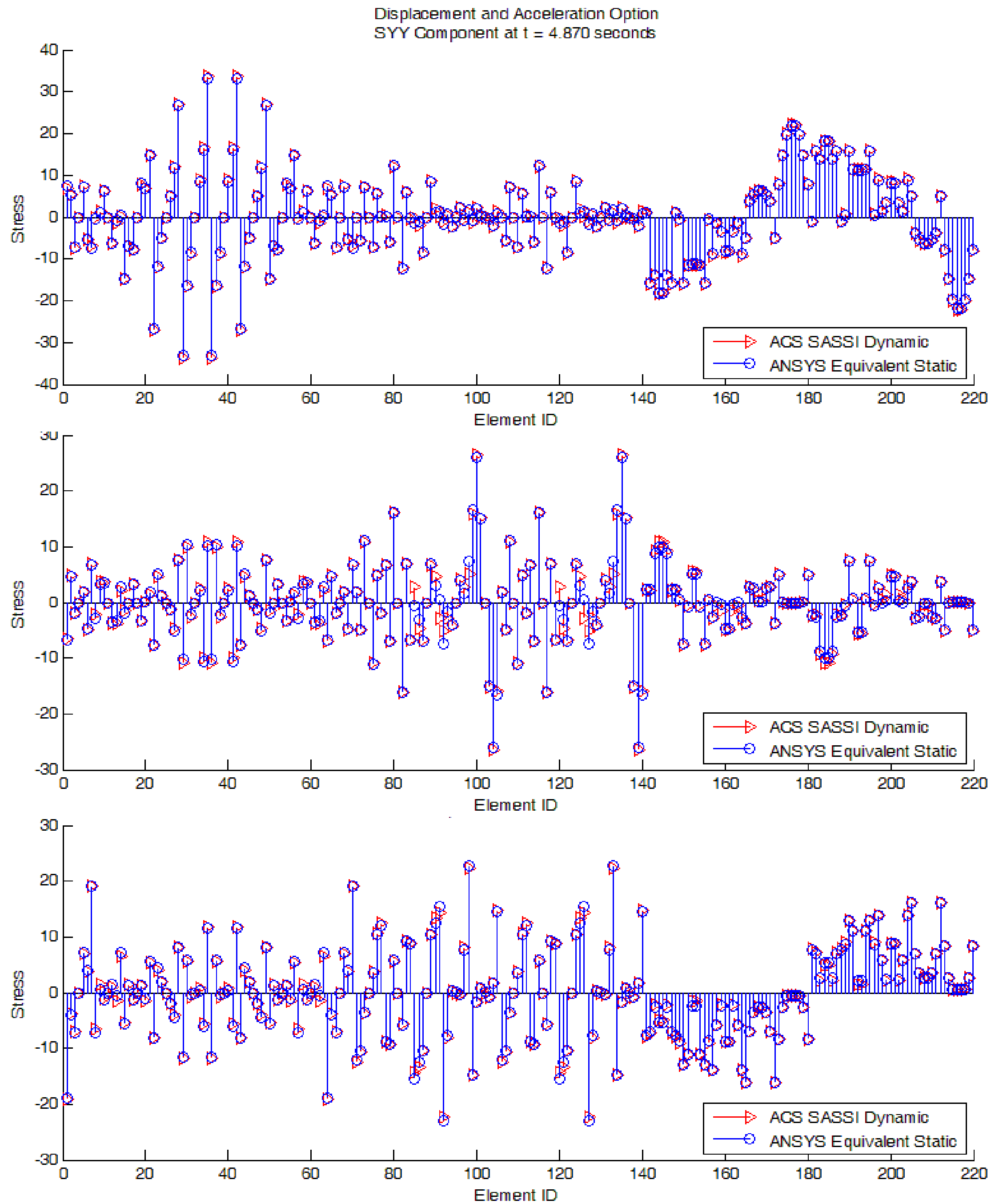
Deeply Embedded Concrete Box
SOLID Elements

Soil Vs=1,000 fps

SXX

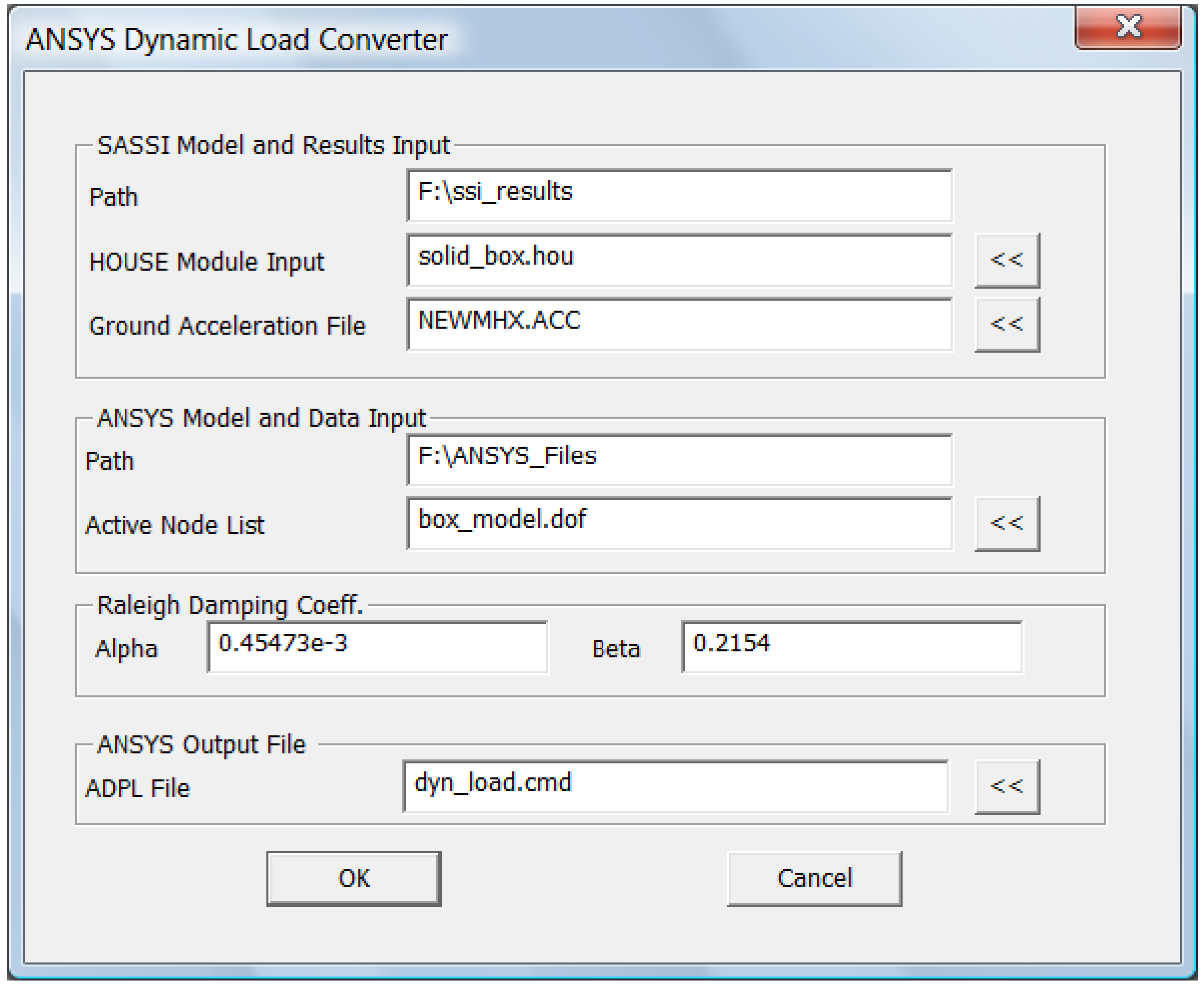
SYY

SZZ


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

ANSYS Dynamic Load Generation from ACS SASSI 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”



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

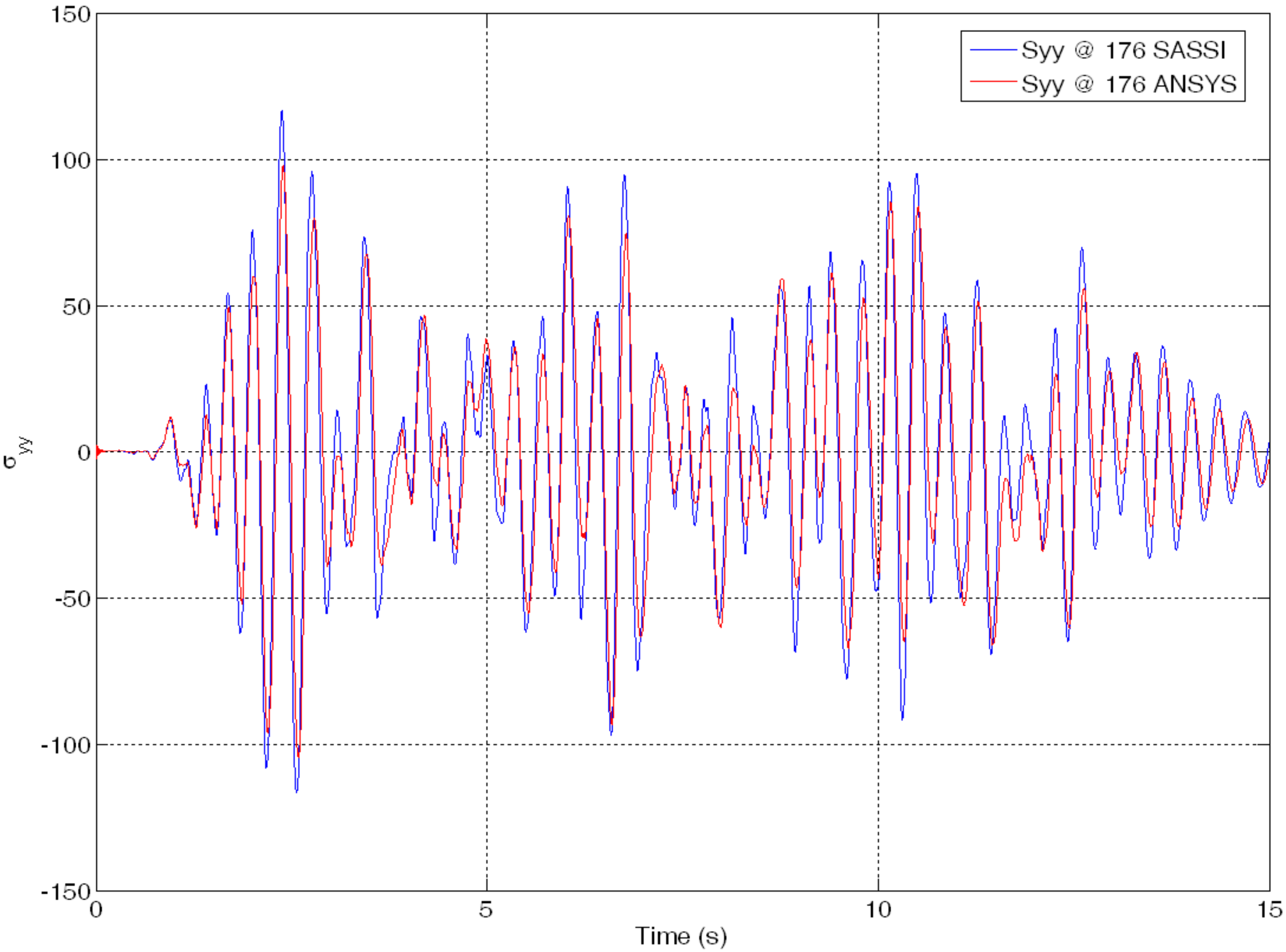
Surface Concrete Box
SOLID Elements
Soil Vs=1,000 fps

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

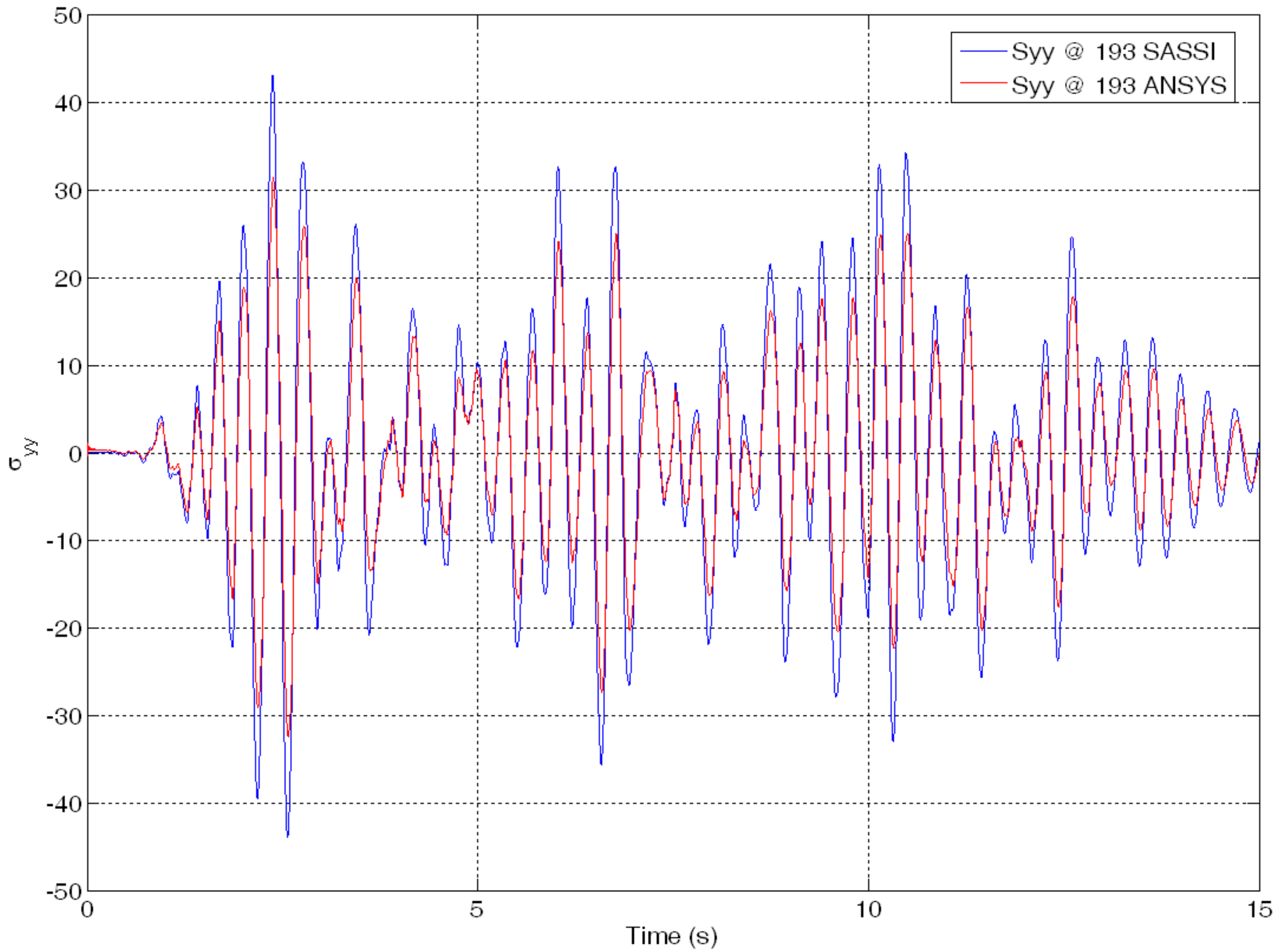
SYY



ANSYS Dynamic vs. ACS SASSI – for Surface SSI Model

Below Ground Surface

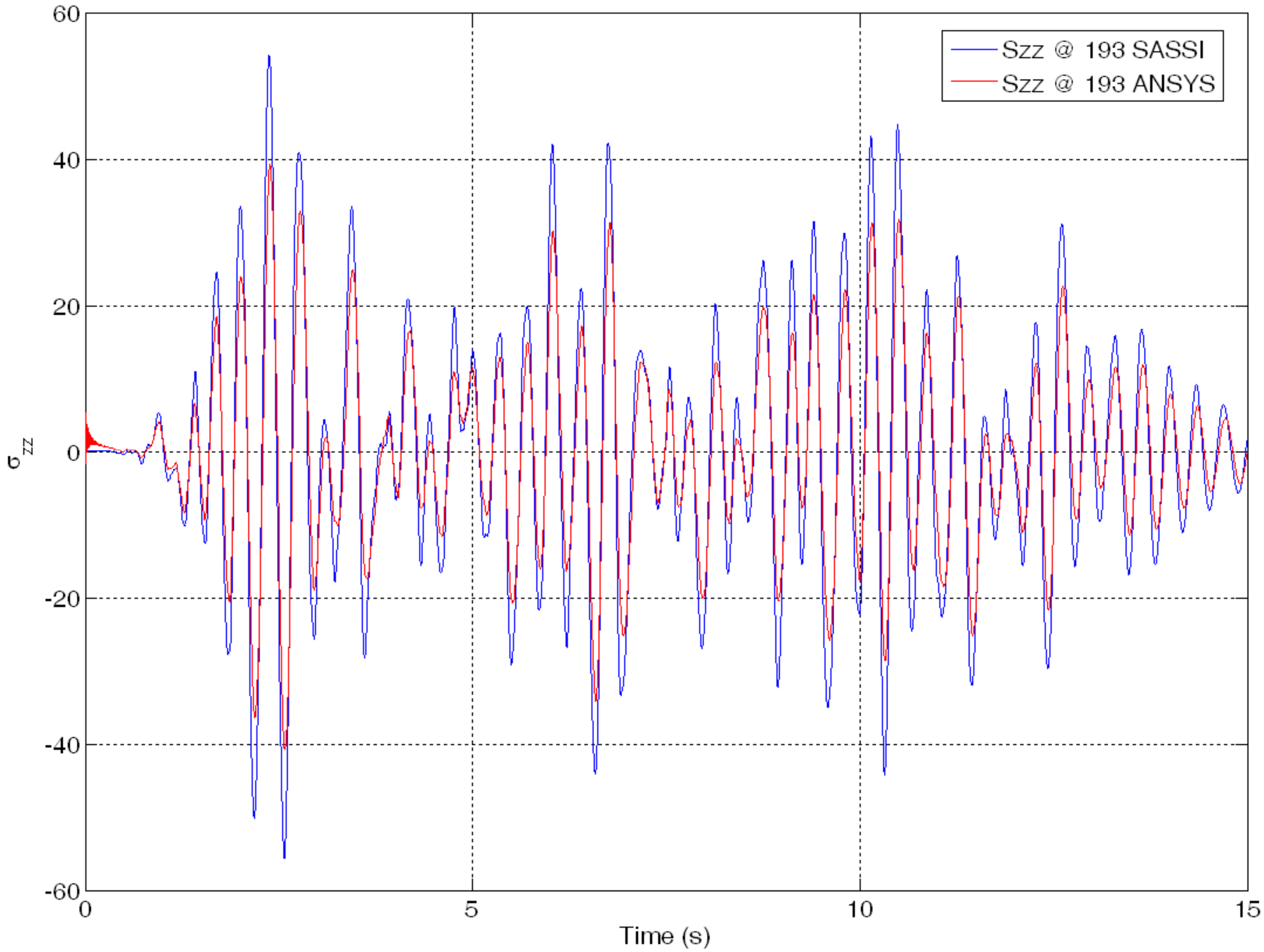
SYY



ANSYS Dynamic vs. ACS SASSI – for Surface SSI Model

Below Ground Surface

SZZ



ANSYS Dynamic vs. ACS SASSI

SSI Analysis

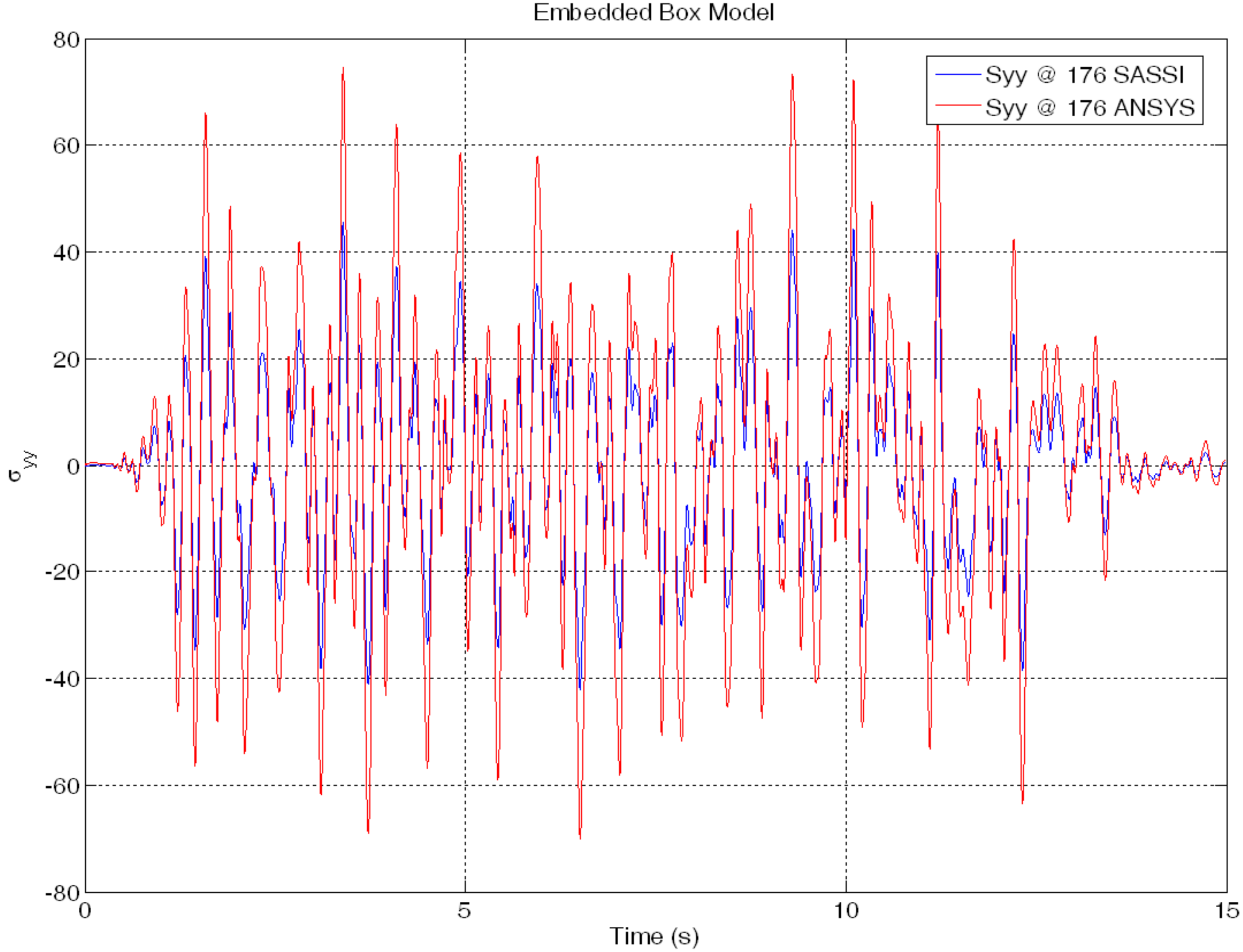
Deeply Embedded Concrete Box
SOLID Elements
Soil Vs=1,000 fps

Seismic Loading for ANSYS:
Ground Acceleration Histories and Relative Displacement Histories wrt Free-Field Surface Option
(No kinematic SSI is included!)

ANSYS Dynamic vs. ACS SASSI – Deeply Embedded SSI Model

Above Ground Surface

SYY

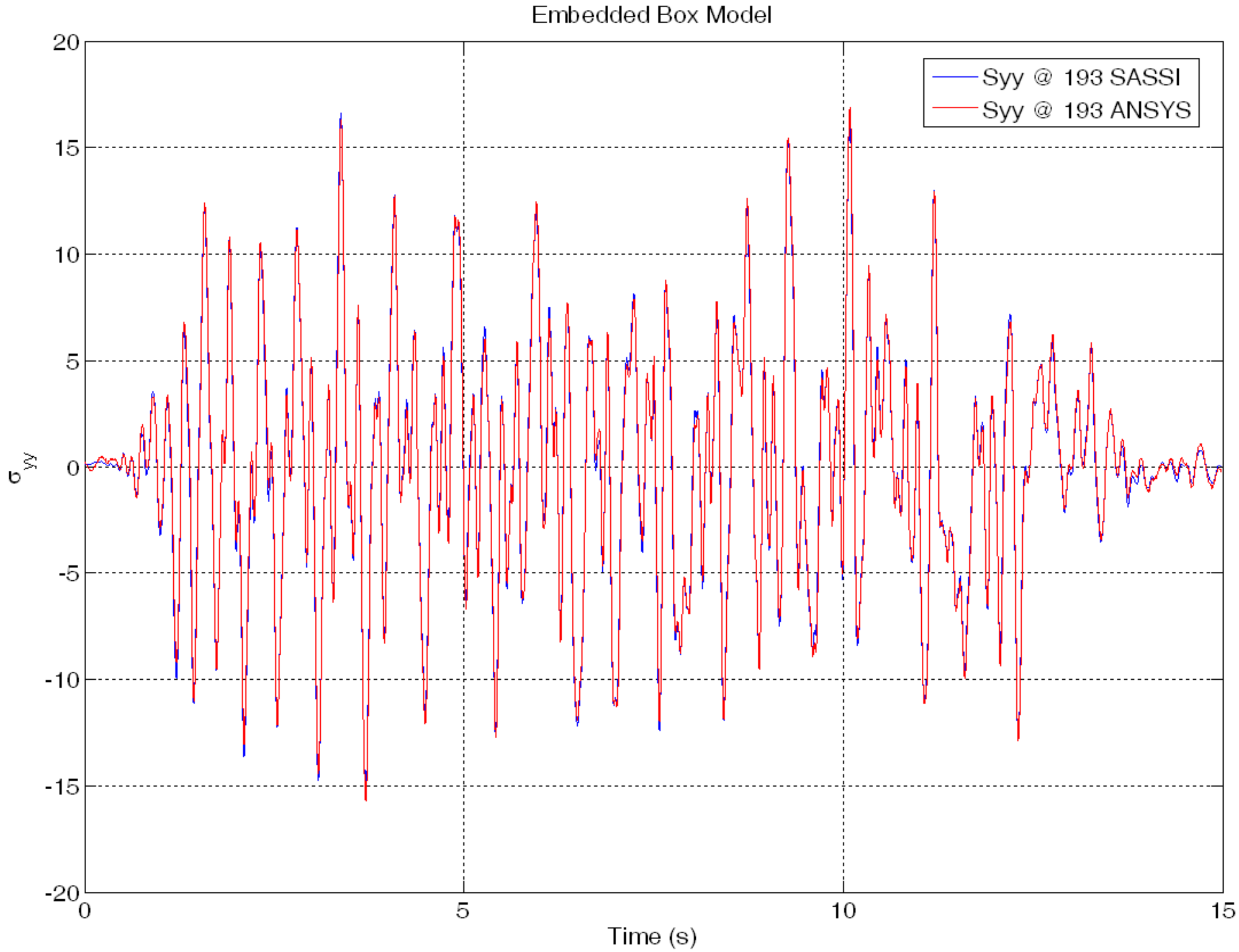


NOTE: In this example ANSYS results does not include kinematic SSI effects on accelerations

ANSYS Dynamic vs. ACS SASSI – Deeply Embedded SSI Model

Below Ground Surface

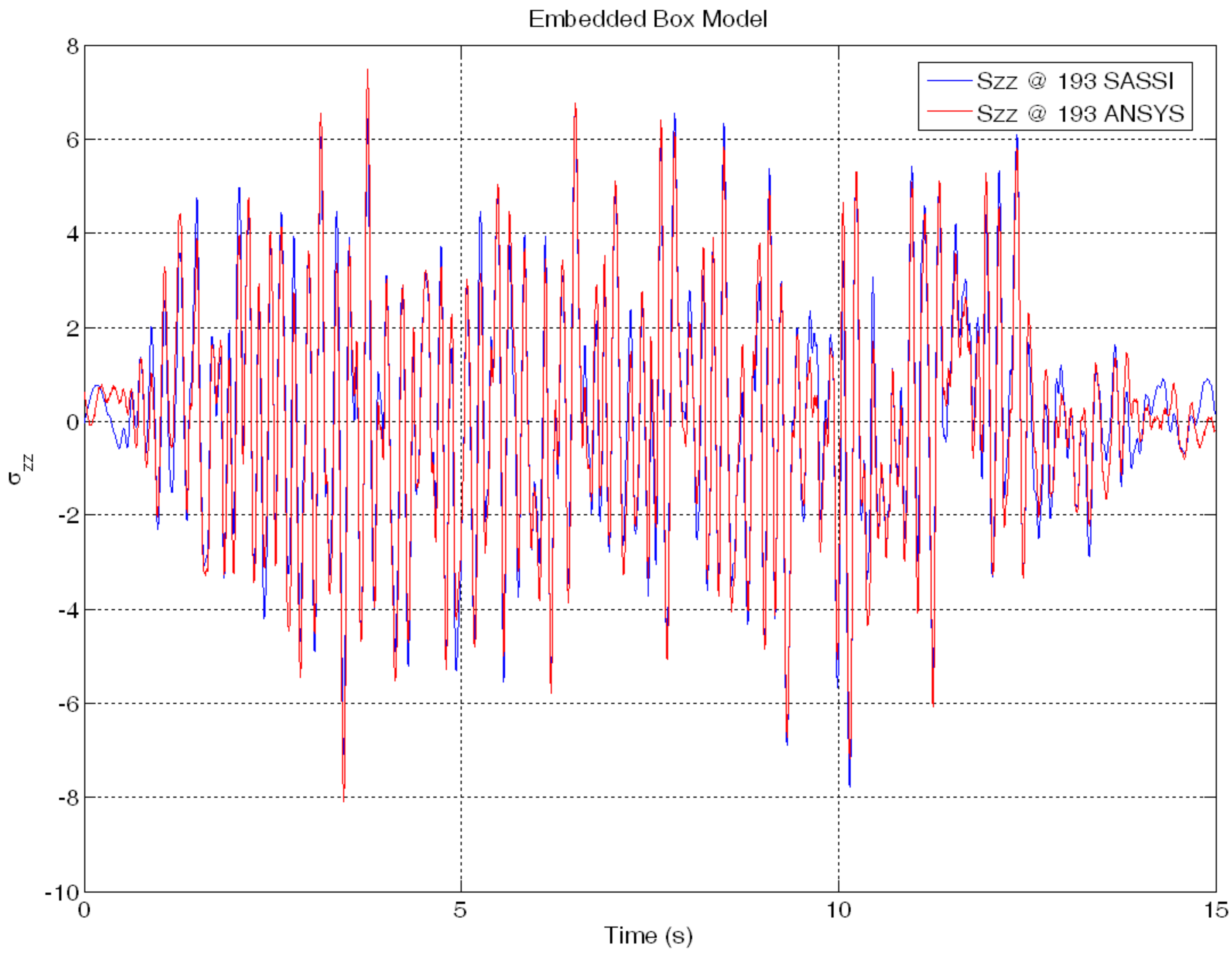
SYY



ANSYS Dynamic vs. ACS SASSI – Deeply Embedded SSI Model

Below Ground Surface

SZZ



New SOILMESH Module for Soil Pressure Computation

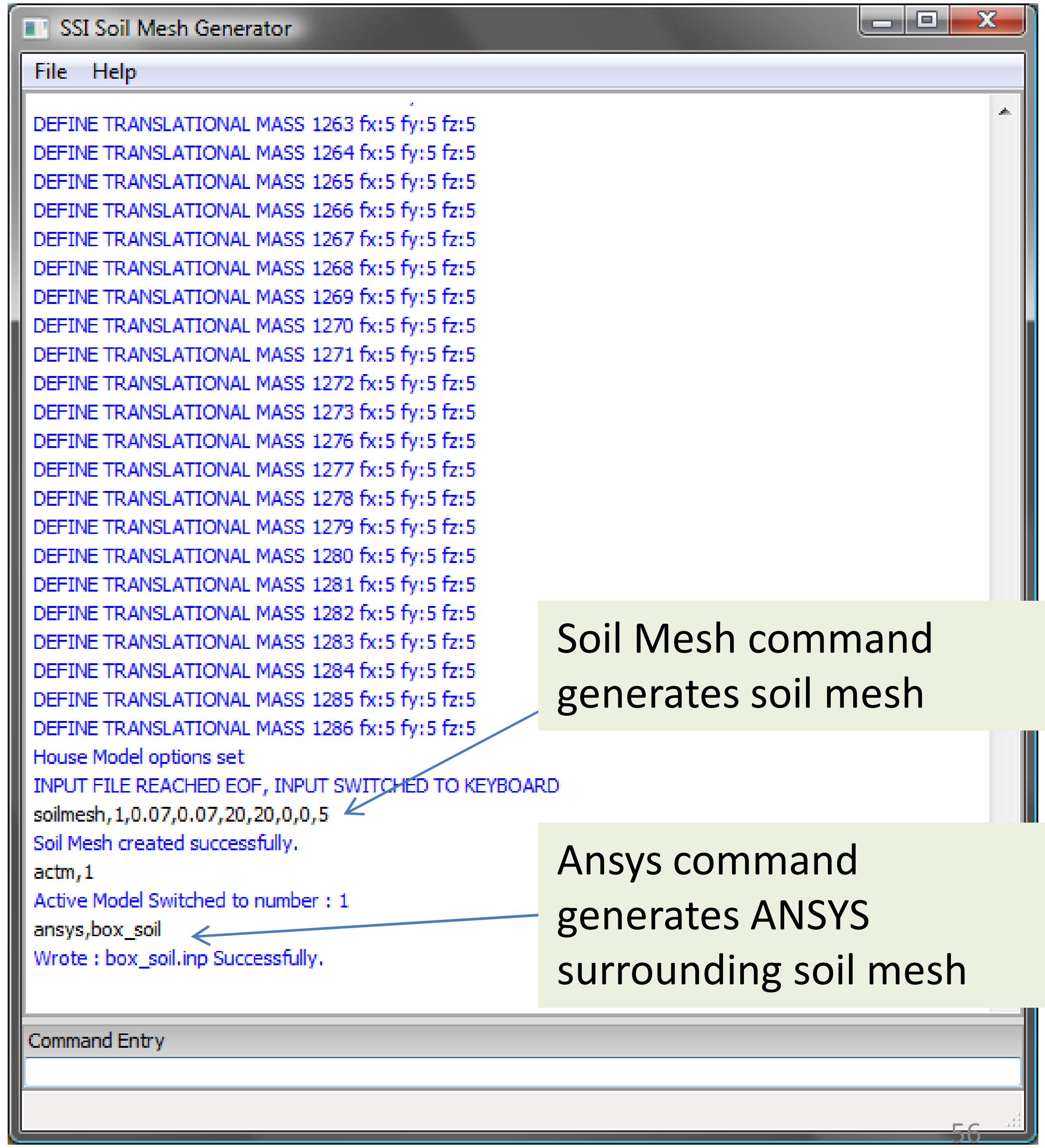
- Input .pre file with SSI model data
- Generates a soil FE model for soil pressure analysis using the "soilmesh" command
- Can export either structural or soil FE model to ANSYS APDL input file
- Computes seismic soil pressures produced using either

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

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

Soil is assumed to be at rest. Soil stiffness is not frequency dependent. The new implementation produces "approximate" seismic soil pressures.

Significant analysis improvement in comparison with the current practice.



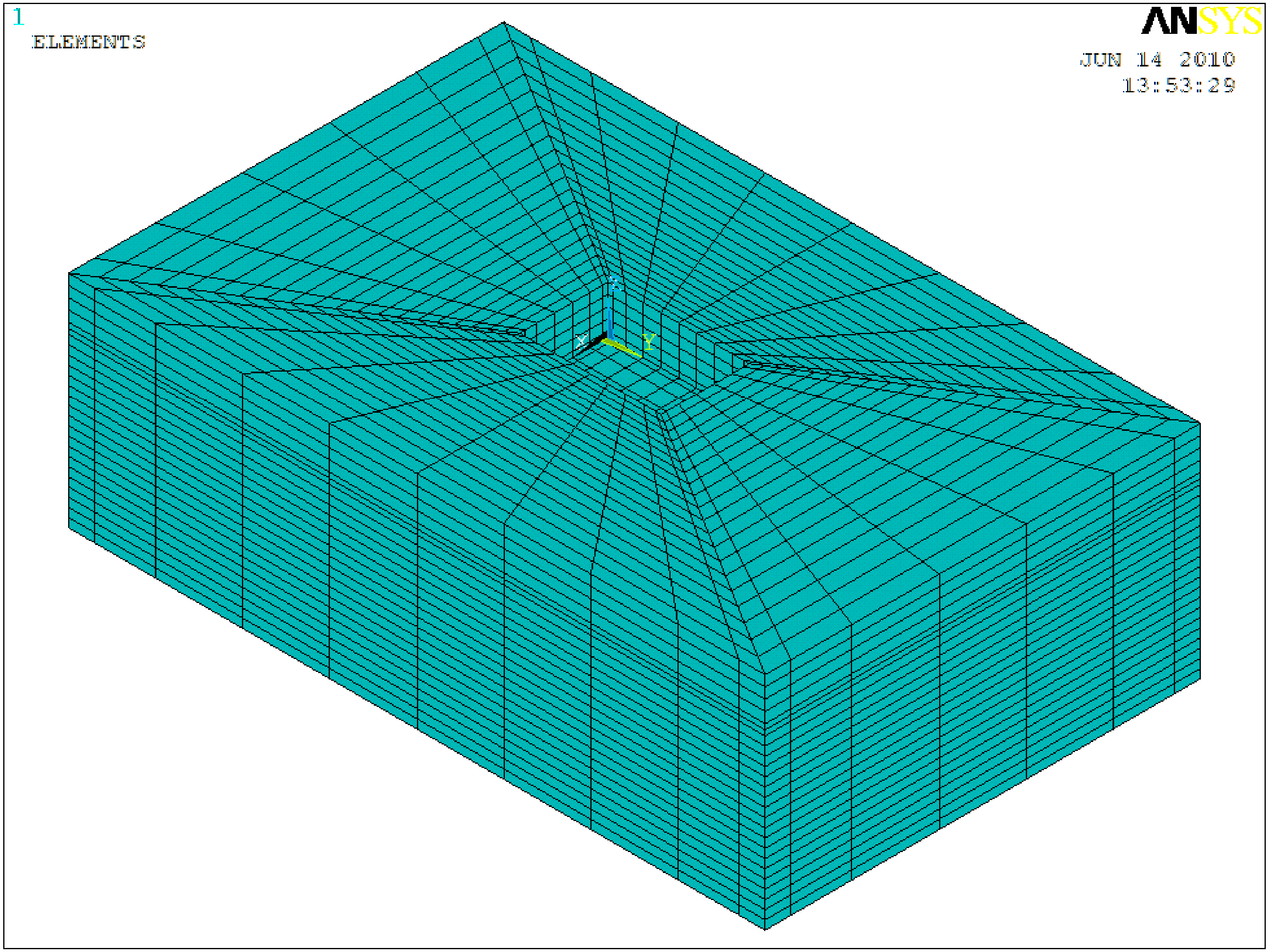
Example of APDL file for Soil FE Model

box_soil.inp - Notepad

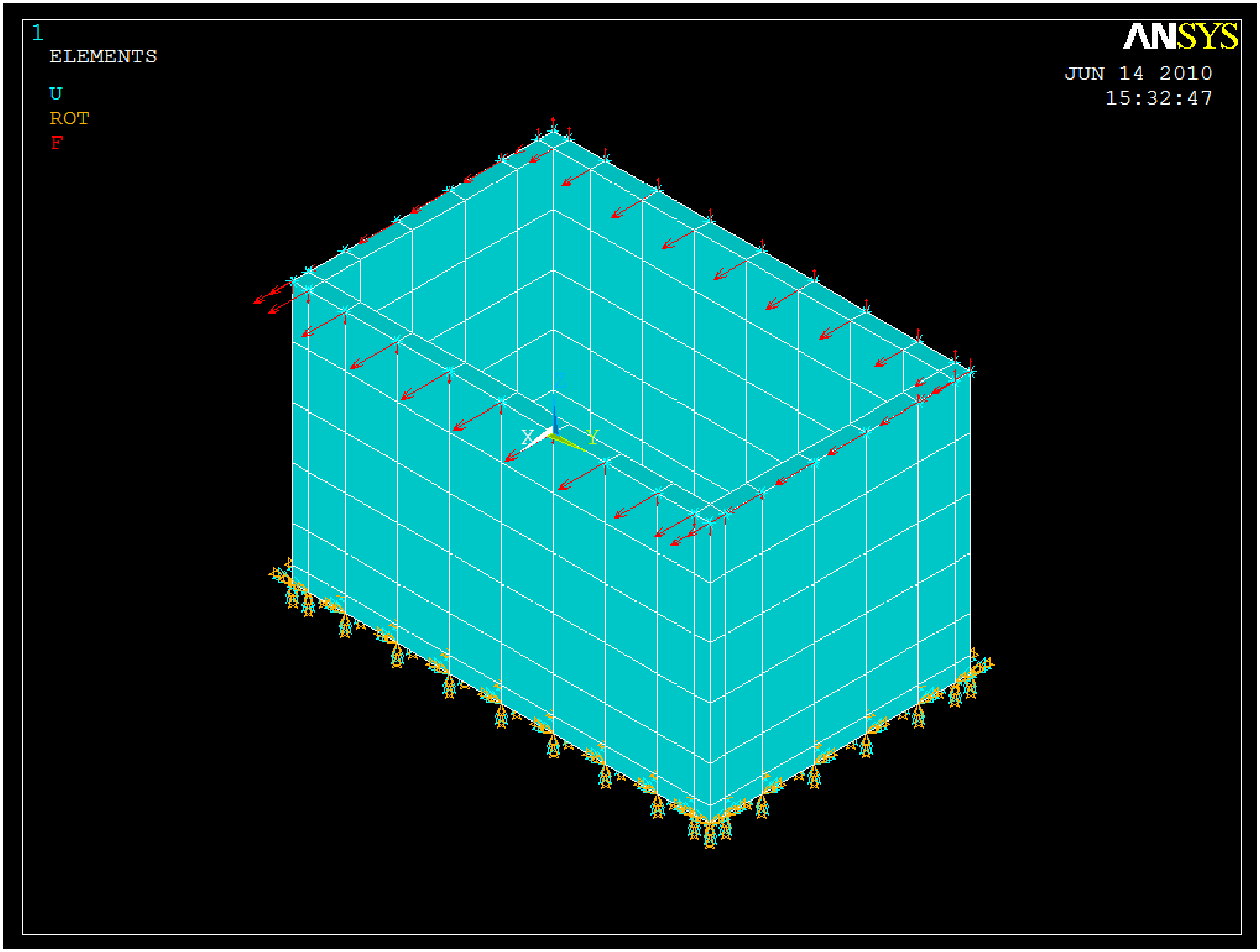
File Edit Format View Help

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

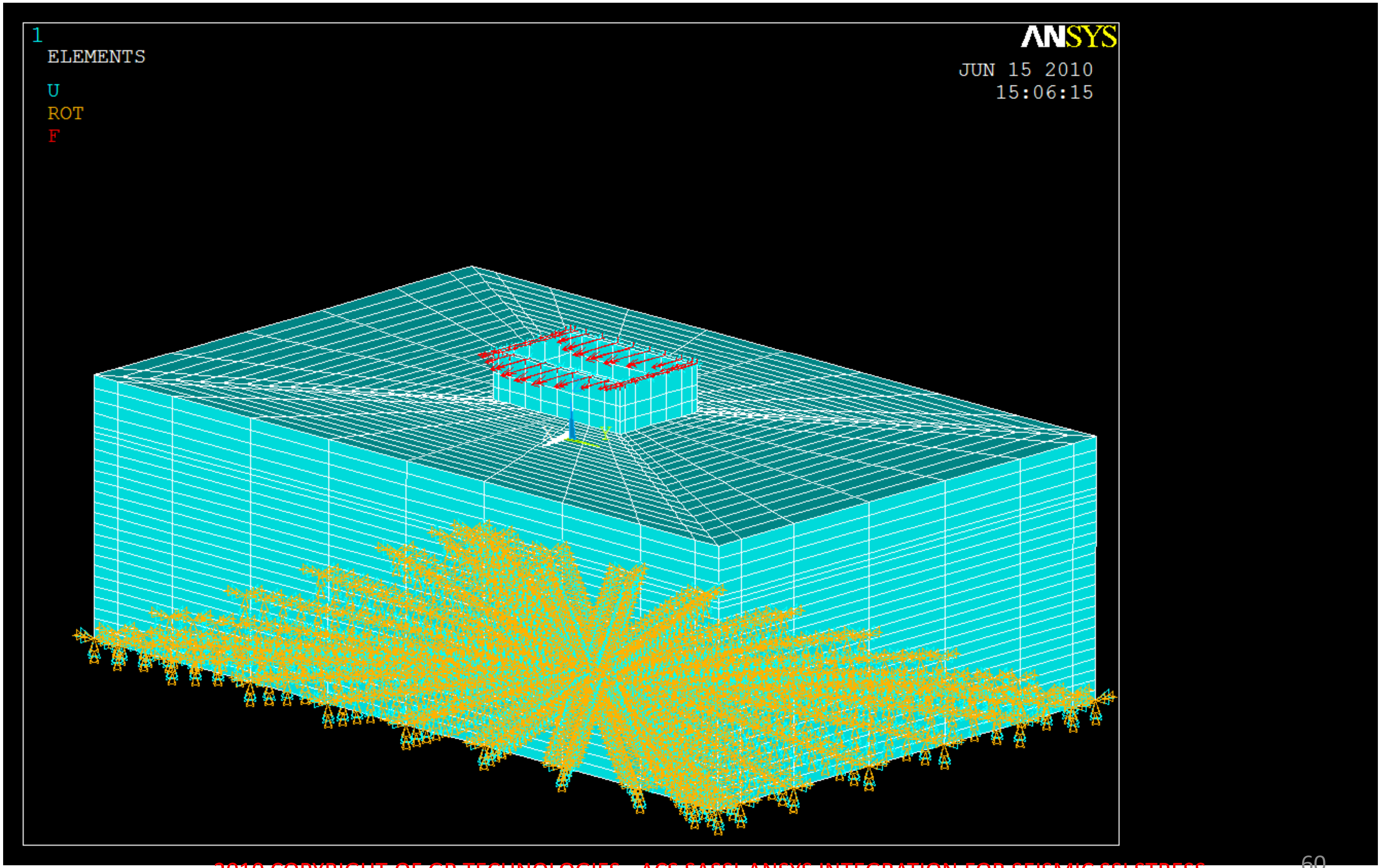
Example of Soil FE model Created Automatically by New SOILMESH Module for A Box Structural Model



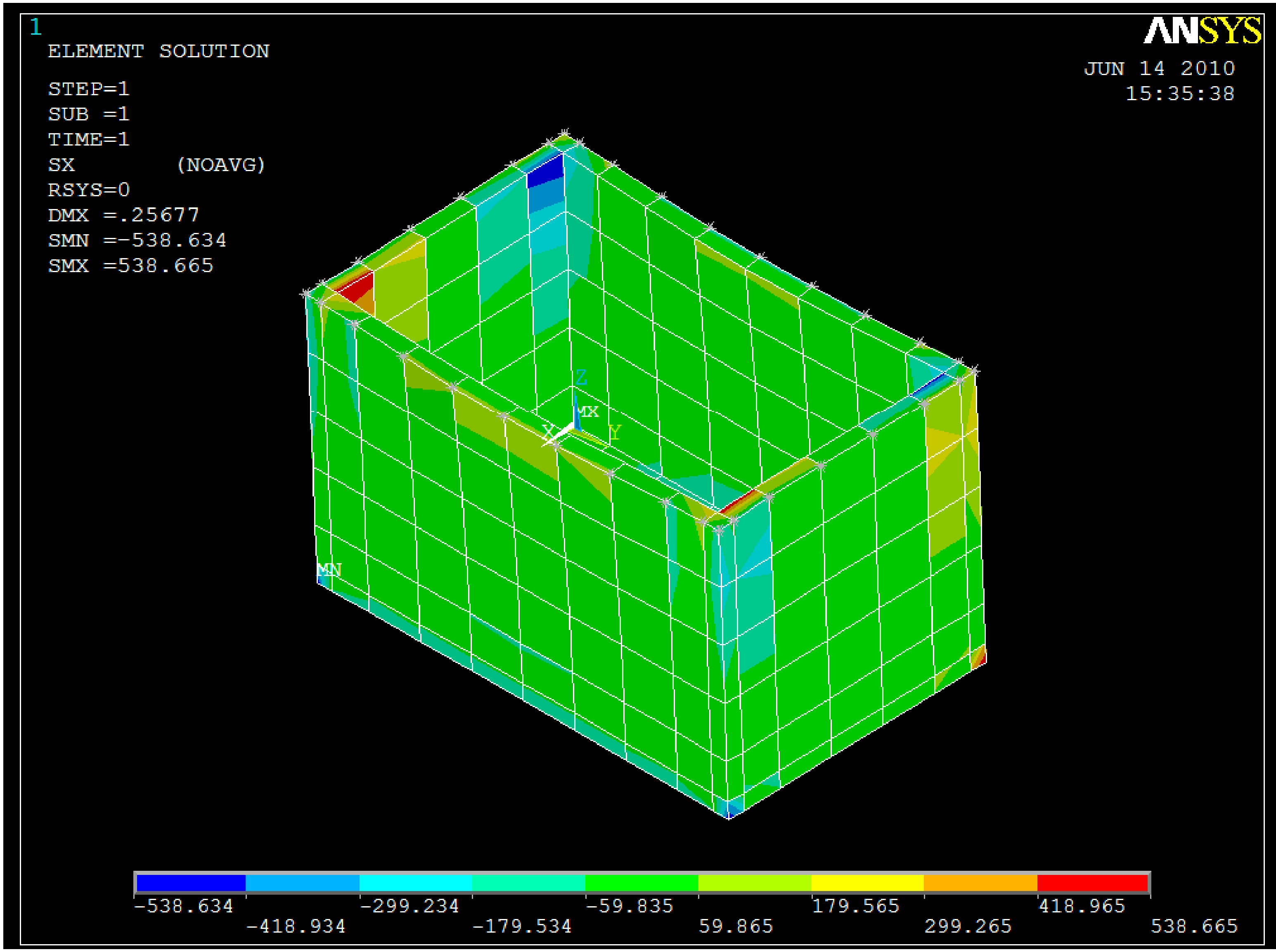
Concrete Box Structural Model (UHS Type)



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



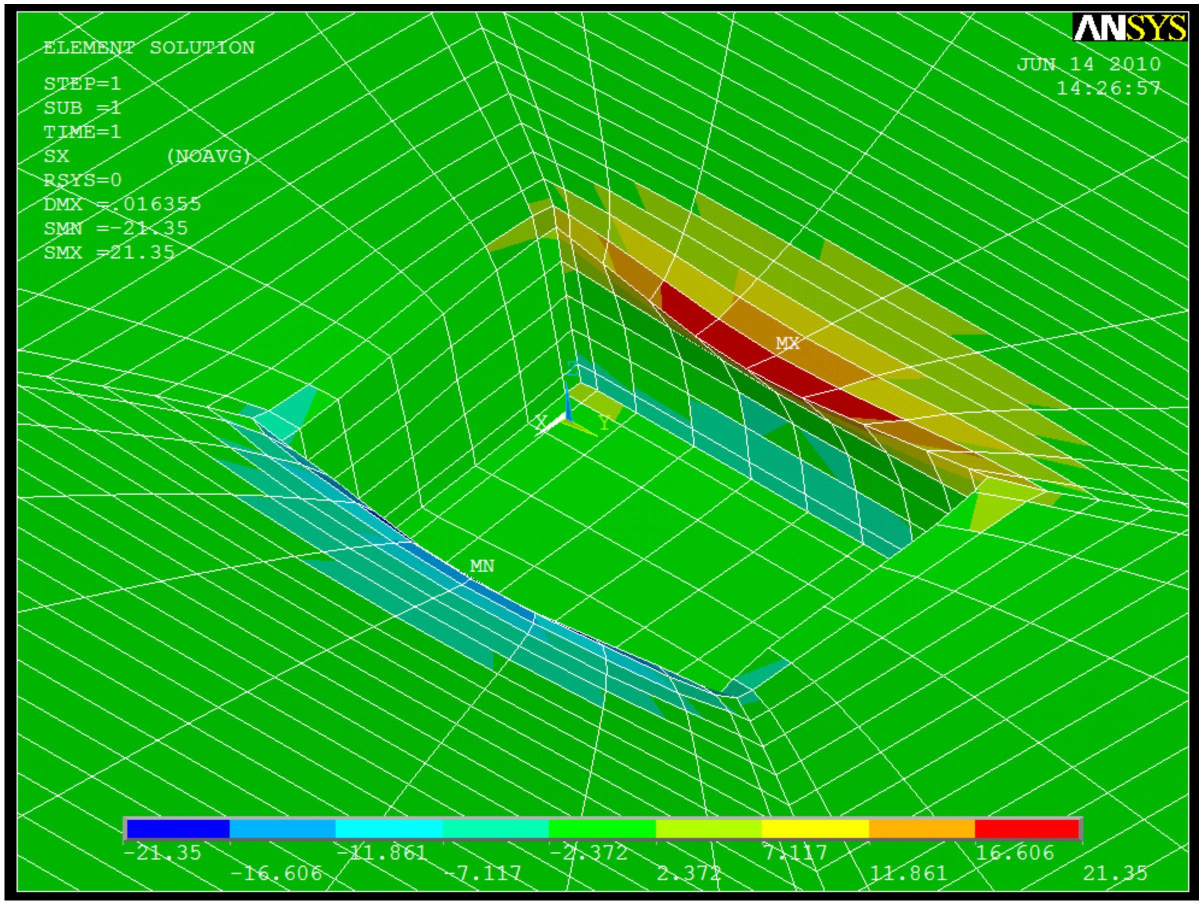
Computed Structural Displacements



Linear Seismic Soil Pressure Analysis

LINEAR (WELDED)

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

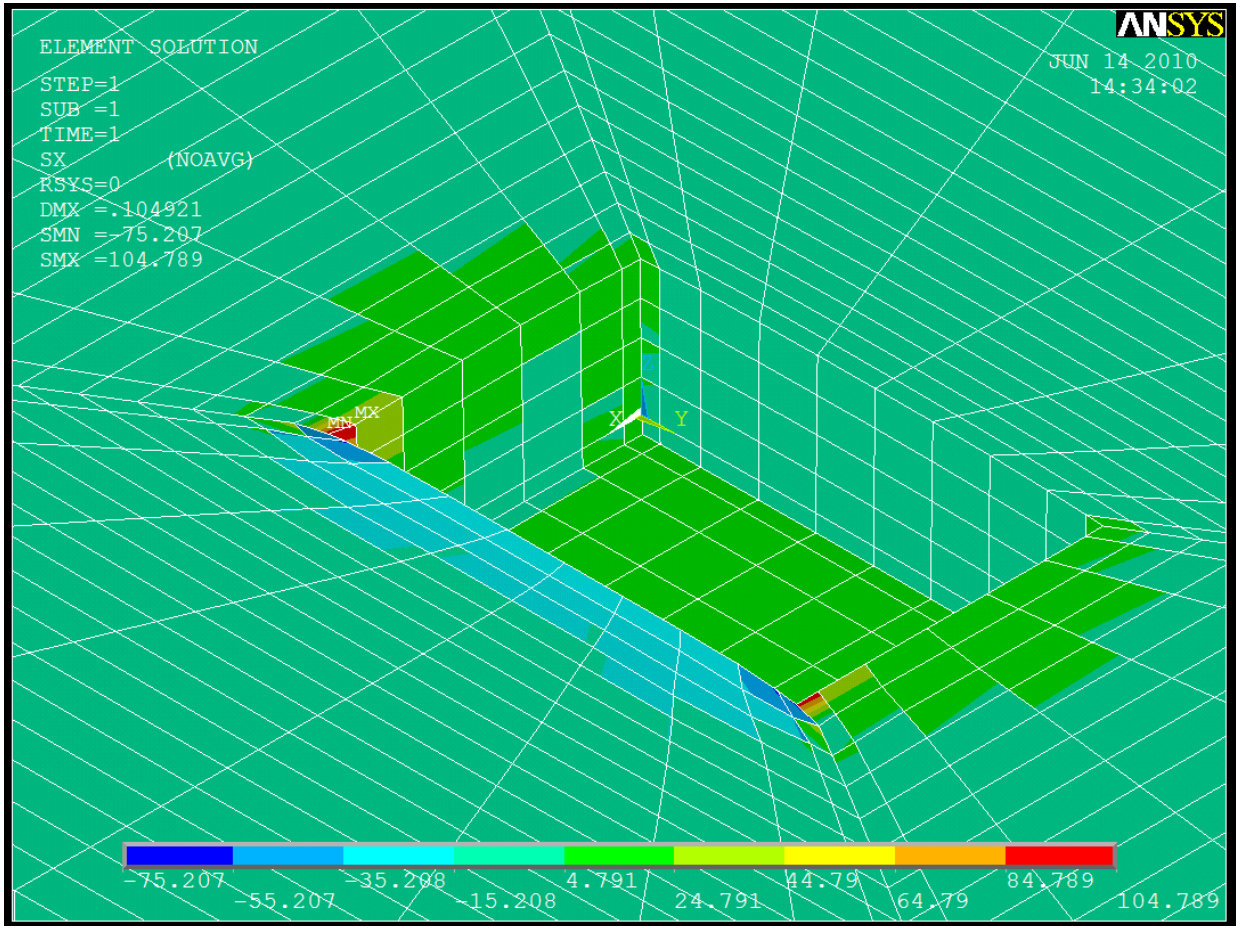


Nonlinear Seismic Soil Pressure Analysis

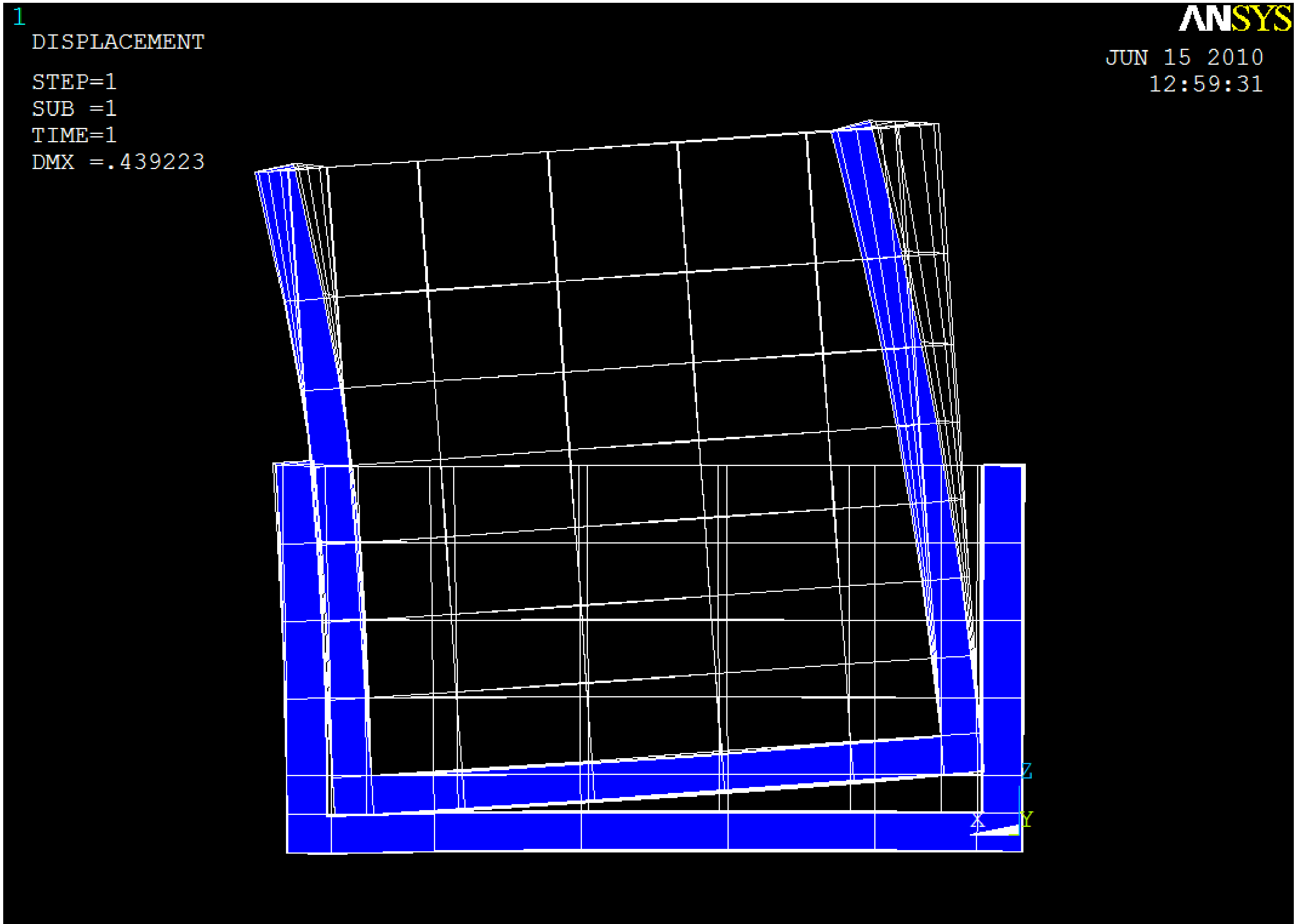
NONLINEAR CONTACT

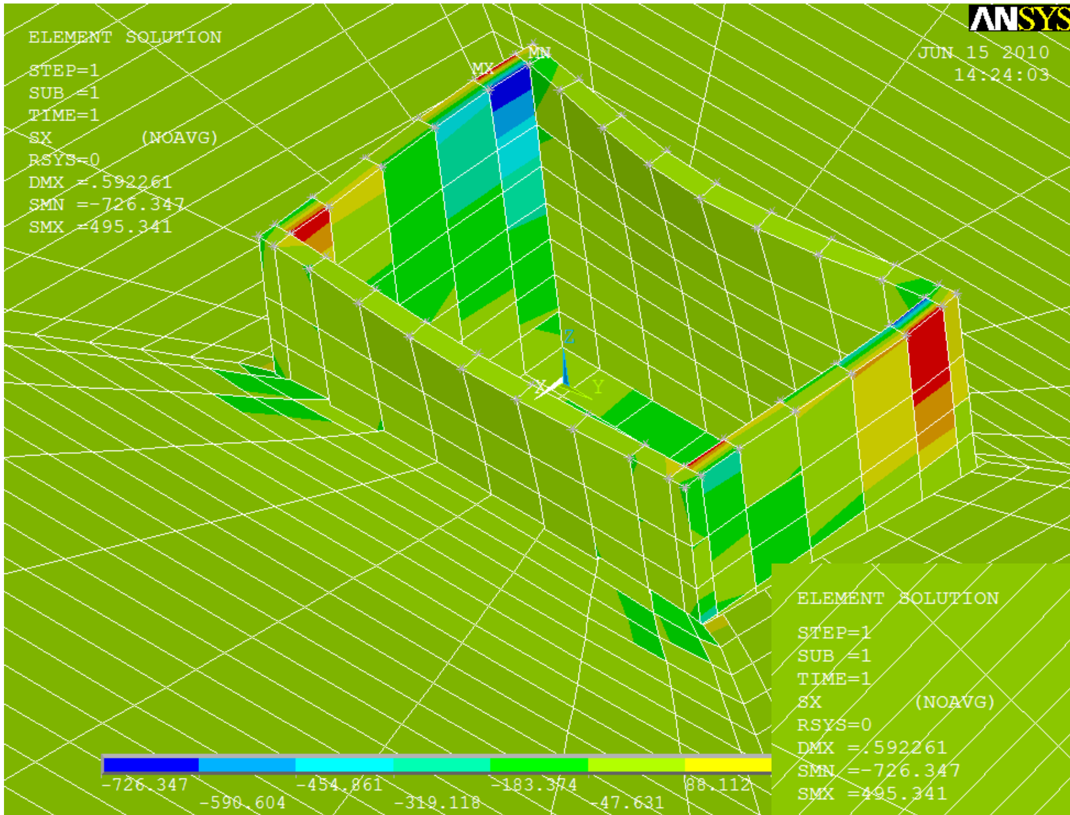
(FOUNDATION SEPARATION)

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



Nonlinear Seismic Soil Pressure Analysis

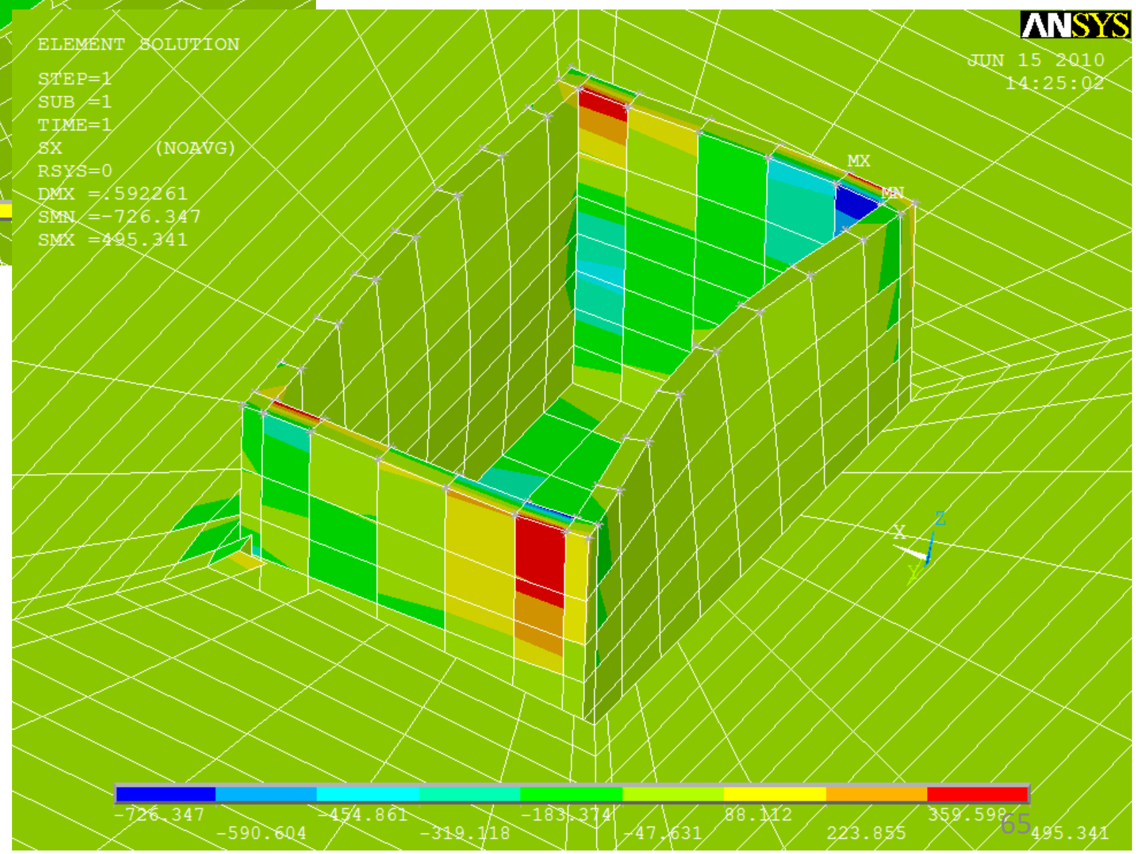




Element Stresses Von Misses

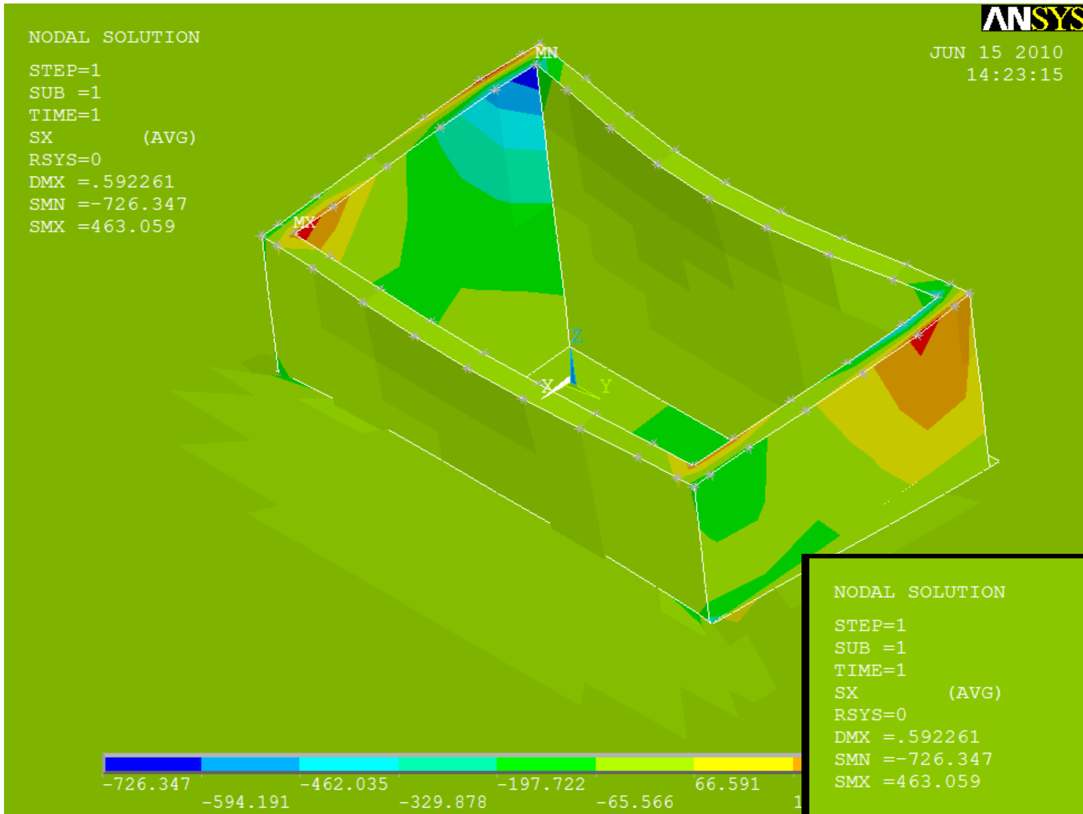
Compression Side View

Tension Side View

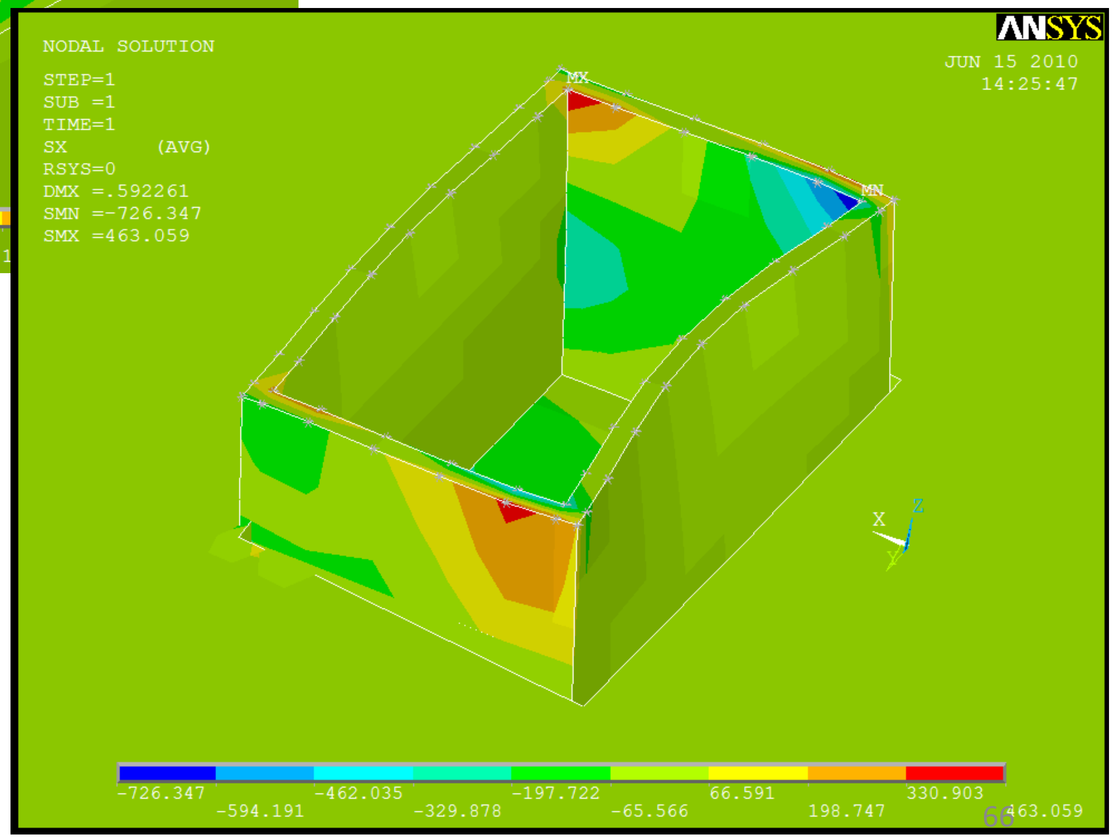


Average Nodal Stresses Von Misses

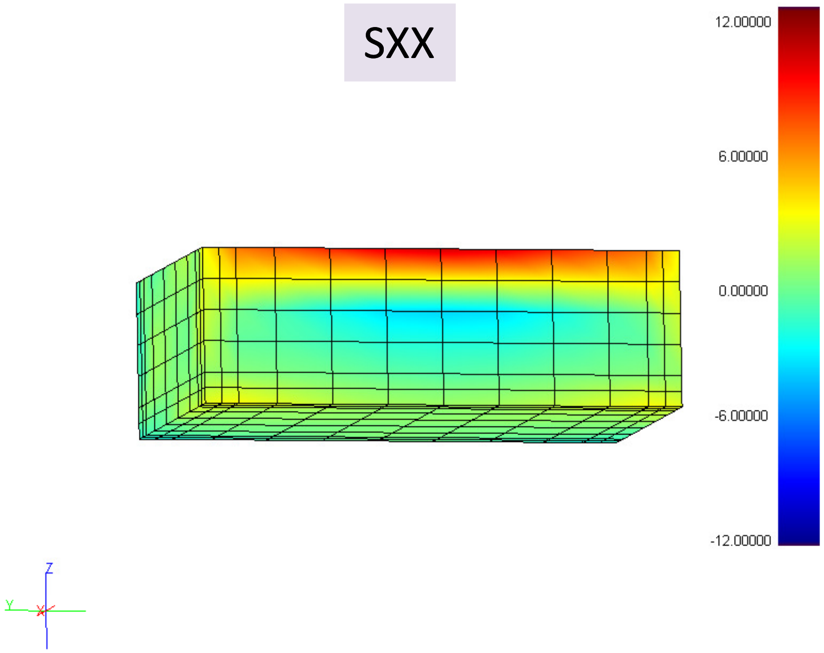
Compression Side View

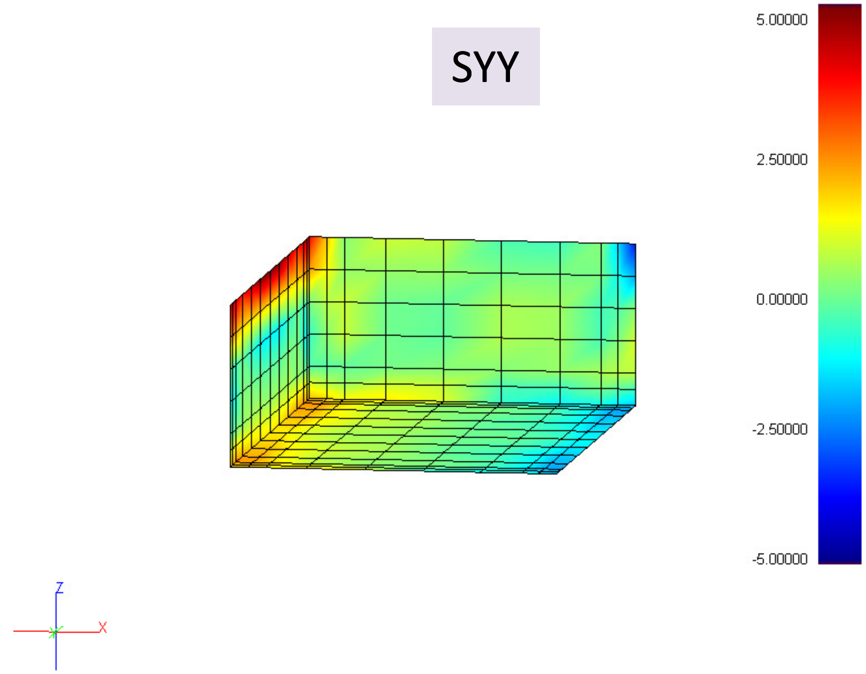


Tension Side View

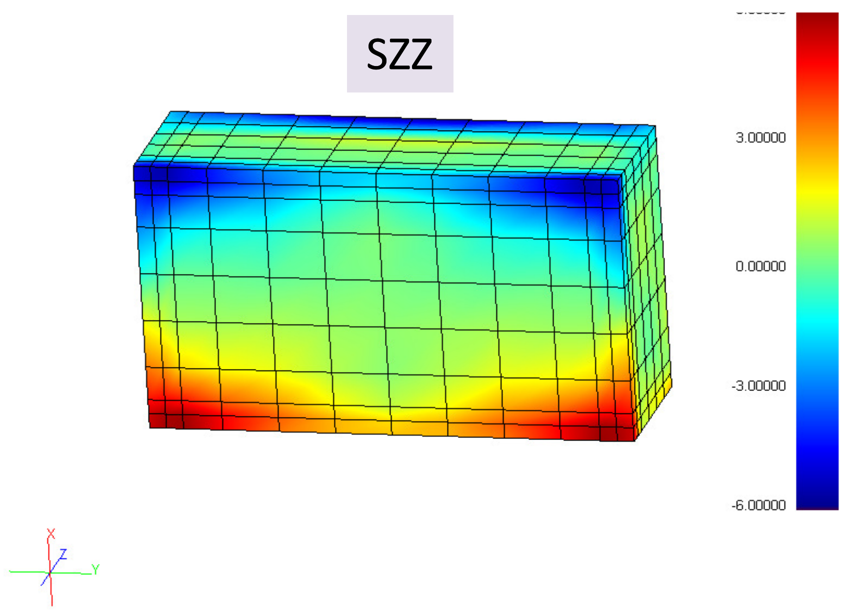


ACS SASSI Seismic Soil Pressures for X-Input (Frame 903)



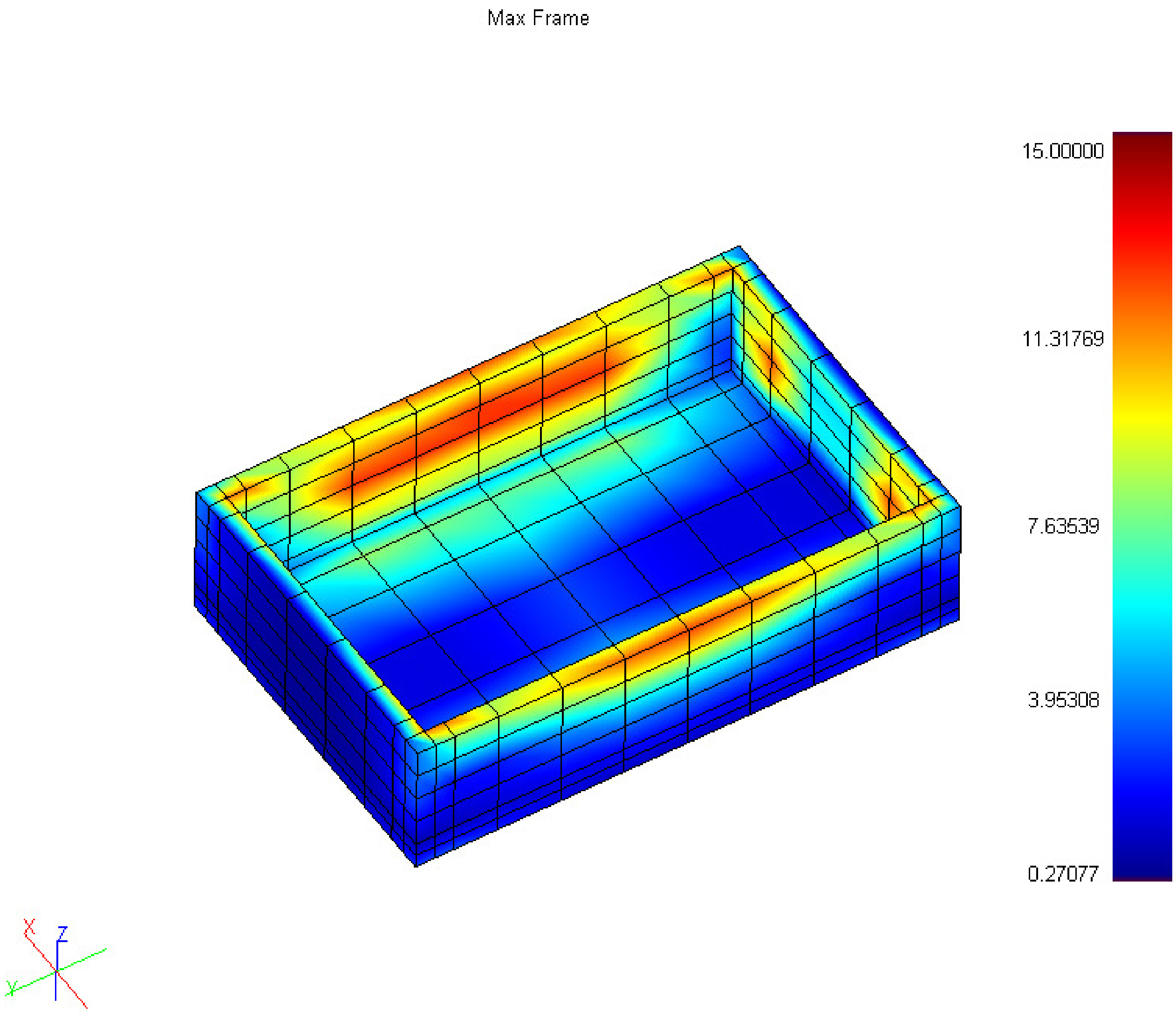


Linear SSI Analysis



ACS SASSI Maximum Seismic Soil Pressures for X-Input

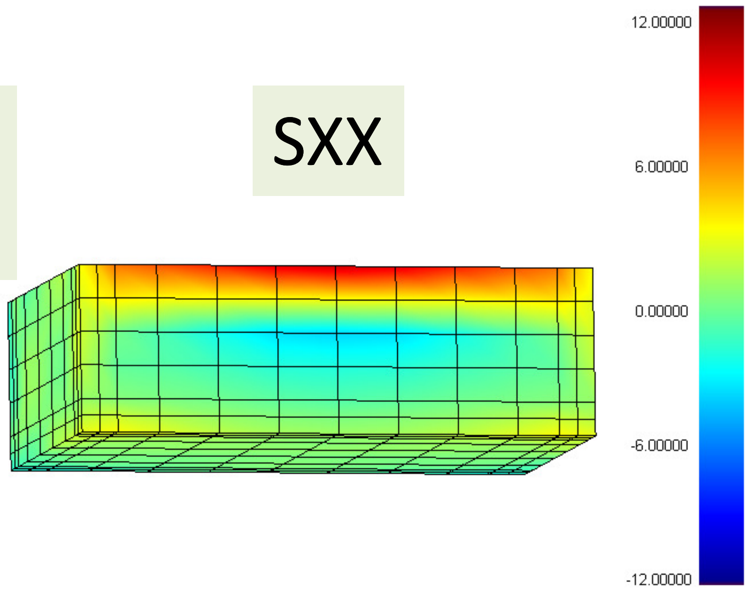
Nodal SXX Stress Contours in Adjacent Soil Elements



ACS SASSI Seismic Soil Pressures for X-Input (Frame 903)

ACS SASSI
Element Center
Stress

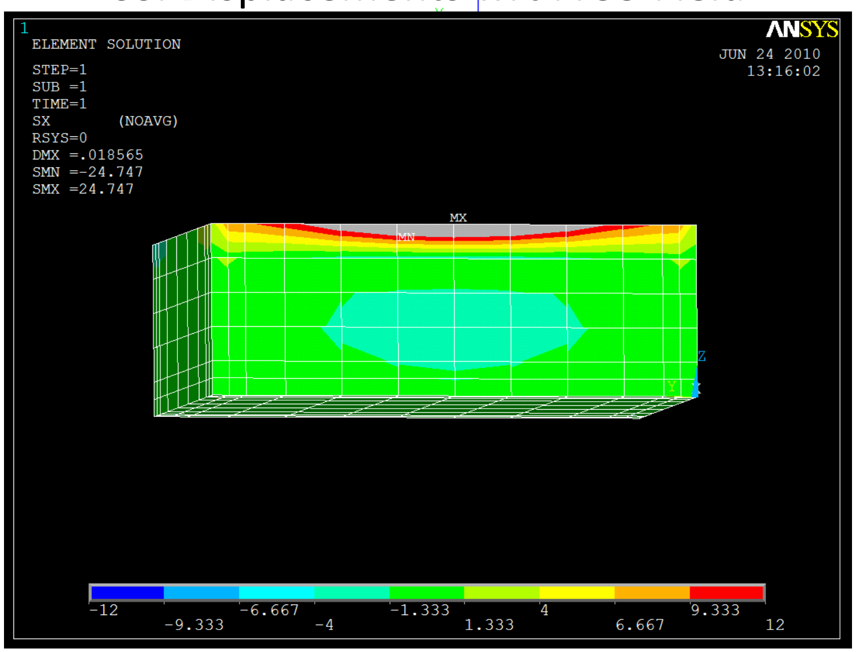
SXX



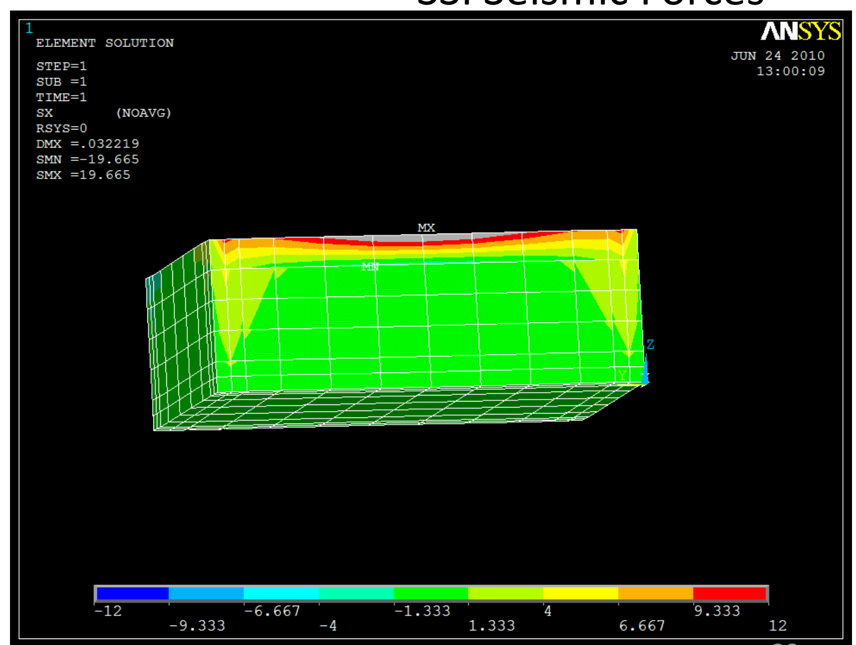
Linear SSI Analysis

ANSYS
Element Node
Stress

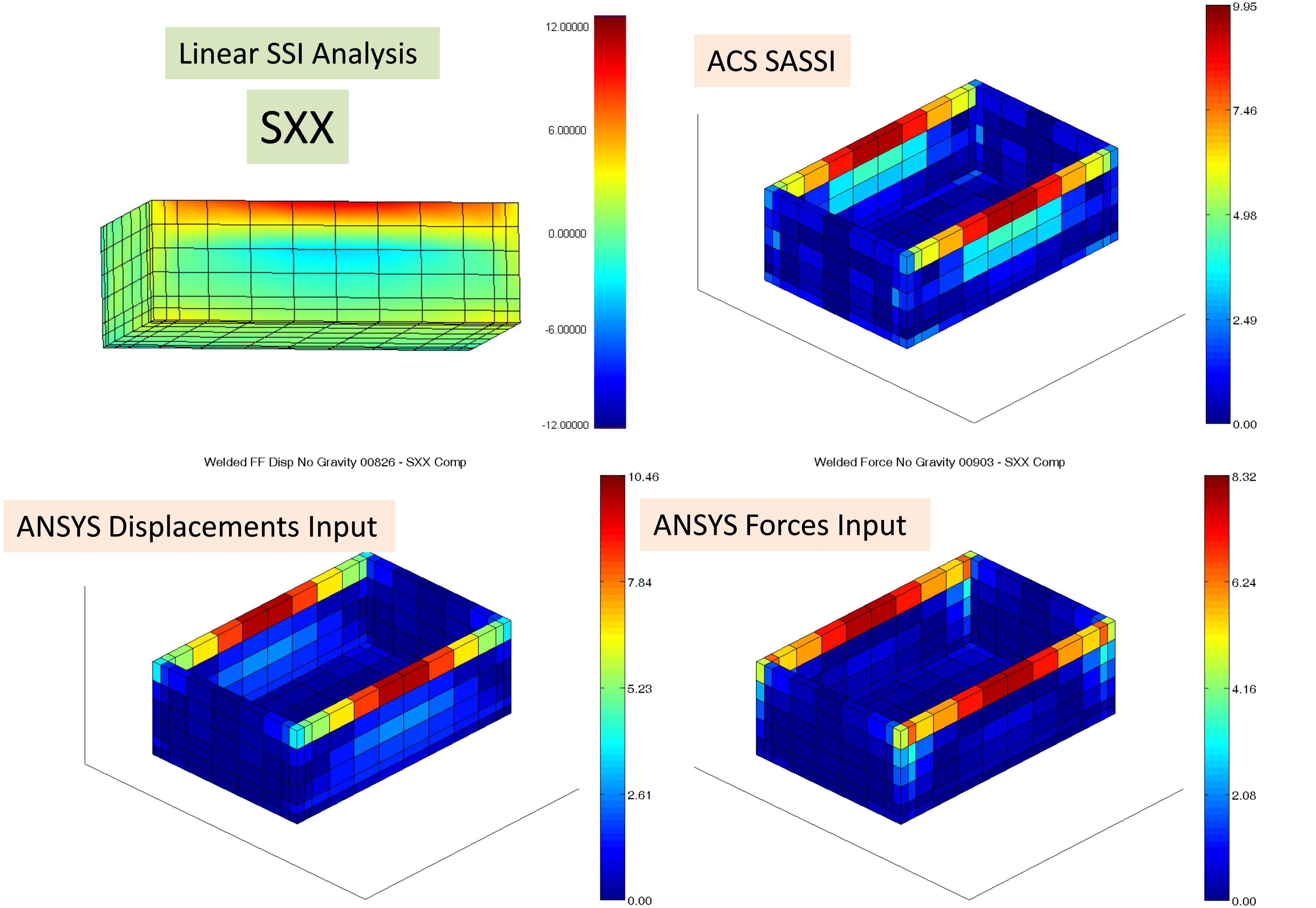
SSI Displacements wrt Free-Field



SSI Seismic Forces



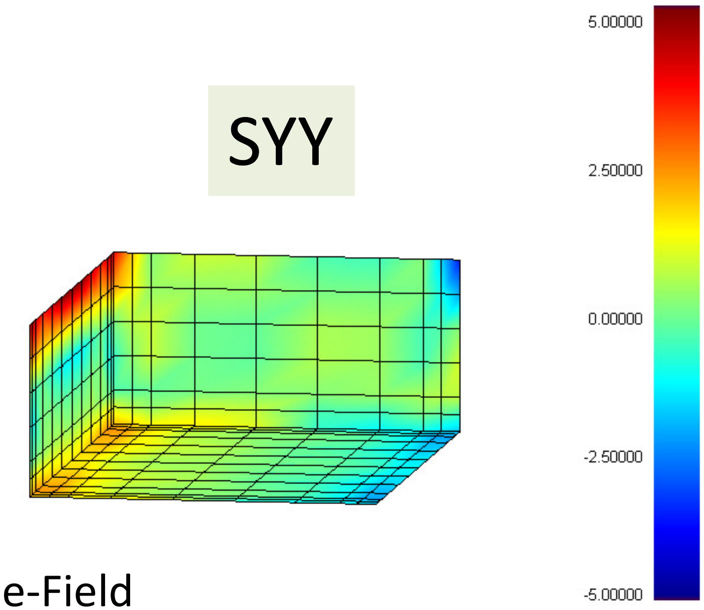
ACS SASSI and ANSYS Element Stresses for X-Input (Frame 903)



ACS SASSI Seismic Soil Pressures for X-Input (Frame 903)

ACS SASSI
Element Center
Stress

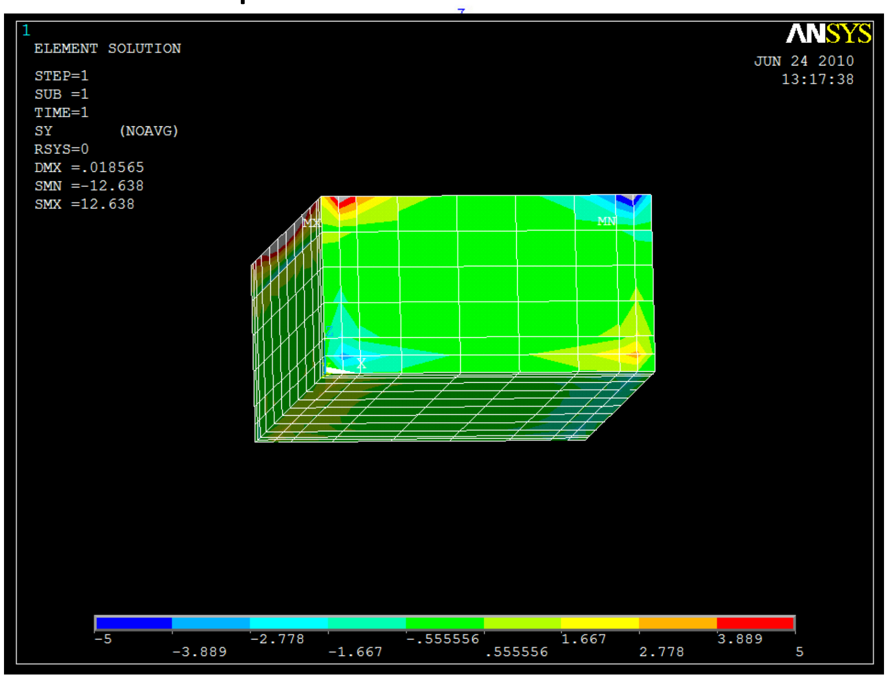
SYY



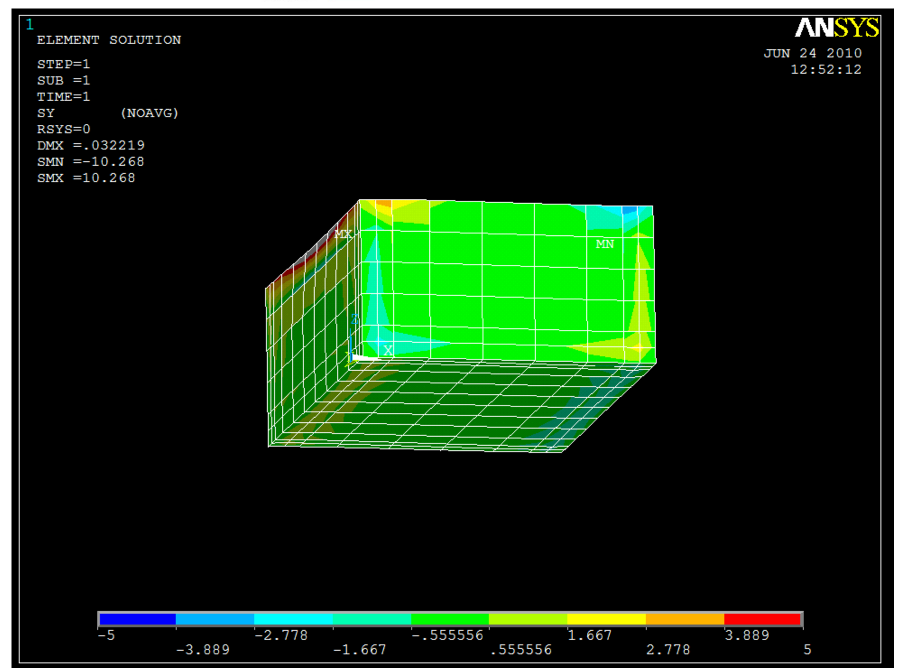
Linear SSI Analysis

ANSYS
Element Node
Stress

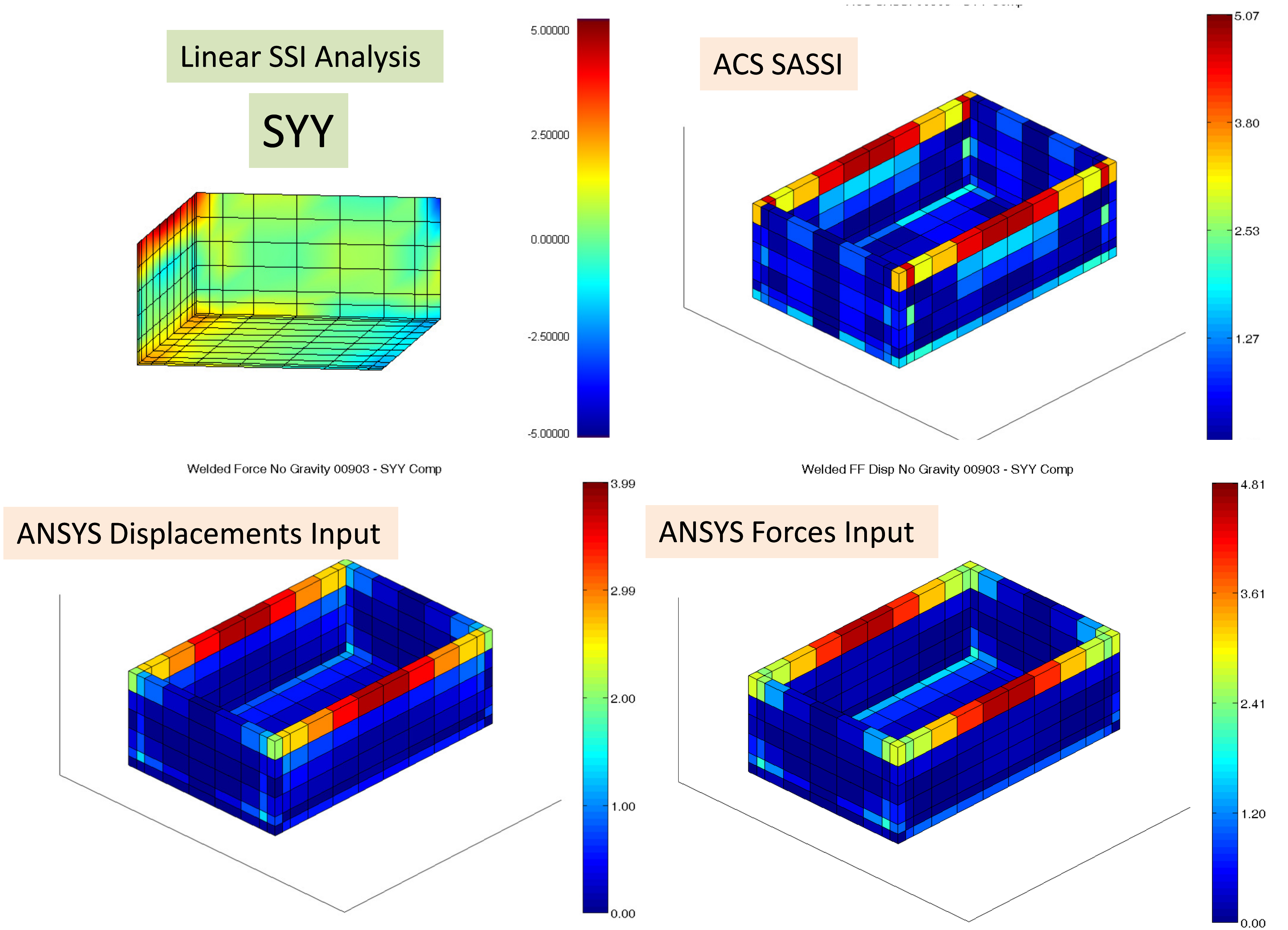
SSI Displacements wrt Free-Field



SSI Seismic Forces



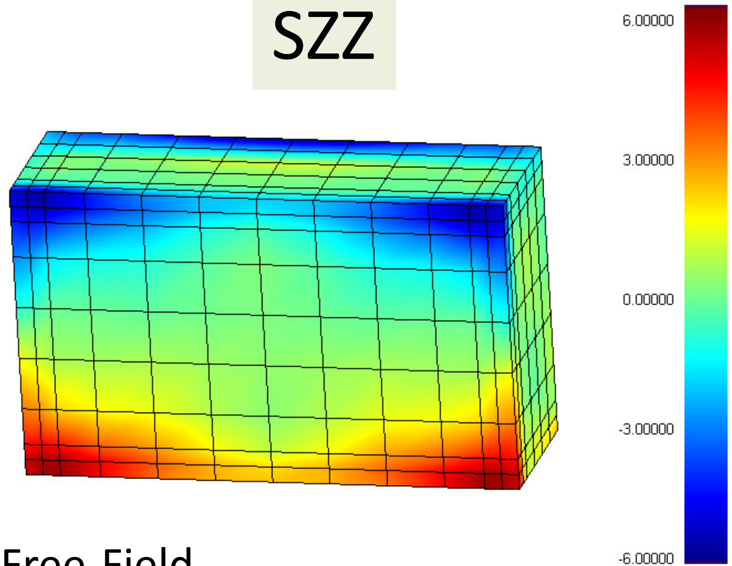
ACS SASSI and ANSYS Element Stresses for X-input (Frame 903)



ACS SASSI Seismic Soil Pressures for X-Input (Frame 903)

SZZ

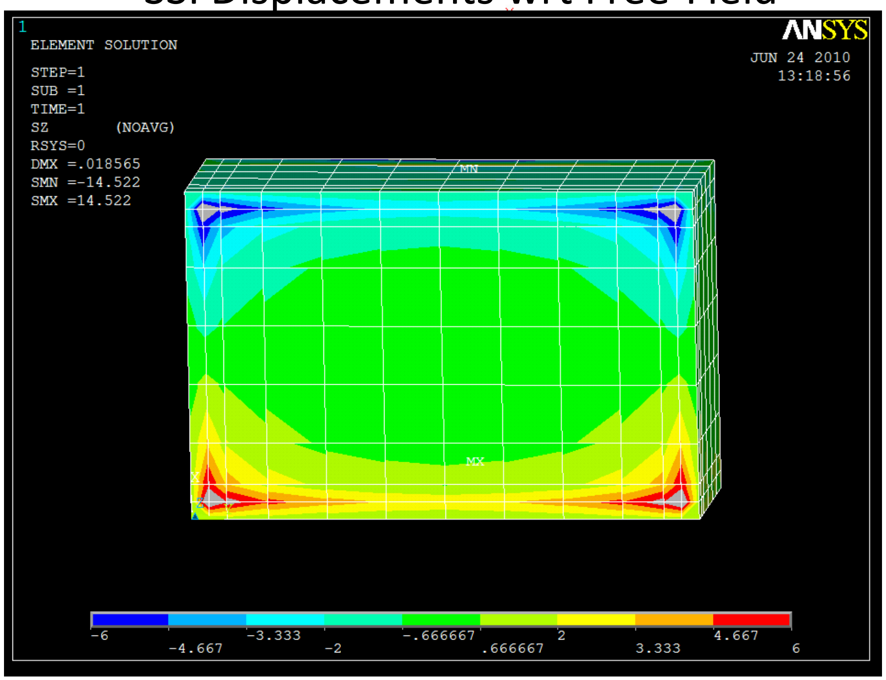
ACS SASSI
Element Center
Stress



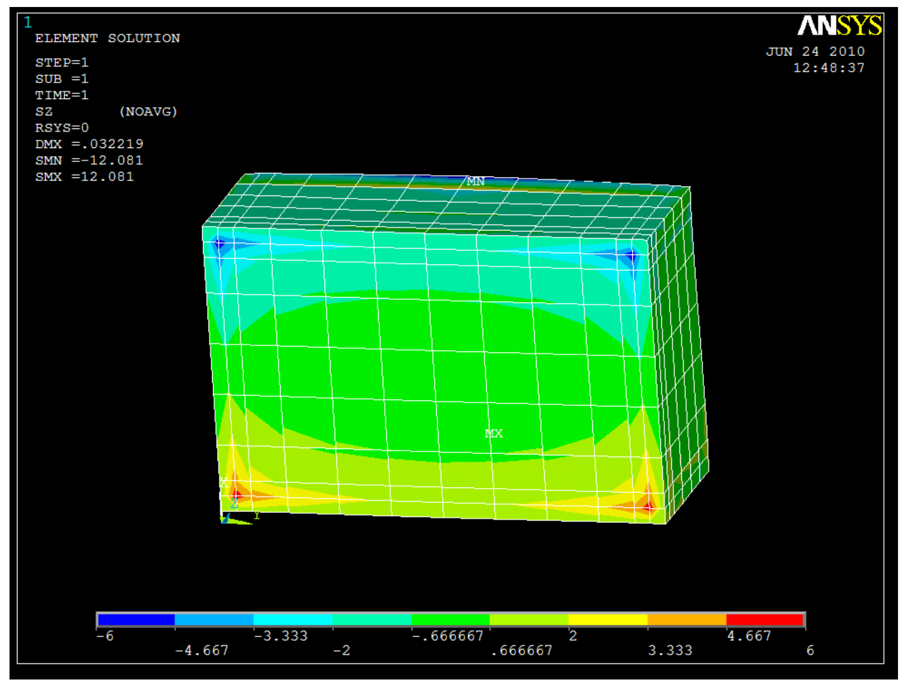
Linear SSI Analysis

ANSYS
Element Node
Stress

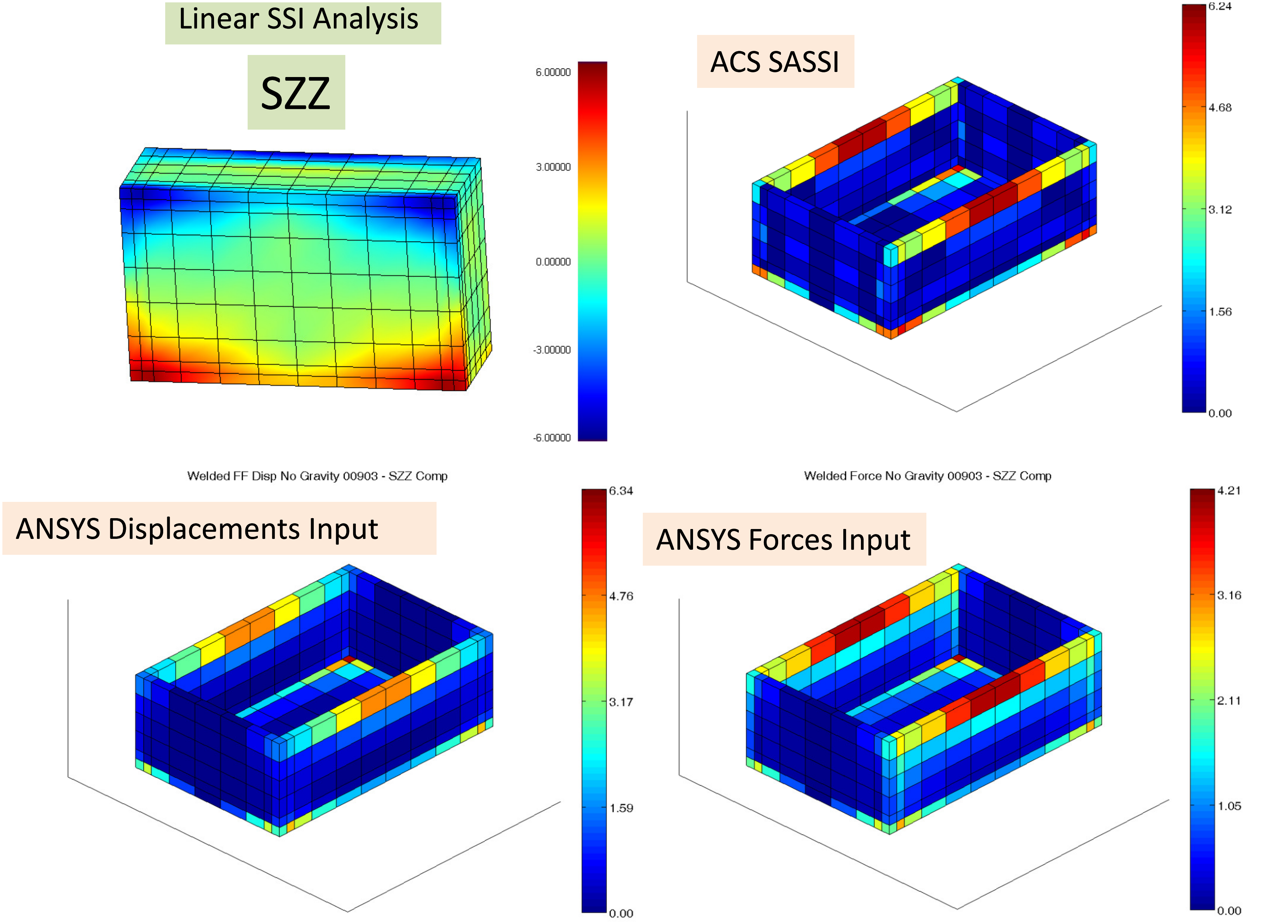
SSI Displacements wrt Free-Field



SSI Seismic Forces

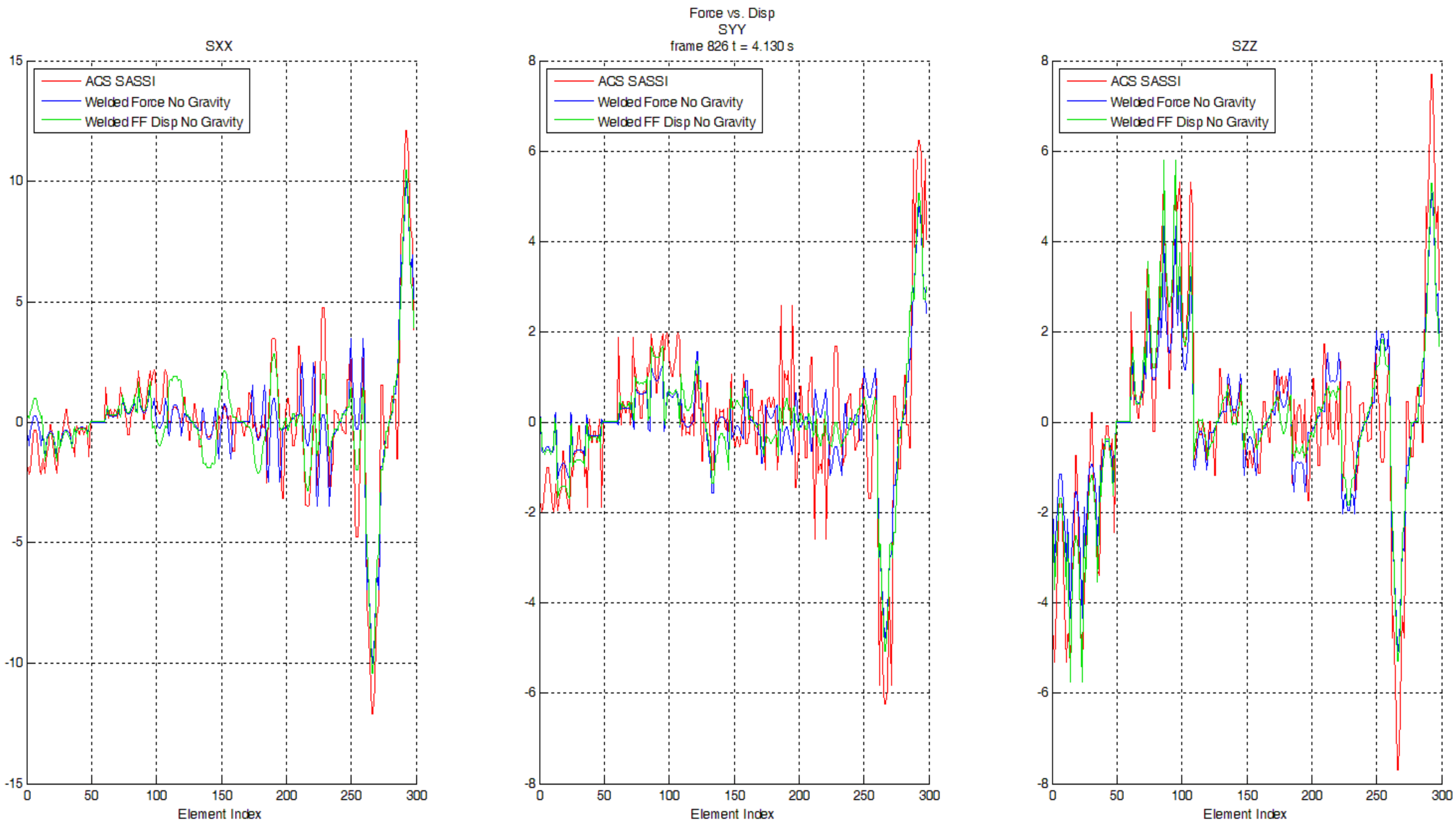


ACS SASSI and ANSYS Element Stresses for X-Input (Frame 903)



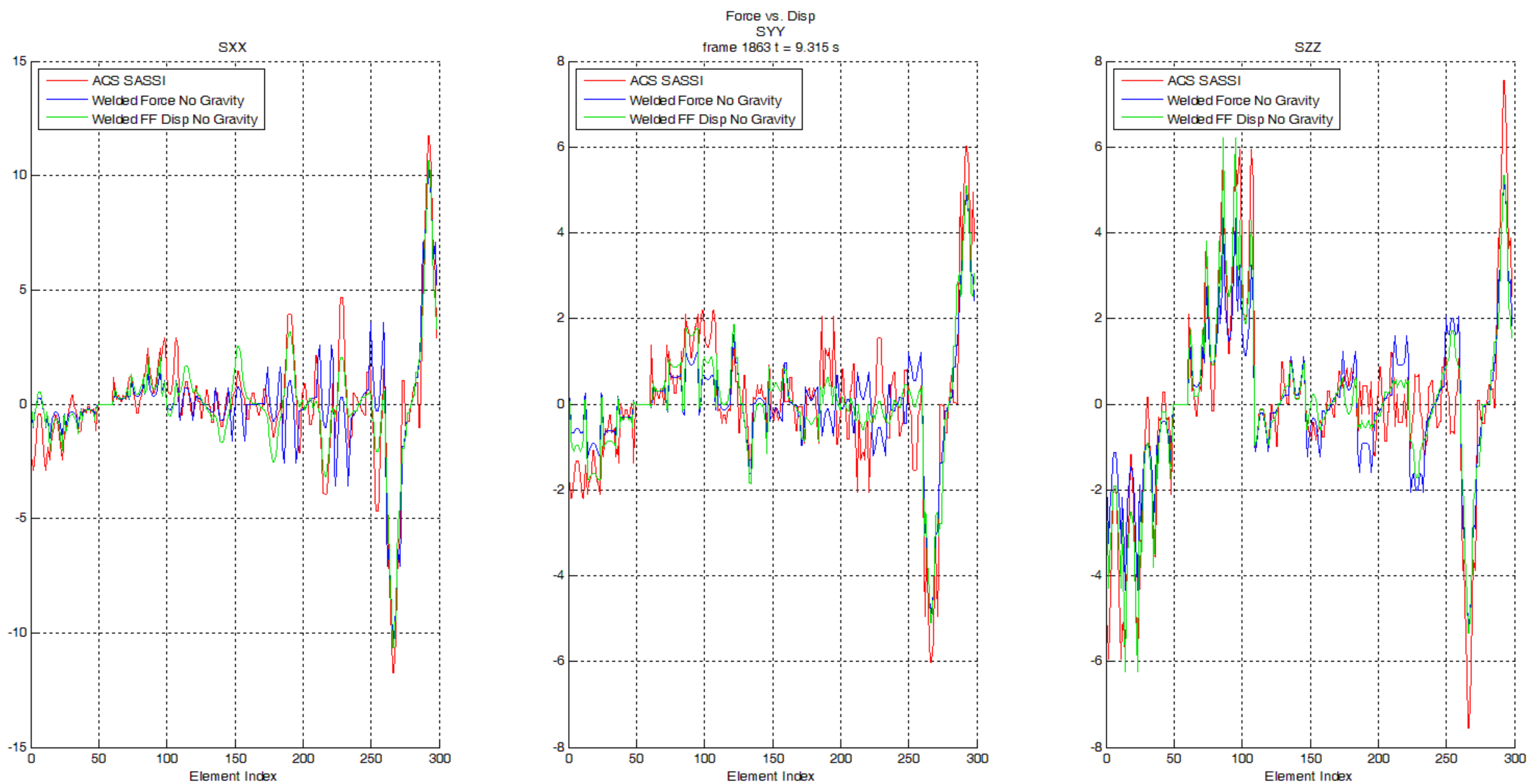
ACS SASSI Seismic Pressures for X-Input (Frame 826)

ACS SASSI vs. ANSYS Equiv. Static Displacements with Free-Field and Seismic Forces
Element Center Stresses SXX, SYY, SZZ



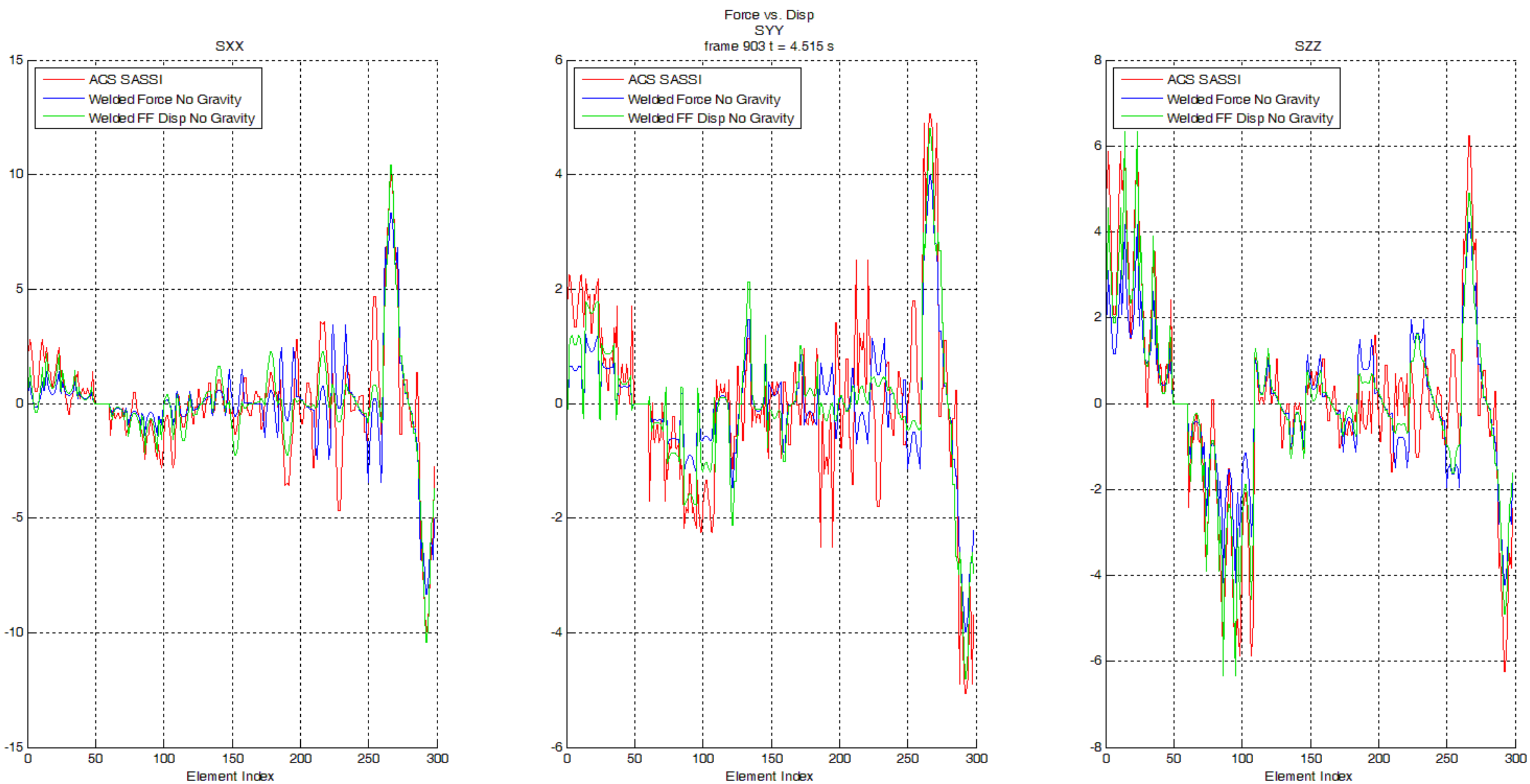
ACS SASSI Seismic Pressures for X-Input (Frame 1863)

ACS SASSI vs. ANSYS Equiv. Static Displacements with Free-Field and Seismic Forces
Element Center Stresses SXX, SYY, SZZ



ACS SASSI Seismic Pressures for X-Input (Frame 903)

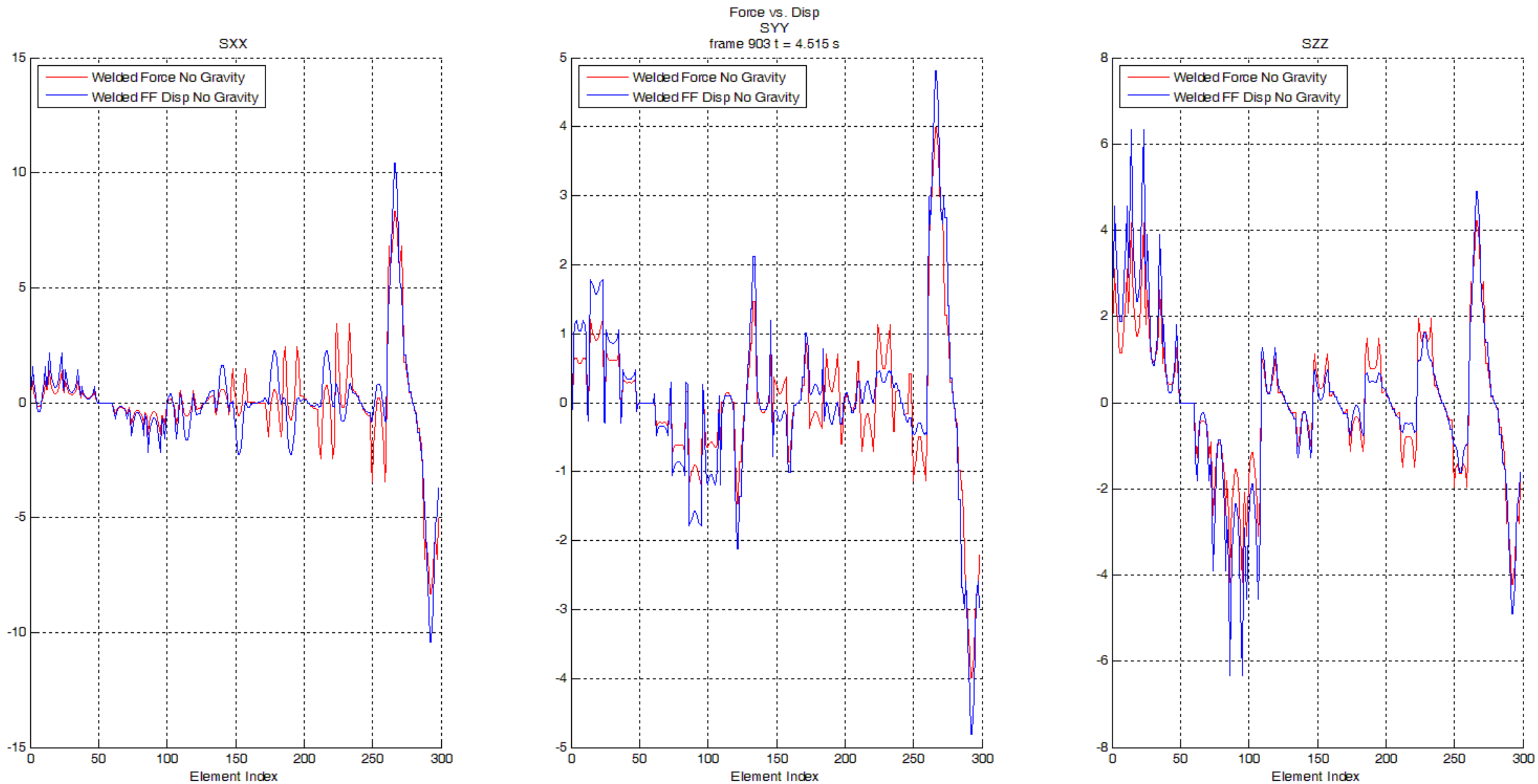
ACS SASSI vs. ANSYS Equiv. Static Displacements with Free-Field and Seismic Forces
Element Center Stresses SXX, SYY, SZZ



ANSYS Equivalent-Static Seismic Stresses for X-Input (Frame 903)

ANSYS Rel. Displacements wrt Free-Field vs. ANSYS Equiv. Static Seismic Forces

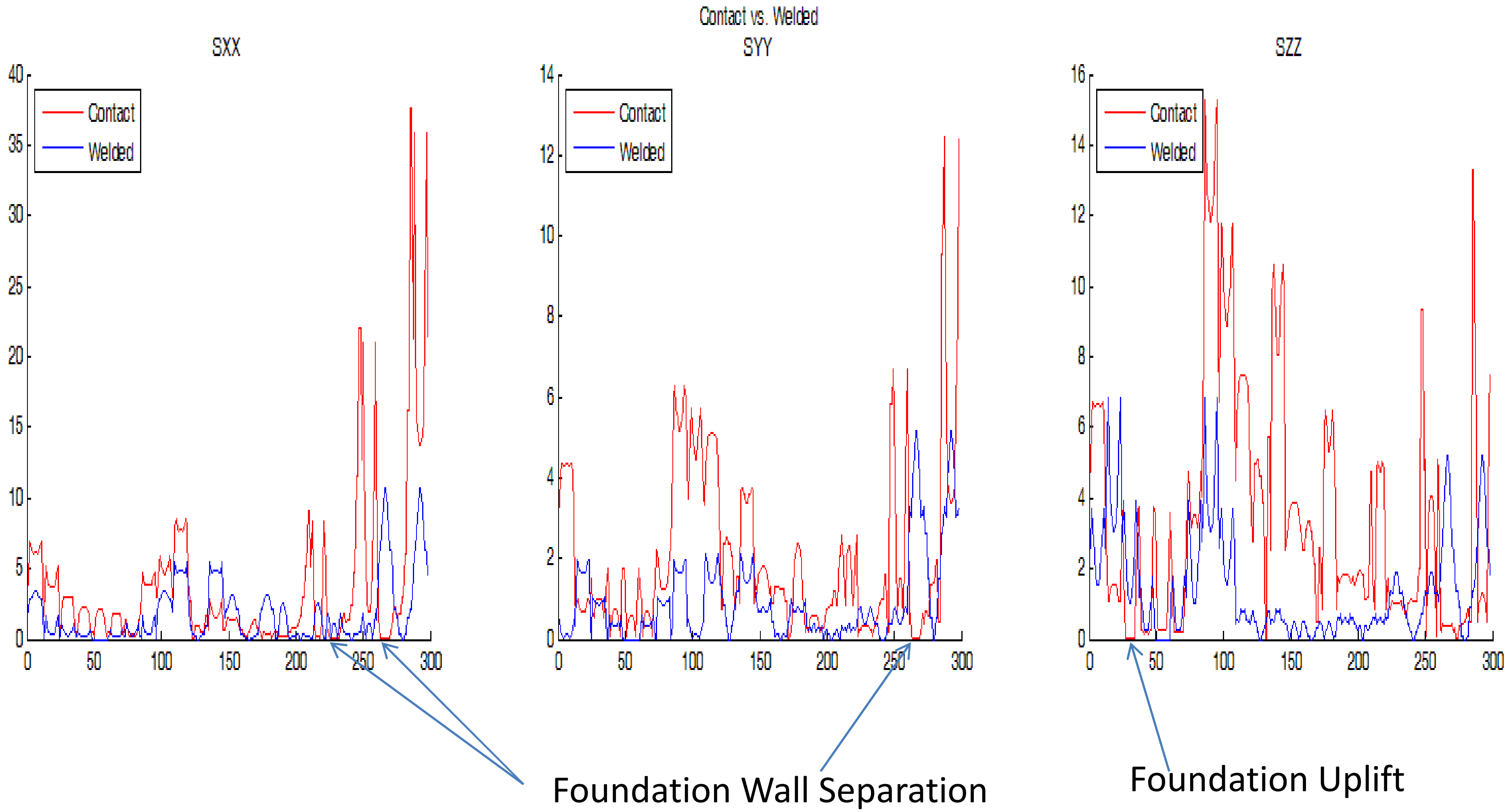
Element Center Stresses SXX, SYY, SZZ



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

ANSYS Equivalent-Static Seismic Force Loading Option

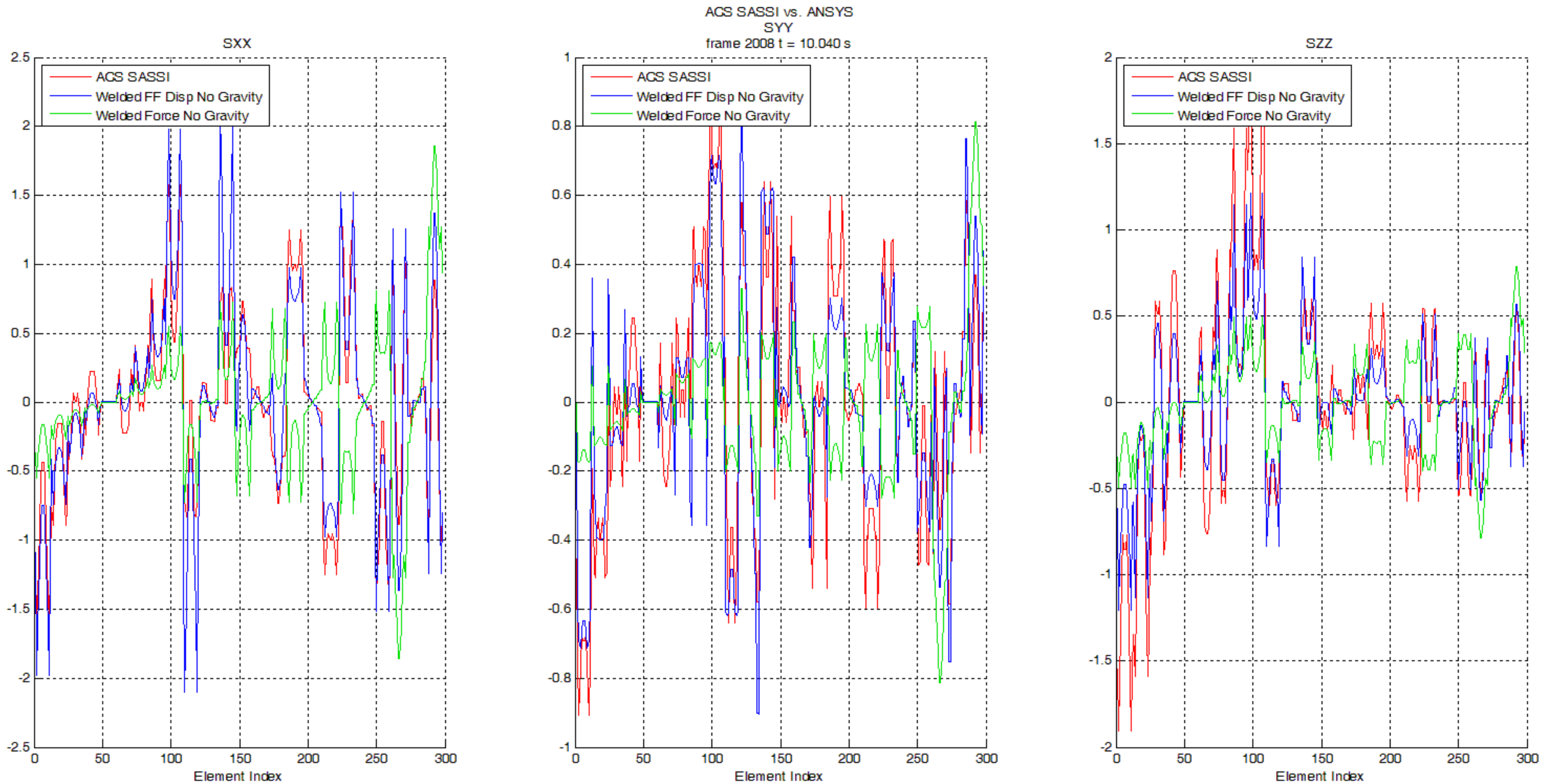
Absolute Values of Element Center Stresses SXX, SYY, SZZ



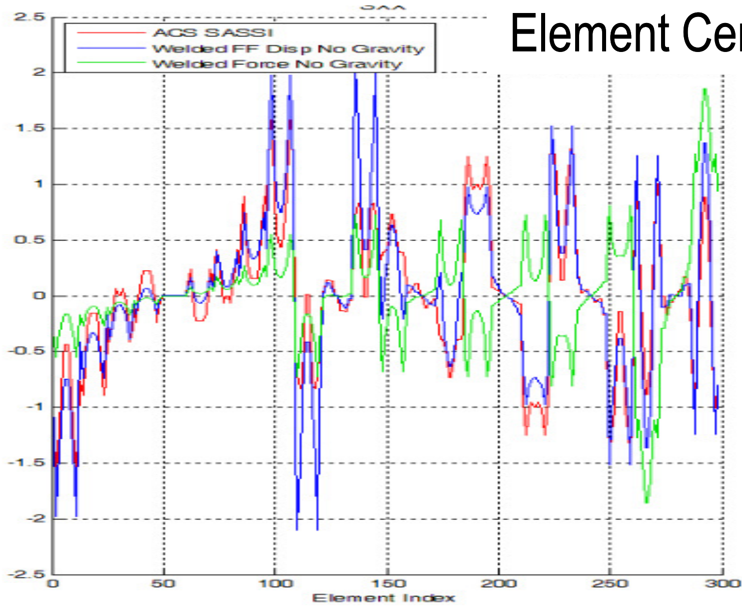
No Mass Box Seismic Stresses for X-Input (Frame 2008)

Half-space Soil Vs=1,000 vs. Backfill Soil Vs = 1,000 on Rock Vs = 5,500fps

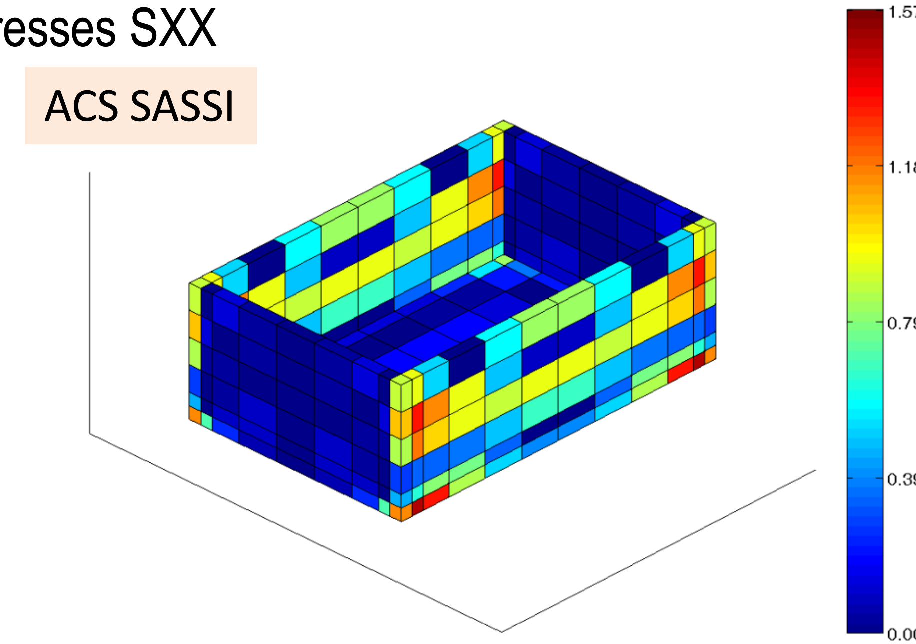
Element Center Stresses SXX, SYY and SZZ

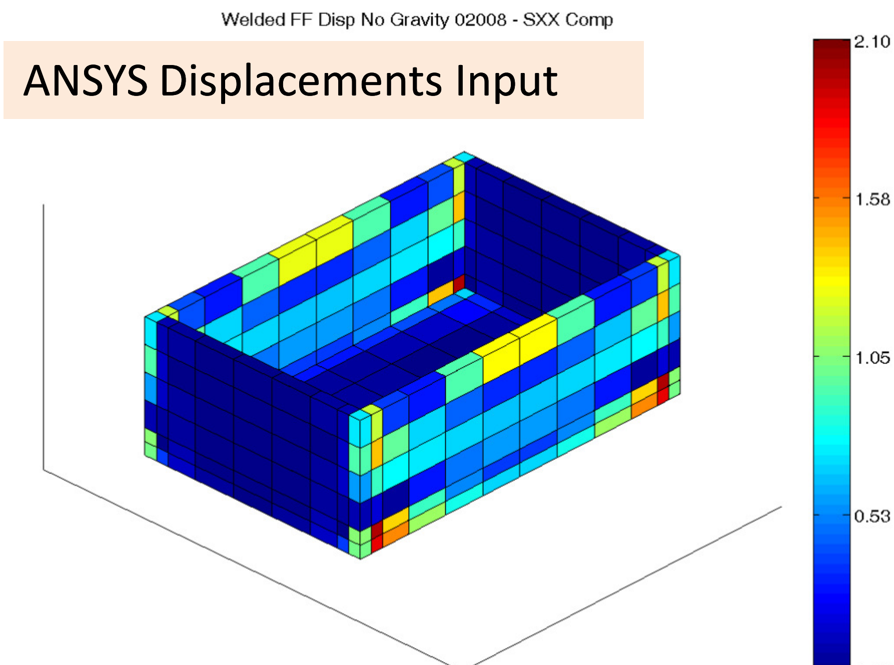


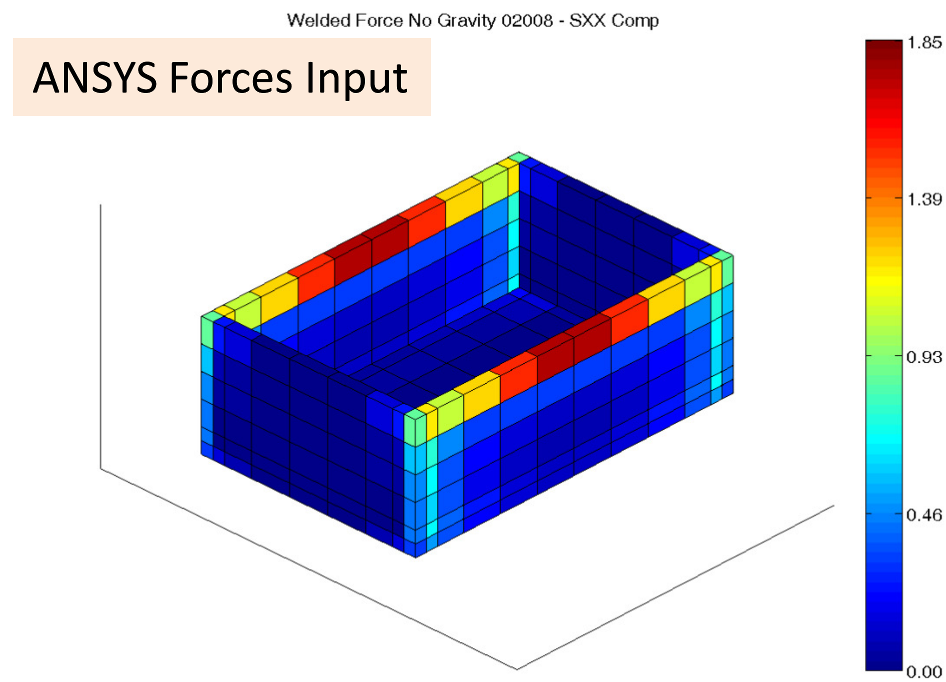
No Mass Box Seismic Stresses for X-Input (Frame 2008)



Element Center Stresses SXX



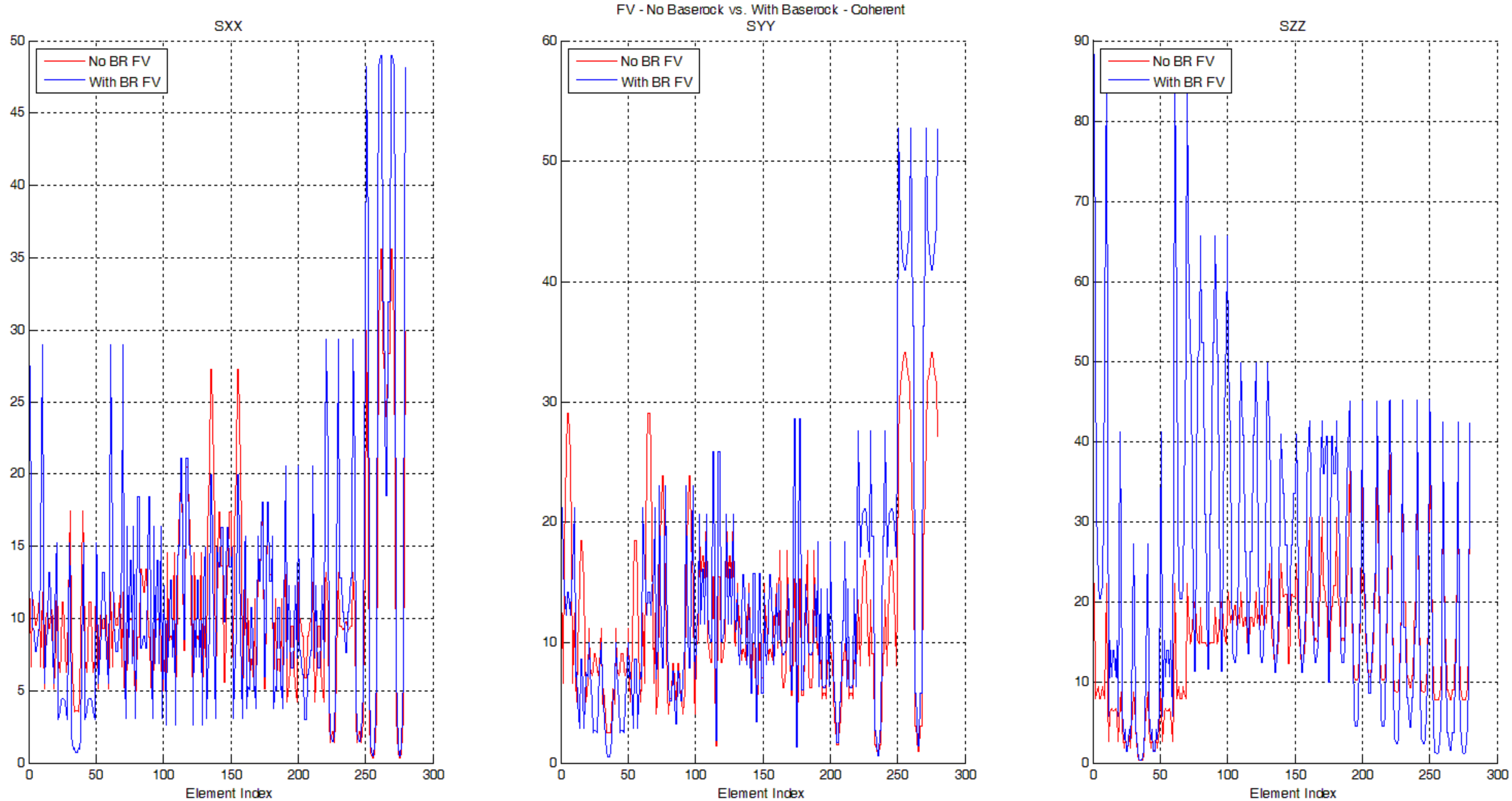




Seismic Pressures for X-Input (Frame 903) Using FV method

Half-space Soil Vs=1,000 vs. Backfill Soil Vs = 1,000 on Rock Vs = 5,500 fps

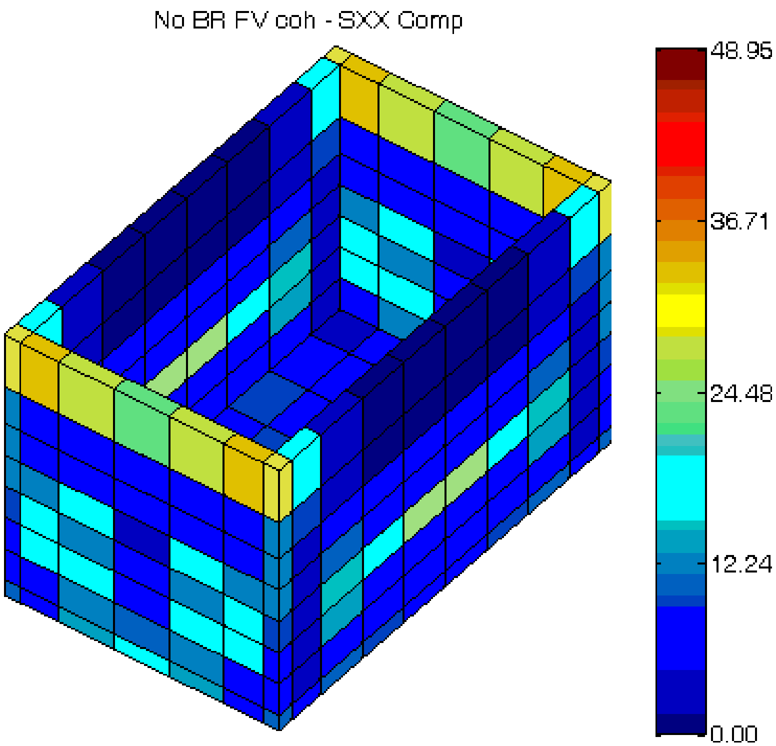
Element Center Stresses SXX, SYY and SZZ



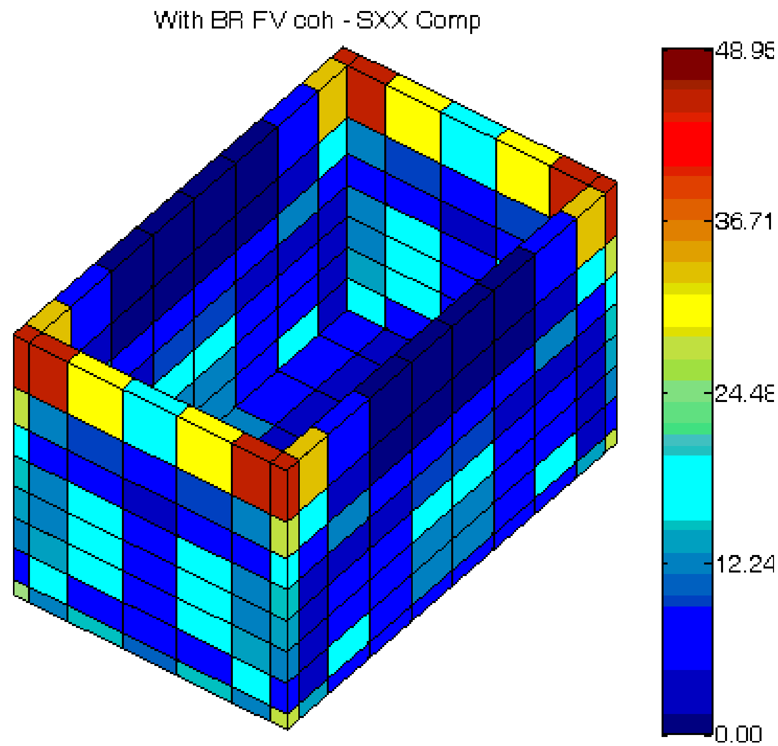
Seismic Stresses for X-Input (Frame 903) Using FV method

Half-space Soil Vs=1,000 vs. Backfill Soil Vs = 1,000 on Rock Vs = 5,500fps

Element Center Stresses SXX



Half-space

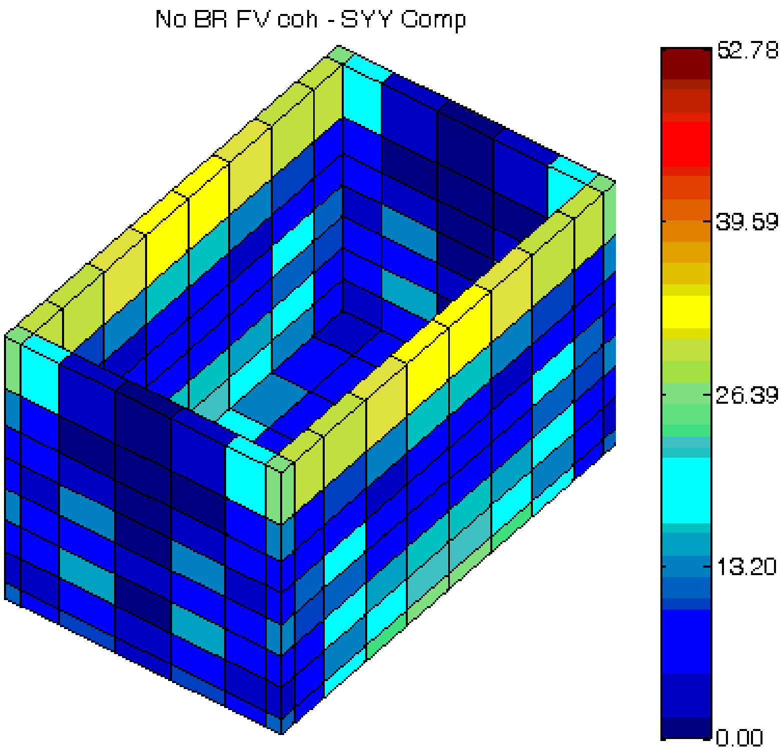


Baserock

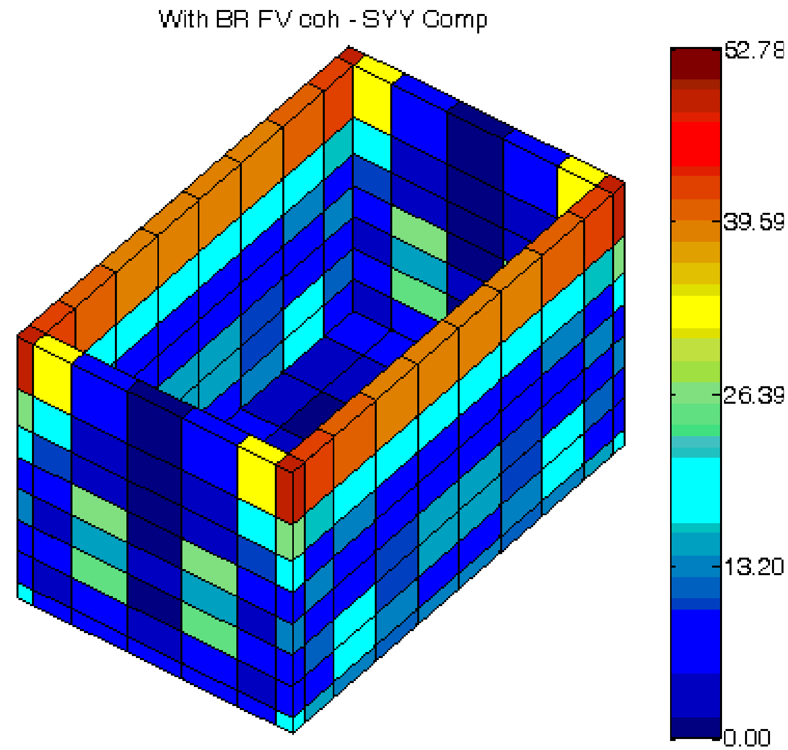
Seismic Stresses for X-Input (Frame 903) Using FV method

Half-space Soil Vs=1,000 vs. Backfill Soil Vs = 1,000 on Rock Vs = 5,500fps

Element Center Stresses SYY



Half-space

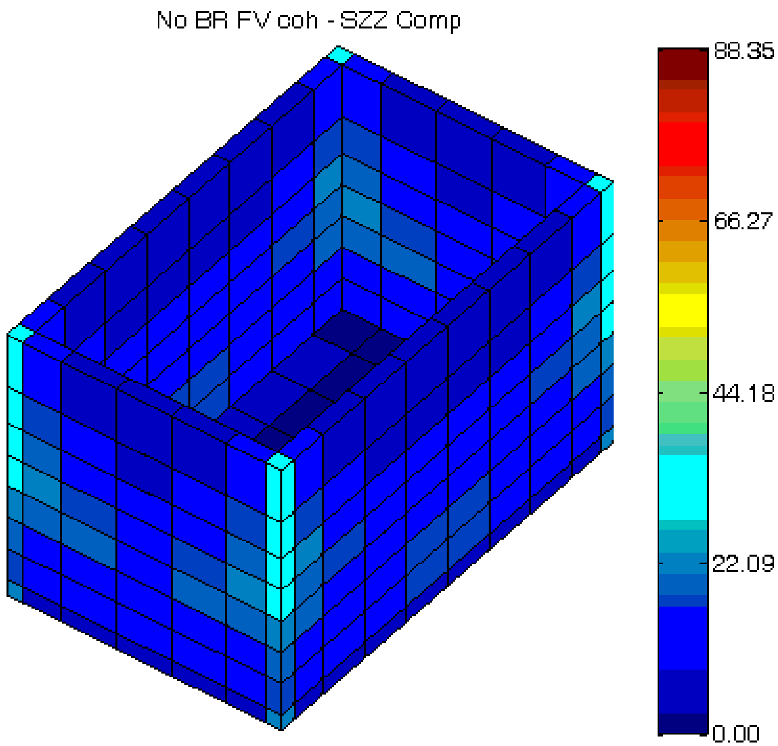


Baserock

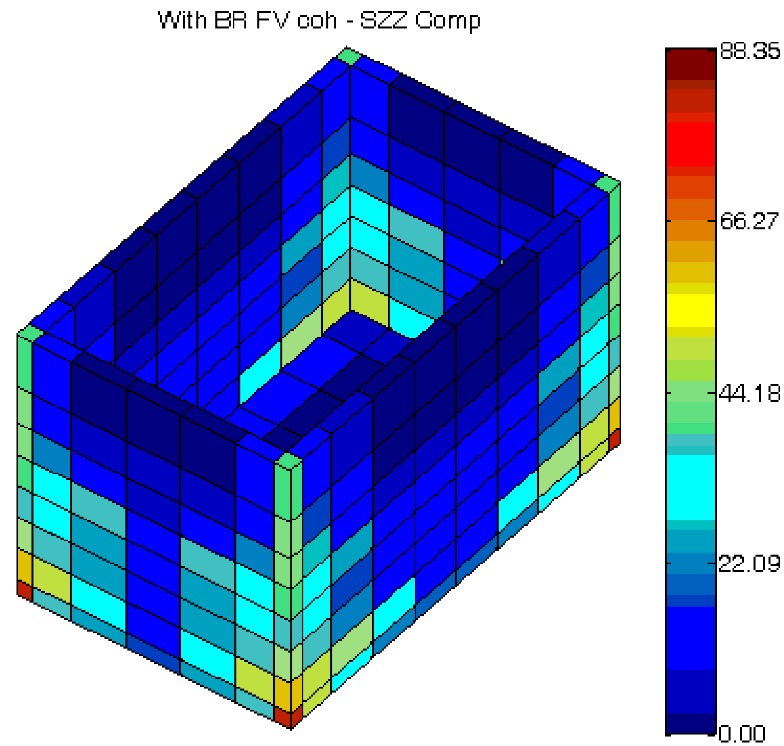
Seismic Stresses for X-Input (Frame 903) Using FV method

Half-space Soil Vs=1,000 vs. Backfill Soil Vs = 1,000 on Rock Vs = 5,500fps

Element Center Stresses SZZ



Half-space



Baserock