ACS SASSI NQA Advances on Seismic SSI Analysis of NPP Structures Using Best Practices in US and Japan

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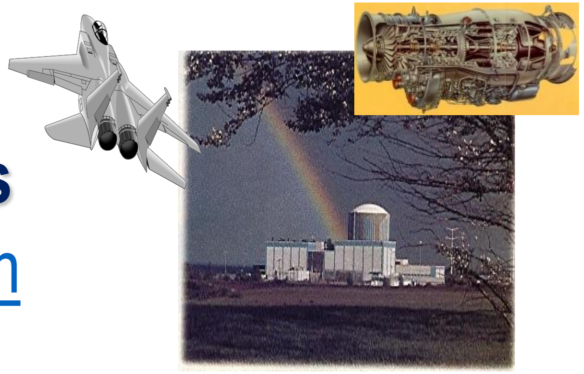


Day 2: Nonlinear Seismic SSI Analysis Based on Best Practices in US and Japan
1-Option UPLIFT Nonlinear Uplift SSI Analysis Per JEAC 4601 Standard

ACS SASSI Workshop, Tokyo
December 2-3, 2021

ACKNOWLEDGEMENT

The development of the new ACS SASSI UPLIFT and NON Advanced and options per Japan JEAC 4601-2015 standard recommendations were developed for almost three years of very intense development effort.

I am very thankful to:

SHIMIZU leading expert structural engineers, especially to Nitta-san and Ikeda-san, for many tens of hours, if not hundreds of hours by now, of precious time during various technical meetings and hundreds of email discussions over these last three years

TERRABYTE for the great support of many thousands of hours per year for last three years for testing the new UPLIFT and NON Advanced options, helping with our Japanese language understanding, and interacting with Japanese industry users of ACS SASSI, especially to Niwa-san, Horiguchi-san, Sugiyama-san, Kanawabe-san, Shono-san, and many others.

1. Option UPLIFT for Foundation Uplift SSI Analysis Per JEAC 4601-2015

(Section 3.5.5.4 and App. 3.6 Requirements)

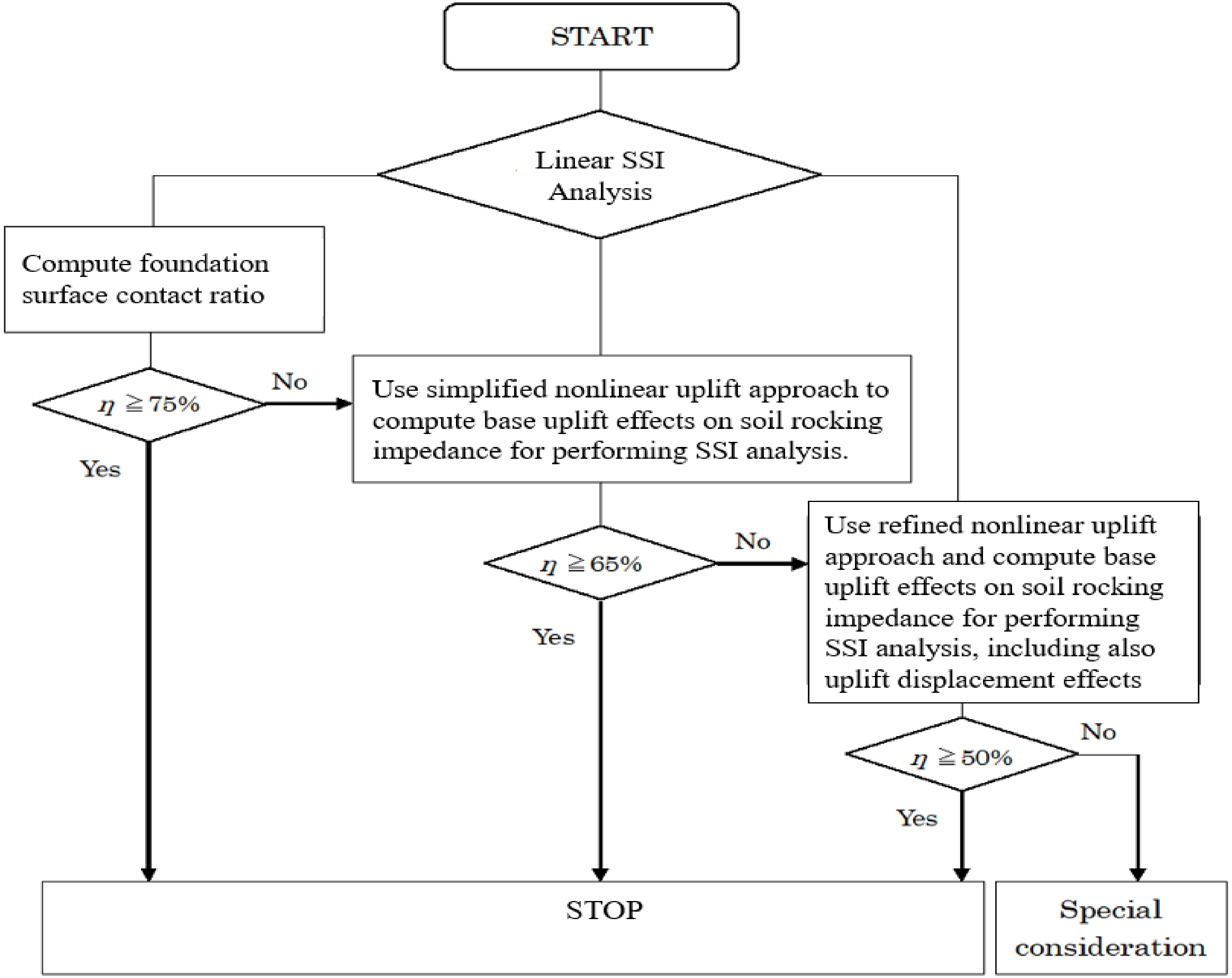
JEAC 4601-2015 Section 3.5.5.4 and App. 3.6

The JEAC 4601-2015 standard [1] recommends two nonlinear uplift approaches applicable based on the basemat uplift severity:

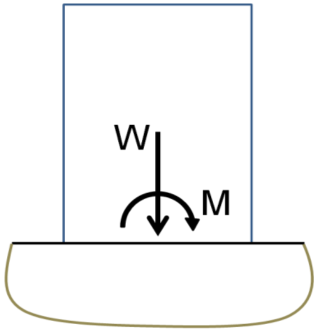
1) A simplified nonlinear uplift approach (Method 1) applicable if the basemat surface contact ratio is in the 65%-75% range, and
2) A refined nonlinear dynamic uplift approach (Method 2) applicable if the surface contact ratio is in the 50%-65% range

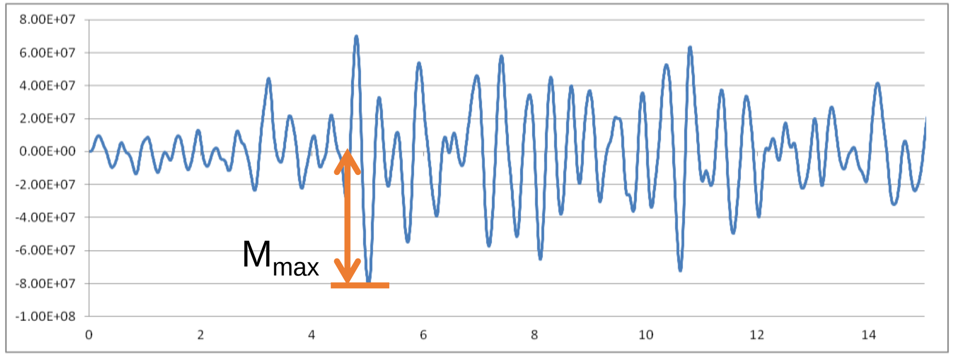
The JEAC 4601-2015 approaches consider the nonlinear foundation uplift effects on the seismic SSI responses based on reducing the base rocking impedances (both stiffness and damping) for the bottom soil under foundation. The more refined nonlinear uplift approach (Method 2) also includes the coupling between the base rocking rotation and the vertical base uplift displacement which could impact significantly on the uplift SSI responses for contact ratios in the 50%-65% range.

JEAC 4601 Contact Ratio Criteria for Seismic Uplift SSI Analysis



Contact Surface Ratio is between 65% and 75%.
Method 1: *Simpler Approach Using Moment Mmax*





M(t) calculated from linear SSI at basemat, M_{max}

SR model assumed

Mo is M value for which uplift occurs at base edge

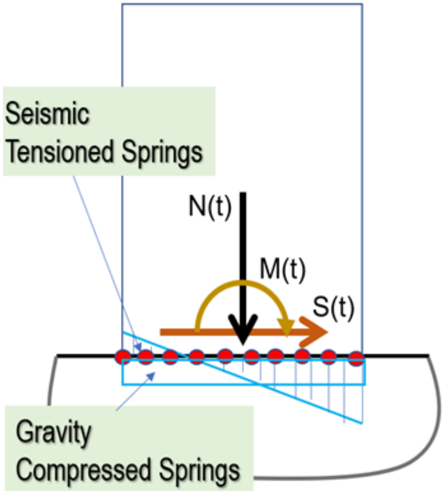
$$M_0 = \frac{W\ L}{\alpha}$$

α = 4.7 or 6.0

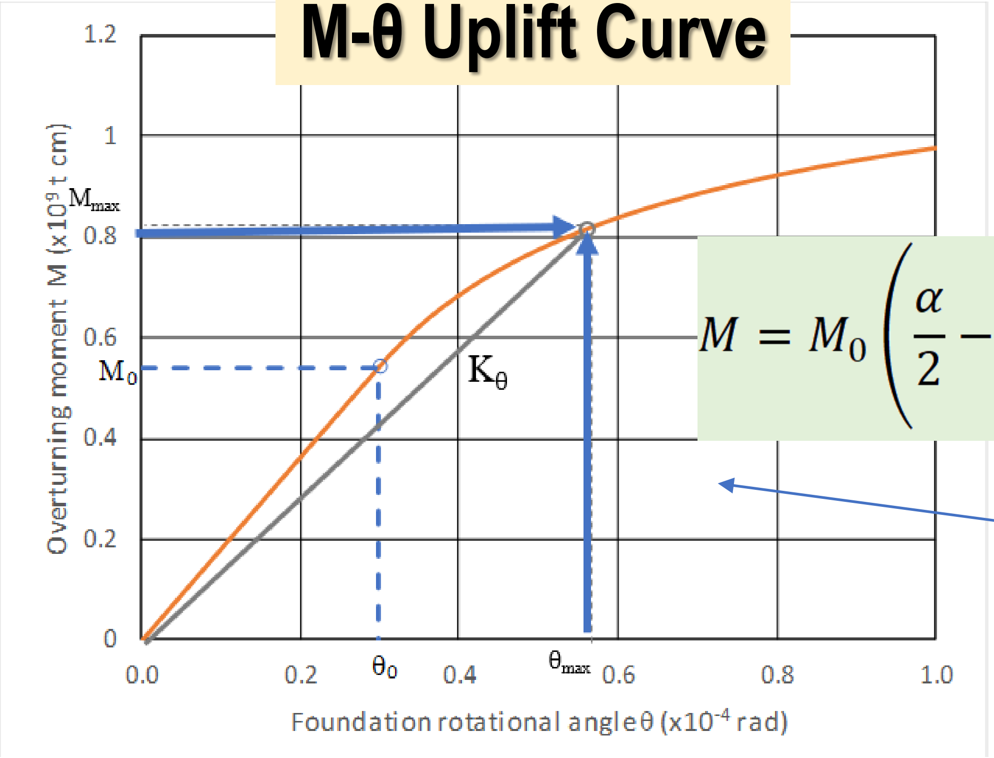
where: W = weight

L = foundation mat width

α = 6.0 for linear distribution, 4.7 for rigid foundation)



M-θ Uplift Curve



$$K_\theta = \frac{M_0}{\theta_0} \Rightarrow \theta_0 = \frac{M_0}{K_\theta^0}$$

Contact Ratio

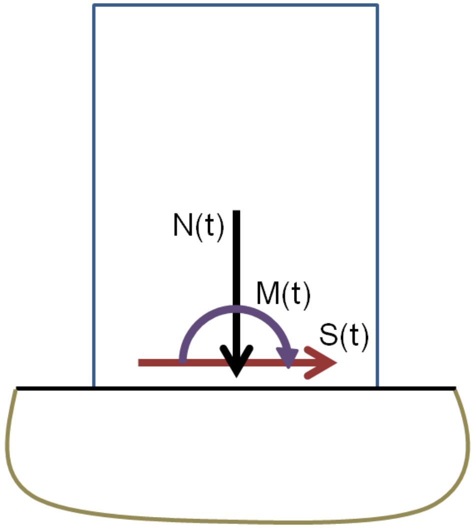
$$M = M_0\left(\frac{\alpha}{2} - \frac{\alpha-2}{2}\left(\frac{\theta_0}{\theta}\right)^{\frac{2}{\alpha-2}}\right) \qquad \eta = \frac{2\alpha}{\alpha-2}\left(\frac{1}{2} - \frac{M_{max}}{WL}\right)$$

Compute

$$\theta = \left(\frac{M_0\ \frac{\alpha-2}{2}}{M_0\ \frac{\alpha}{2} - M}\right)^{\frac{\alpha-2}{2}} \theta_0$$

Compute new rotational Kech and repeat linearized SSI analysis

Contact Surface Ratio is between 50% and 65%
Method 2: JEAC 4601 *Refined Approach Using Moment M(t)*



Surface SSI Model

- Includes coupling between the basemat vertical uplift motion and its rocking motion

- Contact ratio given as a function of time which

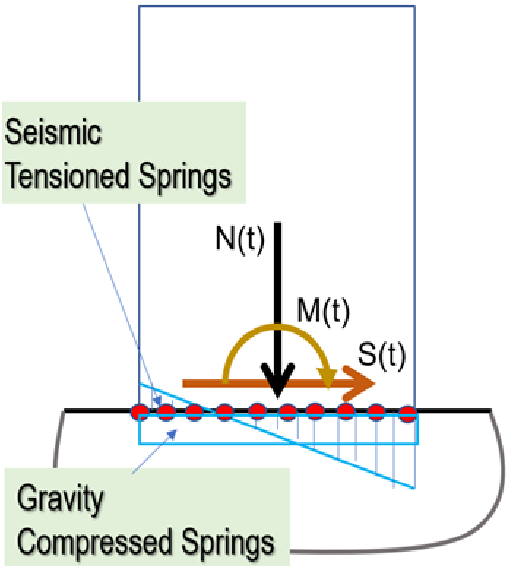
$$\eta(t) = \left(\frac{\theta(t)}{\theta_0}\right)^{\frac{2}{\alpha-2}}$$

- Compute the base center displacements u(t), v(t), and θ(t) for one horizontal direction X or Y by solving ordinary differential equations (ODE)

$$\begin{bmatrix} S(t) \\ N(t) \\ M(t) \end{bmatrix} = \begin{bmatrix} K_H(t) & 0 & 0 \\ 0 & K_V(t) & K_{V\theta}(t) \\ 0 & K_{\theta V}(t) & K_\theta(t) \end{bmatrix} \begin{Bmatrix} w(t) \\ v(t) \\ \theta(t) \end{Bmatrix} + \begin{bmatrix} C_H(t) & 0 & 0 \\ 0 & C_V(t) & 0 \\ 0 & 0 & C_\theta(t) \end{bmatrix} \begin{Bmatrix} \dot{u}(t) \\ \dot{v}(t) \\ \dot{\theta}(t) \end{Bmatrix}$$

α value is 4.7 or 6.0
(*α* = 6.0 for linear distribution, and 4.7 for rigid foundation)

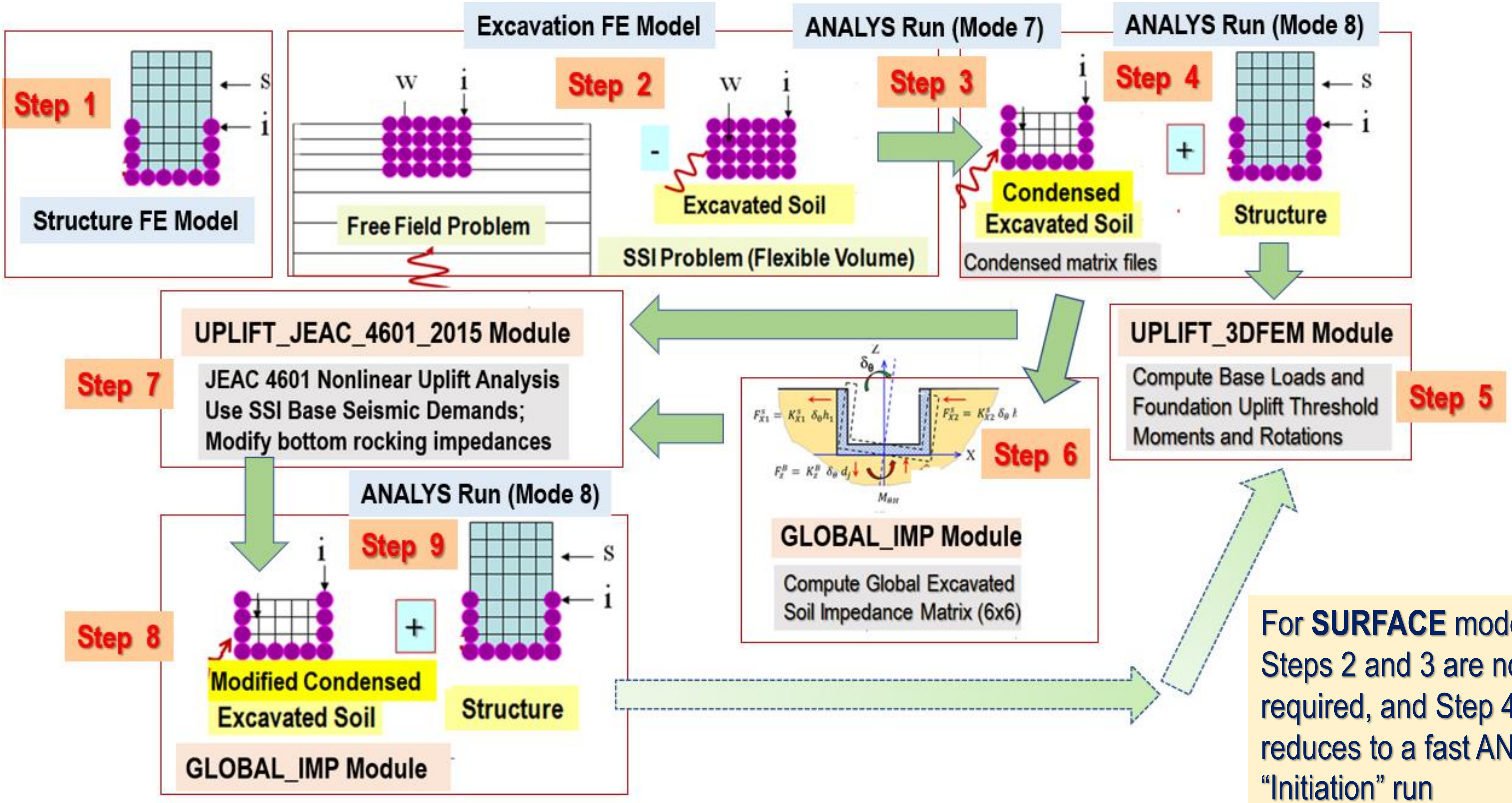
$$M_0 = \frac{W\ L}{\alpha}$$



REMARK:
Mo is computed using 3DFEM SSI model. Then, soil reaction coefficient *α*, is estimated from Mo.

2. ACS SASSI Option UPLIFT Implementation

ACS SASSI Uplift SSI Approach Based on JEAC 4601-2015



For **SURFACE** models, Steps 2 and 3 are not required, and Step 4 reduces to a fast ANALYS "Initiation" run

Option UPLIFT Implementation for 3DFEM Applicable to Surface and Embedded Structures

Compute linearized SSI response for X, Y, and Z directions for structure and bottom springs (S)

Compute SSI response for (static) gravity loads in foundation bottom springs (G)

Compute forces in foundation bottom springs under the S + G effects

Determine the overall seismic base moment and forces computed from spring forces.

Determine contact surface ratio from the spring forces in having tension forces

Determine "critical" time step at which the contact ratio is minimum.

Using "critical" time step, determine seismic factor γ, for *no tension in springs (uplift occurs)*

Using the computed scale factor γ compute the *uplift limit seismic* moment, M_0

Based on base vertical displacements compute rocking θ_0 for M_0

Perform nonlinear uplift analysis using JEAC 4601-2015 approaches

Compute the effective (EQL) stiffness and damping and modify bottom impedances.

Perform linearized SSI restart analysis using the modified soil impedance matrix

ACS SASSI Option UPLIFT Modules for 3DFEM

The ACS SASSI Option UPLIFT SSI analysis capability is implemented based on three specialized software modules:

1) *UPLIFT_3DFEM* module – Computes threshold moments, Moxx, Moyy

2) *GLOBAL_IMP* module – Computes global impedance for dominant frequency

3) *UPLIFT_JEAC_4601_2015* – Integrates base motion differential equation

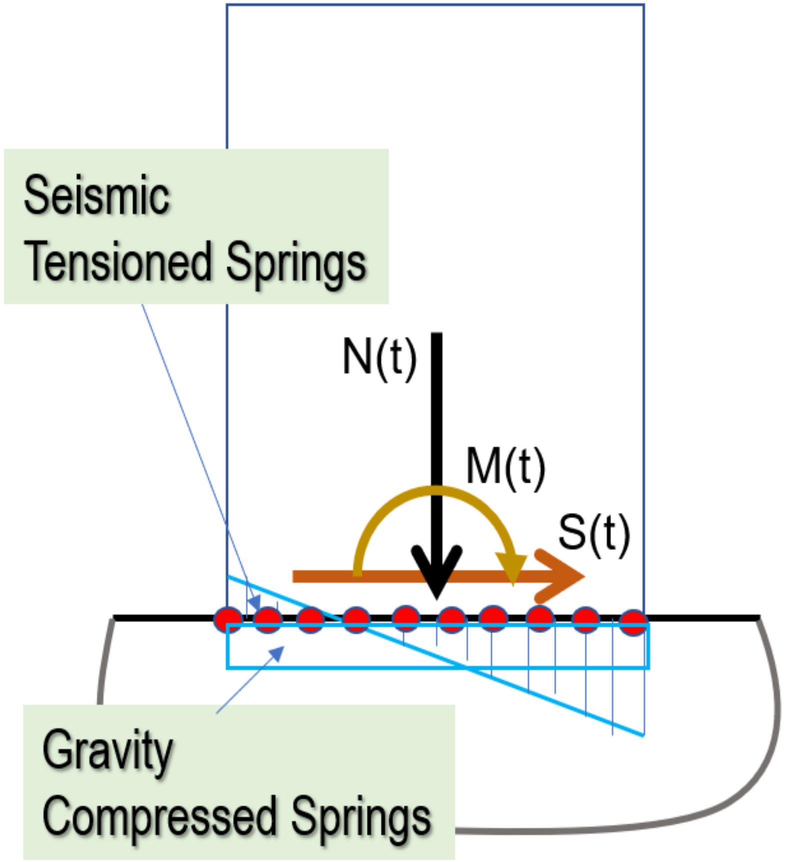
The three UPLIFT modules can be efficiently run without the user intervention based on the batch run files provided with Demo 17. Demo 17 includes UPLIFT SSI case studies for a surface 3DFEM RB and a Stick/SR model, and for an embedded 3DFEM RB model.

ACS SASSI Implementation for Computing 3DFEM Base Threshold Moments Under Gravity (Static) and Seismic (Dynamic) Loads

UPLIFT_3DFEM Module

$$\eta = \frac{A_{contact}}{A_{total}}$$ is computed based on the springs in tension

$$\gamma = \left| \frac{F^{static}}{F^{dynamic}_{max\ tension}} \right|$$ Force scaling coefficients

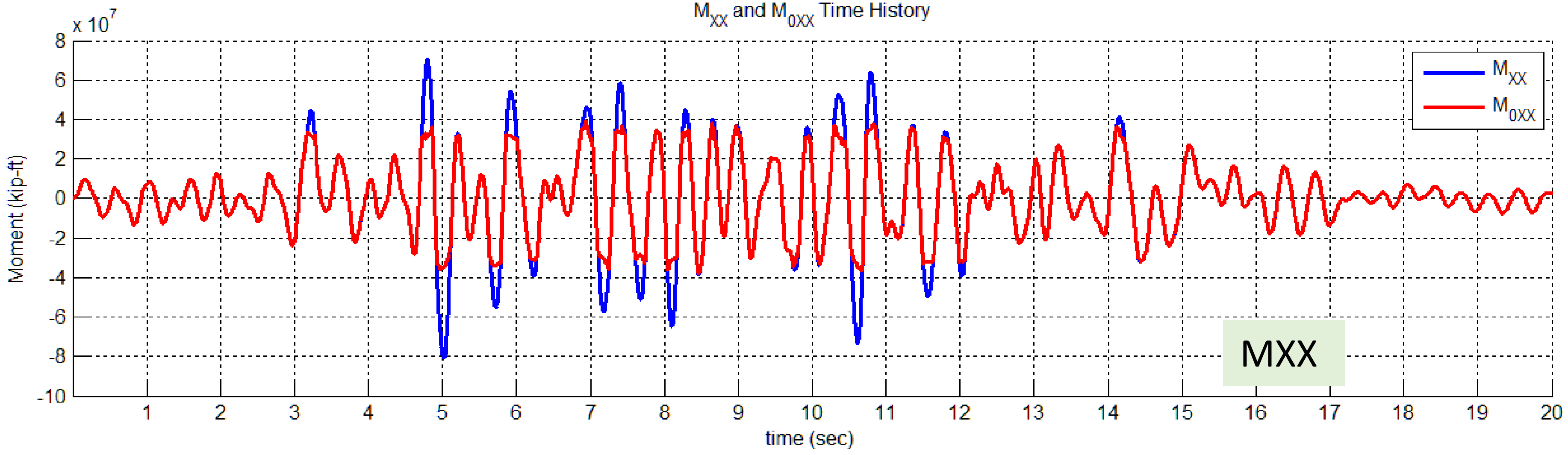


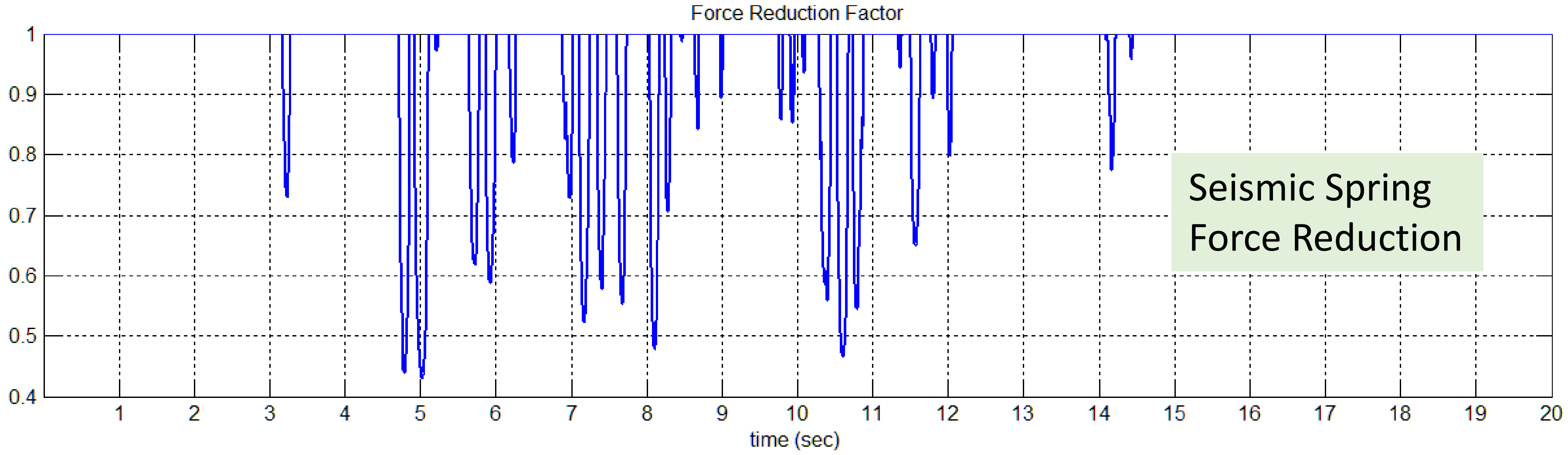
$$M_0 = \sum_j \left(F_j^{static} + \gamma F_j^{dynamic}\right) \cdot d_j$$
is computed for no-tensile springs

θ_0 is computed by linear regression

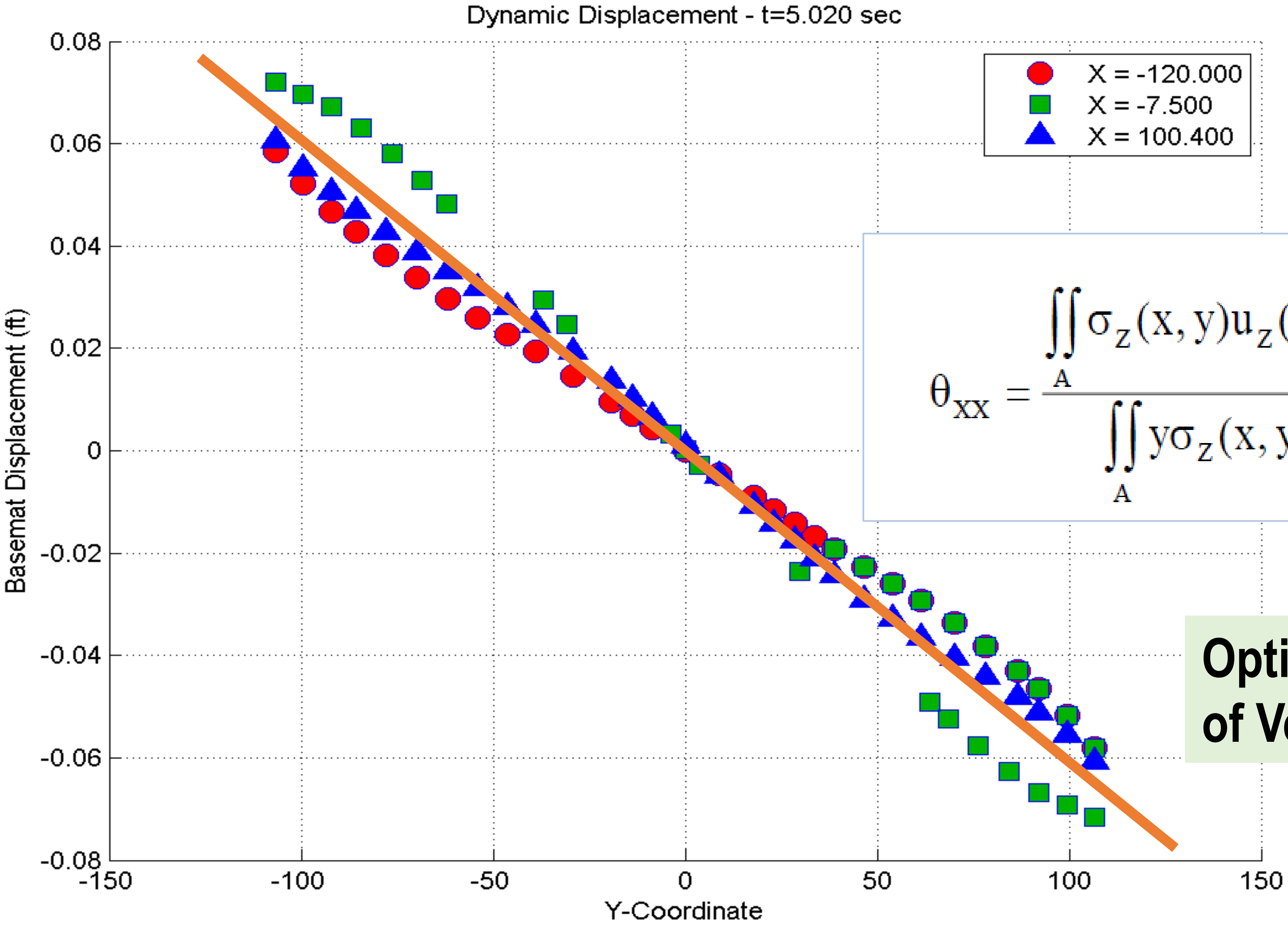
Critical spring based on the no-tension force criterion corresponds to the *minimum spring scale factor*.

Computing Uplift Limit Moment Mo Using Contact Spring Forces Under Seismic & Gravity Effects





RB Base Rocking Displacement for Transverse Y-Direction for Uplift Occurrence (at Time 5.02 sec)

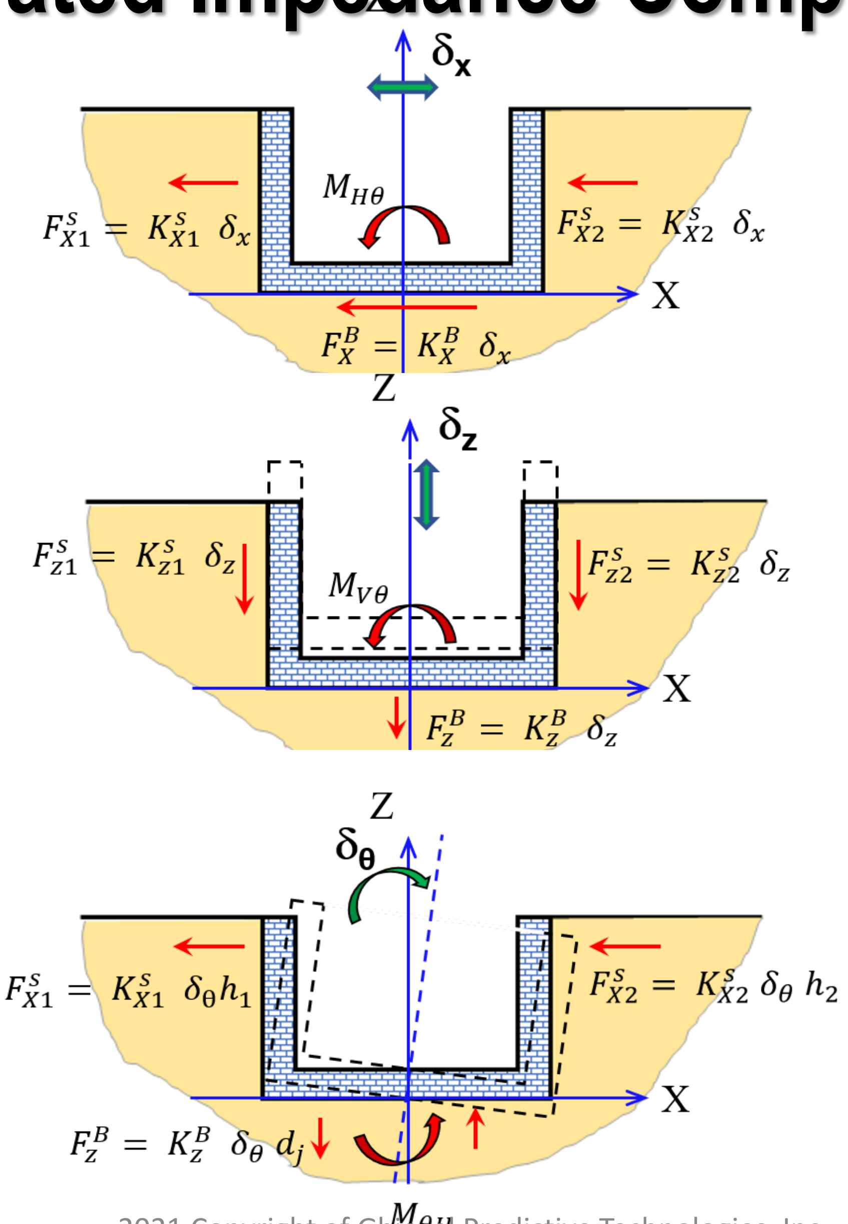


Option 1: Per JEAC Section 3.5.5.2

$$\theta_{XX} = \frac{\iint_A \sigma_Z(x,y)u_Z(x,y)dA}{\iint_A y\sigma_Z(x,y)dA} \quad \text{and} \quad \theta_{YY} = \frac{\iint_A \sigma_Z(x,y)u_Z(x,y)dA}{\iint_A x\sigma_Z(x,y)dA}$$

Option 2: Per Linear Regression of Vertical Displacements

Application to Embedded Structures Using Separated Impedance Components for Bottom and Side Soil



$$K_H = \sum_j (\gamma_{BX} K^B_{Xj} + \gamma_{SX} K^S_{Xj})$$

GLOBAL_IMP Module

Only bottom soil rocking impedance is reduced

$$K_{H\theta} = \sum_j \gamma_{SX}\ K^S_{Xj}\ h_j$$

$$\mathrm{K}(\eta) = \mathrm{K}^{\mathrm{B}}(\eta) + \mathrm{K}^{\mathrm{S}}$$

$$K_V = \sum_j (\gamma_{BZ} K^B_{Zj} + \gamma_{SZ} K^S_{Zj})$$

Includes stiffness reduction factors for the local soil impedances computed based on the "condensed" excavation impedance matrix (ANALYS "Condense Impedance" Option)

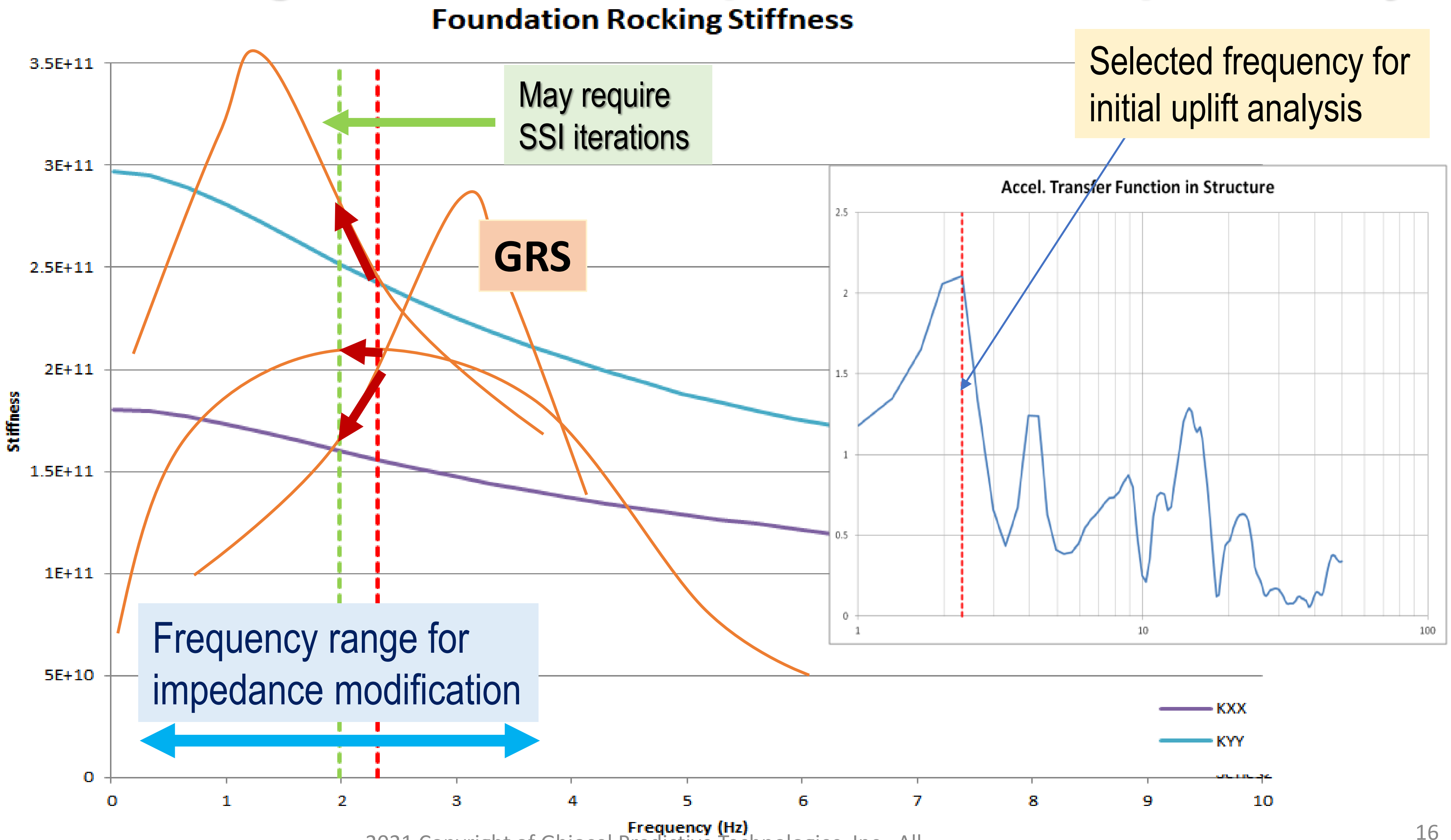
$$K_{V\theta} = \sum_j \gamma_{SZ}\ K^S_{Zj}\ h_j$$

$$K_\theta = \sum_j (K^B_{\theta j} + K^S_{\theta j})$$

$$K_{\theta H} = \sum_j K^S_{\theta Hj}$$

Partial embedment (for a given depth) or separated from soil can be simulated when the excavation matrix is condensed

Frequency Selection for Computing Frequency-Independent Foundation Rocking and Vertical Impedances for Uplift Analysis



Global Excavated Soil Impedances Computed with FVROM Separately for Bottom Soil (Kb) and Side Soil (Ks)

$$K(\eta) = K^{B}(\eta) + K^{S}$$

Ks Side Soil

rb_test_exec_ffv_gimpe_vsd_039.txt - Notepad

File Edit Format View Help

6			
1	1	0.978814489423586E+08	0.600205411196008E+09
1	2	-0.156366222654469E-04	-0.193580696213758E-02
2	2	0.978814489421972E+08	0.600205411195421E+09
1	3	0.102453515864909E-03	-0.158650141383987E-02
2	3	0.147733058838639E-03	0.149676416185685E-03
3	3	0.120420991926416E+09	0.444497979471264E+09
1	4	0.204044249840081E-01	0.571880291681737E-01
2	4	-0.387901057289052E+10	-0.872529354019175E+10
3	4	0.214819100801833E-01	-0.837856583530083E-02
4	4	0.277484896779516E+12	0.422714029543324E+12
1	5	0.387901057288093E+10	0.872529354019683E+10
2	5	-0.103929691656958E+00	-0.707476399838924E-01
3	5	0.100855302065611E+00	-0.278685521334410E-01
4	5	0.100044249743223E+01	0.155399288982153E+01
5	5	0.277484896778842E+12	0.422714029544406E+12
1	6	-0.171312133315951E-01	0.341907285619527E-01
2	6	-0.179550116590690E-01	0.406684288755059E-01
3	6	0.851140864542685E-01	0.180085673928261E-01
4	6	-0.859710469841957E+00	-0.241173759102821E+01
5	6	-0.140295993722975E+01	-0.563571751117706E+00
6	6	0.411251199816289E+12	0.644328056898742E+12

Kb Bottom Soil

rb_test_exec_ffv_gimpe_btm_039.txt - Notepad

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6			
1	1	0.150005246890497E+09	0.367173902991003E+09
1	2	-0.160461913765175E-03	-0.420569658672321E-03
2	2	0.150005246890382E+09	0.367173902990962E+09
1	3	0.641139995423146E-04	-0.335679447744042E-03
2	3	0.289030271233059E-03	-0.151455981722393E-03
3	3	0.940887745803721E+08	0.726086897481987E+09
1	4	0.123210652091075E-01	-0.198398038191954E-01
2	4	0.237055948888405E+10	-0.360160022293755E+09
3	4	-0.235288655967452E-01	0.731955049559474E-02
4	4	0.173388591824422E+12	0.219657441818287E+12
1	5	-0.237055948887168E+10	0.360160022292131E+09
2	5	0.742519632331096E-02	-0.653016596334055E-02
3	5	-0.246530296280980E-01	-0.286893695592880E-01
4	5	0.514871962368488E-01	-0.128739271312952E+00
5	5	0.173388591824653E+12	0.219657441817498E+12
1	6	0.518485612701625E-03	-0.579180661588907E-03
2	6	-0.449214270338416E-02	0.999139342457056E-02
3	6	-0.148978627839824E-02	-0.585613233852200E-03
4	6	-0.431956387736136E+00	0.110512276936788E+00
5	6	0.398745780345052E+00	0.445375568233430E-02
6	6	0.227127267620004E+12	0.246119155935591E+12

Modifying Foundation Impedance Matrix Due to Bottom Soil Rocking Stiffness Reduction

RBC_Uplift_Imp_Red.inp - Notepad

File Edit Format View Help

```
1
-7.20739 -0.00106259 -36.25
```

Surface foundation
Base Center Coordinates

IMP_RED_COEF.txt - Notepad

File Edit Format View Help

```
 17
  1
1.0  1.0  1.0  1.0  0.7  0.7
1.0  1.0  1.0  1.0  1.0  1.0
  2
1.0  1.0  1.0  1.0  0.7  0.7
1.0  1.0  1.0  1.0  1.0  1.0
  3
1.0  1.0  1.0  1.0  0.7  0.7
1.0  1.0  1.0  1.0  1.0  1.0
  4
1.0  1.0  1.0  1.0  0.7  0.7
1.0  1.0  1.0  1.0  1.0  1.0
  5
1.0  1.0  1.0  1.0  0.7  0.7
1.0  1.0  1.0  1.0  1.0  1.0
  6
1.0  1.0  1.0  1.0  0.7  0.7
1.0  1.0  1.0  1.0  1.0  1.0
```

Bottom Soil
Side Soil

Frequency-dependent reduction factors for the local bottom and side soil impedances. It includes real and imaginary parts for X, Y and Z directions

3D Nonlinear Uplift Analysis by Solving Base Motion ODE Equations with Varying Coefficients

$$\begin{bmatrix} N \\ S_x \\ S_y \\ M_{xx} \\ M_{yy} \end{bmatrix} = \begin{bmatrix} K_v & 0 & 0 & K_{v,xx} & K_{v,yy} \\ 0 & K_x & 0 & 0 & K_{x,yy} \\ 0 & 0 & K_y & K_{y,xx} & 0 \\ K_{xx,v} & 0 & 0 & K_{xx} & K_{y,xx} \\ K_{yy,v} & 0 & 0 & 0 & K_{x,yy} \end{bmatrix} \begin{bmatrix} v \\ x \\ y \\ \theta_{xx} \\ \theta_{yy} \end{bmatrix} + \begin{bmatrix} C_v & 0 & 0 & 0 & 0 \\ 0 & C_x & 0 & 0 & 0 \\ 0 & 0 & C_y & 0 & 0 \\ 0 & 0 & 0 & C_{xx} & 0 \\ 0 & 0 & 0 & 0 & C_{yy} \end{bmatrix} \begin{bmatrix} \dot{v} \\ \dot{x} \\ \dot{y} \\ \dot{\theta}_{xx} \\ \dot{\theta}_{yy} \end{bmatrix}$$

UPLIFT_JEAC_2015 Module

$$\eta_{xx} = \left(\frac{\theta_{xx}}{\theta_{0xx}}\right)^{\frac{2}{\alpha-2}}$$

$$\eta_{yy} = \left(\frac{\theta_{yy}}{\theta_{0yy}}\right)^{\frac{2}{\alpha-2}}$$

Stiffness

$$K_V(t) = \eta(t)^{\beta} K_V(0)$$

$$K_{V\theta}(t) = \frac{1-\eta(t)}{2} L \cdot K_V(t)$$

$$K_\theta(t) = \frac{M(t) - K_{V\theta}(t)\cdot v(t)}{\theta(t)}$$

Damping

$$C_V(t) = C_V(0)\cdot \eta(t)^{\frac{\alpha}{2}}$$

$$C_{V\theta} = 0$$

$$C_\theta = C_\theta(0)\cdot \eta(t)^{\frac{\alpha}{2}}$$

Summary of Option UPLIFT Methodology

UPLIFT SSI Analysis Options for Surface Models (IEMBL = 0)

Option UPLIFT analysis for surface 3DFEM models uses

1-Step analysis (per JEAC 4601-2015 practice)

Compute parameter α using $\alpha = WL/Mo$ for the *Surface SSI model* (IEMBL=0). Only the *UPLIFT_3DFEM module* needs to be run to get base moment Mo and α

Use the computed α to perform the uplift SSI analysis for the *Surface SSI model* using *UPLIFT_JEAC_4601_2015*.

NOTE: *The base stress and displacement distributions are linearized per JEAC 4601-2015 requirements (IFBASEROT=0 or 3, w/ and w/o alfa adjustment), or not linearized (IFBASE=1, 2 or 4,5, w/ and w/o alfa adjustment)*

Adjusting Coefficient α Per JEAC 4601-2015 App.3.6

The UPLIFT_JEAC_4601_2015 module provides ***two options*** for adjusting α coefficient:

1. *Adjust α value* to be in the 4.7-6.0 interval – in compliance with JEAC 4601 (IFBASEROT < 3)

   Based on 3DFEM results and computing Mo based on the no-tension criterion in the bottom-soil springs, α = WL/Mo . If α is outside the 4.7-6.0 interval, then adjust its value to be in the interval.
   Compute ratio R = α /4.7. If R < 1, then α = 4.7.
   Compute ratio R = α /6.0. If R > 1, then α = 6.0

2. *No α adjustment.* Calculations of Mo and θo are based on 3DFEM Mo results, but using JEAC equation (IFBASEROT > 3)

   α = WL/Mo with no adjustment

Note: α *adjustment applicable to both surface and embedded SSI models.*

UPLIFT SSI Analysis Options for Embedded Models (IEMBL > 0)

Option UPLIFT provides ***two uplift** approaches* for 3DFEMs including three options (IEMBL=1,2,3)

A. 2-Step analysis Using Options 1 and 2 (per JEAC 4601-2015 practice)

1. Compute parameter α using α = WL/Mo for the *Modified Embedded SSI model (unbonded)* (IEMBL=1). Only the UPLIFT_3DFEM module needs to be run to get base moment Mo and α
2. Use the computed α in Step 1 to perform the entire uplift SSI analysis for the *Design-Condition Embedded SSI model*. (IEMBL=2). Automatic for Step 2 to use of given α from Step 1.

B. 1-Step Approach Using Option 3 (not in compliance with JEAC 4601-2015)

3. Compute parameter α using α = WL/Mo for the *Design-Condition Embedded SSI model*, in which Mo is the overall foundation moment. Use the computed α to perform the the entire uplift SSI analysis for the *Design-Condition Embedded SSI model*. (IEMBL=3). Automatic for Option 3.

   ***NOTE:** The Mo is computed by including both the bottom-soil and side-soil contributions. NOT IN COMPLIANCE WITH Japanese JEAC 4601-2015. Also, no base soil stress linearization is applied.*

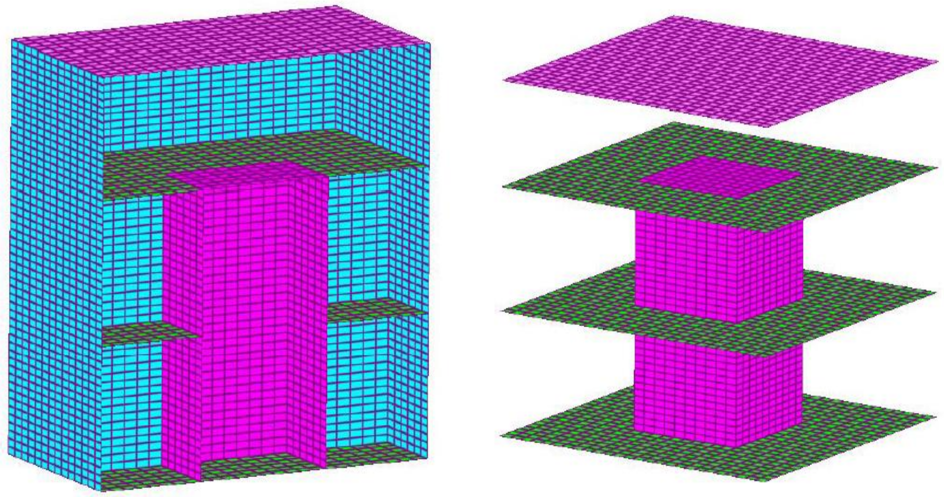
User Input Guide

Line/Variable	Description
Line 1	
Variable	Model name variable that was defined by user for SSI analysis
Line 2	
Variable 1 (ELEMTYPE)	= 0 for ACS SASSI 3DFEM or SR/Stick SSI Model = 1* for No ACS SASSI Model is available. Only the SR/Stick model dynamic properties and base moment time histories are required. Apply the JEAC 4601-2015 App.3.6 equation for computing Mo moments.
Variable 2 (IEMBL)	= 0 for Surface Model to perform uplift SSI analysis (with all modules) = 1 for *Modified Embedded Model* (with Unbonded Side-Soil) *to compute the alfa soil reaction coefficients* (with UPLIFT_3DFEM module) = 2 for *Design-condition Embedded Model* (with elastic foundation walls connected to side-soil) *to compute base loads for a given the alfa soil reaction coefficients* computed for the IEMBL=1 option (with all modules) = 3 for *Design-condition Embedded Model* to perform the entire uplift SSI iterative analysis (with all modules)
Variable 3 (IFBASEROT)	= 0,3 Base moments and rotations computed based on the Linearized bottom-soil stress and displacement distributions; use WM for base rotation per JEAC 4601 Section 3.5.5.2 (Option 1, WM-LIN) = 1,4 Base moments and rotations computed based on the non-linearized bottom-soil computed stress and displacement distributions; use WM for base rotation per JEAC 4601 Section 3.5.5.2 (Option 2, WM) = 2,5 Base moments and rotations computed based on the non-linearized bottom-soil computed stress and displacement distributions; use base displacement linear regression for base rotation (Option 3, LR) *NOTE:* If the selected option number is < 3, it includes *automatic adjustment* of parameter α values to be inside 4.7-6.0 interval per JEAC requirement. If the selected option number is > 3, it includes *no adjustment* of parameter α values to be inside 4.7-6.0 interval per SSI analysis results.
Variable 3 (DIFF)	= Percent difference that is acceptable for the uplift SSI solution convergence based on the computed maximum base moments
Variable 4 (CONTANI)	= 0 no contact surface animation frames are generated = 1 contact surface animation frames are generated

3. Examples and Verification

Demo 17 on Surface & Embedded RB Complex Uplift SSI Analysis

RB Complex

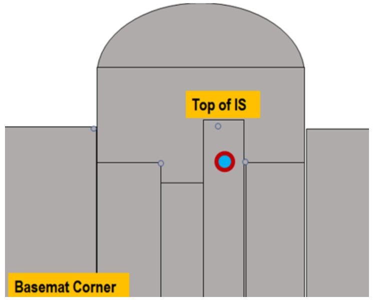


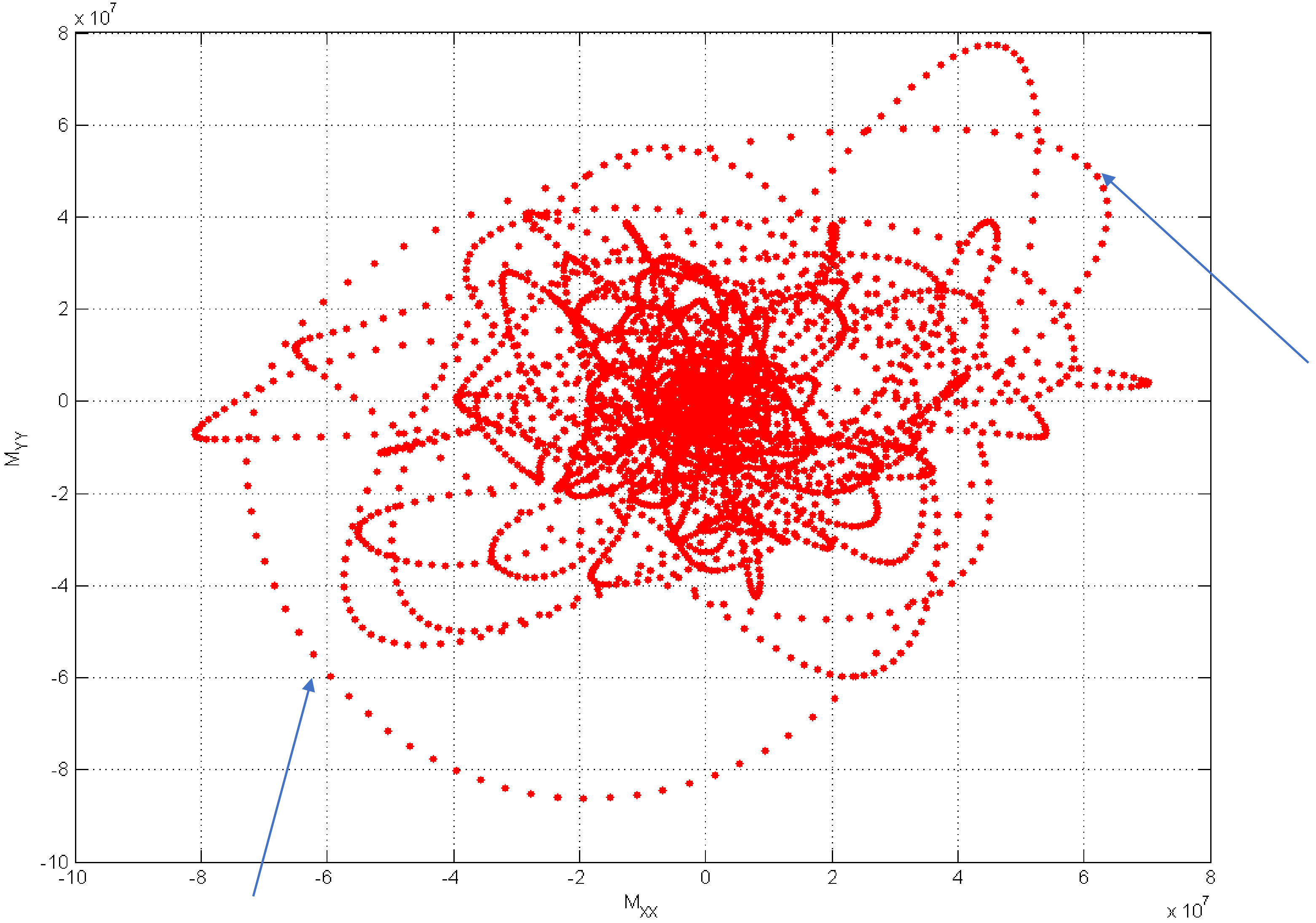
The embedded RB model has a foundation depth of 12.5m. The soil profile corresponds to a deep uniform soil formation with a Vs = 720 m/s.

Seismic inputs were 0.40g for Surface RB model and 0.50g for Embedded RB model.

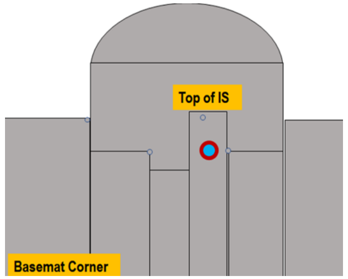
	Surface Analysis		Embedded Analysis
1	Build the ACS SASSI structure FE model, including stiff springs for the structure nodes on the basemat at the soil surface interface.	1	Build the ACS SASSI structure FE model, including stiff springs for the structure nodes on the basemat at the soil surface interface. The walls below ground surface level are connected to the excavated soil at the soil layer interfaces with weak springs for an unbonded interface.
		2	Build the ACS SASSI excavated soil FE model to be mesh-compatible with the structure FE model
		3	Run the excavated soil model SSI analysis using the ANALYS "Condensed Impedance" option (Mode=7) to produce the condensed soil impedance matrix
2	Perform the initial linear ACS SASSI SSI analysis using ANALYS "Initiation" Option (Mode=1).	4	Perform the initial linear ACS SASSI SSI analysis using ANALYS "SSI with Condensation" option (Mode=8)
3	Post-process the SSI analysis to create binary stress database	5	Post-process the SSI analysis to create binary stress databases
4	Review few nodal acceleration transfer functions to identify the dominant SSI frequency for the global rocking modes for the X and Y directions	6	Review few nodal acceleration transfer functions to identify the dominant SSI frequency for the global rocking modes for the X and Y directions
5	Modify the .upl uplift module input file to reflect the selected SSI dominant rocking mode frequency and range of interest.	7	Modify the .upl uplift module input file to reflect the selected dominant frequency and range.
6	Run the UPLIFT_3DFEM module to compute based on the base spring forces and node displacements, the seismic global base time-varying loads and the uplift threshold values of the base moments and the foundation rotations.	8	Run the UPLIFT_3DFEM module to compute based on the base spring forces and node displacements, the seismic global base time-varying loads and the uplift threshold values of the base moments and the foundation rotations.
7	Run the GLOBAL_IMP module to compute the global soil impedances for the soil under the foundation basemat for a reduced SSI frequency subset.	9	Run the GLOBAL_IMP module to compute the global soil impedances for the soil under the foundation basemat (the global impedances are split in bottom soil and side soil contributions) for a reduced SSI frequency subset.
8	Run the UPLIFT_JEAC_4601_2015 module to compute the foundation contact area and the base motions (translations and rocking motions) including the uplift vertical displacement effects per the JEAC 4601 Appendix 3.6 recommendations.	10	Run the UPLIFT_JEAC_4601_2015 module to compute the foundation contact area and the base motions (translations and rocking motions) including the uplift vertical displacement effects per the JEAC 4601 Appendix 3.6 recommendations.

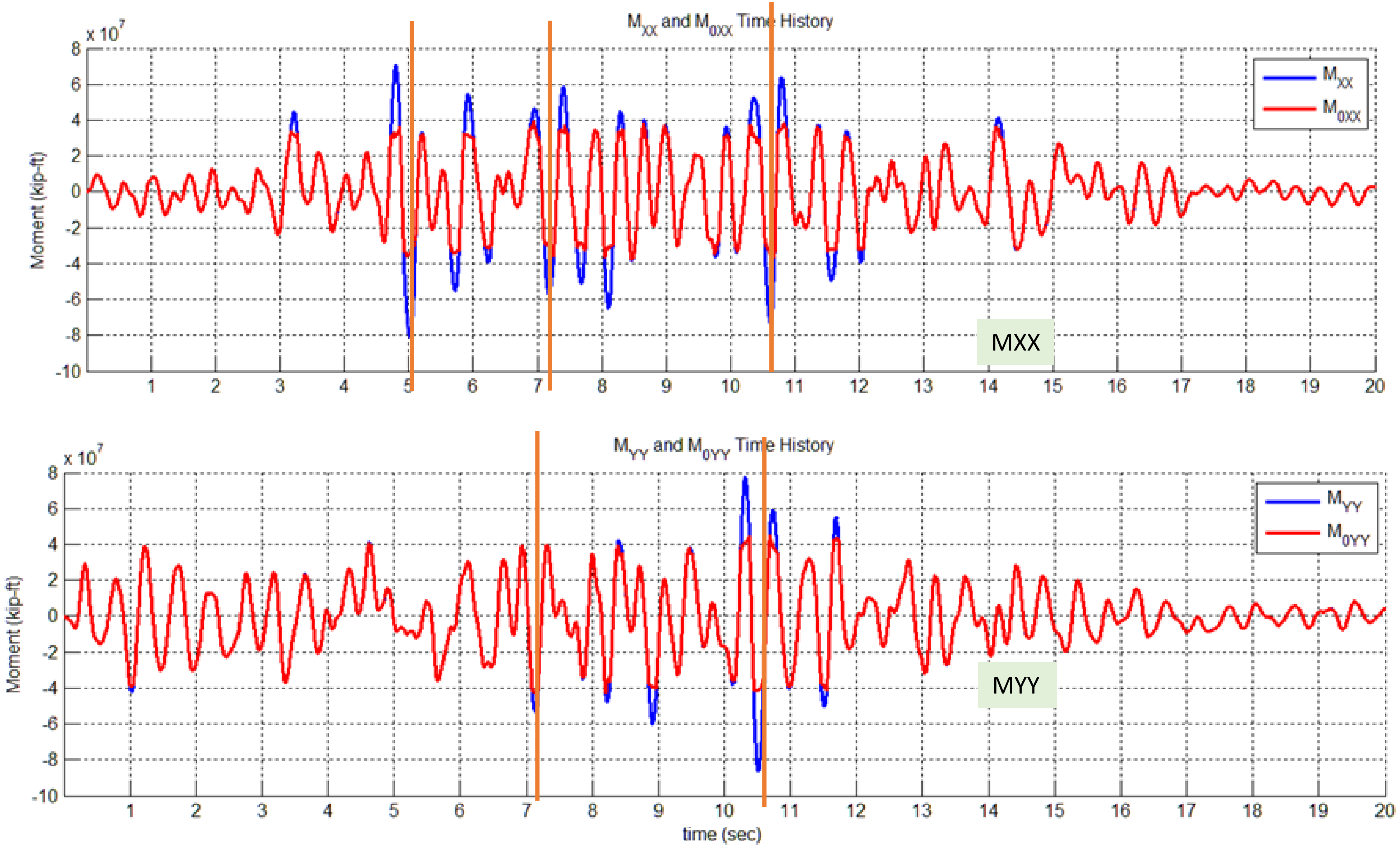
Surface RB Complex Nonlinear Uplift SSI Analysis Study for Combining X and Y Seismic Motion Effects



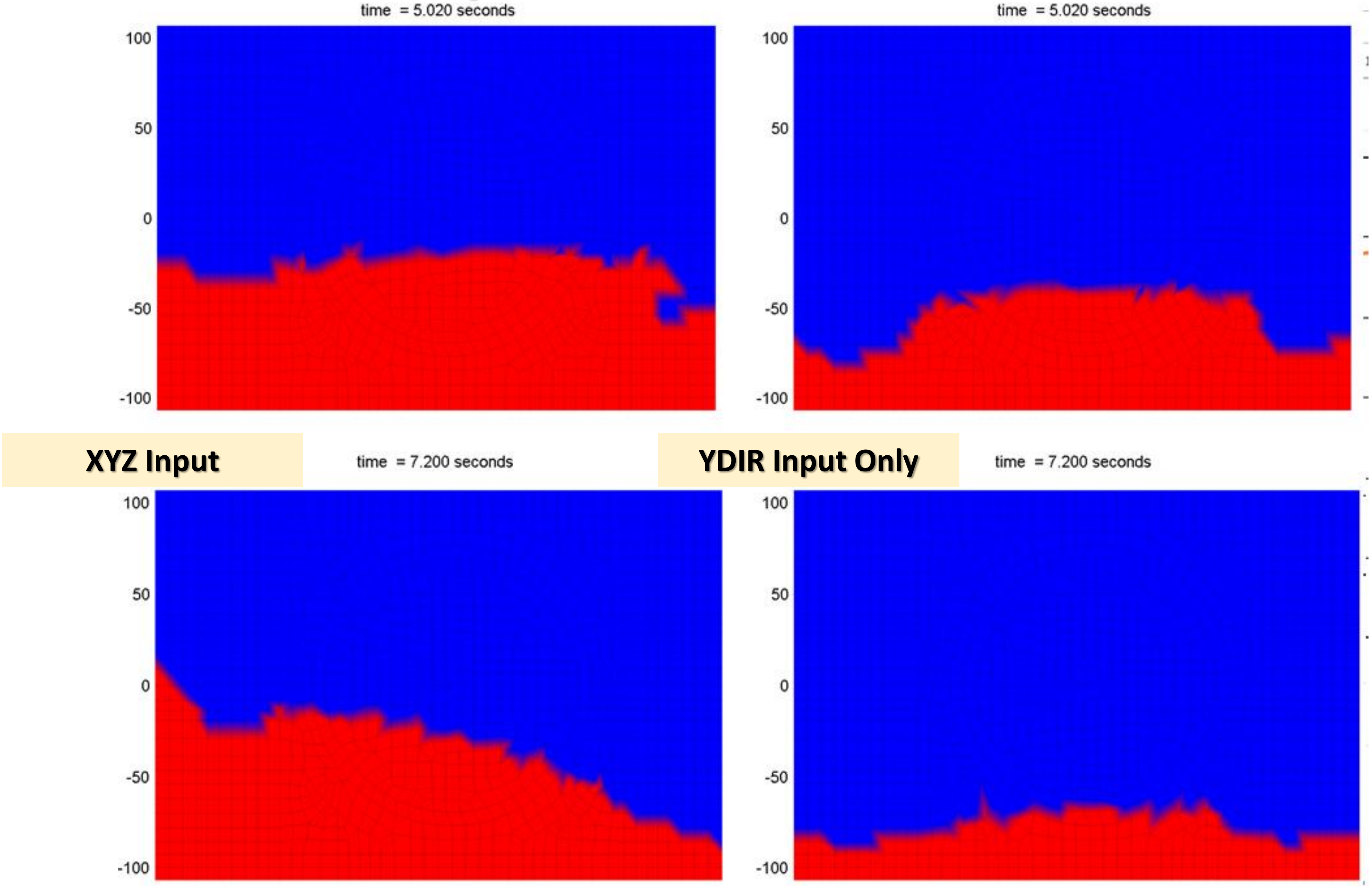


Nonlinear Uplift Limit Base Moments (Mo) for X and Y Directions

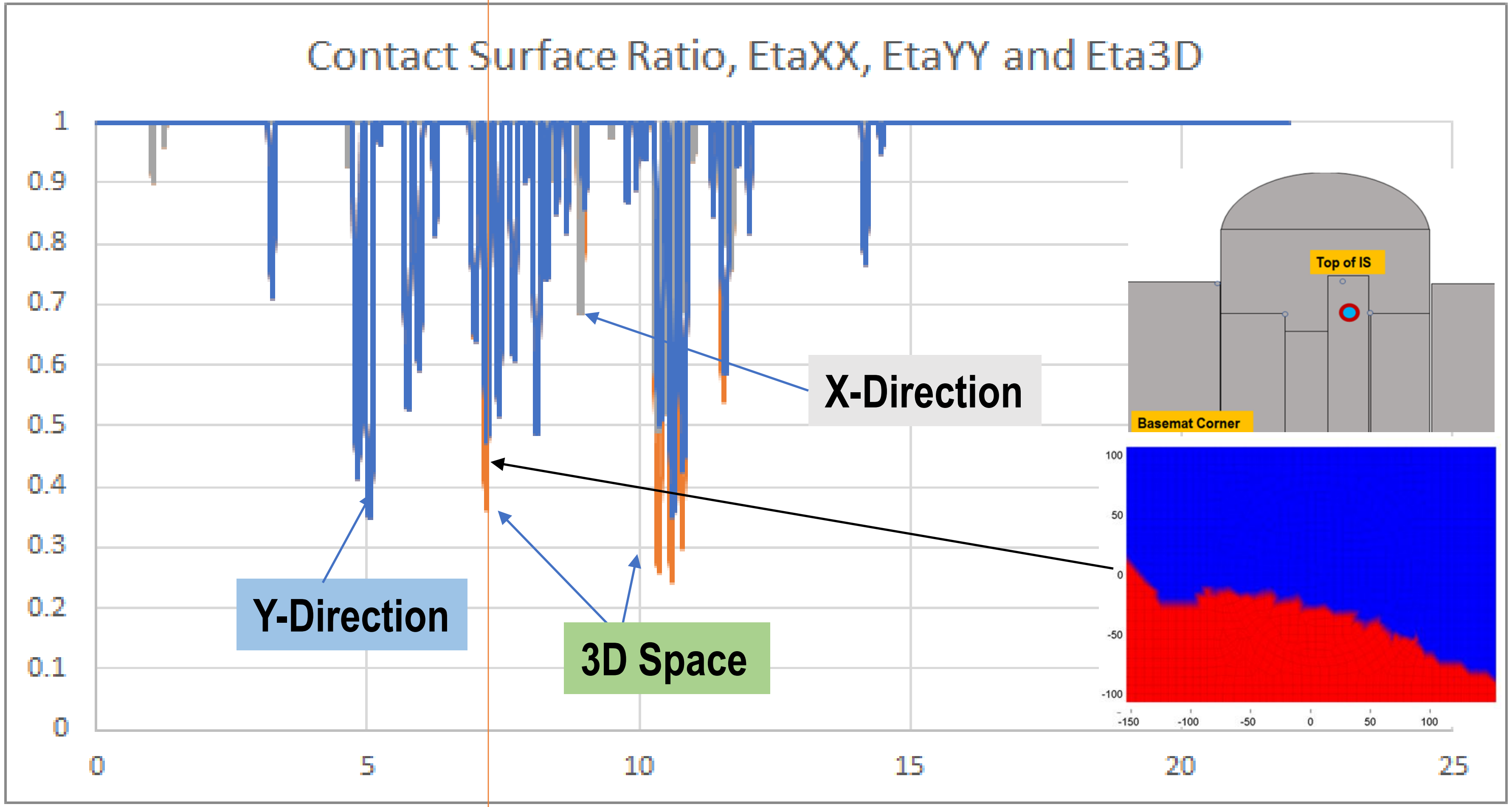




Contact Surface at Uplift Occurrences at 5.02 sec and 7.20 sec



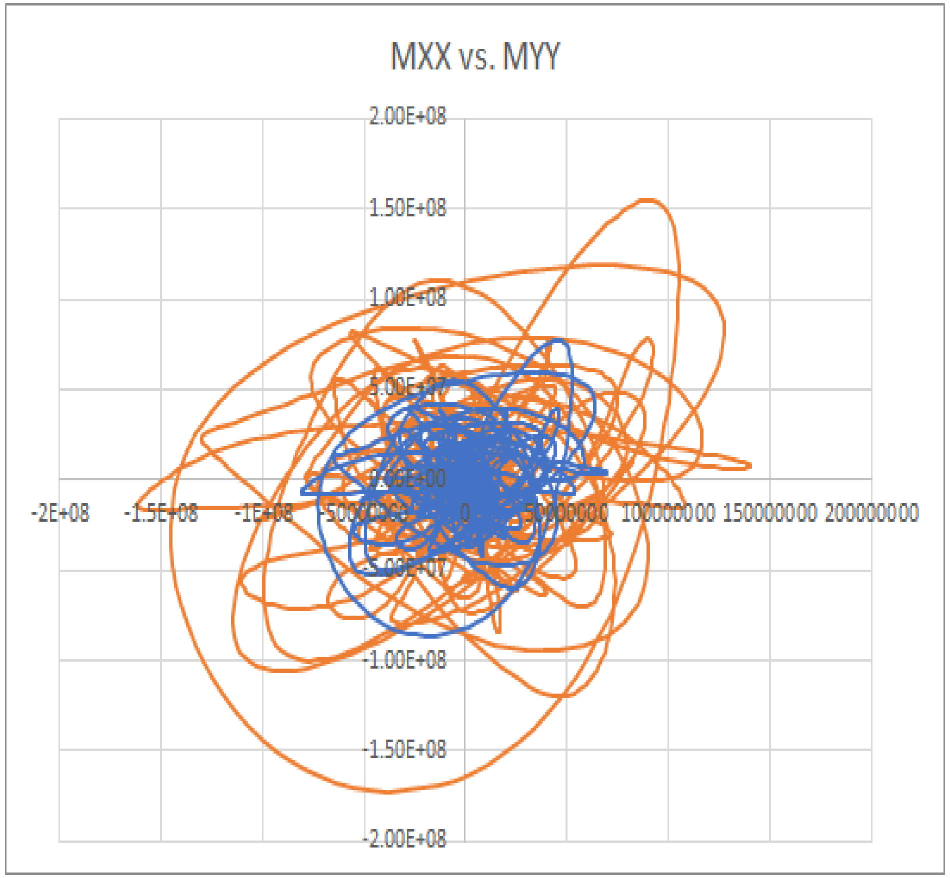
Contact Surfaces for X (Longitudinal) and Y (Transversal) Directions and Combined for 1.4g

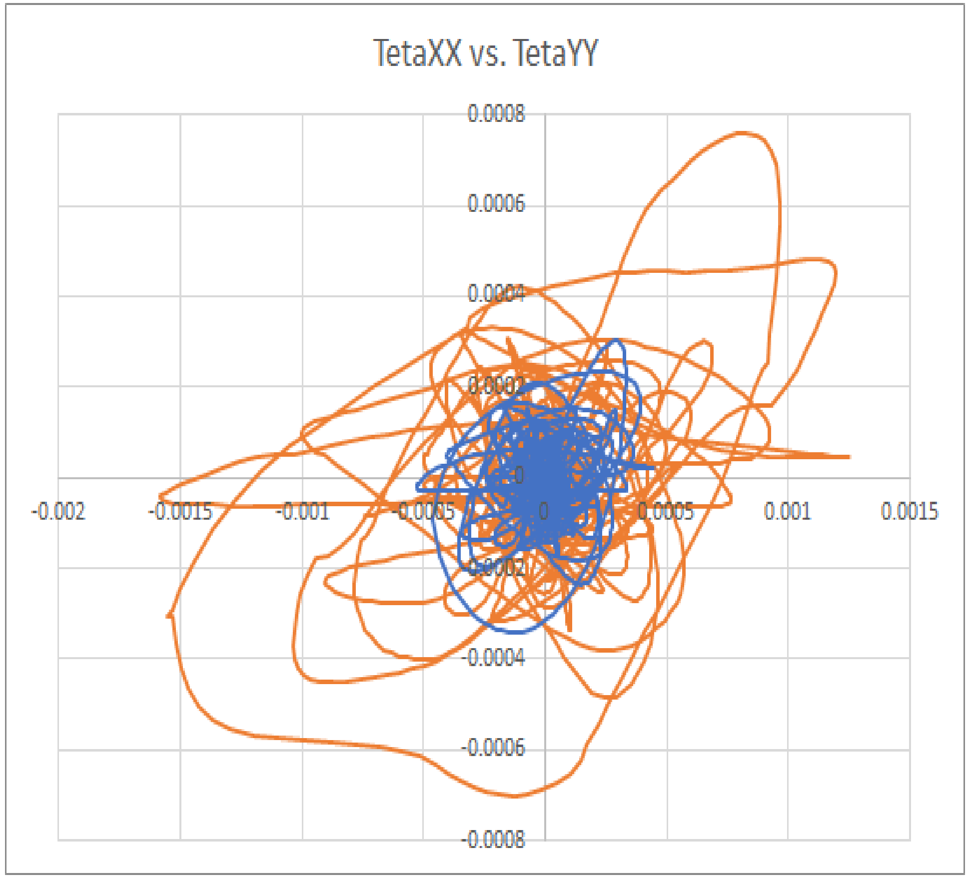


MXX vs. MYY and TetaXX vs. TetaYY for 1.4g

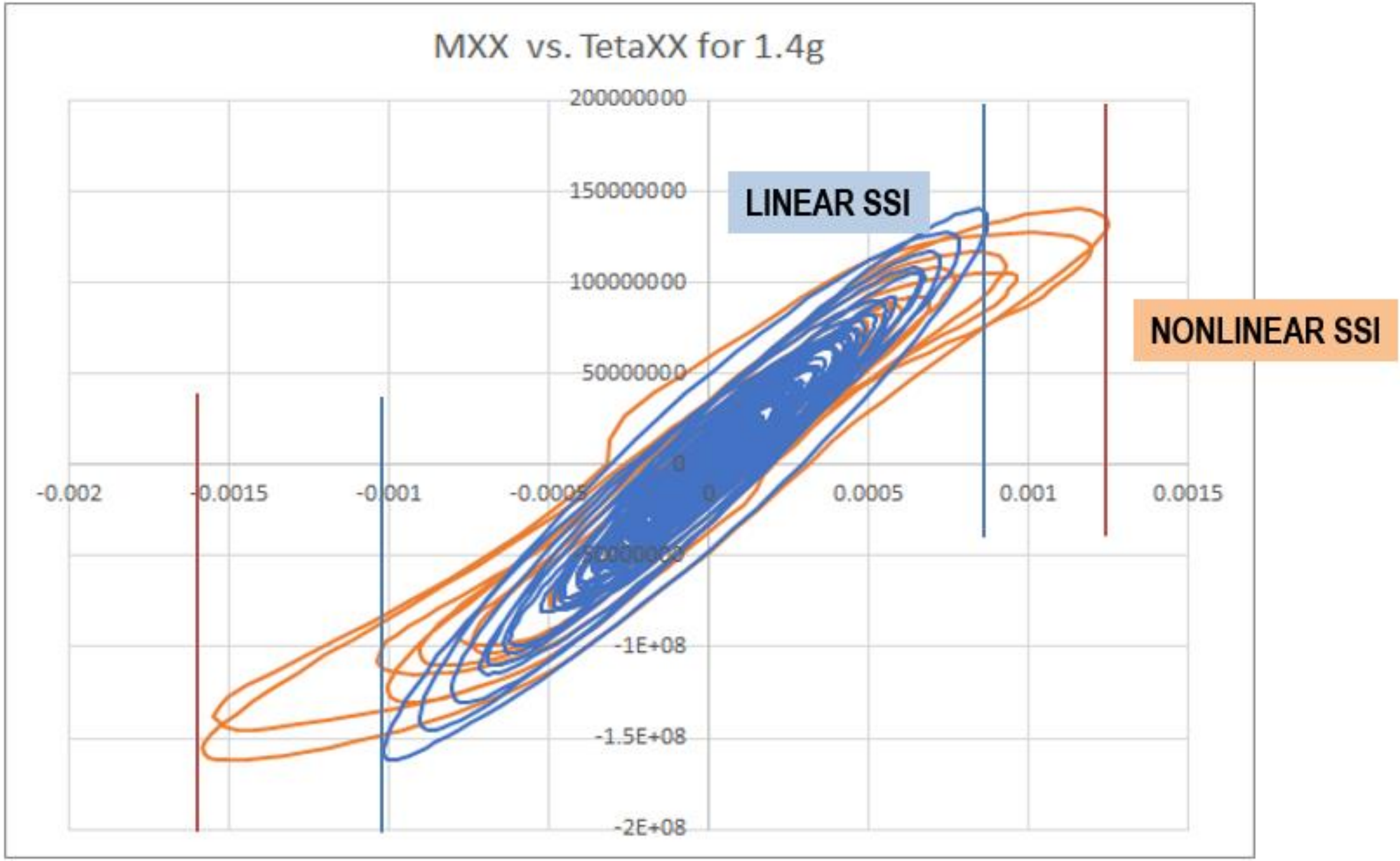
MXX-MYY

TetaXX-TetaYY

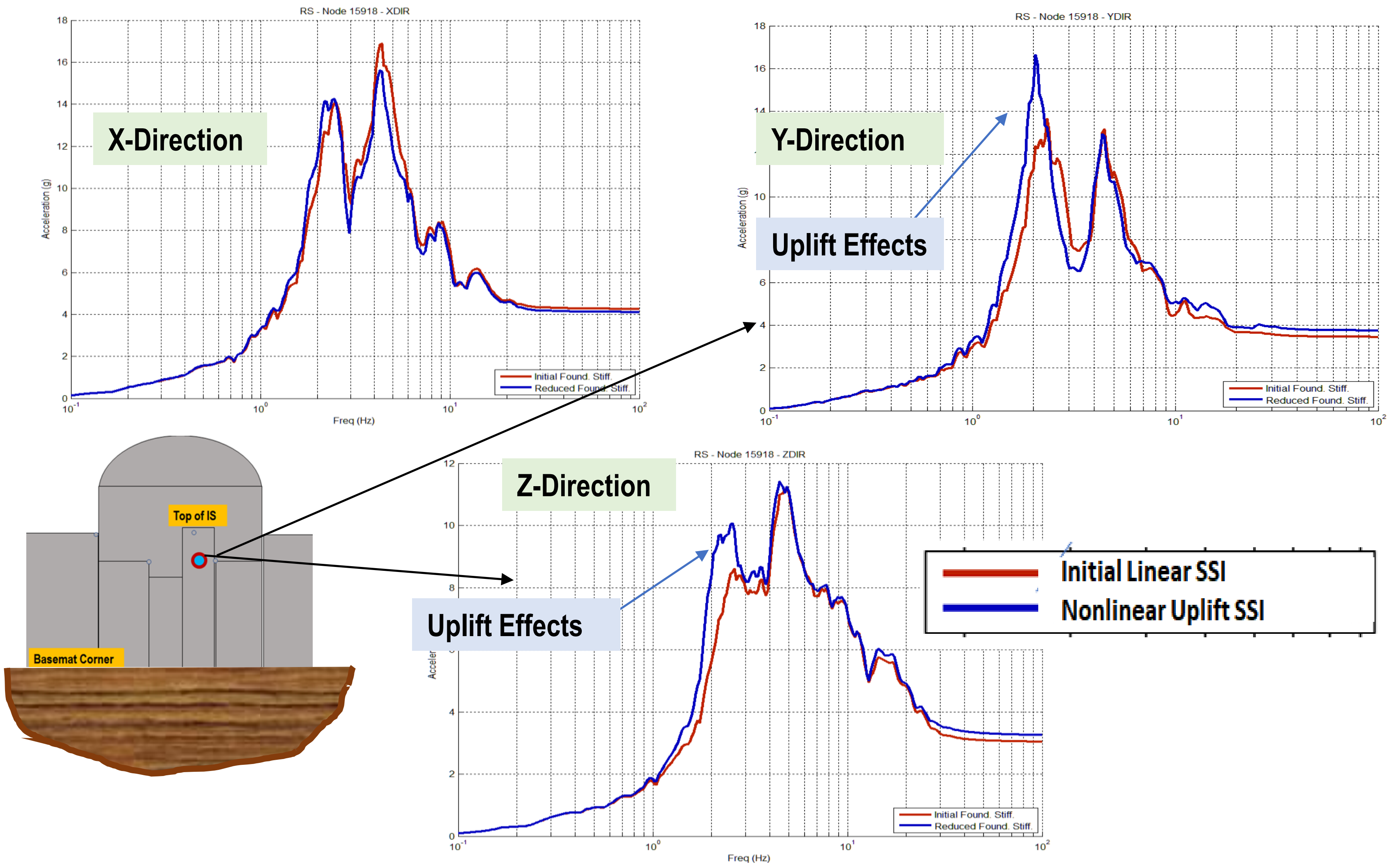




Base Uplift Moment-Rotation Curve for Linear SSI vs. Nonlinear SSI

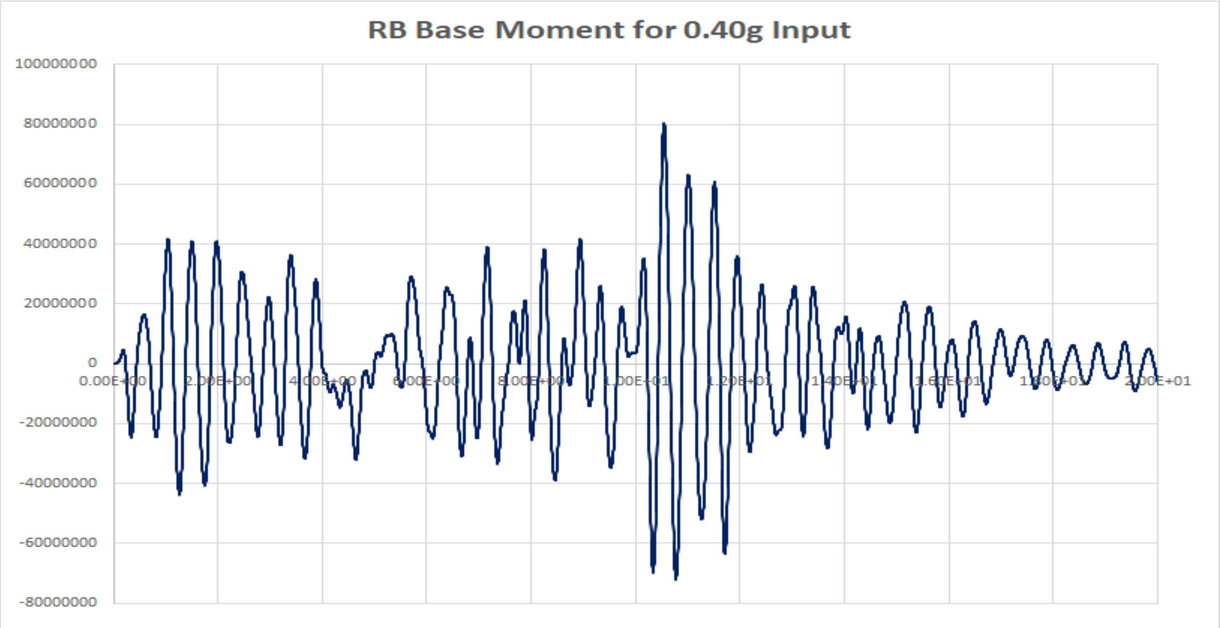


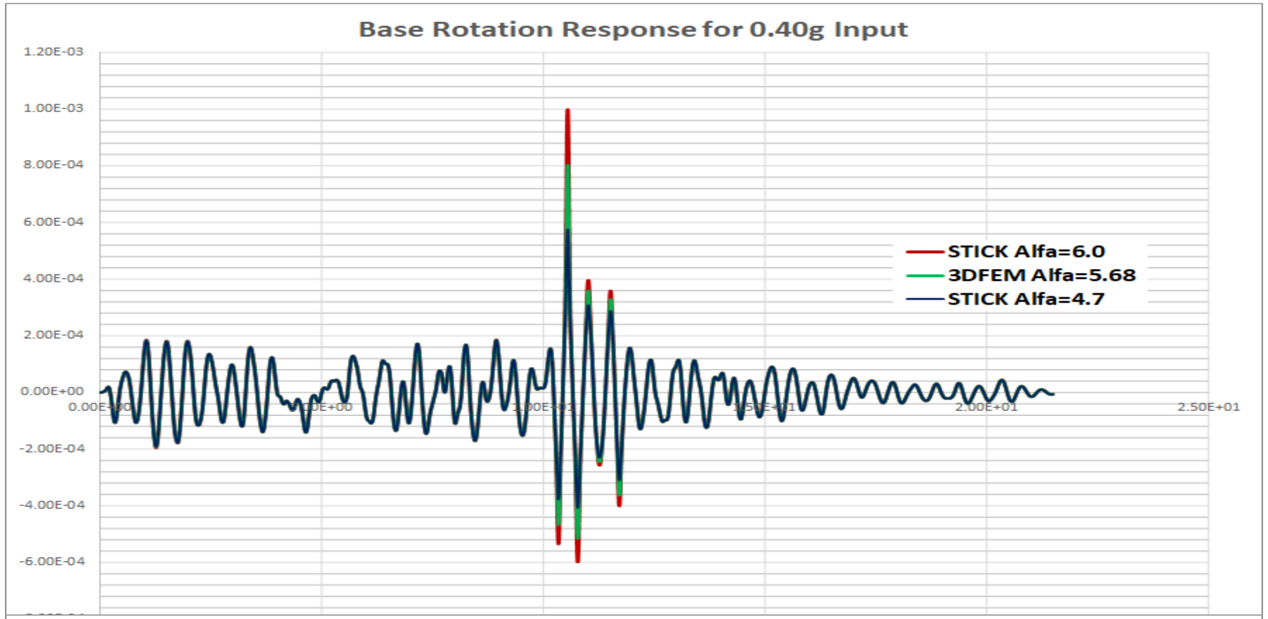
ISRS Computed for Linear SSI vs. Nonlinear Uplift SSI Analysis for Surface RB Complex

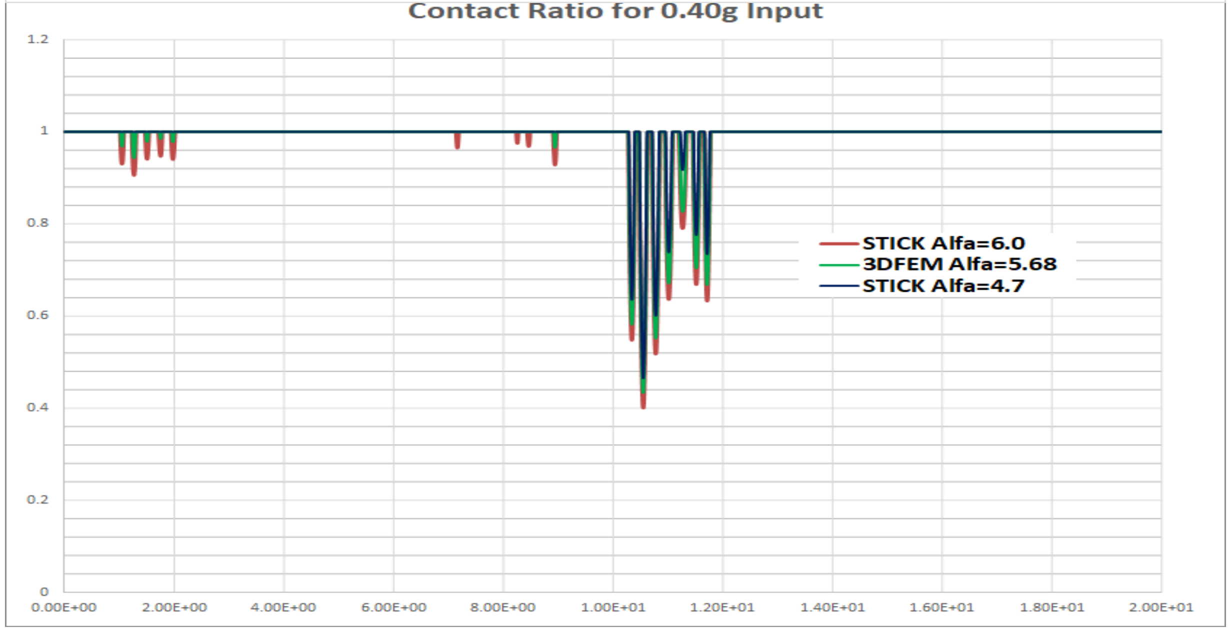


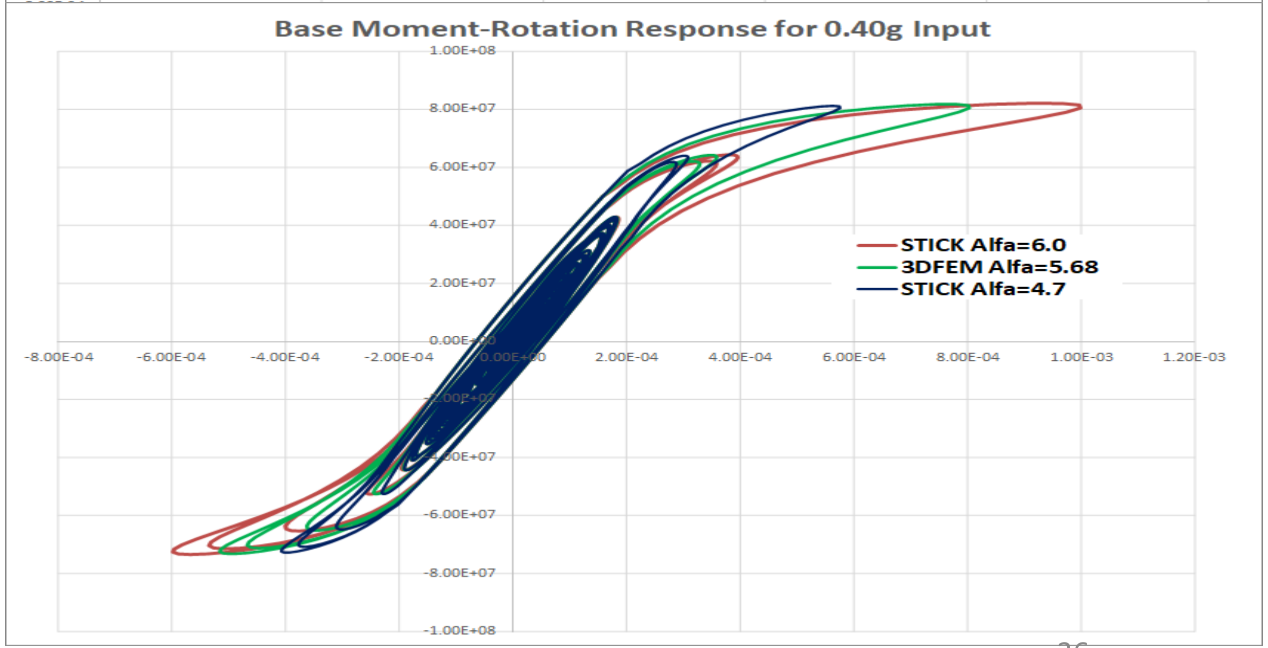
3DFEM vs. Surface Stick for 0.40g Input

Surface UPLIFT Stick vs. 3DFEM for Different Alfa for 0.40g Input







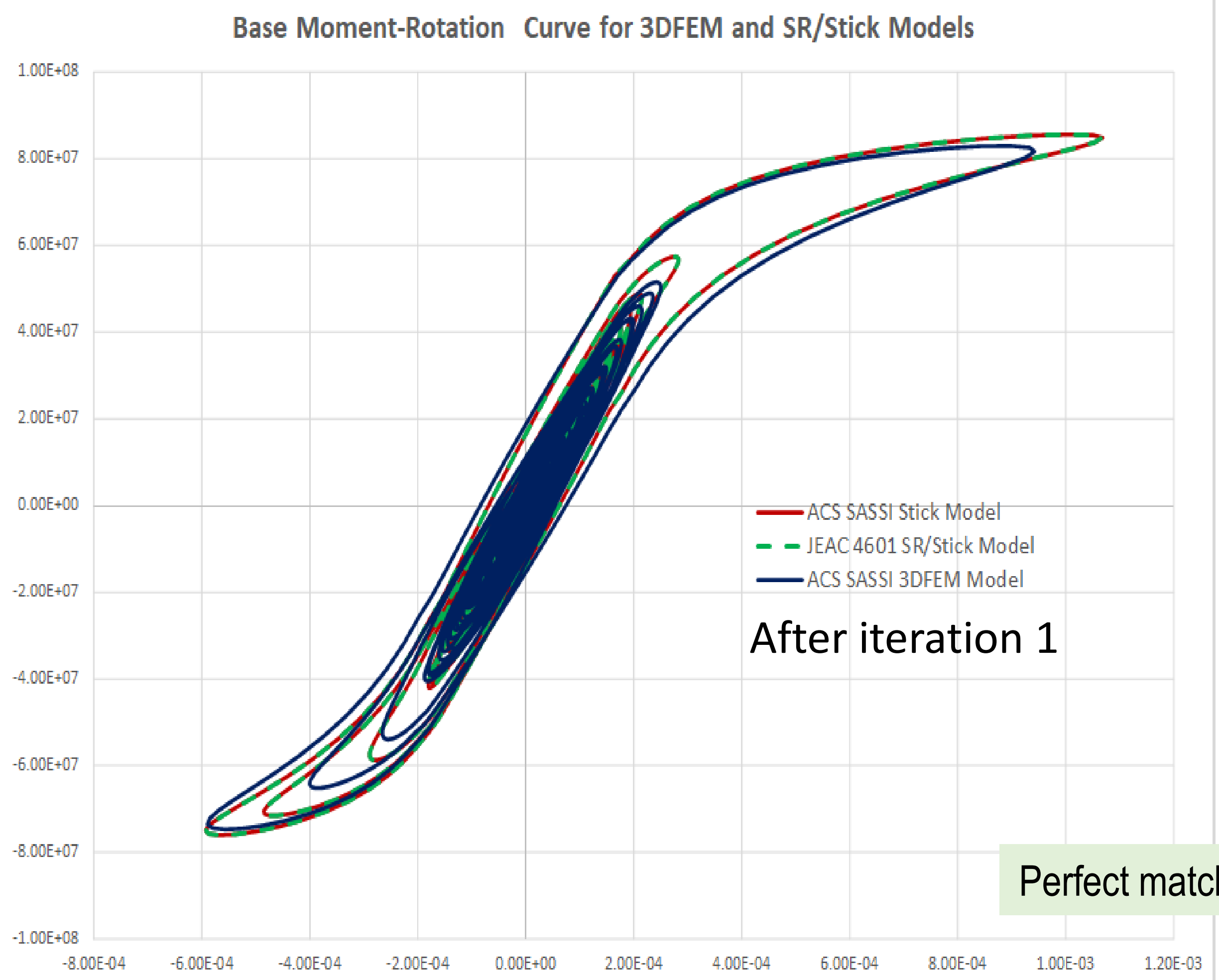


Comparison of Surface Stick and 3DFEM Uplift Parameters for Computed Alfa = 5.57 (converged in 2 iterations)

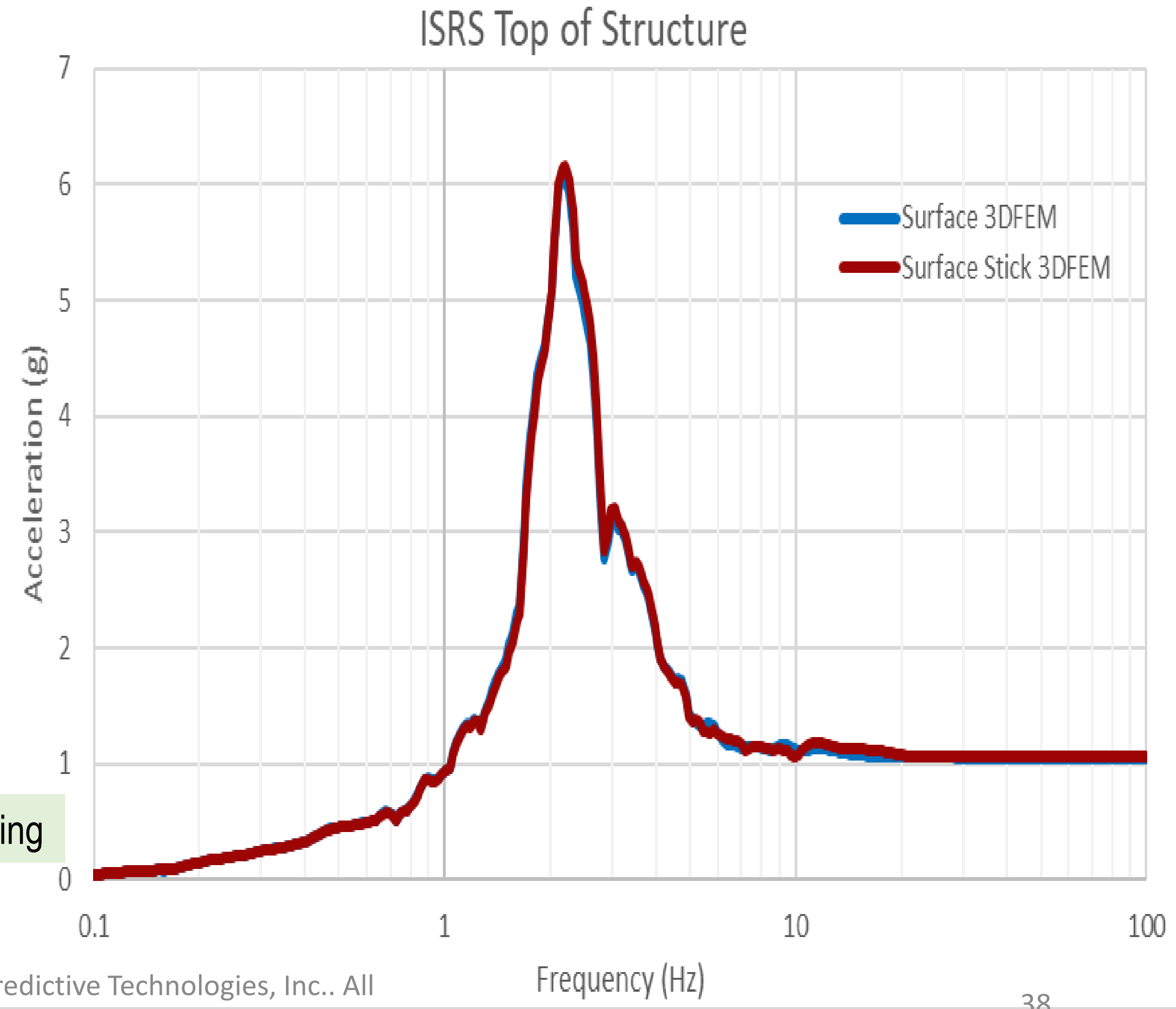
Model	Input Max Acc. (g)	Min. Contact Ratio	Threshold Moment (M_{0yy})	Threshold Rotation (θ_{0yy})	Maximum Moment	Maximum θ_{yy}	Alpha
SURF 3DFEM	0.40	0.532	3.94E+07	2.82E-04	7.359E+07	5.332E-04	5.57
SURF Stick 3DFEM	0.40	0.477	3.94E+07	1.92E-04	7.741E+07	6.475E-04	5.57
SURF Stick SR *	0.40	0.360	3.94E+07	1.92E-04	8.560E+07	1.067E-03	5.57

* Results after *1st iteration* per JEAC 4601 (not fully converged)

Surface UPLIFT Stick vs. 3DFEM for Alfa = 5.57 for 0.40g Input



Perfect matching

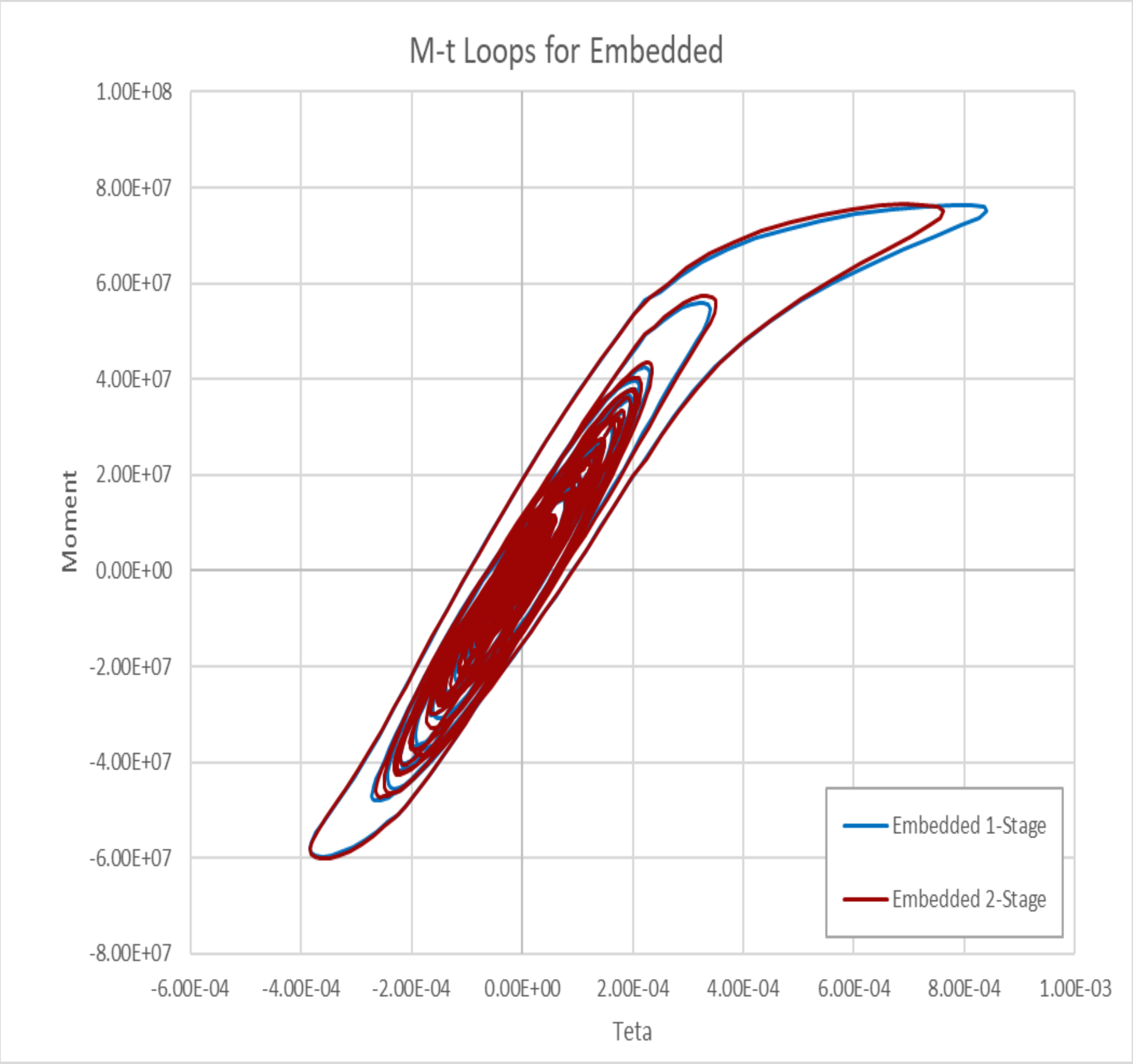


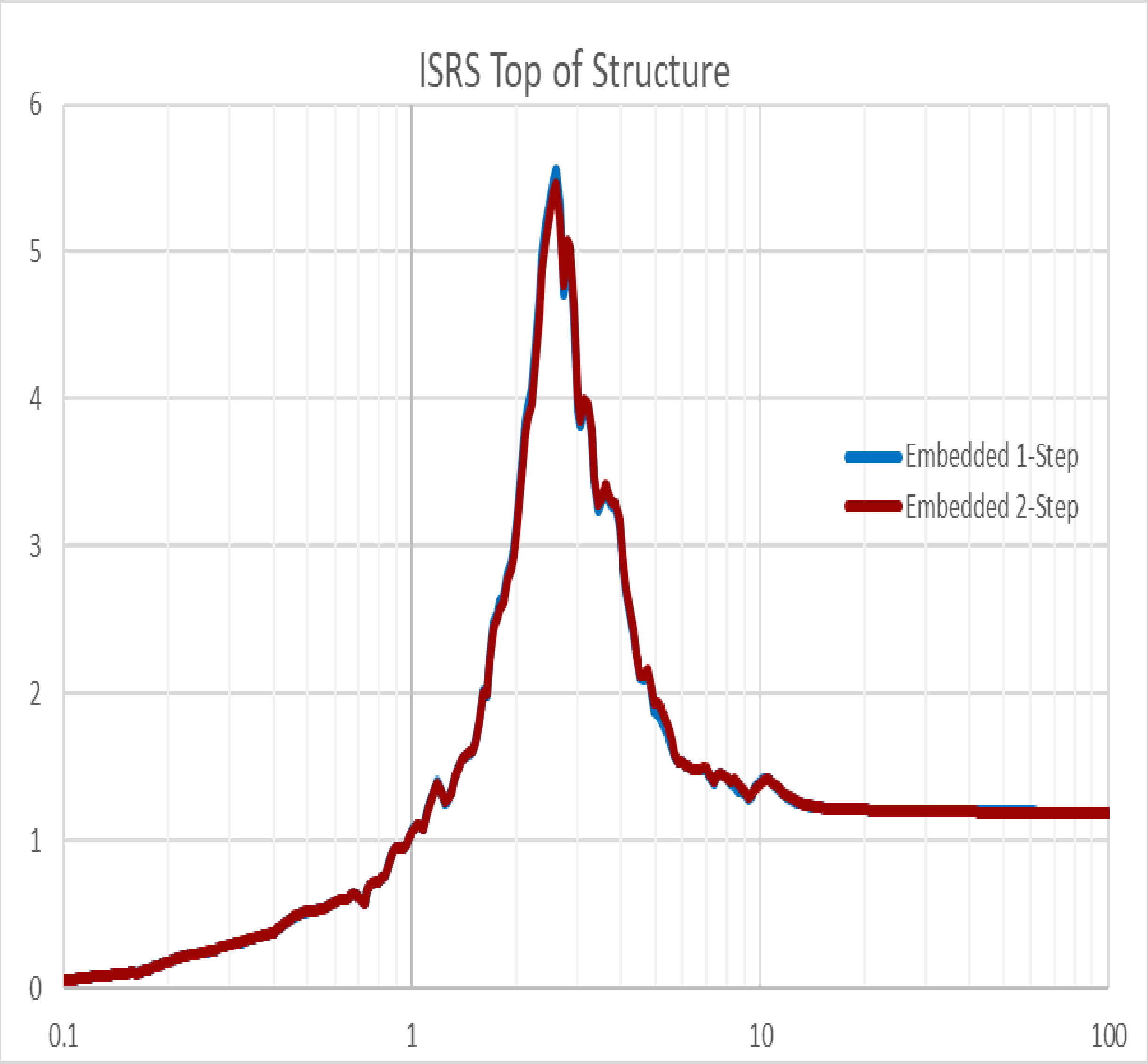
Comparisons for Surface Stick for 0.40g and Embedded 3DFEM for 0.50g for Uplift Parameters (converged in 2 iterations)

Model	Input Max Acc. (g)	Min. Contact Ratio	Threshold Moment (M_{0yy})	Threshold Rotation (θ_{0yy})	Maximum Moment	Maximum θ_{yy}	Alpha
EMB 1-Step (Option 3)	0.50	0.437	3.94E+07	2.35E-04	7.643E+07	8.410E-04	5.19
EMB 2-Step (Options 1-2)	0.50	0.504	3.94E+07	2.26E-04	7.650E+07	7.616E-04	5.57
SURF 3DFEM	0.40	0.532	3.94E+07	2.82E-04	7.359E+07	5.332E-04	5.57
SURF Stick 3DFEM	0.40	0.477	3.94E+07	1.92E-04	7.741E+07	6.475E-04	5.57
SURF Stick SR *	0.40	0.360	3.94E+07	1.92E-04	8.560E+07	1.067E-03	5.57

* Results after 1st iteration per JEAC 4601 (not fully converged)

Embedded UPLIFT 3DFEM 2-Step and 1-Step Approaches for 0.50g

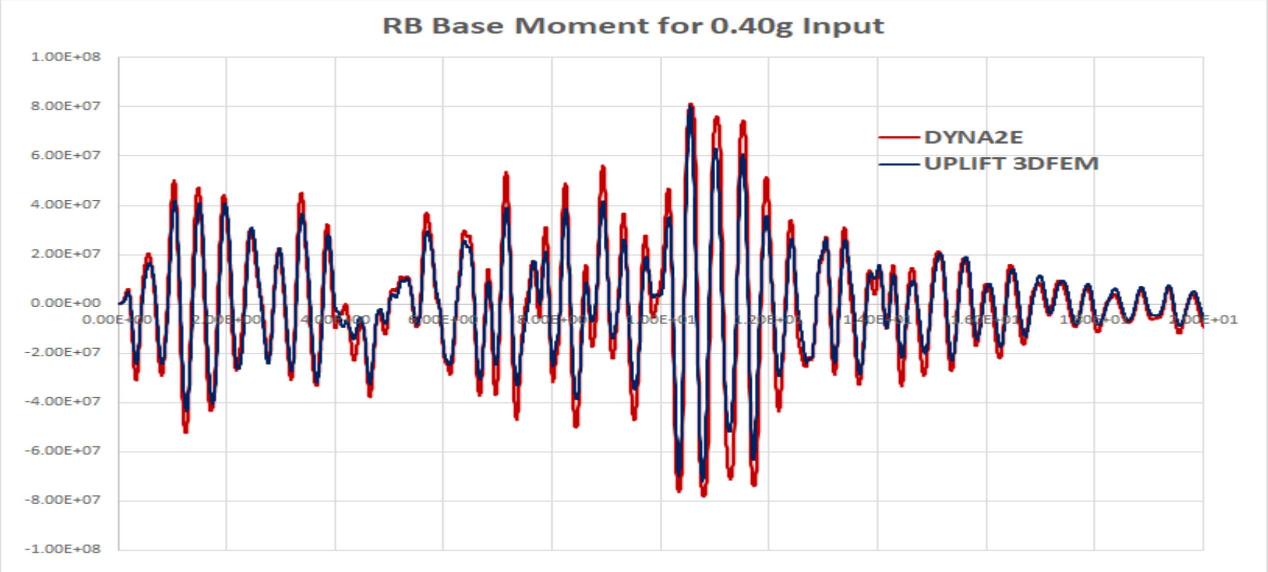


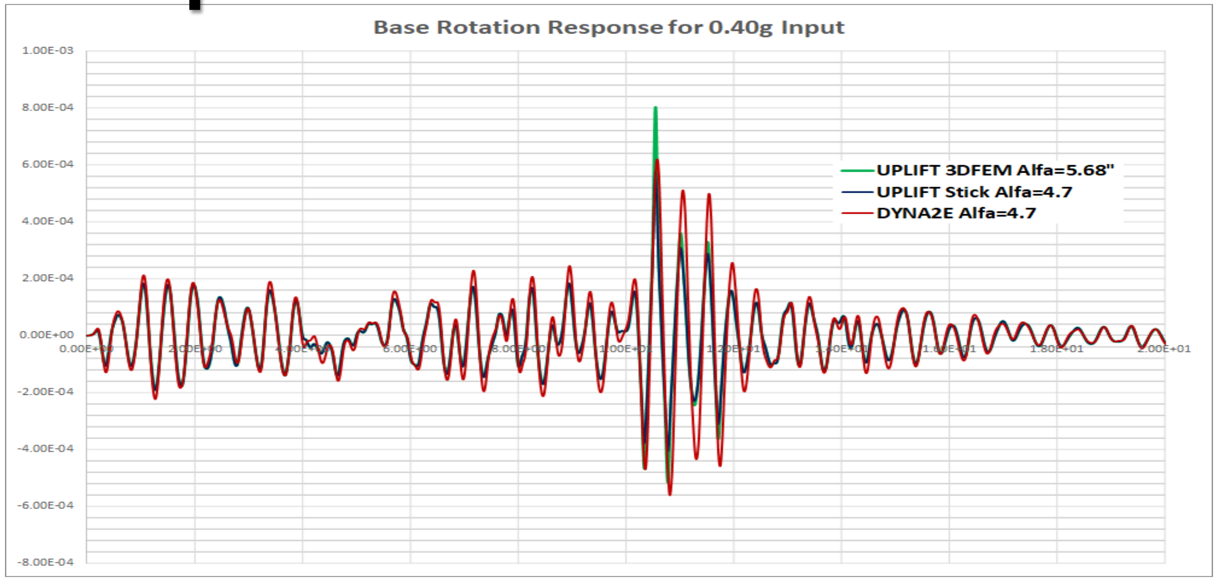


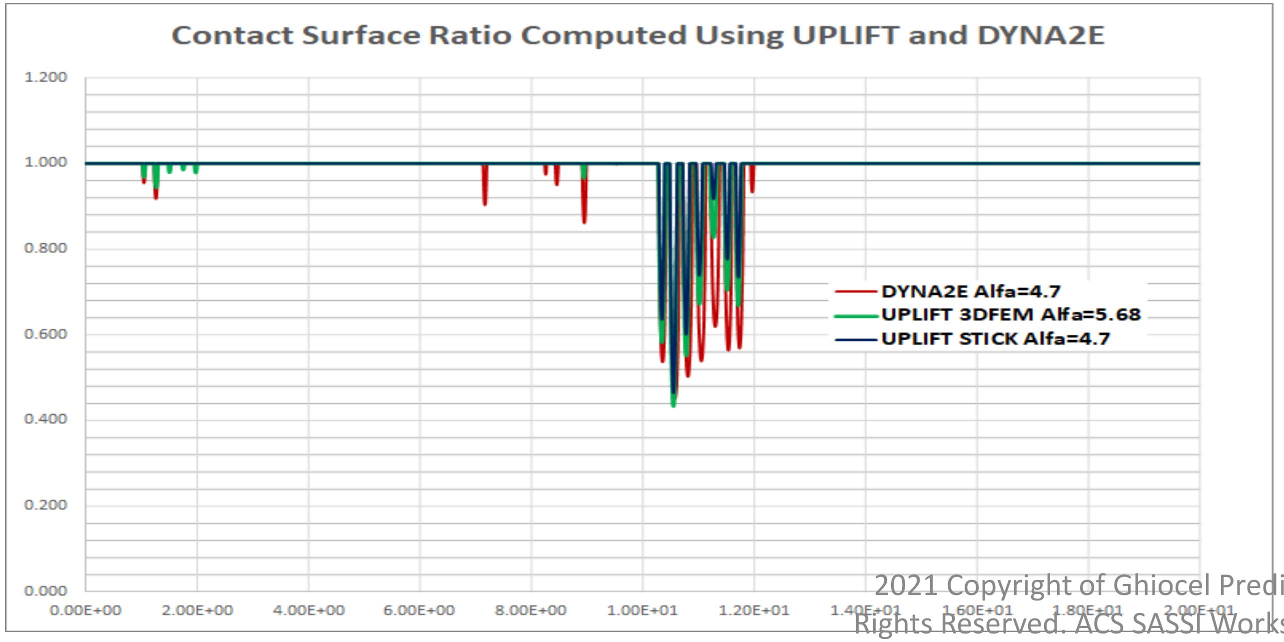
UPLIFT vs. DYNA2E Results for Surface Stick for 0.40g Input

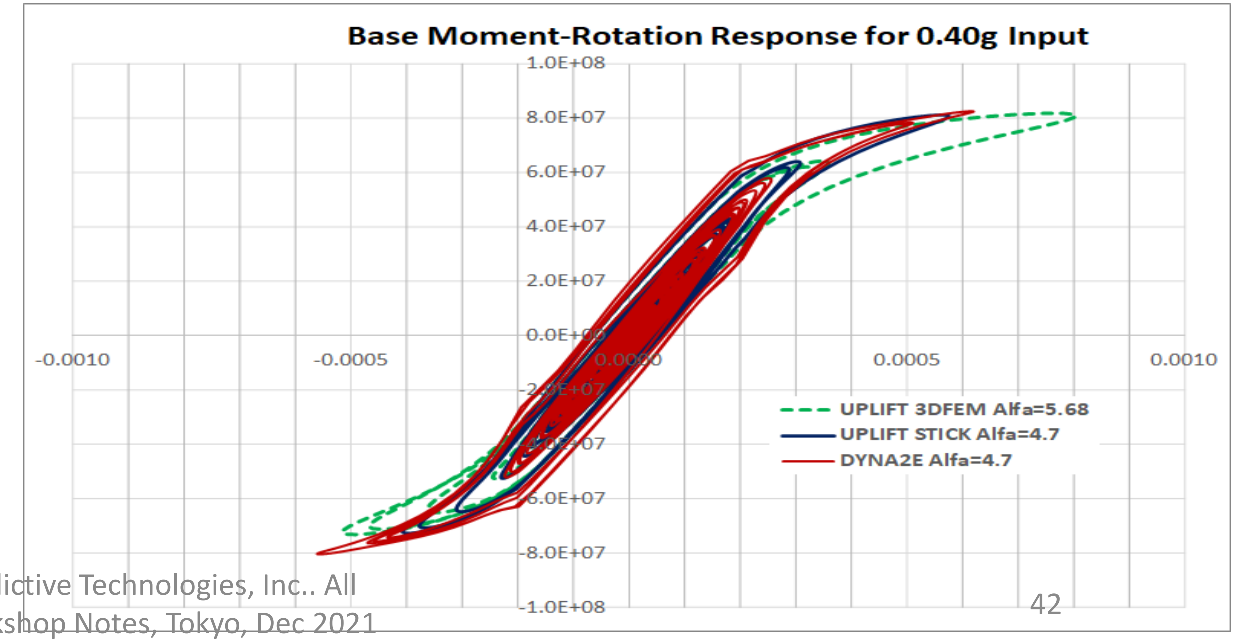
(Very thankful to SHIMIZU and TERRABYTE for Providing Japanese DYNA2E Software Results)

UPLIFT Stick vs. DYNA2E Stick Models with assumed Alfa=4.7 vs. UPLIFT 3DFEM with computed Alfa=5.68

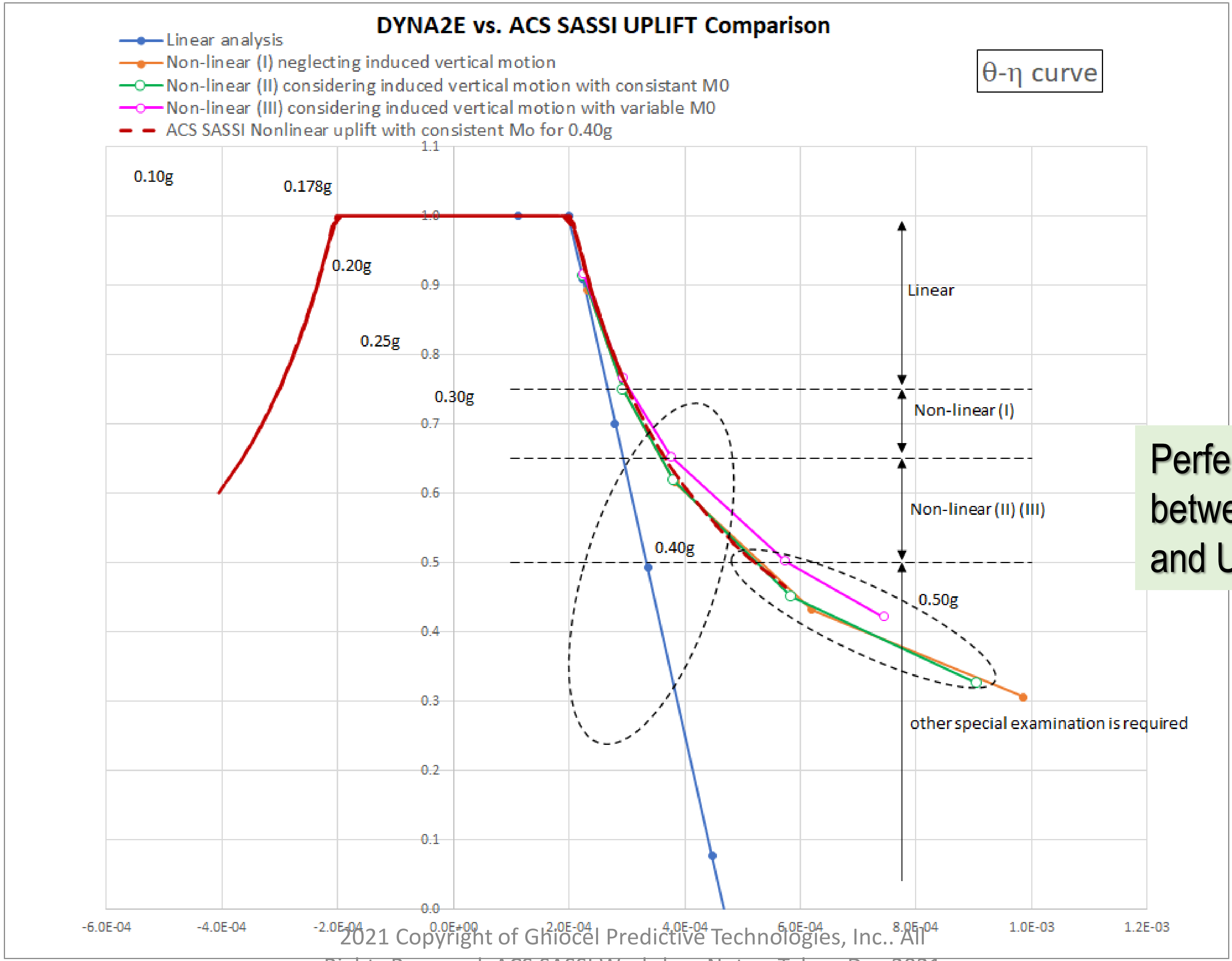






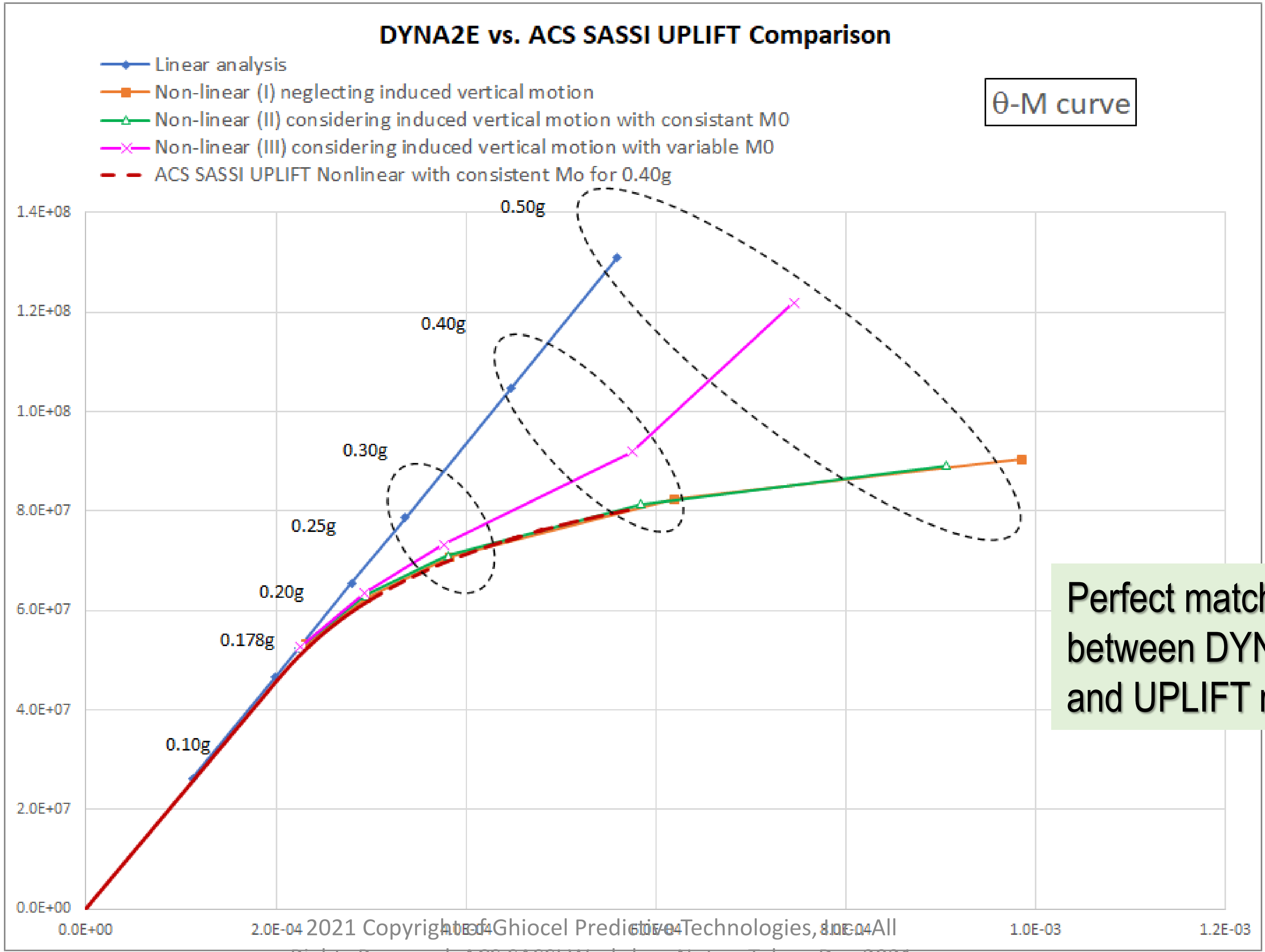


UPLIFT and DYNA2E Stick Model Uplift Results for Alfa=4.7



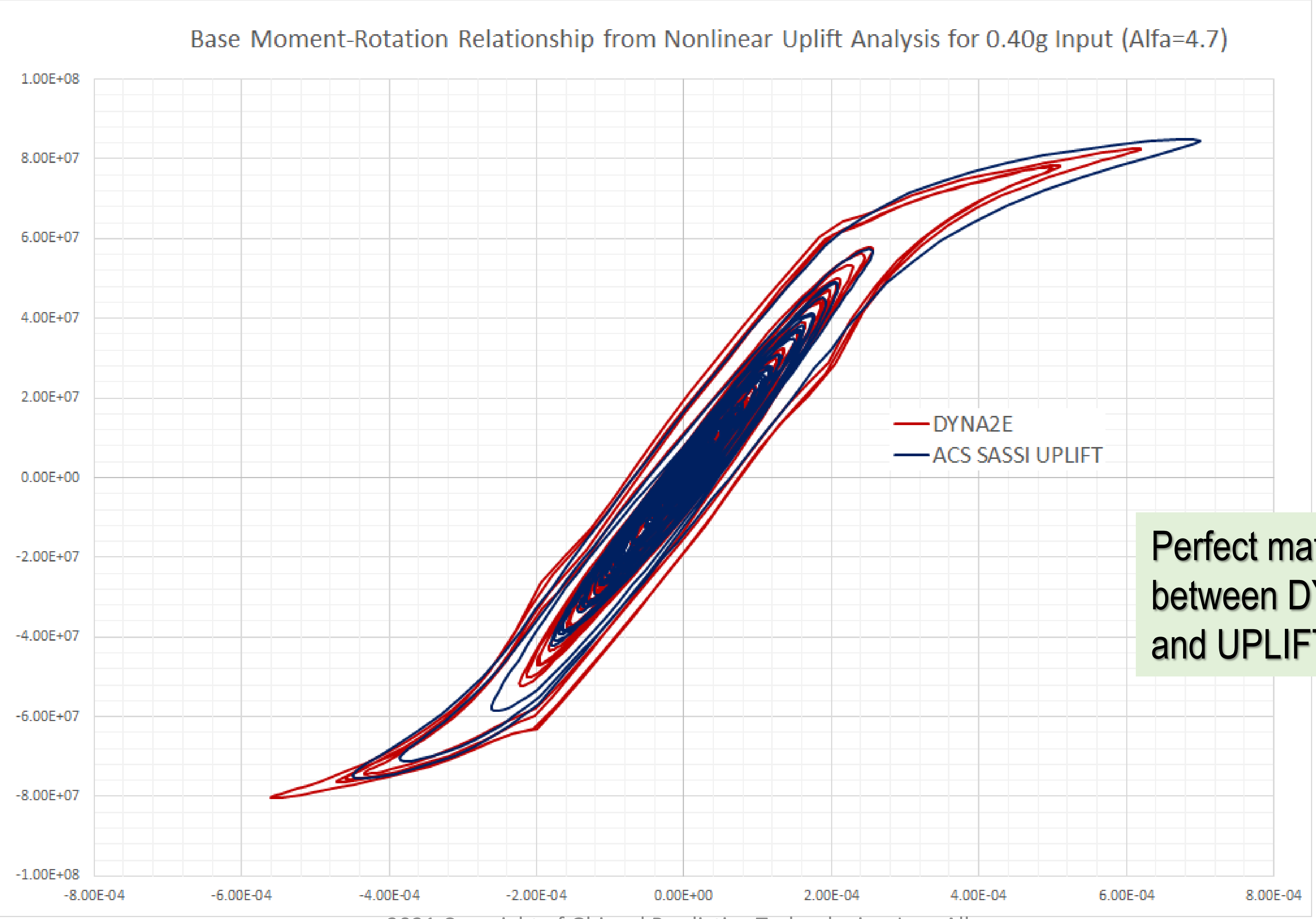
Perfect matching between DYNA2E NL(II) and UPLIFT results

UPLIFT and DYNA2E Stick Model Uplift Results for Alfa=4.7



Perfect matching between DYNA2E NL(II) and UPLIFT results

UPLIFT and DYNA2E Base Moment-Rotation for Alfa=4.7 and 0.40g



Perfect matching between DYNA2E NL(II) and UPLIFT results

Concluding Remarks on Option UPLIFT Advantages Using 3DFEM

1- The ACS SASSI implementation uses directly 3DFEM for uplift SSI analysis. *The soil reaction coefficients used in JEAC 4601-2015 App.6 equations can be accurately computed based on the 3DFEM seismic SSI analysis*. The soil reaction coefficients vary between 4.7 and 6.0 for surface SSI models.

2- The nonlinear uplift analysis using 3DFEM can be applied not only for the two separated horizontal X and Y seismic inputs, but also for the *simultaneous X and Y seismic inputs*.

3- The *embedment effects are well captured using 3DFEM within the ACS SASSI methodology* in complex frequency. The embedment introduces as a coupling between the foundation horizontal and the rocking soil motions due to the side-soil resistance, that is automatically included in the ACS SASSI SSI solution. For the 3DFEM SSI models, the global foundation soil impedances are computed by integrating the distributed soil impedances over the foundation surface area for all the foundation-soil interface nodes assuming a rigid body motion of the foundation. The *simple Novak's approach is no longer needed*.

4- For the embedded 3DFEM foundations, it is particularly needed that *the bottom-soil and side-soil impedances are computed separately* using FVROM-INT, since per the JEAC 4601-2015 App. 3.6, only the *bottom-soil rocking impedances need to be adjusted* for including the nonlinear foundation uplift effects, while the side-soil impedances could remain unchanged. *FVROM can also include the eventual wall-soil separation effects on excavation impedances* for given depth.

ACS SASSI NQA Advances on Seismic SSI Analysis of NPP Structures Using Best Practices in US and Japan

Ghiocel Predictive Technologies Inc.

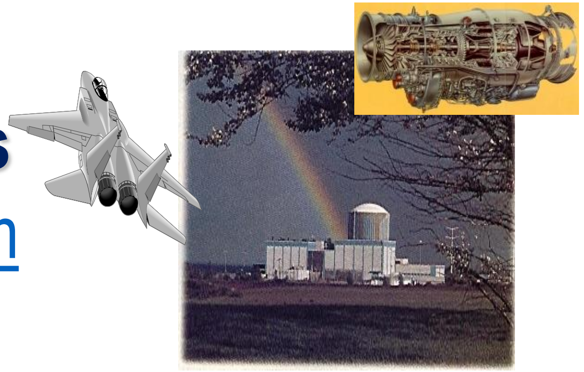
Dr. Dan M. Ghiocel

Member of ASCE 4 & 43 Standards

Email: dan.ghiocel@ghiocel-tech.com

Ghiocel Predictive Technologies Inc.

http://www.ghiocel-tech.com



Day 2: 2 - Advances for Efficient SSI Modeling of Deeply Embedded SMR

2.1 Specific SSI Modeling Aspects of Deeply Embedded SMR Structures

2.2 Flexible Volume Reduced-Order Modeling (FVROM-INT) Approach

2.3 Comparative SMR Studies Including Linear vs. Nonlinear SSI Analyses

ACS SASSI Workshop, Tokyo

December 2-3, 2021

Presentation Content:

Day 2: 2 - Advances for Efficient SSI Modeling of Deeply Embedded SMR

2.1 Specific SSI Modeling Aspects of Deeply Embedded SMR Structures

2.2 Flexible Volume Reduced-Order Modeling (FVROM or FVROM-INT) Approach

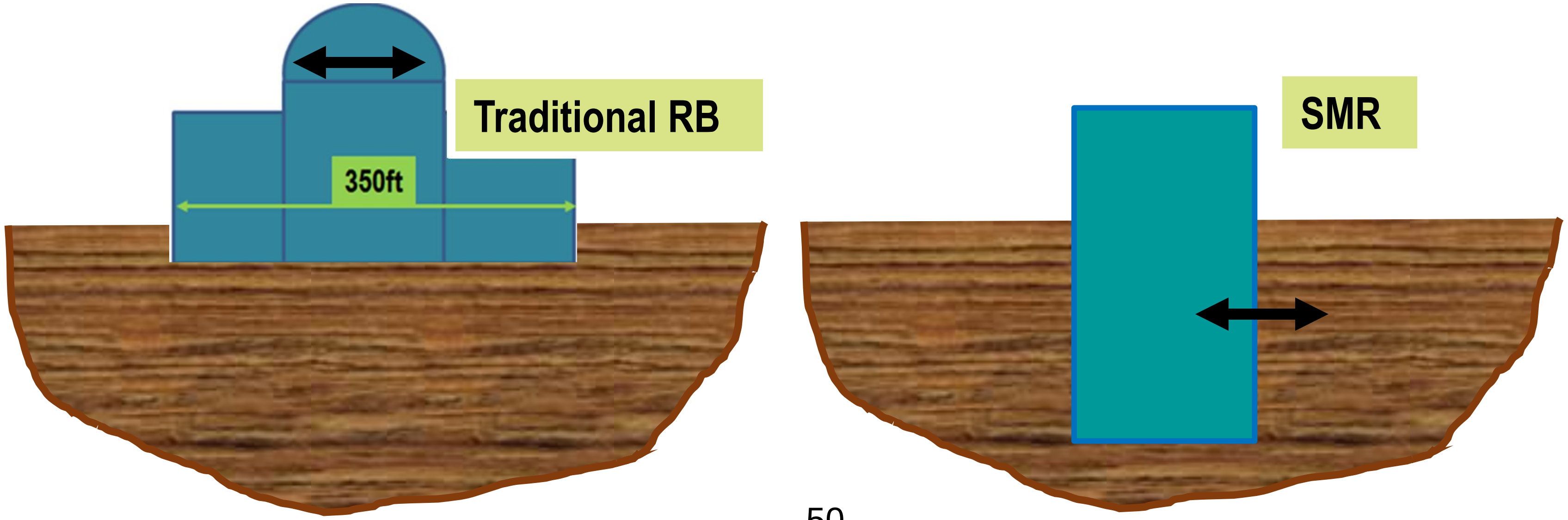
2.3 Comparative SMR Studies Including Linear vs. Nonlinear SSI Analyses per US and Japan Standards

Question & Answers Session

2.1 Specific SSI Modeling Aspects of Deeply Embedded SMR Structures

What is particular to SSI Analysis of DES/SMR?

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

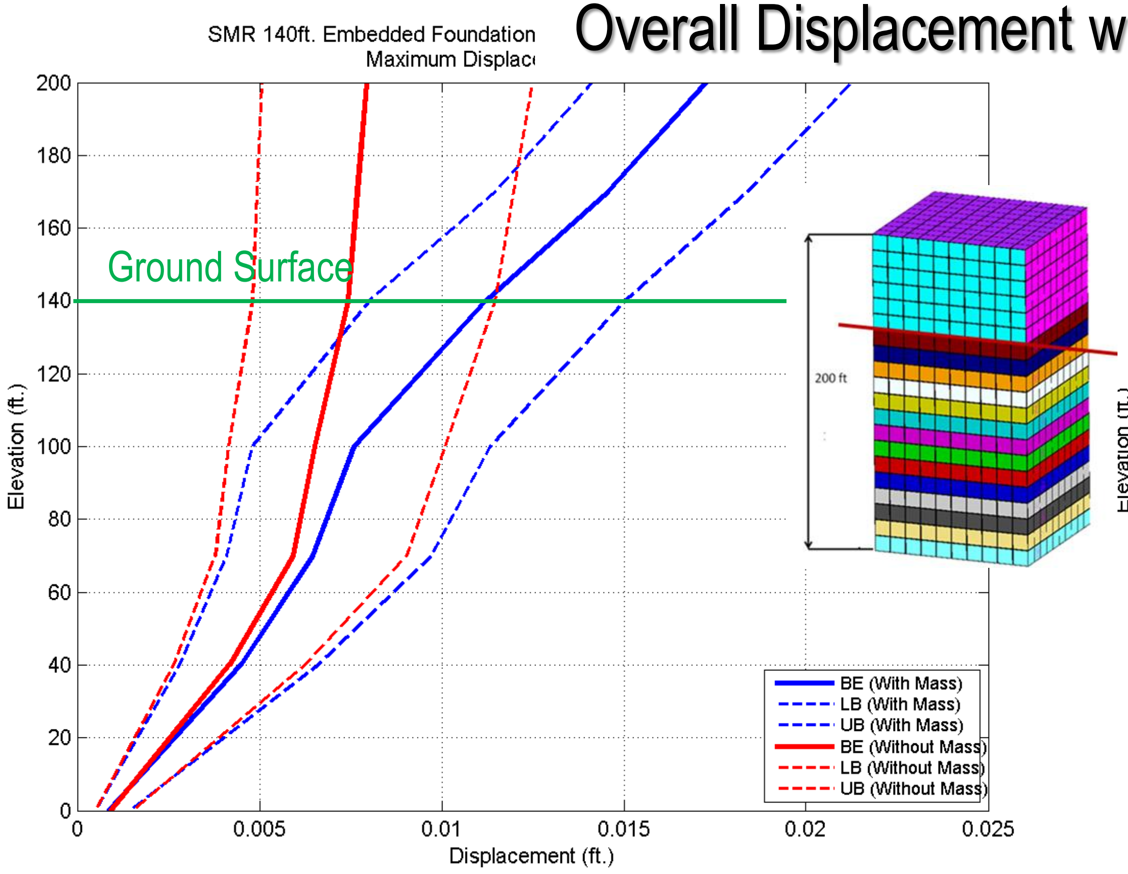


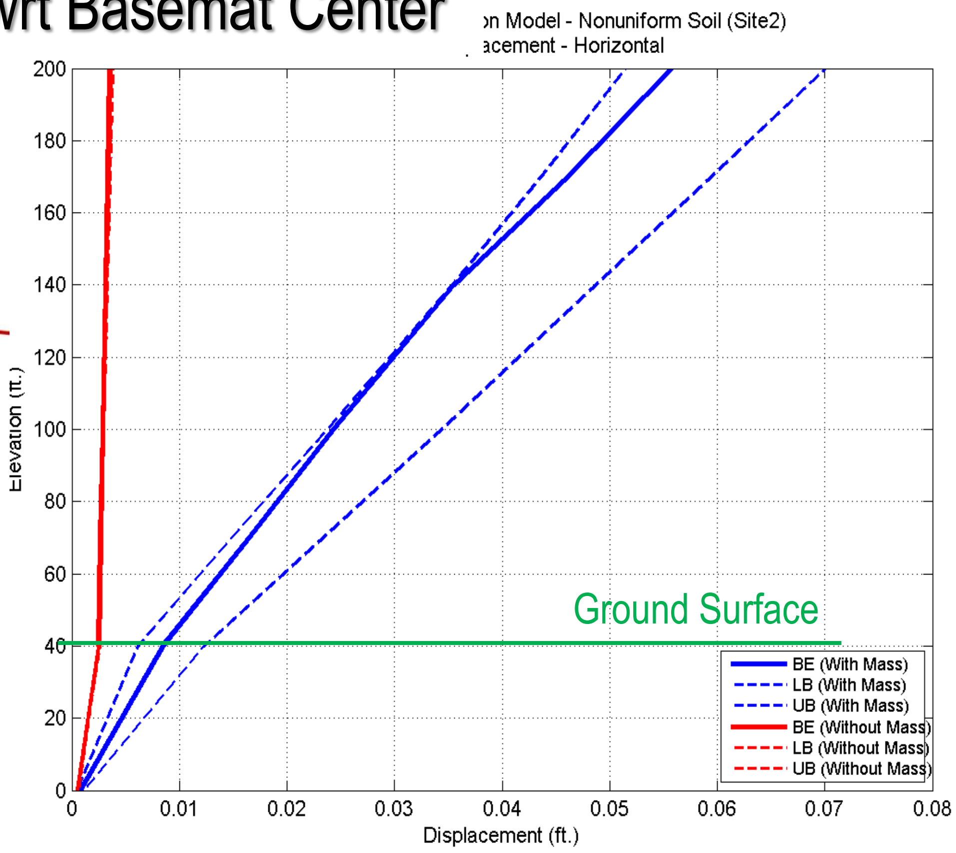
Effects of Kinematic SSI for Embedded SMR

140 ft Embedment

40 ft Embedment

Overall Displacement wrt Basemat Center





REMARKS:

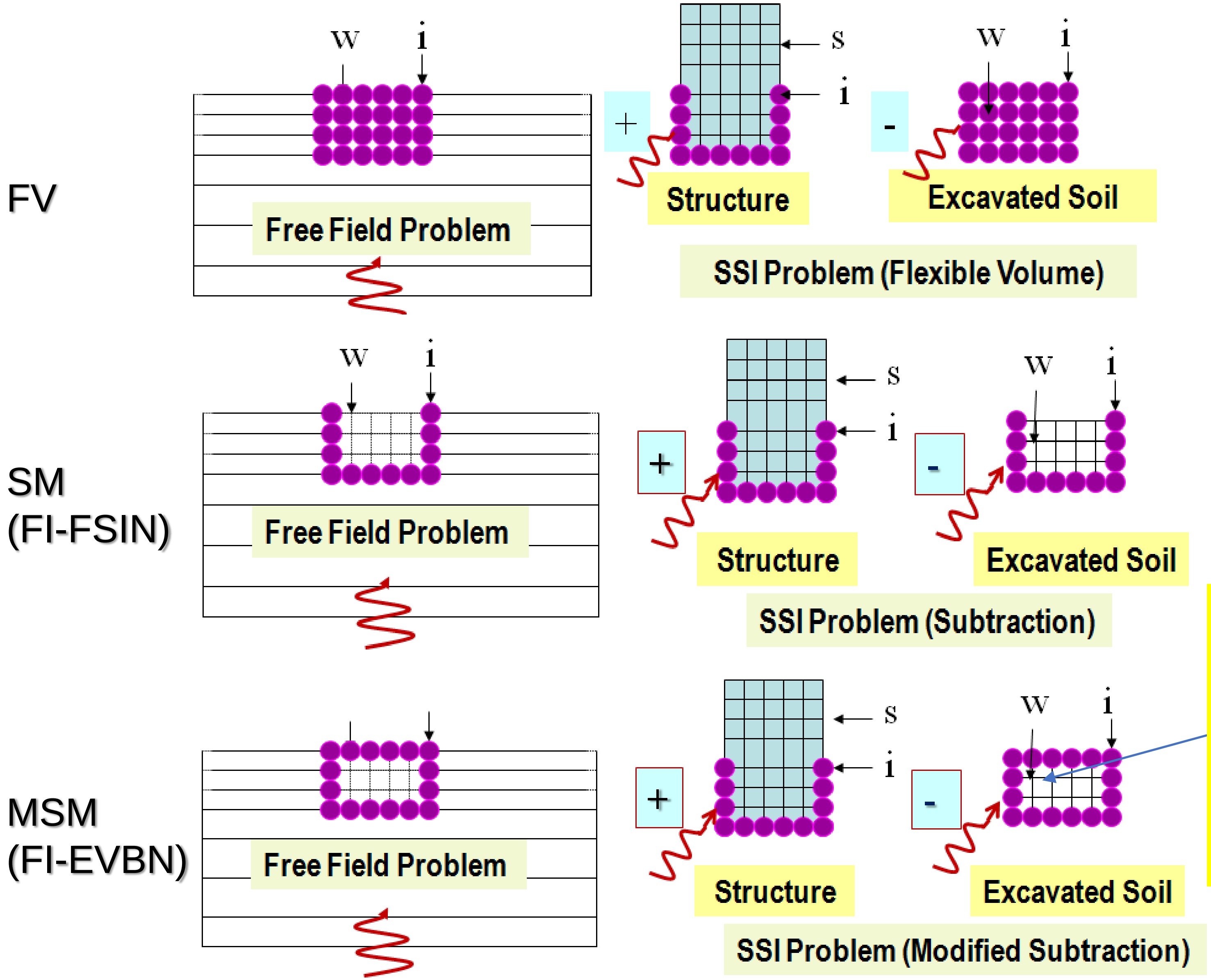
- For 140 ft embedment kinematic SSI is dominant, 80-90% below surface, and about 50% above surface
- For 40 ft embedment the kinematic SSI much less significant, only 20-30% below surface and less than 10 % above surface.

Effects Interaction Nodes Distribution Inside Excavation Volume

Uniform vs. Nonuniform Soils

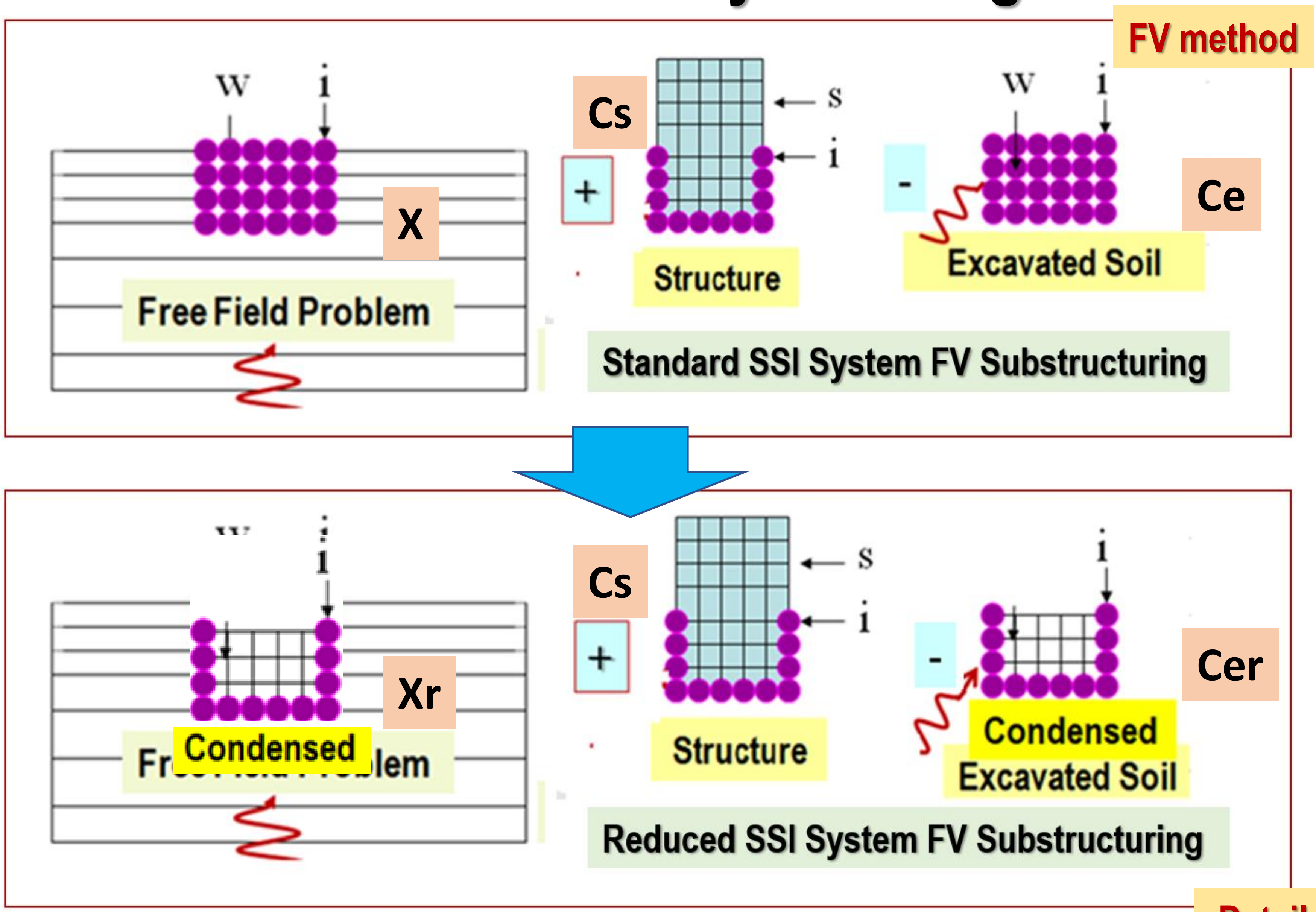
Standard SASSI Flexible Volume Methods for Embedded Structures

Flexible Volume Substructuring Approaches



ACS SASSI methods to include additional internal interaction nodes. FFV (ESM with multiple levels – skip parameter) and new FVROM, FVROM-INT

Fast Seismic SSI Analysis Using FVROM-INT Approach



The excavated soil dynamic matrix is a frequency-dependent large-size full complex matrix.

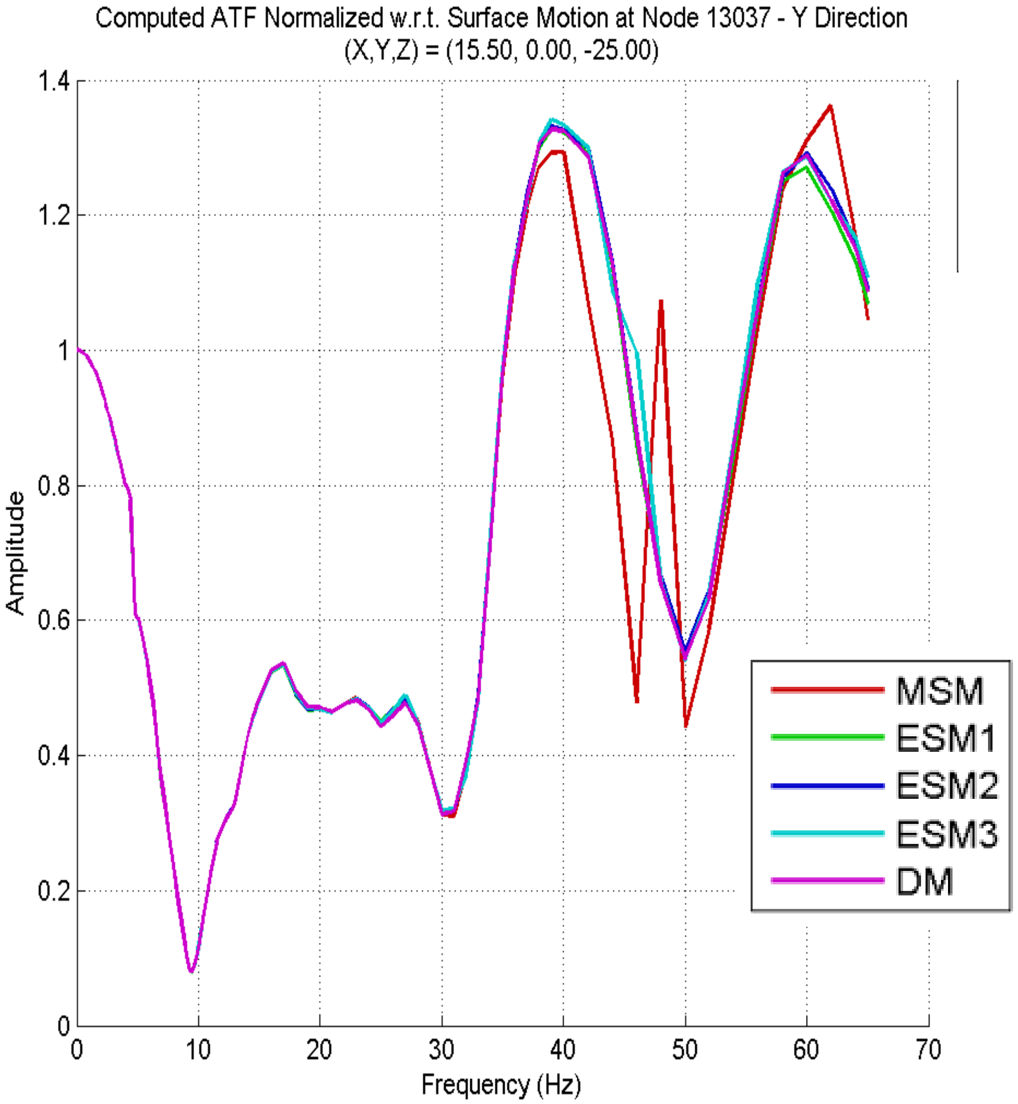
Due to its lack of sparseness, the inclusion of this matrix in the SSI solution affects largely the numerically efficiency of the FV substructuring as defined in the original SASSI approach.

Using a frequency-dependent matrix condensation scheme, the size of this large-size matrix can be hugely reduced, and by this large speedups of SSI solution are obtained.

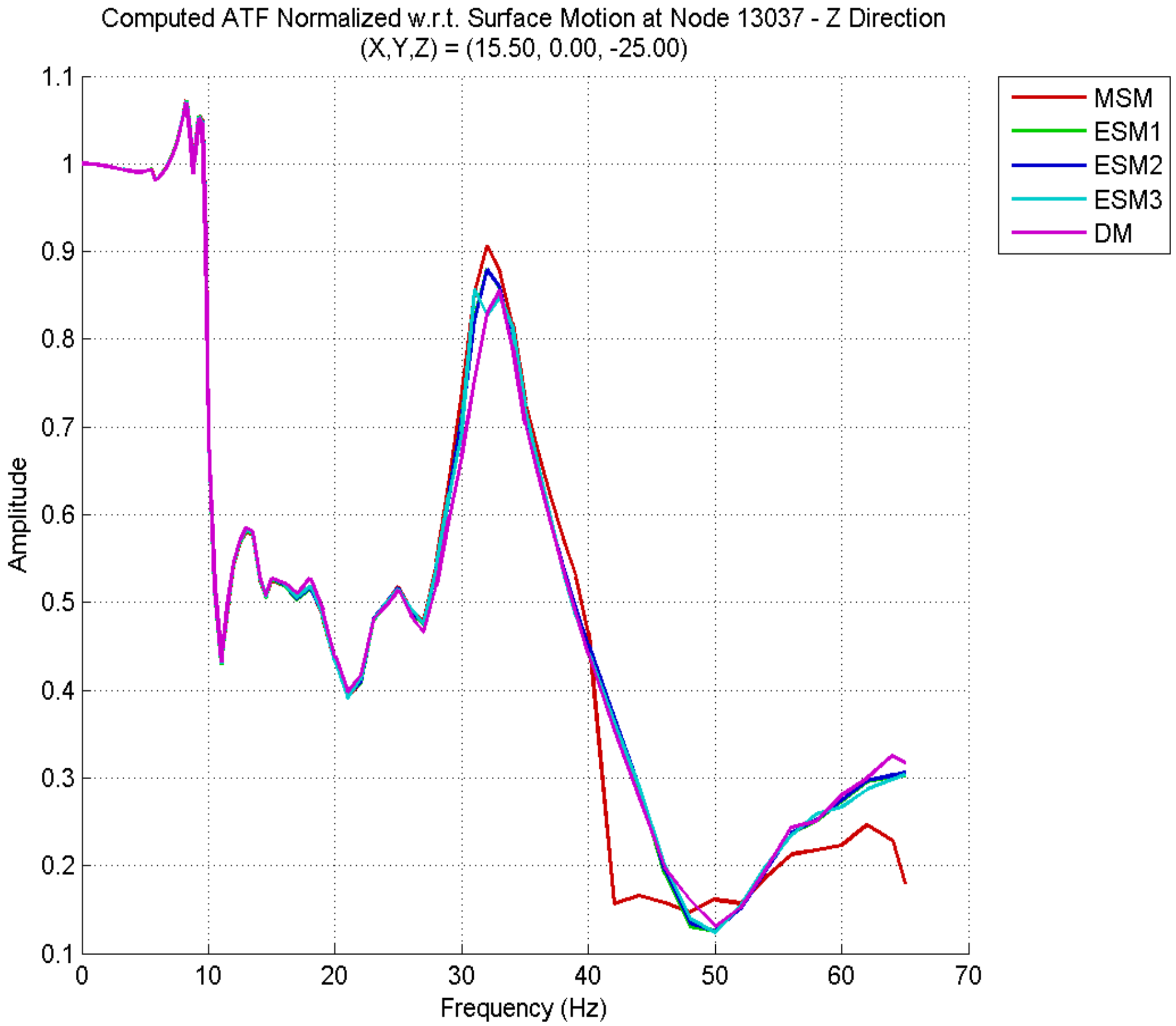
Details on FVROM, FVROM-INT in next presentation

MSM Approach Fails for Deeply Embedded Structures

Direction X



Direction Z



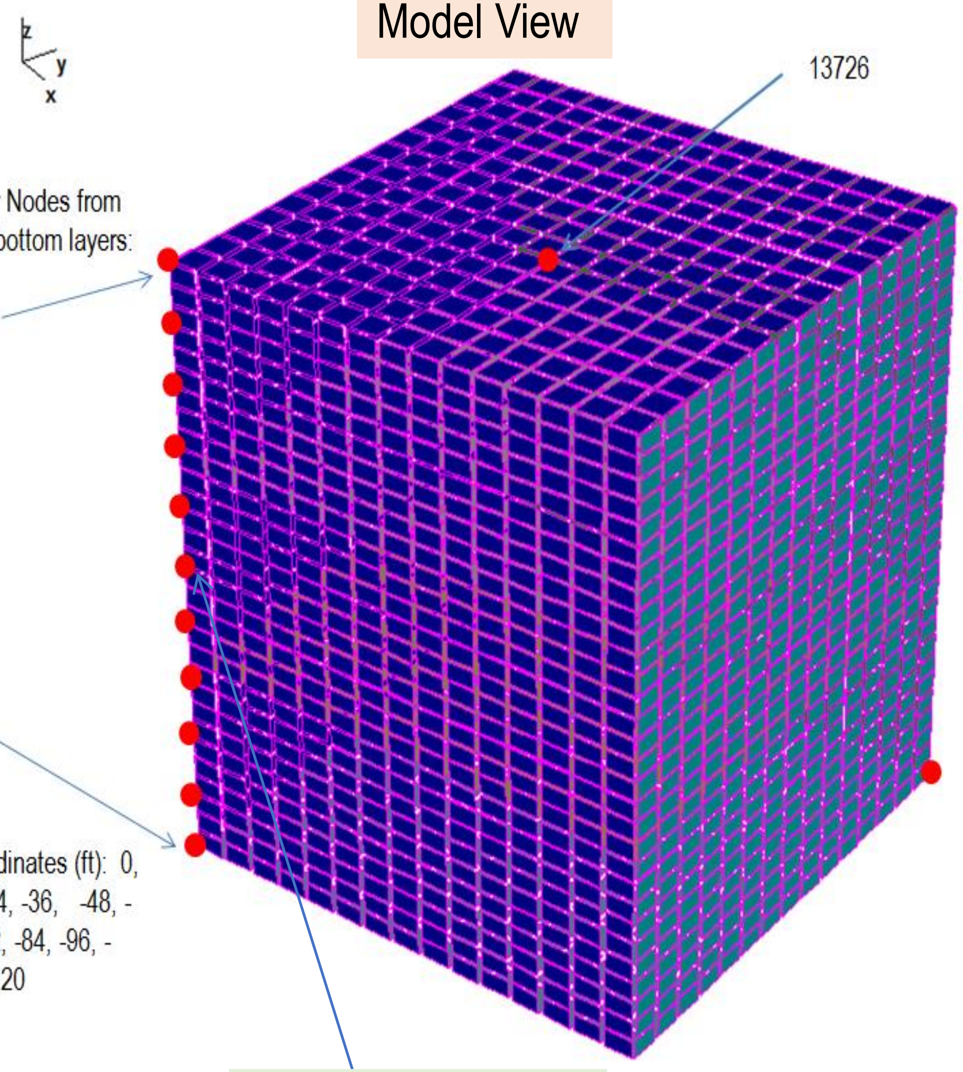
Fully Embedded (Massless) SMR Methodology Study

Volume Size: 120 ft x 80 ft x 80 ft

Model View

Corner Nodes from top to bottom layers:

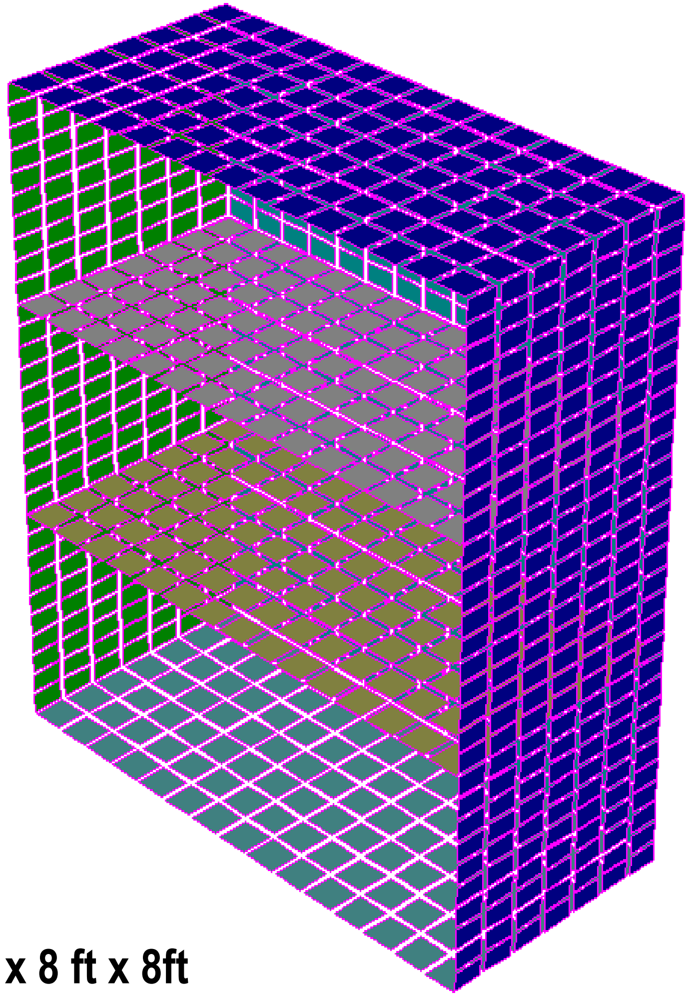
7681, 6913, 6145, 5377, 4609, 3841, 3073, 2305, 1537, 769, 1



Z-coordinates (ft): 0, -12, -24, -36, -48, -60, -72, -84, -96, -108, -120

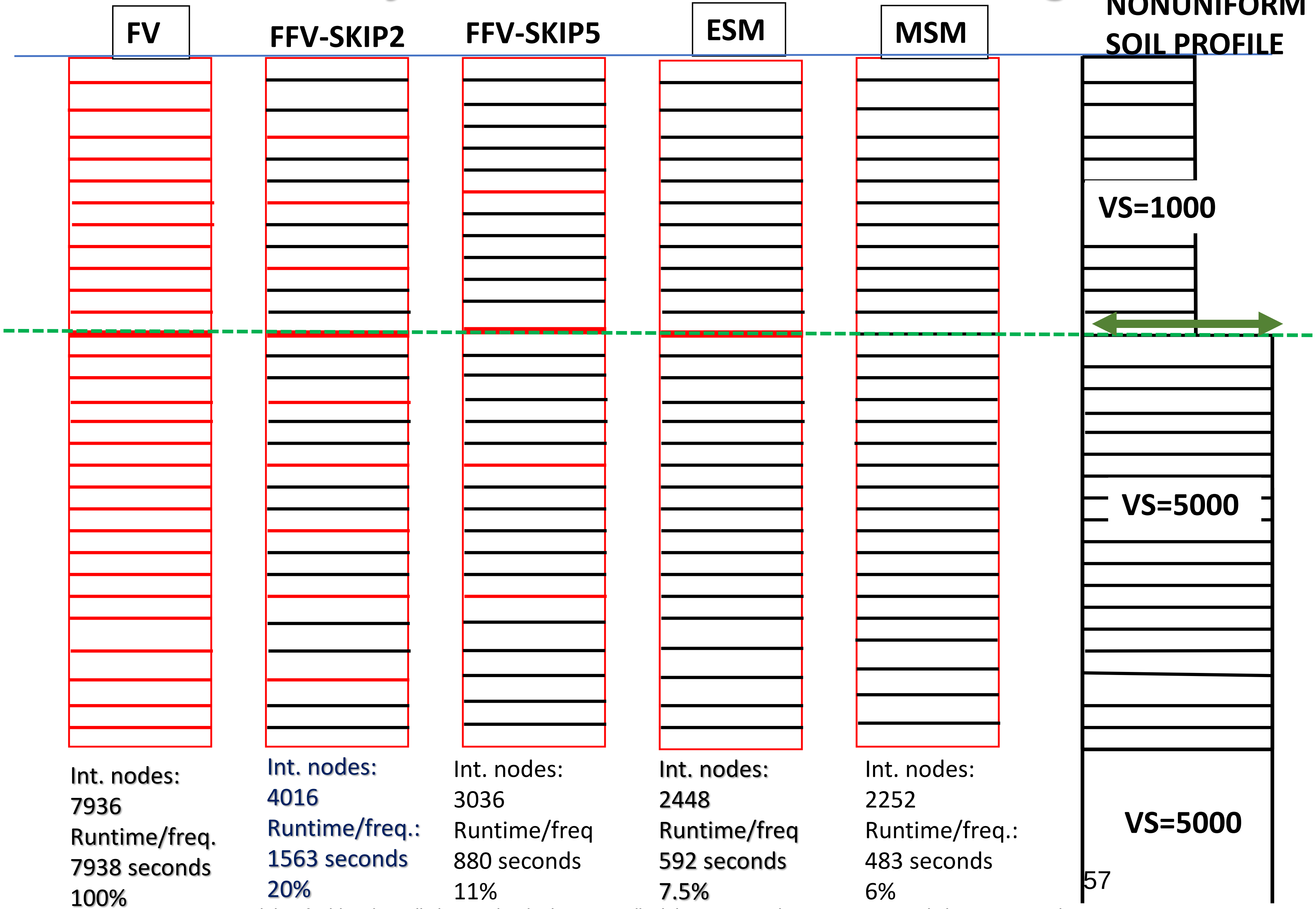
FFV-Skip 2 Levels

Vertical Section

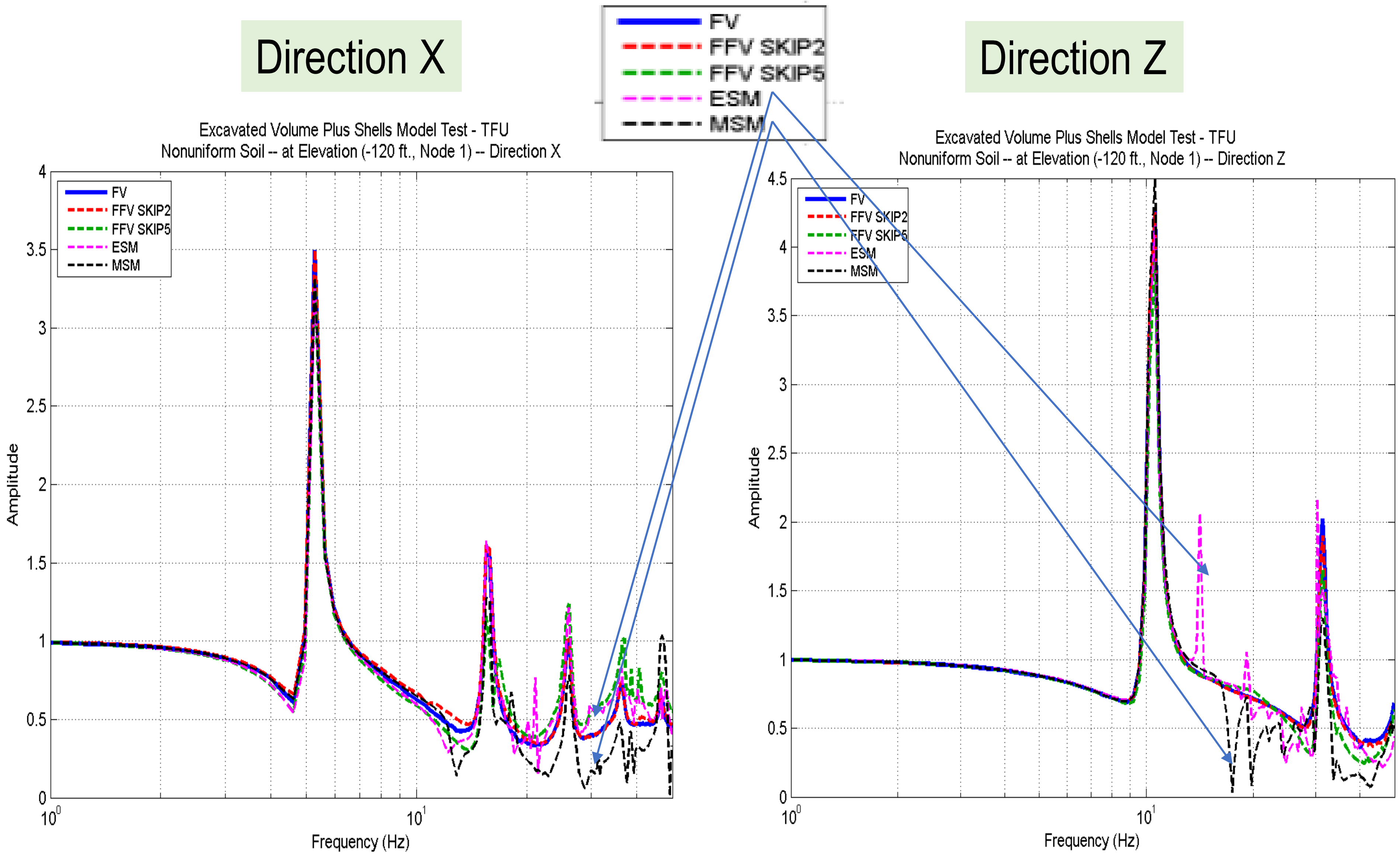


Mesh 4 ft x 8 ft x 8ft
7,938 Interaction Nodes

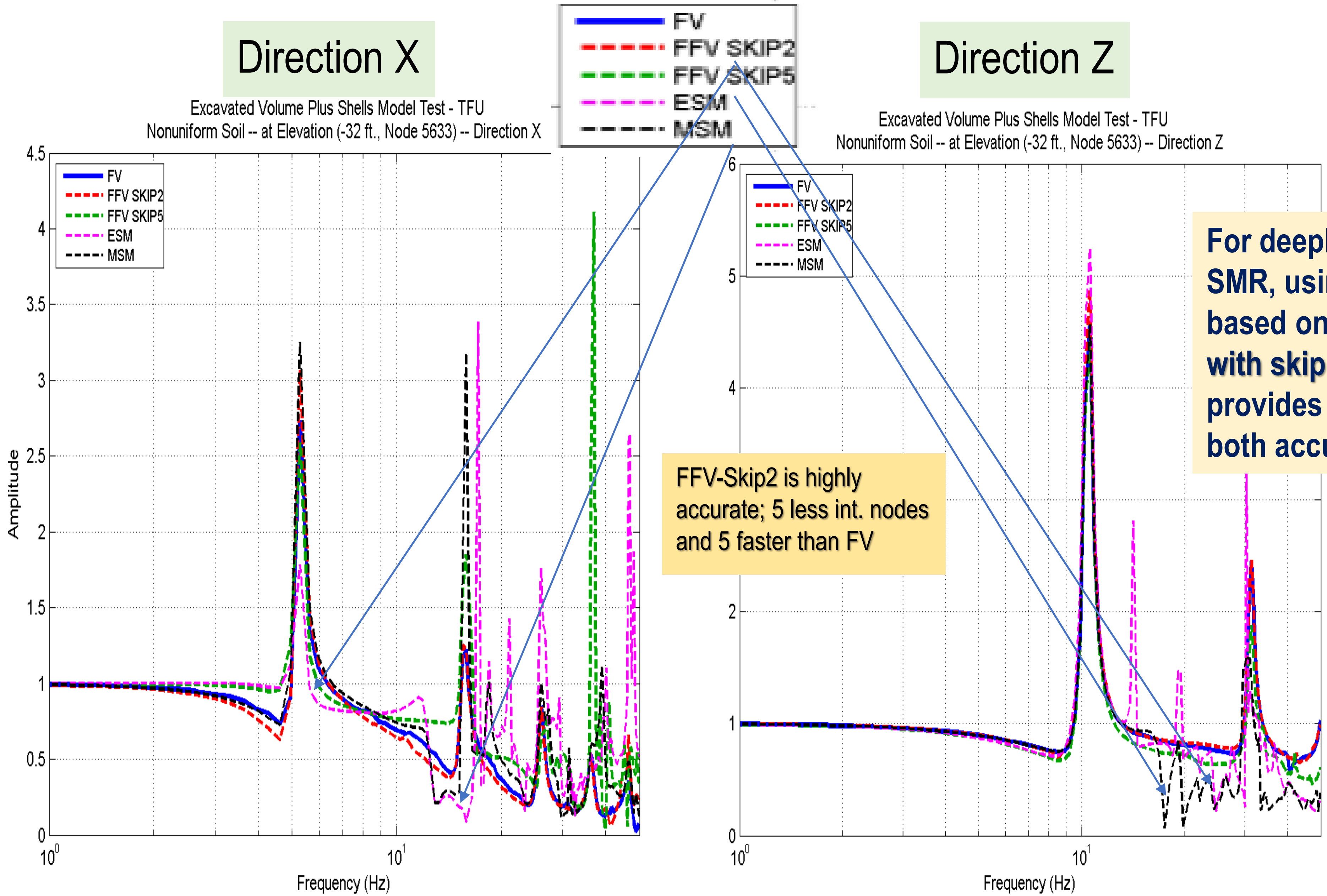
Excavation Study on SASSI FV Substructuring Methods



Comparative ATF at -120 ft Depth (Foundation Level)



Comparative ATF at -32 ft Depth (1/4 of Embedment)



FFV-Skip2 is highly accurate; 5 less int. nodes and 5 faster than FV

For deeply embedded SMR, using FVROM-INT based on an original FFV with skip 2-3 SSI model provides optimal solution, both accurate & efficient.

Effects of Excavation Meshing

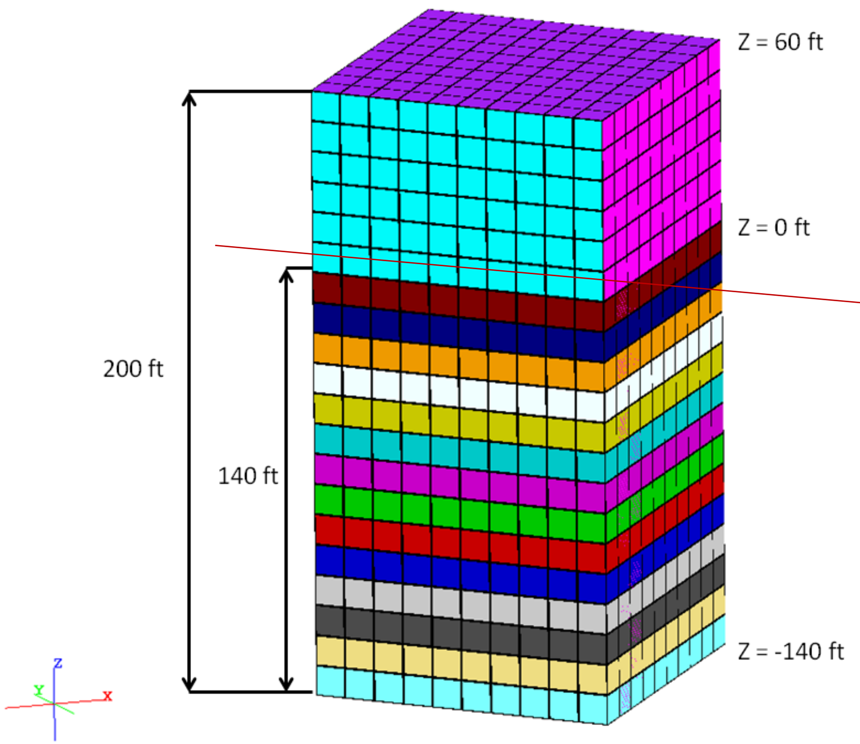
Uniform vs. Nonuniform Soils

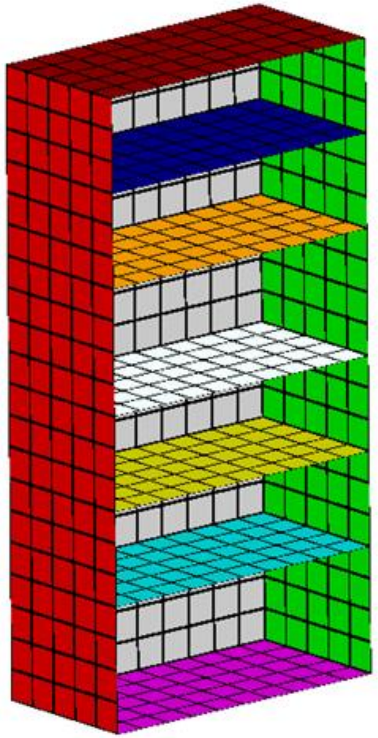
Excavation Volume Mesh Nonuniformity Study

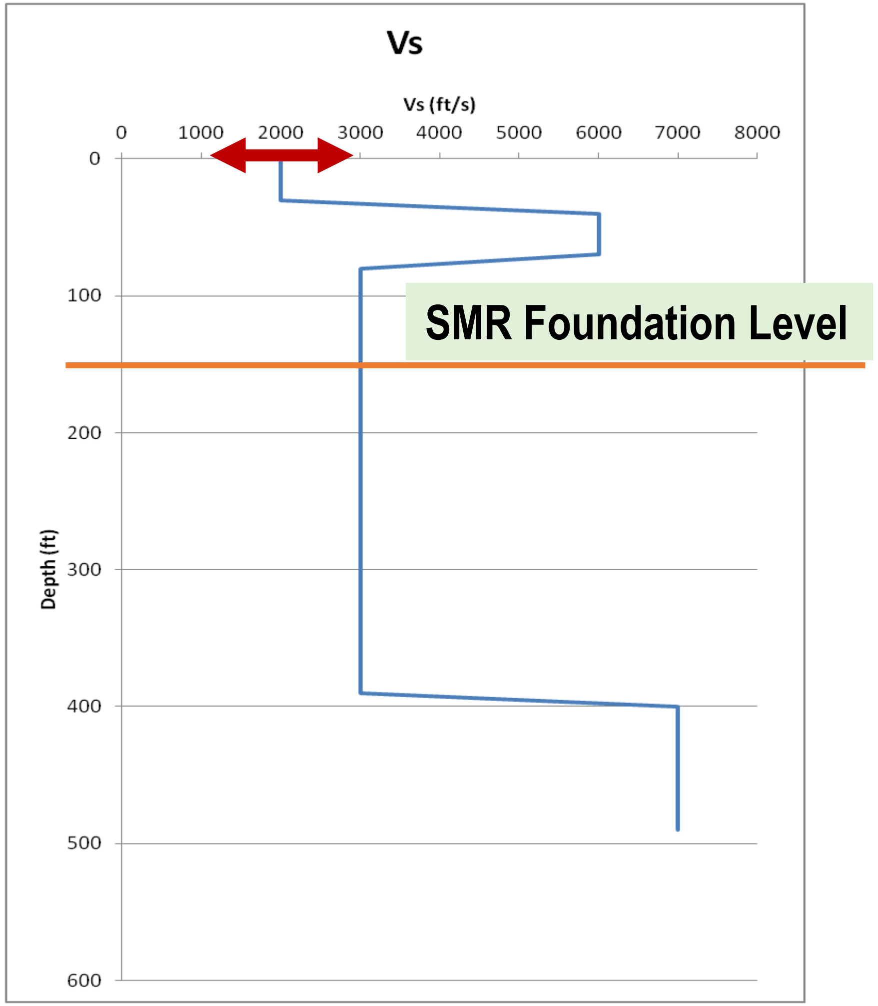
Volume Size: 200 ft x 100 ft x 100 ft

140 ft Embedded SMR Model

Vs Soil Profile (fps)



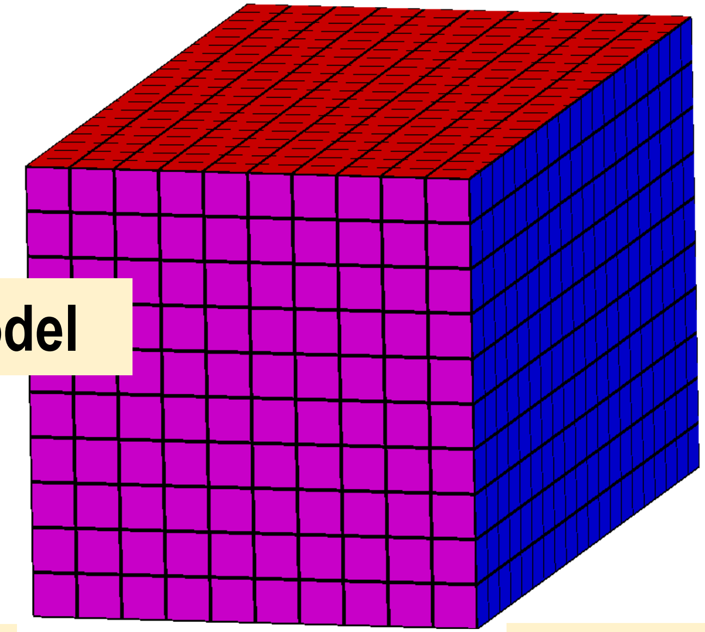




SMR size: 100 ft x 100 ft X 200 ft
Embedment: 140 ft
Mesh size: 10 ft X 10 ft X 10 ft
Number of Nodes: 2,580
Interaction Nodes: 1,815

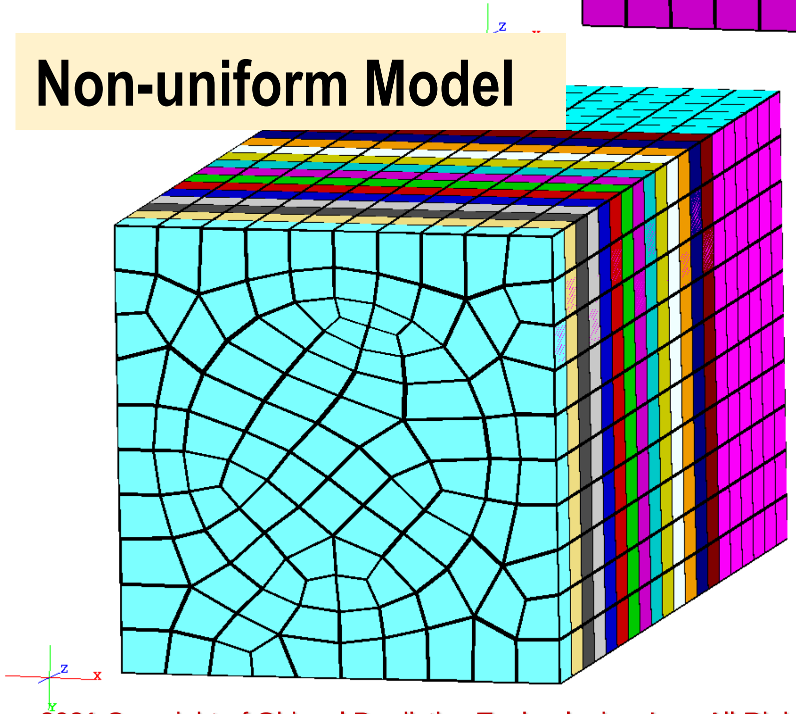
140 ft Embedment SMR Excavation Volume Meshes

Uniform Model

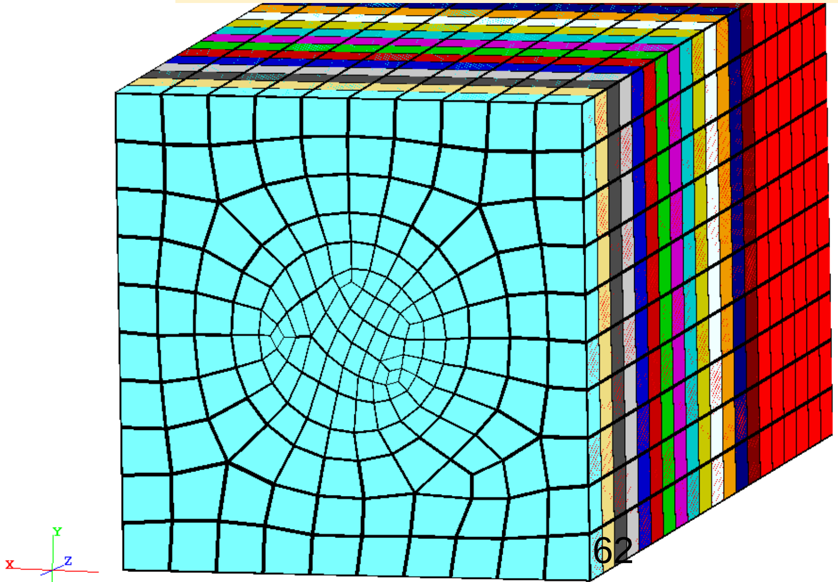


For nonuniform meshes the average radius values are used.

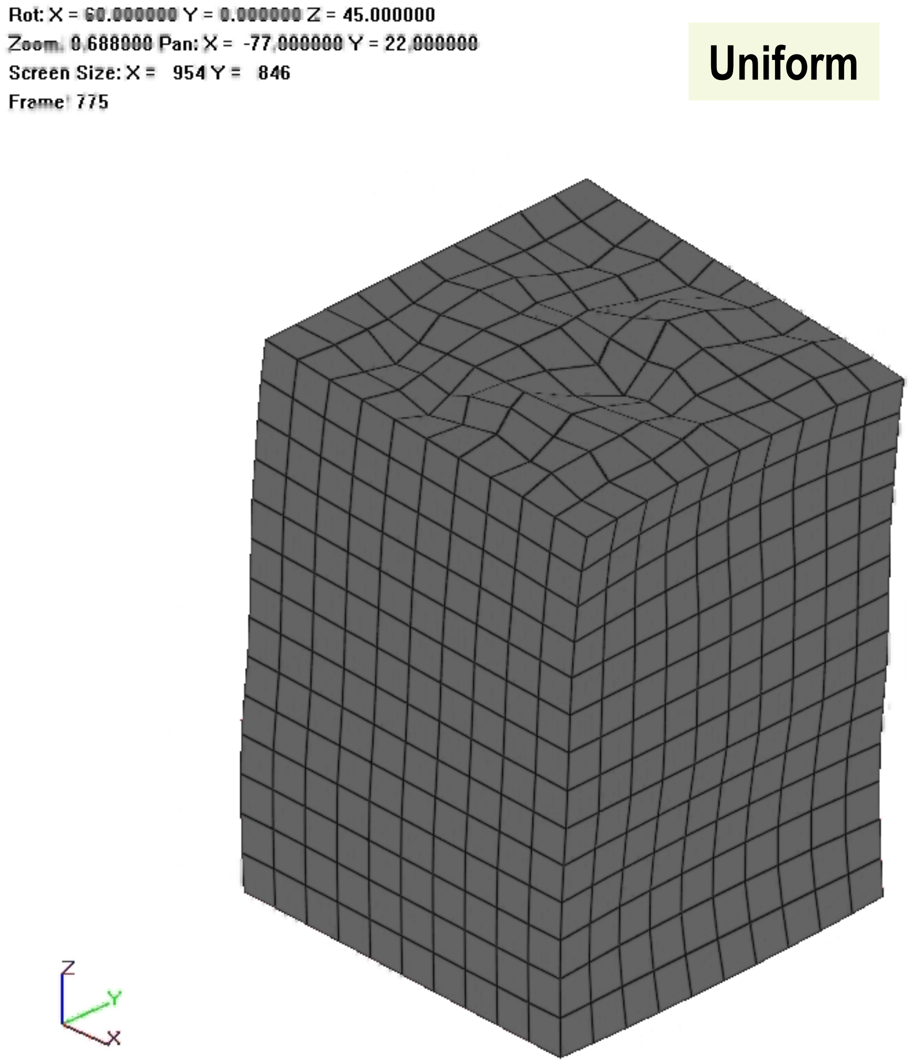
Non-uniform Model



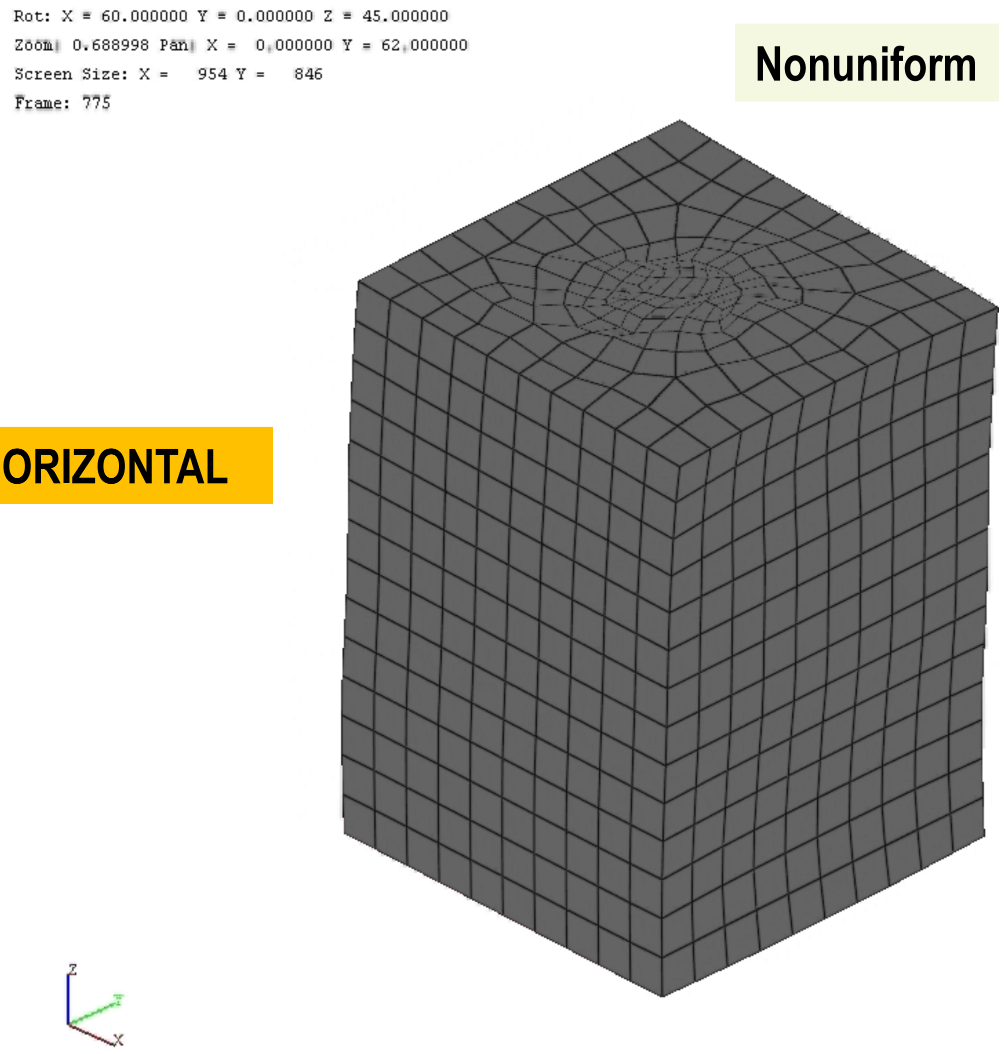
Refined Non-uniform Model



Effects of Excavation Volume FE Meshing.
Uniform Mesh vs. Nonuniform Mesh for Horizontal Motion



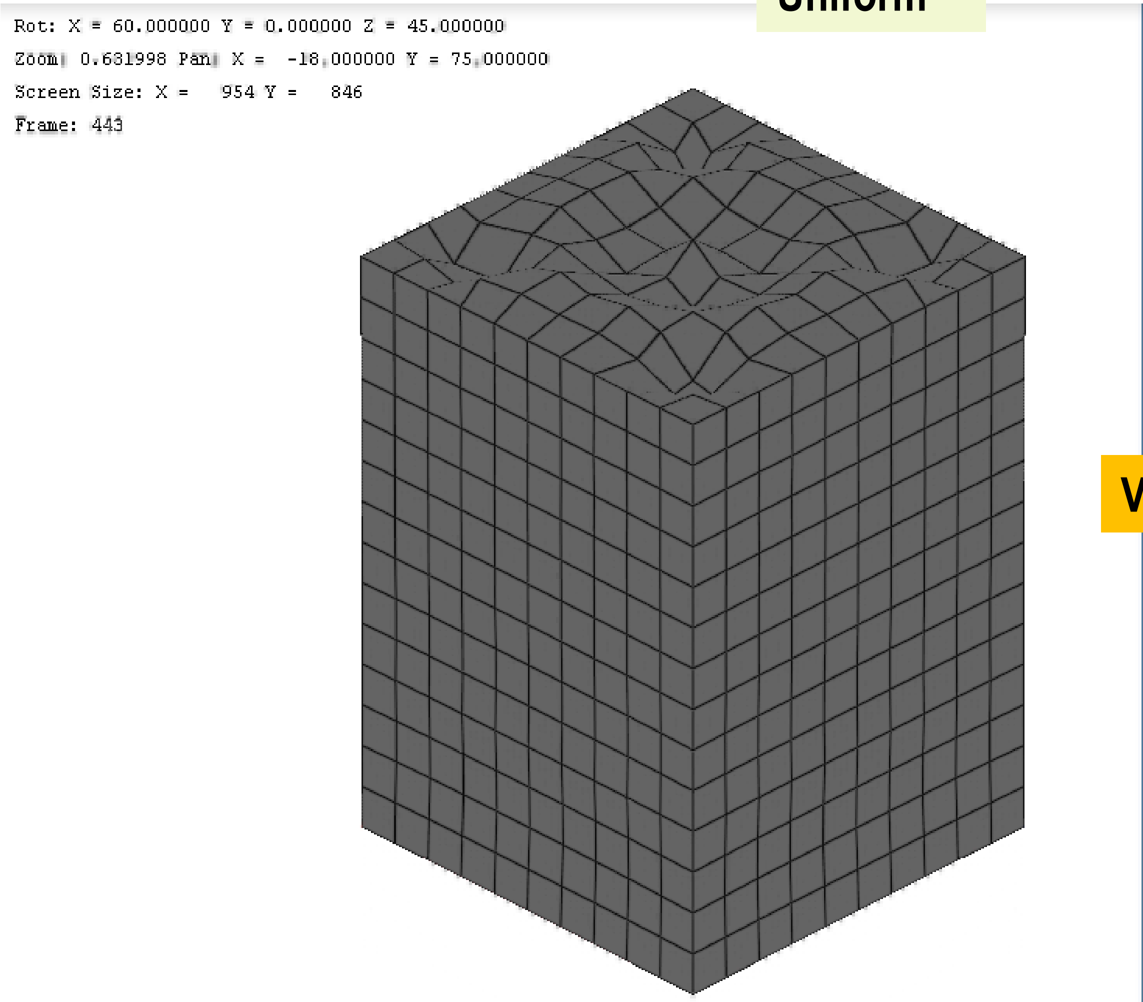
HORIZONTAL



Regular uniform mesh excavation FE models capture accurately the high-frequency wave scattering effects.

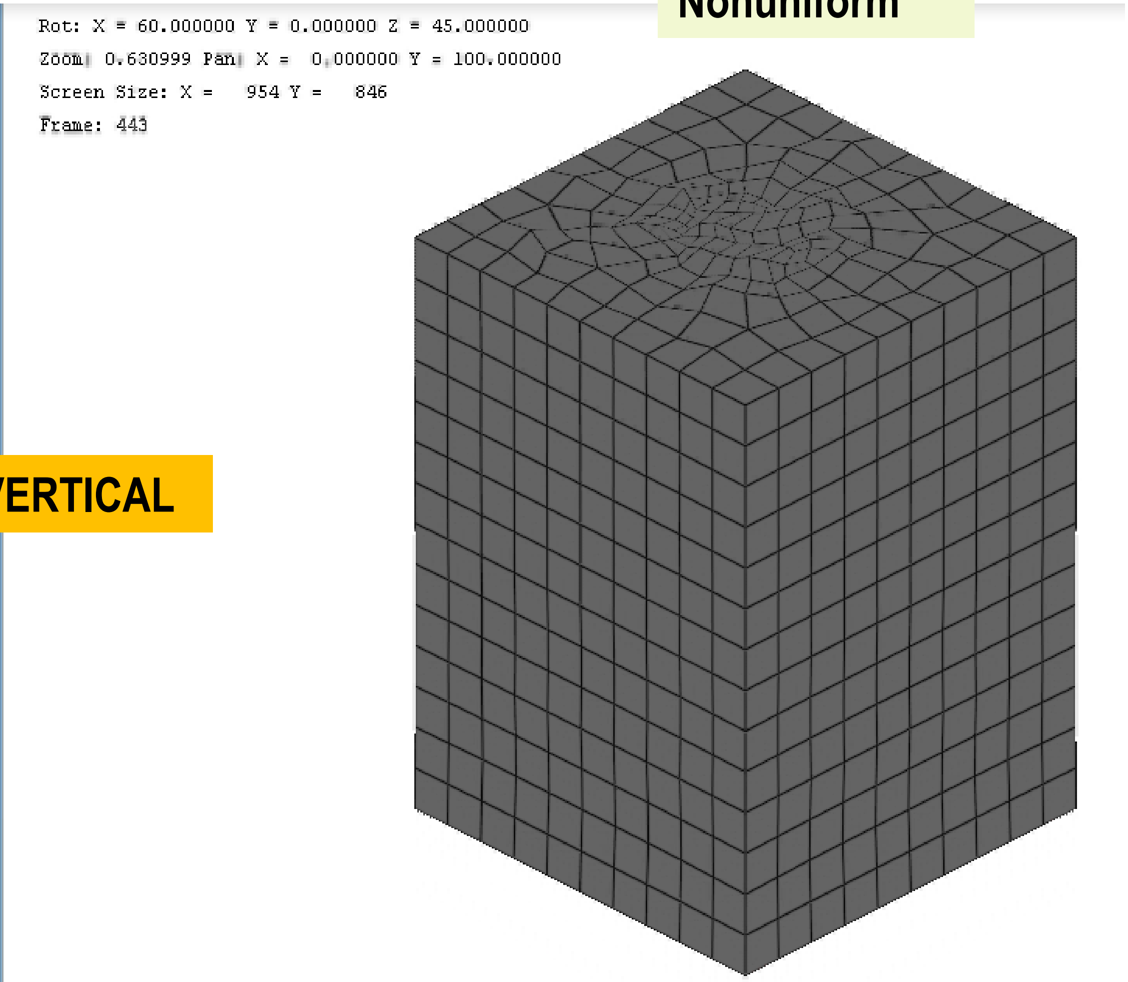
Effects of Excavation Volume FE Meshing.
Uniform Mesh vs. Nonuniform Mesh for Vertical Motion

Uniform



VERTICAL

Nonuniform



Regular uniform mesh excavation FE models capture accurately the high-frequency wave scattering effects.

BROOKHAVEN
NATIONAL LABORATORY

BNL-102434-2013

Seismic Soil-Structure Interaction Analyses of a Deeply Embedded Model Reactor – SASSI Analyses

J. Nie, J. Braverman, M. Costantino

October 2013

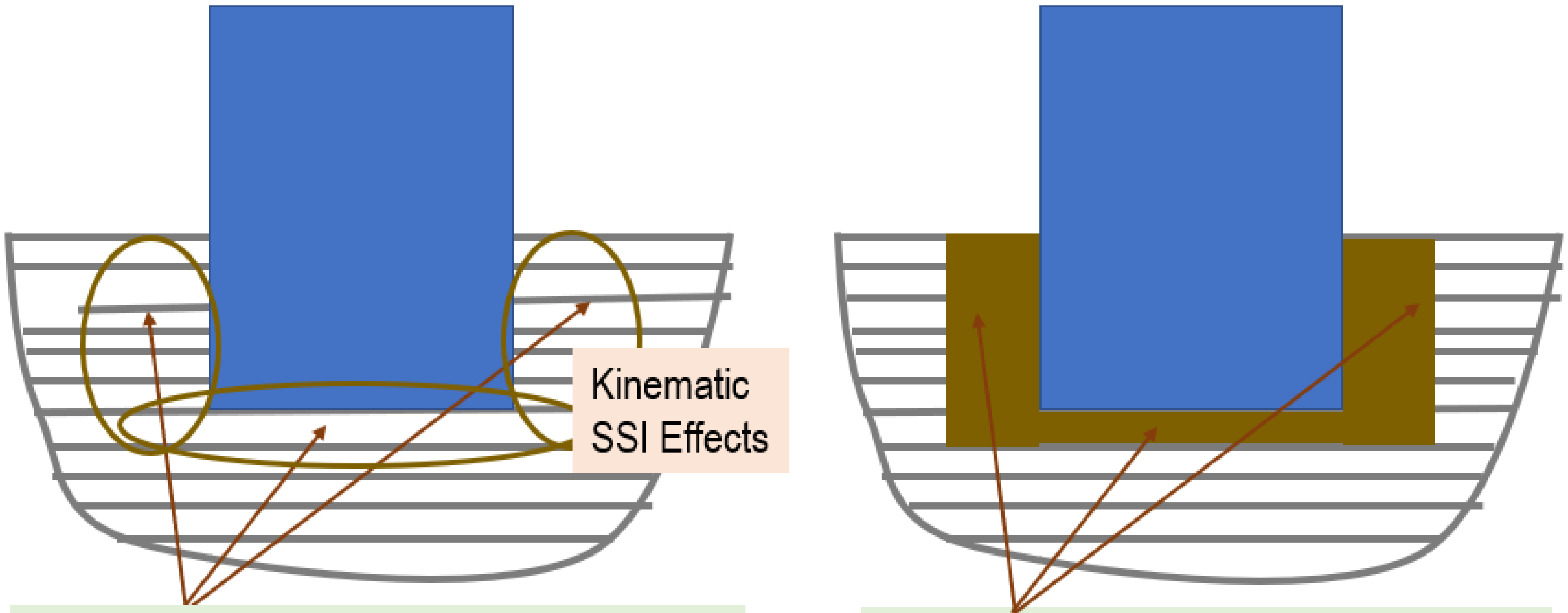
Therefore, it is recommended to pursue further improvements in the frequency domain codes in parallel to the ongoing research to develop and benchmark the time domain codes. Some of the key improvements are listed below:

(1) Re-establish/develop a modern, modularized (pluggable for incorporating future capabilities), and parallel code base for SASSI;
(2) "Profile" the code (i.e., analyze the efficiency of various parts of the code) and optimize the code to expedite the execution speed;
(3) Implement/automate certain capabilities based on industry guidelines for using SASSI (e.g., addressing the need for regular excavated soil mesh for any reasonable finite element structural model, approximating local soil nonlinearity, automating the treatment of soil layering, implementing advanced data management, etc.);
(4) Investigate the number-theoretic (e.g., GLP) enhanced subtraction method (ESM, which was proposed and briefly tested in this study); and
(5) Incorporate methods to consider uncertainties in soil properties.

Extend *Near Field Soil Mesh*, Eventually Including Iterated Strain-Compatible Soil Properties Pressure Calculations

"*Standard*" SASSI Modeling

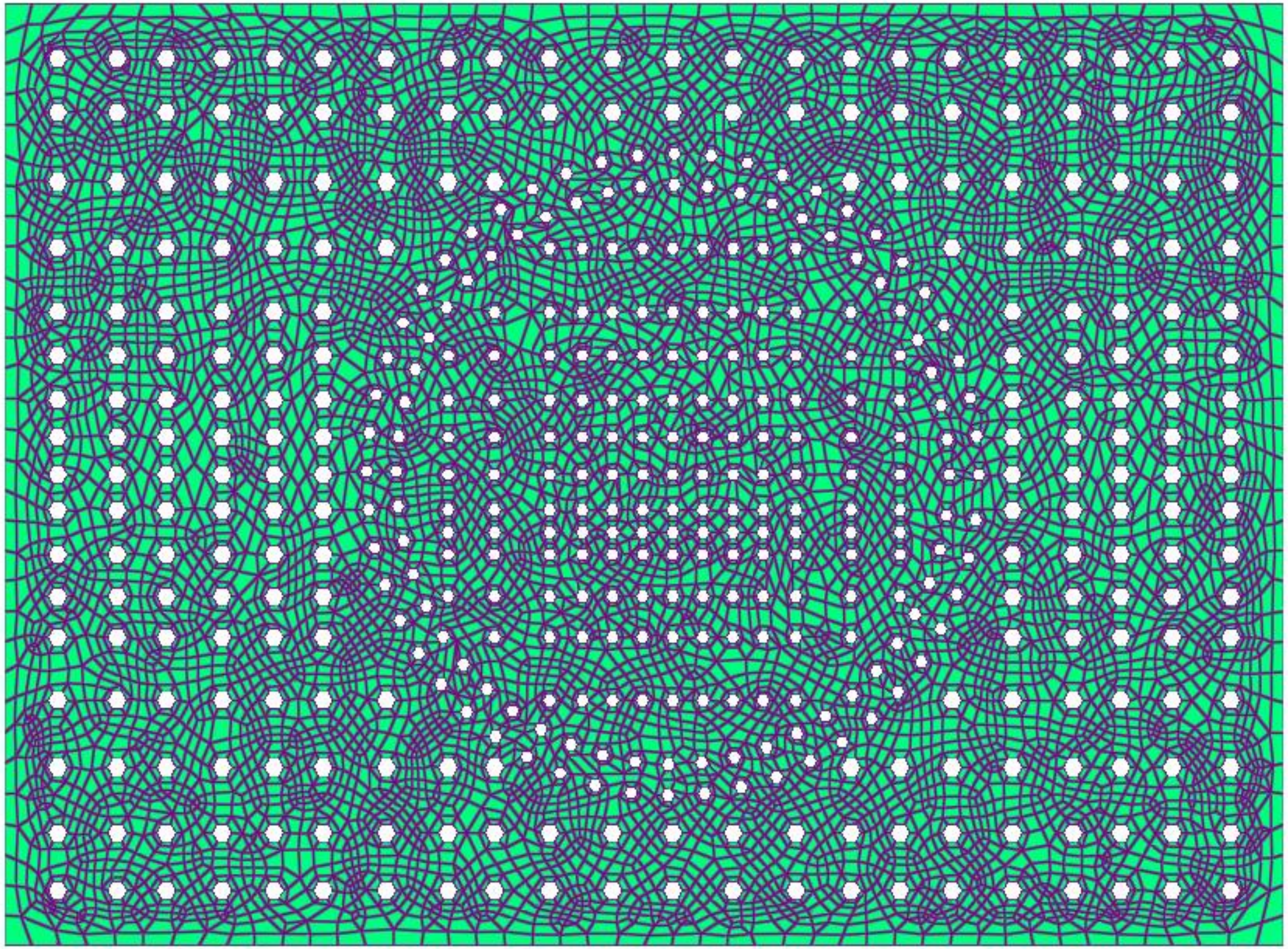
"*Improved*" SASSI Modeling

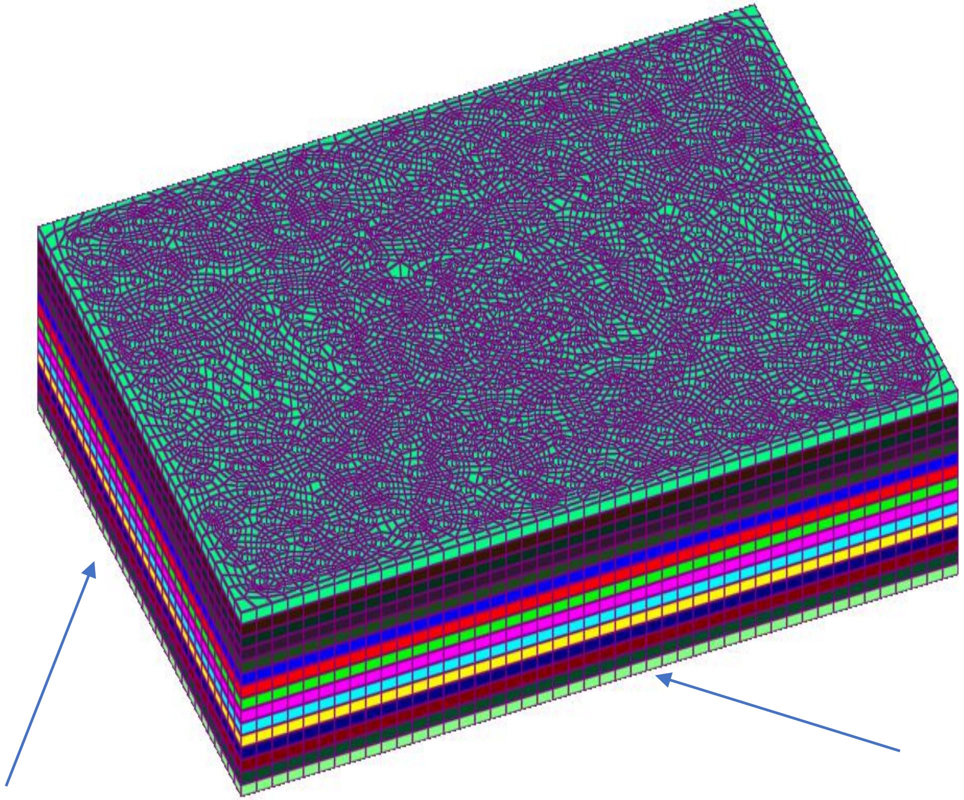


Typically, SSI model uses in the vicinity of foundation iterated strain-compatible soil layer properties computed using iterative 1D wave propagation equivalent-linear approach, *EQL via SHAKE methodology*. Kinematic SSI effects are neglected.

SSI model uses in the vicinity of foundation iterated strain-compatible soil layer properties computed using iterative 3D SASSI equivalent-linear approach to capture kinematic SSI effects, *EQL via fast SASSI iterations.*

RB Complex Pile Foundation Example Extending Near Field Mesh to Obtain A Regular & Coarser Excavation Volume Mesh)



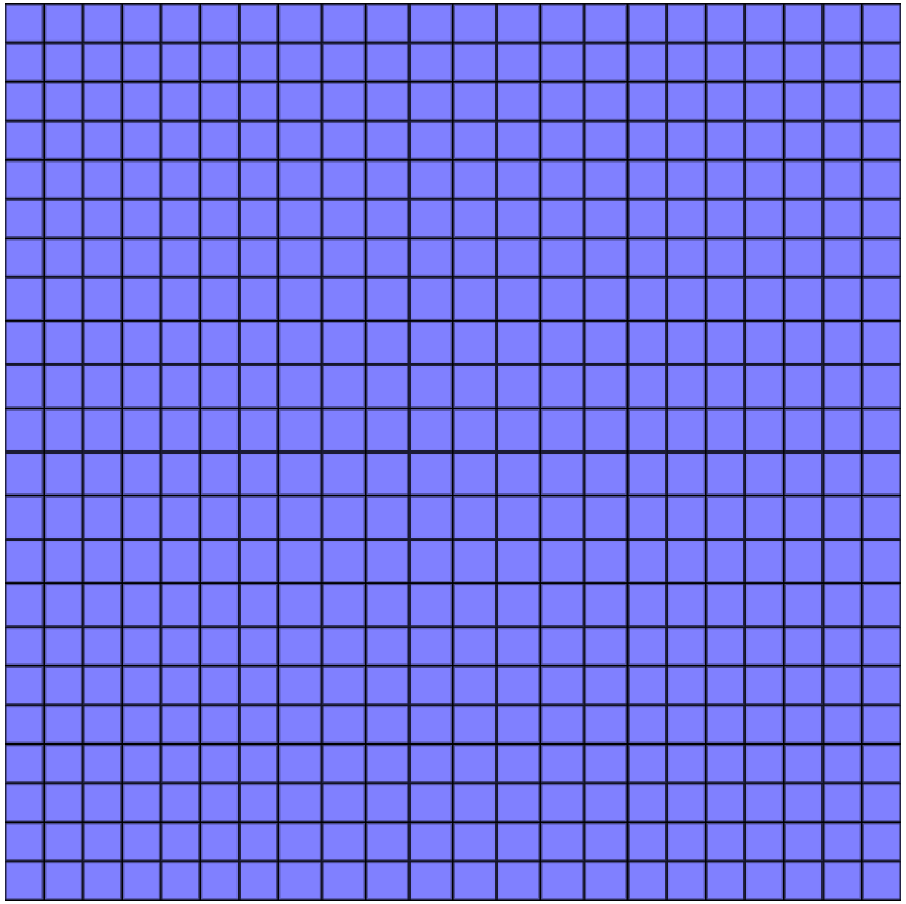


Brings Both Accuracy and Speed Up

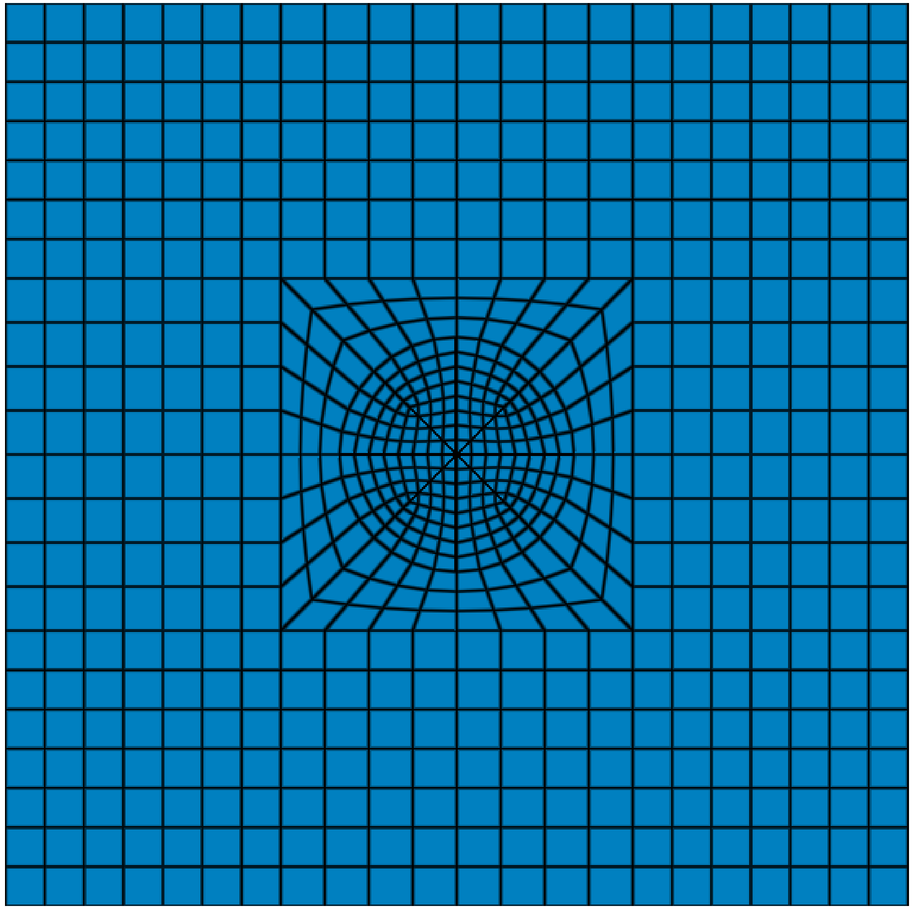
SSI runtime was about 2,600 sec. per frequency on a 128 GB RAM Windows PC

REDUCEINT Command to Get Uniformly Spaced Interaction Nodes

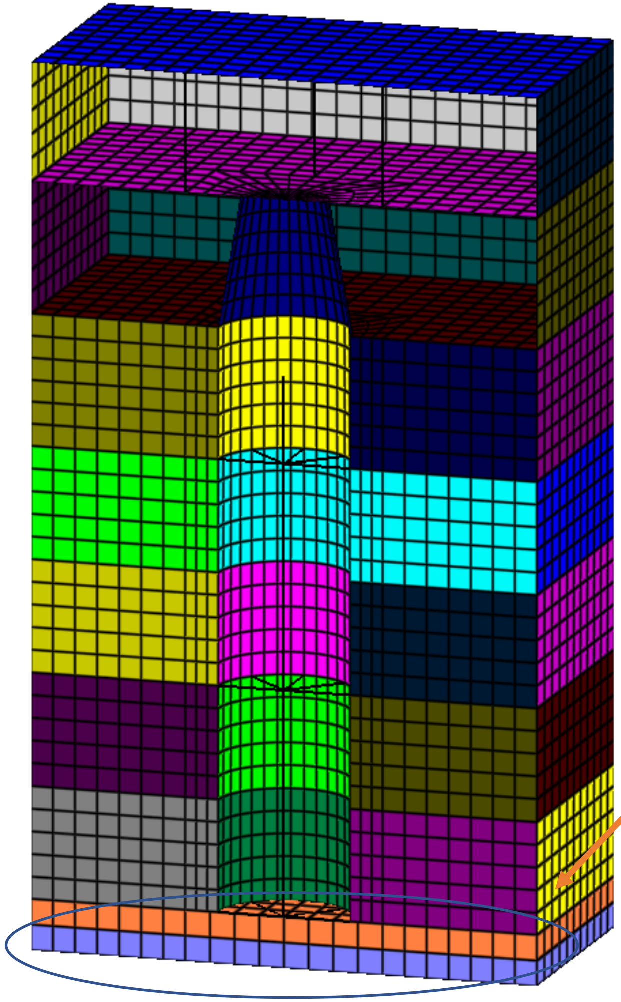
OPTION 1: ***Extend FE Mesh.***
Using Transition Mesh Under Foundation



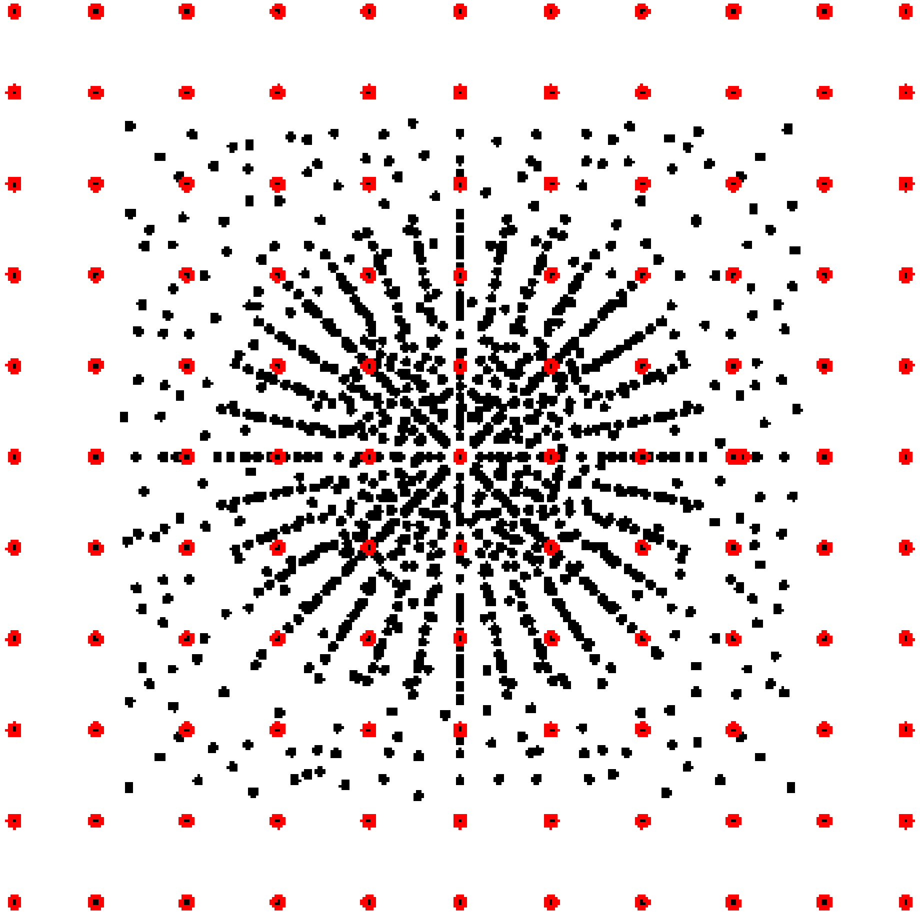
OPTION 2: ***No change in FE Mesh***
Using ***REDUCEINT*** command for interaction node spacing



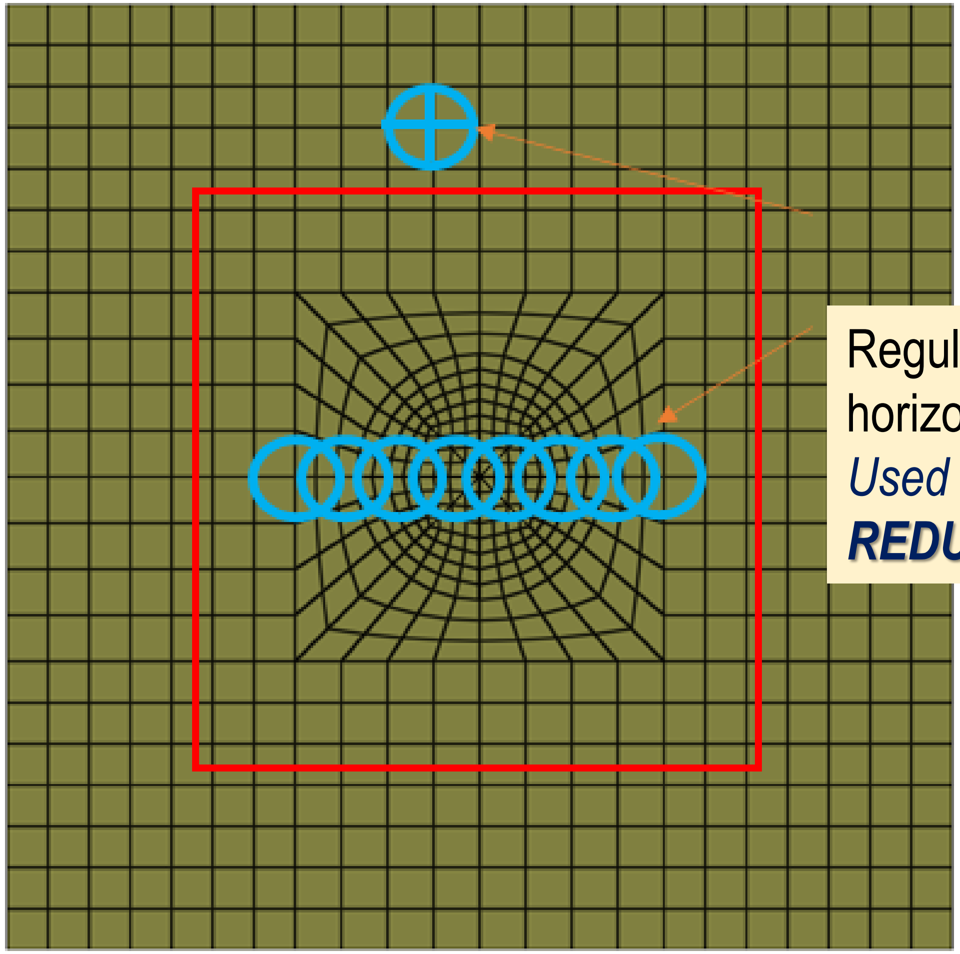
Option 1: Transition Mesh to Get Regular Uniform Spacing Between Interaction Nodes (Red Dots)



Two level transition mesh including two soil layers below SMR foundation



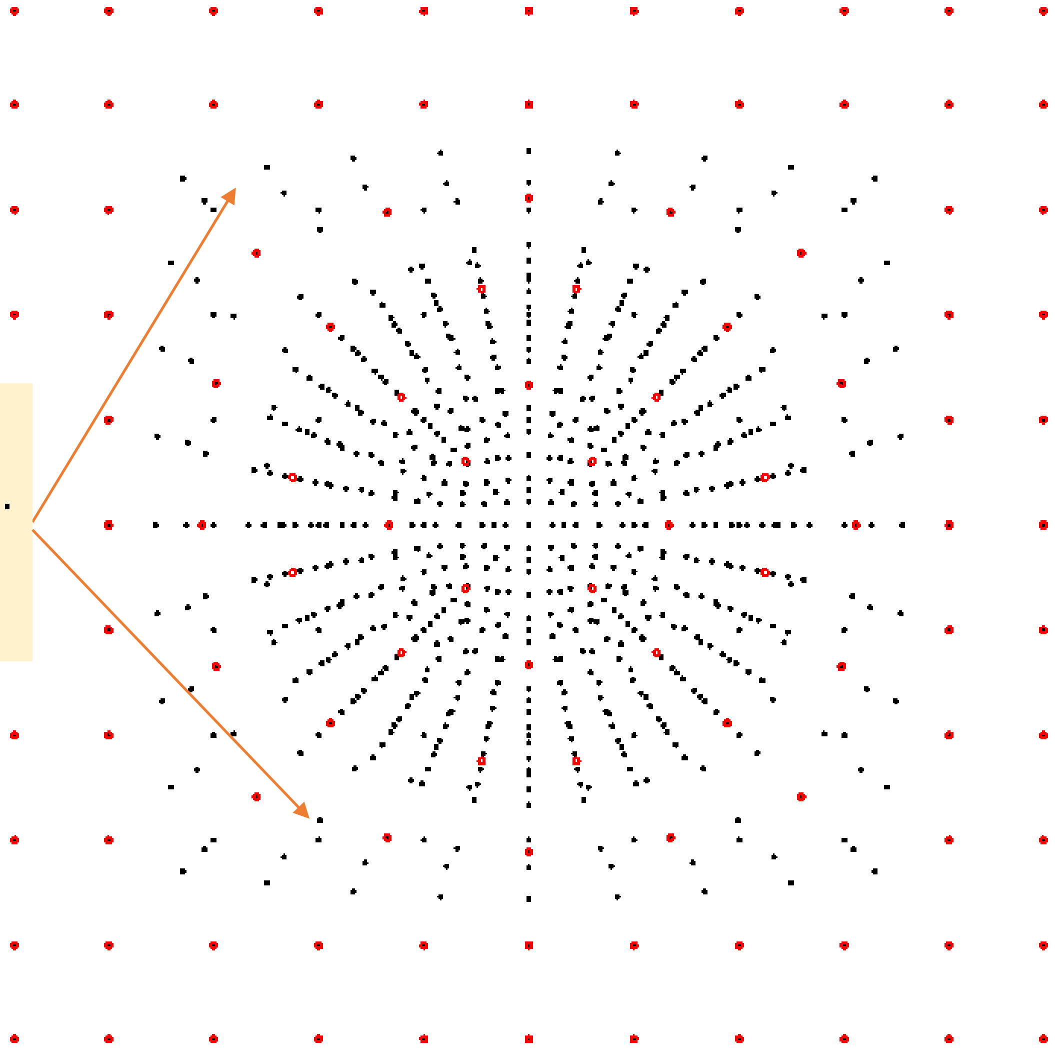
Option 2: Uniform Spacing for Interaction Nodes With REDUCEINT



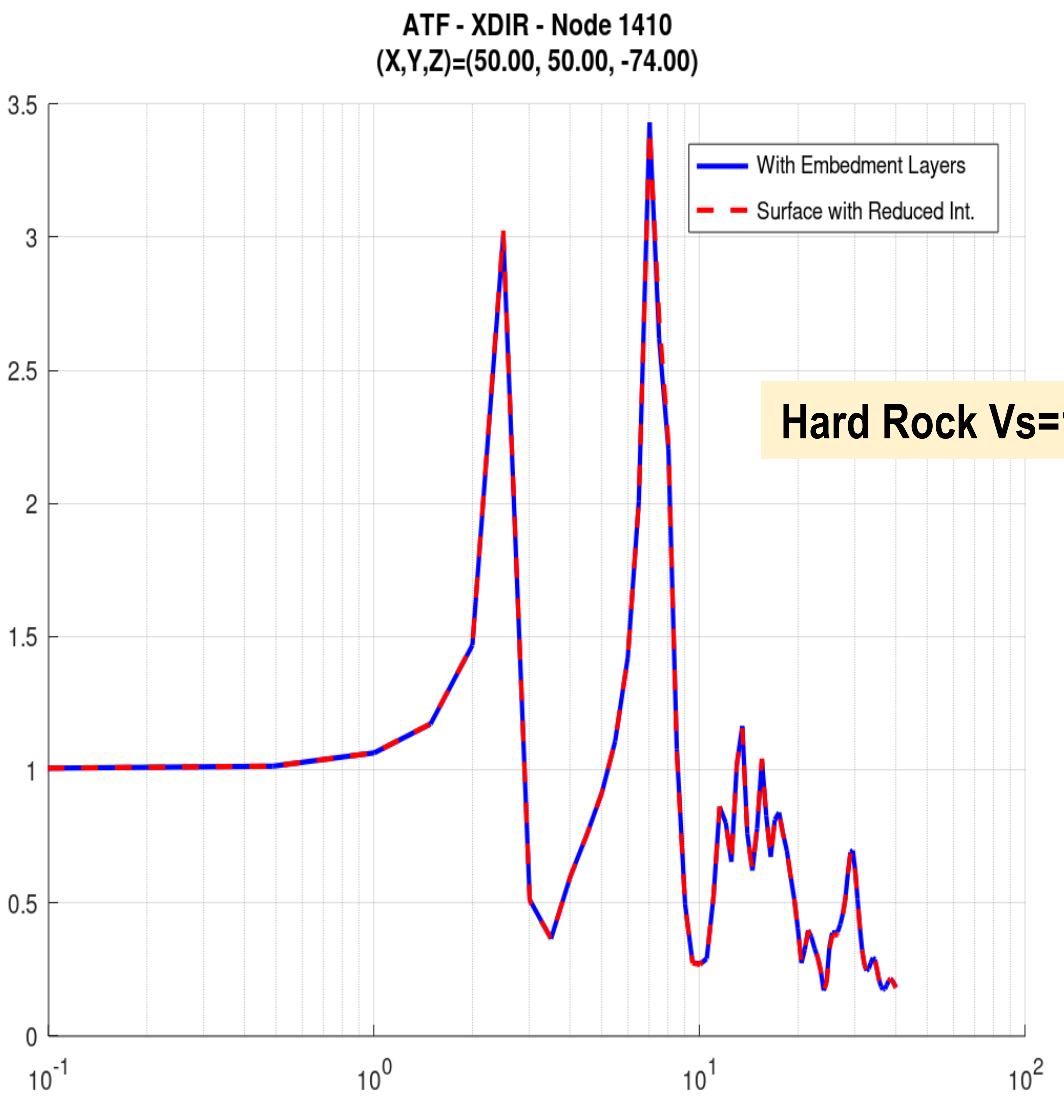
Regular mesh has a horizontal size is 4.54m.

Used UI command

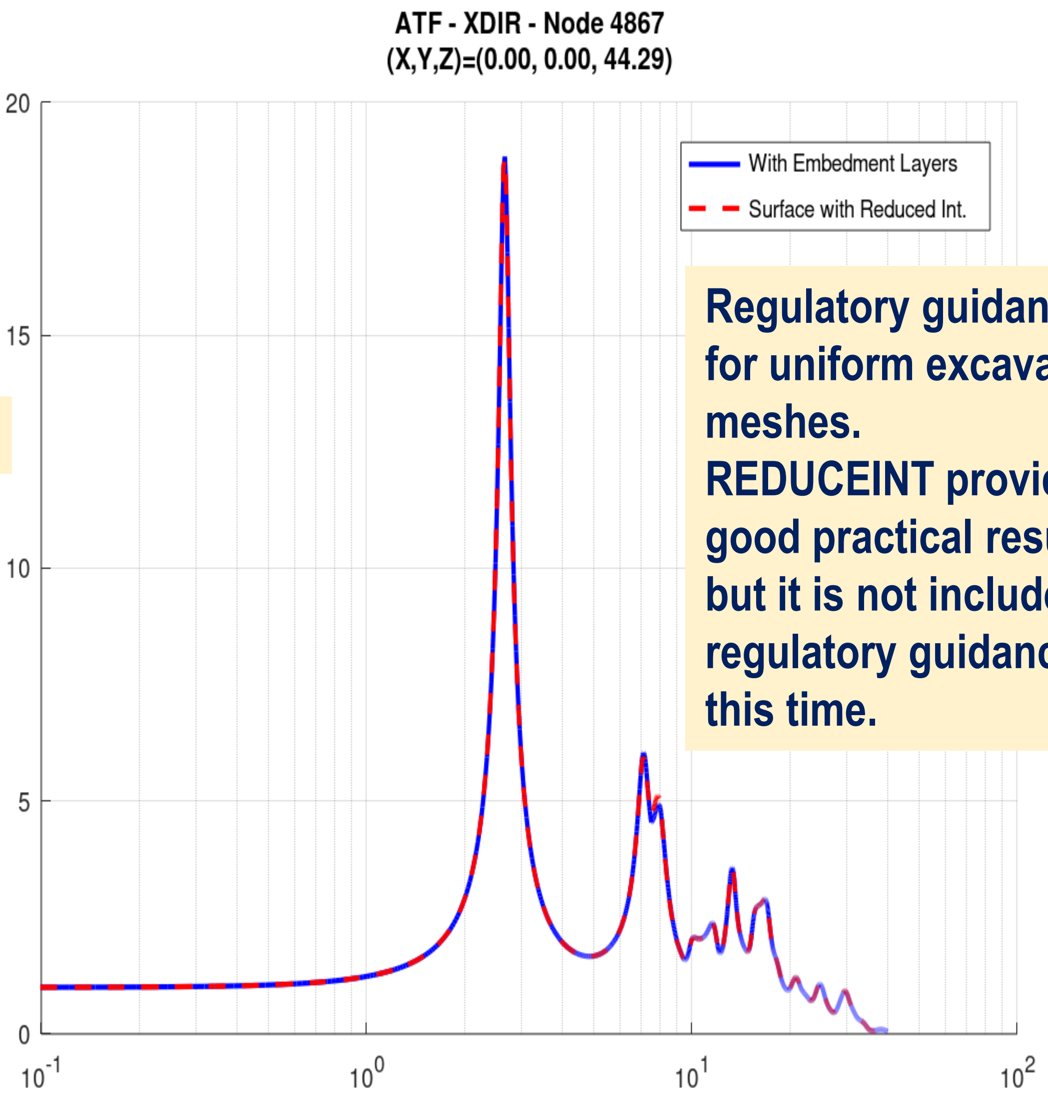
REDUCEINT,4



Computed ATF for Option 1 (Transition Mesh) and 2 (REDUCEINT)



Hard Rock Vs=10,000fps



Regulatory guidance is for uniform excavation meshes. REDUCEINT provides good practical results, but it is not included in regulatory guidance at this time.

Effects of Inclined SV and P Waves, and Rayleigh HO Waves on SMR ISRS and Soil Pressures

Uniform vs. Nonuniform Soils

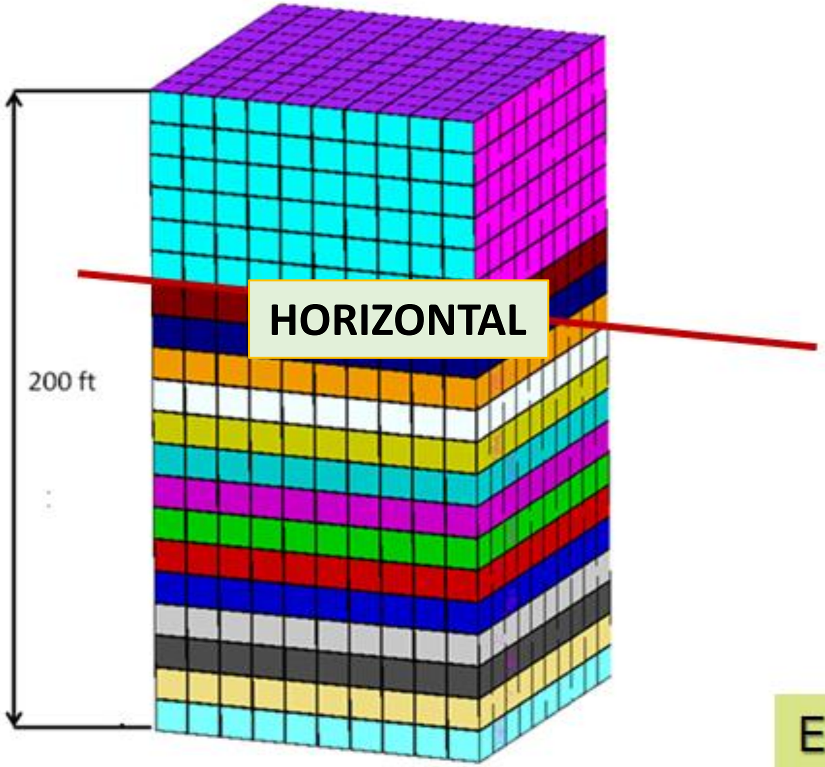
Inclined SV-P and High-Order R Waves

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

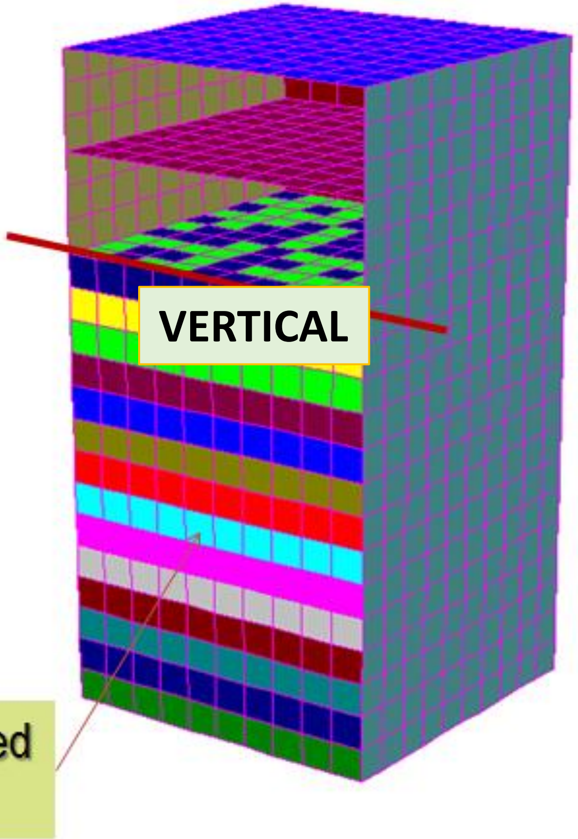
"There is in fact evidence to suggest that most of the energy approaching the ground surface results from body waves inclined within about 30 degree of the vertical. These includes the effects of the high-order surface wave modes."

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

Deeply Embedded 3D SMR Model (3D1D)



Generic SMR Structure

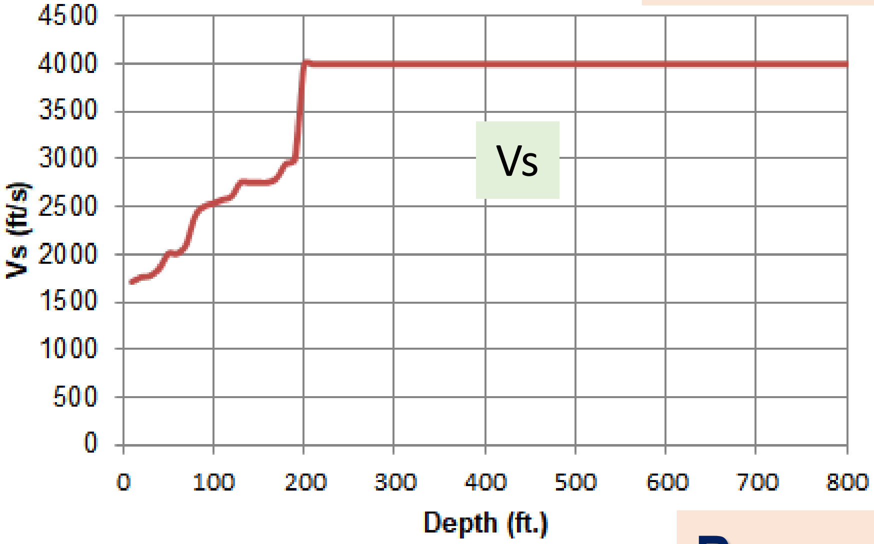


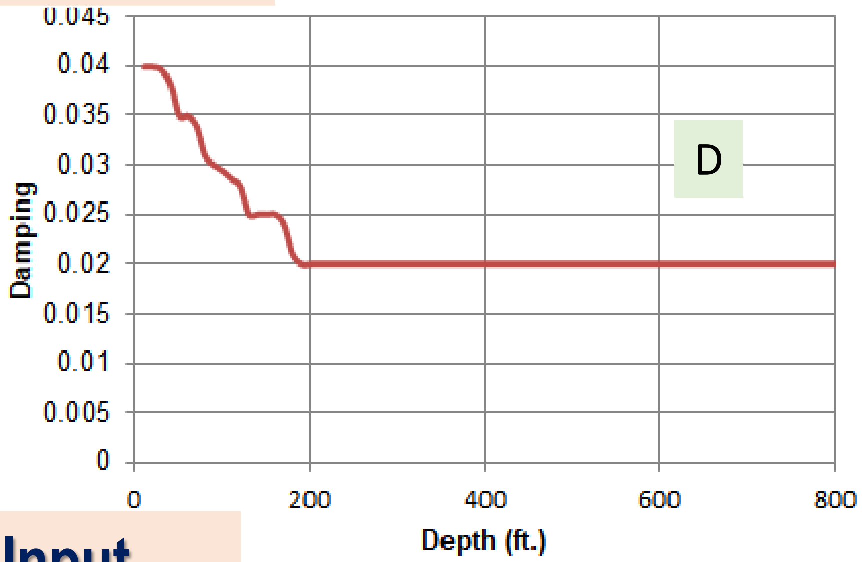
SMR size: 100 ft x 100 ft X 200 ft
Embedment: 140 ft
Mesh size: 10 ft X 10 ft X 10 ft
Number of Nodes: 2,580
Interaction Nodes: 1,815

140 ft Embedment SMR SSI Model (use FV method)

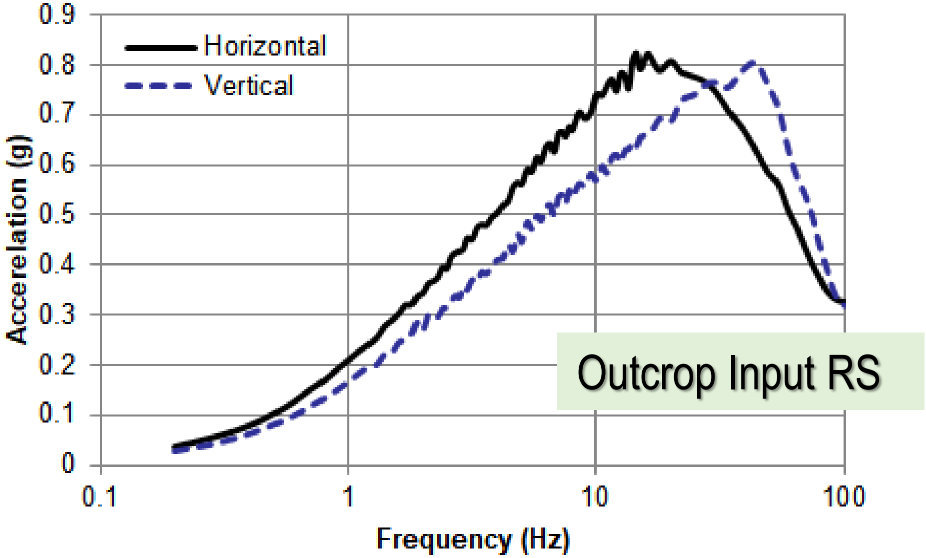
Soil Layering and Seismic Input at Baserock

Soil Property Profiles



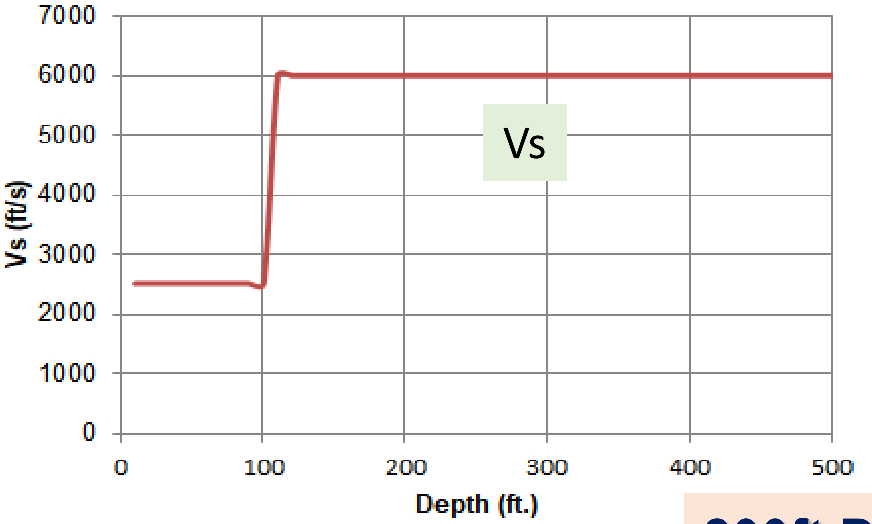


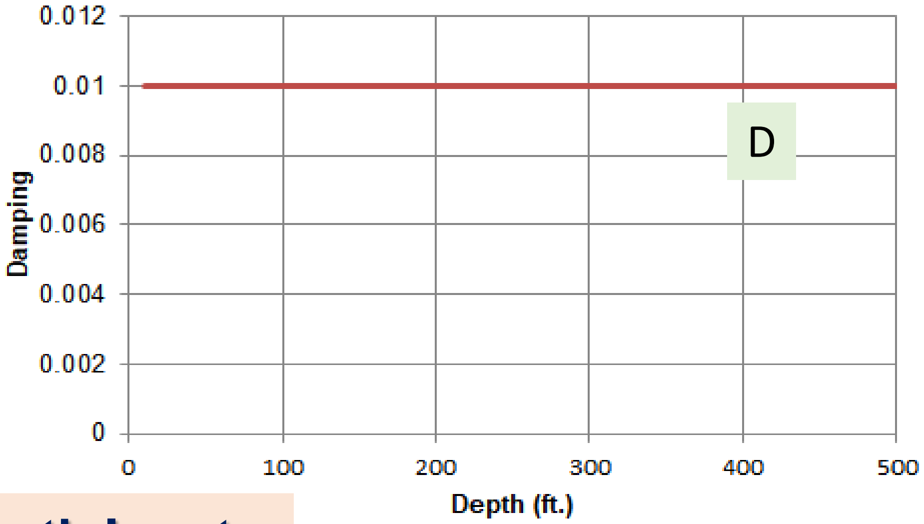
Baserock Input



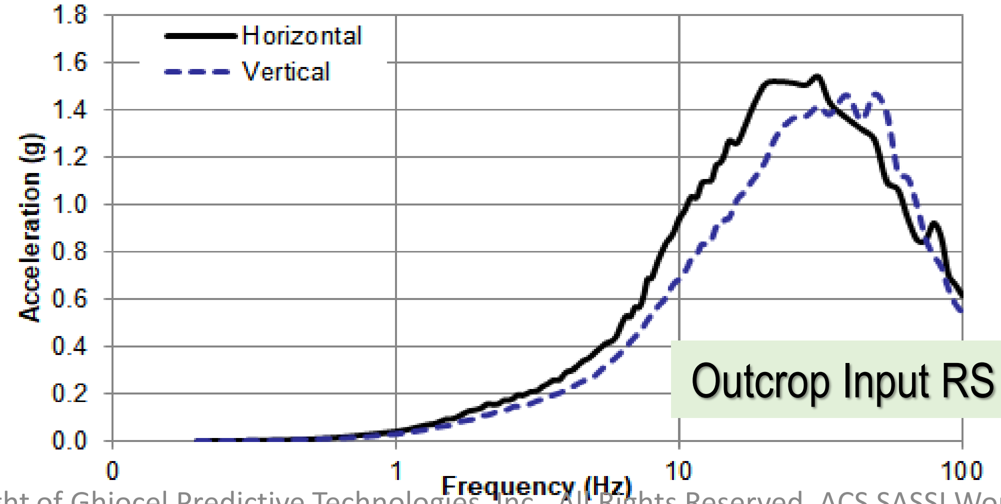
Soil Layering with Step Increase in Stiffness

Soil Property Profiles





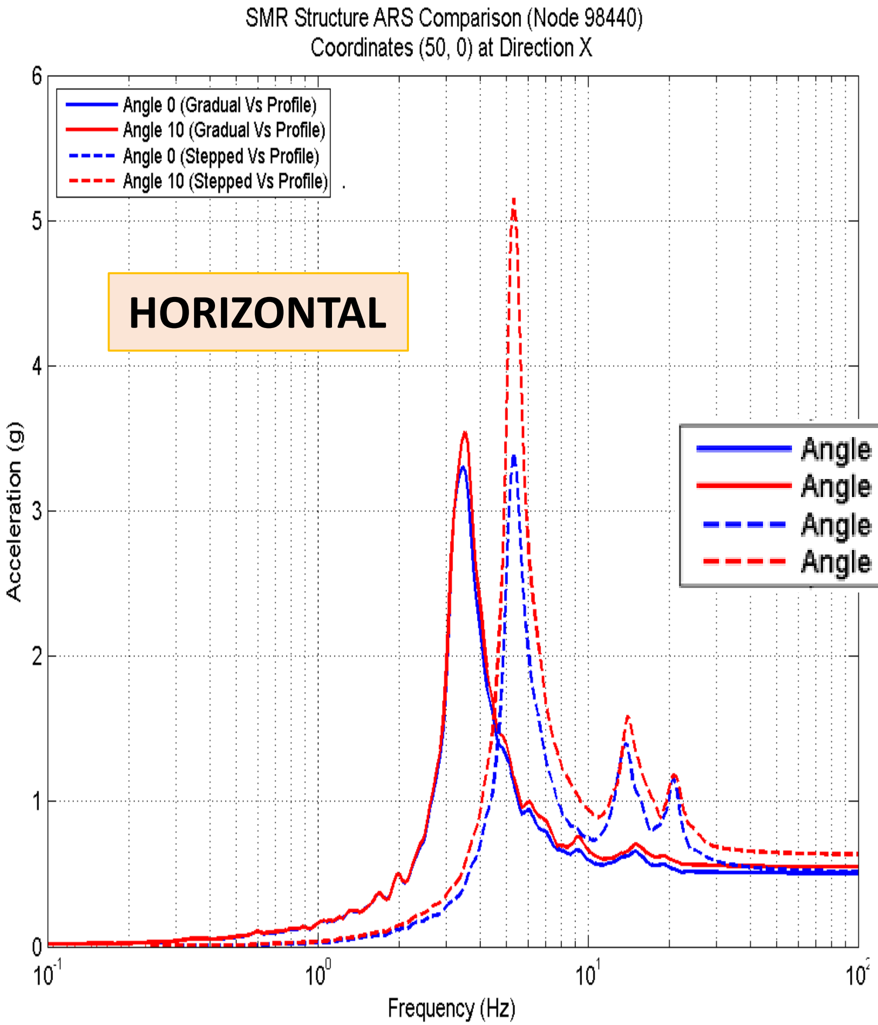
200ft Depth Input

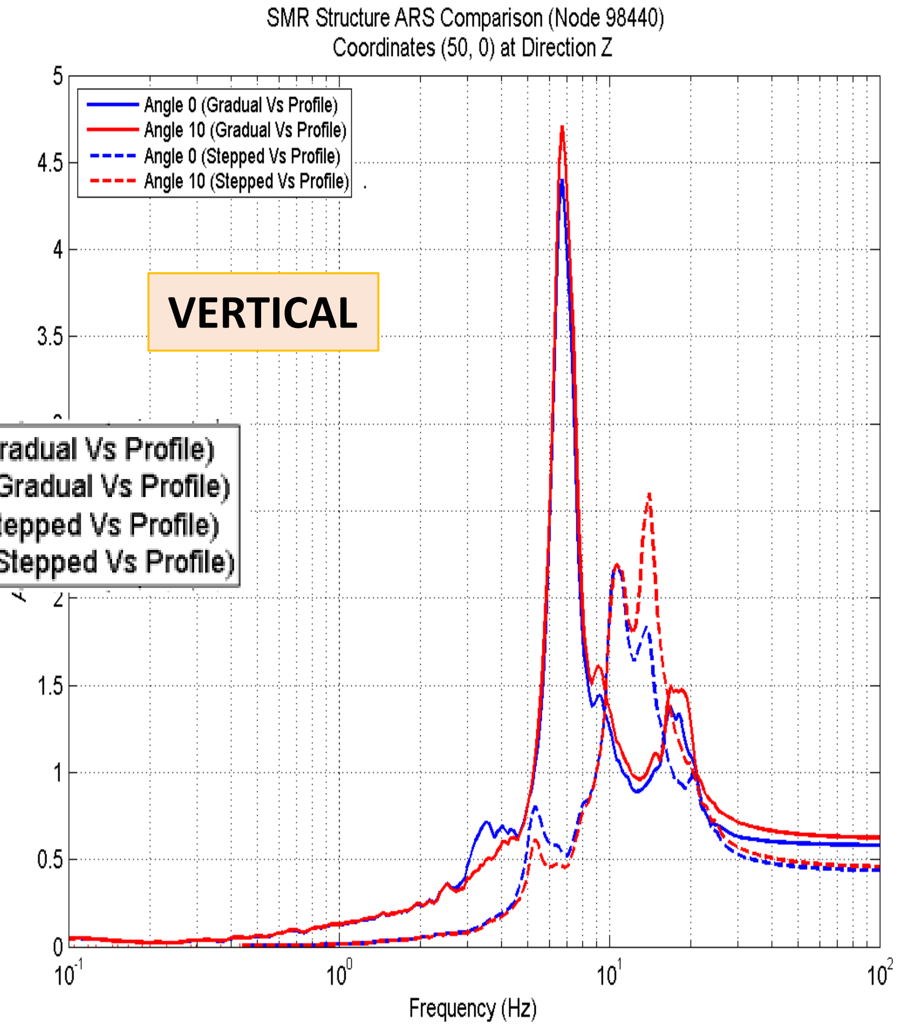


Outcrop Input RS – Very High Frequency

SV-P Waves with 0 and 10 Angles for Two Soils

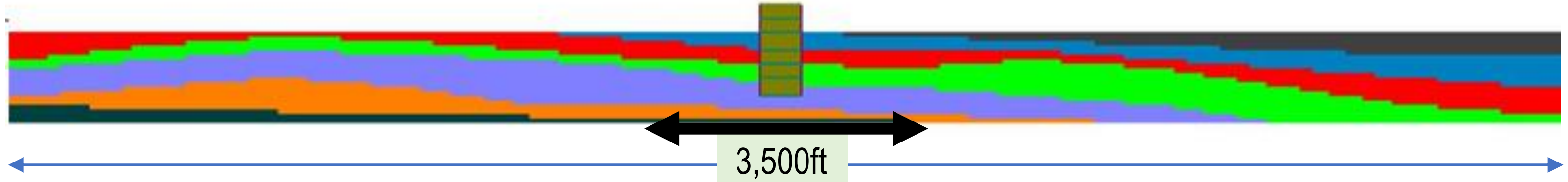
3D SMR Model ISRS at Ground Surface at Edge

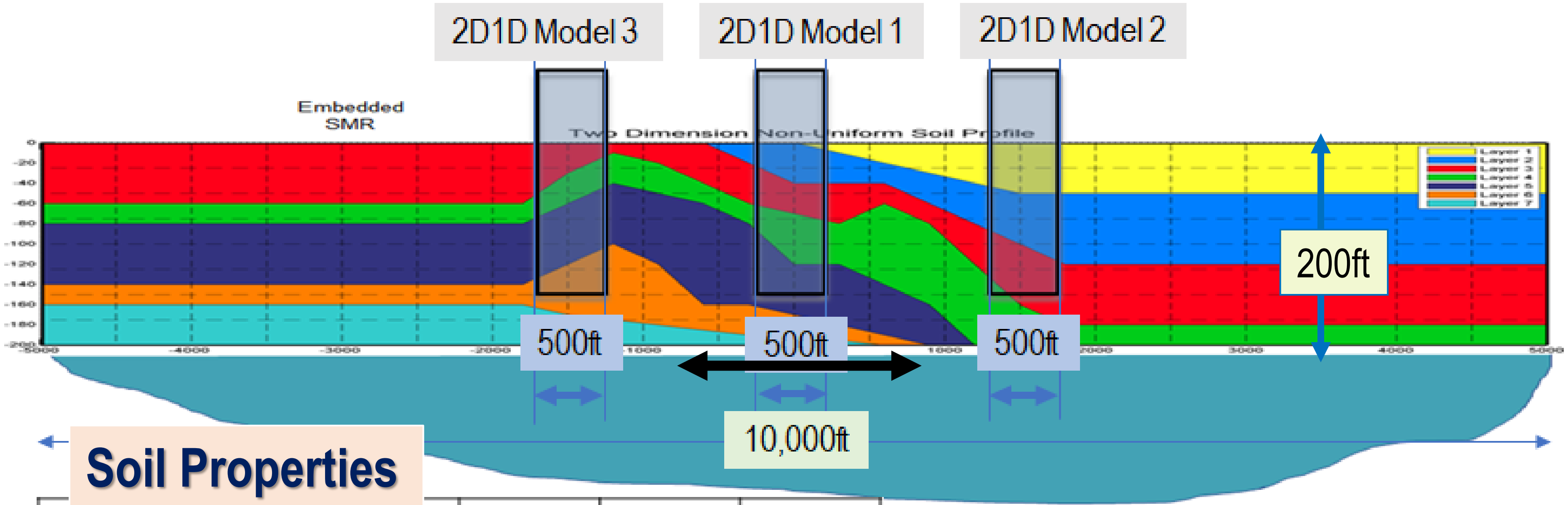




Angle 0 (Gradual Vs Profile)
Angle 10 (Gradual Vs Profile)
Angle 0 (Stepped Vs Profile)
Angle 10 (Stepped Vs Profile)

2D1D and 2D2D Embedded SMR SASSI Models





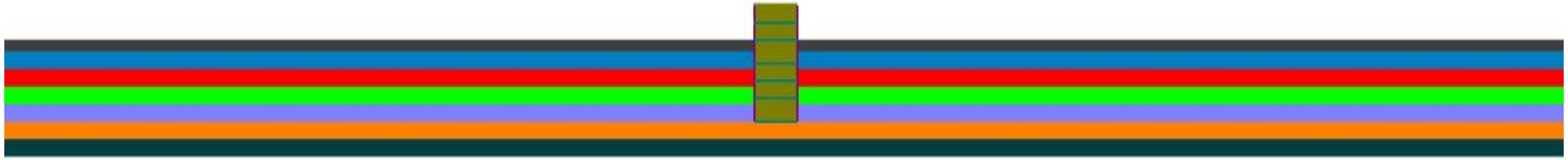
Soil Properties

Layer	Thickness	Specific Weight	SV Wave Velocity	P Wave Velocity	Damping Ratio
1	20	0.13	1500	3000	0.04
2	30	0.13	1750	3500	0.04
3	30	0.13	2000	4000	0.035
4	30	0.13	2500	5000	0.03
5	30	0.13	2750	5500	0.025
6	30	0.13	3000	6000	0.02
7	30	0.13	4000	8000	0.02
Half Space	Infinite	0.13	4000	8000	0.02

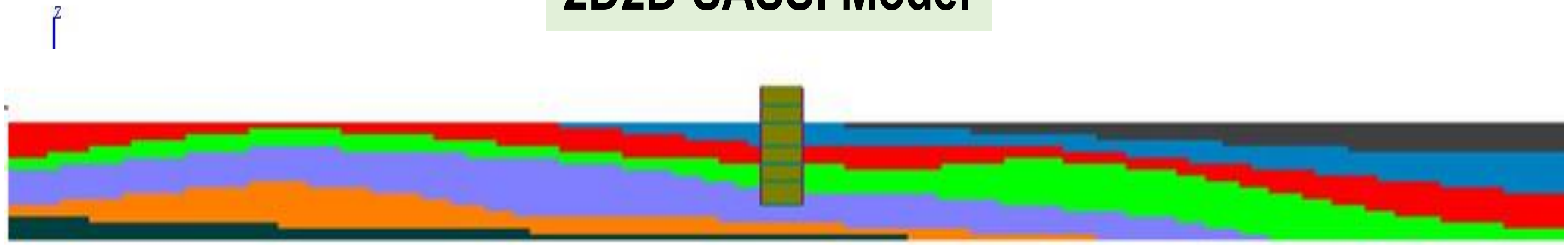
Slopes variable up to 1/10

2D1D and 2D2D Embedded SMR SASSI Models

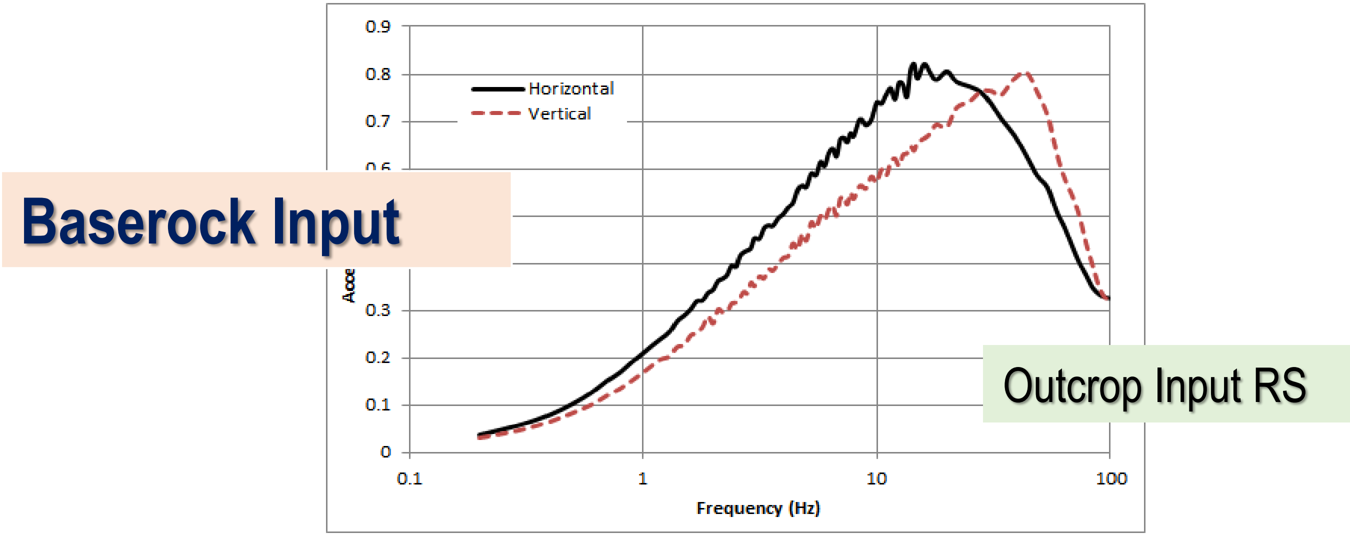
2D1D SASSI Model



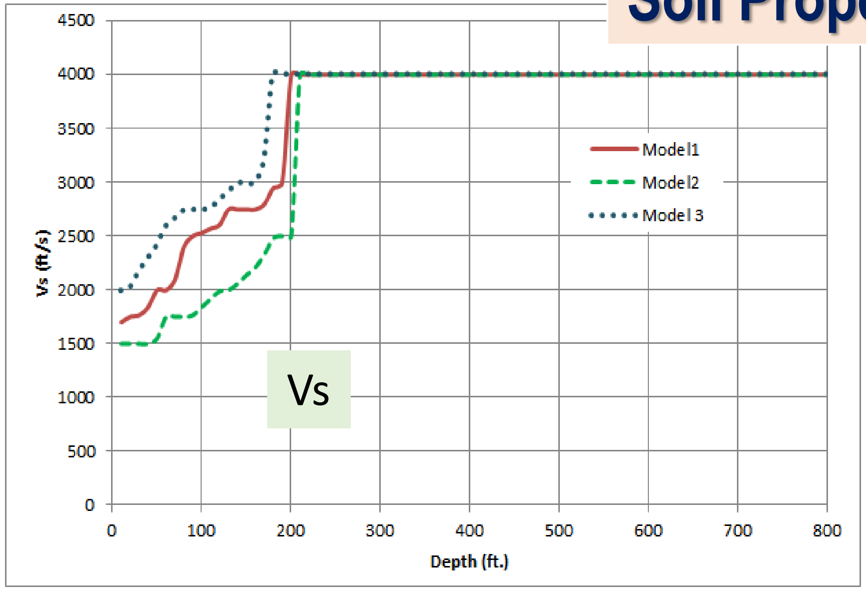
2D2D SASSI Model

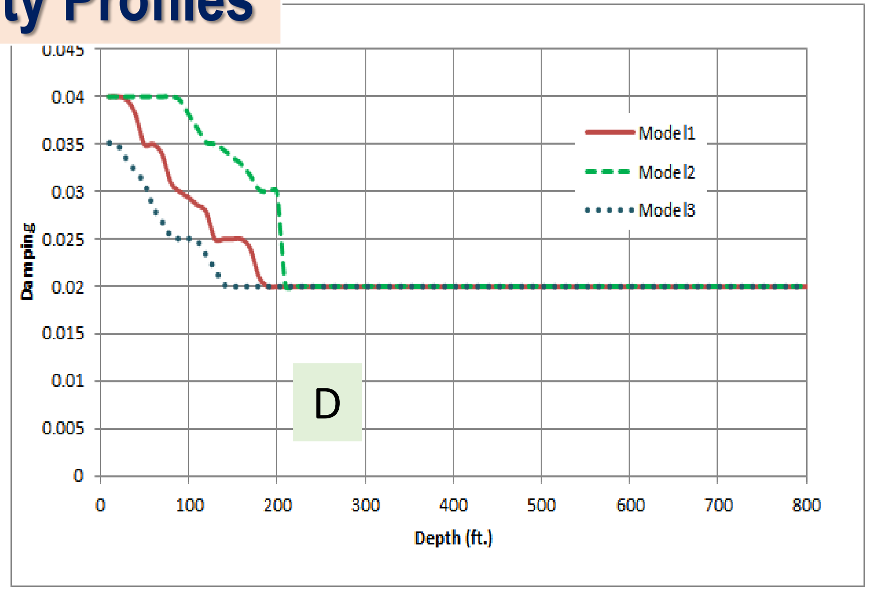


Soil Layering for 2D1D SSI Models; M1, M2 and M3

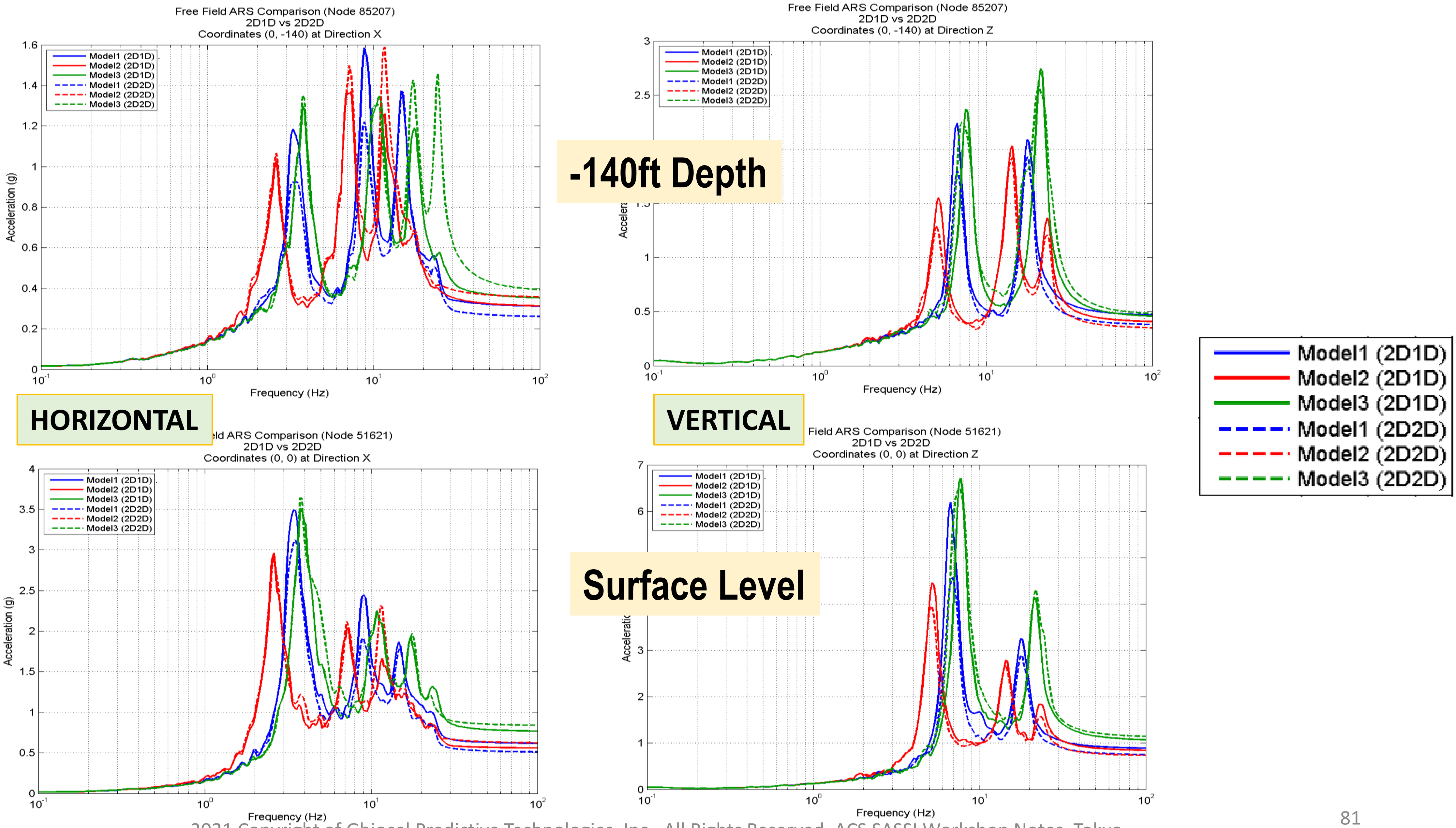


Soil Property Profiles

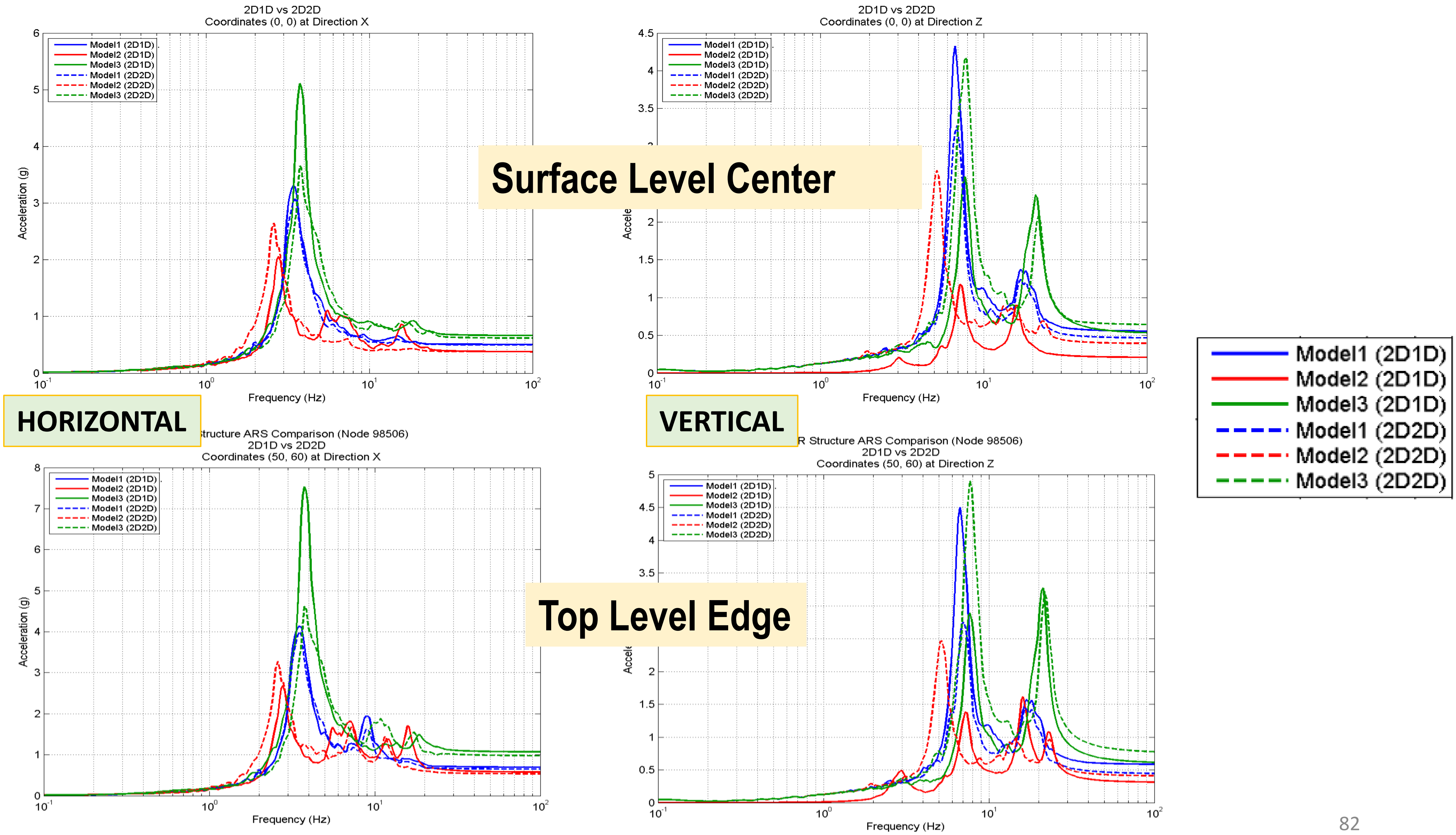




Free-Field Responses for 2D2D and 2D1D Soil Models

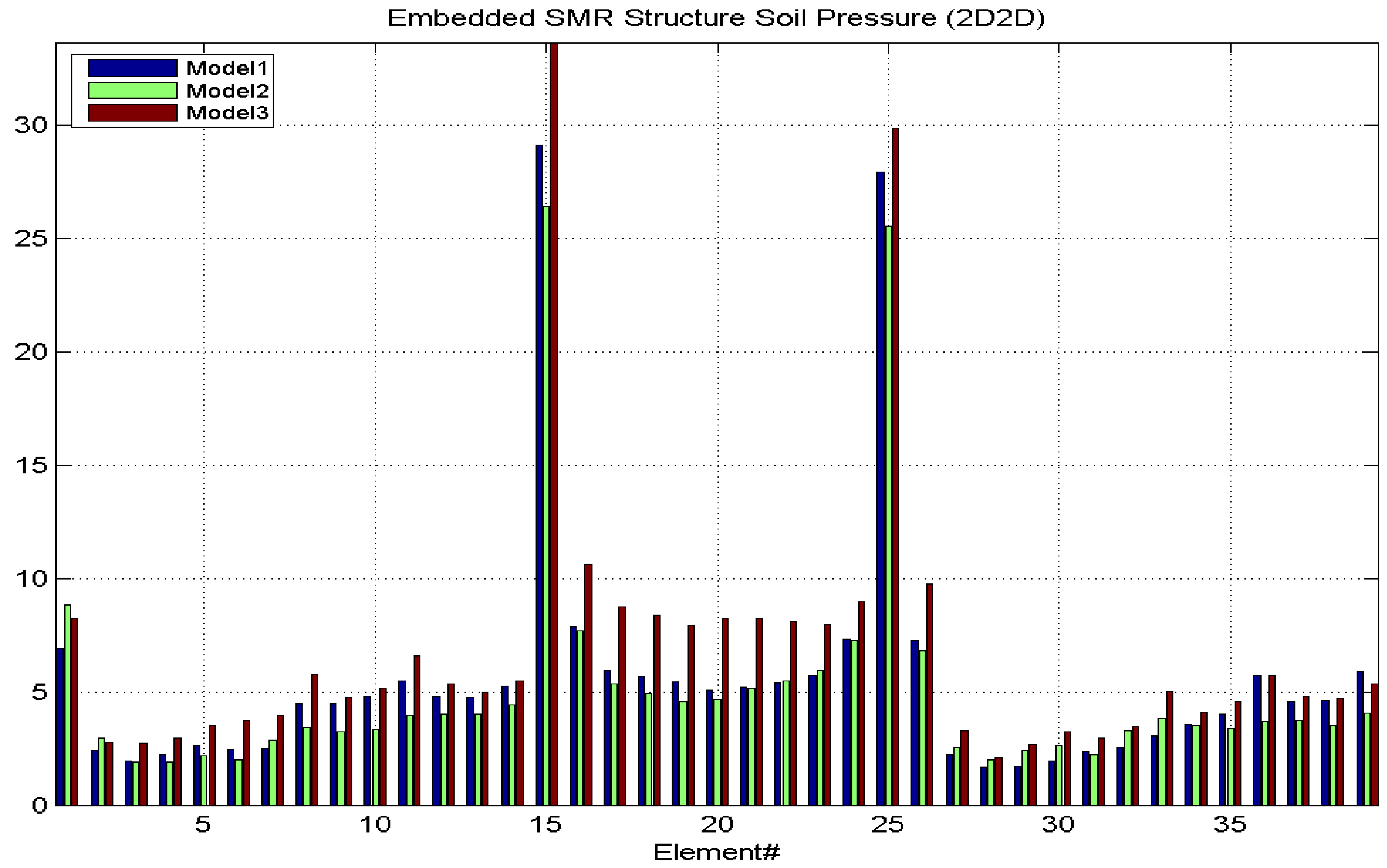


SMR Responses for 2D2D and 2D1D Soil Models



SMR Responses for 2D2D Soil Layer Models

2D SMR Maximum Seismic Soil Pressures



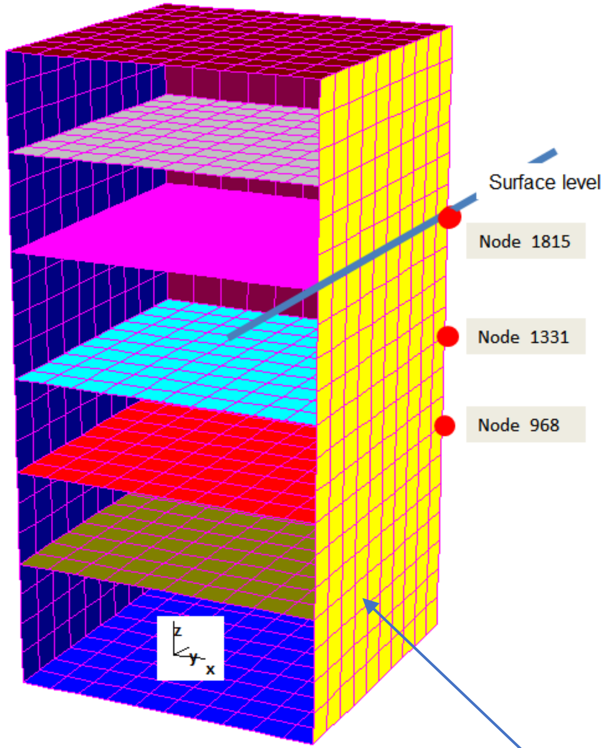
SSSI Effects for Deeply Embedded SMR

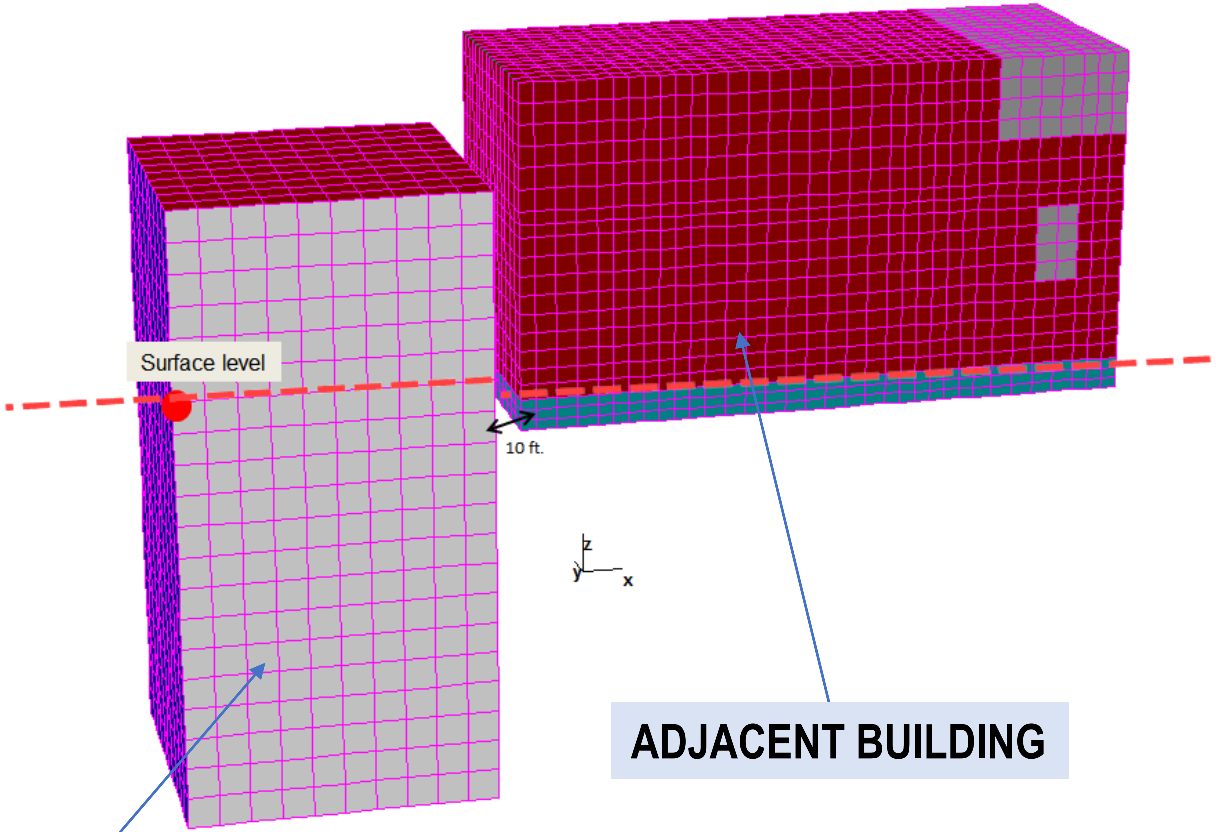
Uniform vs. Nonuniform Soils

Seismic SSSI Effects on SMR Under Coherent and Incoherent Seismic inputs

Embedded SMR SSI Model

Embedded SMR SSSI Model



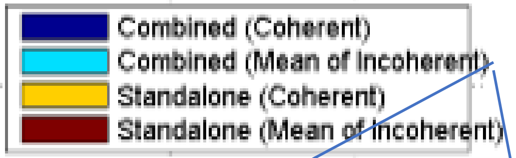


ADJACENT BUILDING

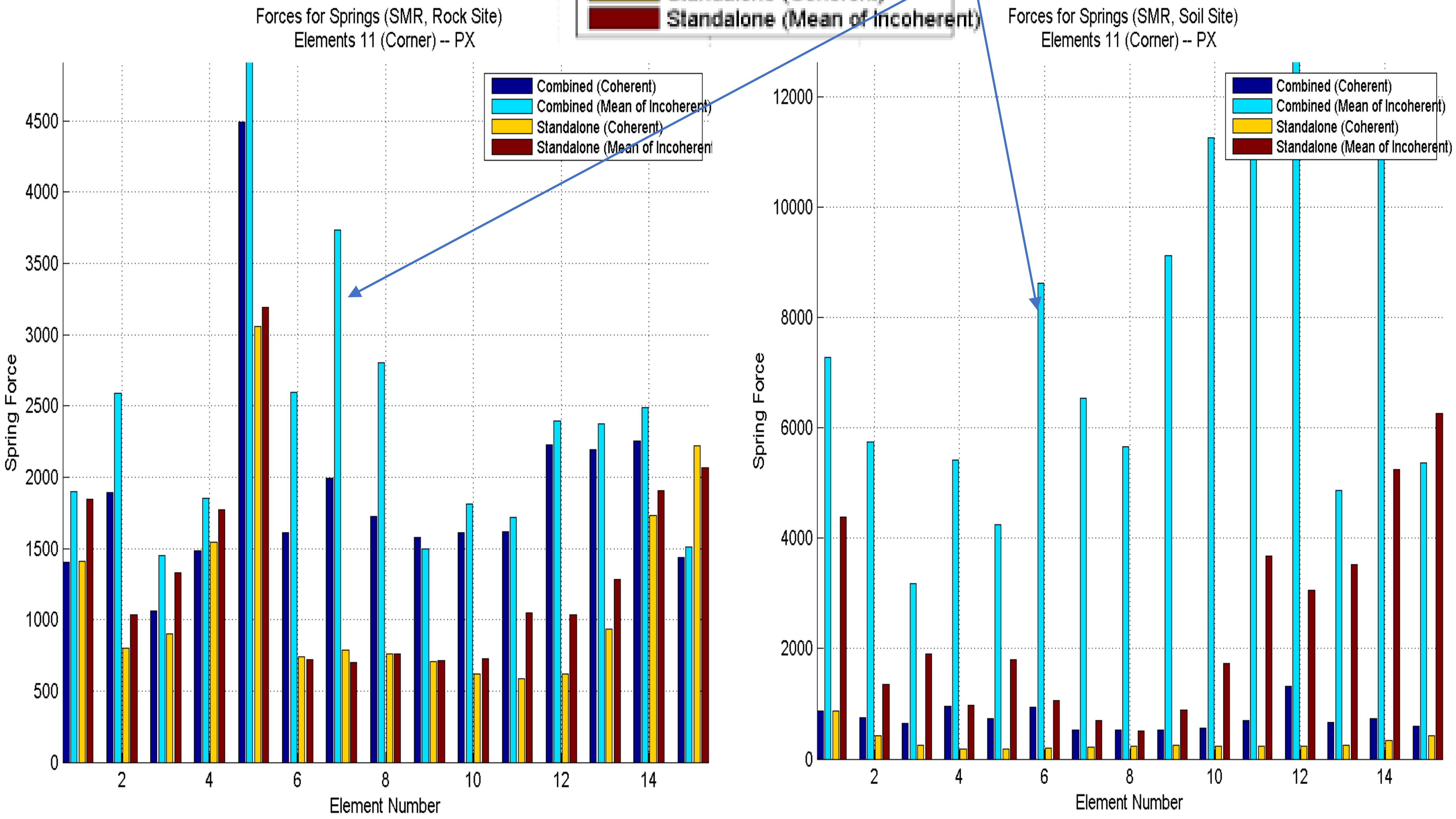
EMBEDDED SMR

SSSI Effects on Seismic Soil Pressure (Spring Forces) Along the SMR Vertical Corner Edge Near AB

Rock Site



Soil Site

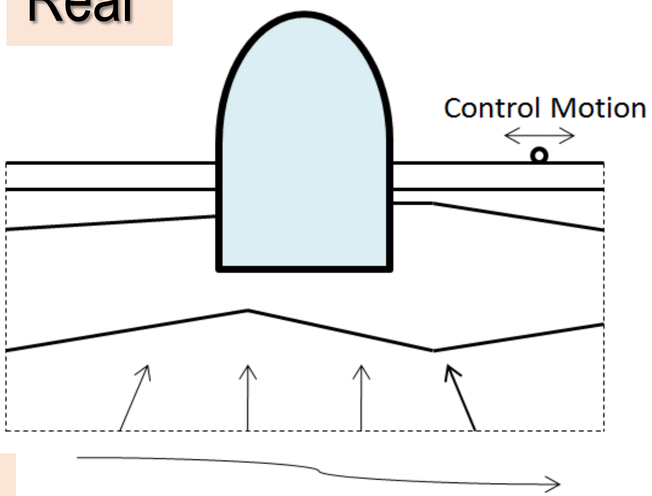


2.2 Flexible Volume Reduced-Order Modeling (FVROM or FVROM-INT) Approach

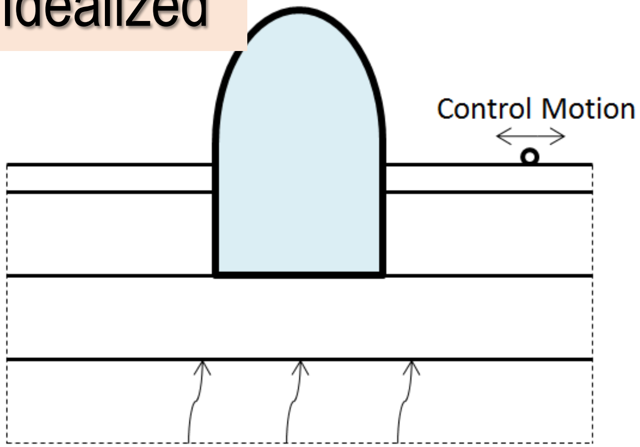
Note: FVROM-INT uses FVROM combined with a fast interpolation of excavation impedance matrix

Time-Domain Direct SSI Analysis with Surrounding Soil FE Modeling

Real

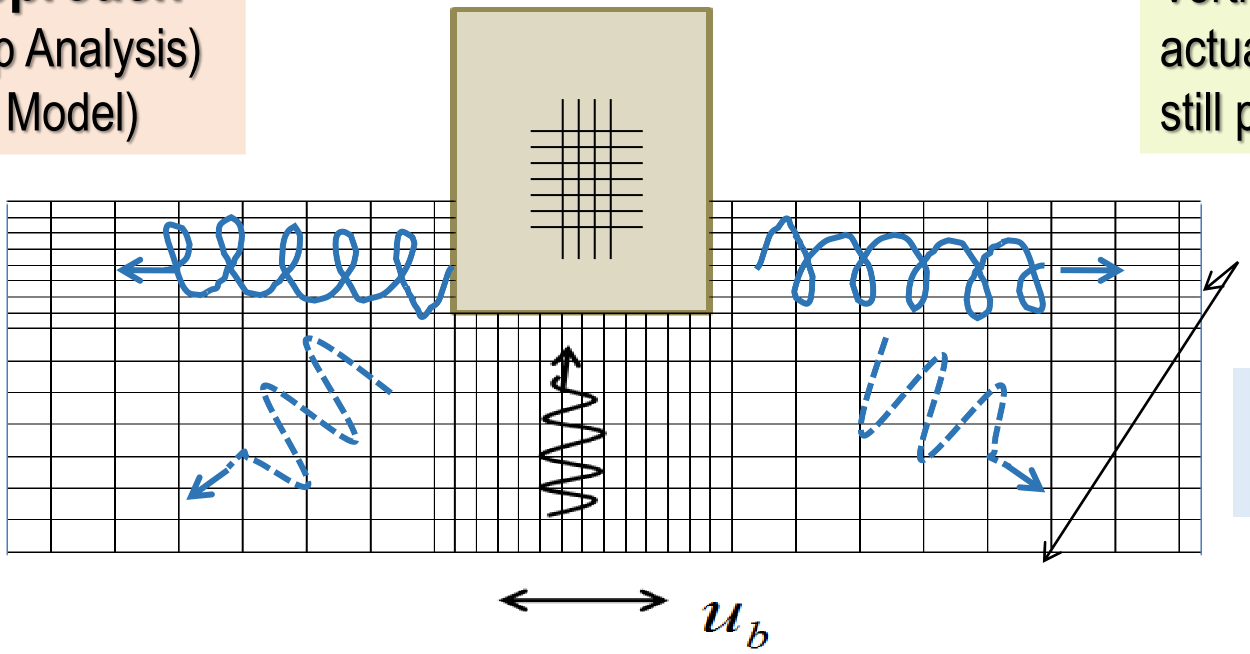


Idealized



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

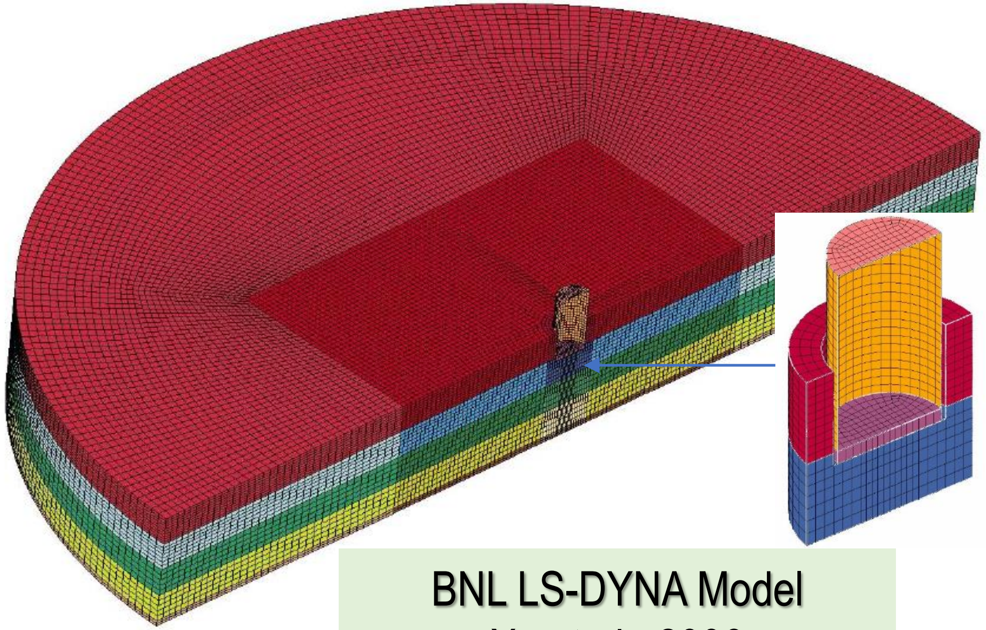
Vertical wave propagation is used to replace actual complex ground motion pattern, but still produce specified motion at control point.



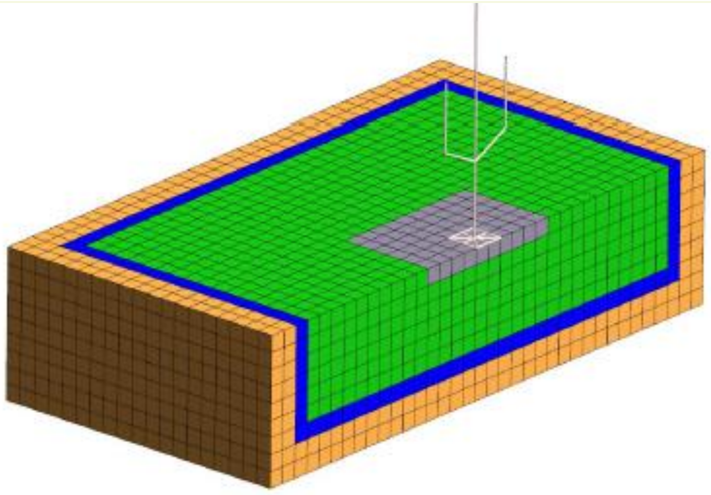
Conventional or Absorbant Boundaries
(stiffness, damping, soil motion)

Includes enormous amount of solid elements.
Up to 95-99% of elements are for soil modeling.

Direct SSI Approach and SASSI Approach Models

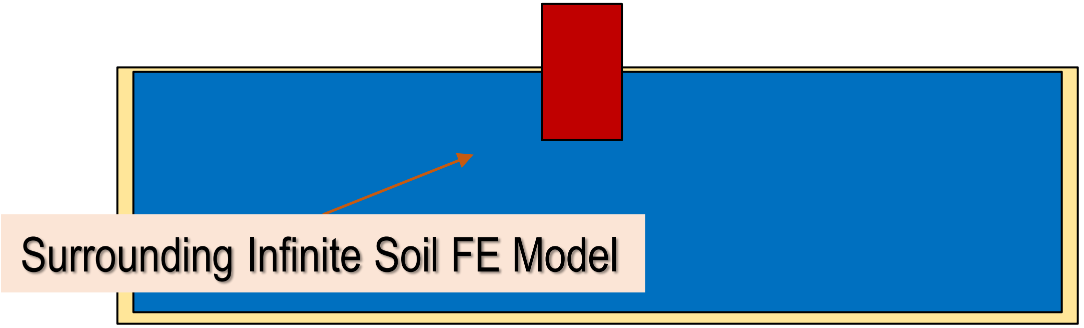


BNL LS-DYNA Model
Xu et al., 2006

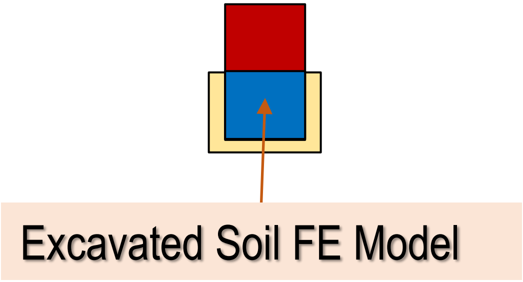


E-SSI Model (Low Frequency)
Neboja et al., 2015

Direct SSI Approach Model



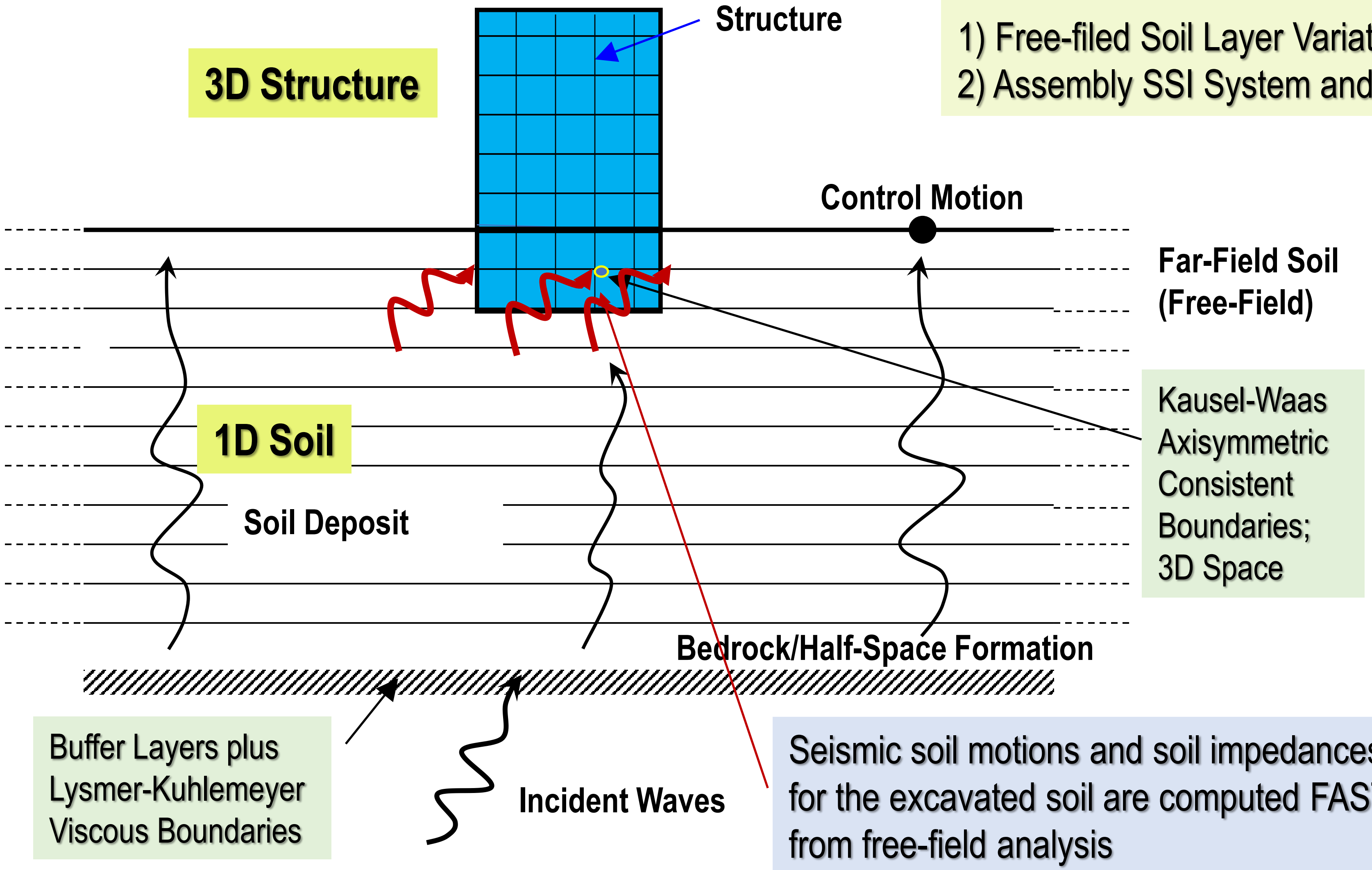
SASSI Approach Model



Standard SASSI Substructuring Methodology Uses 3D1D SSI Models

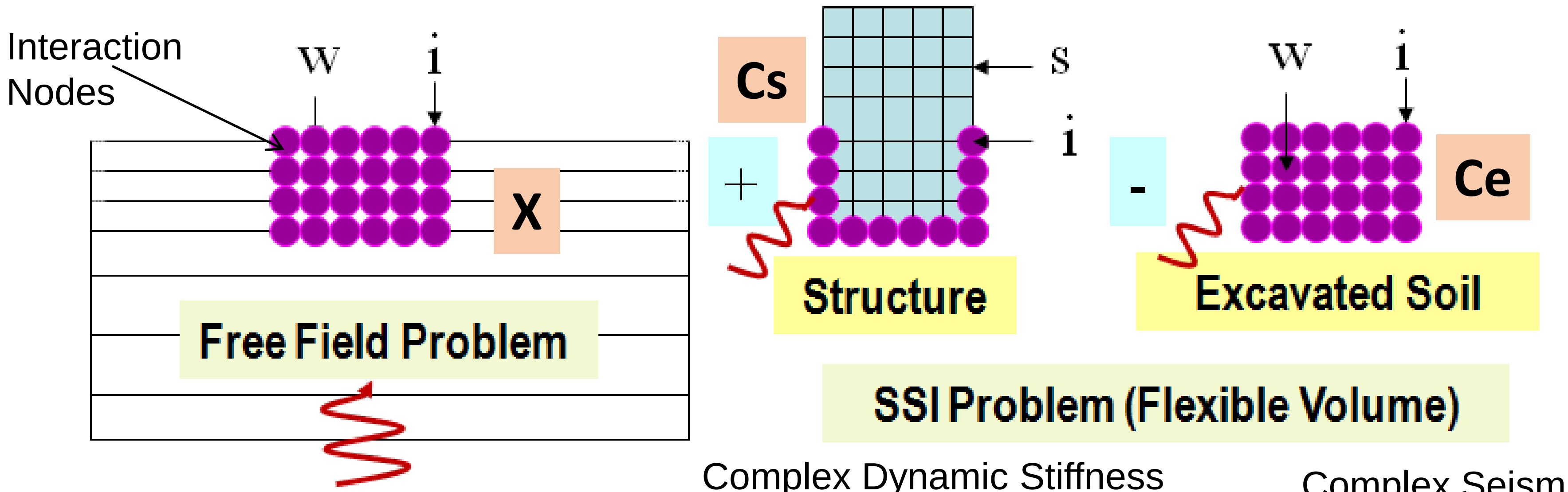
System Components Aspects:

1) Free-filed Soil Layer Variation (1D)
2) Assembly SSI System and Solve (3D)



Seismic soil motions and soil impedances for the excavated soil are computed FAST from free-field analysis

Standard SASSI Flexible Volume Method Description



Complex Dynamic Stiffness

Complex Seismic Load Vector

Complex Frequency Domain Formulation:

$$\boxed{C(\omega)\,U(\omega) = Q(\omega)}$$

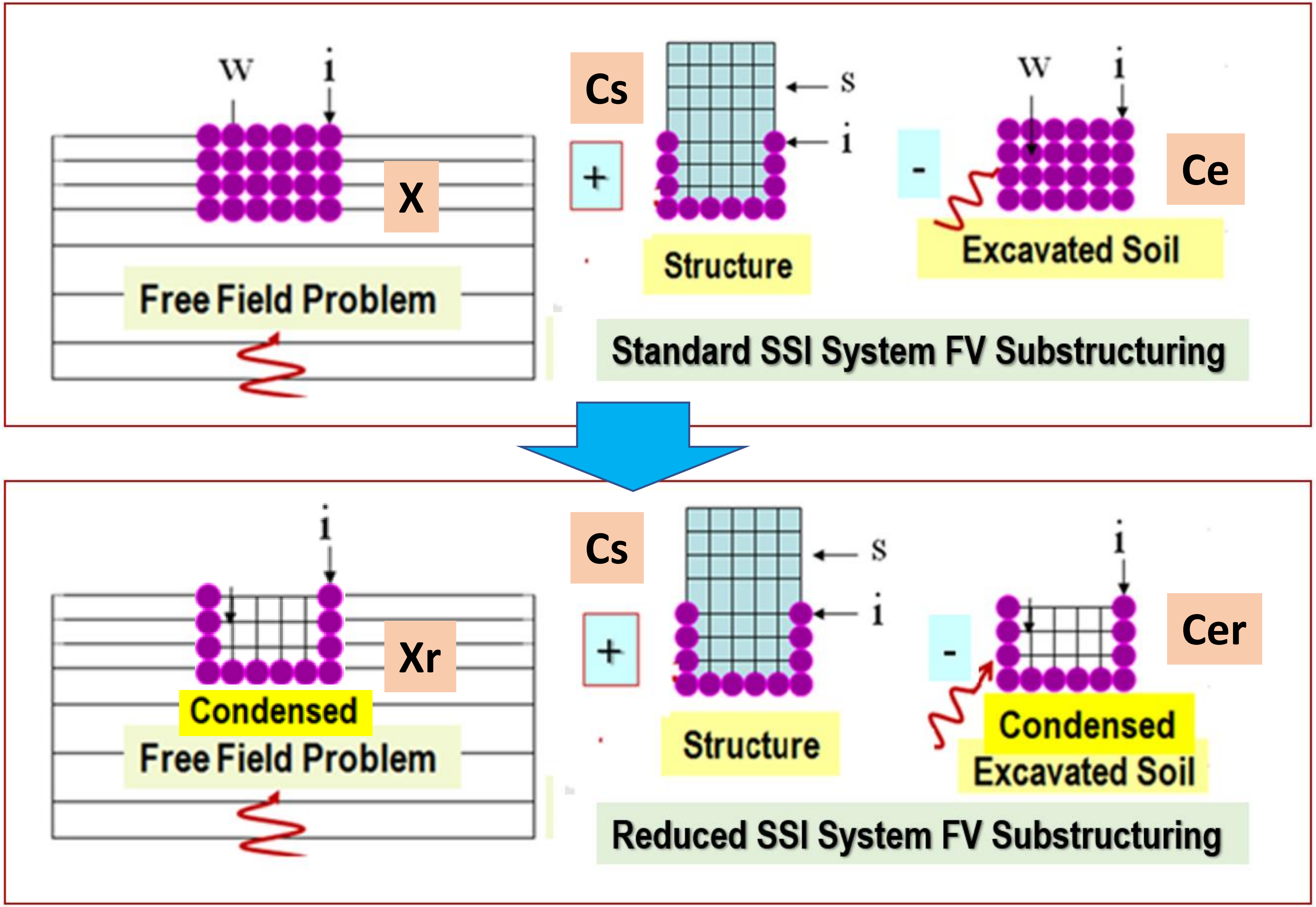
Complex Soil Impedance Terms

Complex Absolute Displacements

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

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

Fast SSI Analysis Using Excavation Reduced-Order Modeling



The excavated soil dynamic matrix is a frequency-dependent large-size full complex matrix.

Due to its lack of sparseness, the inclusion of this matrix in the SSI solution affects largely the numerically efficiency of the FV substructuring as defined in the original SASSI approach.

Using a frequency-dependent matrix condensation scheme, the size of this large-size matrix can be hugely reduced, and by this large speedups of SSI solution are obtained.

ACS SASSI Flexible Volume Reduced-Order Modeling (FVROM)

Flexible Volume Reduced-Order Modeling (FVROM) SSI approach uses the condensation of the excavated soil impedance matrix $\mathbf{Z}(\omega)$ at the foundation-soil interface nodes (all the other excavation internal nodes and ground surface nodes are eliminated).

The excavated soil matrix $\mathbf{Z}(\omega)$ is computed based on the the soil layering impedance matrix and the excavated soil dynamic matrix, i.e. $\mathbf{Z}(\omega) = \mathbf{X}(\omega) - \mathbf{C}^{\mathrm{e}}(\omega)$ at each SSI frequency.

The SSI response is obtained using the SSI system with a reduced-size soil impedance matrix $\tilde{\mathbf{Z}}_{\mathrm{ii}}(\omega)$ and the reduced-size load vector $\{\tilde{\mathbf{F}}_{\mathrm{i}}(\omega)\}$ at each SSI frequency.

The SSI equation system becomes for the reduced-size SSI system:

$$\left(\left[\mathbf{C}_{\mathrm{ii}}^{\mathrm{S}}\right] + \tilde{\mathbf{Z}}_{\mathrm{ii}}\right)\{\mathbf{U}_{\mathrm{i}}\} + \left[\mathbf{C}_{\mathrm{is}}^{\mathrm{S}}\right]\{\mathbf{U}_{\mathrm{s}}\} = \left\{\tilde{\mathbf{F}}_{\mathrm{i}}\right\}$$

$$\left[\mathbf{C}_{\mathrm{si}}^{\mathrm{S}}\right]\{\mathbf{U}_{\mathrm{i}}\} + \left[\mathbf{C}_{\mathrm{ss}}^{\mathrm{S}}\right]\{\mathbf{U}_{\mathrm{s}}\} = \{\mathbf{0}\}$$

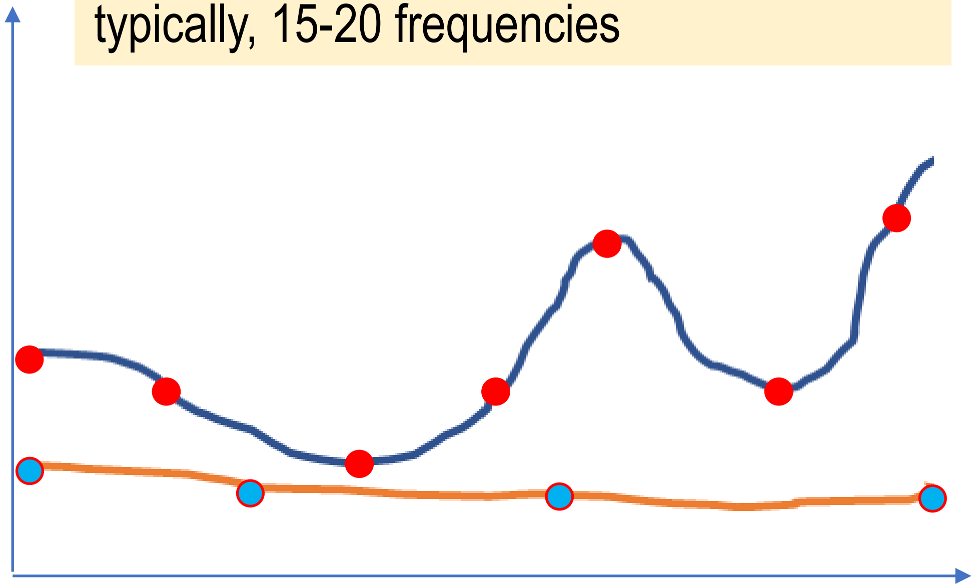
Reduced-Size Excavated Soil Impedance and Reduced-Size Seismic Load Vector

FVROM-INT Is Numerically Efficient Extension of FVROM Approach

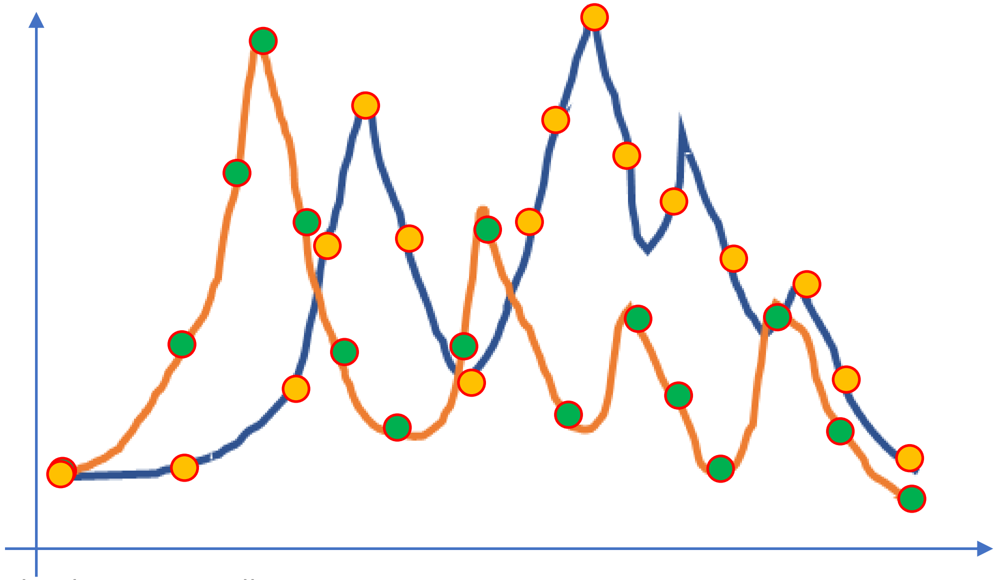
For numerical efficiency, excavation impedance matrix condensation can be combined with the interpolation in frequency of the reduced-size impedance matrix. This approach with combines matrix condensation and interpolation is called FVROM-INT (FVROM with INTerpolation).

Since the excavated *soil impedance variation in frequency is much smoother than the SSI response* variation, the use of interpolation is highly efficient for the overall computational effort of SSI analysis.

A reduced number of frequency solutions required for impedance interpolation; typically, 15-20 frequencies

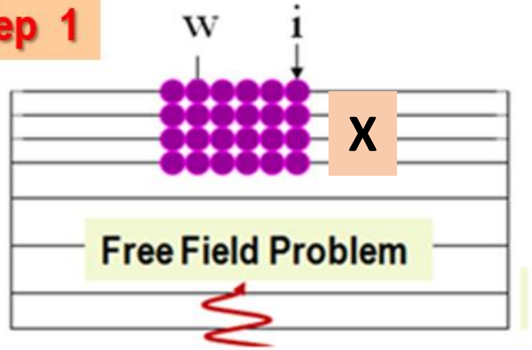


Many frequency solutions required for SSI response interpolation; typically, 180-280 frequencies



FVROM-INT Using Excavation Impedance Interpolation

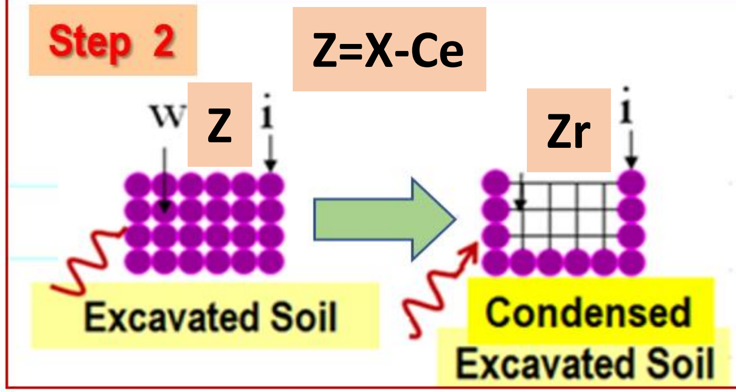
Step 1



Identify Key Frequencies Based on Free-Field Excavated Soil Dynamics

Perform the site response analysis by *running the SOIL module* to identify a reduced set of key frequencies for the excavated soil dynamics in free-field. Both the frequency-dependence of the excavated soil impedance matrix and its associated seismic load vectors are considered. The *dense SSI frequencies* for the SITE module which will be used for final SSI analysis are automatically *adjusted* based on the *key frequencies.*

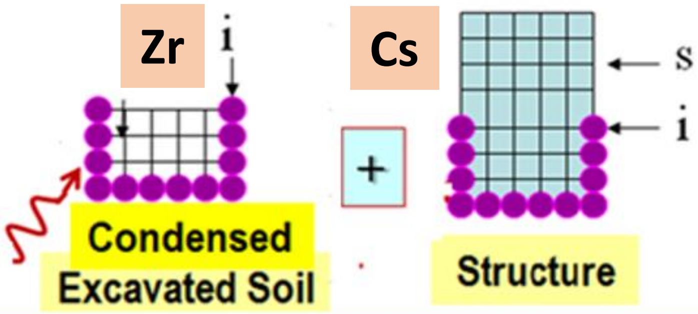
Step 2



Condense Soil Matrix for Key Frequencies and Interpolate for All Frequencies

The frequency-dependent excavated soil dynamic matrix is condensed for the foundation-soil interface nodes for *key frequencies only*. This is accomplished by *running ANALYS option "Condense Impedance" (Mode 7).* Then, the reduced excavation dynamic matrix and seismic load vector are interpolated *for all dense SSI frequencies* by *running the CNDS_INTERP module*. Reduced soil matrices can be also exported to ANSYS for performing a SSI harmonic analysis via SASSI methodology.

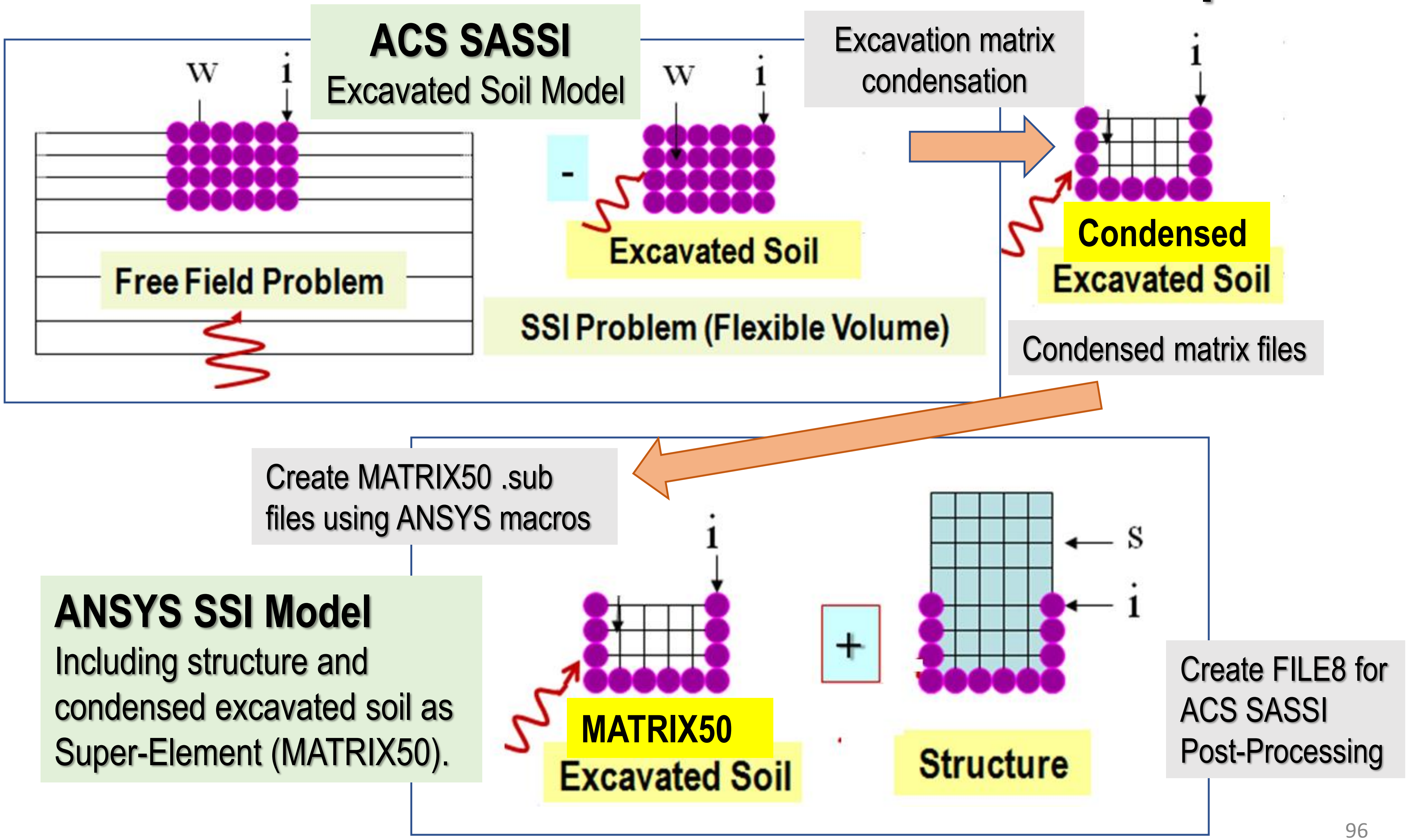
Step 3



Compute SSI Solution Using Reduced Excavation Matrix for All Frequencies

The interpolated reduced excavation dynamic matrix and seismic load vectors computed *for all SSI frequencies* are assembled with the structure model, and the SSI solution is obtained for each frequency. This is accomplished by *running ANALYS option "SSI with Condensation" (Model 8).* The final SSI solution running time and the soil impedance file sizes are much smaller since the number of interaction nodes is minimal. Speed ups of 5-15 times are expected for detailed deeply embedded models.

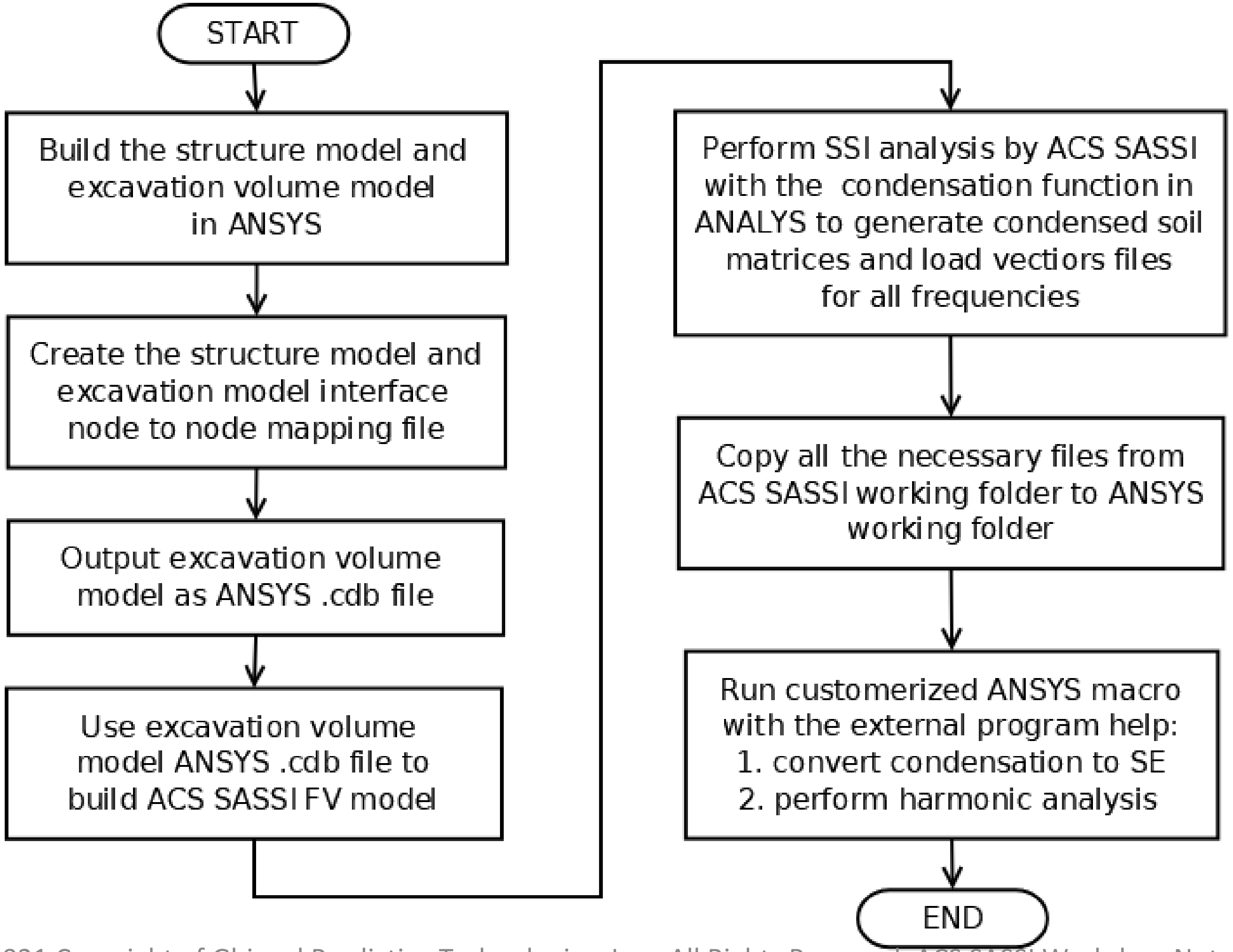
ACS SASSI Option AA-R for ANSYS Fast-Harmonic SSI Analysis Using Reduced Excavated Soil Matrix as MATRIX50 Super-Element



ANSYS Fluid SSI Analysis (with FLUID30) Via ACS SASSI Option AA-R. Condensed Excavation Soil Matrix is Passed to ANSYS for FSSI Analysis.

The ACS SASSI condensed excavated soil impedance matrix passed as a super-element (SE) to ANSYS that is automatically integrated with ANSYS structure model.

ANSYS or ACS SASSI to prepare excavation FE model for ACS SASSI condensation run



ACS SASSI excavation impedance condensation run

ANSYS SSI harmonic analysis run using prepared macros

Option AA-R Files for ANSYS SSI Analysis

The Option AA-R files required for the ANSYS Runs are:

prep_se.exe	Application
SSI2ANSYS.exe	Application
do_cdns_ssi.mac	MAC File
do_condense_hrm.mac	MAC File
fread_data.mac	MAC File
gen_condense_se.mac	MAC File
use_condense_se.mac	MAC File

To run the *ANSYS SSI harmonic analysis*, the user needs ONLY to input in the ANSYS command line the name of the ***do_cdns_ssi*** macro:

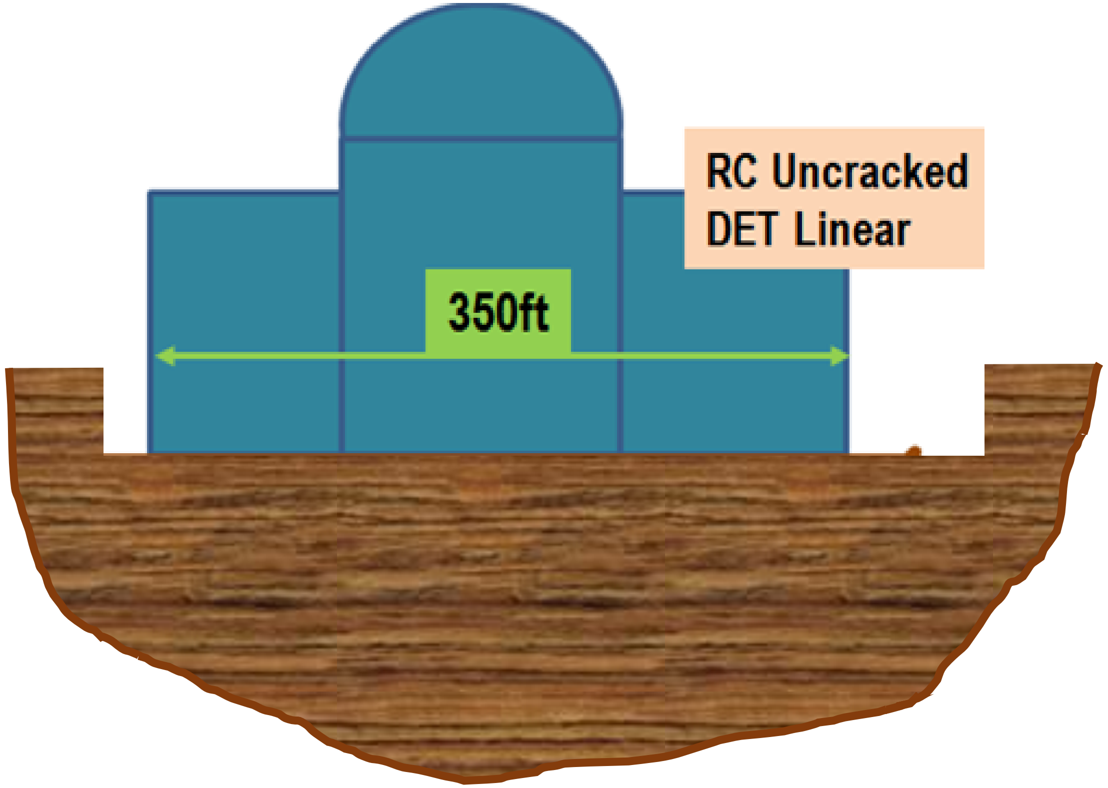
do_cdns_ssi,'structure_modelname,'ssi_freqs','txt'

where the ***ssi_freqs.txt*** file includes the SSI analysis frequencies

ANSYS *do_cdns_ssi* Macro

```
! do_cdns_ssi
!*******************************************************************************
!*   do_cdns_ssi  Start                                                        *
!*******************************************************************************
!*##############################################################################
!    do_cdns_ssi call to few MACROs to perform SSI analysis in ANSYS using
!       harmonic analysis.
!       First, it calls MACRO of "gen_condense_se" to generate super element file
!       for for first frequency.
!       Then, it calls MACRO of "use_condense_se" to create SE data for first
!       Last, it calls MACRO of "do_condense_hrm" to do harmonic analysis frequency
!       by frequency in the order that is set in the frequency data file.
!****---------------------------------------------------------------------------
!    Pre-condition:
!
!****---------------------------------------------------------------------------
!    Call the Macro with the right arguments
!
!    do_cdns_ssi,arg1,arg2,arg3,
!
!    ARG1 [chr,sc,in] = ANSYS structure data base file name (.db), i.e.
!                       'rb_test_stru'
!    ARG2 [chr,sc,in] = The file name of the frequency for SSI analysis, i.e.
!                       'rb_test_ssi_freq'
!    ARG3 [chr,sc,in] = file extension name of the frequency for SSI analysis, i.e.
!                       'txt'
!
!    EXAMPLE: do_cdns_ssi,'rb_test_stru','rb_test_ssi_freq','txt',
!
!    Result will be save in ARG6 & ARG7 components
! ##############################################################################
!
gen_condense_se,ARG1,'se_dof','job_name'
use_condense_se,job_name,
ARG72 = ARG2
ARG73 = ARG3
do_condense_hrm,job_name,'SE_DOF',ARG72,ARG73,
```

Embedded RB Model Analysis for Direct SSI vs. FVROM-INT SSI



RB Complex SSI Model Information:

- Number of Nodes: About 80,000
- Number of Interaction Nodes: About 8,000
- Embedment Depth: 45 ft
- Excavation includes 6 Embedment Layers
- Direct SSI Approach: Fast FV with 4 out of 7 interaction node layers

Seismic SSI Analysis Runtime:

ACS SASSI Direct Runtime: 733 units

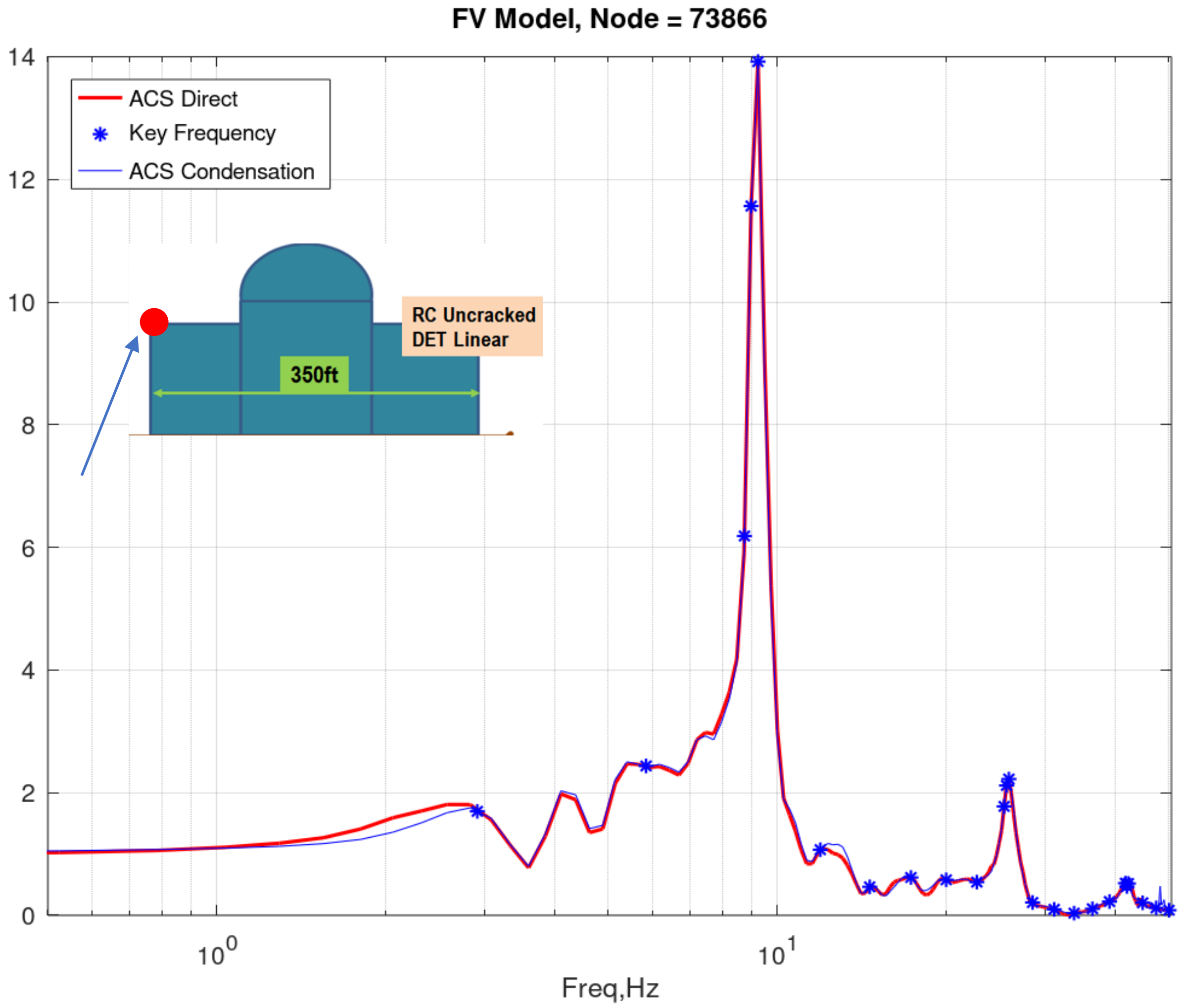
ACS SASSI with Condensation Runtime: 176 units

Speed Up due to Condensation: 4.2

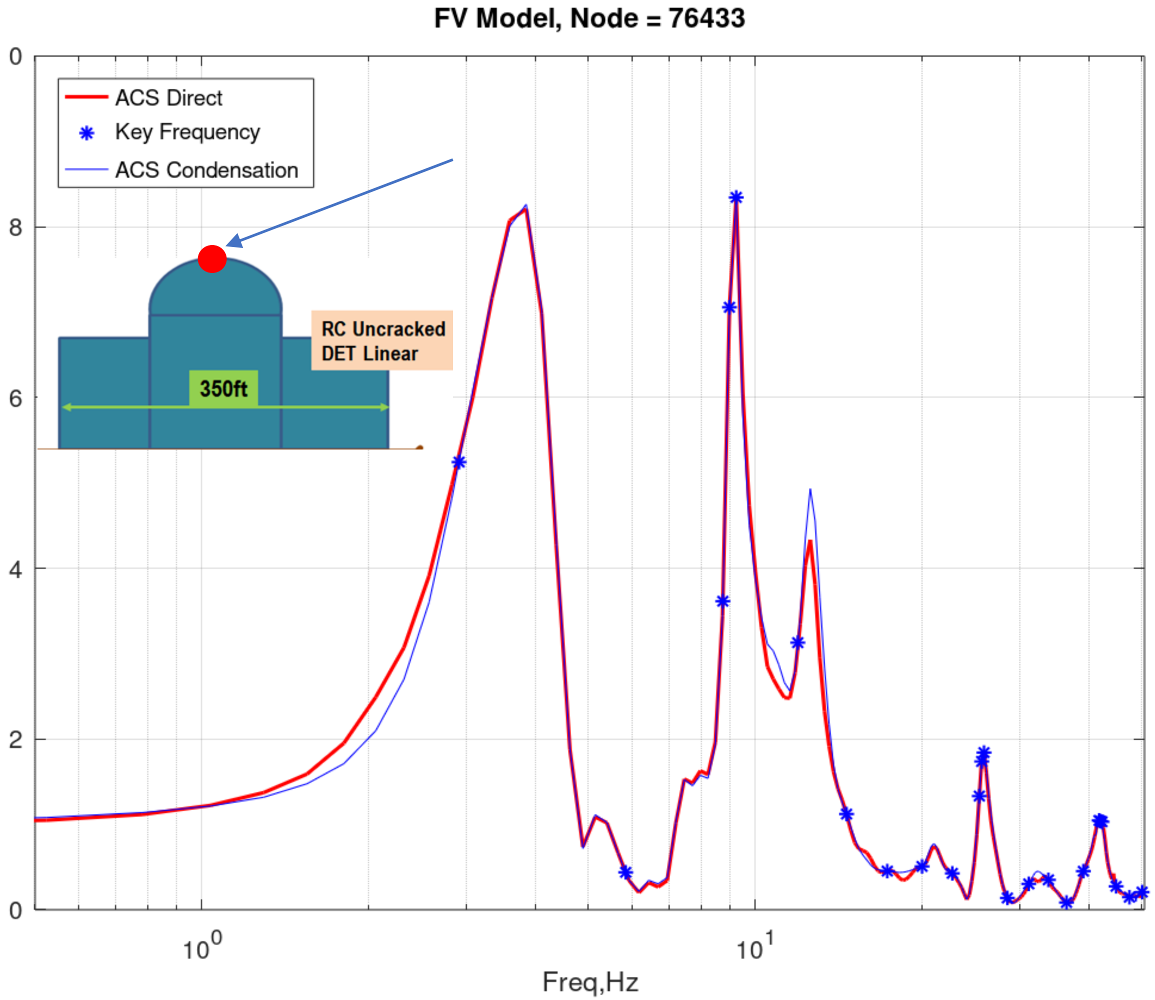
Larger speed ups up to 5-8 times for larger-size SSI models with deep embedment and larger number of interaction nodes.

Embedded RB SSI Analysis: Direct SSI (FFV) vs. FVROM-INT SSI

Top Corner of NI

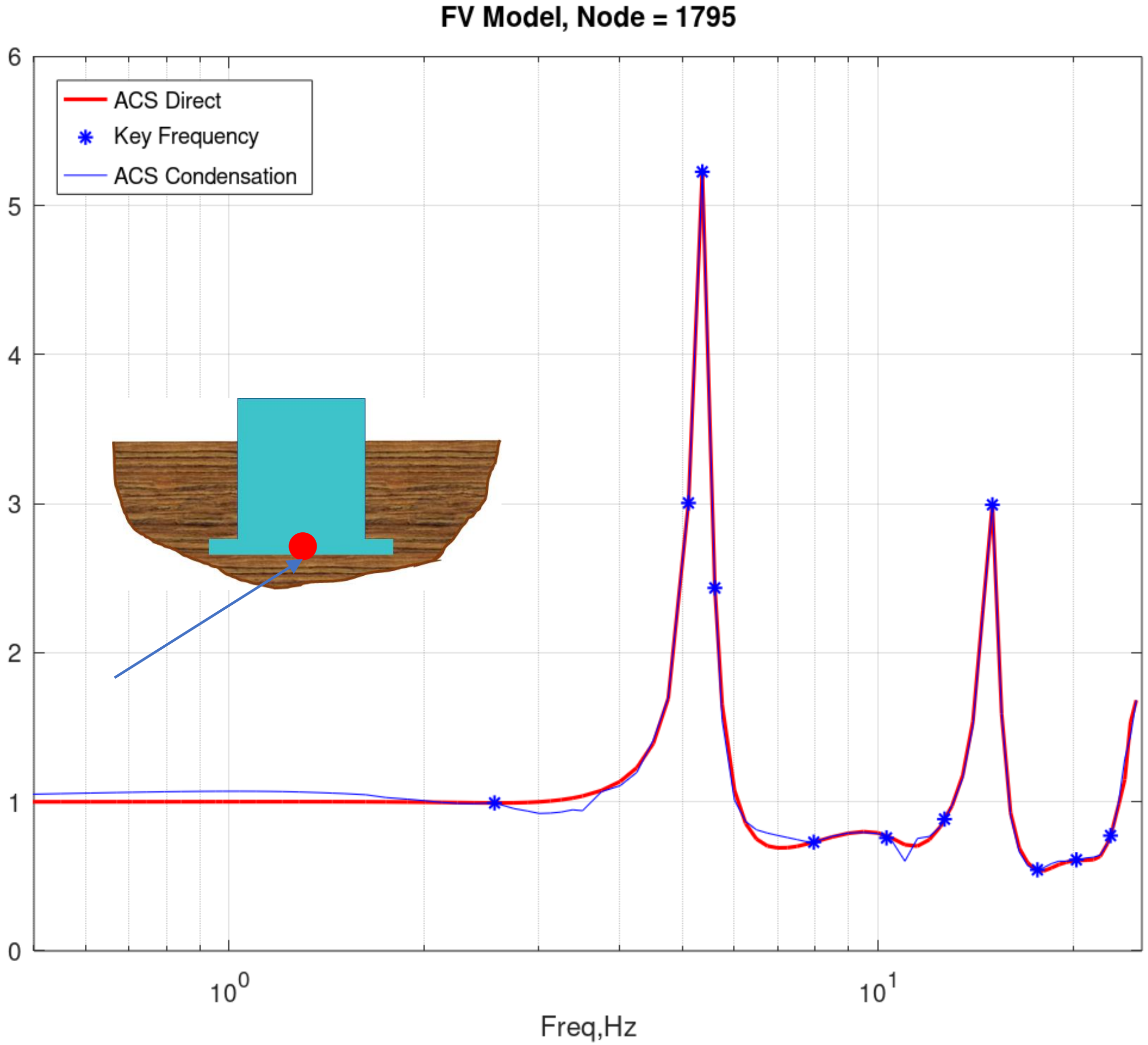


Top of Containment Shell

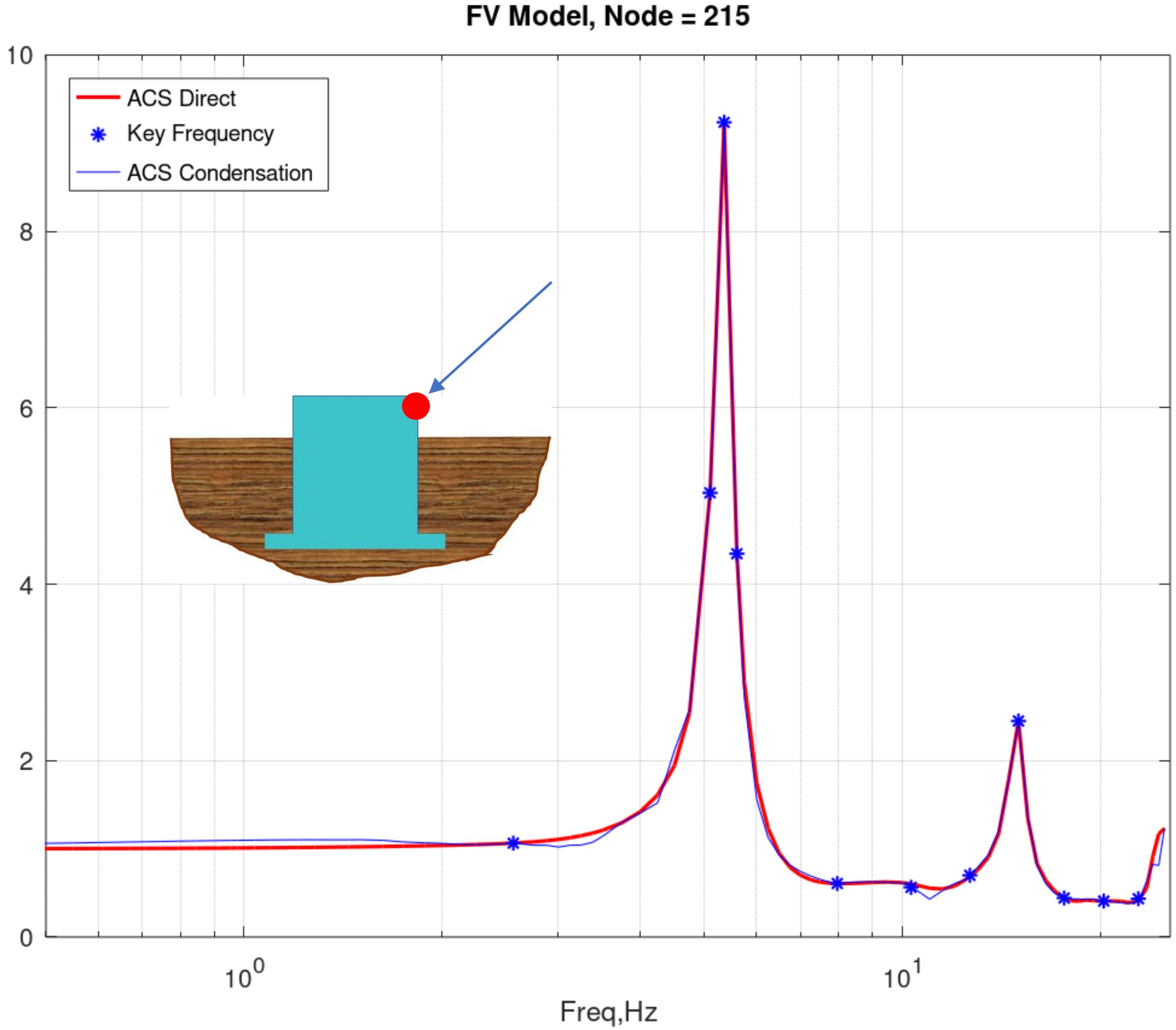


Deeply Embedded SMR: Direct SSI (FV) vs. FVROM-INT SSI

Basemat Center

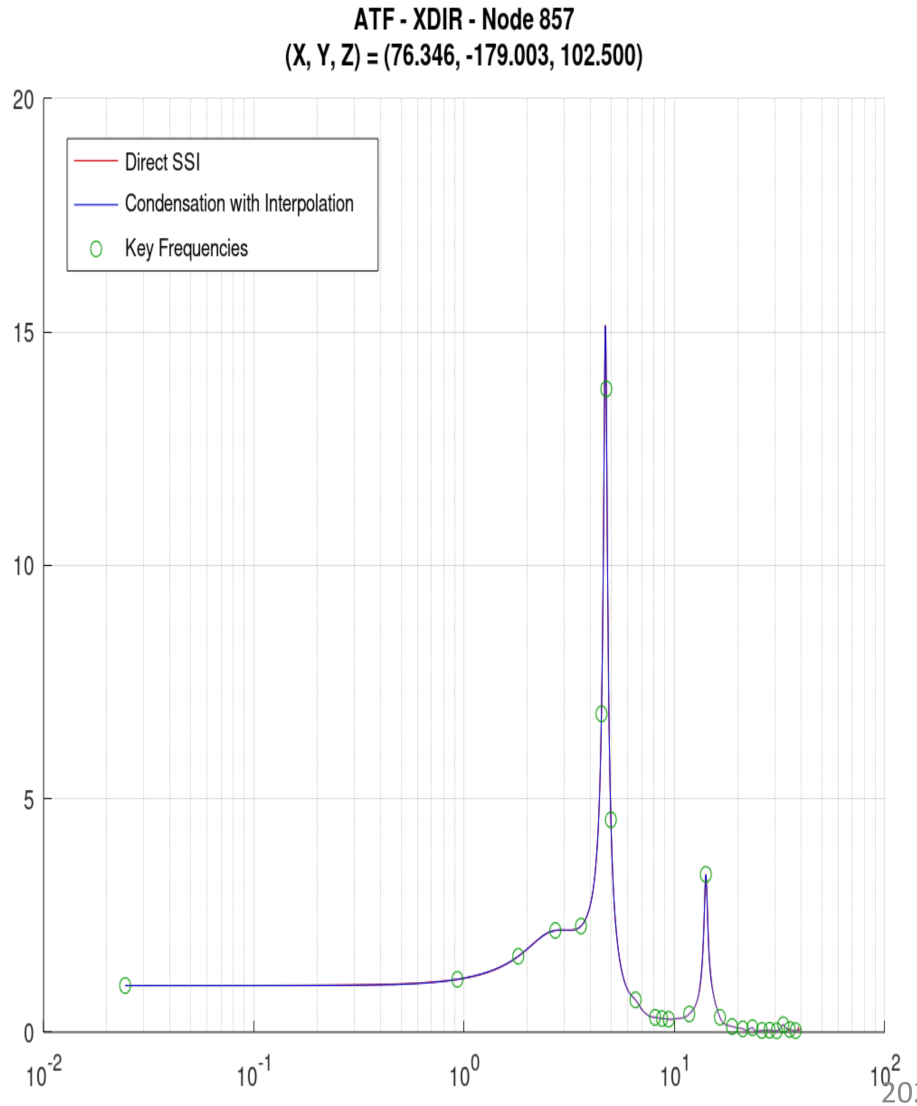


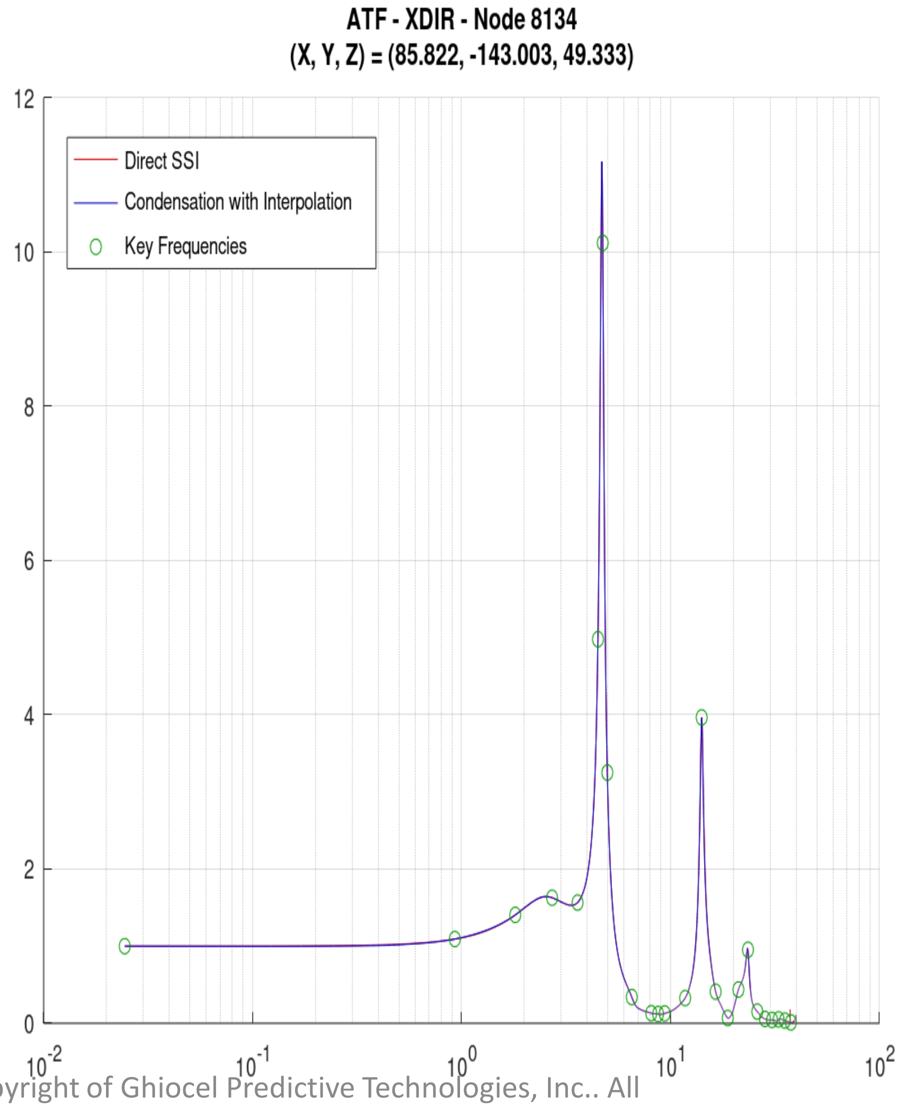
Top of SMR Structure

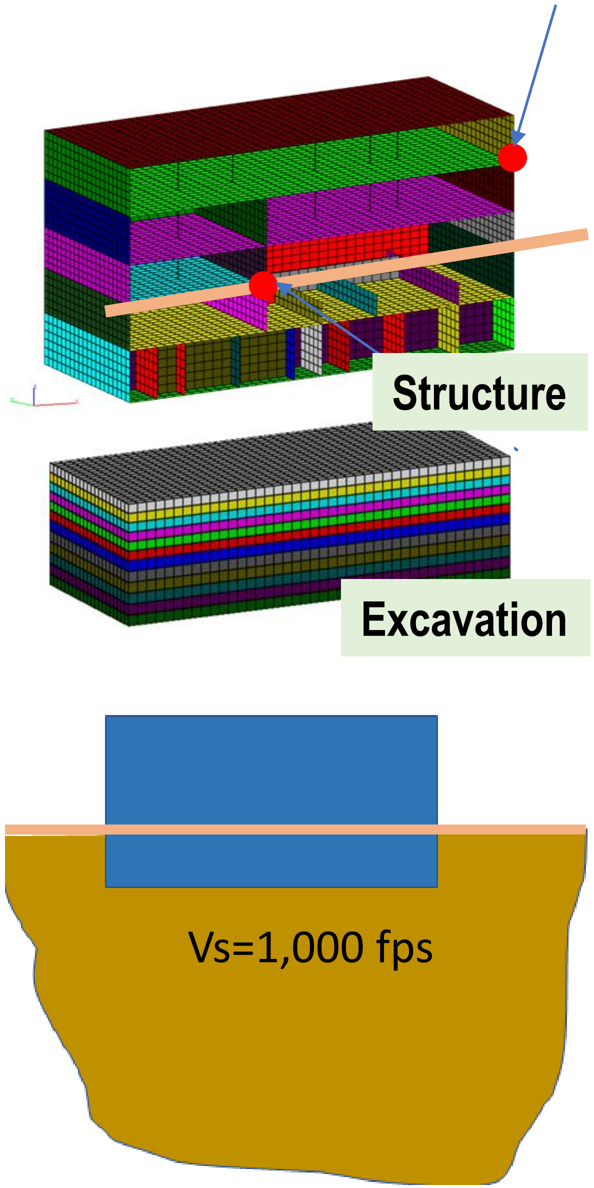


Deeply Embedded Structure (DES); Direct vs. FVROM-INT SSI.

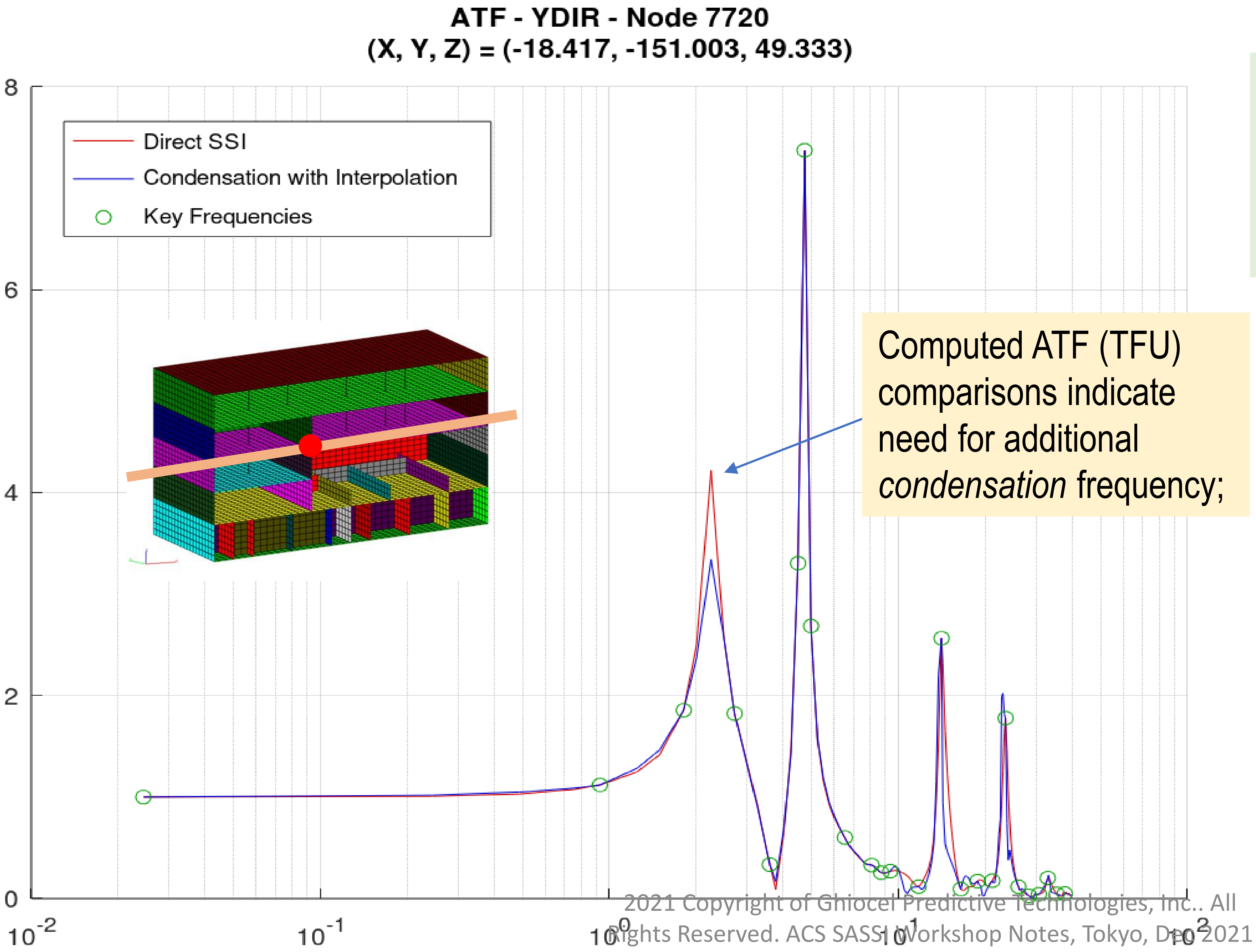
Case 1: Uniform Soil Deposit





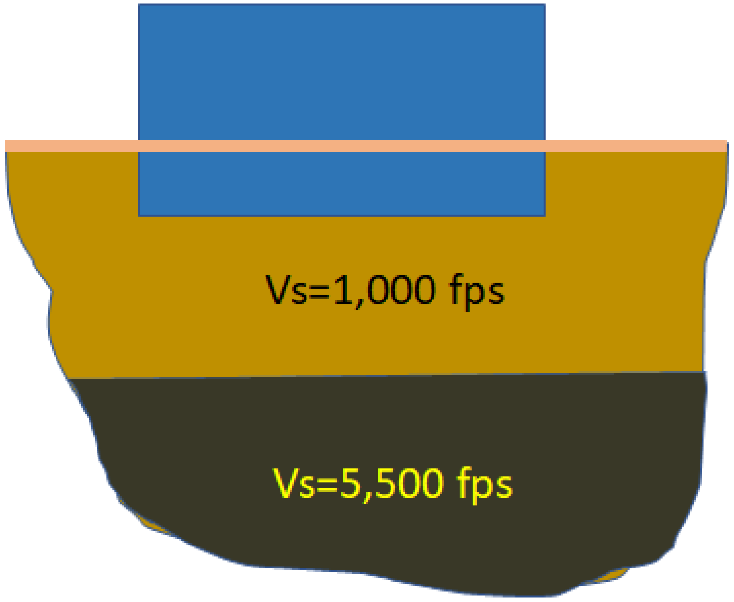


Deeply Embedded Structure (DES); Direct vs. FVROM-INT SSI.
Case 2: Non-Uniform Soil Deposit

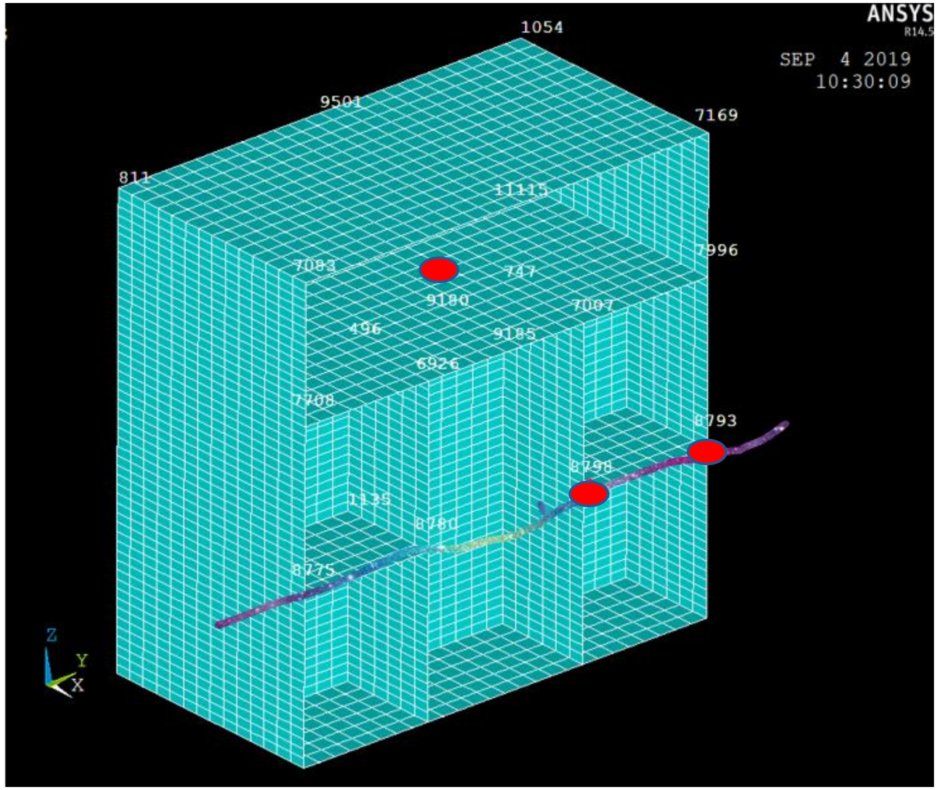


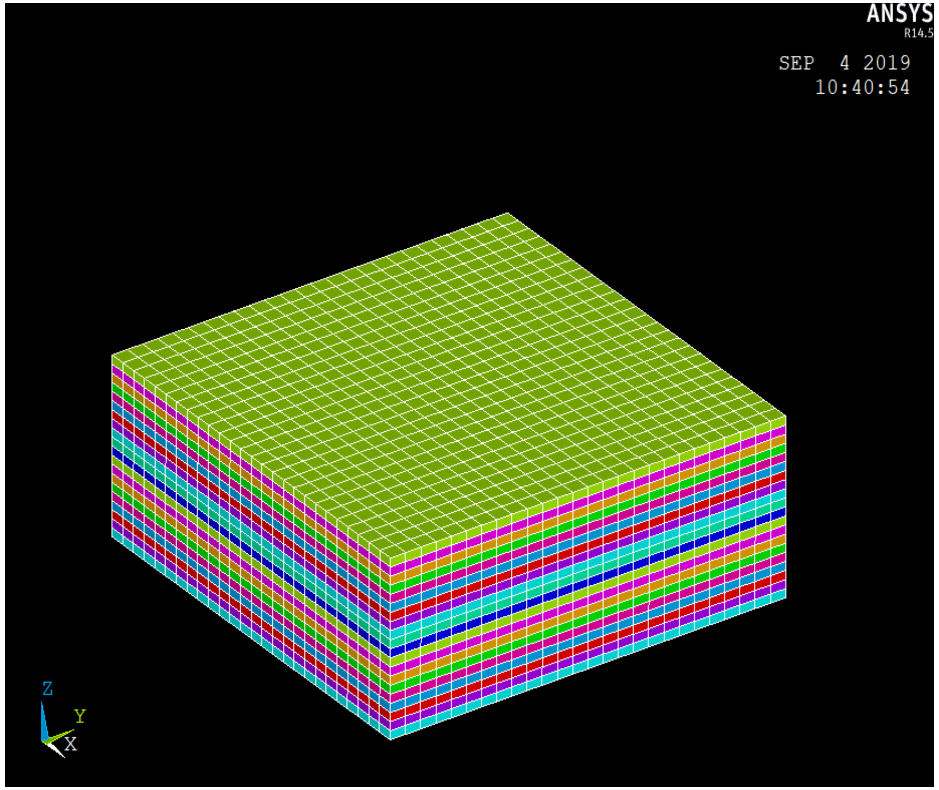
Computed ATF (TFU) comparisons indicate need for additional *condensation* frequency;

Nonuniform soil site with a soft soil layer with Vs = 1,000 fps down to the 100ft depth sitting on a much stiffer soil formation with Vs = 5,500 fps.



Option AA-R Sensitivity Studies for Embedded RB Using FVROM Approach and REDUCEINT Command





Remarks:
- Embedded RB SSI Model has 11195 nodes and 11756 SHELL elements
- Excavated soil includes 20 Embedment Layers (1.2m thickness), 15309 nodes
- Uniform soil with Vs = 720m/s
- Excavation has a regular mesh with 20 embedment layers;

Deeply Embedded RB Model Runtimes Using ACS SASSI Direct SSI vs. FVROM SSI with Option AA-R/ANSYS SSI Analysis

Table 1

ACS SASSI Direct and Option AA-R SSI Runtimes Per frequency

Modeling Approach	All Interface Nodes Are Condensation Nodes (Using INTGEN,3 Command as for SM)			
	Interaction nodes	Interface Nodes	Direct SSI (seconds)	Condensed SSI (seconds)
SM	2809	2809	202	1782
MSM	3434	2809	297	2036
FFV	5309	2809	602	3381
FV	15308	2809	12378	12678

Table 2

ACS SASSI Direct and Option AA-R SSI Runtimes Per frequency

Modeling Approach	Half Interface Nodes Are Condensation Nodes (Using INTGEN,3 and REDUCEINT Commands)			
	Interaction nodes	Interface Nodes	Direct SSI (seconds)	Condensed SSI (seconds)
SM	1405	1405	45	865
MSM	1718	1405	63	925
FFV	2657	1405	173	1212
FV	7665	1405	1551	6683

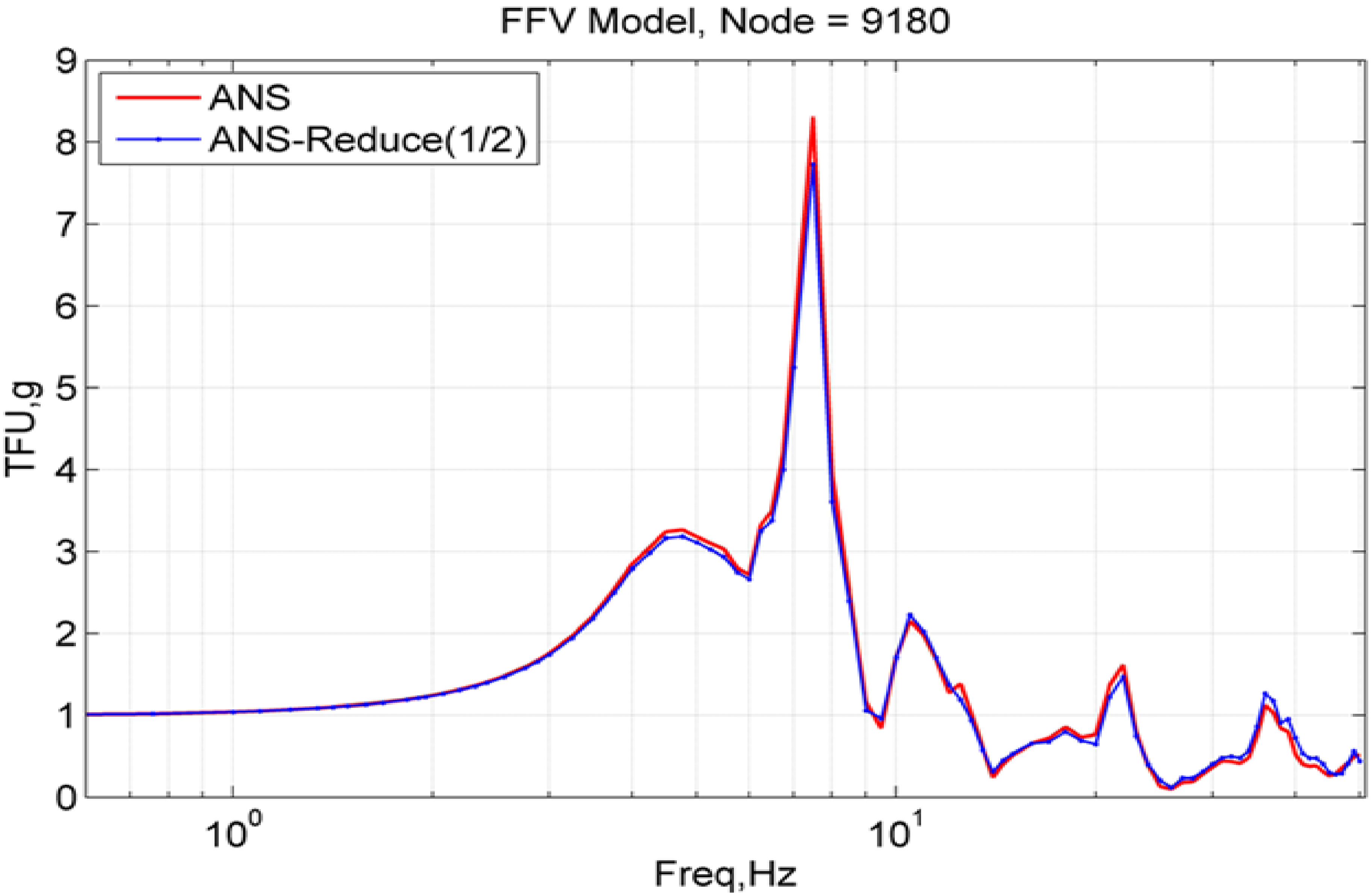
Older 64 RAM PC with limited RAM for FV with 15,308 interaction nodes

The FVROM SSI analysis is done for single frequency with no interpolation of the excavation impedance matrix.

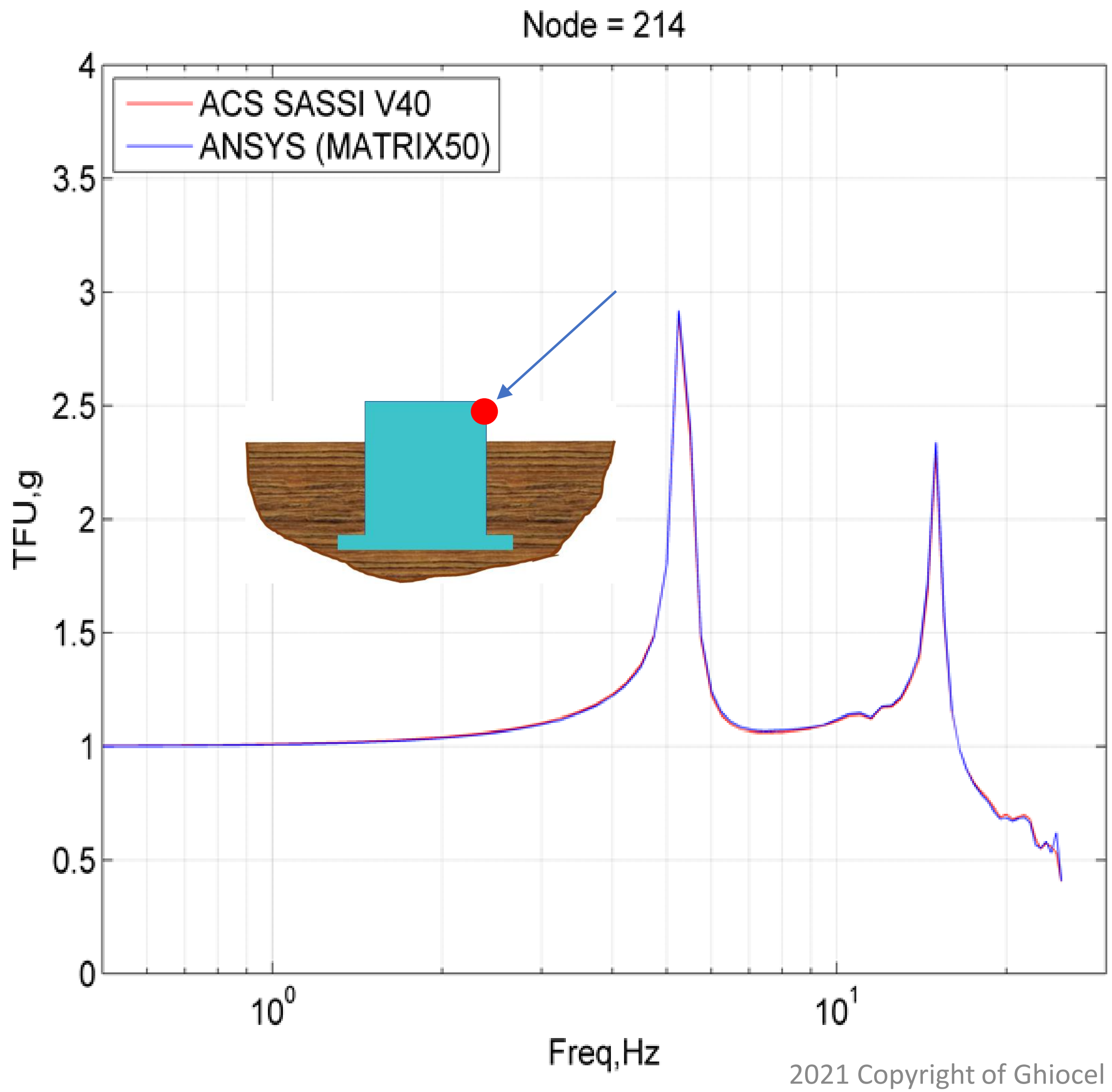
REDUCEINT was used to reduce the number of interaction nodes to half (twice larger radius).

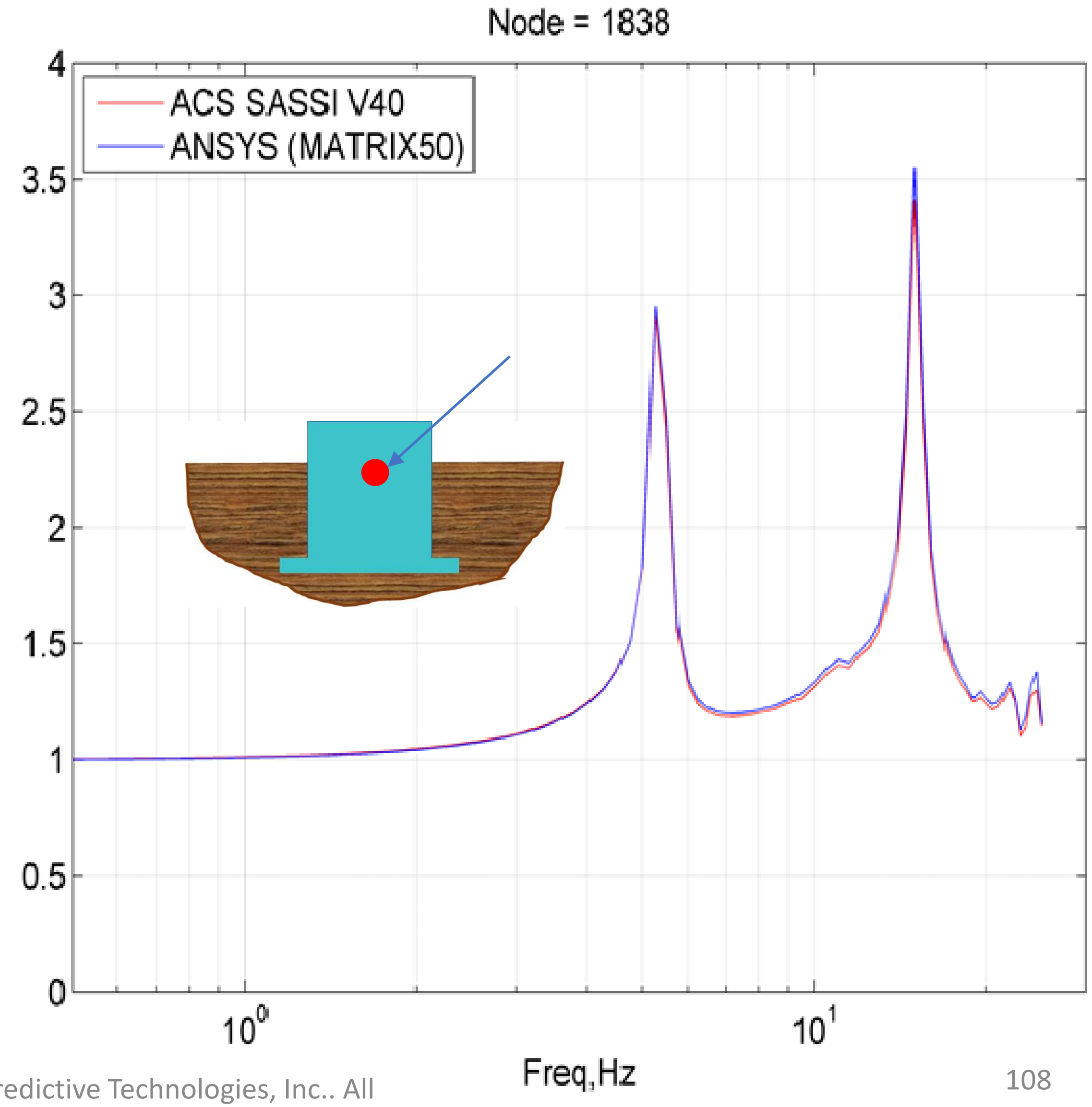
The numerical efficiency of REDUCEINT command is large.

ATF for Condensed Excavation ANSYS Using All and Only Half Interface Nodes for FFV (with REDUCEINT Command)

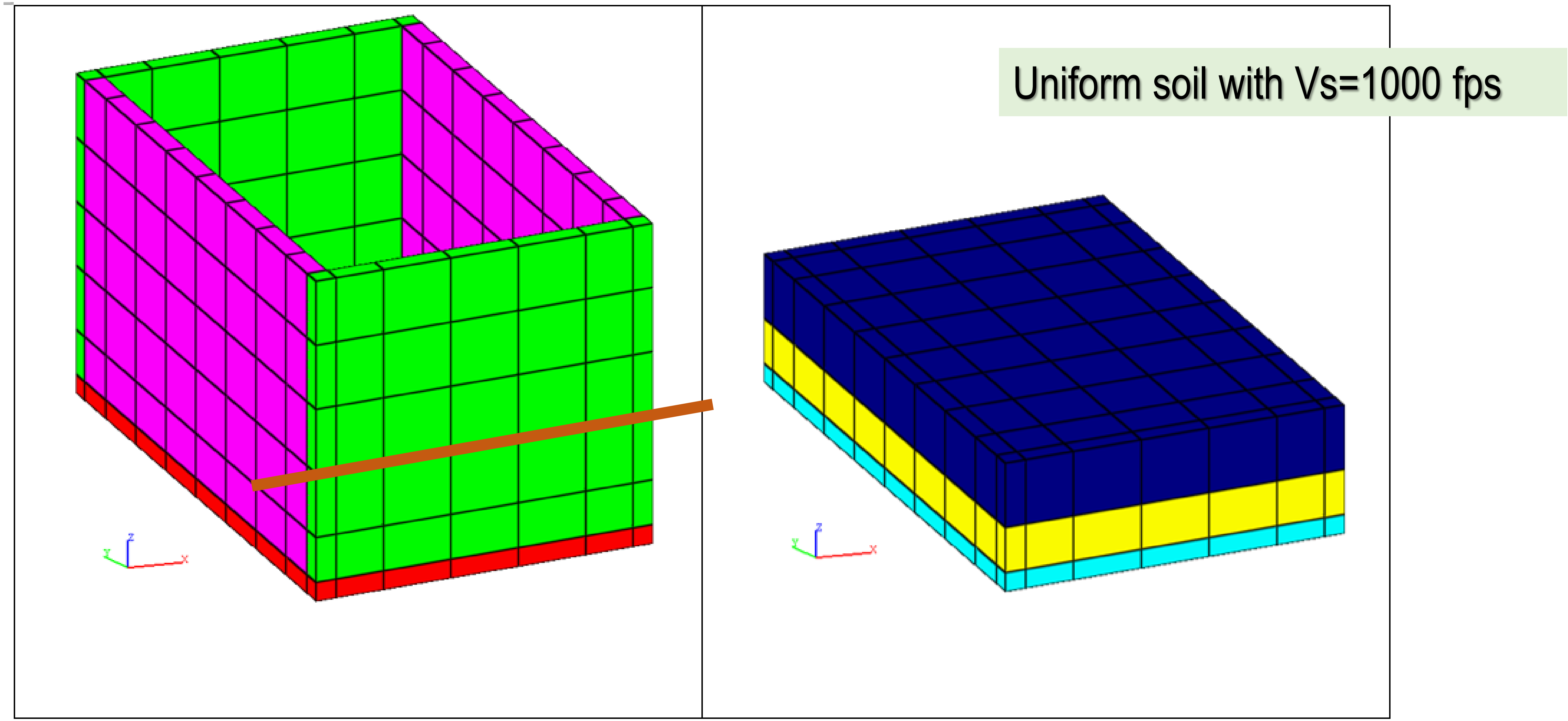


FVROM ATF Using ACS SASSI and Option AA-R ANSYS Models



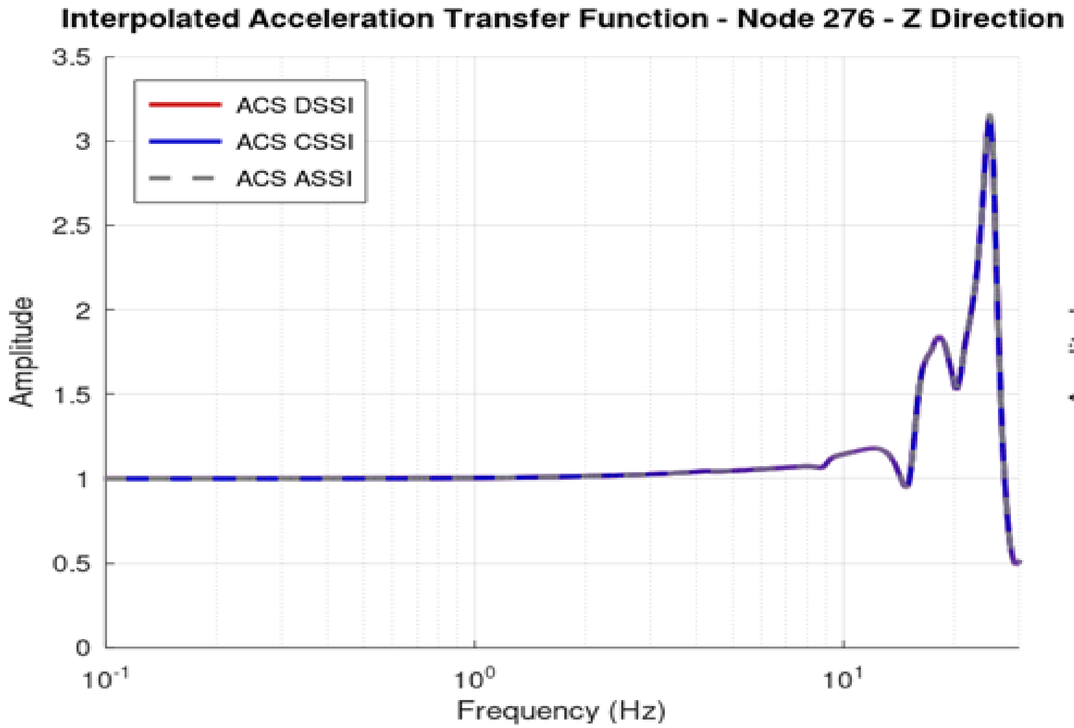


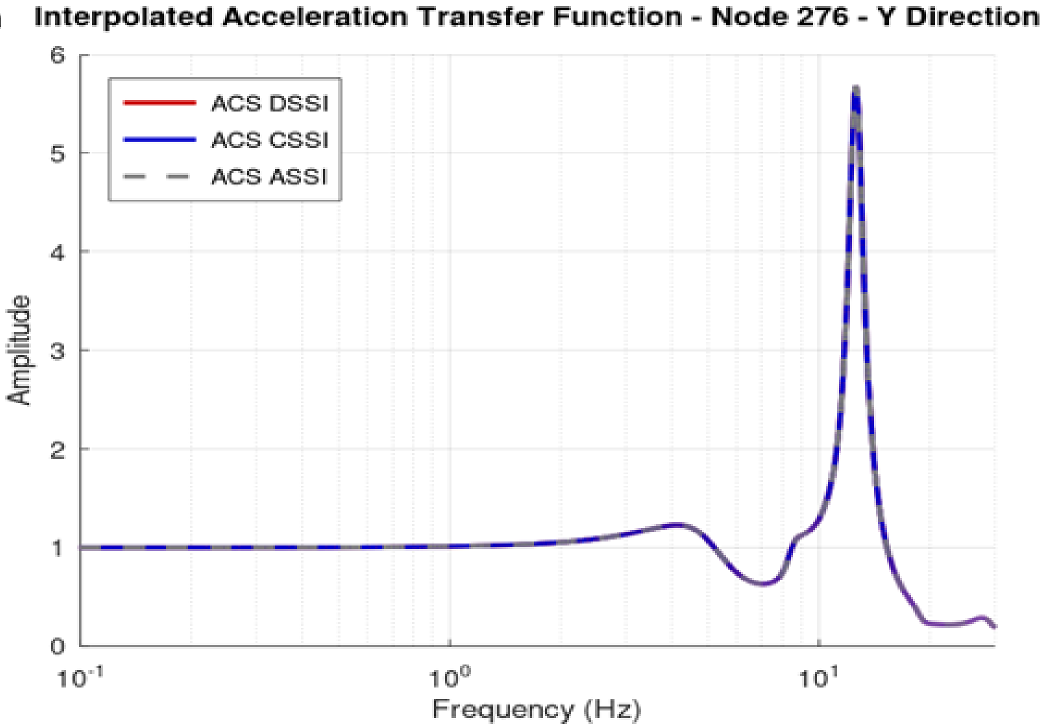
Validation of Option AA-R for ANSYS SSI Harmonic Analysis Using Condensed Soil Impedance, V&V Problem

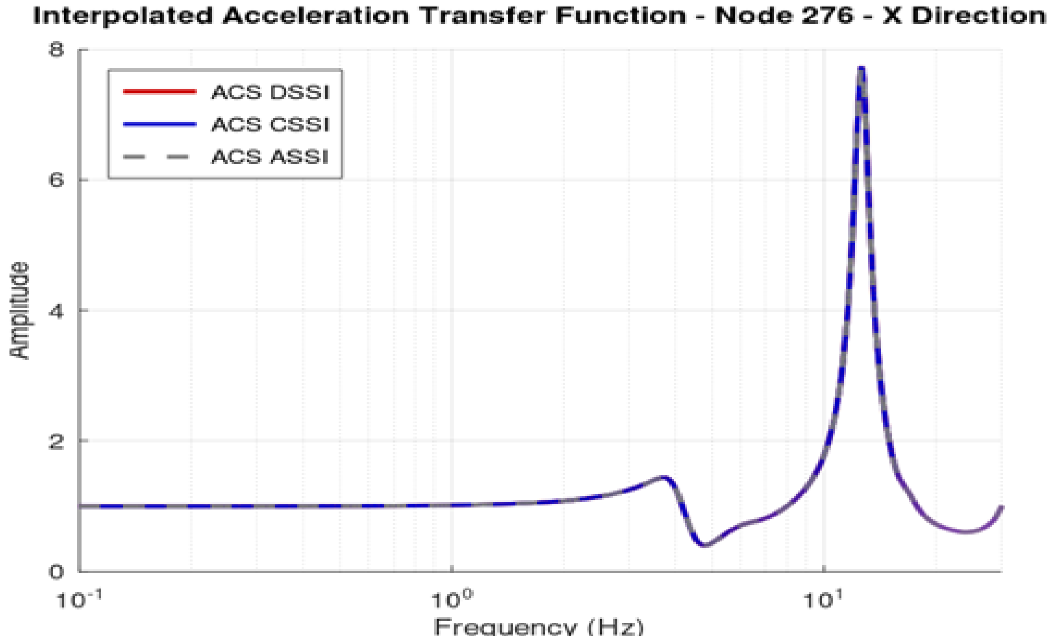


Structure Model

Excavation Model



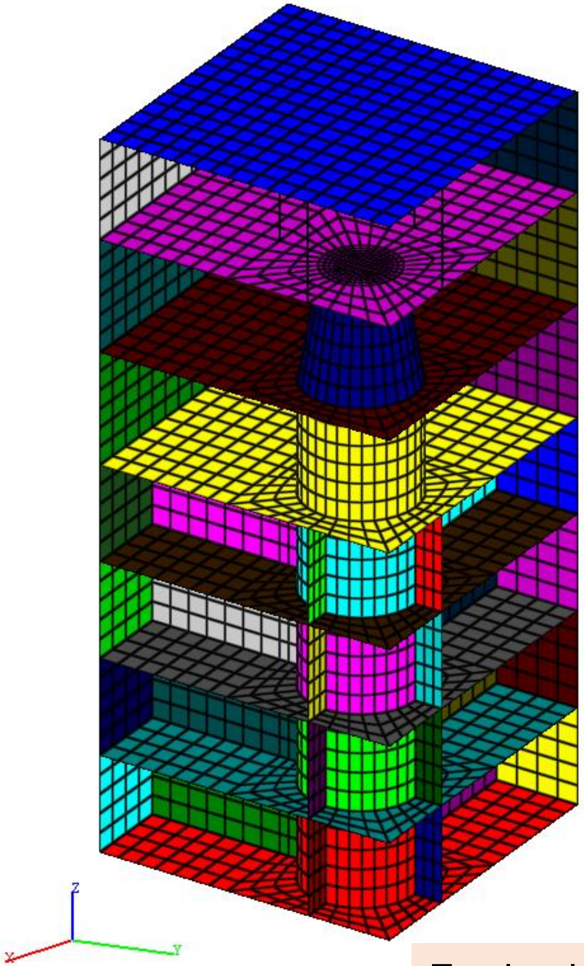




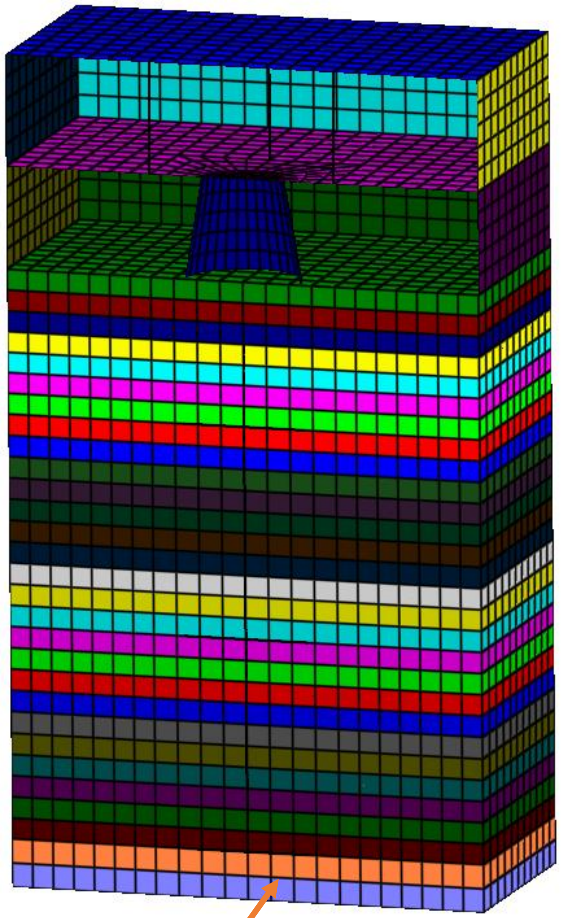
Perfect matching between ACS SASSI and ANSYS results with condensation. V&V Problem 59

FVROM Applied to Embedded SMR SSI Model Using FFV (ESM)

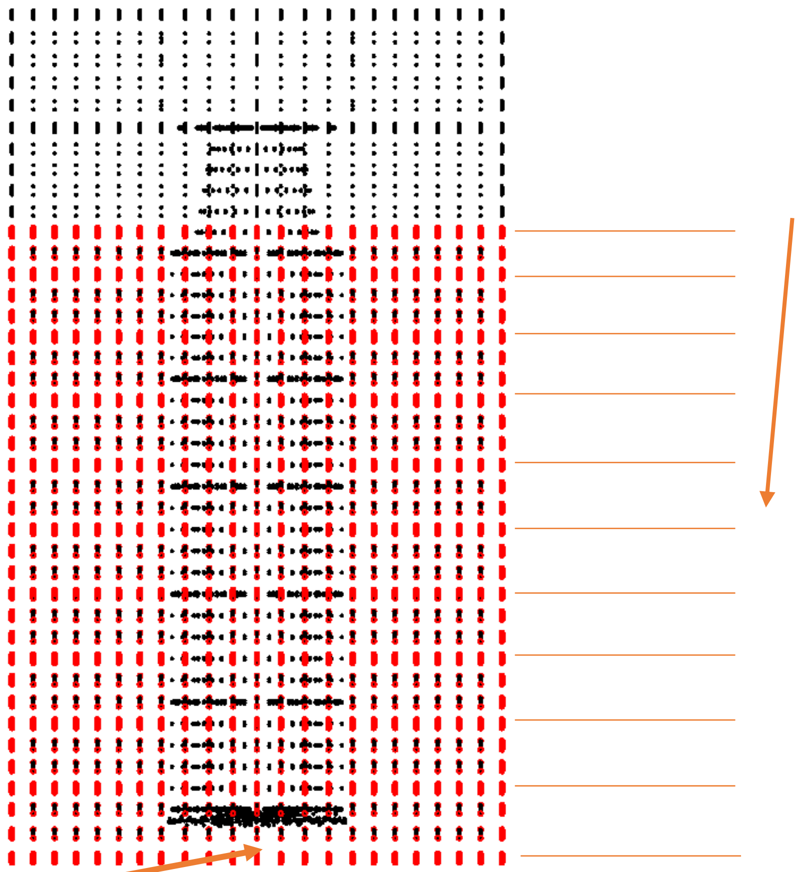
Structure Model (Quarter)



SMR SSI Model

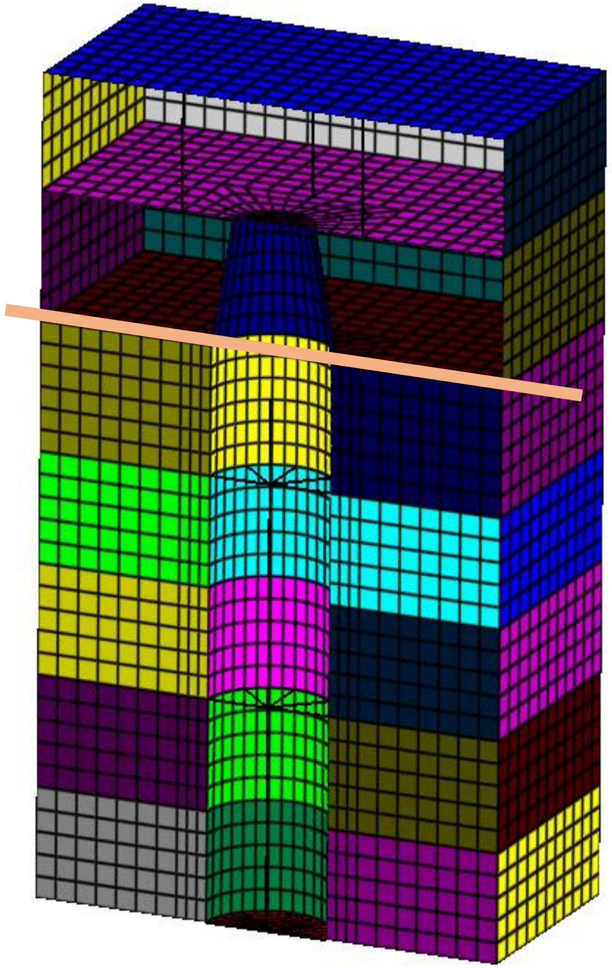


FFV Interaction Nodes



Two level transition mesh including two soil layers below foundation

Embedded SMR Linear/Nonlinear SSI Analysis Using FVROM-INT (20 SOIL key frequencies and 200 SSI frequencies) – new test



Using 4 parallel runs on 128 GB RAM workstations

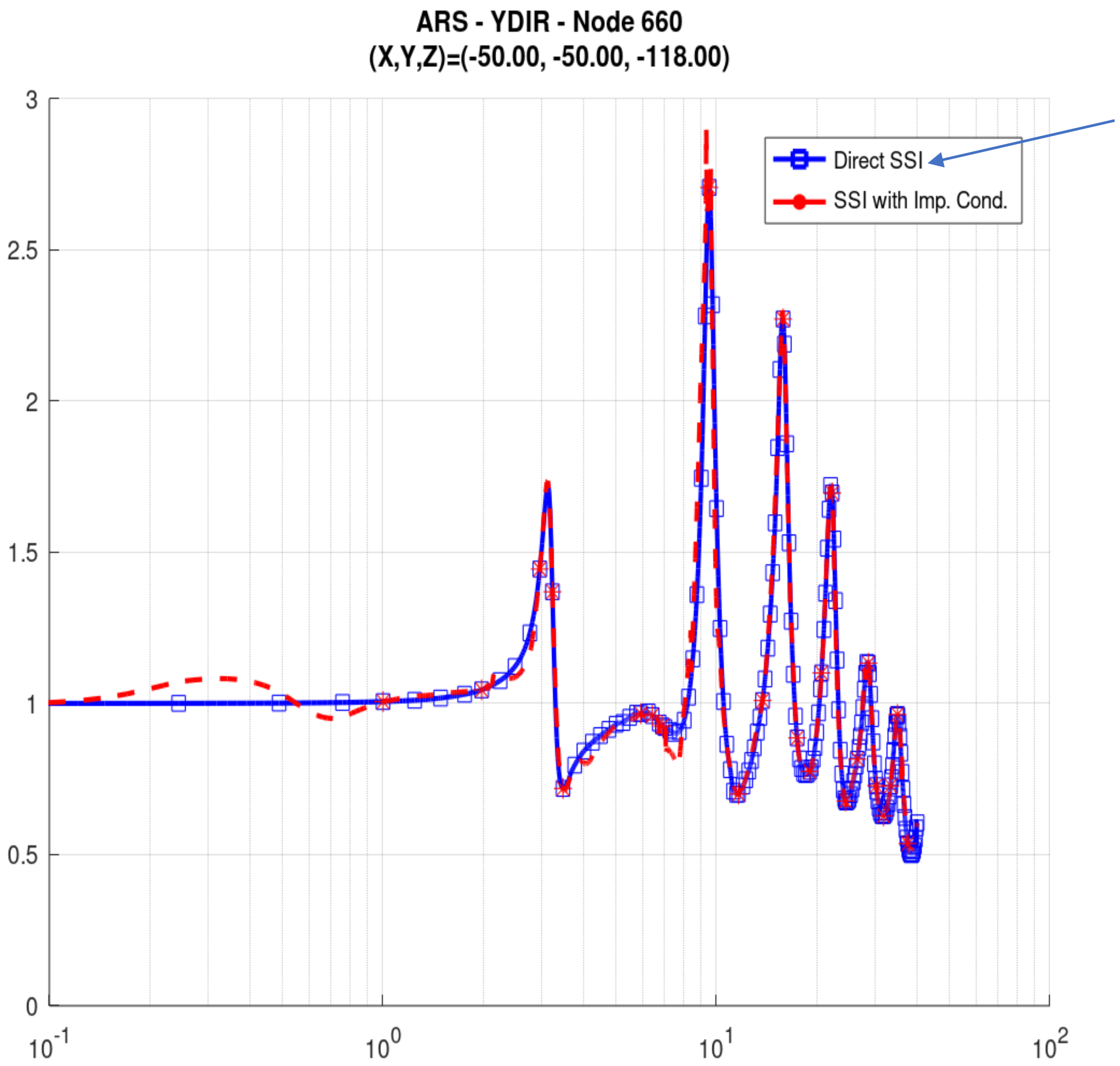
	Running Time		Node Counts		# of Freq.
	Total (h)	Per Freq (h)	Int. Nodes	Cond. Nodes	
Condensation	2.79	0.11	7491	3081	20
Interpolation			-	3081	200
SSI Solution	2.77	0.01	-	3081	200
	5.6 hours				

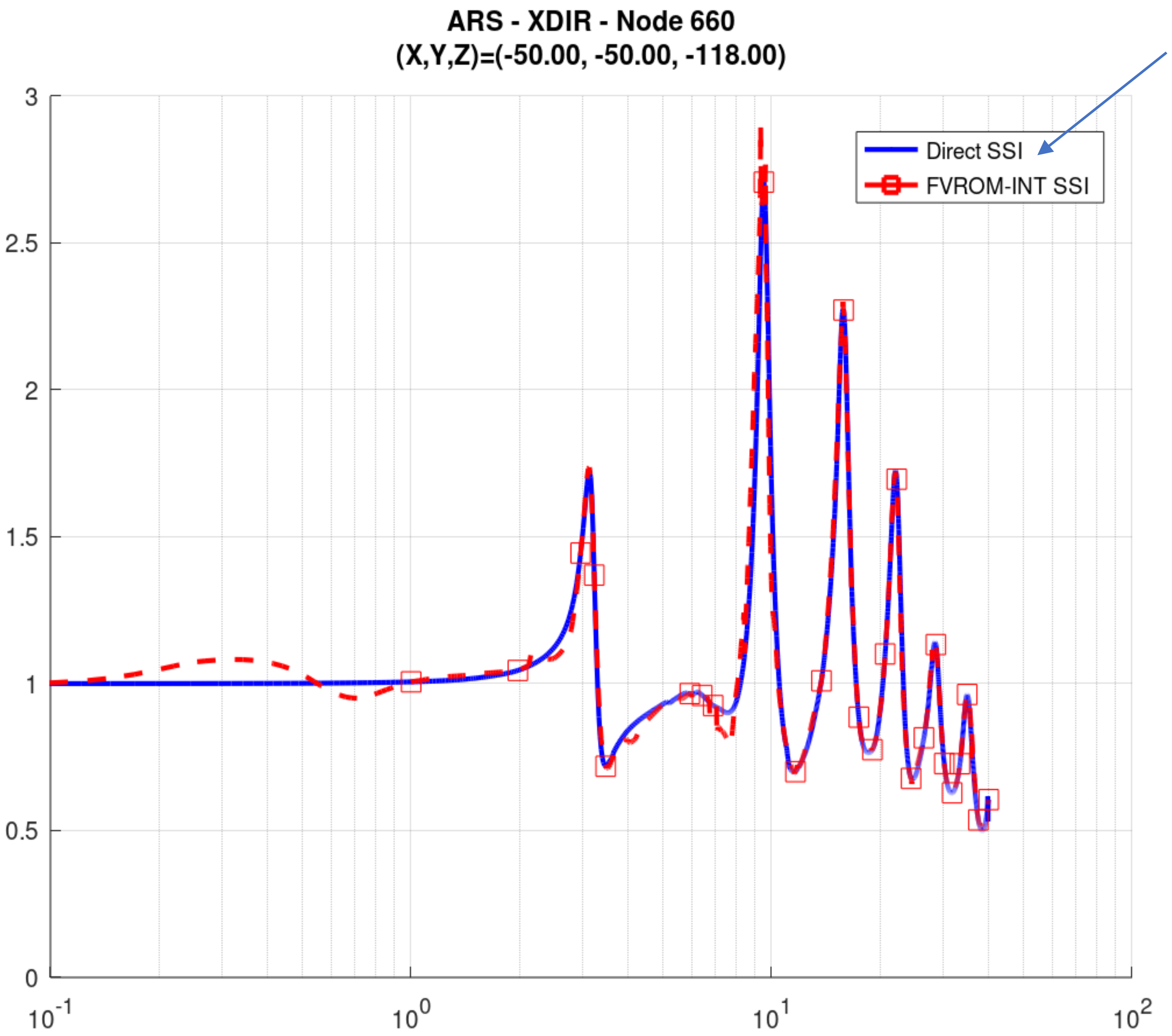
Speed up ratio = 3.50

	Running Time		Node Counts		# of Freq.
	Total (h)	Per Freq (h)	Int. Nodes	Cond. Nodes	
Direct SSI	19	0.097222	7491	-	200
	19.4 hours				
	Speed ratio =		3.497354		

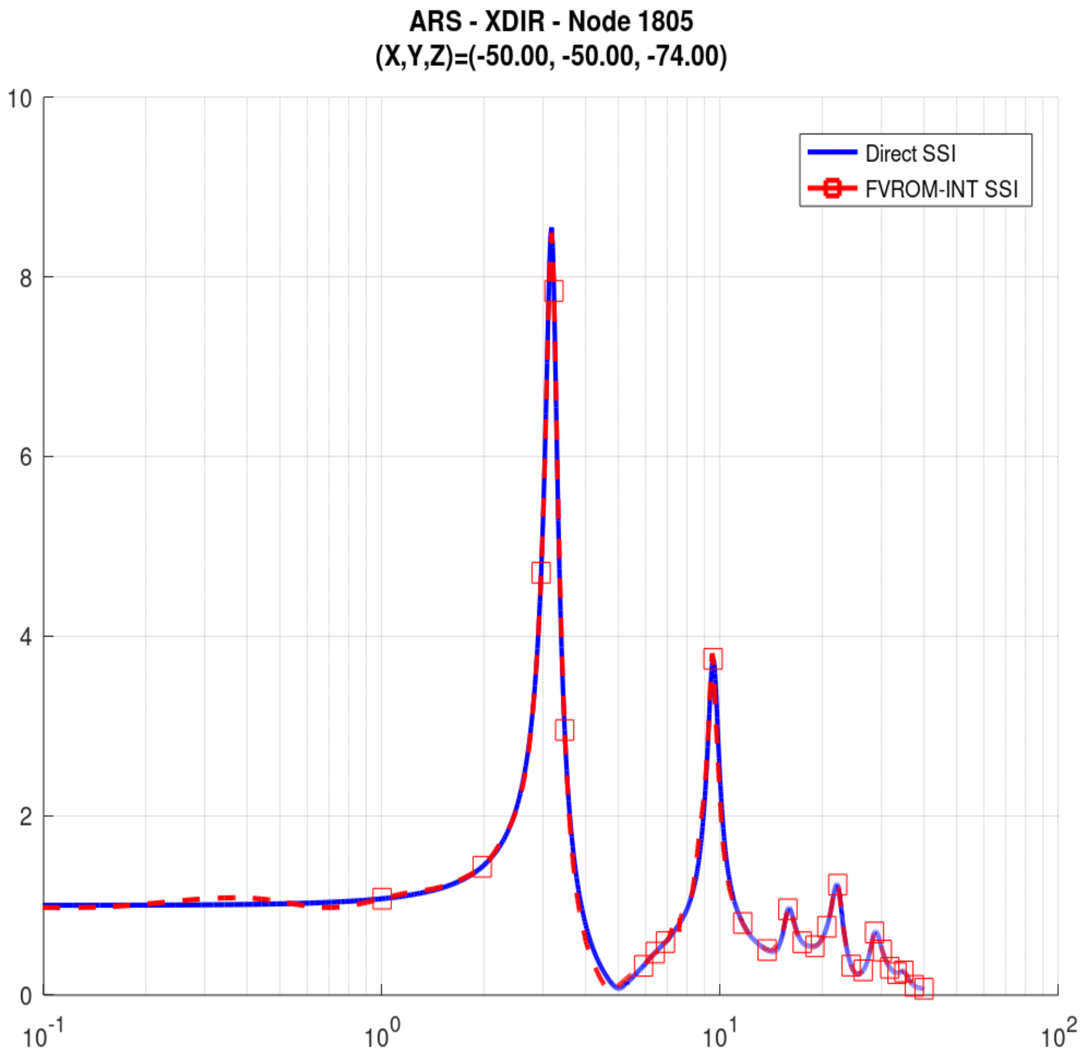
1 minute/freq per one nonlinear walls-nonlinear interface iteration.
3 iterations are less than 10% difference in elements, 4-5 ideal

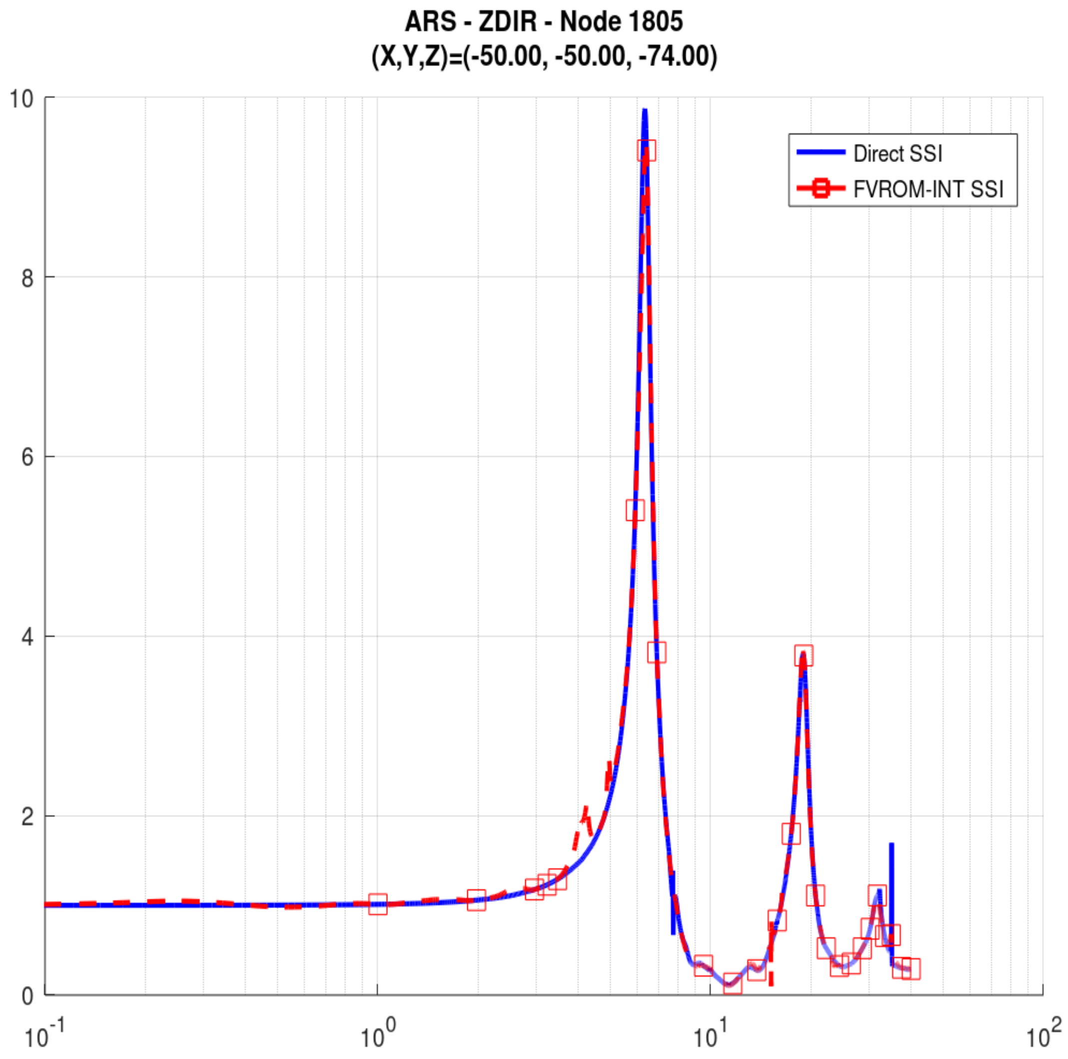
Deeply Embedded SMR ATF (TFU) Checking at Basemat Level in X-Dir Using FVROM-INT (20 key & 200 SSI frequencies)



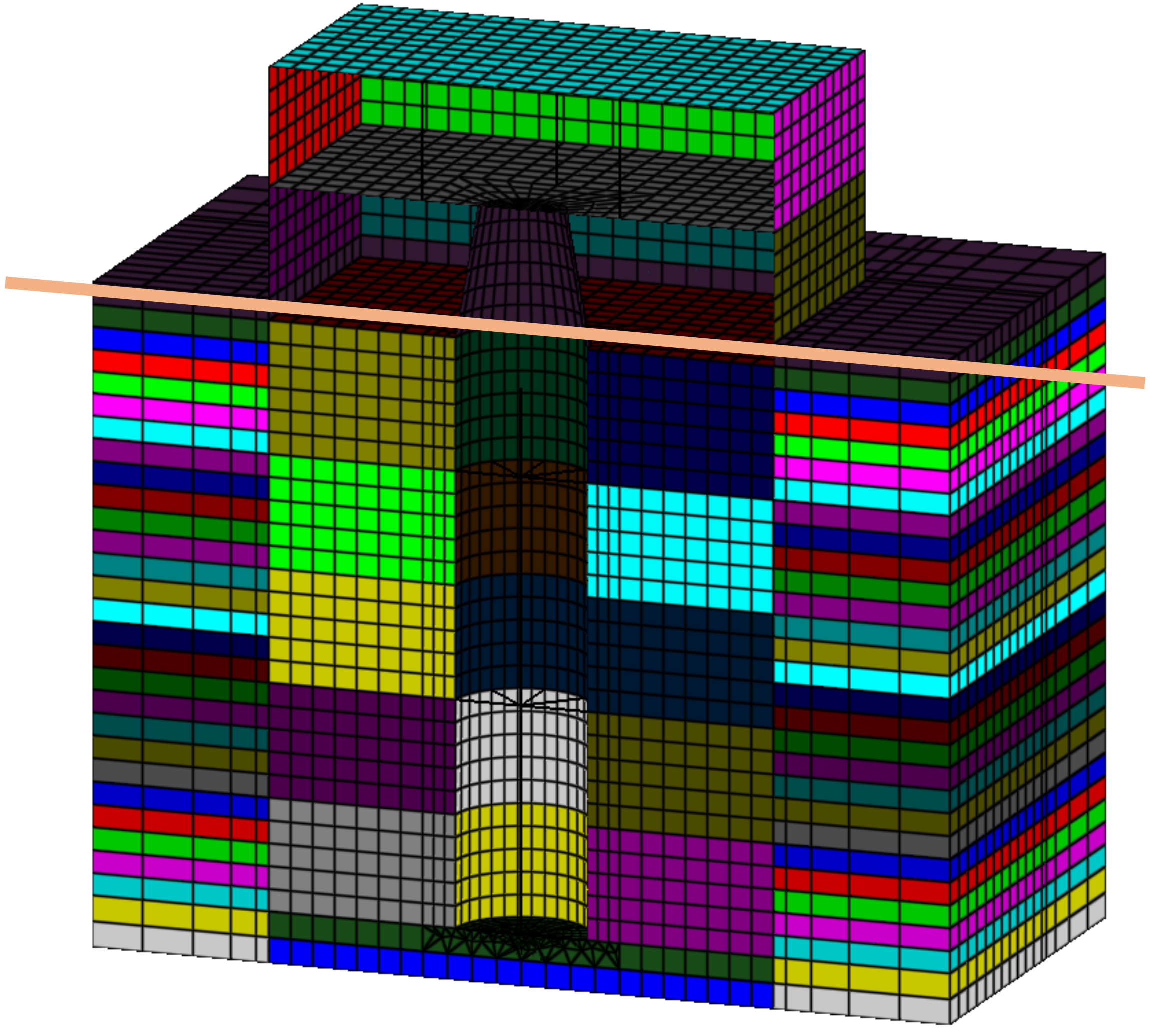


Deeply Embedded SMR ATF (TFU) Checking at Basemat Level in X-Dir and Z-Dir Using FVROM-INT (20 key & 200 SSI frequencies)





Embedded SMR Model Including Adjacent Nonlinear Soil Behavior (21 SOIL key frequencies and 200 SSI frequencies)



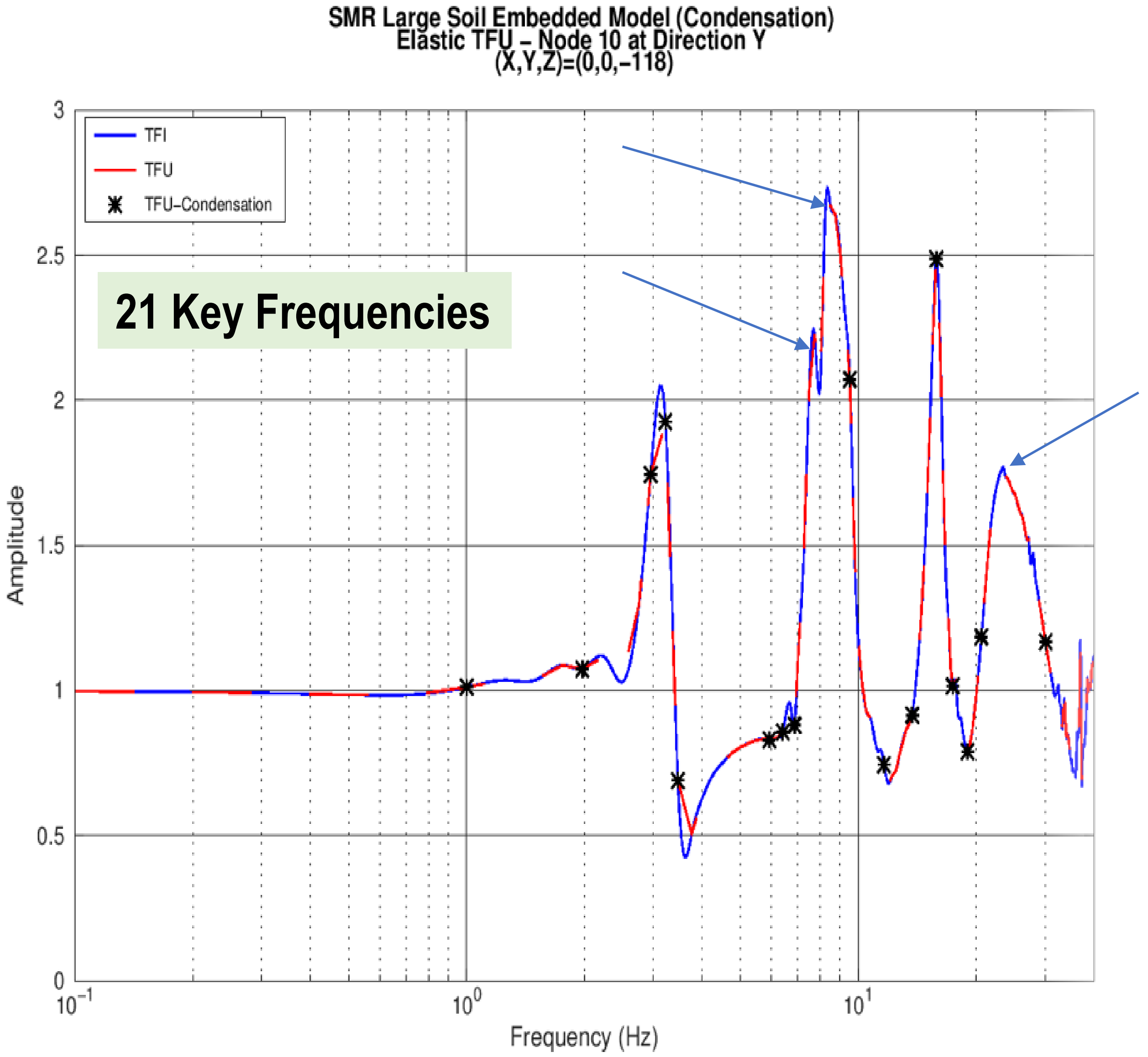
Using 4 independent runs on 512 GB RAM workstations					
	Running Time		Node Counts		# of Freq.
	Total (h)	Per Freq (h)	Int. Nodes	Cond. Nodes	
Condensation	12.08	0.58	14441	4801	21
Interpolation			-	4801	200
SSI Solution	5.15	0.03	-	4801	200
	17.2	**hours**			

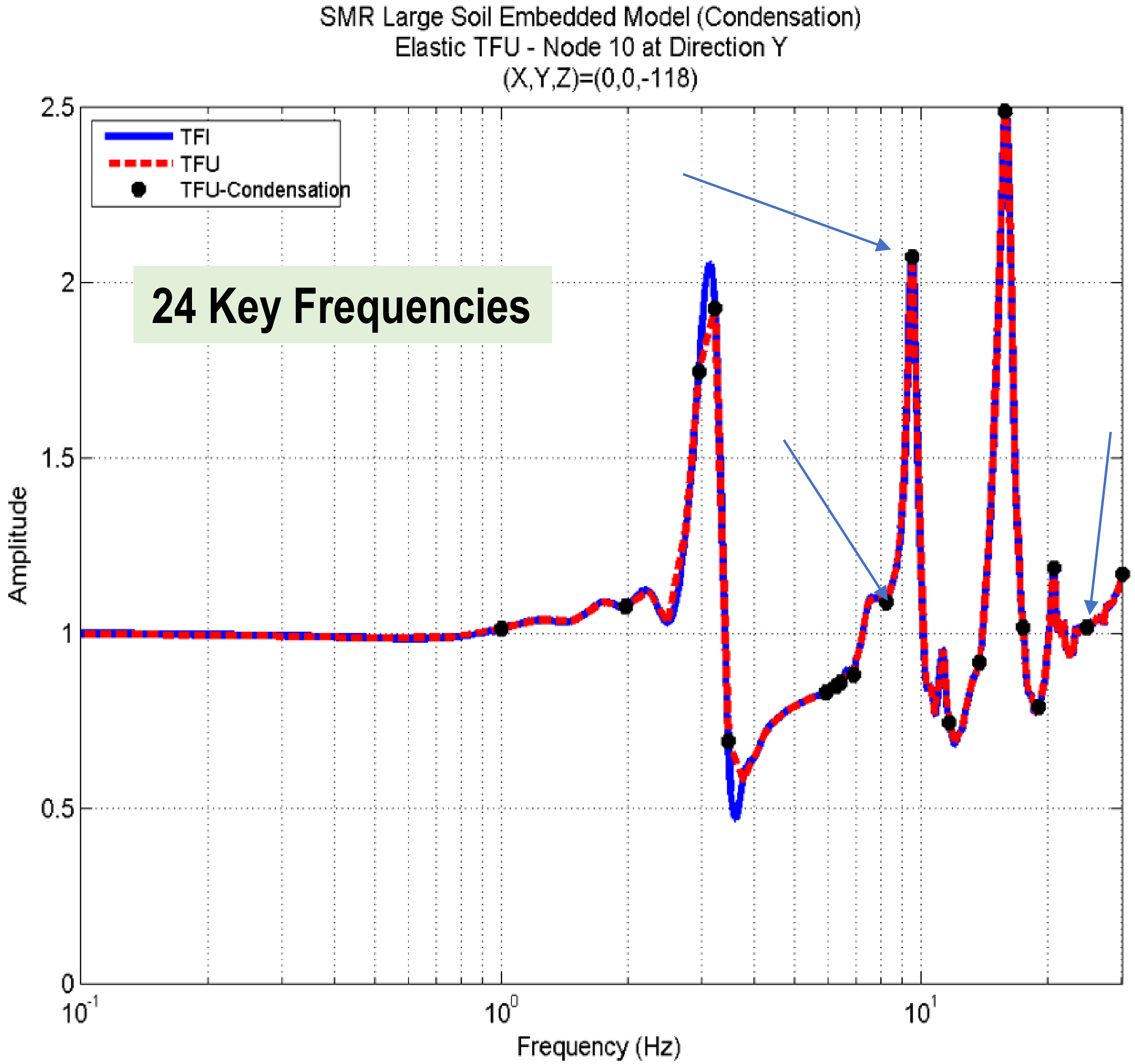
Speed up ratio = 6.70

	Running Time		Node Counts		# of Freq.
	Total (h)	Per Freq (h)	Int. Nodes	Cond. Nodes	
Direct SSI	115.00	0.575	14441	-	200
	115.0	**hours**			
	Speed ratio =		**6.67576**		

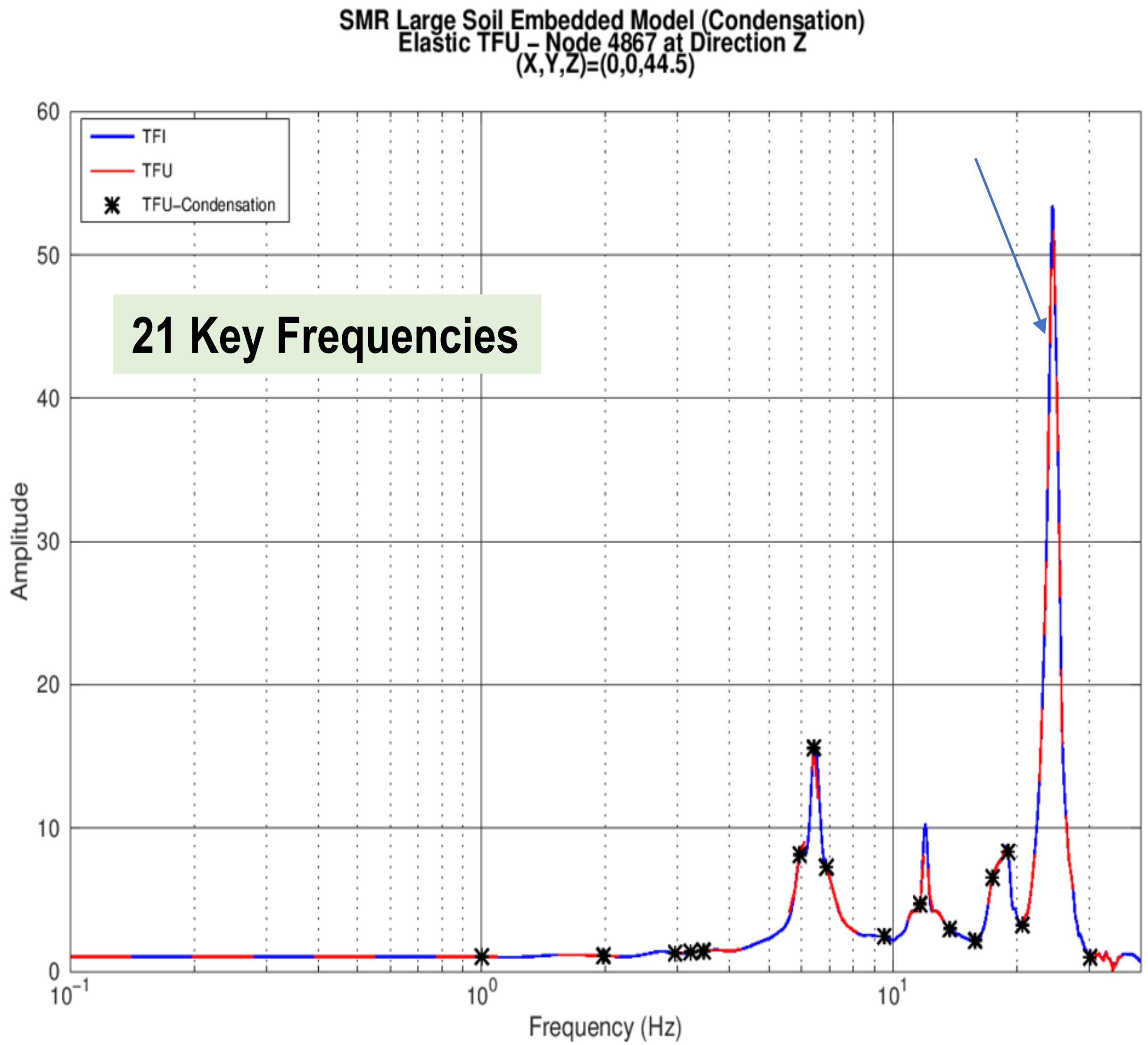
2 minutes/freq per one nonlinear walls-nonlinear interface iteration.
3 iterations are less than 10% difference in elements, 4-5 ideal

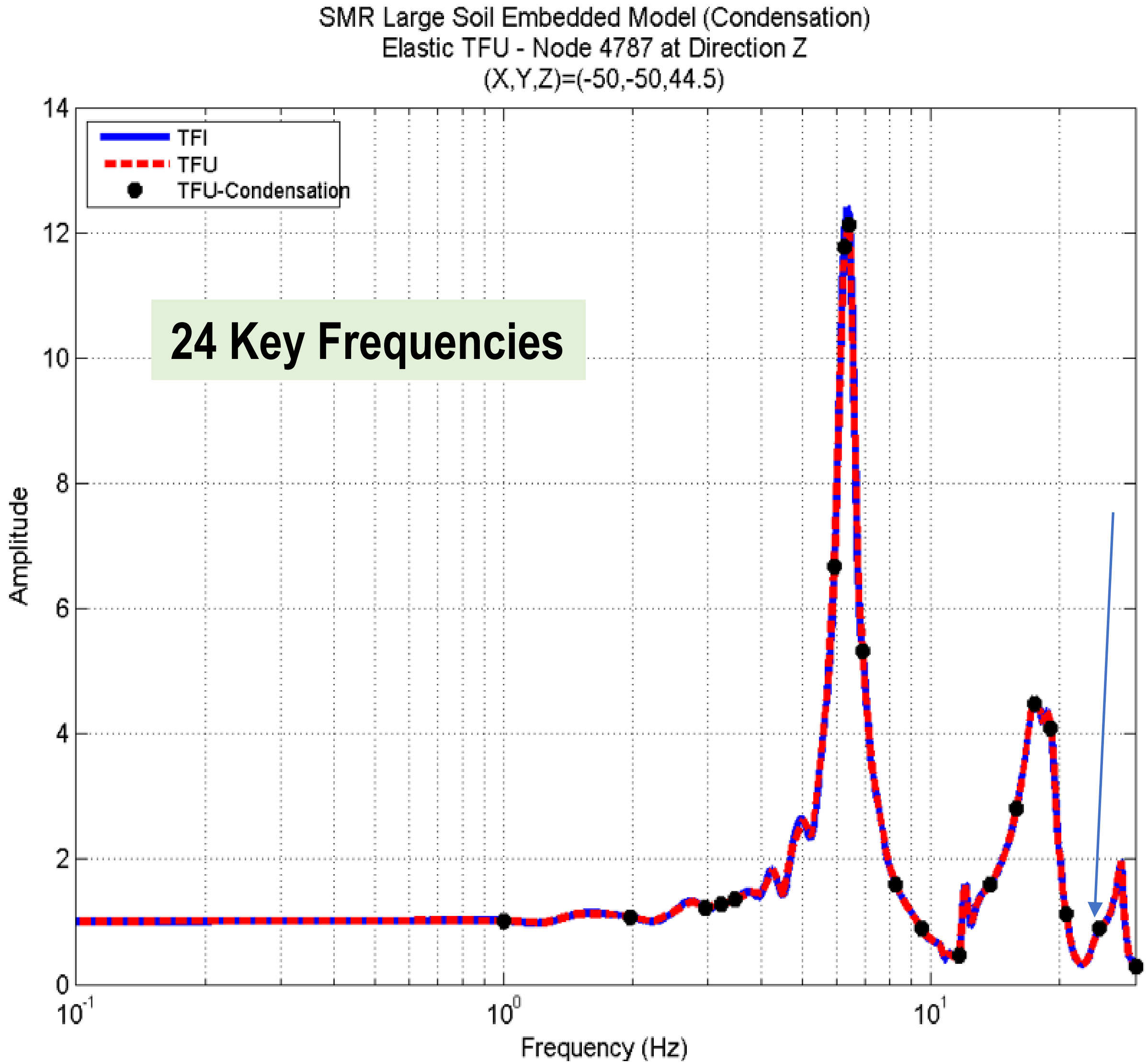
SMR SSI ATF (TFU) for FVROM-INT w/ 21 vs. 24 Key Frequencies





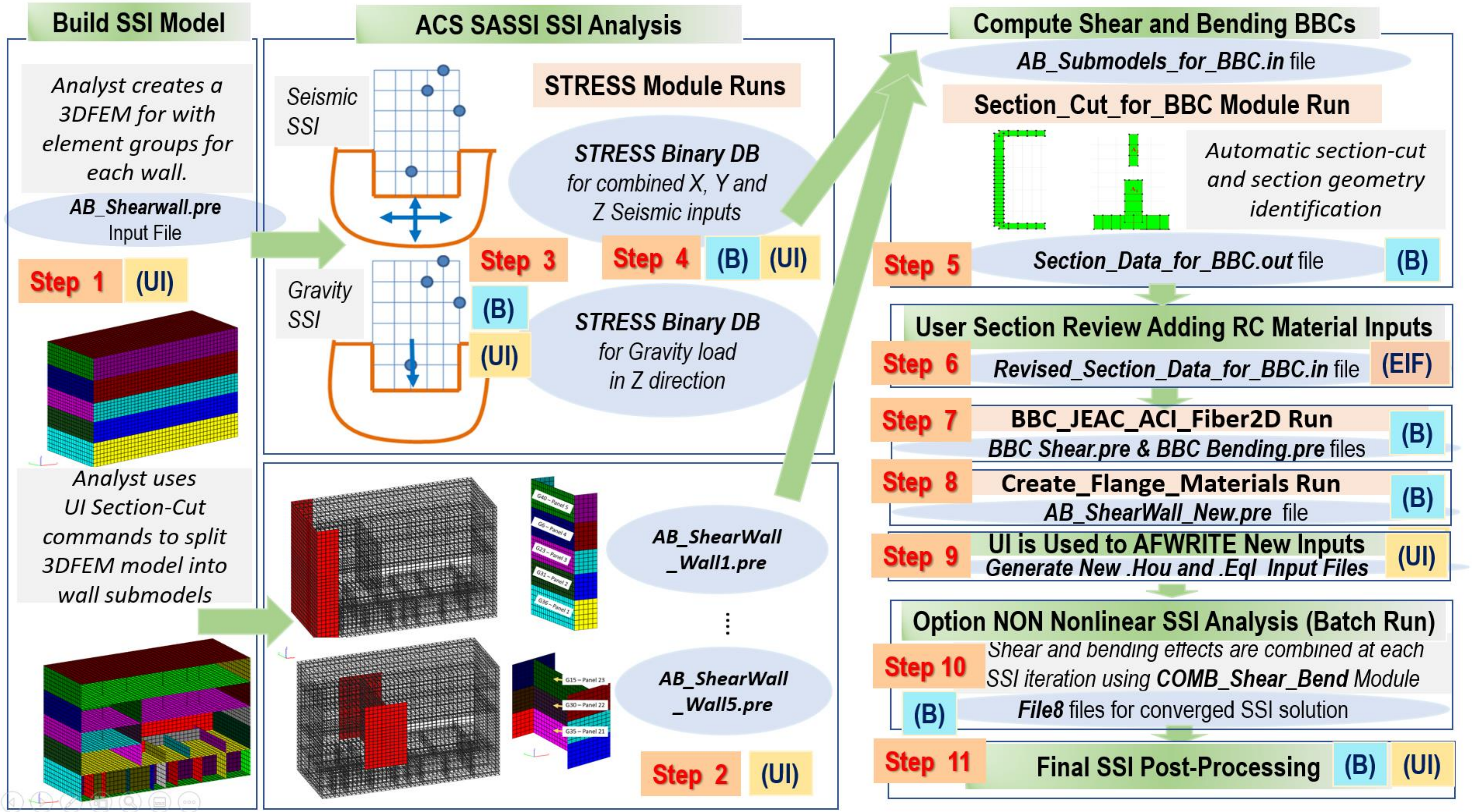
SMR SSI ATF (TFU) for FVROM-INT w/ 21 vs. 24 Key Frequencies



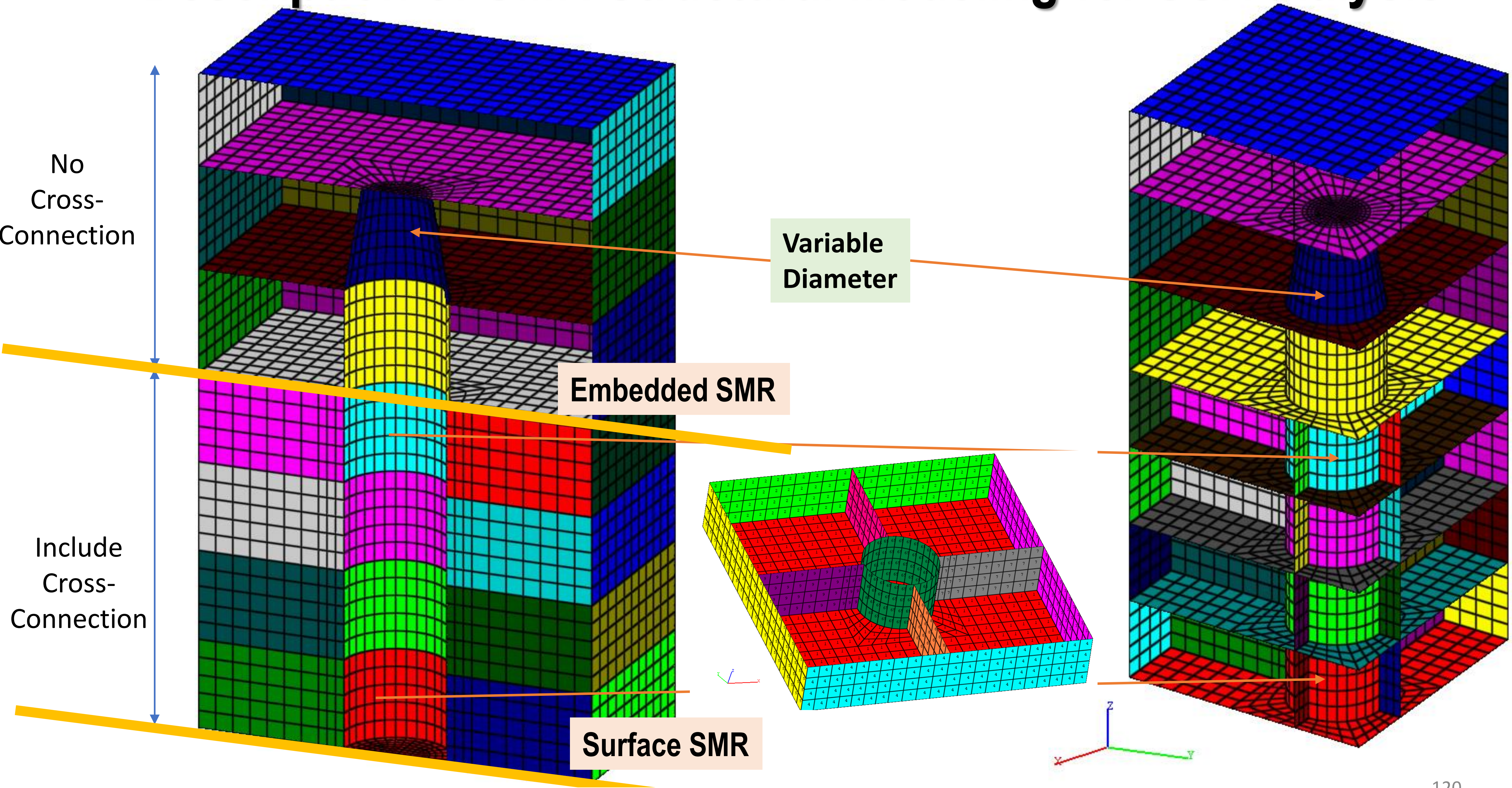


2.3 Comparative SMR Studies Including Linear vs. Nonlinear SSI Analyses Using US and Japan Standards

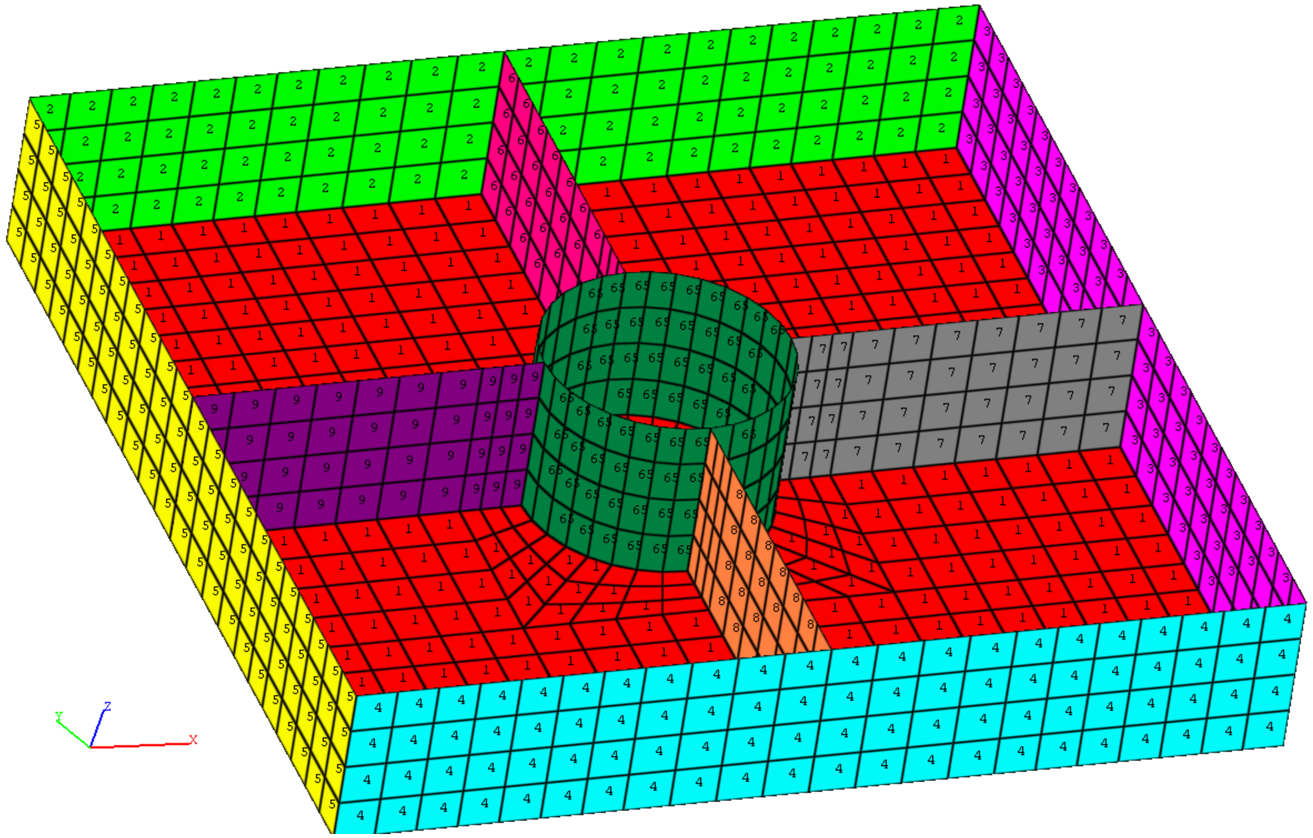
(Uses Fast FVROM-INT Restart Analysis for Nonlinear SSI Iterations)
(See new Demo 19 in V.4.3.2)


Build SSI Model
Analyst creates a 3DFEM for with element groups for each wall.
AB_Shearwall.pre
Input File
Step 1
(UI)
Analyst uses UI Section-Cut commands to split 3DFEM model into wall submodels
ACS SASSI SSI Analysis
Seismic SSI
Gravity SSI
STRESS Module Runs
STRESS Binary DB for combined X, Y and Z Seismic inputs
Step 3
Step 4
(B)
(UI)
(B)
(UI)
STRESS Binary DB for Gravity load in Z direction
AB_ShearWall_Wall1.pre
AB_ShearWall_Wall5.pre
Step 2
(UI)
Compute Shear and Bending BBCs
AB_Submodels_for_BBC.in file
Section_Cut_for_BBC Module Run
Automatic section-cut and section geometry identification
Step 5
Section_Data_for_BBC.out file
(B)
User Section Review Adding RC Material Inputs
Step 6
Revised_Section_Data_for_BBC.in file
(EIF)
Step 7
BBC_JEAC_ACI_Fiber2D Run
BBC Shear.pre & BBC Bending.pre files
(B)
Step 8
Create_Flange_Materials Run
AB_ShearWall_New.pre file
(B)
Step 9
UI is Used to AFWRITE New Inputs
Generate New .Hou and .Eql Input Files
(UI)
Option NON Nonlinear SSI Analysis (Batch Run)
Step 10
Shear and bending effects are combined at each SSI iteration using COMB_Shear_Bend Module
(B)
File8 files for converged SSI solution
Step 11
Final SSI Post-Processing
(B)
(UI)

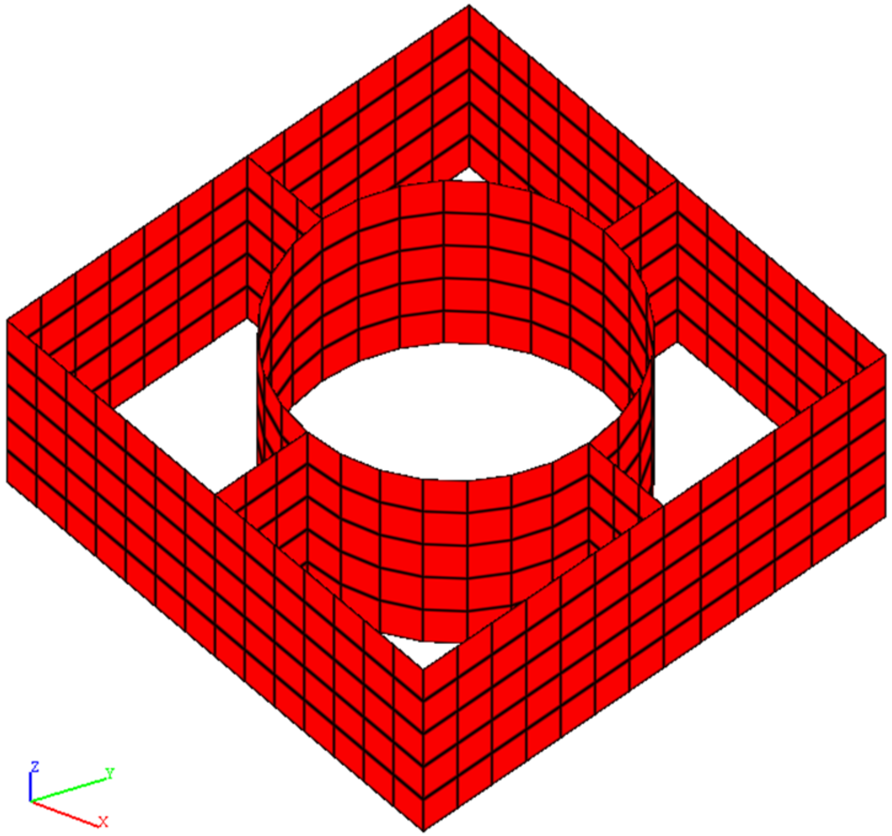
Description of SMR Structural Modeling for SSI Analysis



SMR Model has Same Configuration with Ning's Model

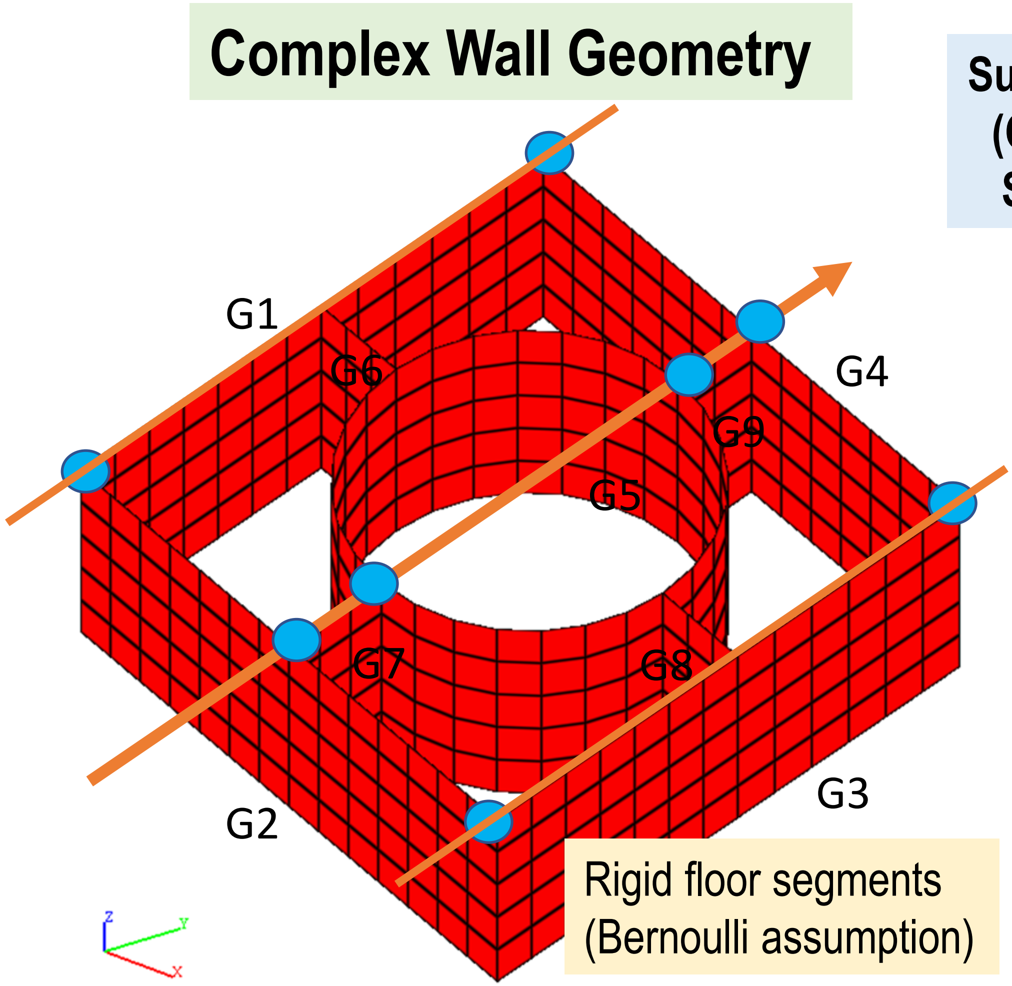


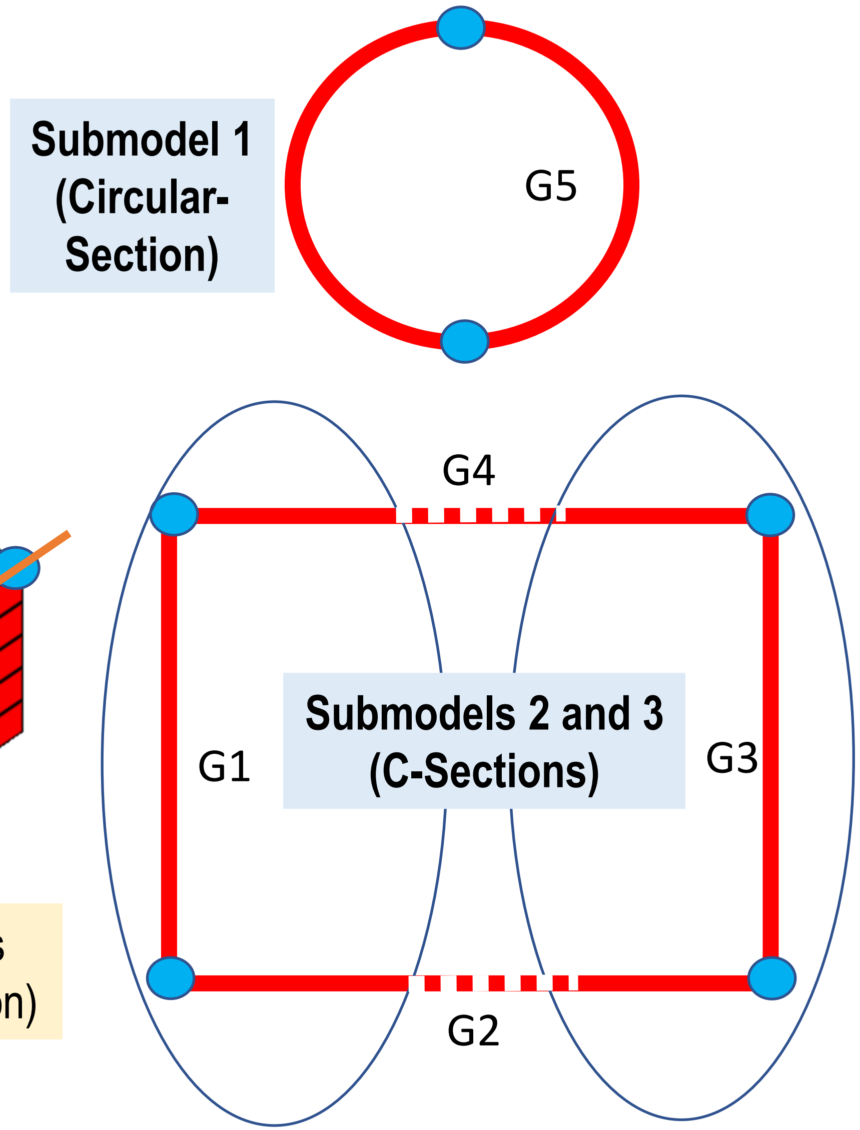
SMR Structure

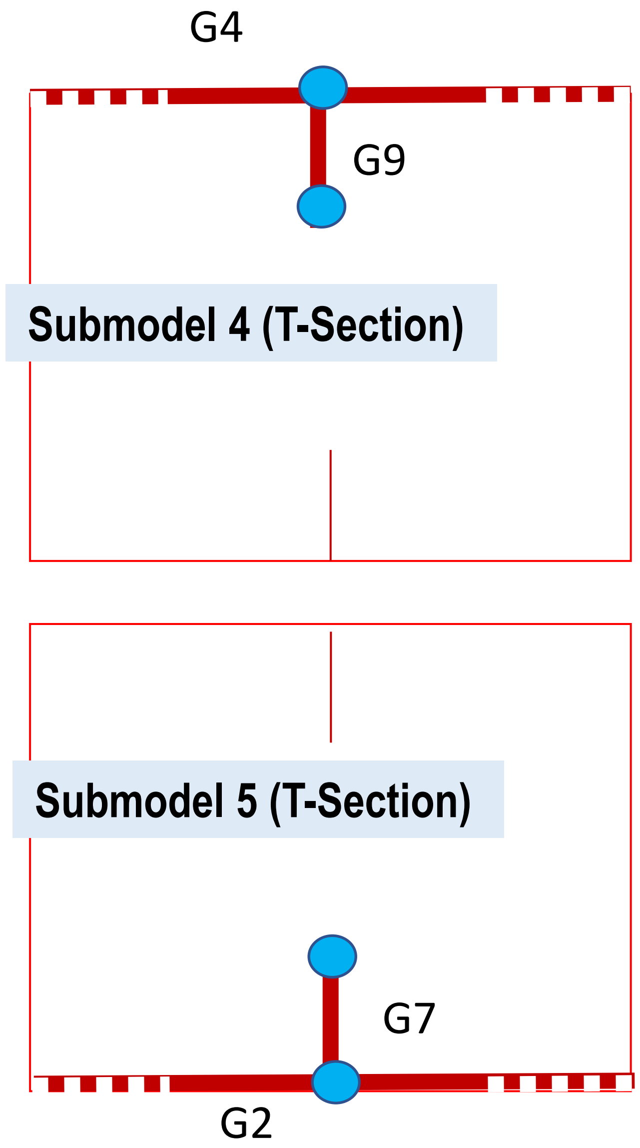


Section Configuration

Handling Complex Geometries Using Multiple Submodels (.pre)





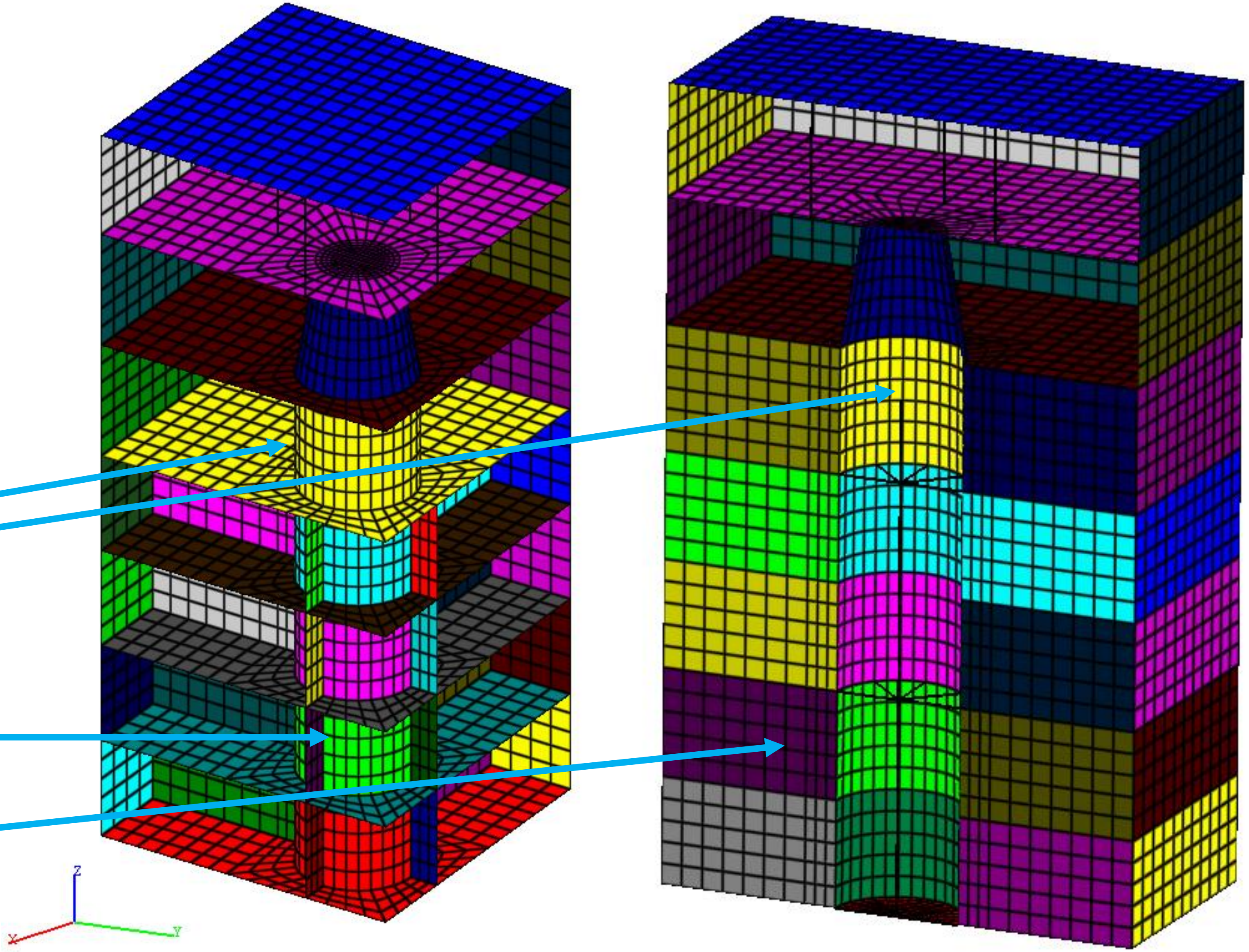


Splitting SMR Model in 9 Wall Submodels

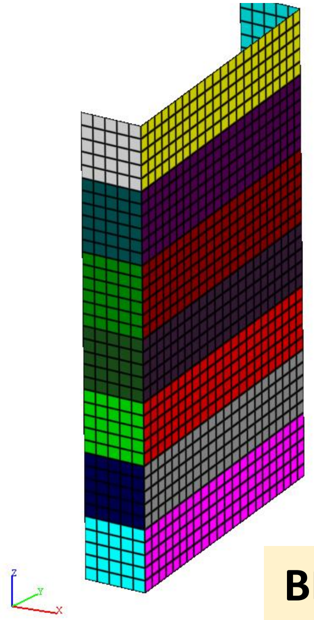
SMR_SURF_cuts - Notepad

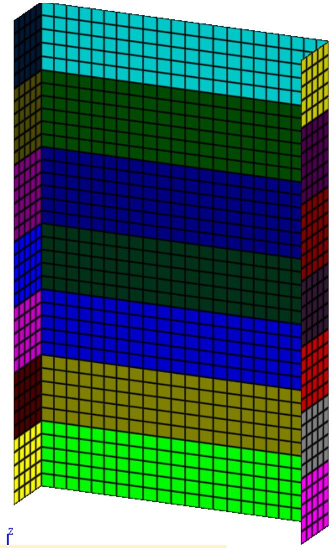
File Edit Format View Help

```
var,PATH,C:\SSI\SMR2021\Model-Pre-files\
var,MODELNAME,SMR_SURF_Final
DMODEL,0
DMODEL,1
DMODEL,2
DMODEL,3
DMODEL,4
DMODEL,5
DMODEL,6
DMODEL,7
DMODEL,8
DMODEL,9
CUTCLR,1,9,1
ACTM,0

INP,@PATH[1]\@MODELNAME[1].pre

**************************************************
* CIRCULAR MIDDLE SECTION
CUTADD,1,65,RANGE,1,160,1
CUTADD,1,66,RANGE,1,160,1
CUTADD,1,67,RANGE,1,160,1
CUTADD,1,68,RANGE,1,160,1
CUTADD,1,69,RANGE,1,192,1
CUT2SUB,1,1
ACTM,1
WRITE,@PATH[1]\@MODELNAME[1]_circular.pre
ACTM,0

**************************************************
* INTERIOR MIDDLE WALLS 1
CUTADD,2,6,RANGE,1,50,1
CUTADD,2,15,RANGE,1,50,1
CUTADD,2,24,RANGE,1,50,1
CUTADD,2,33,RANGE,1,50,1
CUTADD,2,42,RANGE,1,60,1
CUTVOL,2,-25,25,50,50,-118,-4.3
CUT2SUB,2,2
ACTM,2
WRITE,@PATH[1]\@MODELNAME[1]_interior1.pre
ACTM,0

**************************************************
```

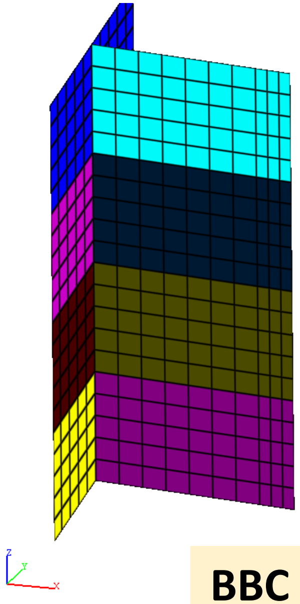


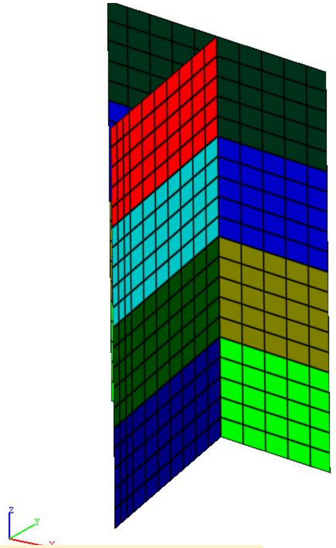
SMR Wall Submodels (4 Exterior, 1 Circular, 4 Connections)



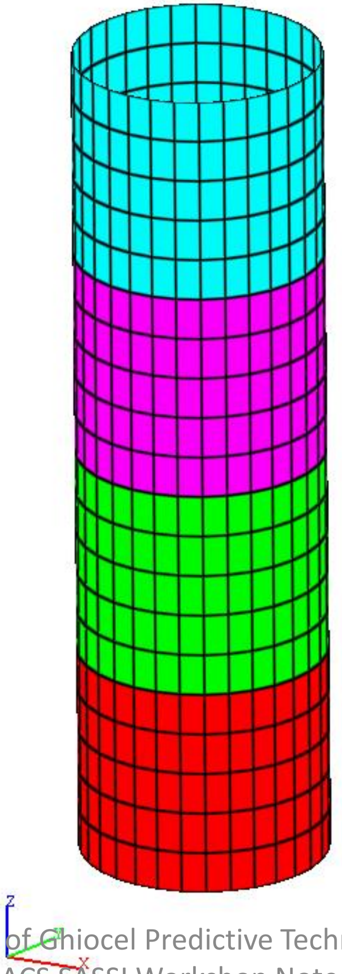


BBC_2DFiber
Dw=0

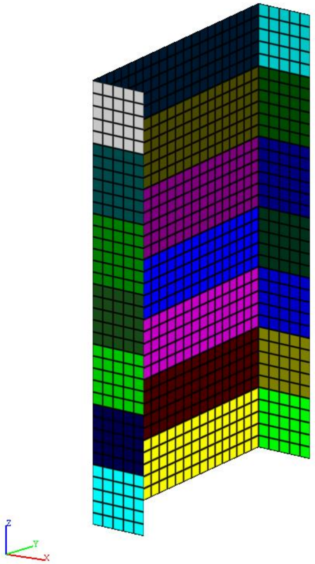


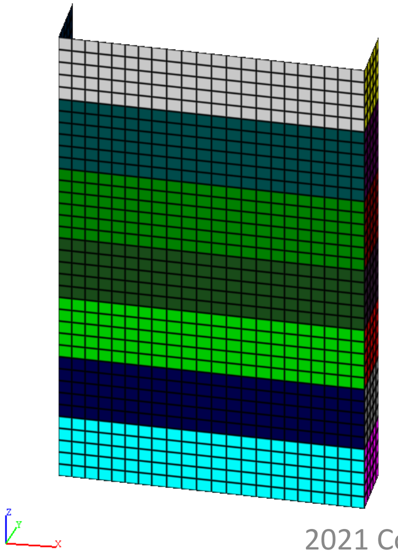


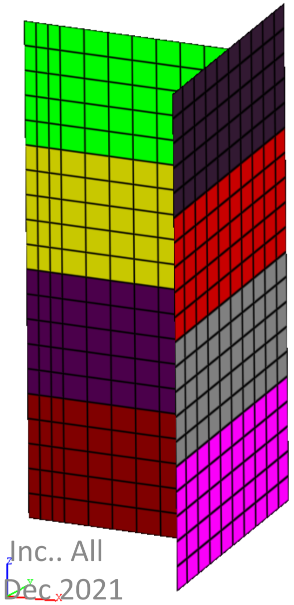
BBC_JEAC_ACI (Dw>0)
BBC_2DFiber (Dw<0)

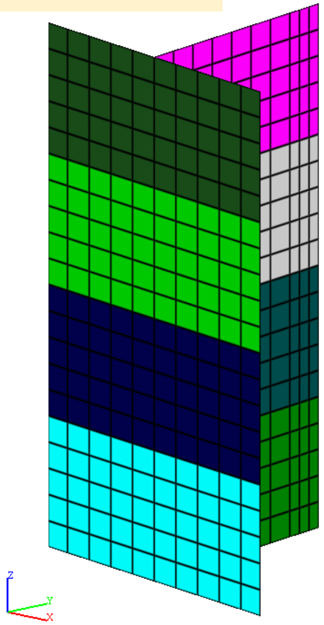


BBC_JEAC_ACI (Dw>0)
BBC_2DFiber (Dw<0)

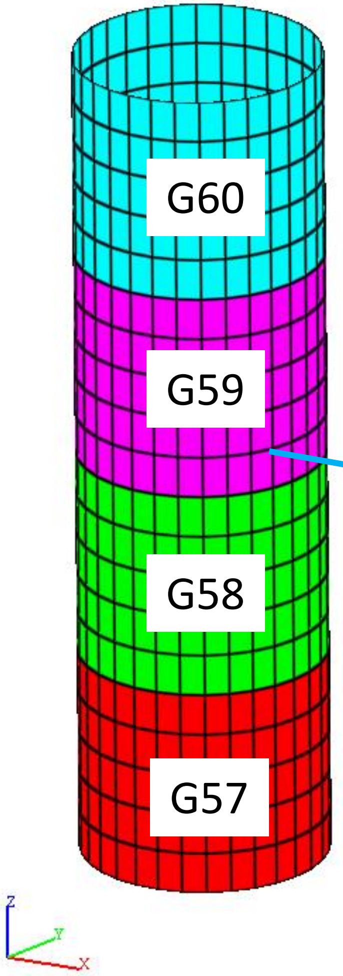








SMR Panel Numbering for Circular Closed Section Wall



P55,P56

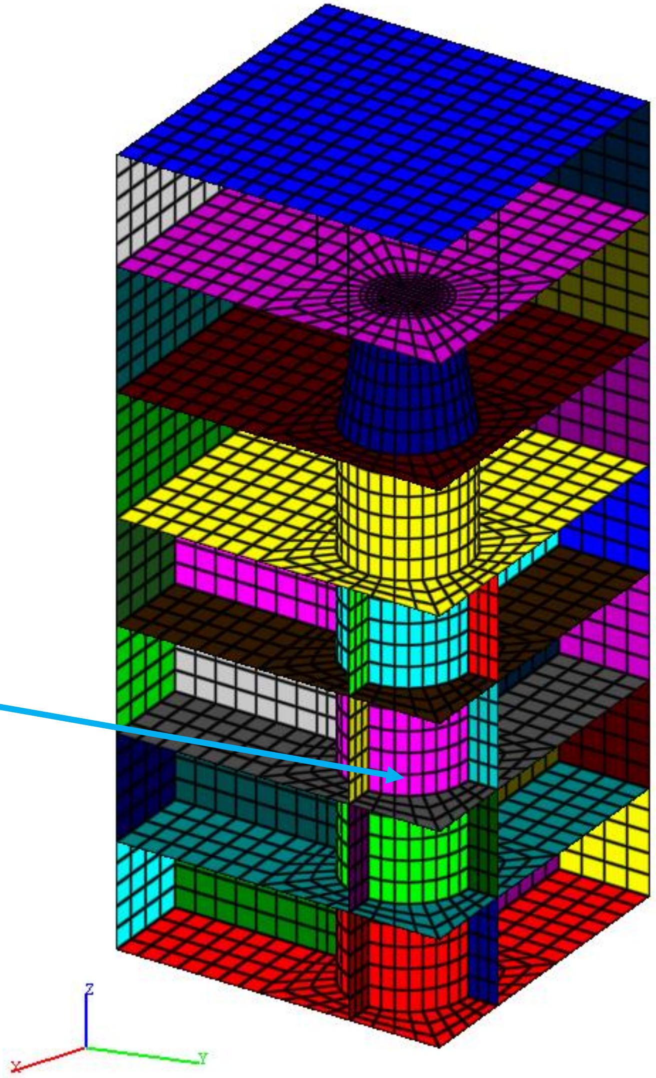
P53,P54

P51,P52

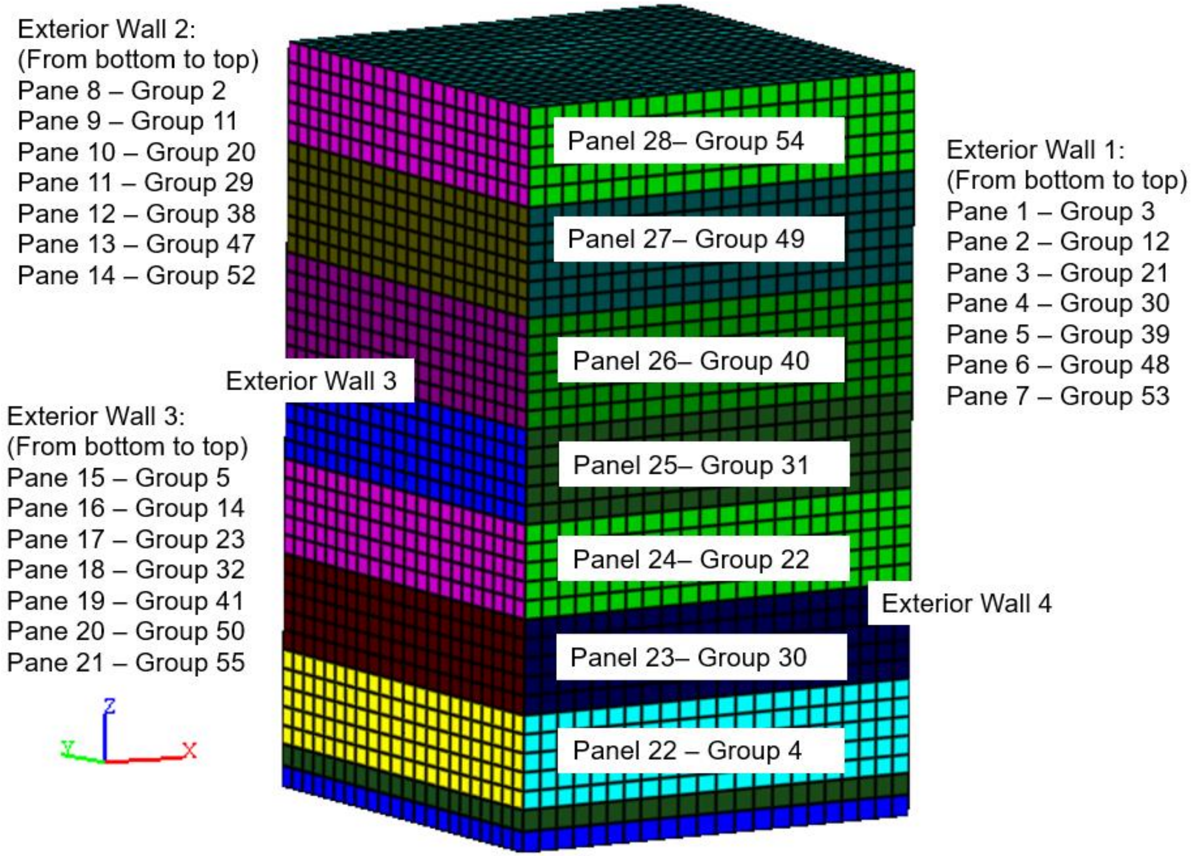
P49,P50

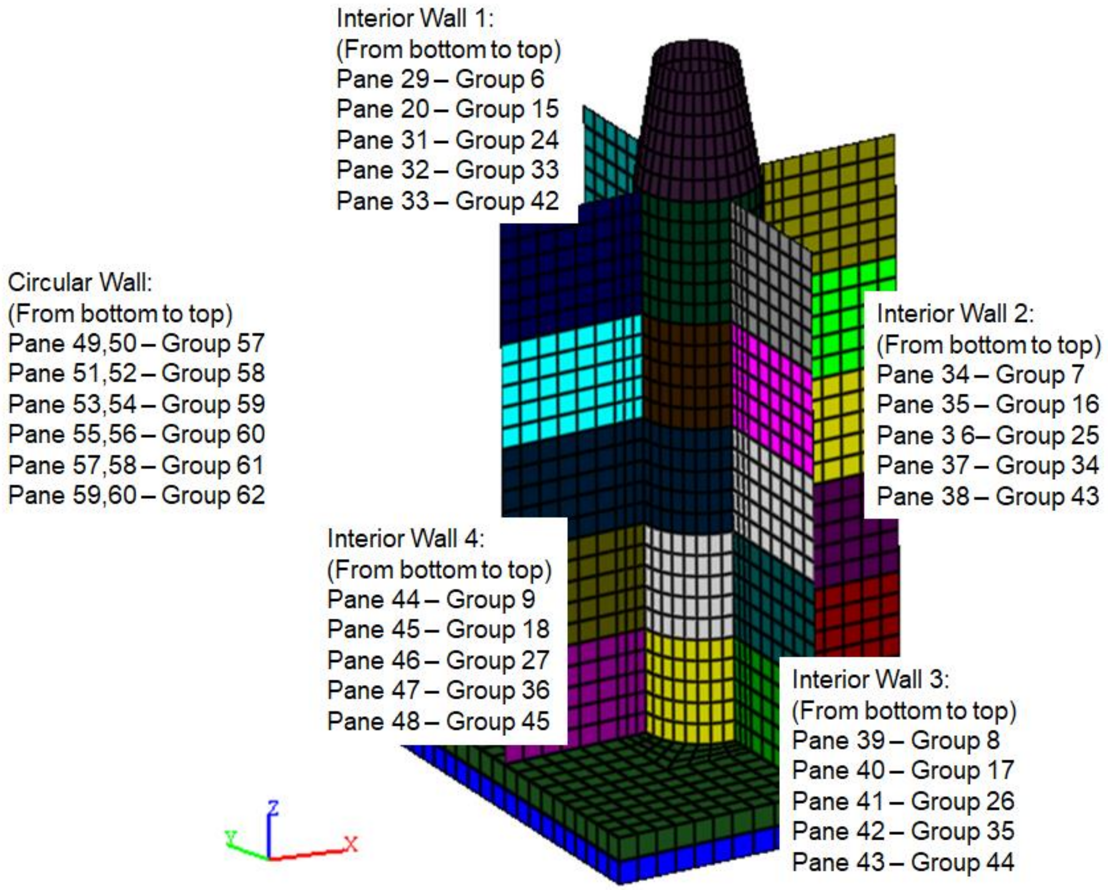
Panel Numbering:

P,49,57,20,1,1 X
P,50,57,20,1,1 Y
P,51,58,20,1,1 X
P,52,58,20,1,1 Y
P,53,59,20,1,1 X
P,54,59,20,1,1 Y
P,55,60,20,1,1 X
P,56,60,20,1,1 Y

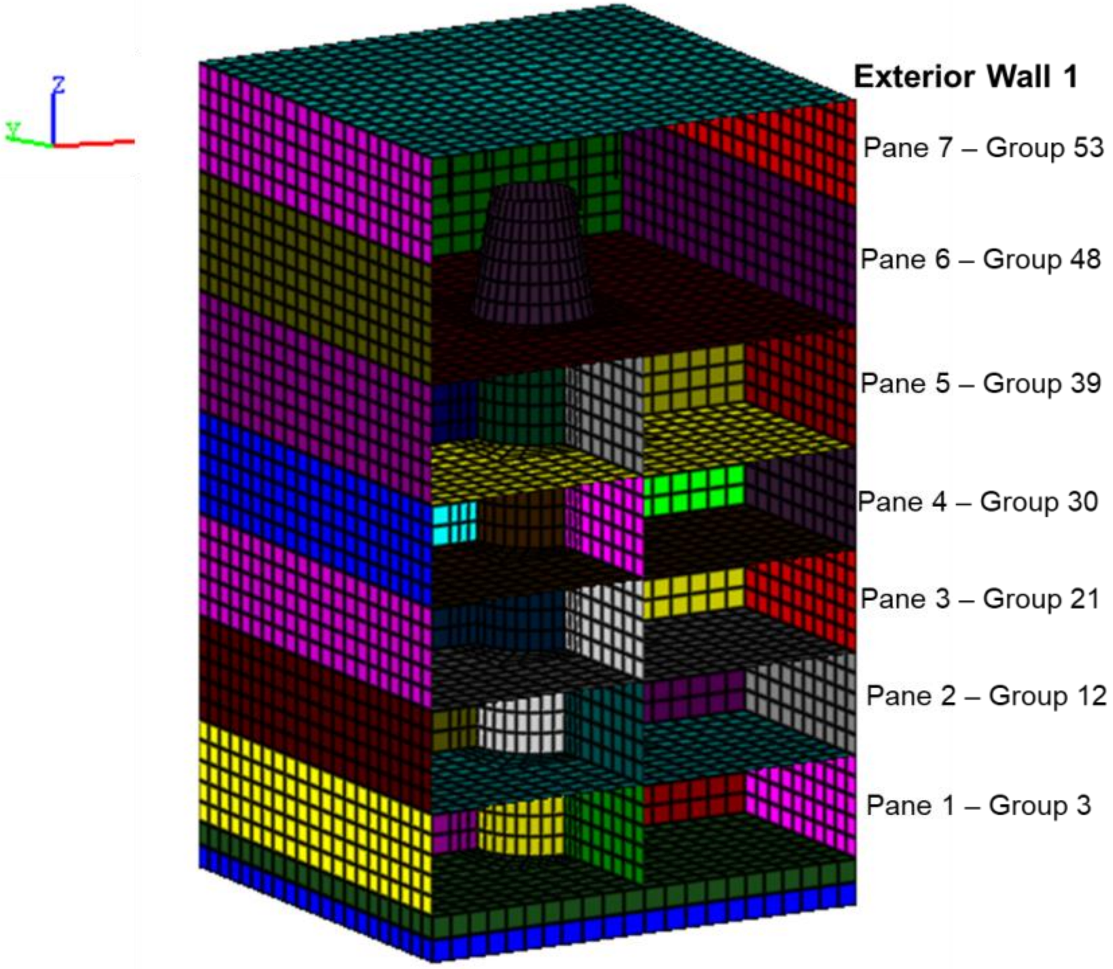


Panel and Associated Group Numbering for SMR 3DFEM Model





SMR Wall Verification of 2D Fiber Model vs. JEAC 4601. SMR Model – V&V Problem 65 for V4.3.2



Shear Wall Reinforcement:

Flange 1 Vertical Rebar Ratio = 1.195%

Flange 2 Vertical Rebar Ratio = 1.598%

Web Vertical Rebar Ratio = 1.246%

Web Horizontal Rebar Ratio = 0.953%

Concrete Material Properties:

Elastic Modulus = 24854600 (Kn/m2)

Compression Strength = 33000 (Kn/m2)

Yield Strain = 0.002

Ultimate Strain = 0.004

Rebar Material Properties:

Young modulus = 205000000. (Kn/m2)

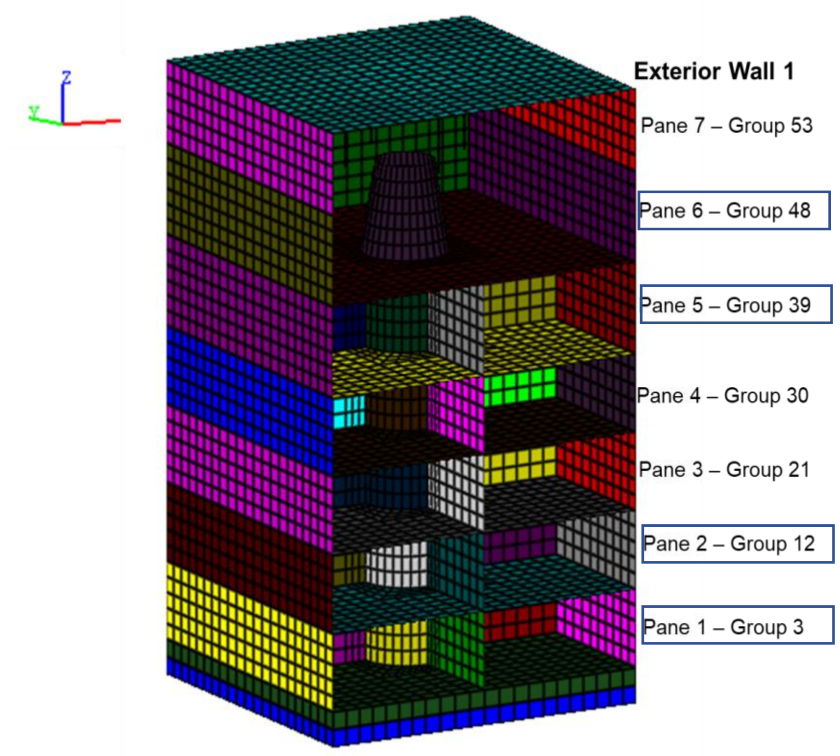
Yield Strength = 345000. (Kn/m2)

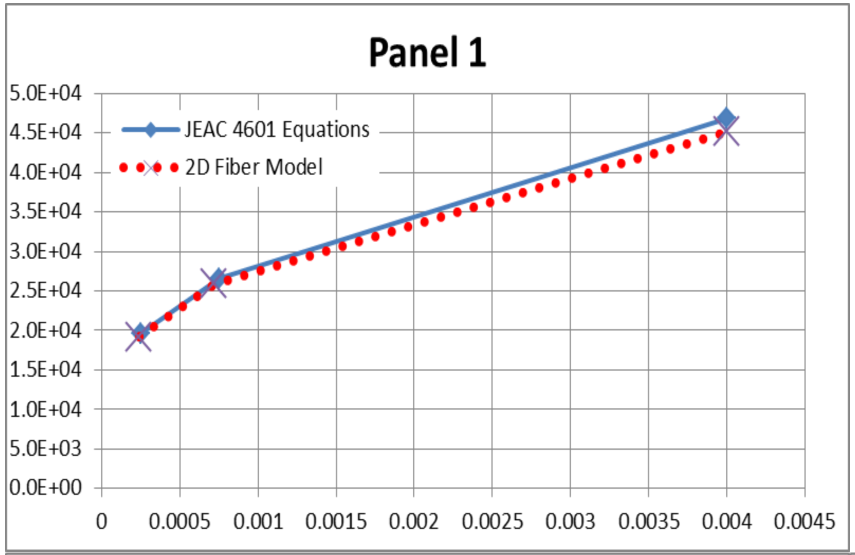
Yield strain = 0.00185

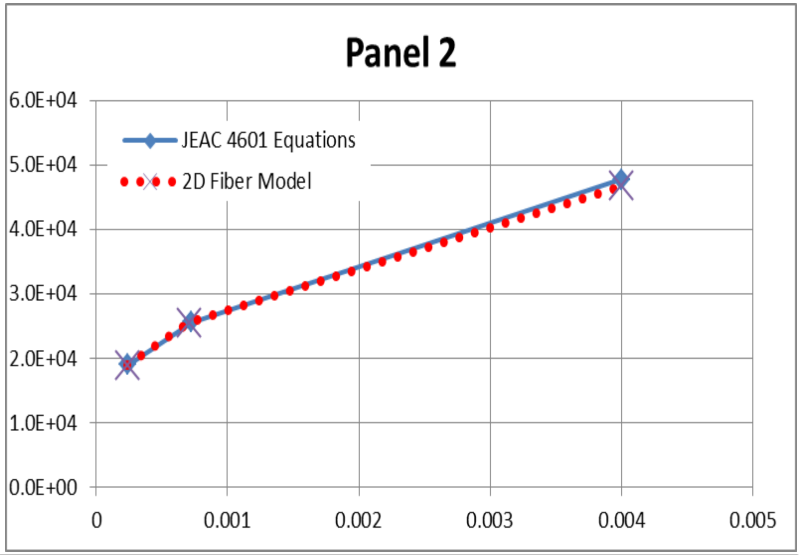
Ultimate strain = 0.05

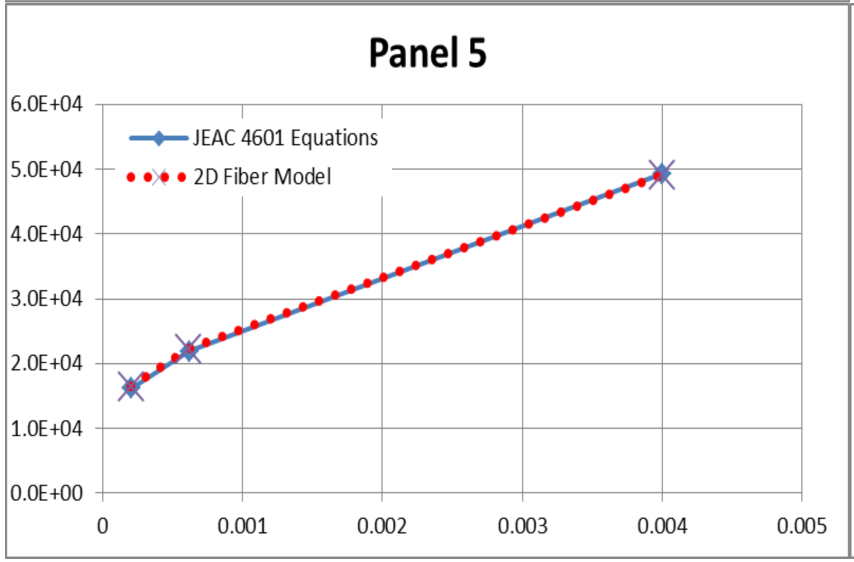
JEAC 4601 vs. 2DFiber Shear BBC (BBC_JEAC_ACI_Fiber2D.exe)

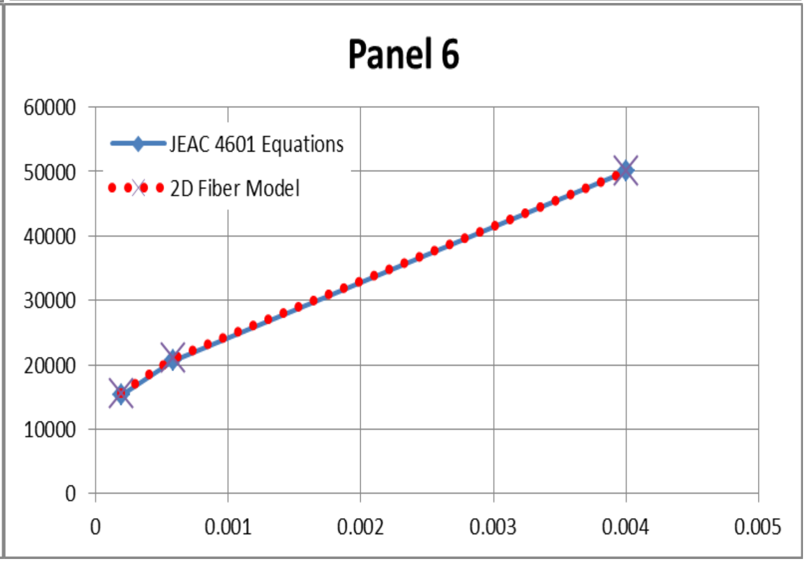
C-Shape Exterior Wall





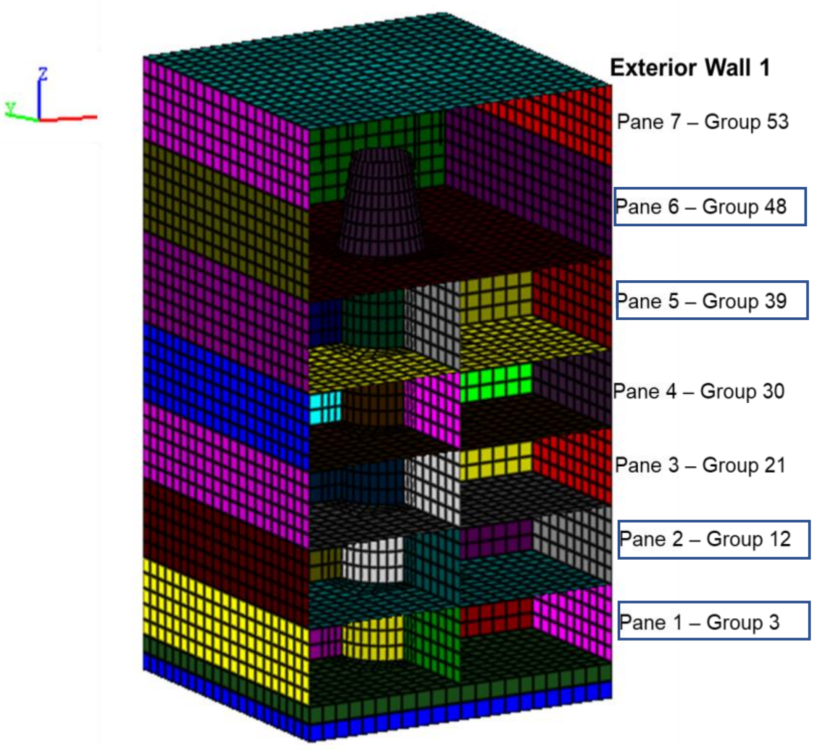


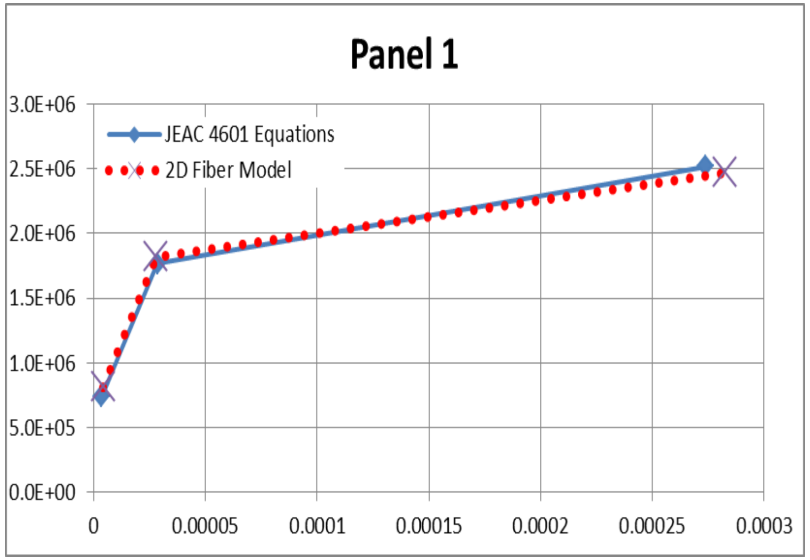


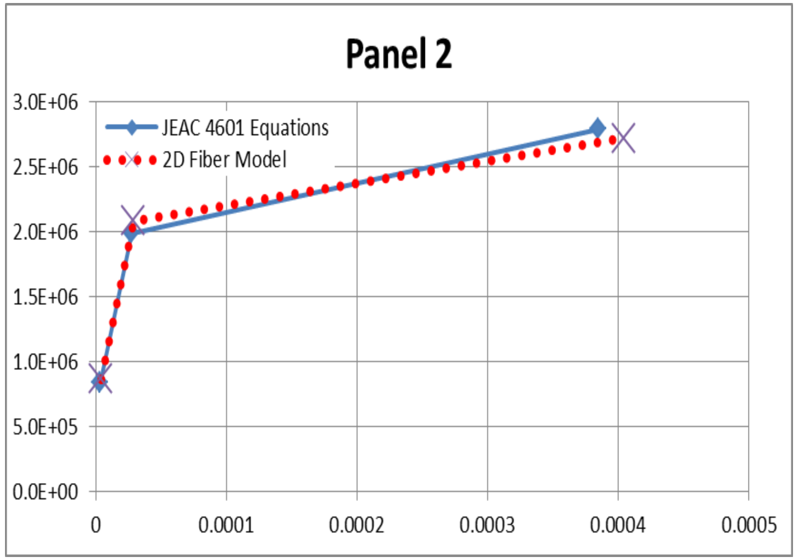


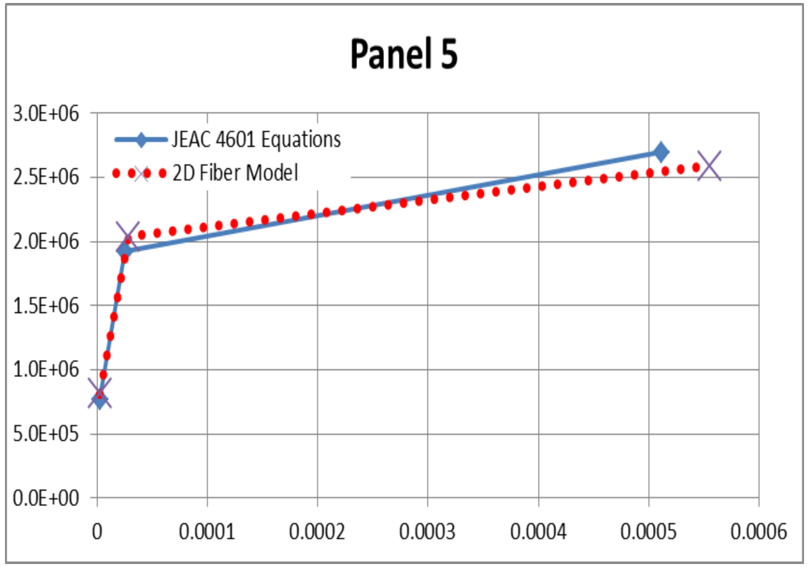
JEAC 4601 vs. 2DFiber Bending BBC (BBC_JEAC_ACI_Fiber2D.exe)

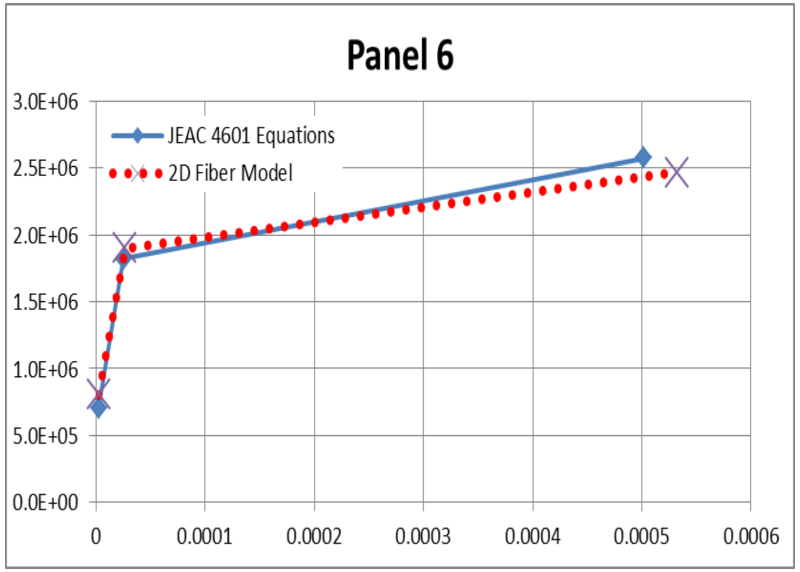
C-Shape Exterior Wall







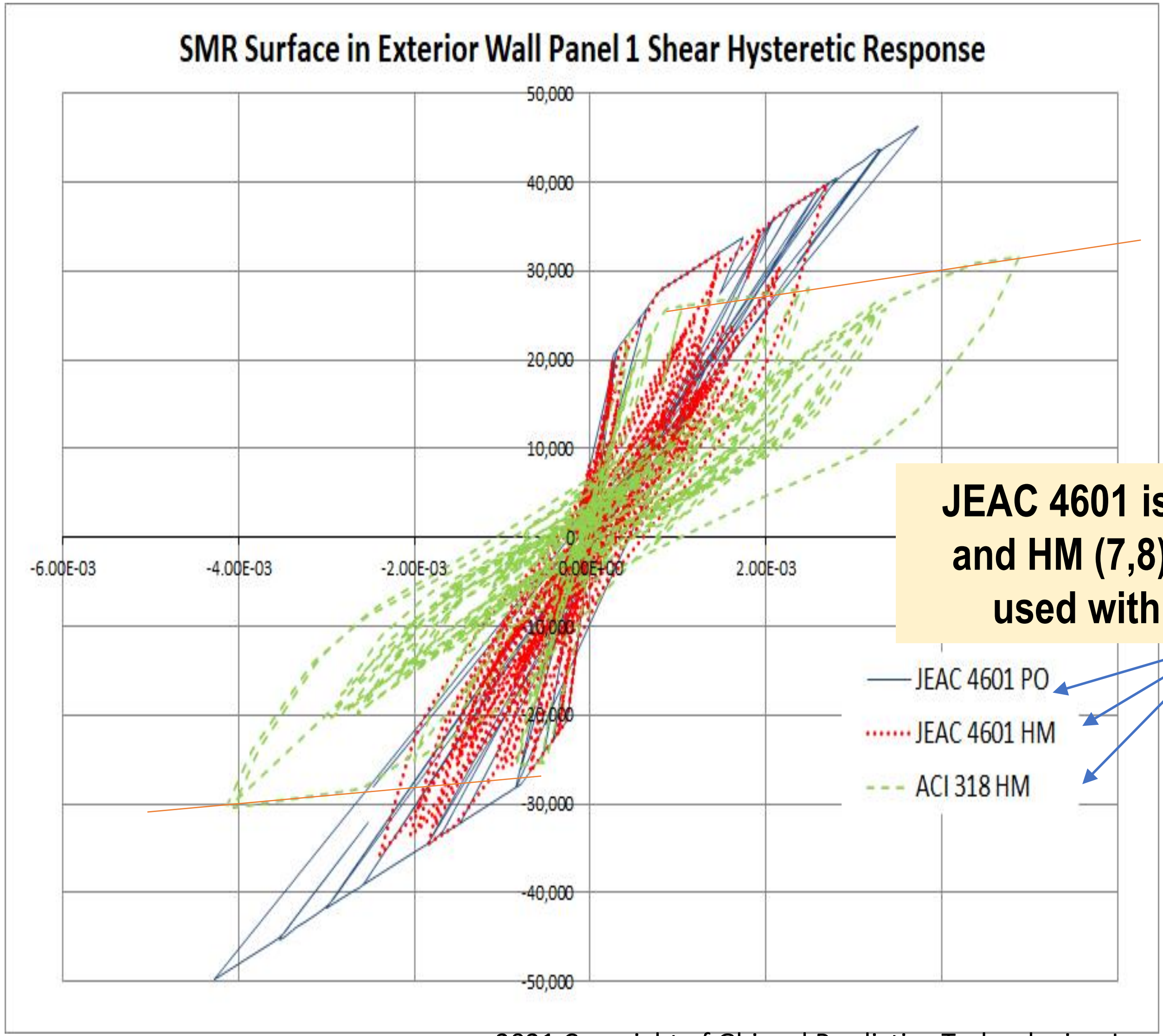




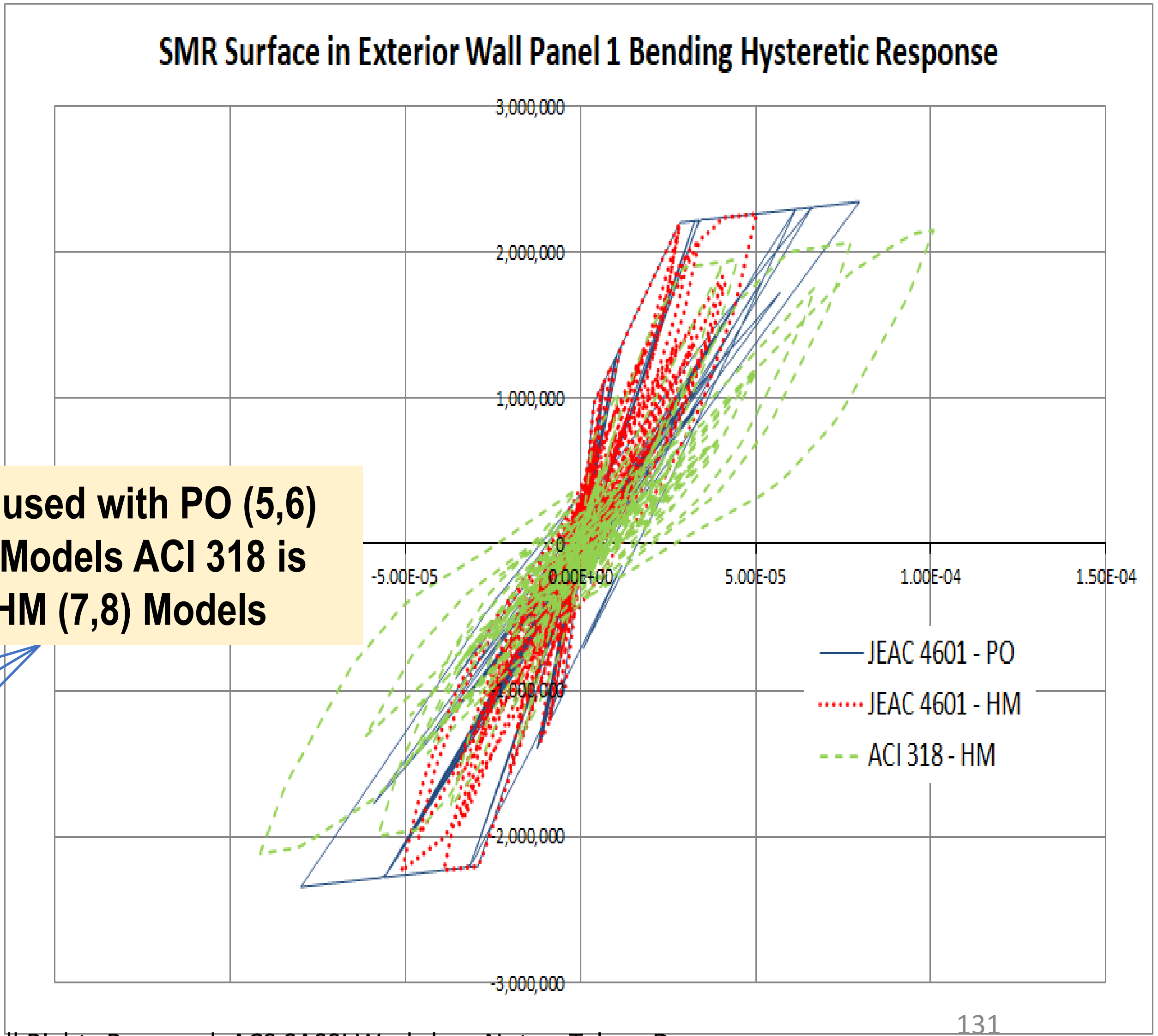
Surface SMR Model for

1st Floor Exterior Wall Response Using JEAC 4601 and ACI 318 Option 1

SHEAR



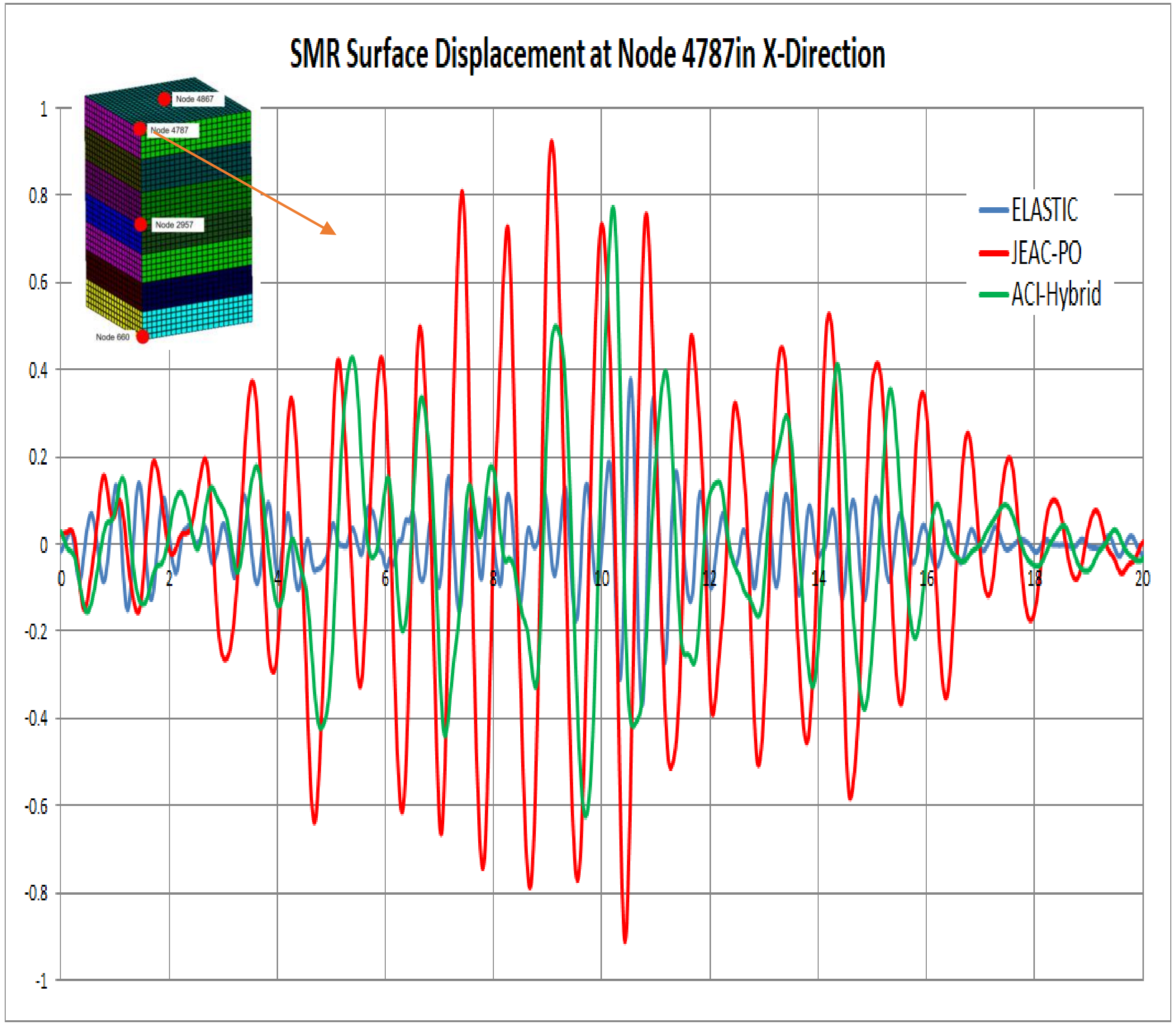
BENDING



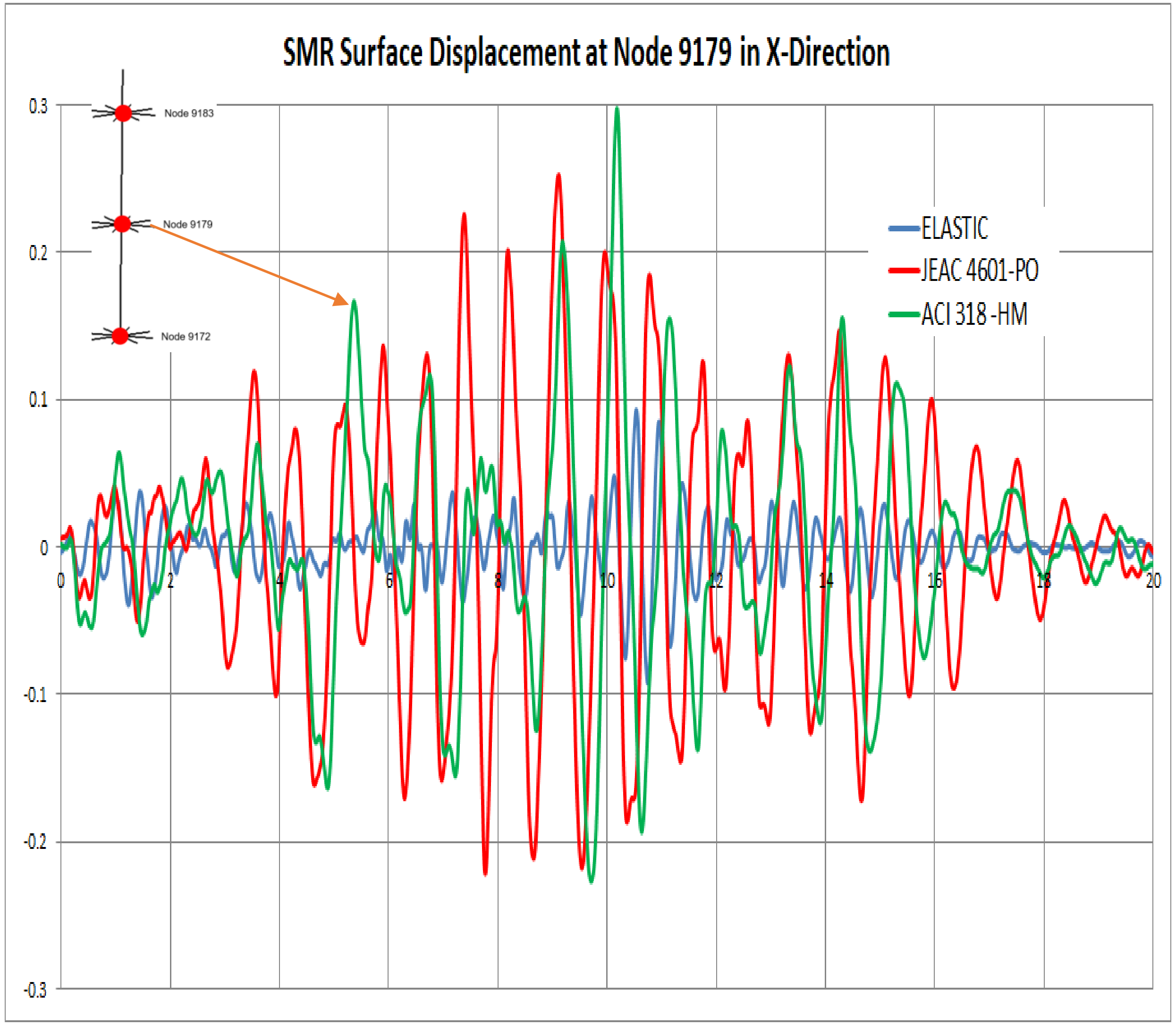
JEAC 4601 is used with PO (5,6) and HM (7,8) Models ACI 318 is used with HM (7,8) Models

Displacements in SMR Using JEAC 4601 and ACI 318 Option 1

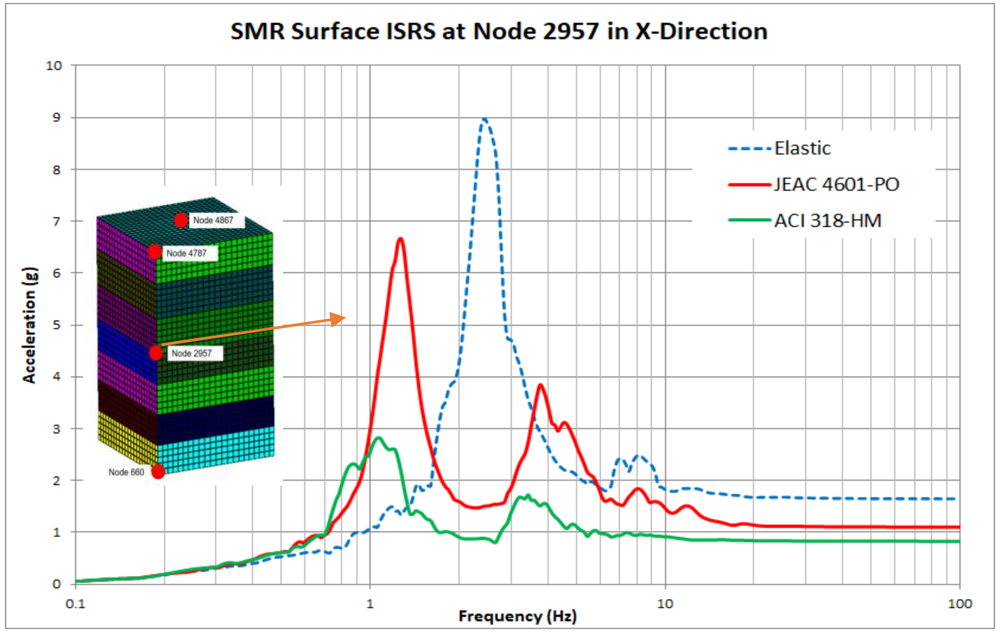
SMR Structure Top Corner

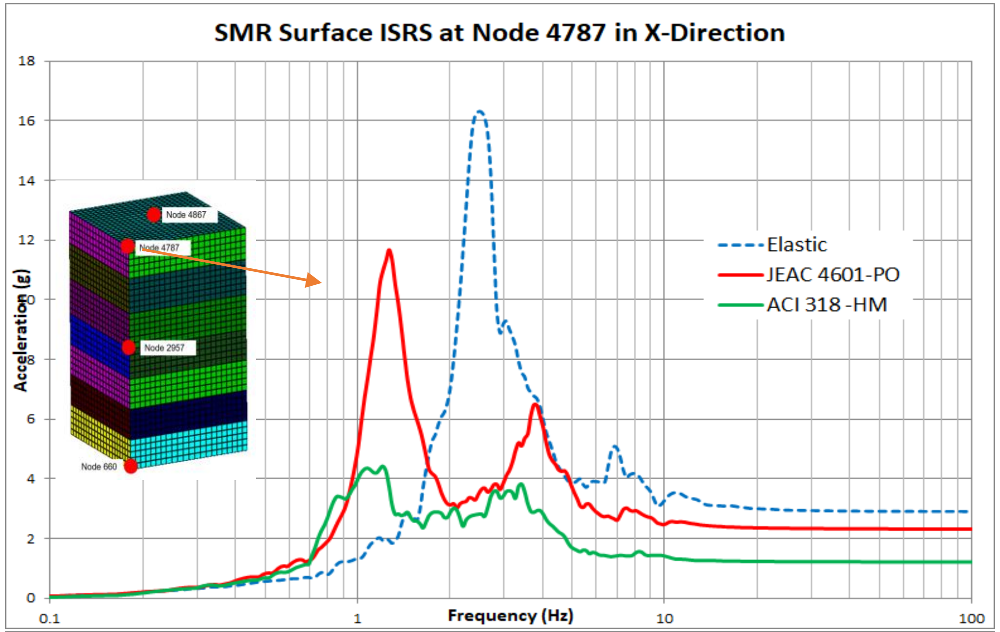


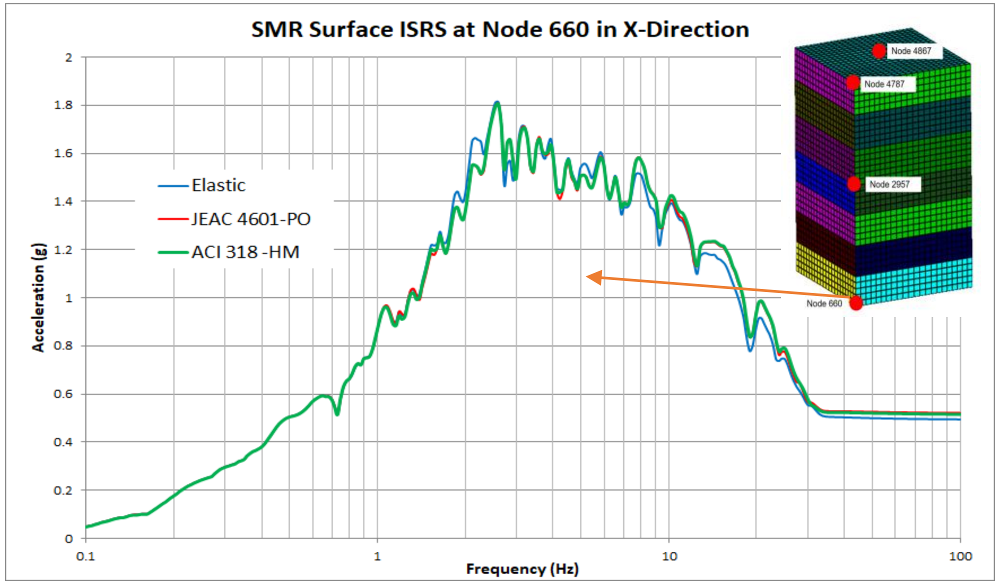
RVC Mid Elevation

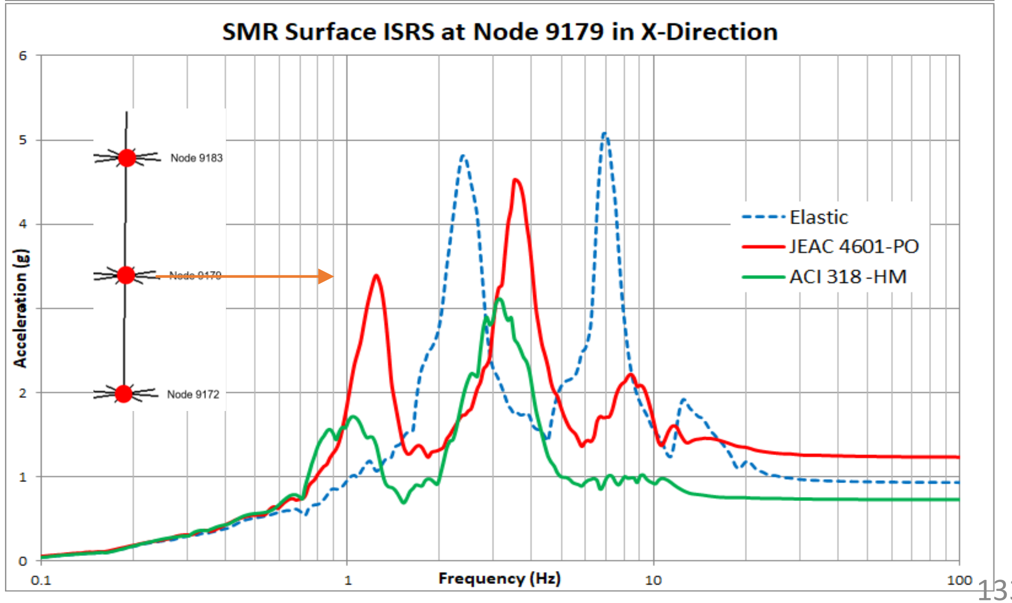


ISRS in Surface SMR Using JEAC 4601 and ACI 318 Option 1



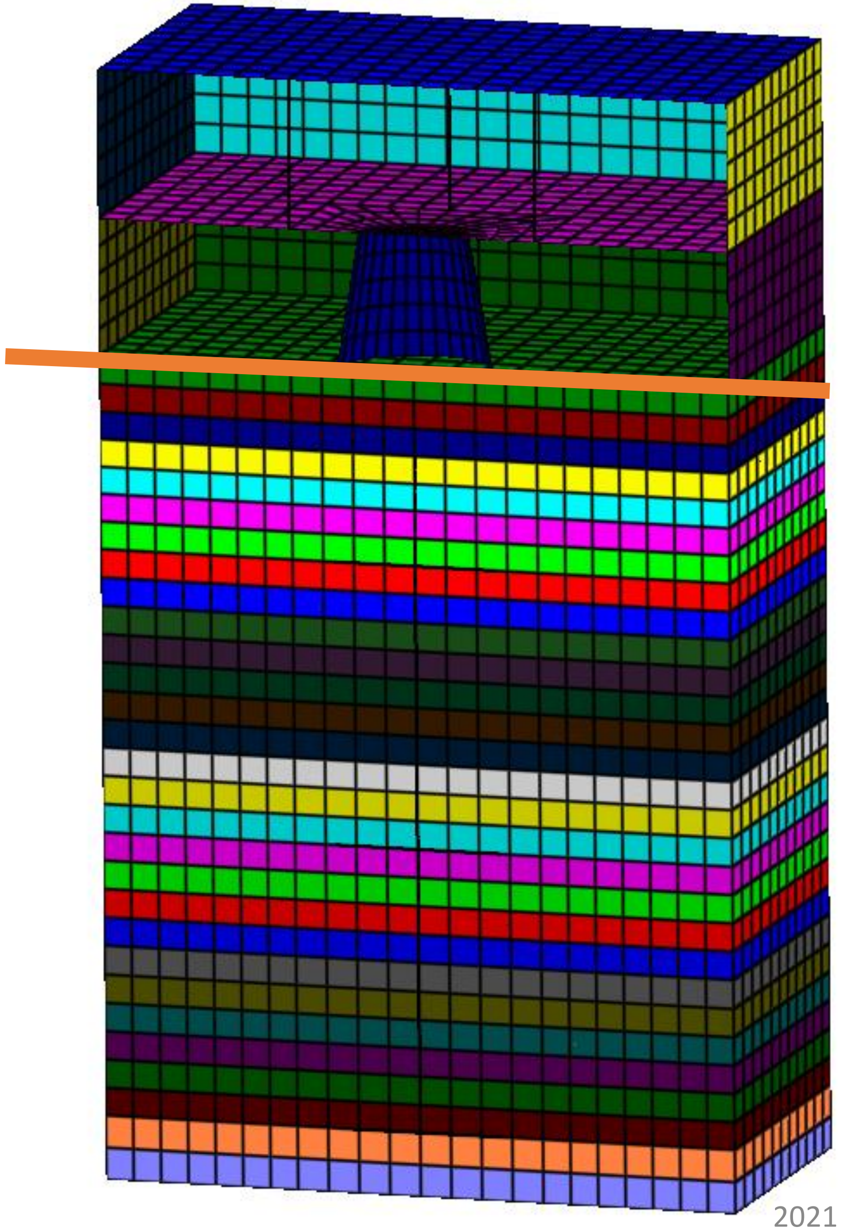


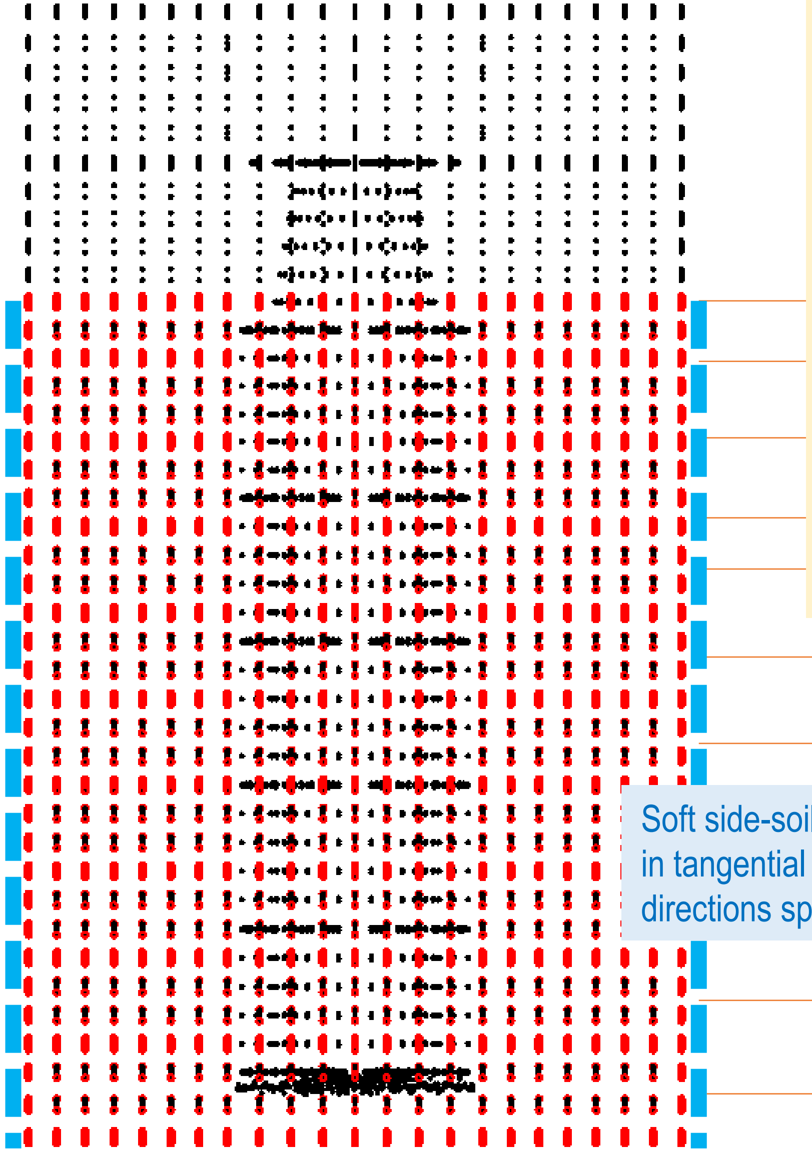




Deeply Embedded SMR Model

Embedded SMR Results w/ Welded vs. Smooth Soil Interface



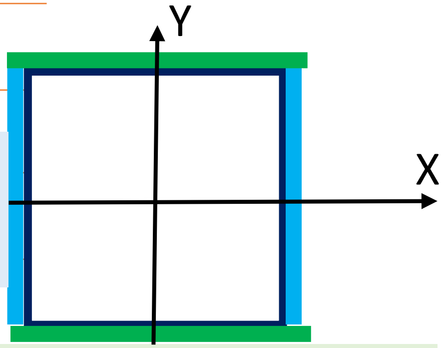


Side-soil interface modeling:

- **Welded interface:**
  Rigid springs for X, Y and Z directions

- **Smooth interface:**
  Rigid springs in normal directions X, Y and Z, and soft springs in tangential directions X, Y and Z

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

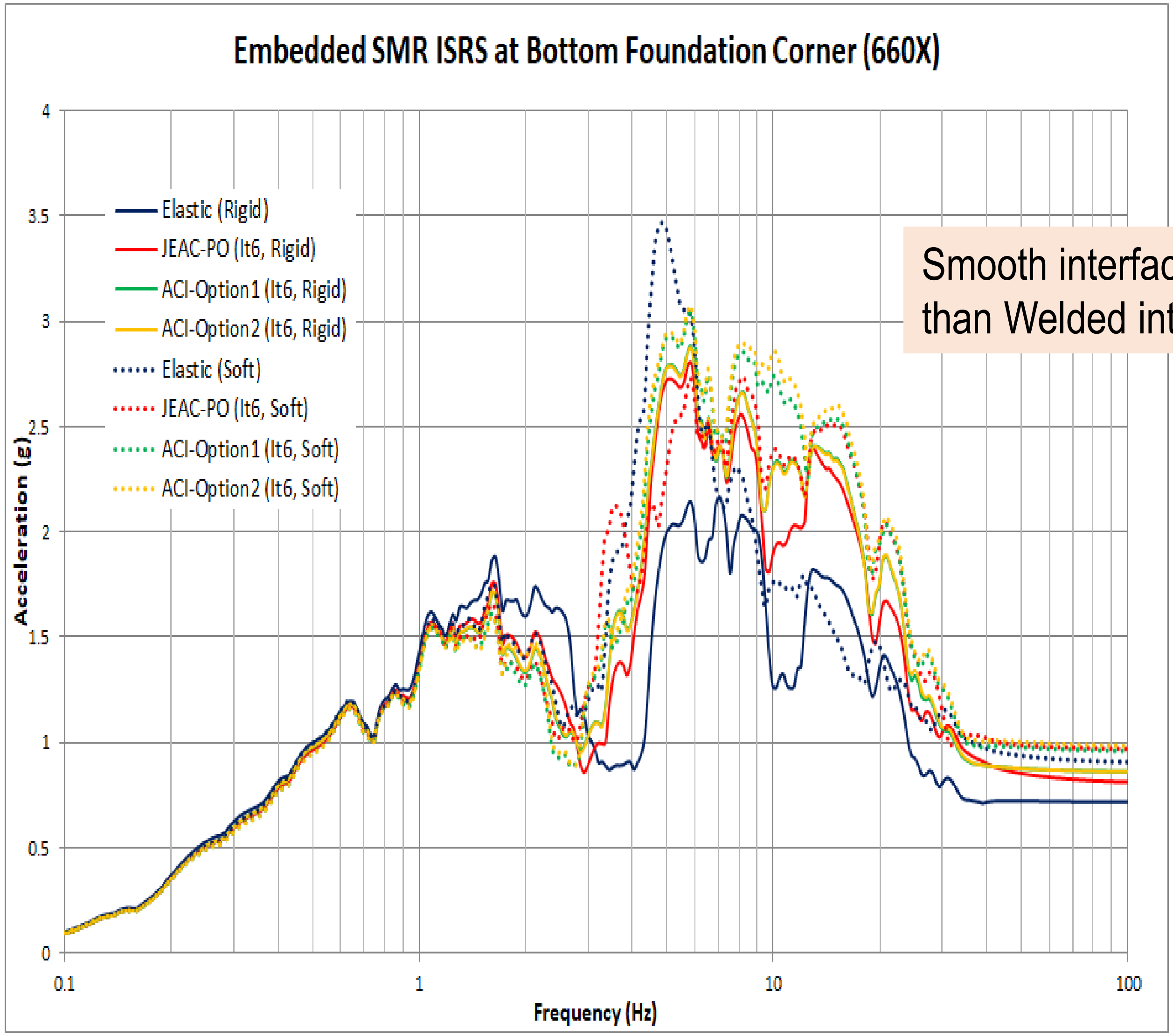


Soft side-soil springs in tangential X and Z directions springs

SMR ISRS Below Surface - Smooth vs. Welded Interface for 0.80g

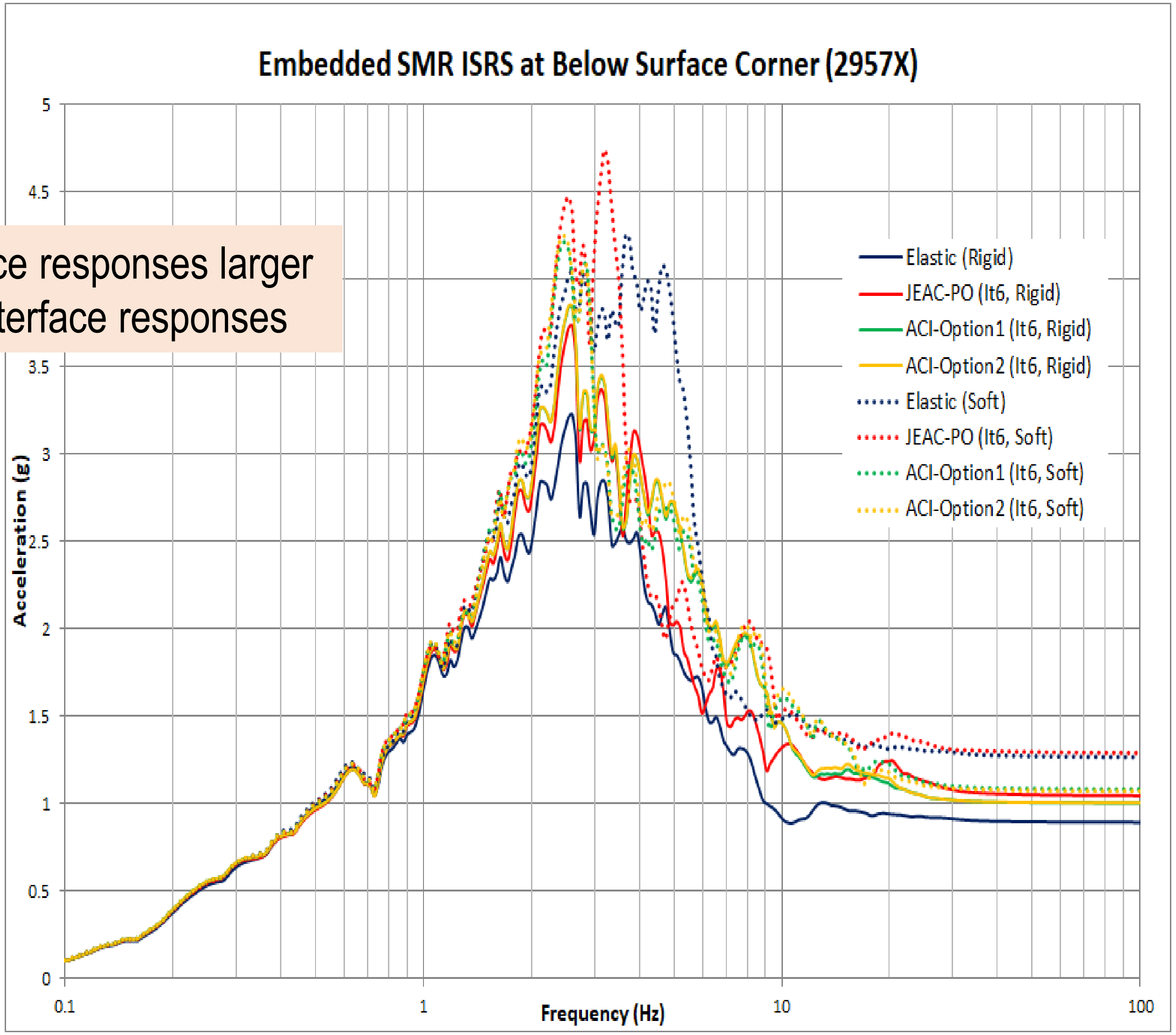
Linear Tangential Springs
Linear/Nonlinear Walls

-118ft Depth



Smooth interface responses larger than Welded interface responses

-30ft Depth

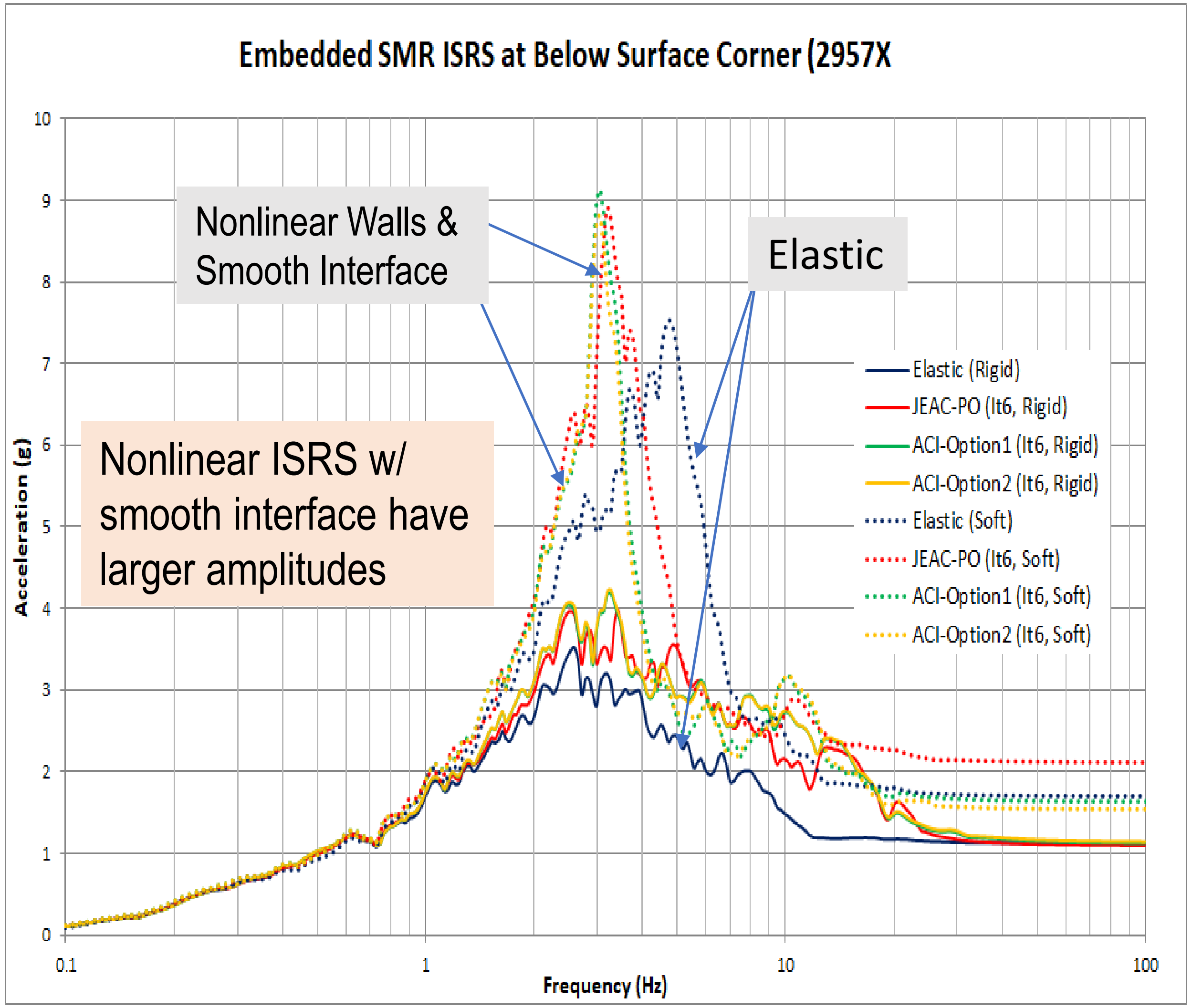


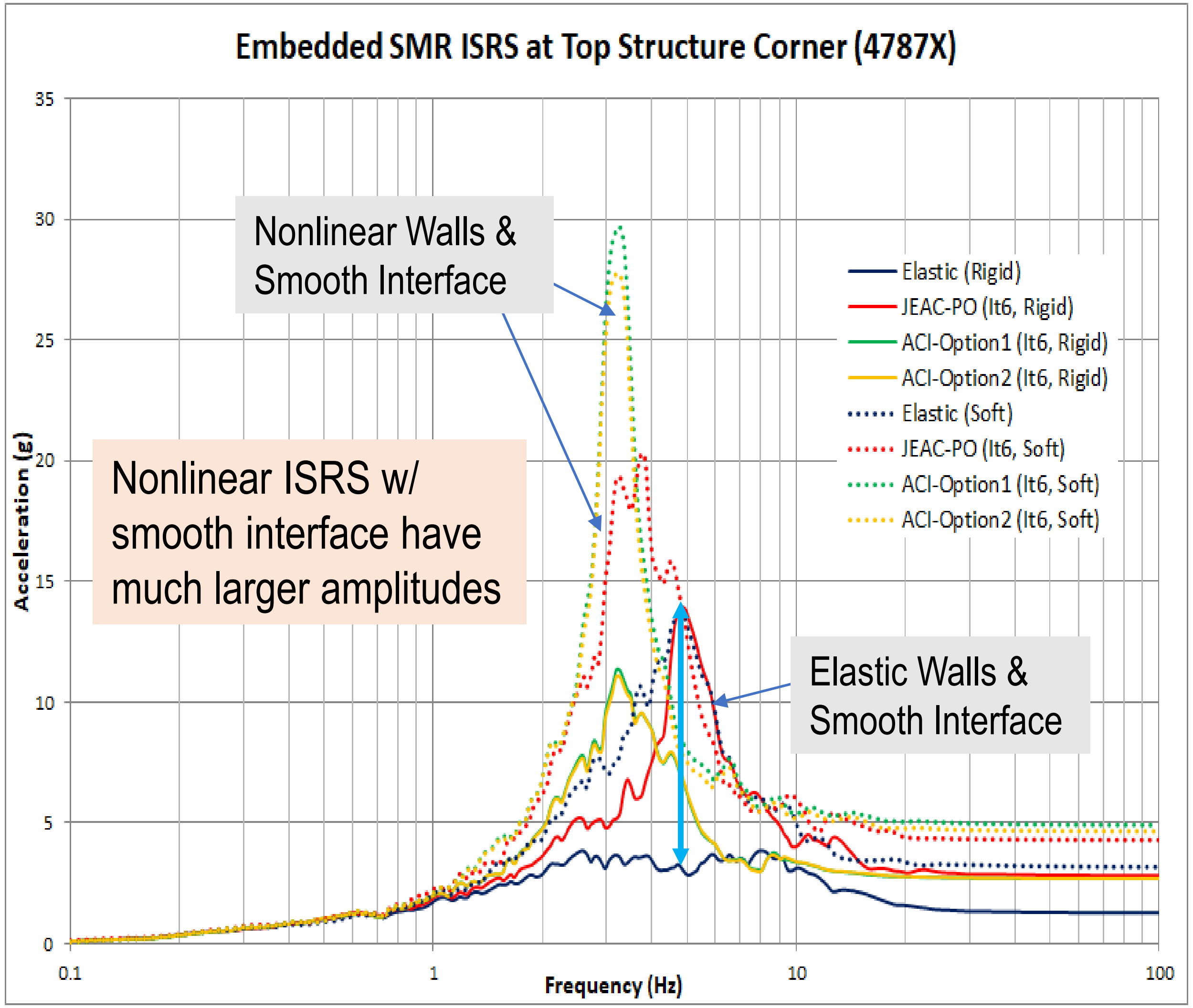
SMR ISRS Above Surface - Smooth vs. Welded Interface for 0.80g

-30ft Depth

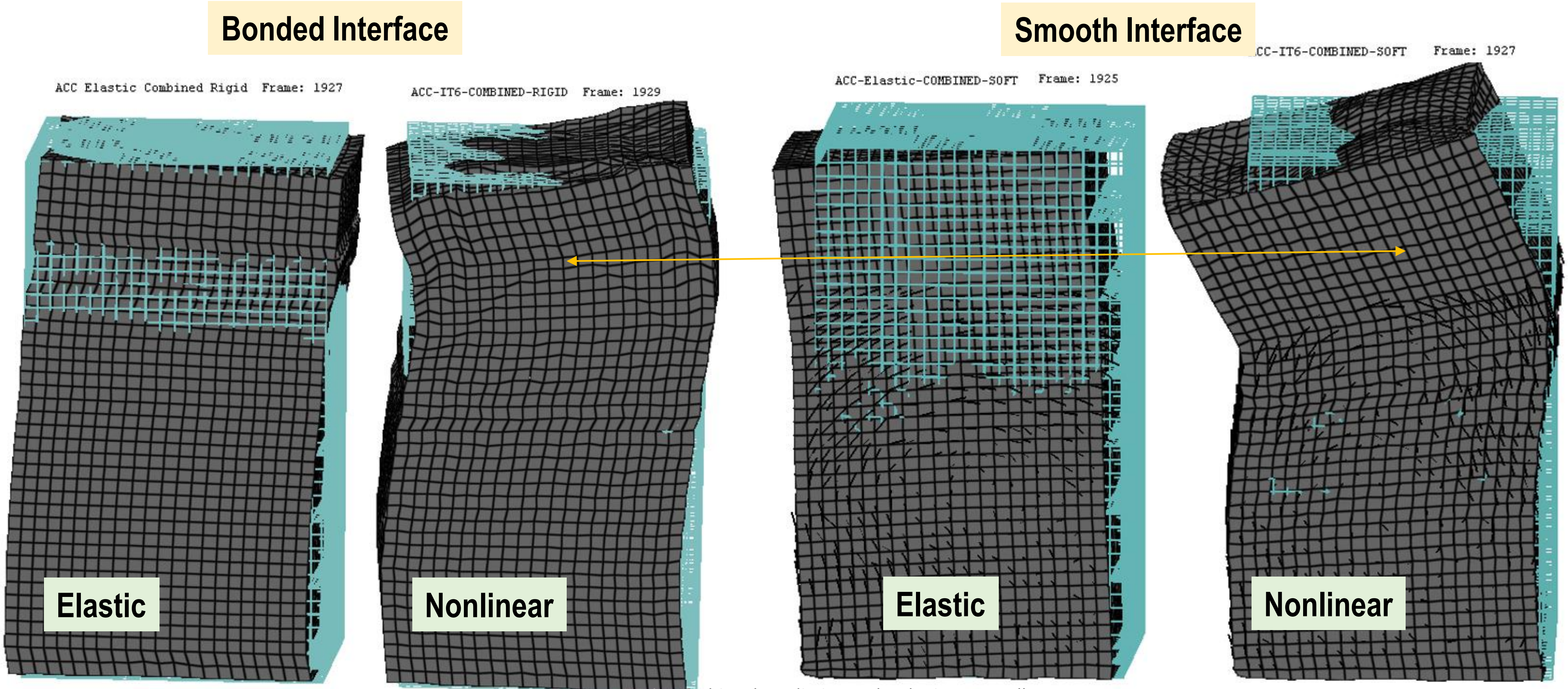
Linear Tangential Springs
Linear/Nonlinear Walls

44.5ft Above Ground

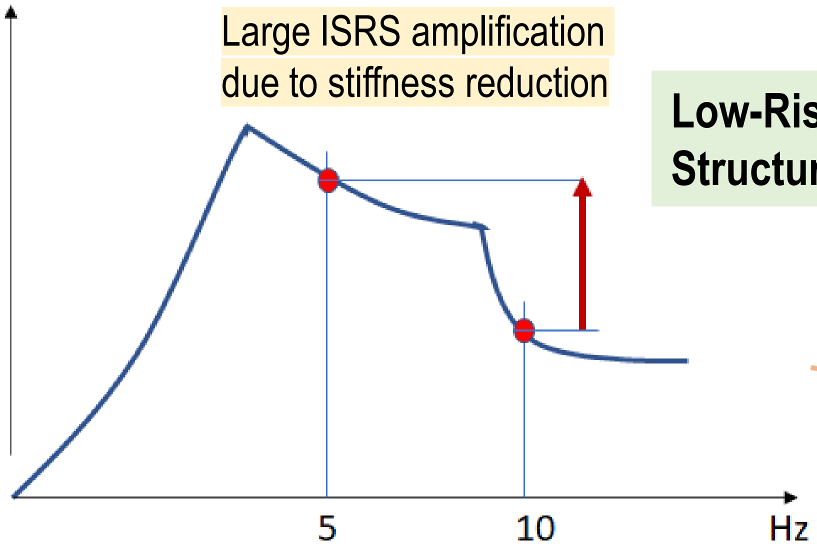




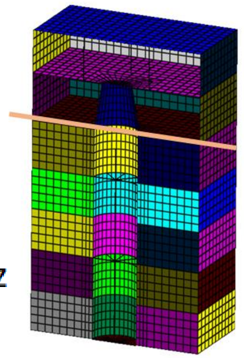
Embedded SMR Instant Acceleration Profile for Elastic and Nonlinear SSI Analysis with Welded & Smooth Side-Soil Interface

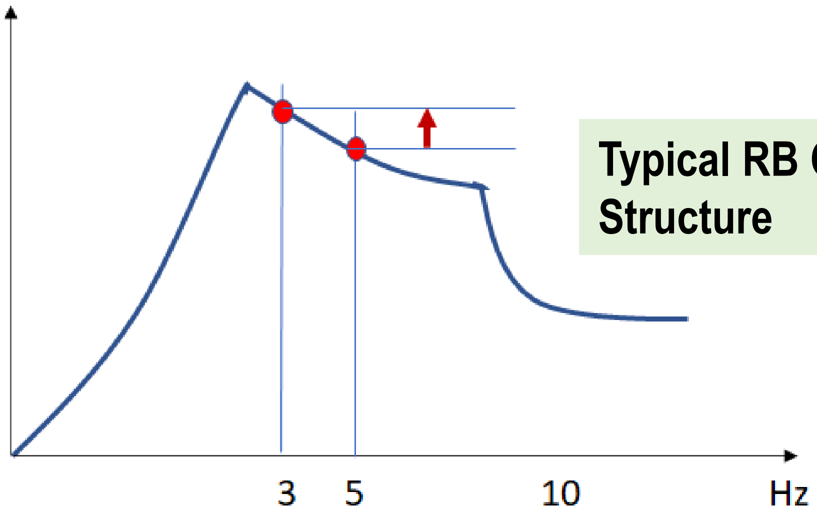


Low-Rise SMR Super Structure Frequency is Shifted to Lower Frequencies due to Nonlinear Wall & Interface Stiffness Reduction

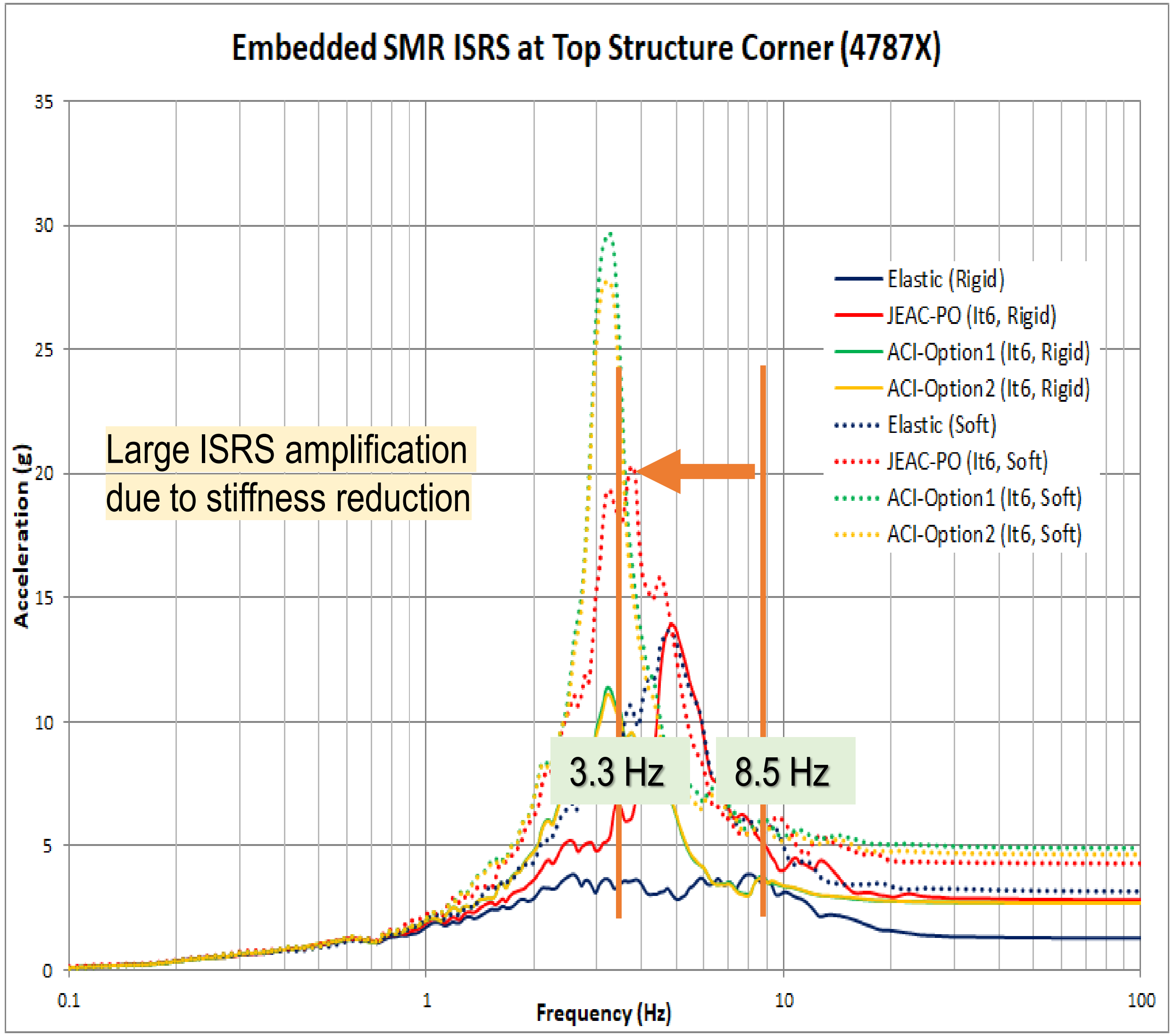


Low-Rise SMR Structure

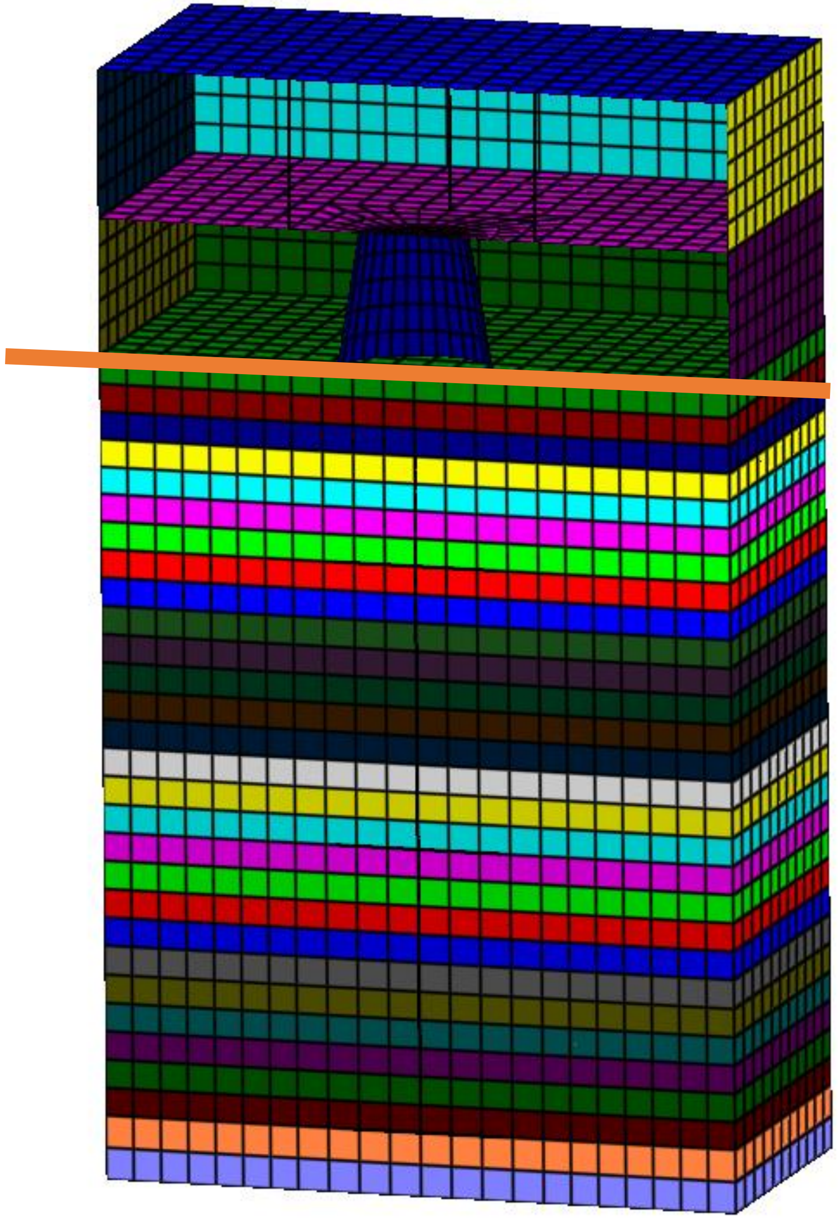


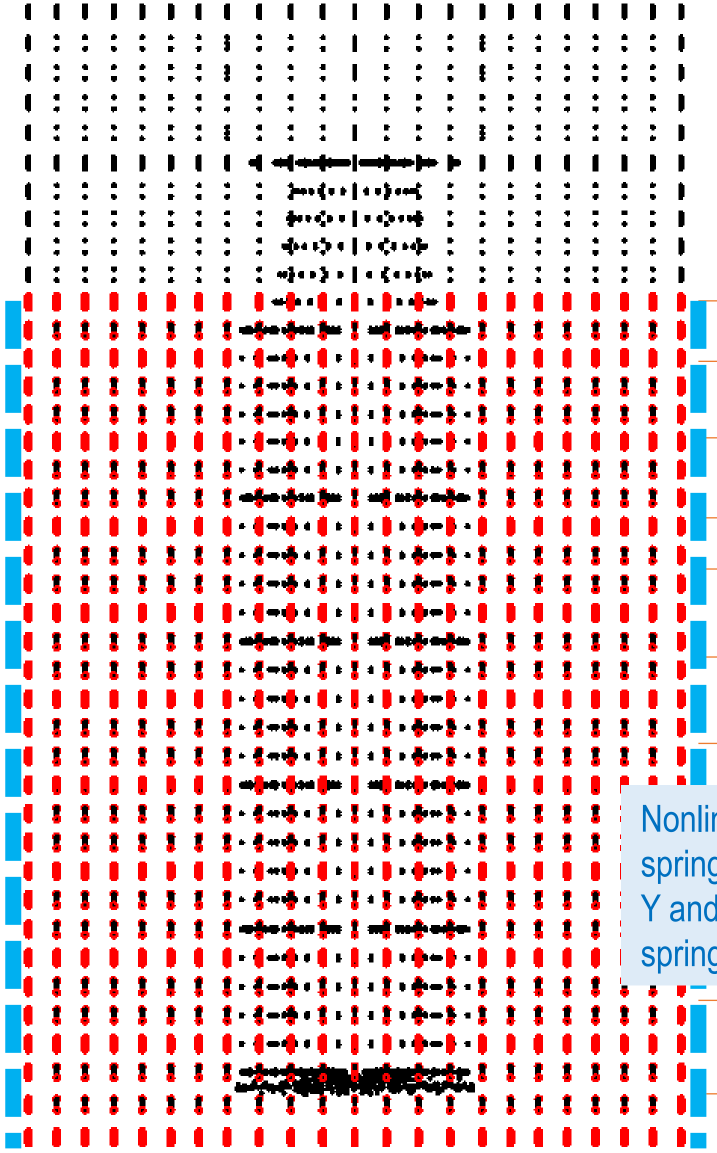


Typical RB Complex Structure



Embedded SMR with Nonlinear Springs at Soil Interface for 0.60g

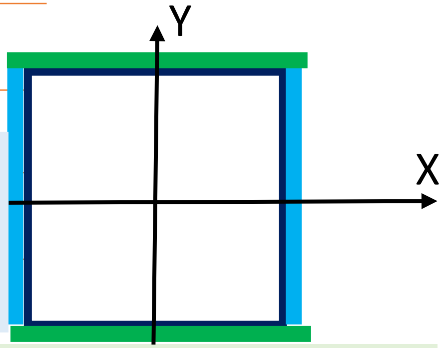




Side-soil interface modeled using nonlinear springs:

- **Nonlinear interface**

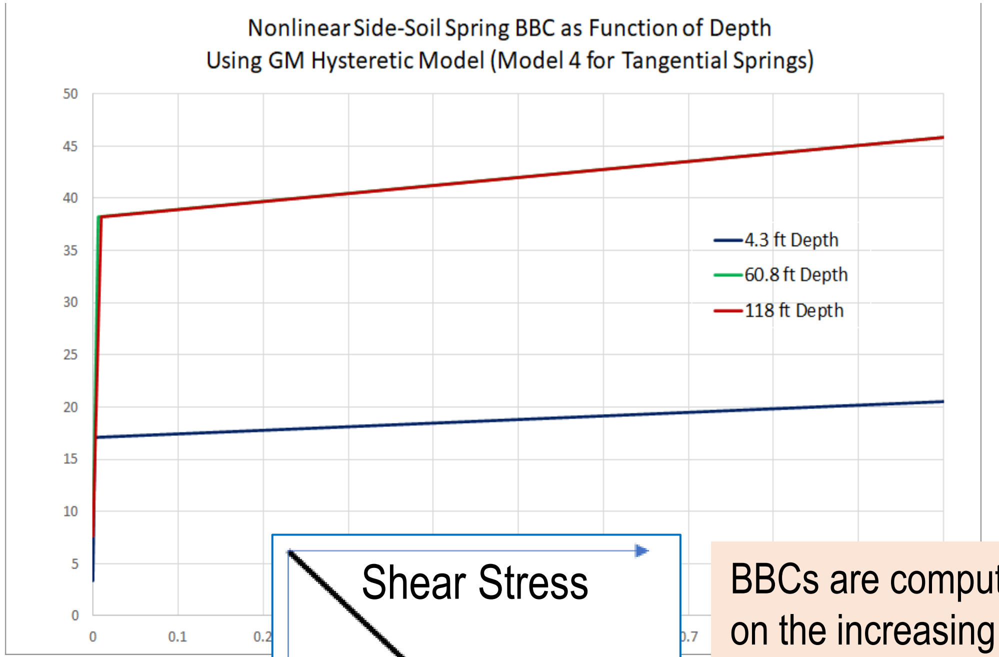
Rigid springs in normal directions X, Y and Z, and nonlinear springs in tangential directions X, Y and Z. Friction forces vary with depth.

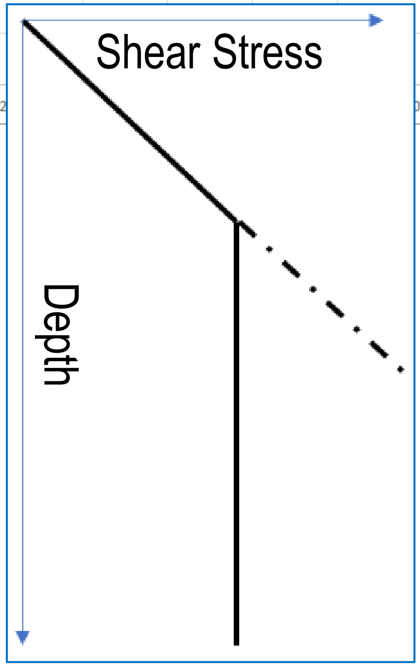


Nonlinear side-soil springs in tangential Y and Z directions springs

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

Adjusted Tangential Spring BBCs for Soil Interface as Function of Depth. Applied General Massing Hysteretic Soil Model (Model 4)

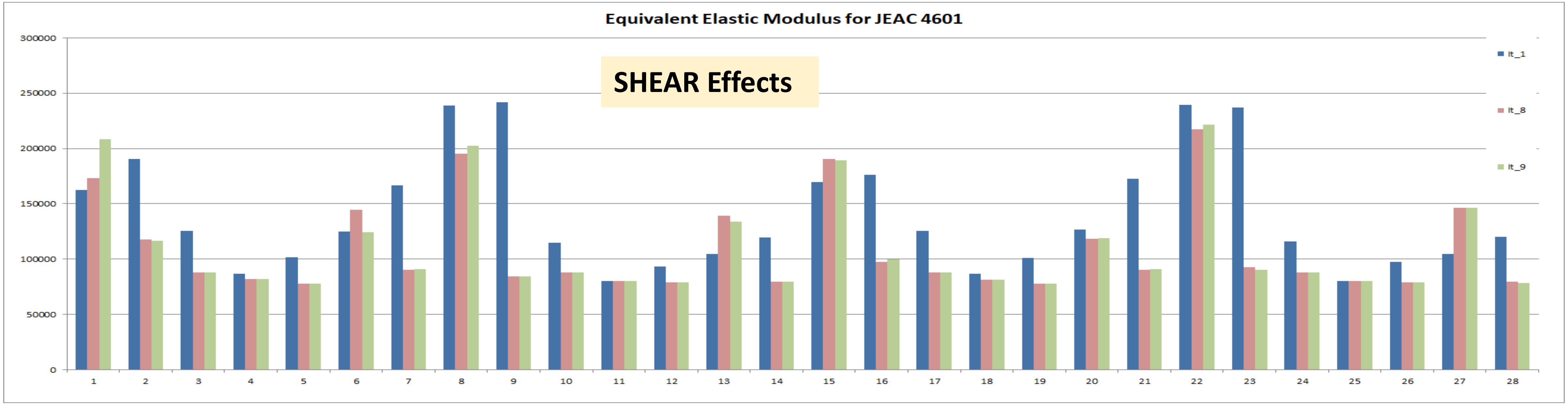


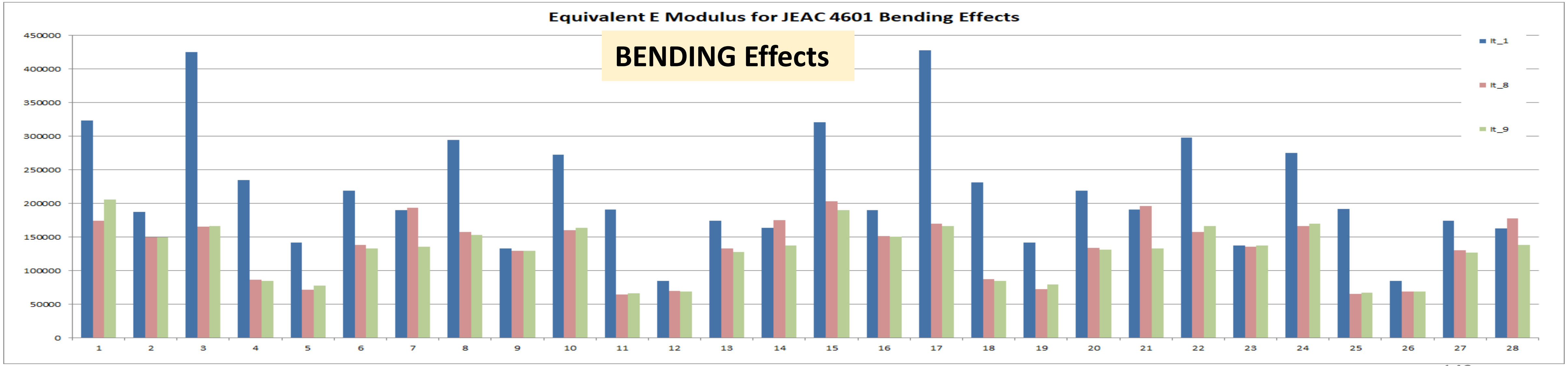


BBCs are computed based on the increasing static soil pressure on the lateral wall down to layer 8 for which the shear stress is above 2ksf (API standard). Then, shear spring BBC stays the same for larger depths.

Layer Top	KX, KY and KZ	Crack displ	Crack Force	Yelding displ	Yielding Force	Ultimate Disp	Ultimate
SURFACE	1.00E+06	3.00E-06	3.00E+00	1.50E-03	15	1	18
1	1.00E+06	3.42E-06	3.42E+00	1.71E-03	17.07628	1	20.49153
2	1.00E+06	4.02E-06	4.02E+00	2.01E-03	20.09801	1	24.11761
3	1.00E+06	4.62E-06	4.62E+00	2.31E-03	23.11973	1	27.74368
4	1.00E+06	5.23E-06	5.23E+00	2.61E-03	26.14146	1	31.36976
5	1.00E+06	5.82E-06	5.82E+00	2.91E-03	29.09292	1	34.9115
6	1.00E+06	6.42E-06	6.42E+00	3.21E-03	32.11465	1	38.53758
7	1.00E+06	7.03E-06	7.03E+00	3.51E-03	35.13638	1	42.16365
8	1.00E+06	7.65E-06	7.65E+00	3.82E-03	38.22838	1	45.87405
9	1.00E+06	7.65E-06	7.65E+00	4.13E-03	38.22838	1	45.87405
10	1.00E+06	7.65E-06	7.65E+00	4.44E-03	38.22838	1	45.87405
11	1.00E+06	7.65E-06	7.65E+00	4.75E-03	38.22838	1	45.87405
12	1.00E+06	7.65E-06	7.65E+00	5.06E-03	38.22838	1	45.87405
13	1.00E+06	7.65E-06	7.65E+00	5.37E-03	38.22838	1	45.87405
	1.00E+06	7.65E-06	7.65E+00	5.68E-03	38.22838	1	45.87405
	1.00E+06	7.65E-06	7.65E+00	5.99E-03	38.22838	1	45.87405
	1.00E+06	7.65E-06	7.65E+00	6.30E-03	38.22838	1	45.87405
	1.00E+06	7.65E-06	7.65E+00	6.61E-03	38.22838	1	45.87405
	1.00E+06	7.65E-06	7.65E+00	6.91E-03	38.22838	1	45.87405
	1.00E+06	7.65E-06	7.65E+00	7.22E-03	38.22838	1	45.87405
	1.00E+06	7.65E-06	7.65E+00	7.53E-03	38.22838	1	45.87405
	1.00E+06	7.65E-06	7.65E+00	7.84E-03	38.22838	1	45.87405
	1.00E+06	7.65E-06	7.65E+00	8.16E-03	38.22838	1	45.87405
	1.00E+06	7.65E-06	7.65E+00	8.47E-03	38.22838	1	45.87405
	1.00E+06	7.65E-06	7.65E+00	8.78E-03	38.22838	1	45.87405
	1.00E+06	7.65E-06	7.65E+00	9.09E-03	38.22838	1	45.87405
26	1.00E+06	7.65E-06	7.65E+00	9.40E-03	38.22838	1	45.87405
27	1.00E+06	7.65E-06	7.65E+00	9.70E-03	38.22838	1	45.87405
28	1.00E+06	7.65E-06	7.65E+00	1.00E-02	38.22838	1	45.87405
29	1.00E+06	7.65E-06	7.65E+00	1.04E-02	38.22838	1	45.87405

JEAC Convergence Study: It. 1 and 8,9 for Eeql or External Walls



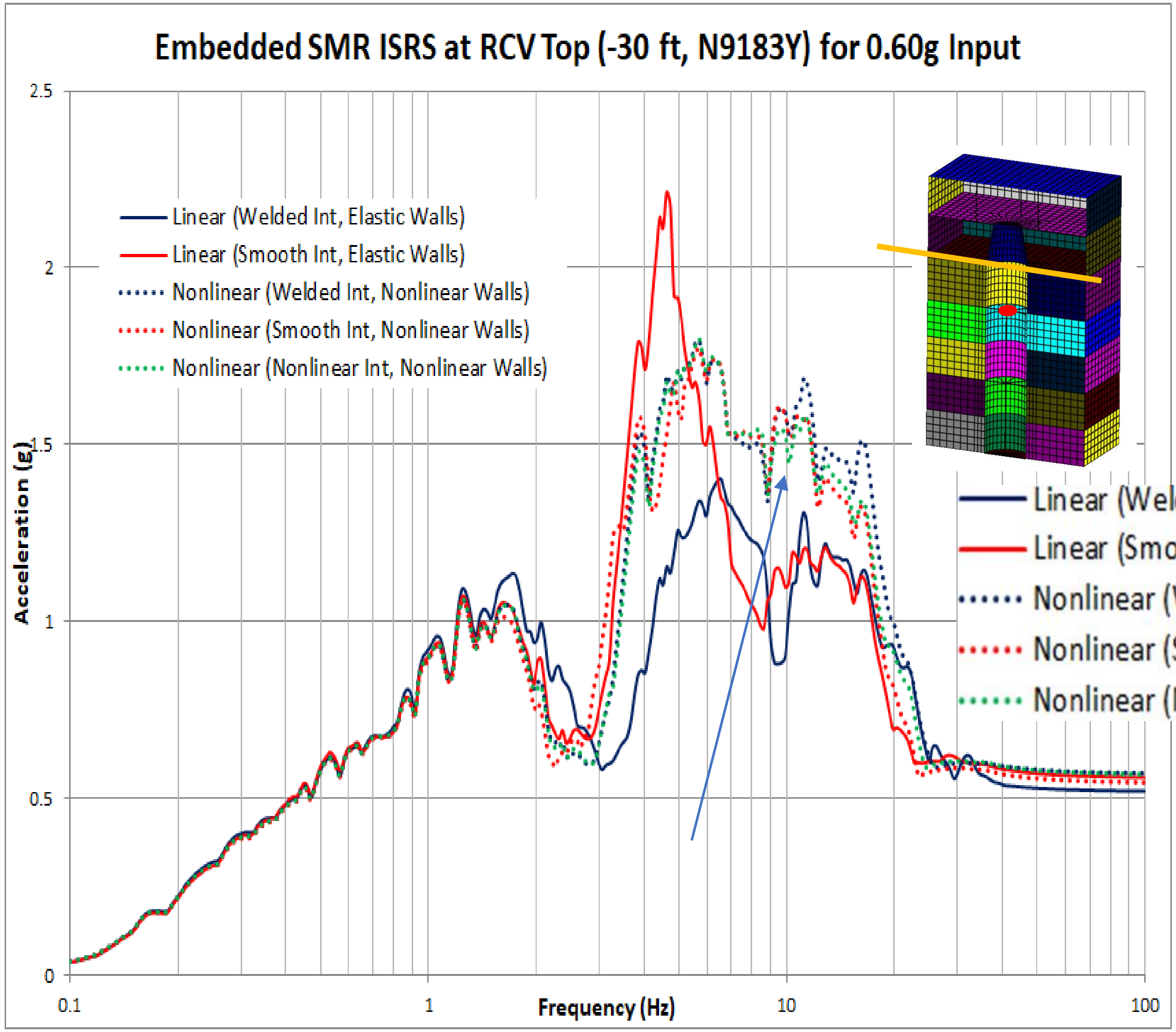


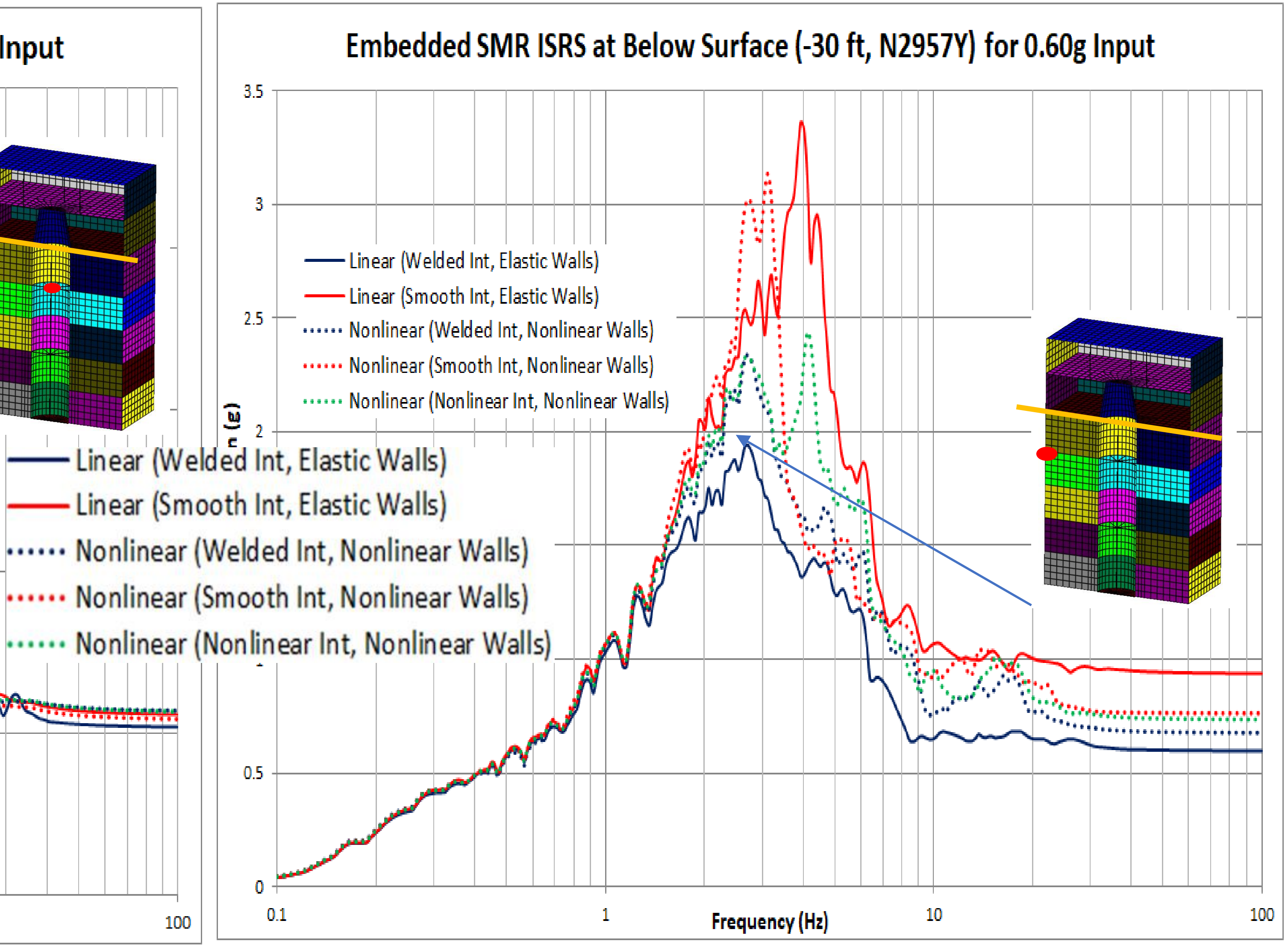
SMR ATF Below Surface for Linear vs. Nonlinear Soil Interface for 0.6g

-30ft Depth

Linear/Nonlinear Tangential Springs
Linear/Nonlinear Walls ACI 318

-30ft Depth



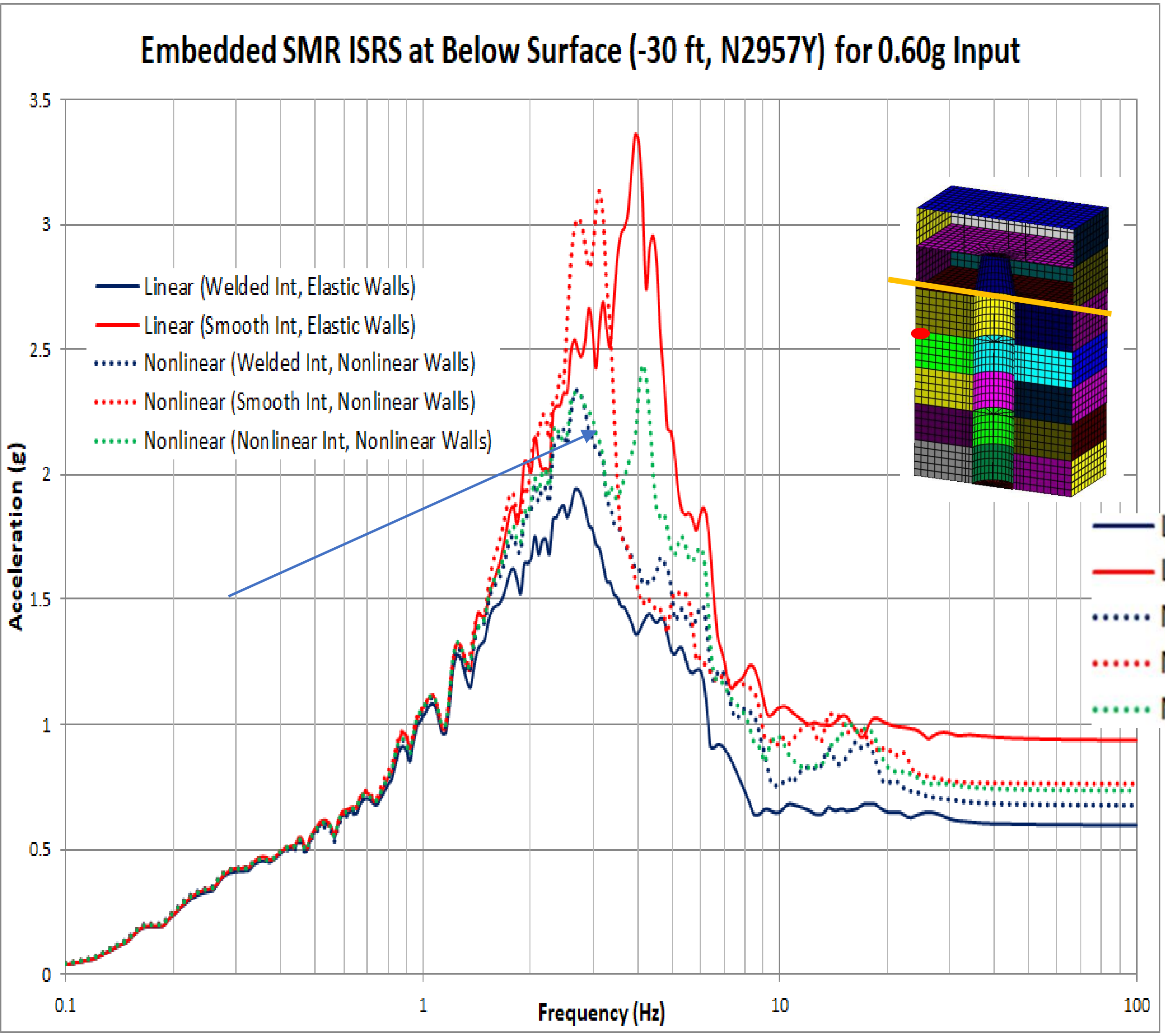


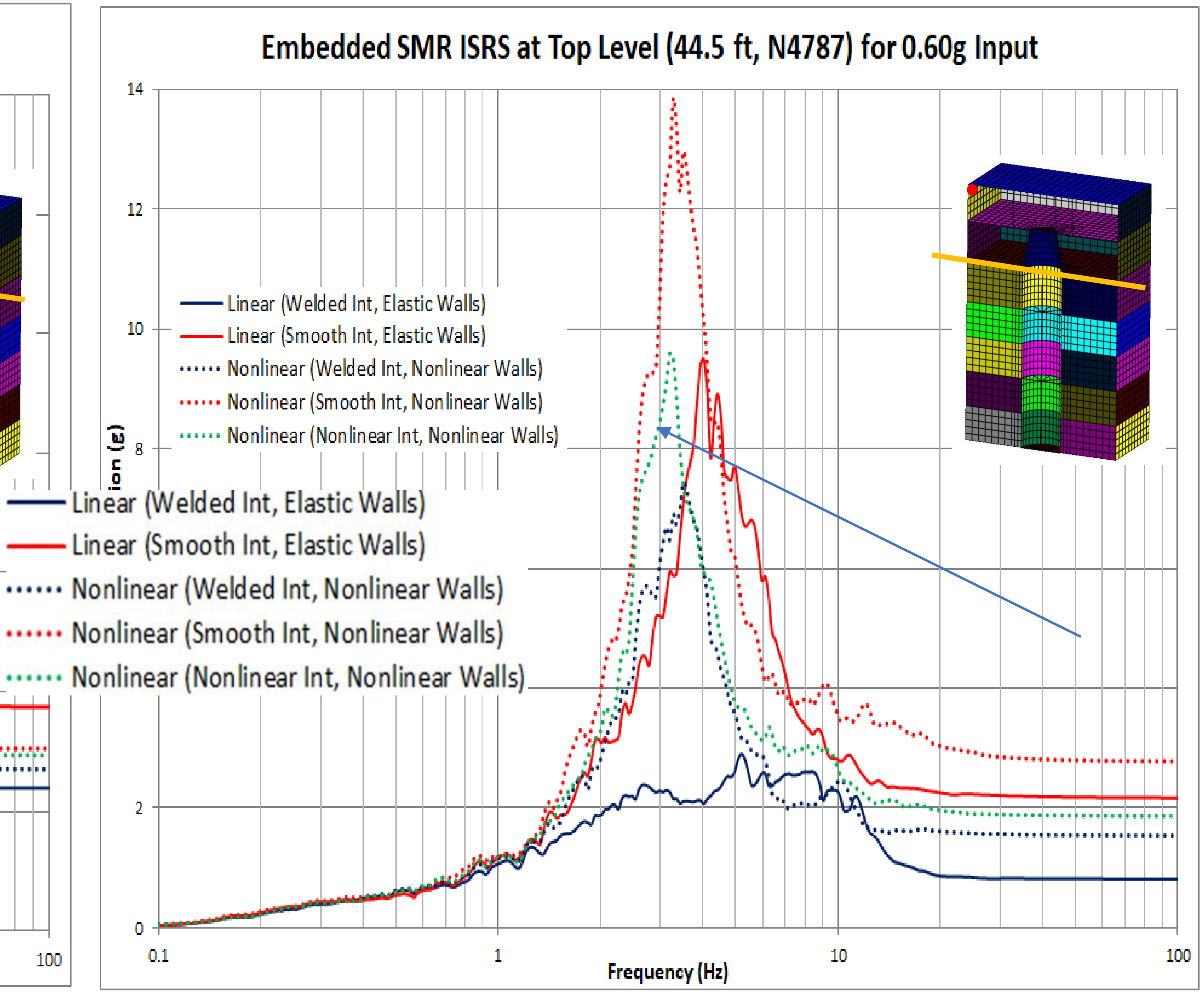
SMR ISRS Below Surface for Linear vs. Nonlinear Interface for 0.6g

-30ft Depth

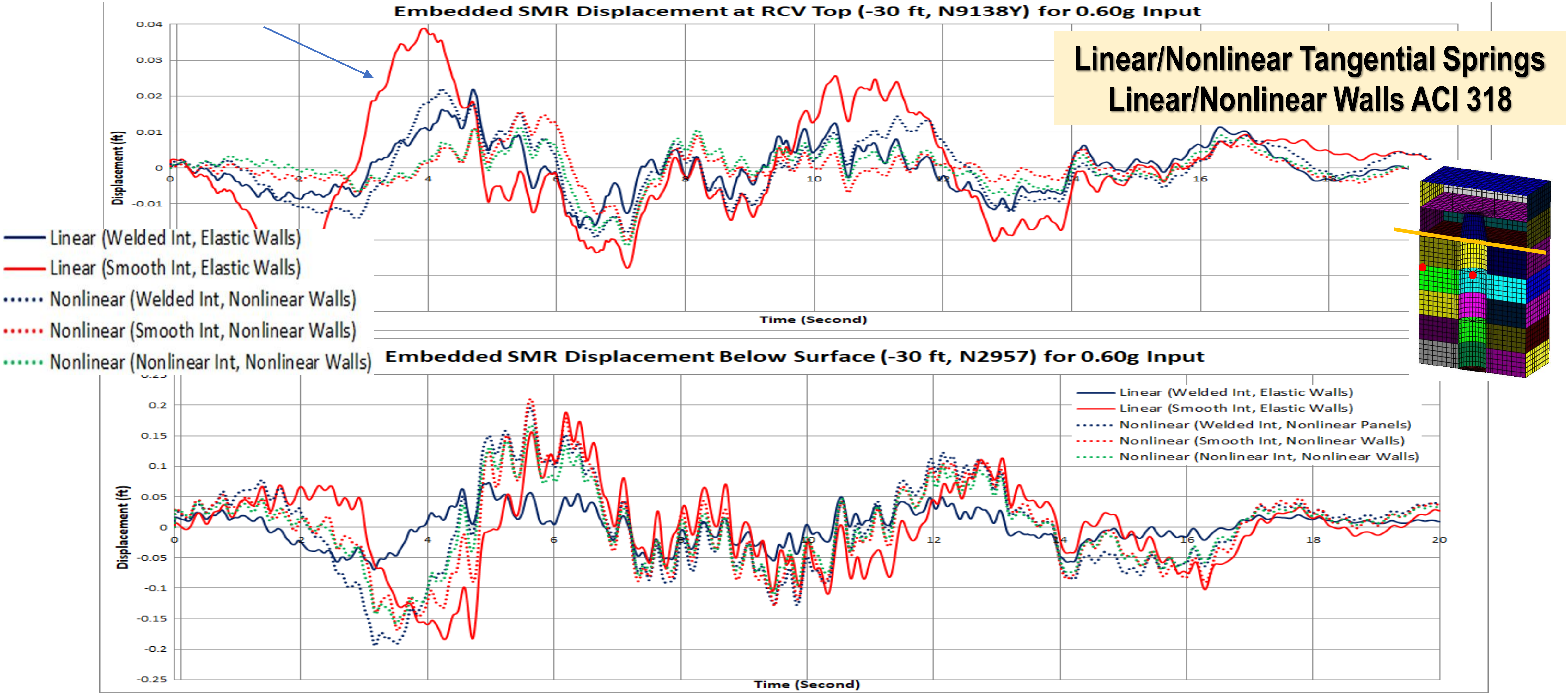
Linear/Nonlinear Tangential Springs
Linear/Nonlinear Walls ACI 318

44.5ft Above Ground



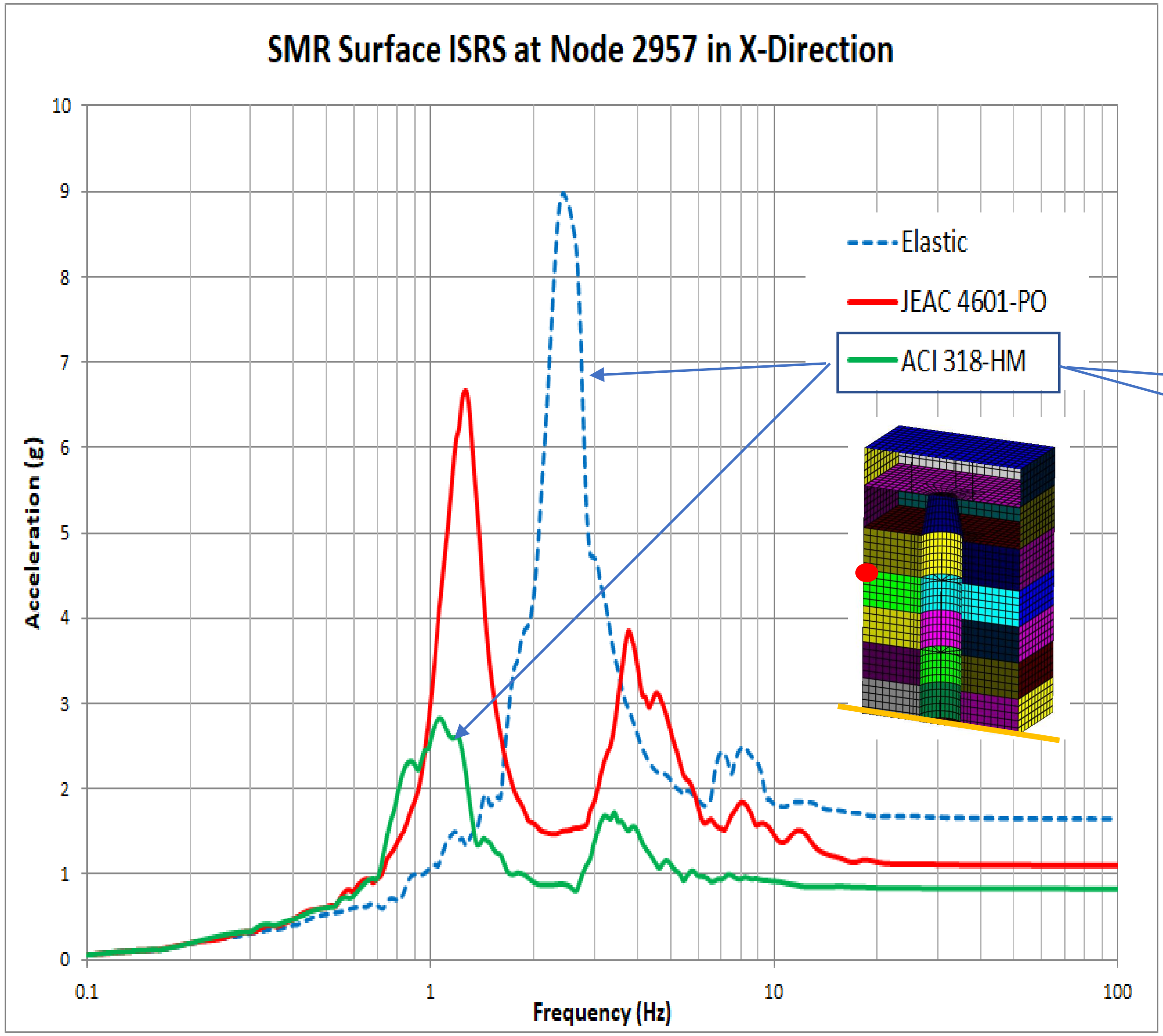


SMR Displacements for Linear vs. Nonlinear Soil Interface for 0.6g wrt Foundation Base Center Location

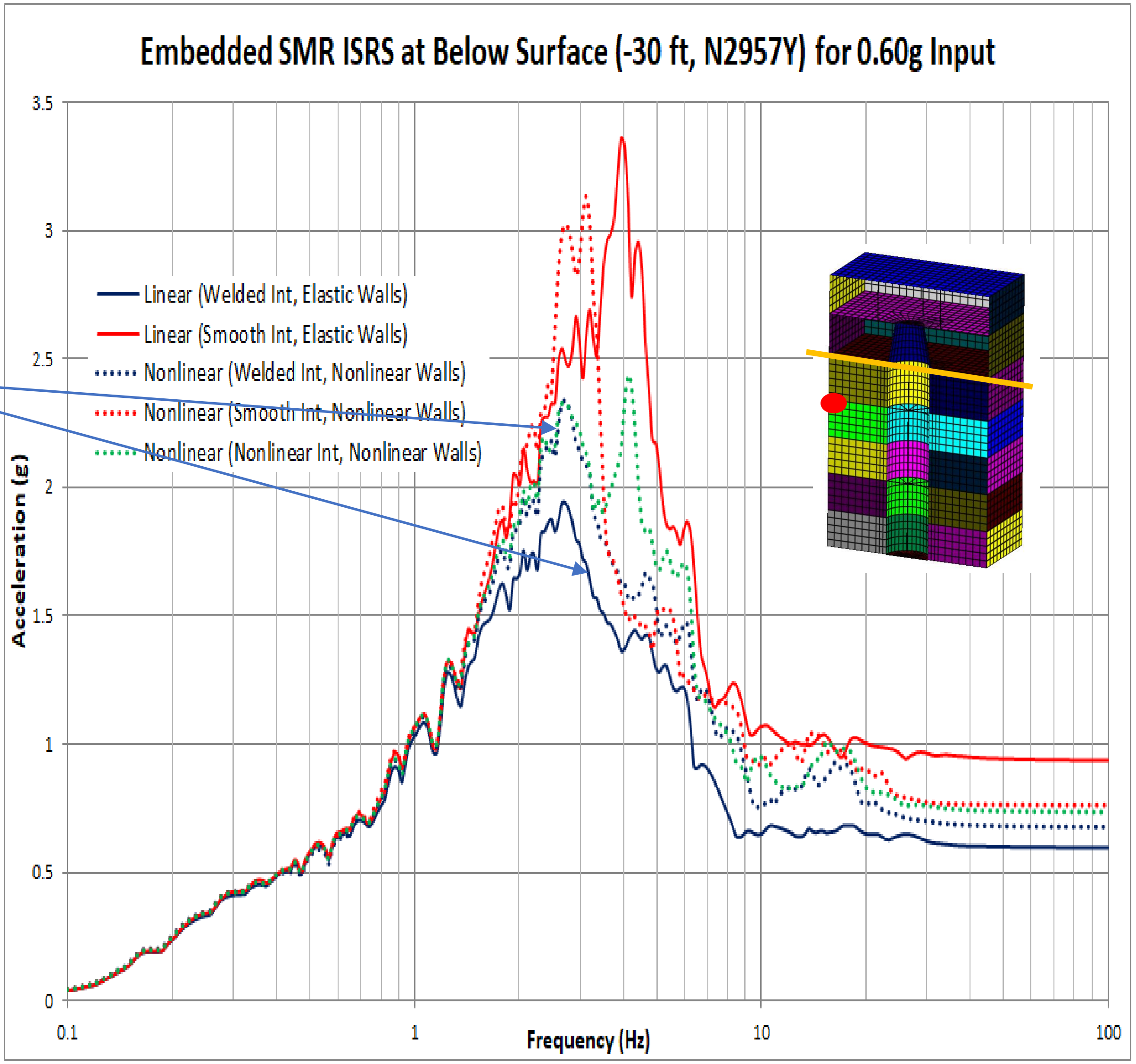


Surface SMR vs. Embedded SMR Linear & Nonlinear ISRS for 0.6g

SURFACE SMR



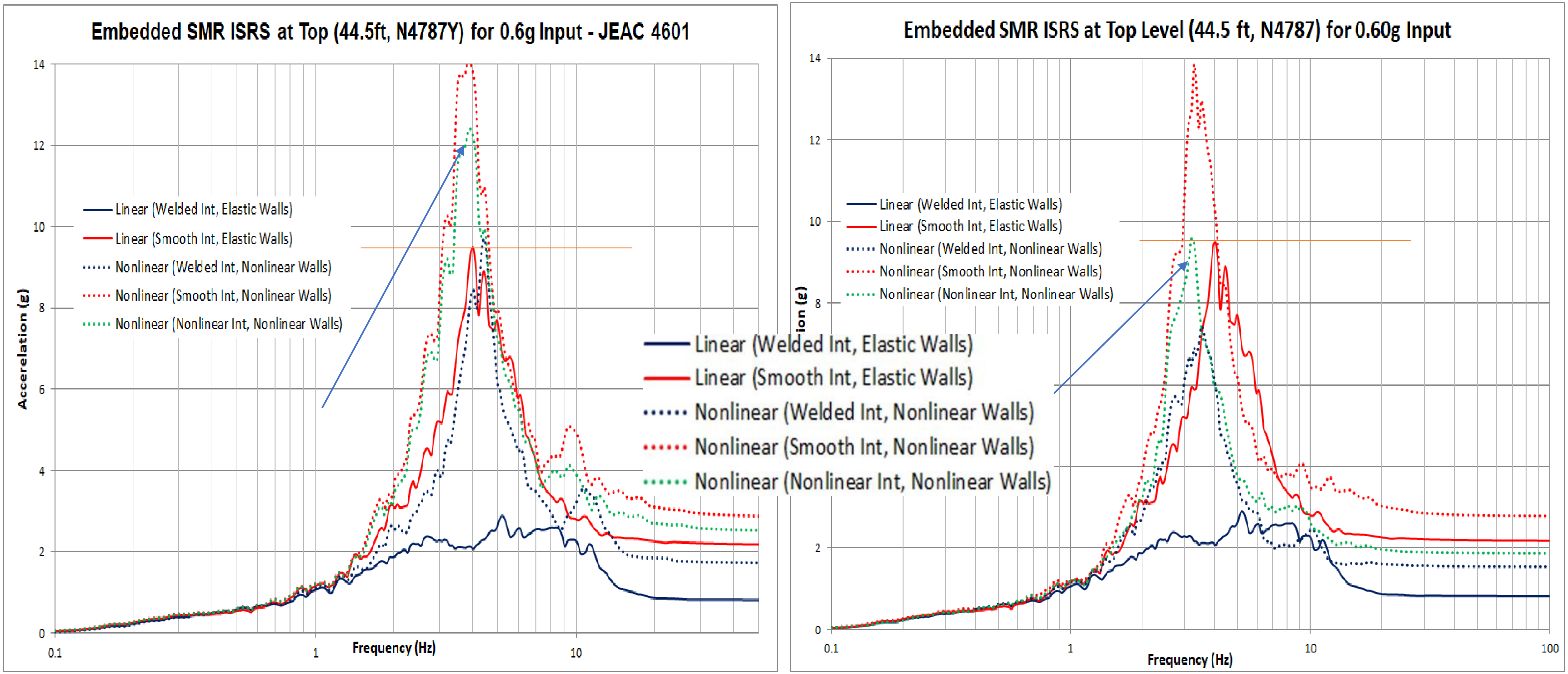
EMBEDDED SMR



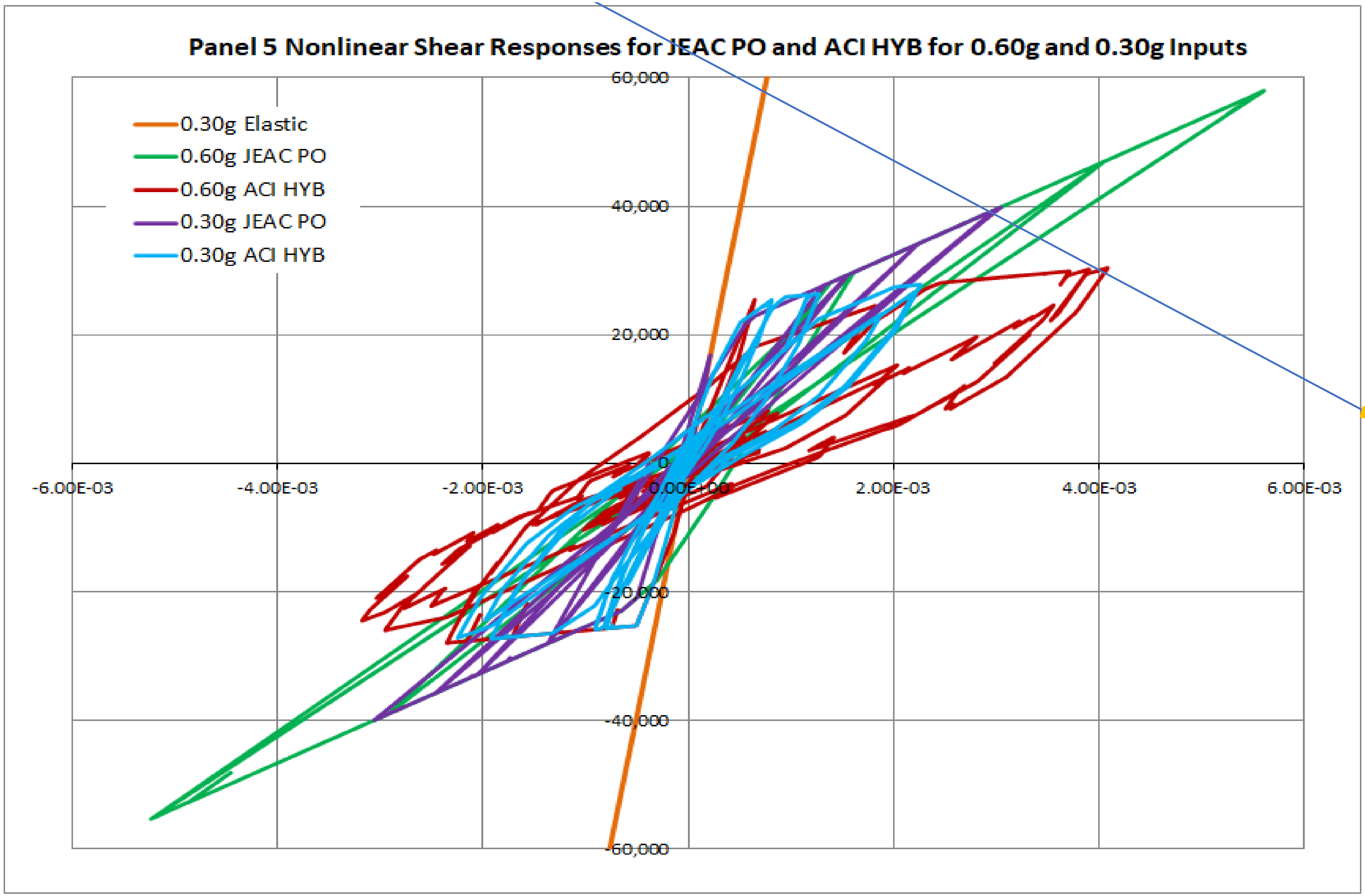
SMR ISRS Using JEAC 4601 PO vs. ACI 318 HM for 0.60g

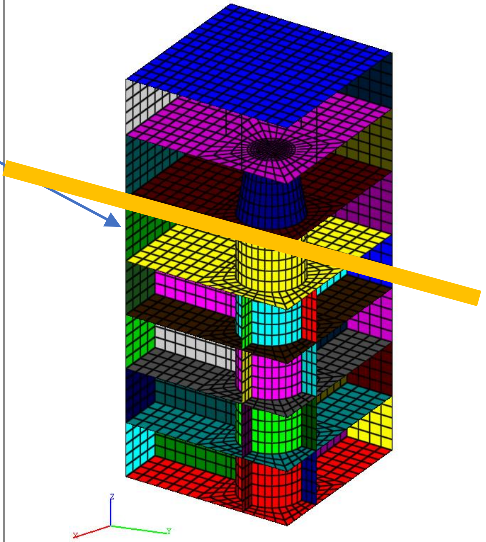
JEAC 4601 PO Models

ACI 318 HM Models

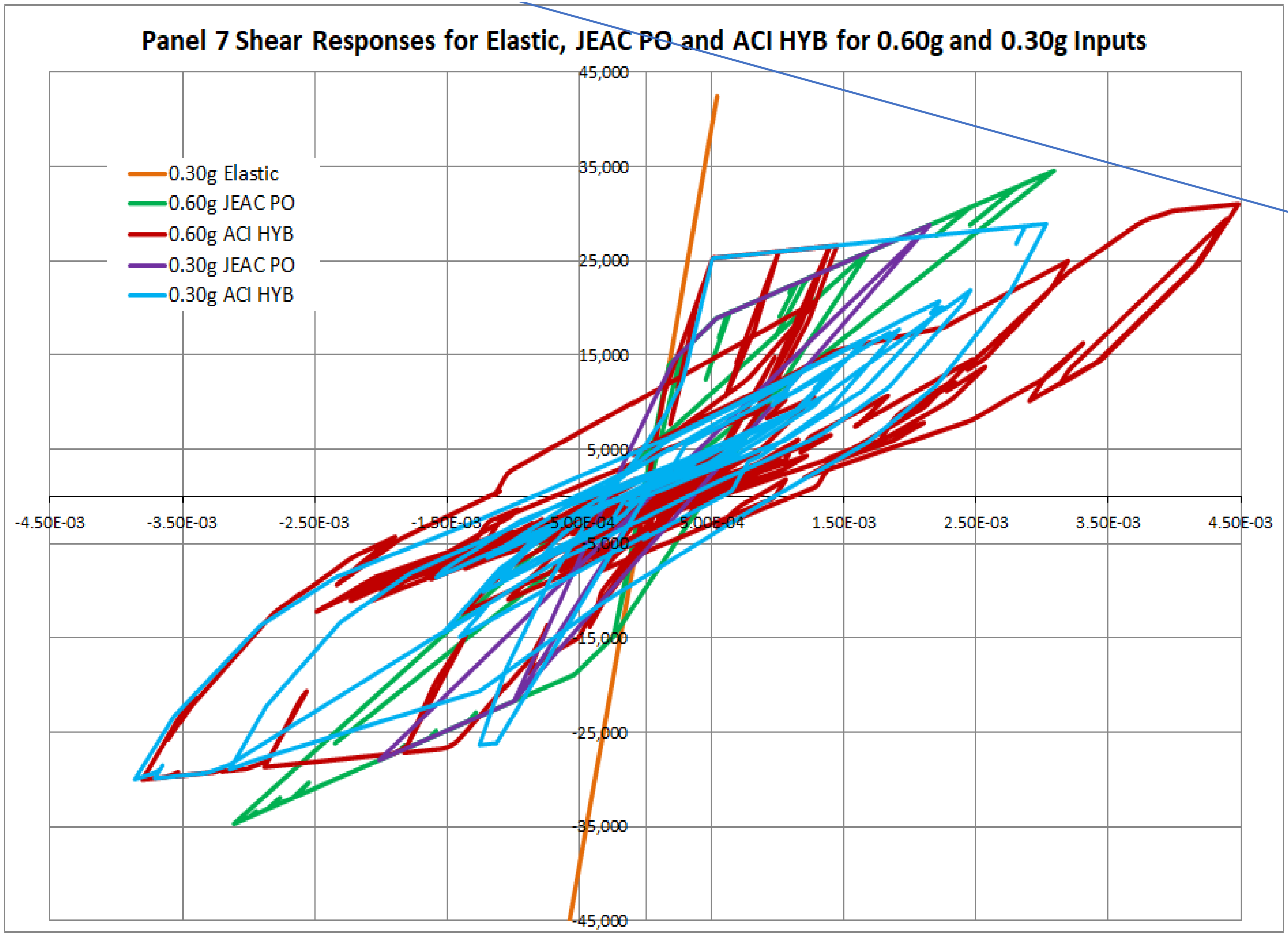


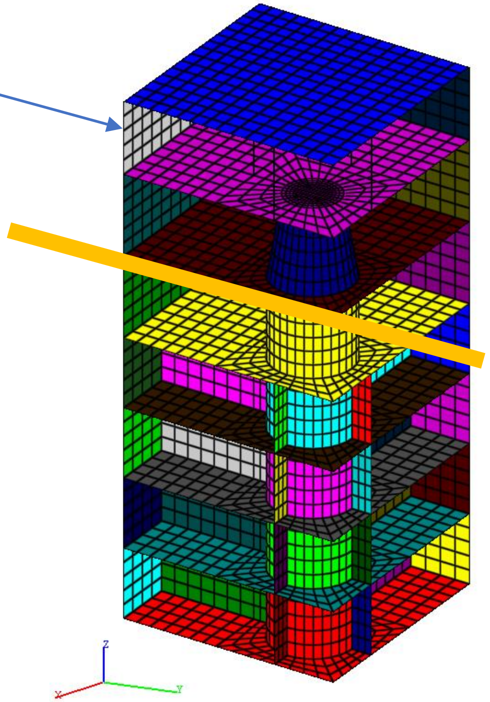
Exterior Wall Panels 5 Shear Response for 0.30g and 0.60g Inputs



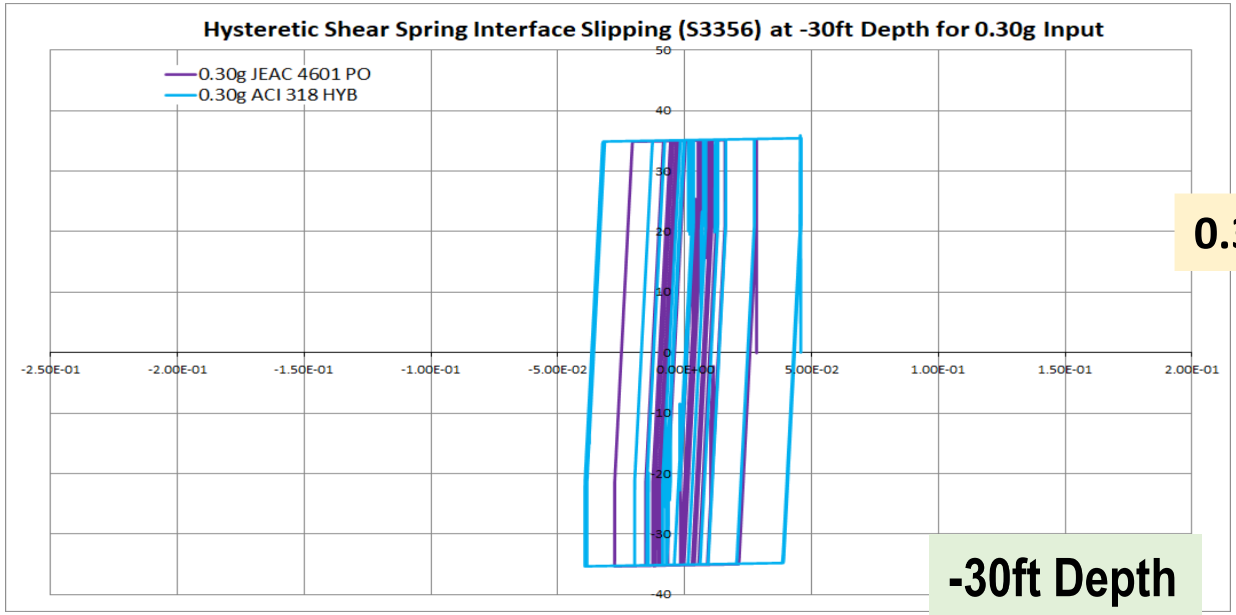


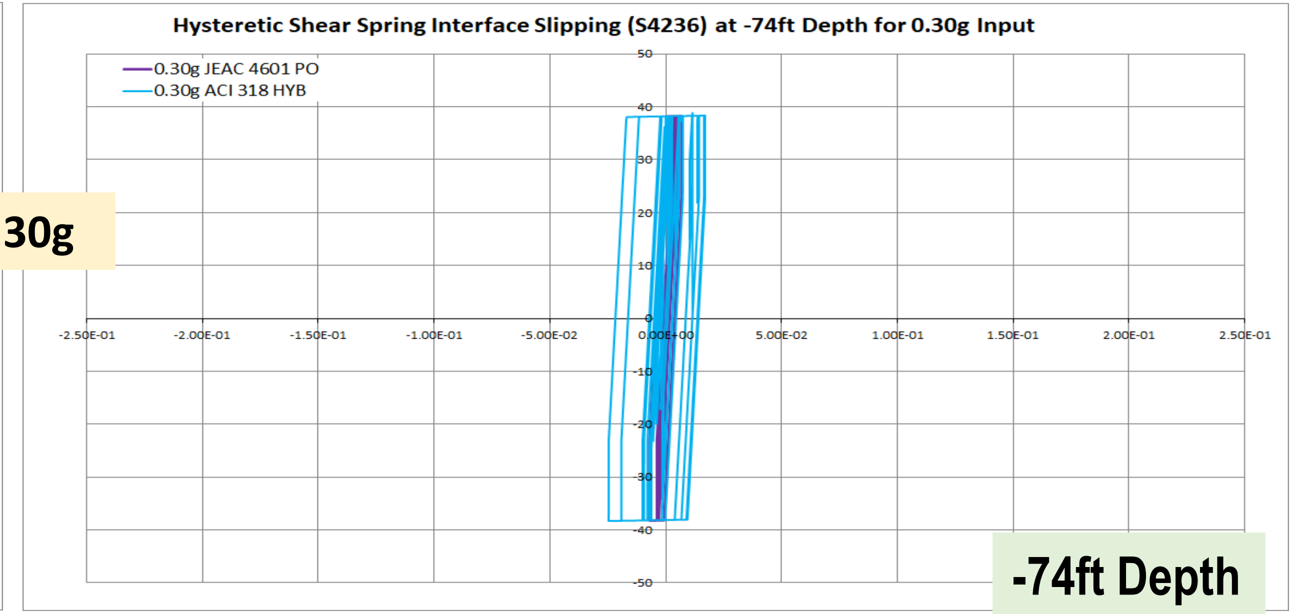
Exterior Wall Panels 7 Shear Response for 0.30g and 0.60g Inputs





Nonlinear Interface Z-Responses for 0.30g and 0.60g

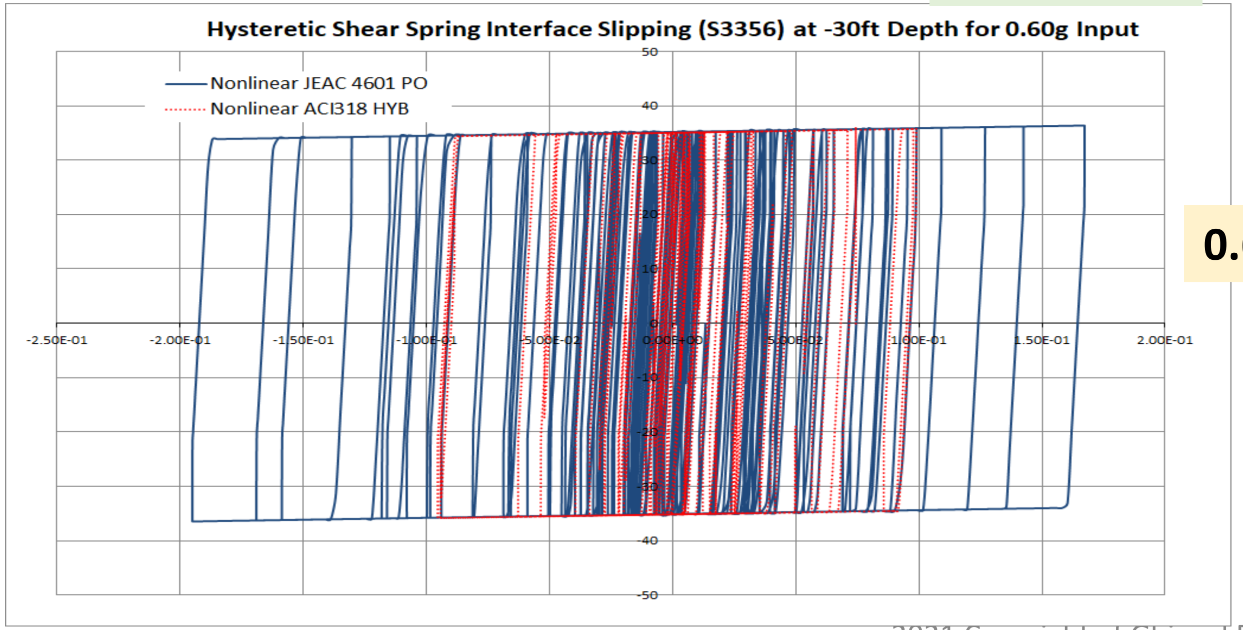


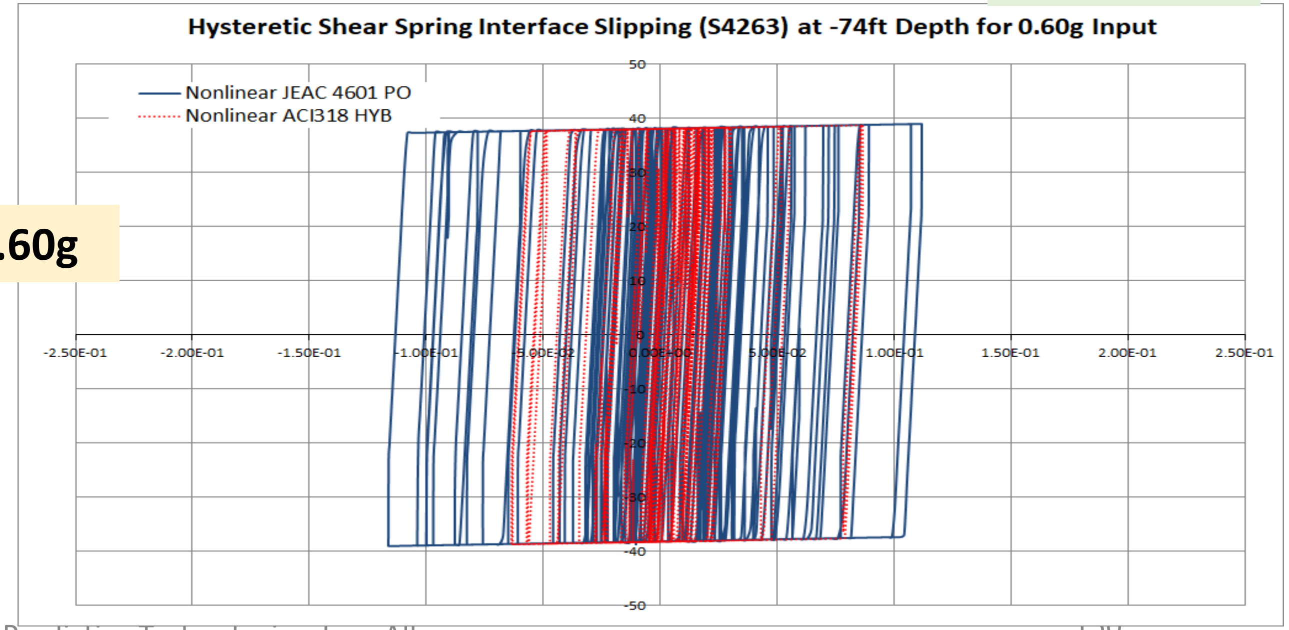


0.30g

-30ft Depth

-74ft Depth





0.60g

Few Practical Remarks for Embedded SMR Nonlinear Behavior

1) In general, nonlinear structure behavior *reduces the SMR structural forces, but increases the displacements.* The effect of damping increase due to nonlinear behavior is much less significant for the embedded SMR, than for a surface structure.

2) At lower elevations, as the location of the RCV supports, nonlinear ISRS amplitudes are lower than linear ISRS amplitudes in low-frequency range (0-5Hz), but *nonlinear ISRS can be higher than linear ISRS in mid-high frequency range (5-20Hz)*.

Few Practical Remarks for SMR Wall-Soil Interface Modeling

1) *US Practice:* The use of the *linear SSI analysis with a smooth interface* (linear, very low spring stiffness) appears to provide slightly conservative SSI responses in comparison with the ACI HM nonlinear responses per US practice; for the ISRS above ground surface for all frequencies, and below surface for frequencies under 10Hz, and apparently for all structural forces.
The above results indicate that the SMR seismic SSI methodology based on linear SSI and smooth side-soil interface is overall conservative .

2) *Japan practice:* The *linear SSI analysis with a smooth interface* (linear, very low spring stiffness) appears to provide less conservative ISRS and structural force responses in comparison with the JEAC PO nonlinear responses per Japan practice. However, this is a relative aspect since the JEAC PO models per Japan practice are more conservative than the ACI HM models per US practice, specifically for SMR study, by up to 30% for ISRS for frequencies under 10 Hz and up to 100% for nonlinear structural forces.

Outliers: The nonlinear ISRS amplitudes at some locations below surface and frequencies above 10 Hz are larger by up to 50% than ISRS computed using the linear SSI with smooth interface model.

More SMR result investigations are required to confirm the above observations are generally valid.

Thank You!