

SEISMIC BASE-ISOLATION FOR DEEPLY EMBEDDED ARC-100 SMR DESIGN

Dan M. Ghiocel¹, Daniel Lemley², Branko Galunic²

¹ Ghiocel Predictive Technologies, Inc., Pittsford, New York, US

² United Engineers & Constructors, Mt. Laurel, New Jersey, US

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Objective

The objective of this presentation is to structure for the standard baseline plant. *provide technical insights of the seismic SSI analysis of the base-isolated deeply embedded ARC-100 SMR*

To date, there is *no accumulated US industry practical design experience for deeply embedded seismically base-isolated SMR design.*

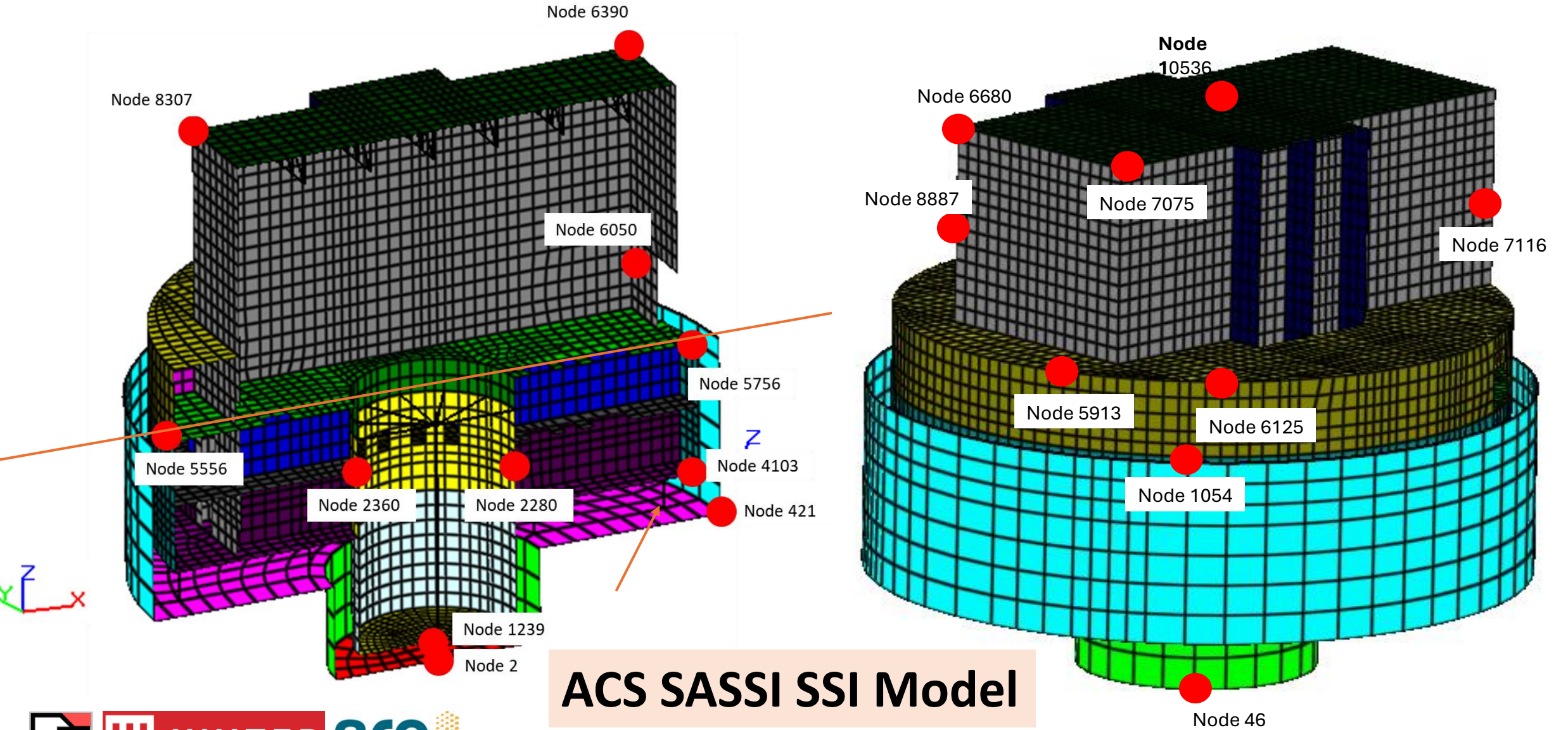
The SMR embedment depth is 66.5 ft. The investigated base-isolation system solution for this ARC-100 SMR study project was a 2D global isolation system consisting of 28 Friction Pendulum (FP) hysteretic isolators distributed at the SMR upper foundation base-level at a 43.5 ft depth below ground surface.

Presentation Content

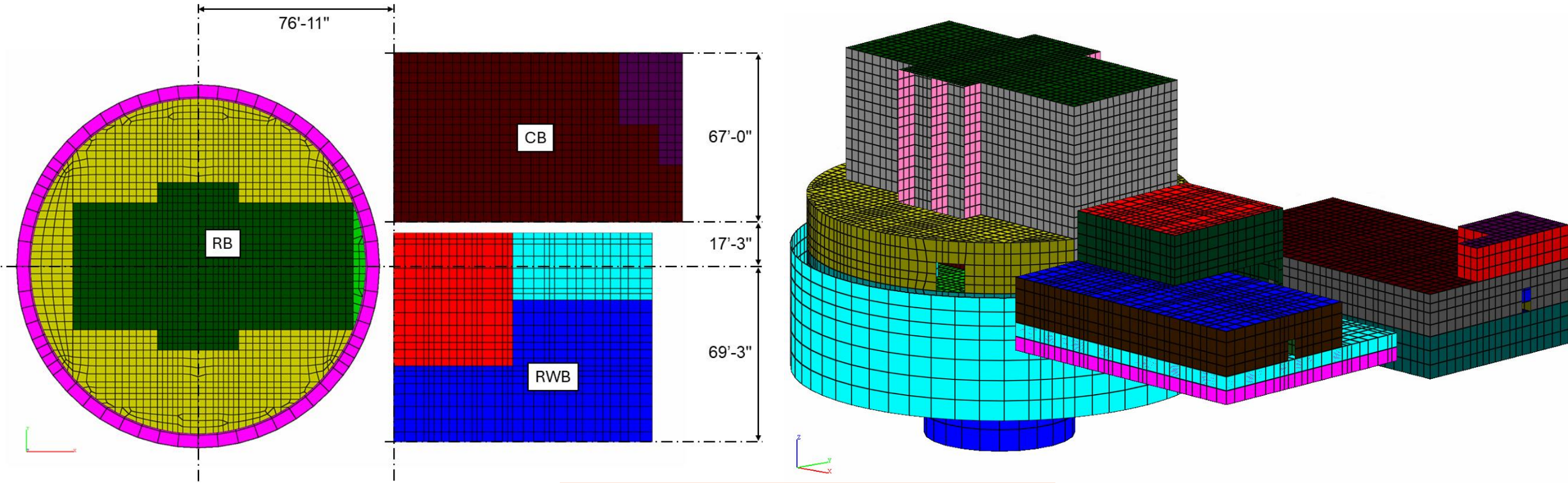
1. SEISMIC SSI MODELING OF BASE-ISOLATED EMBEDDED ARC-100 SMR (6)
2. GENERIC SITE SEISMIC PARAMETERS AND SEISMIC INPUT SIMULATION (2)
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1. SEISMIC SSI MODELING FOR BASE-ISOLATED EMBEDDED ARC-100 SMR STRUCTURE

ARC-100 SMR SSI Model (Rock)



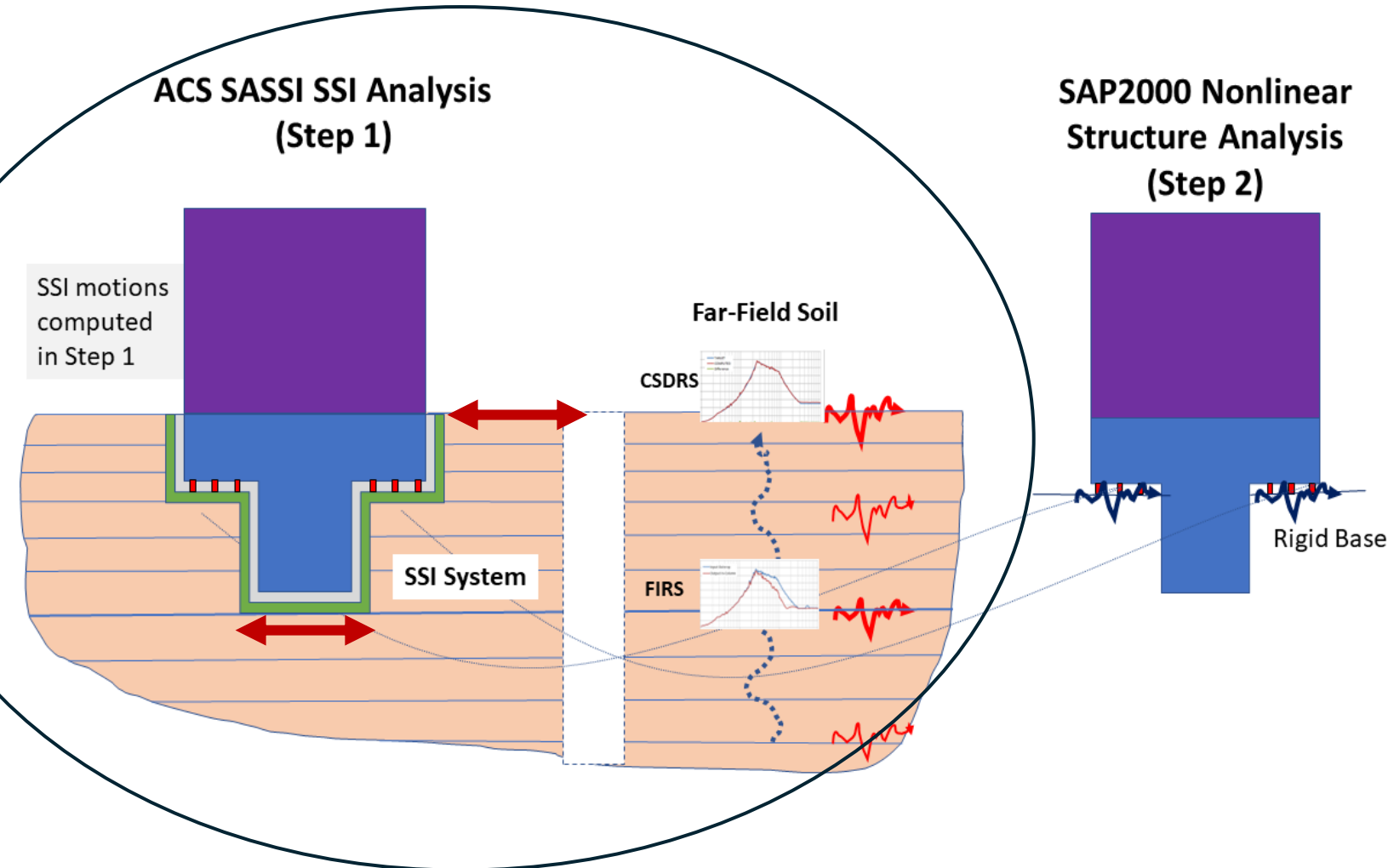
Seismic ARC-100 RB-RWB-CB Structure SSSI Model (Soil)



ACS SASSI SSSI Model

The SSSI structure FE model contains a total of 25,014 nodes and 69 groups with 26,273 elements. The SSSI excavated soil model has a total of 11,203 nodes.

Seismic SSI Analysis Methodology Using Multistep Approach Per ASCE 4-16 Chapter 12



The multistep seismic SSI analysis solution was performed in two (cascaded) steps as recommended in the ASCE 4-16 Section 12:

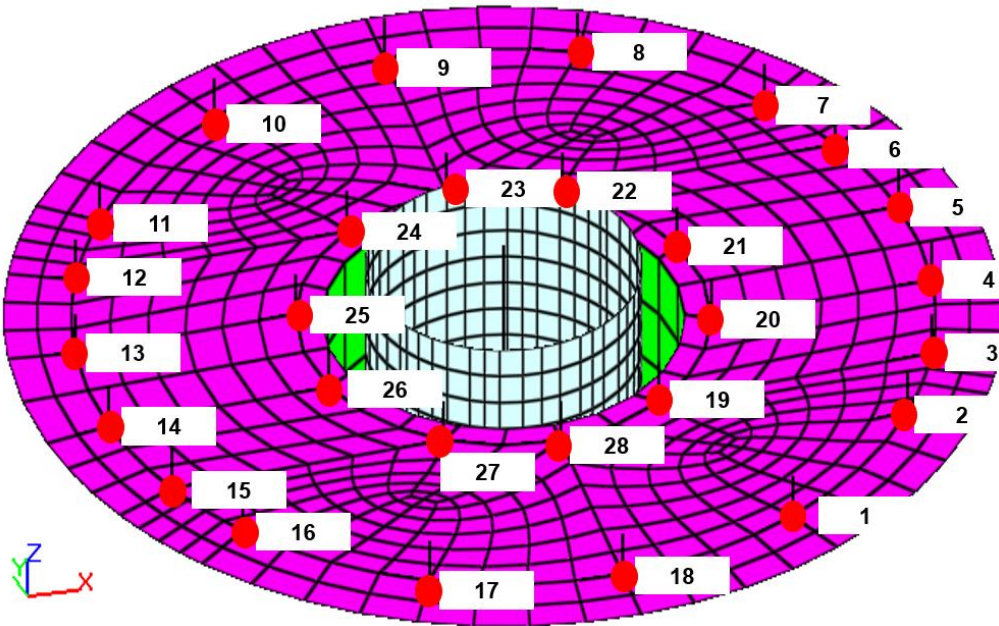
In *Step 1*, an *iterative* seismic linearized SSI analysis is performed in complex frequency domain to determine the SSI foundation response motion for *the iterated equivalent-linear FP isolator properties*.

In *Step 2*, a nonlinear dynamic analysis of the isolated superstructure is performed in time-domain using highly refined nonlinear FP isolator models excited by the SSI response motions computed at the isolator pedestal support locations.

For Step 1, for overall SSI analysis, the ACS SASSI Option NON or briefly ACS SASSI NON software was applied, while for Step 2, for nonlinear superstructure analysis, the SAP2000 software was applied

28 FP Isolator Distributed at the Foundation Upper Level; 18 FPI on Outer Circle (1-18) & 10 FPI on Inner Circle (19-28)

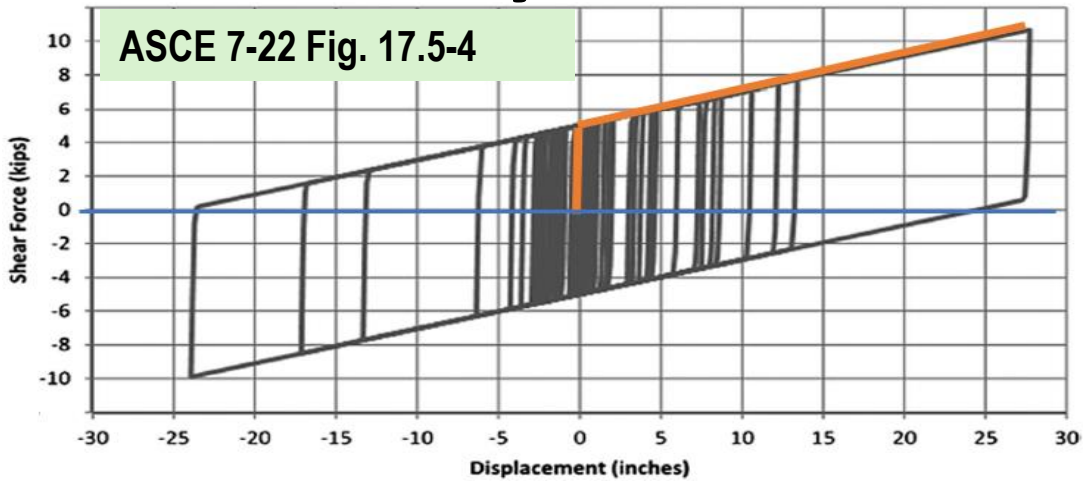
FPI 15680-26 Type with Different Gravity Vertical Axial Forces (from 1373 kips to 3371 kips)



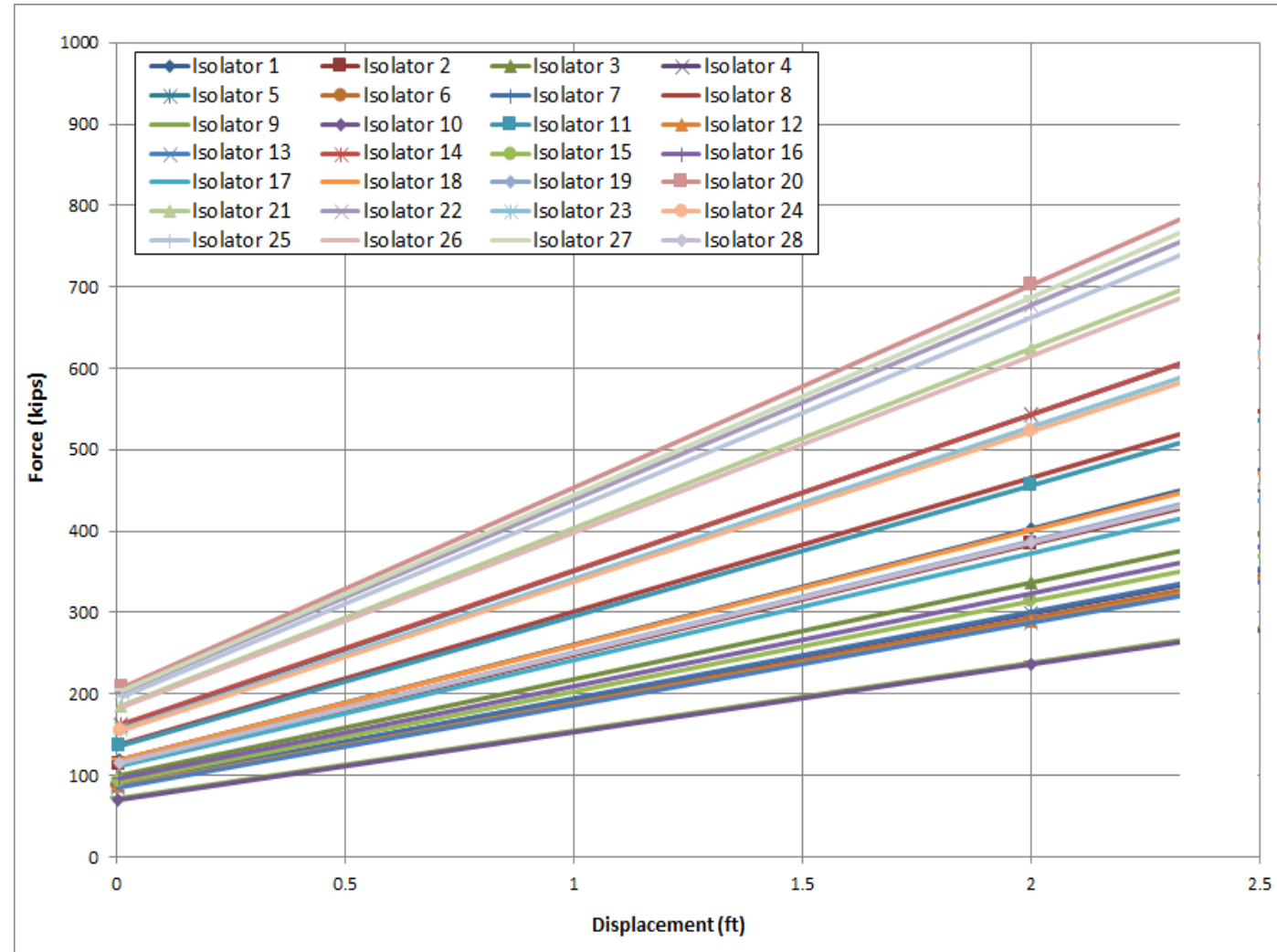
Isolator Number (BBC #)	Friction Pendulum Isolator Type	Isolator Vertical Stiffness (k/in)	Isolator Axial Force (kips)	Isolator Bottom Node No.	Coordinates			μ Average	Effective Radius (in)
					X-Coor. (ft)	Y-Coor. (ft)	Z-Coor. (ft)		
1	FPI 15680-26	200000	1935	16064	61.082	8.75	-38	0.062	163
2	FPI 15680-26	200000	1837	16065	56.414	25	-38		
3	FPI 15680-26	200000	1615	16066	49.333	37.065	-38		
4	FPI 15680-26	200000	1435	16067	26.969	55.5	-38		
5	FPI 15680-26	200000	2603	16068	0	61.705	-38		
6	FPI 15680-26	200000	1409	16069	-26.969	55.5	-38		
7	FPI 15680-26	200000	1444	16070	-49.333	37.065	-38		
8	FPI 15680-26	200000	2235	16071	-56.414	25	-38		
9	FPI 15680-26	200000	1144	16072	-61.082	8.75	-38		
10	FPI 15680-26	200000	1135	16073	-61.082	-8.75	-38		
11	FPI 15680-26	200000	2187	16074	-56.414	-25	-38		
12	FPI 15680-26	200000	1391	16075	-49.333	-37.065	-38		
13	FPI 15680-26	200000	1373	16076	-26.969	-55.5	-38		
14	FPI 15680-26	200000	2609	16077	0	-61.705	-38		
15	FPI 15680-26	200000	1505	16078	26.969	-55.5	-38		
16	FPI 15680-26	200000	1554	16079	49.333	-37.065	-38		
17	FPI 15680-26	200000	1785	16080	56.414	-25	-38		
18	FPI 15680-26	200000	1920	16081	61.082	-8.75	-38		
19	FPI 15680-26	200000	1861	16082	28.363	8.75	-38		
20	FPI 15680-26	200000	3371	16083	16	25	-38		
21	FPI 15680-26	200000	2996	16084	0	29.682	-38		
22	FPI 15680-26	200000	3252	16085	-16	25	-38		
23	FPI 15680-26	200000	2529	16086	-28.363	8.75	-38		
24	FPI 15680-26	200000	2506	16087	-28.363	-8.75	-38		
25	FPI 15680-26	200000	3184	16088	-16	-25	-38		
26	FPI 15680-26	200000	2957	16089	0	-29.682	-38		
27	FPI 15680-26	200000	3304	16090	16	-25	-38		
28	FPI 15680-26	200000	1849	16091	28.363	-8.75	-38		

Modeling of FP Isolator Hysteretic Behavior For SSI

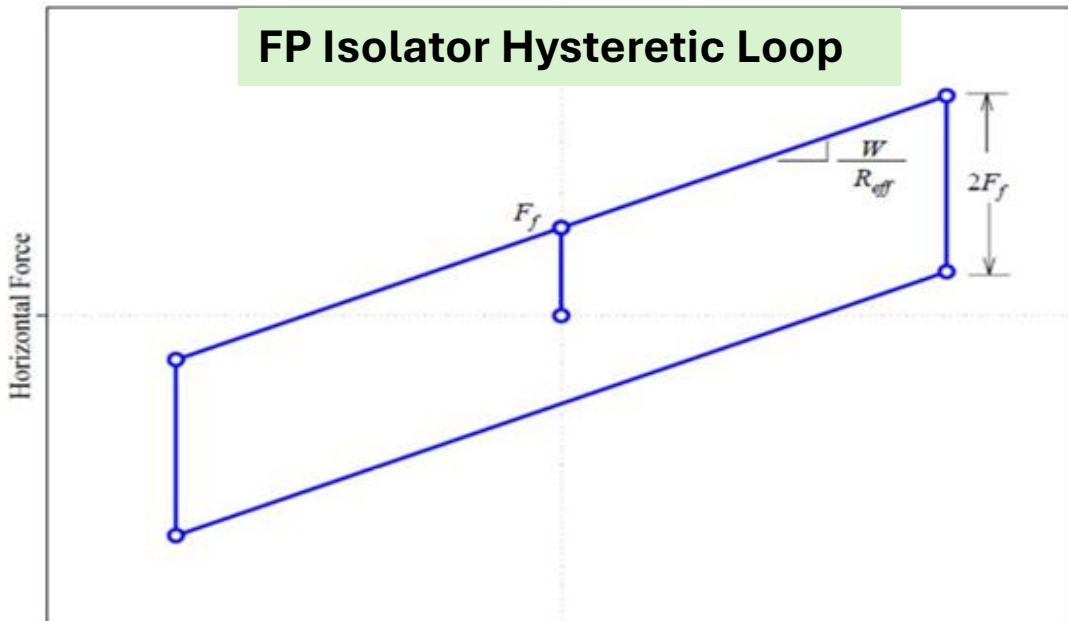
Analysis Per ASCE 7-22 Chapter 17 Guidance



28 FP Isolator Back-Bone Curves (BBC)

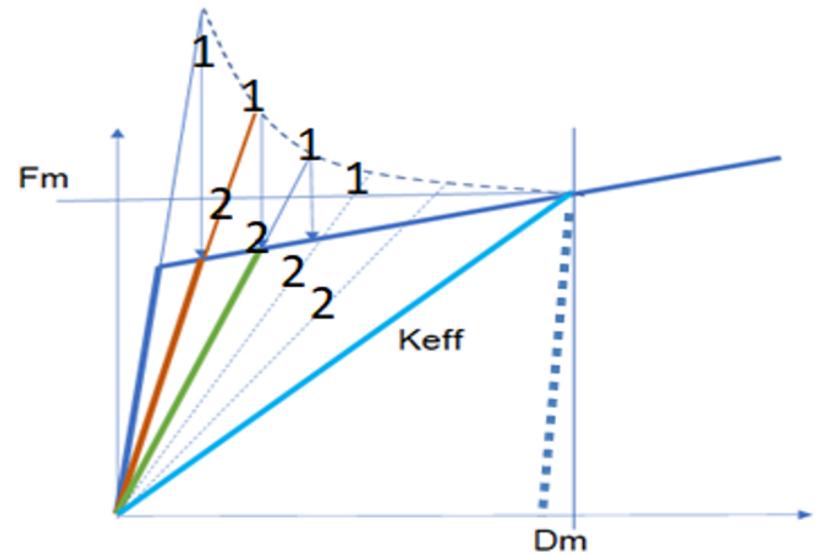


FP Isolator Hysteretic Loop

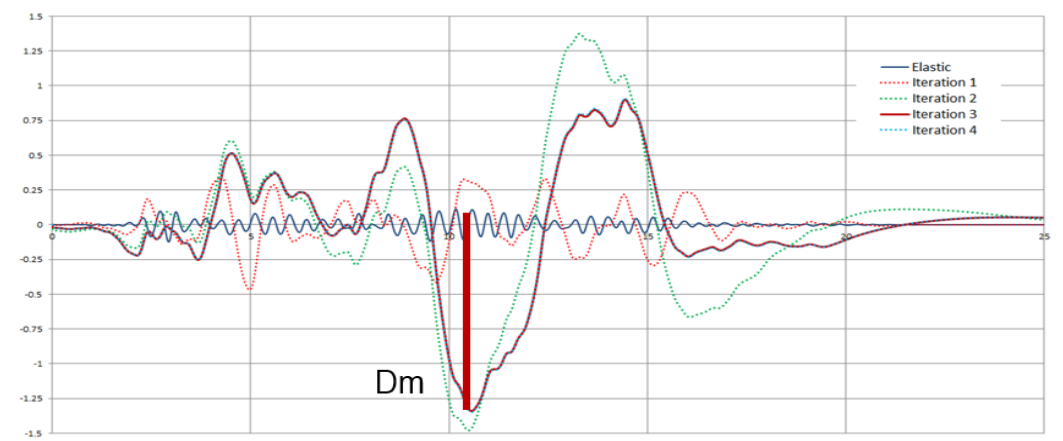


ACS SASSI Option NON Fast-Convergent Iterative Equivalent-Linear SSI Analysis for Modeling FP Isolator Hysteretic Behavior

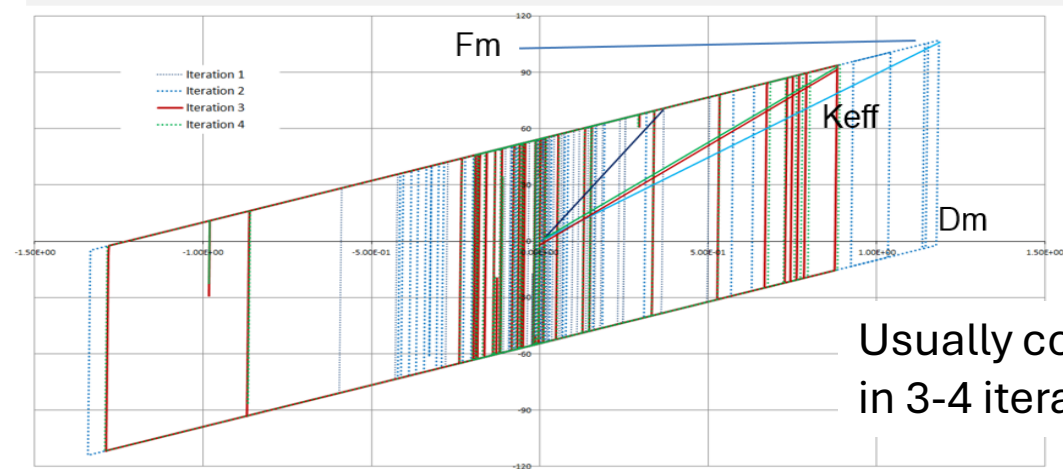
Iterative procedure couples the equivalent-linear SSI analysis to compute FPI sliding displacements in substep 1, with fast local hysteretic cyclic analyses in time domain to compute nonlinear forces in each FP isolator using bilinear models in substep 2. Then, compute $K_{eff} = f(D_m, F_m)$.



Substep 1: Equivalent-linear SSI analysis to get isolator displacements



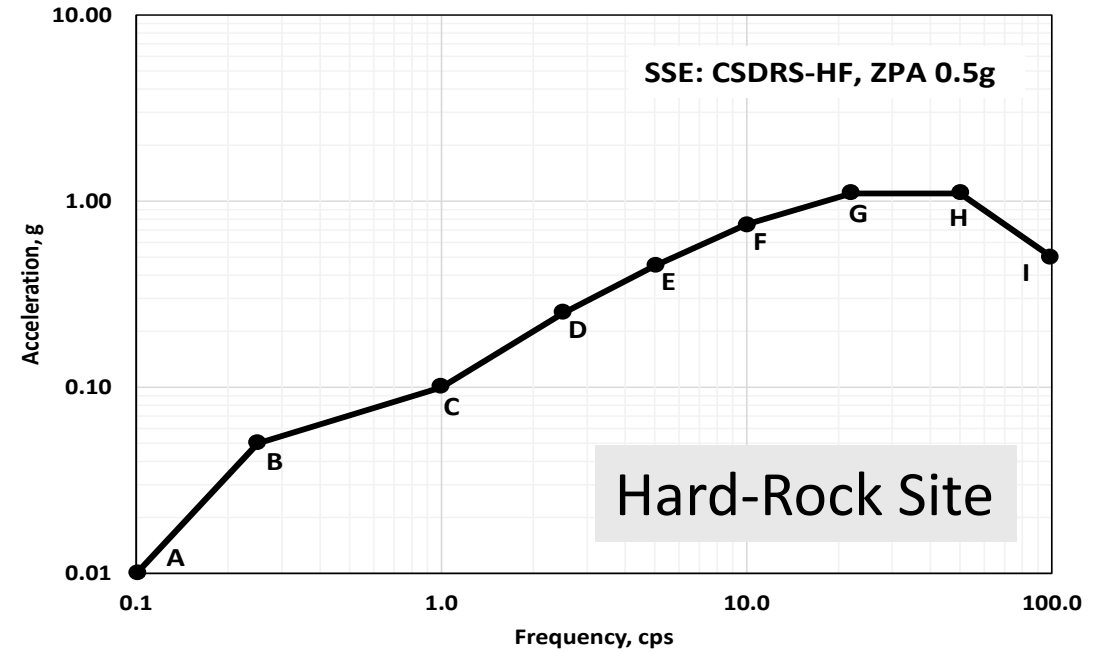
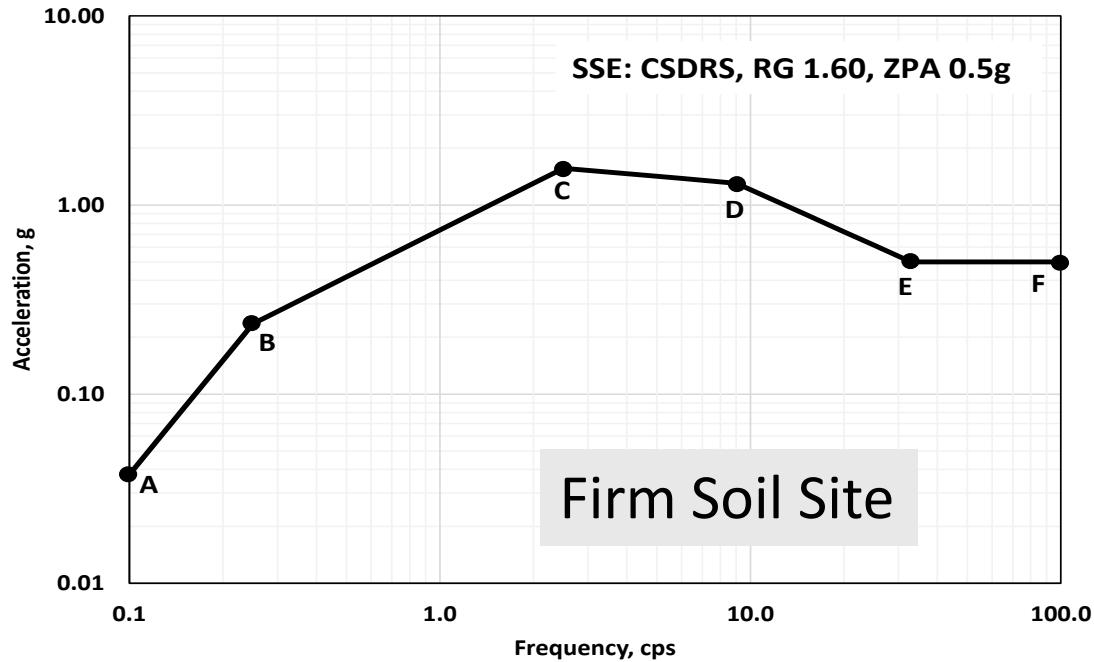
Substep 2: Hysteretic cyclic analysis to get nonlinear isolator forces



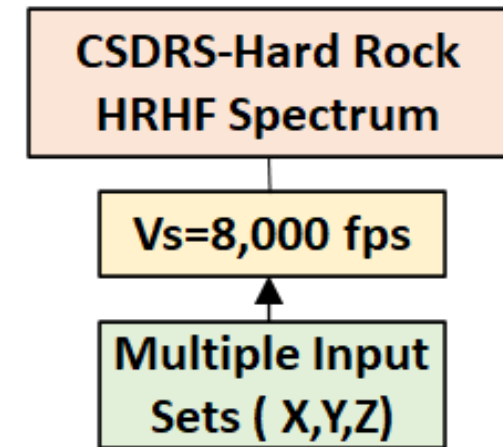
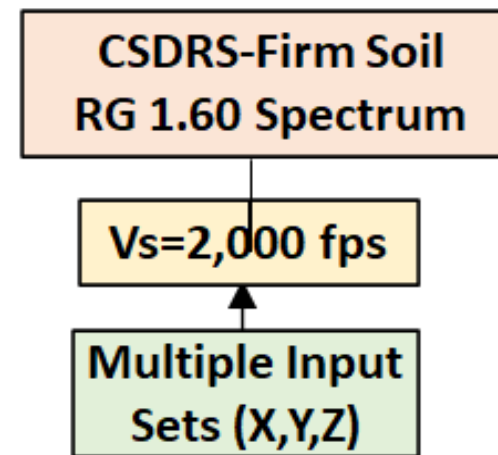
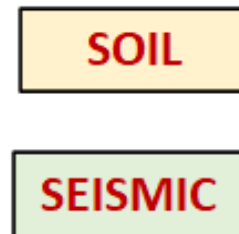
Usually convergent in 3-4 iterations

2. GENERIC SITE SEISMIC PARAMETERS AND SEISMIC INPUT SIMULATION

Postulated SSE For DBE Shaking (for 0.50g, Same for H and V)



Generic Soil Site Conditions



Specific Requirements for Seismic Inputs for Isolated Structures for Computing 80th Percentile DBE Responses

The ASCE 4-16 Chapter 12 applicable to base-isolated structures requires for the DBE shaking to compute the 80th percentile seismic responses, and for the 150% DBE shaking to compute the 90th percentile responses.

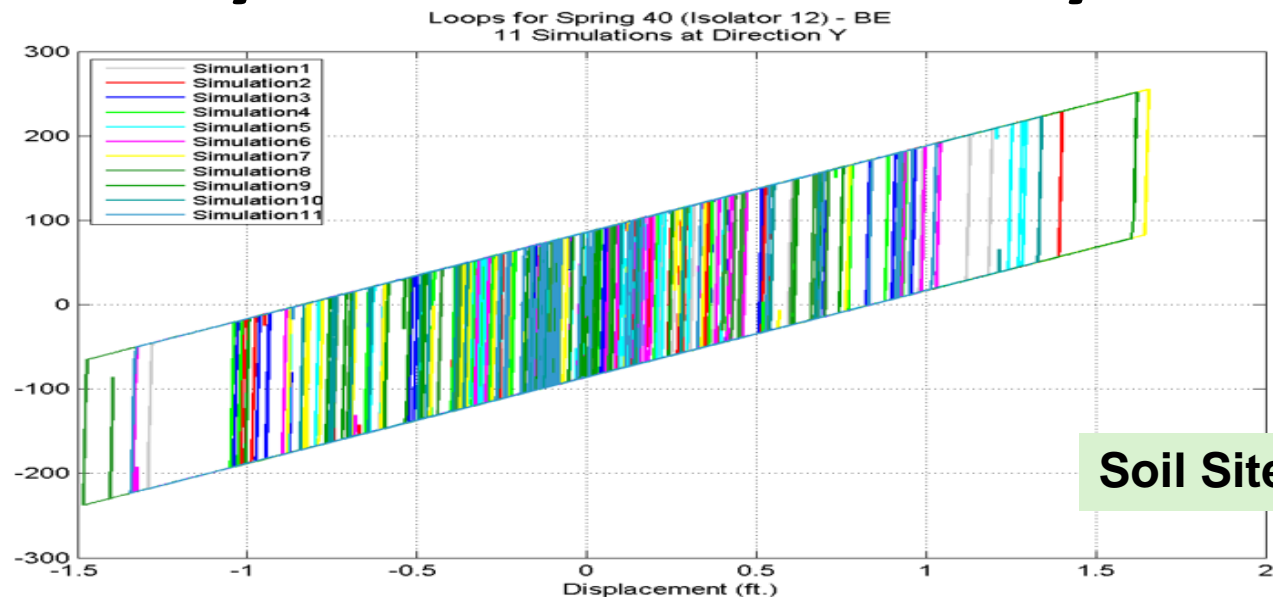
To be compliant with the latest requirements for the DBE shaking, including ASCE 4-21 Chapter 12 draft, Rev 13, and ASCE 7-22 Chapter 17, to compute the 80th percentile DBE responses a set of 33 seismic SSI simulations was considered for each generic site condition.

33 simulations = 11 seismic input sets x 3 soil variations, BE, LB,UB, for each generic site.

For the two generic site conditions, the soil bounding variations was considered assuming a 0.50 coefficient of variation of the soil shear modulus, which is the minimum variation acceptable for the deterministic SSI analysis for well investigate sites, in accordance with the ASCE 4-16 Section 5.1.7 and NUREG-0800 Standard Review Plan 3.7.2.

3. REVIEW OF FEW RELEVANT ARC-100 SMR STRUCTURE SSI RESPONSES

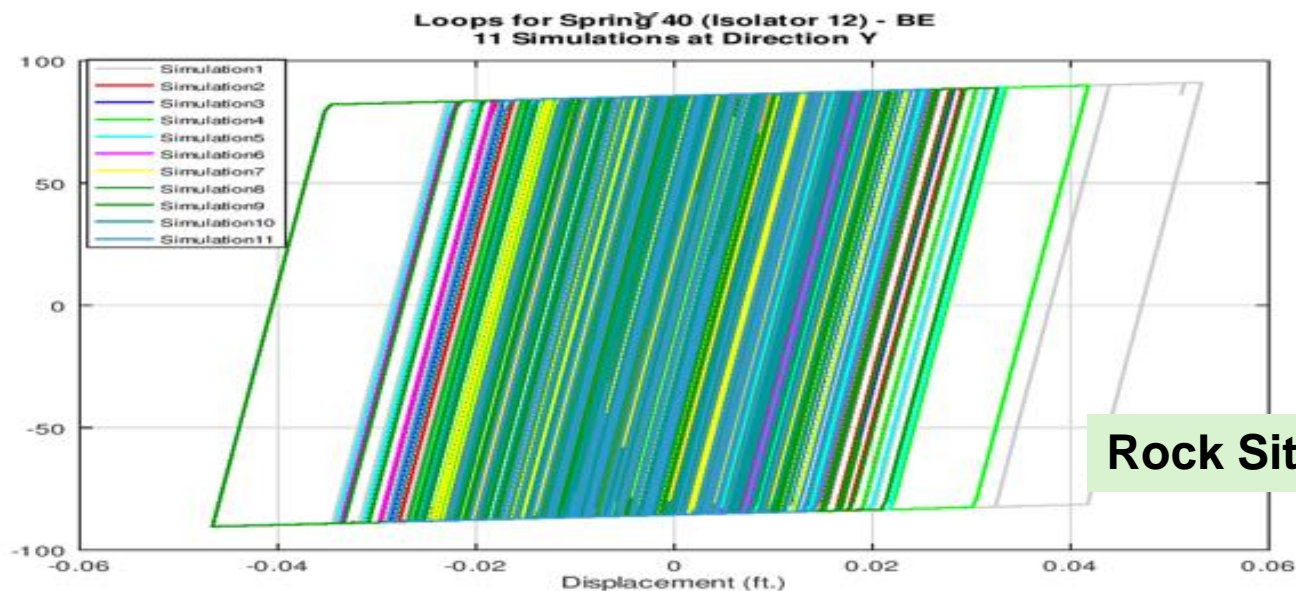
SSI Analysis FP Isolator #12 Hysteretic Loops for Y-Direction



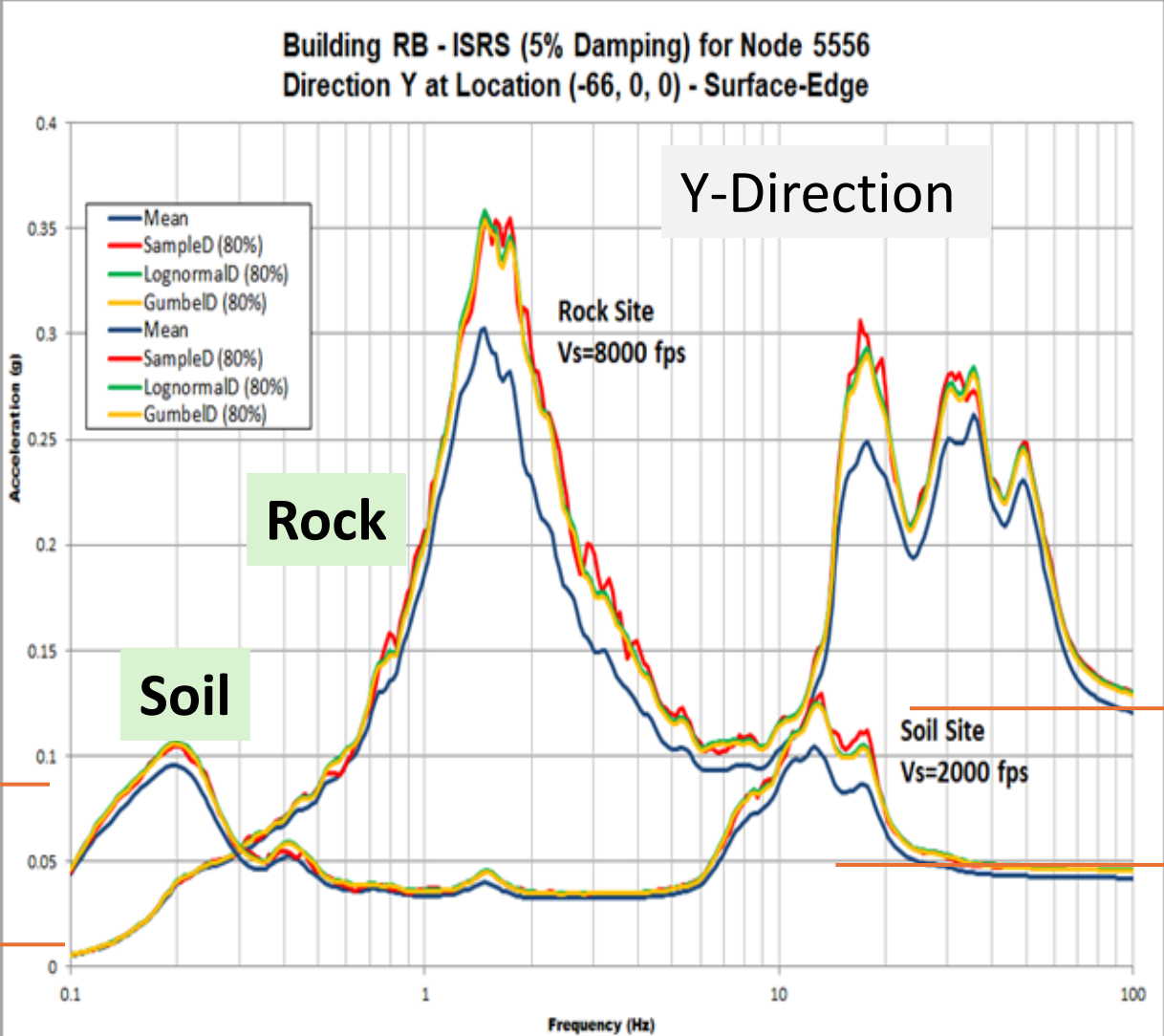
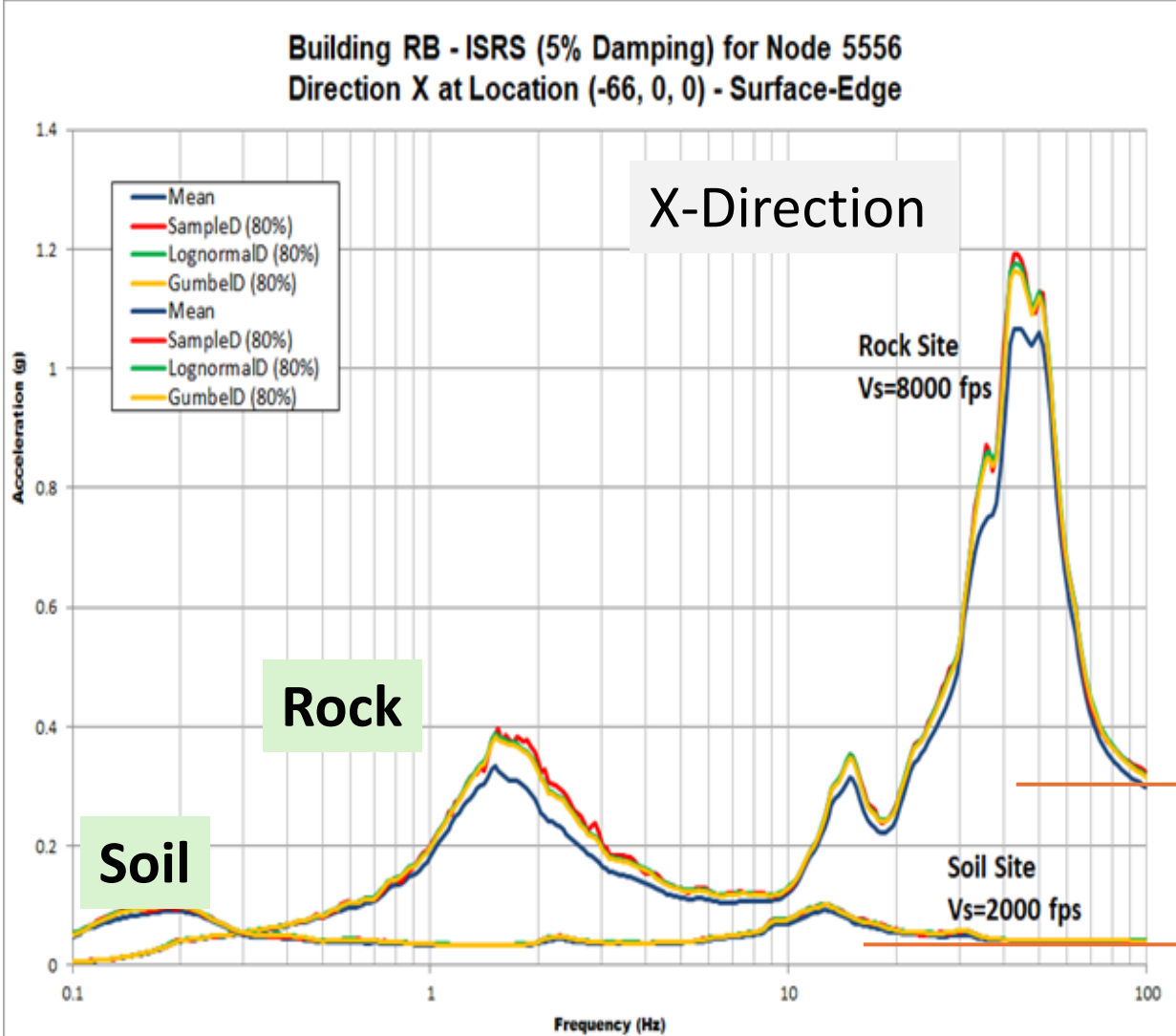
It should be noted that for the BE soil and CSDRS input, the 11 simulated FP isolator displacements *are up to 1.7 ft*, while for the BE rock and CSDRS-HF input, the 11 simulated FP isolator displacements *are up to only 0.05 ft*.

This indicated a reduction in the isolator sliding displacement of about *35 times* for the rock site versus the soil site.

The larger reduction of the isolator displacements for the rock site is due to the high-frequency input with a fast sign-switching acceleration motion for the CSDRS-HF.

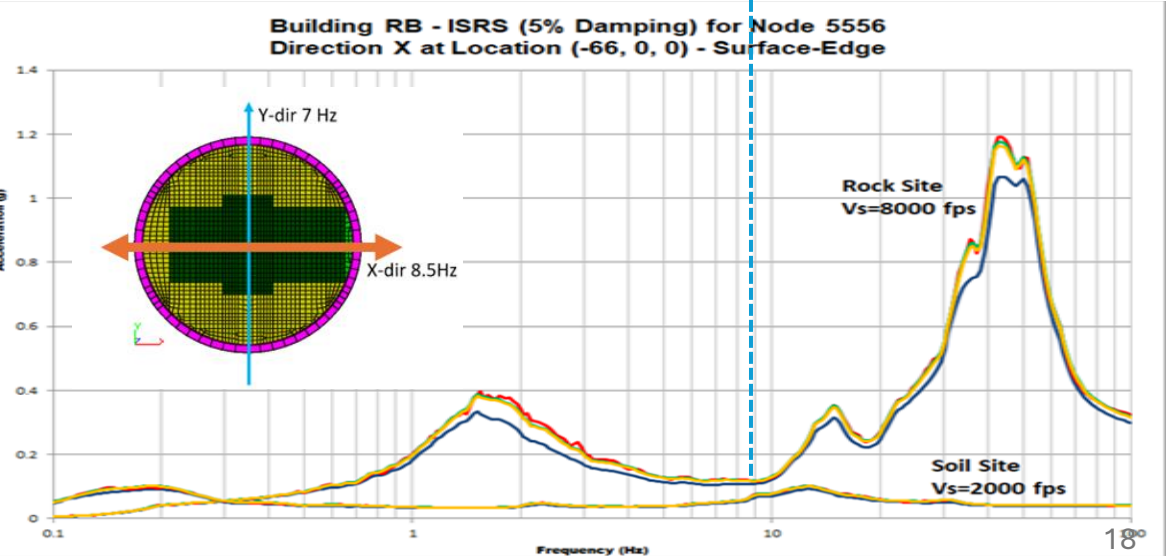
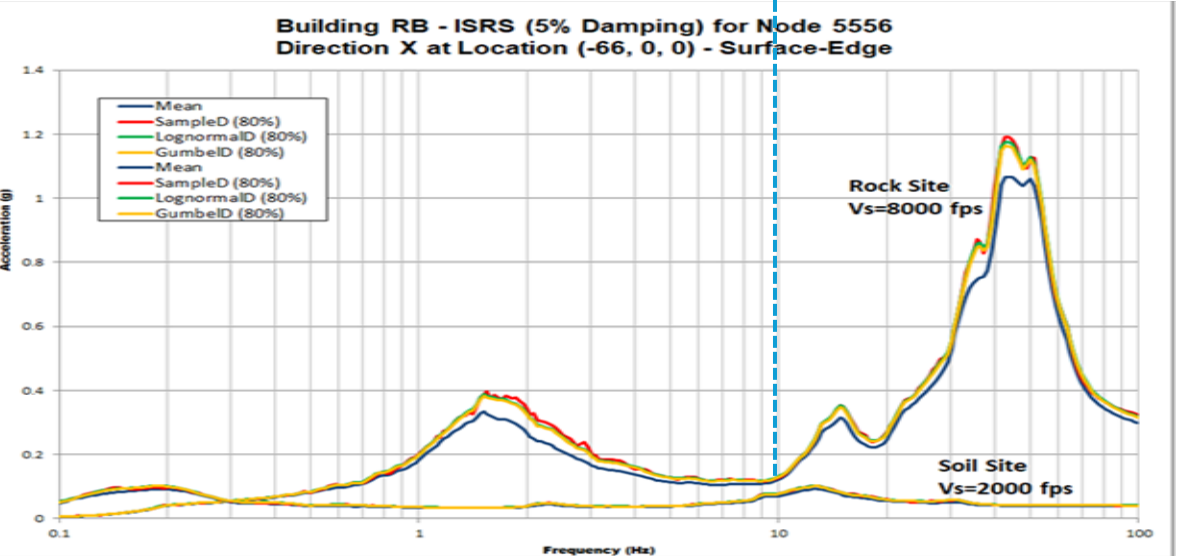
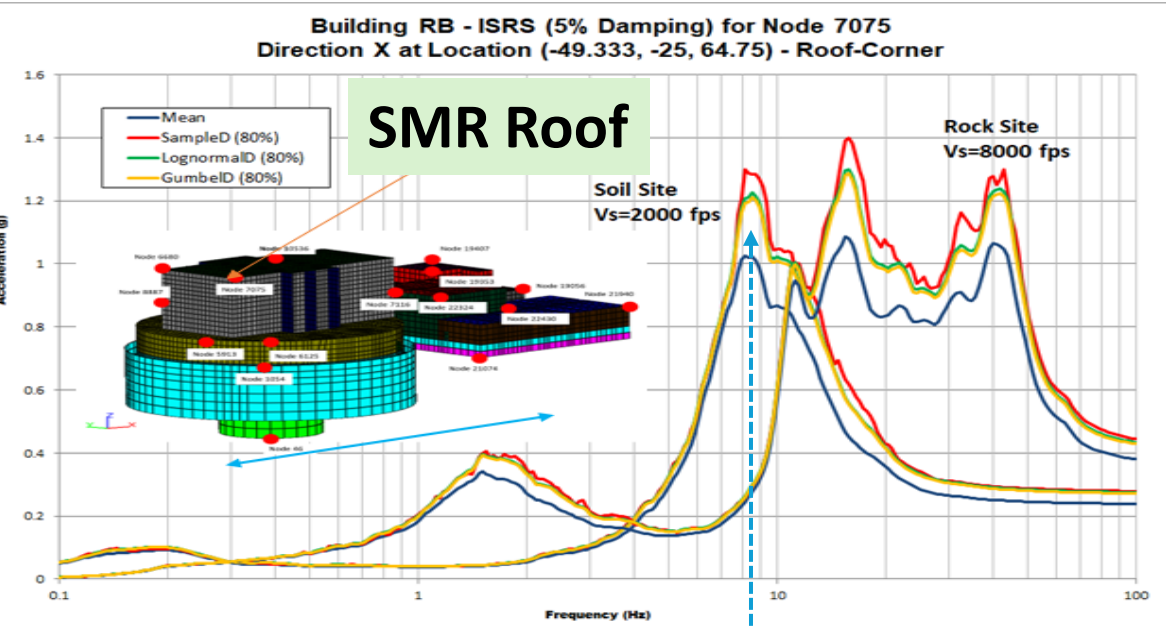
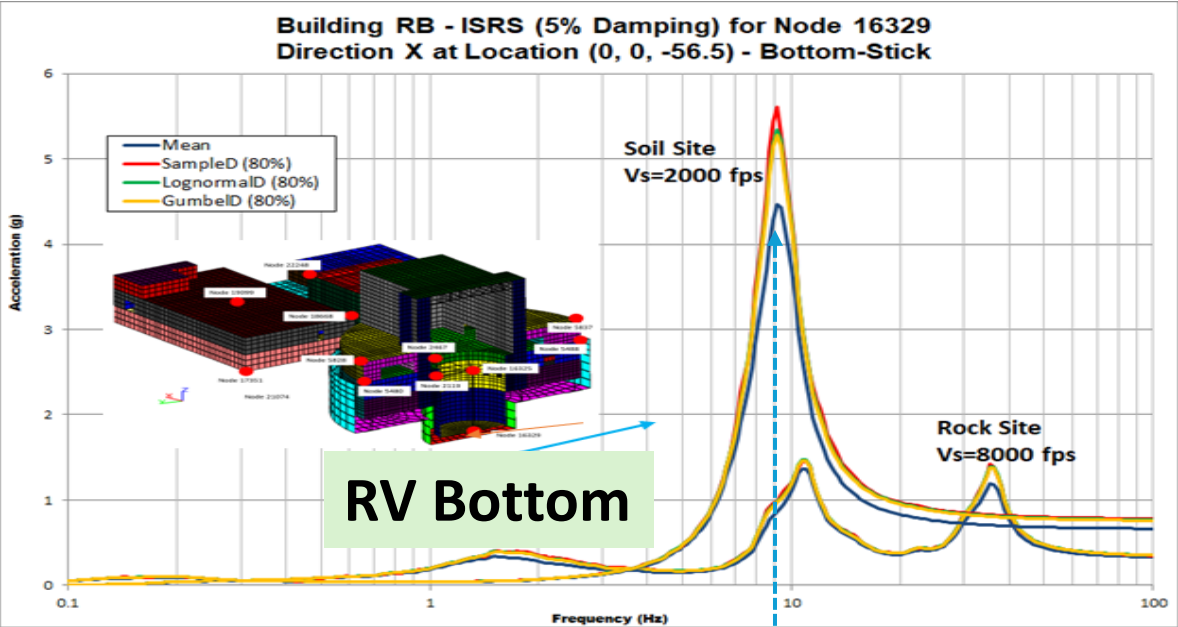


Mean and 80 NEP ISRS at Ground Surface Level (Node 5556)

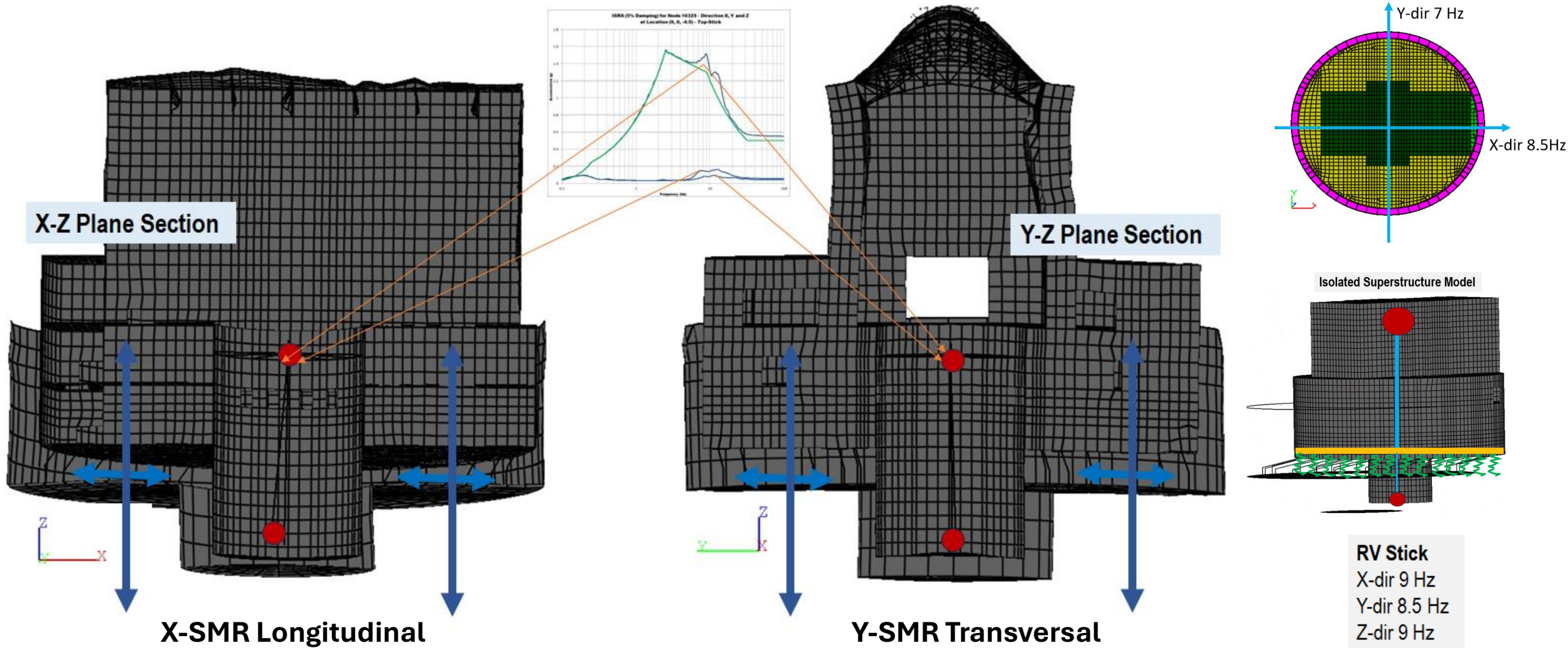


4. DETRIMENTAL DYNAMIC COUPLING AND REMEDIAL ACTIONS

Mean and 80 NEP X-Dir ISRS at RV Stick Bottom and SMR Roof

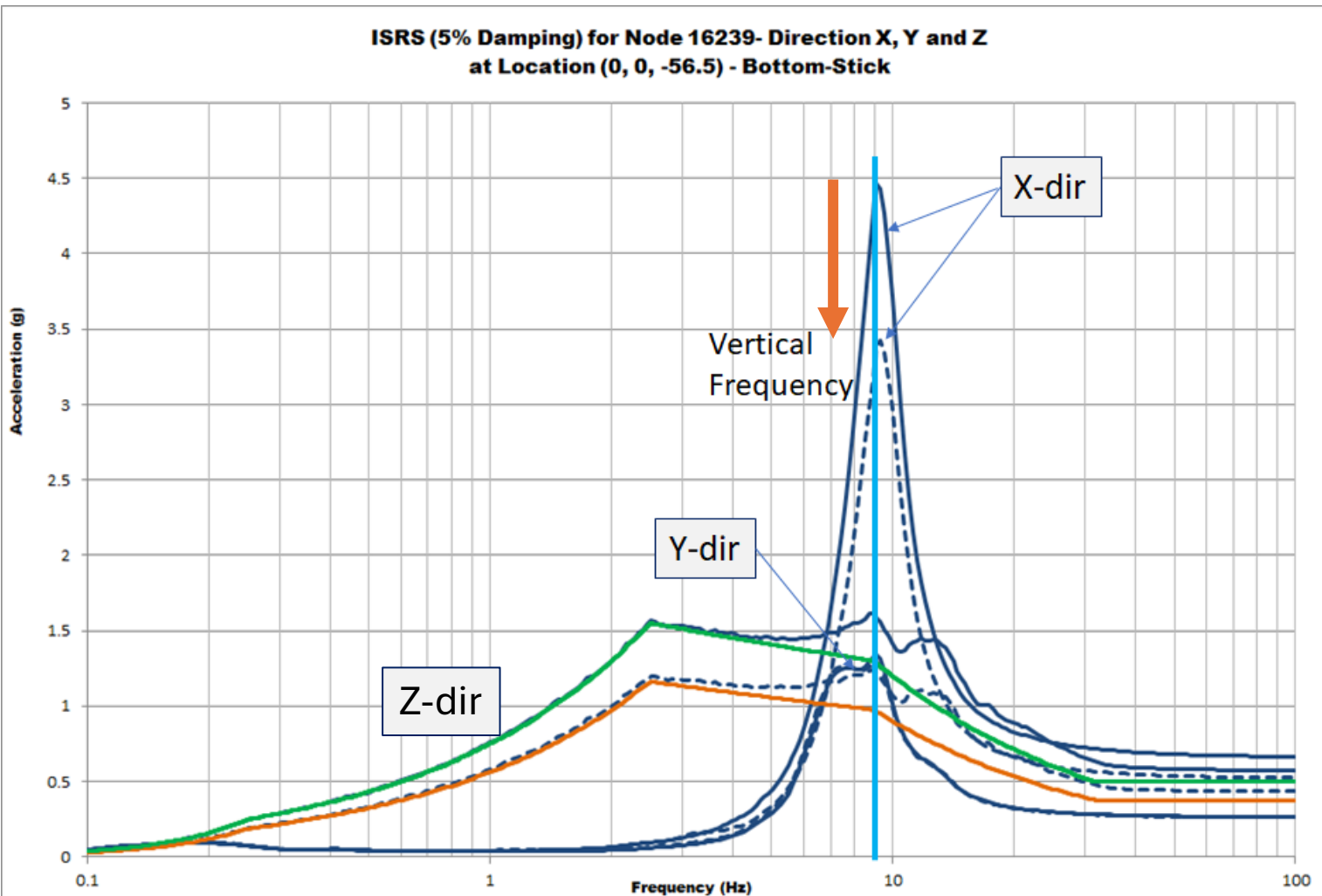


SMR Structural Accelerations in X and Y Directions for Soil



Quantitative Checking for V-H Dynamic Coupling Effects

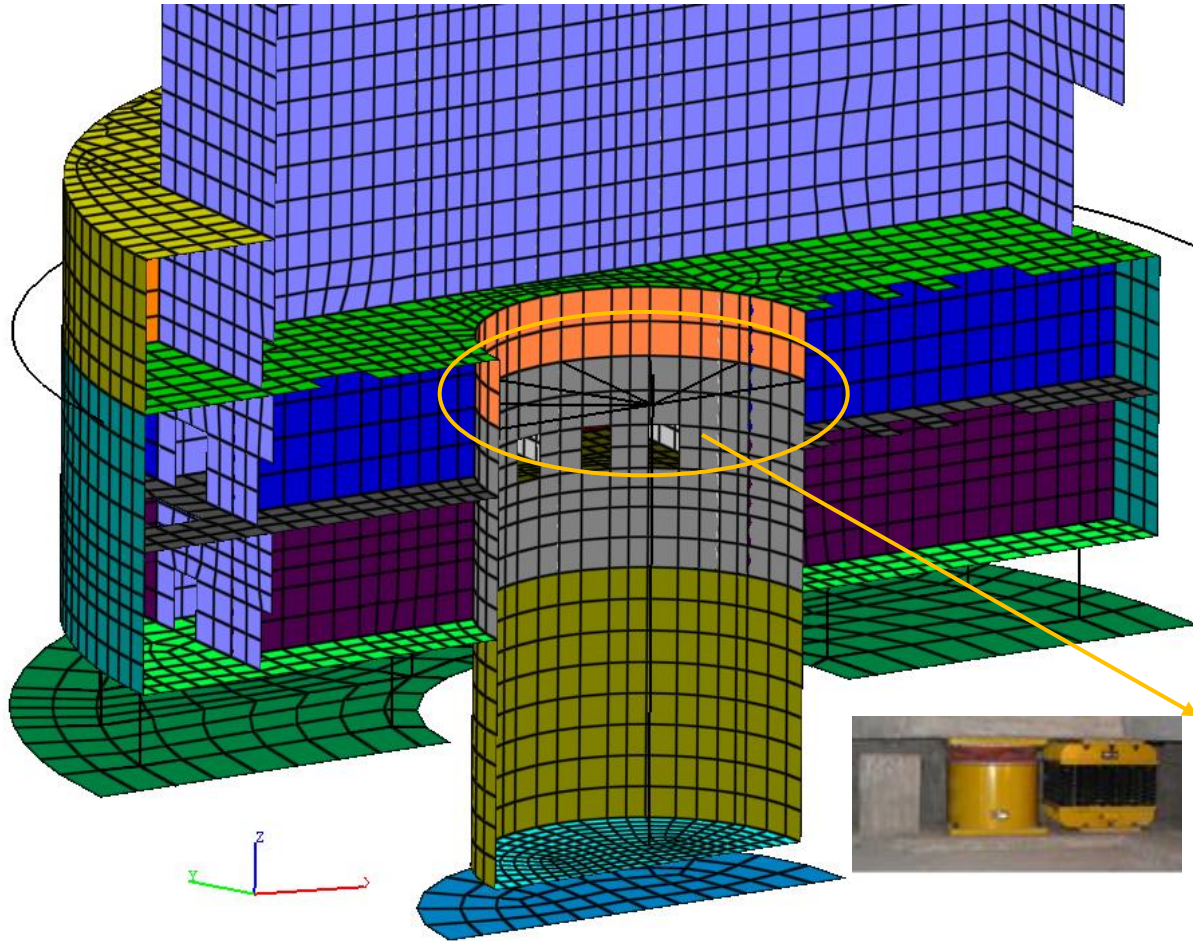
We compared the ISRS X, Y, Z computed at the RV stick bottom location for the vertical input acceleration of 0.5 g and a 25% reduced vertical input acceleration, $0.375g = 0.75 \times 0.50g$.



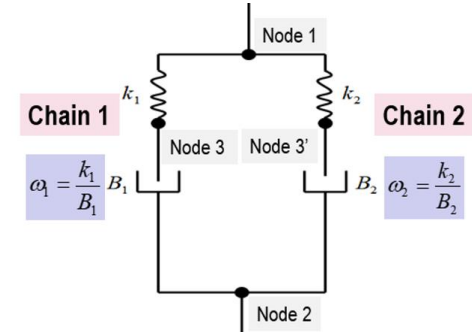
Large X response amplification due to dynamic coupling of vertical and horizontal Superstructure mode responses and RV Stick (inverse cantilever) horizontal mode response;

Large vibration energy transfer from the vertical Superstructure motion to the horizontal RV stick motion at bottom location (top of inverse cantilever).

Adding GERB BCS 3 Isolation Devices at RV Beam Supports

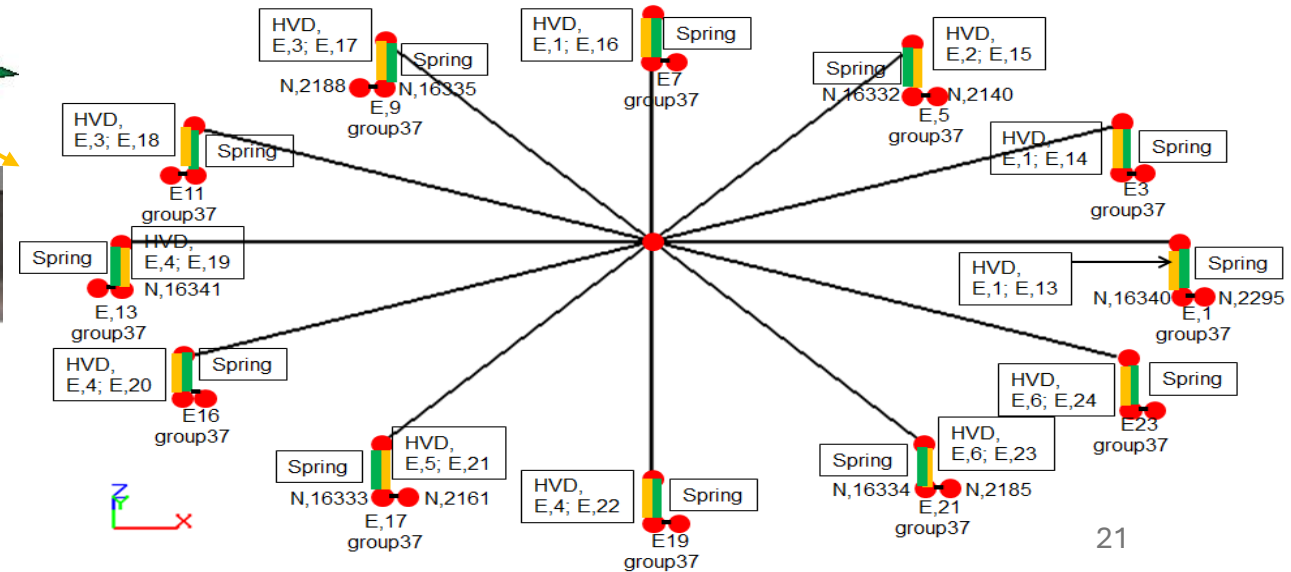


GERB HVD Device

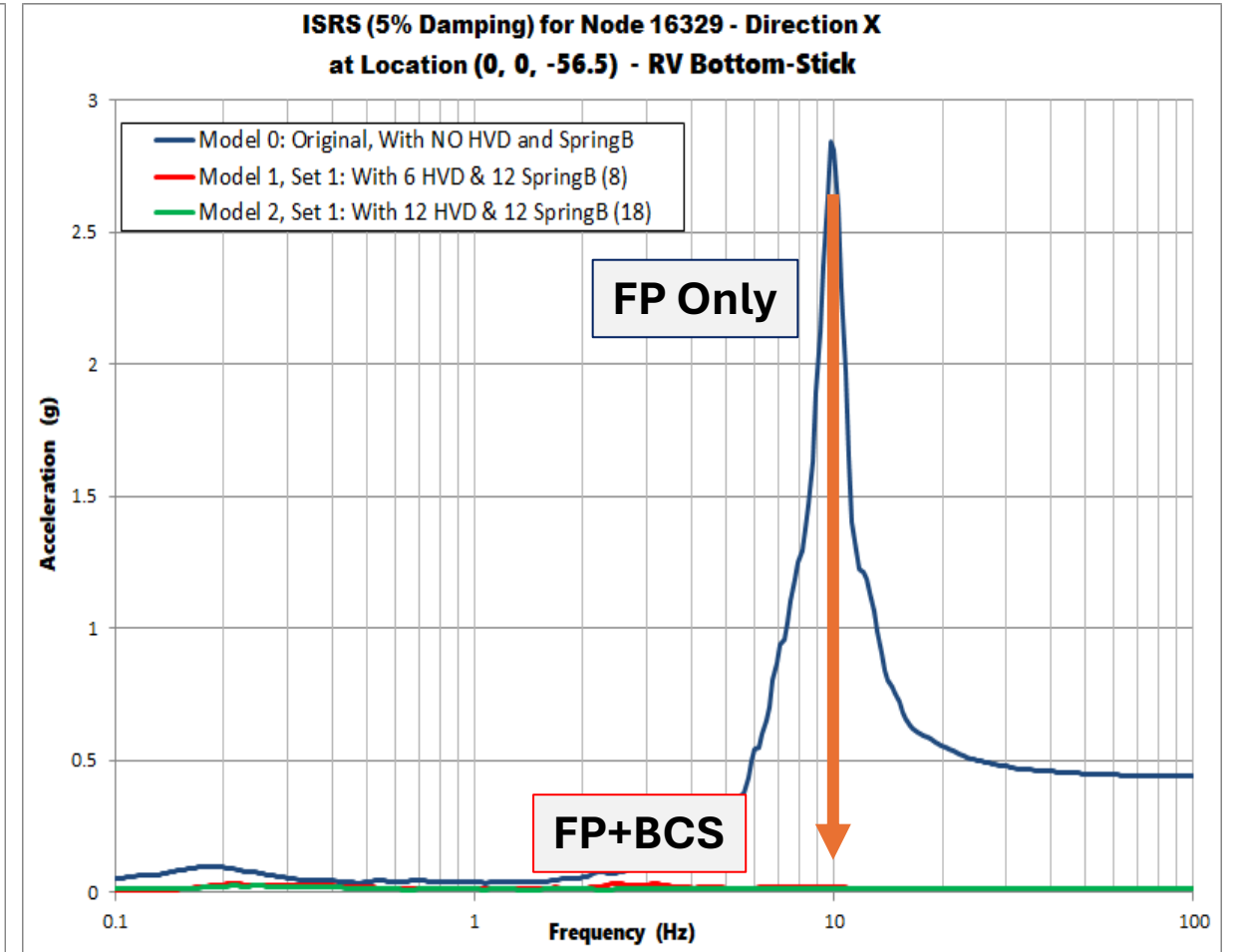
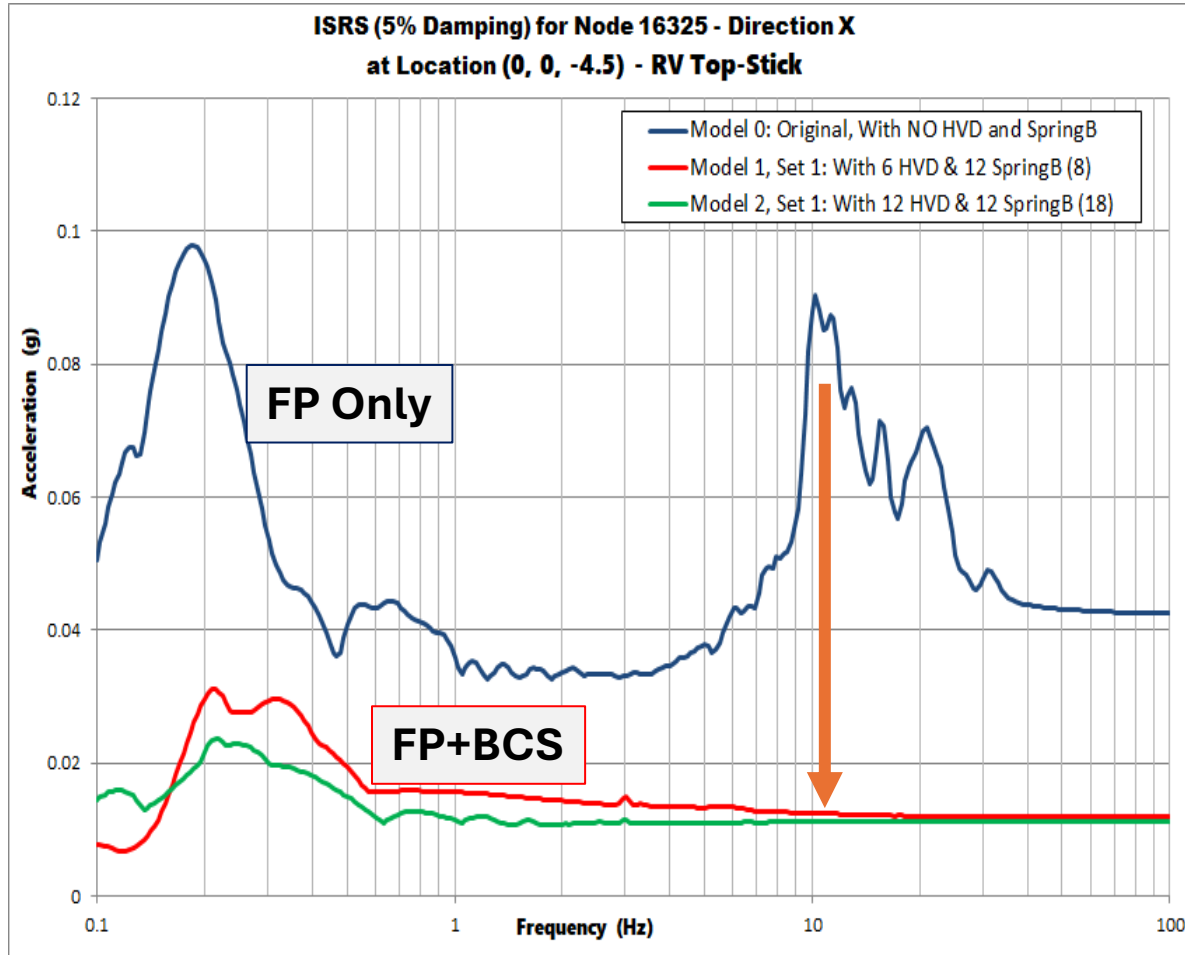


4-Parameter Maxwell Model

ACS SASSI includes special frequency-dependent HVD (based on GERB modeling in publications). There are four frequency-dependent complex stiffnesses (K_h , K_v , B_h , B_v) for each Maxwell chain. Total eight parameters for a HVD unit.

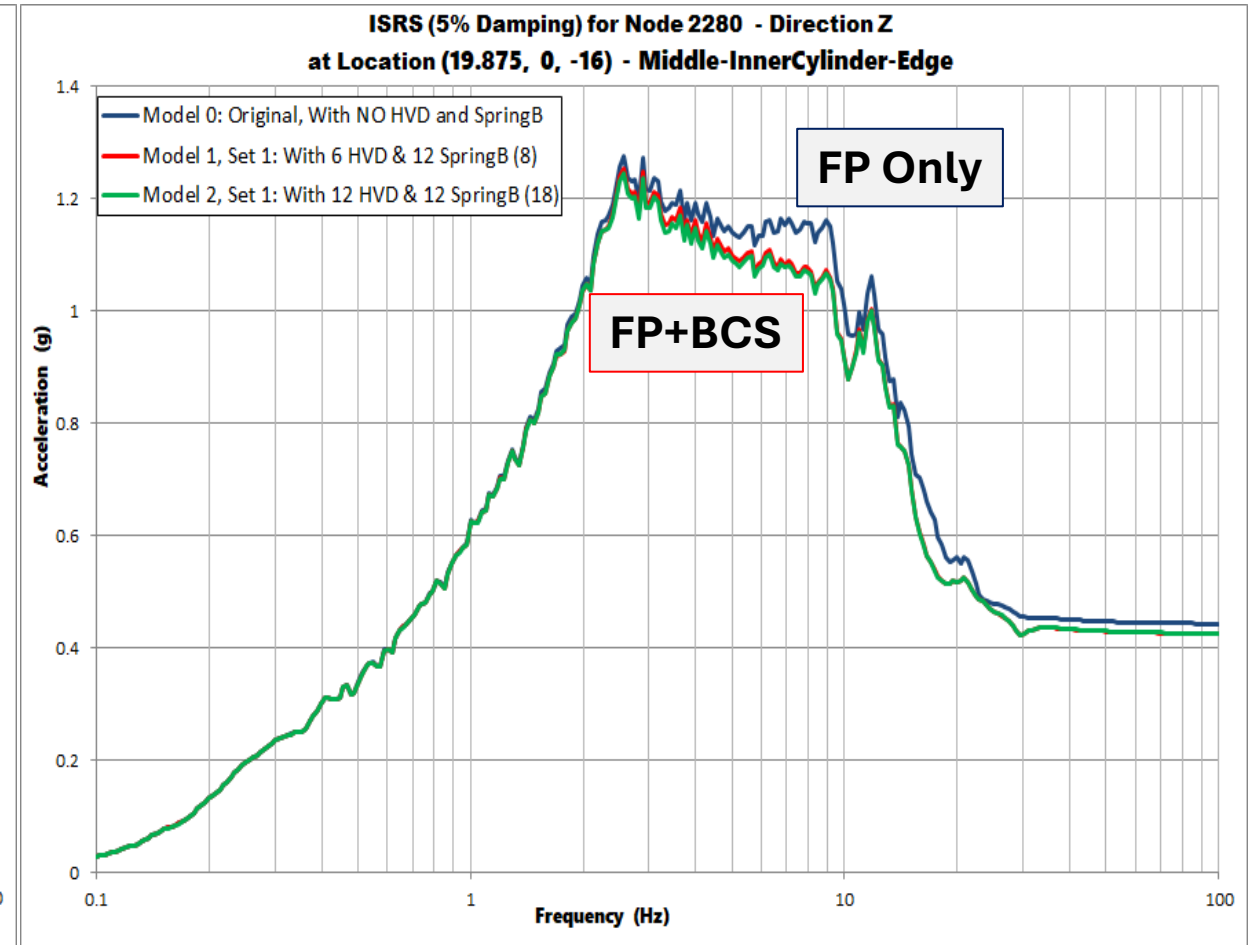
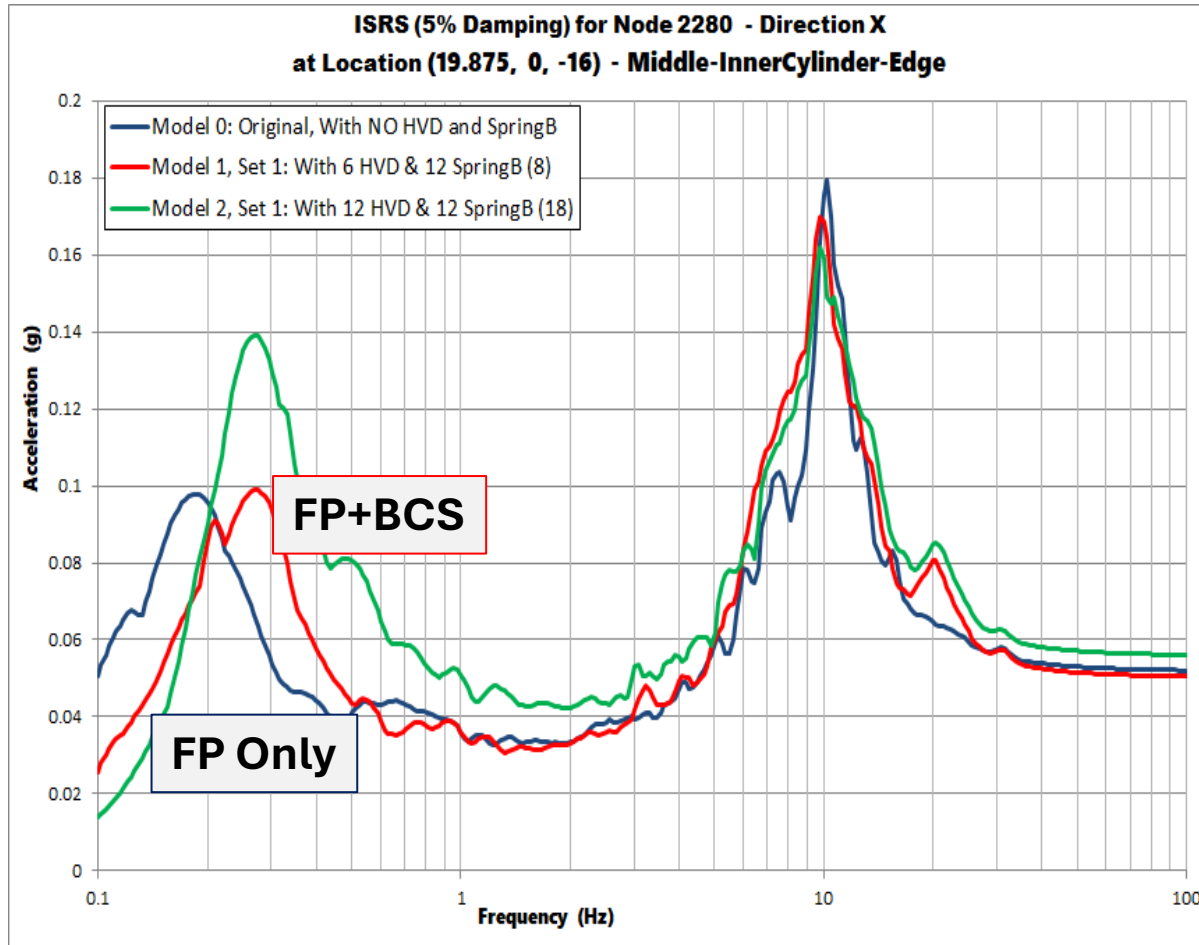


ISRS at RV Stick Top and Bottom Locations in X Direction



The ISRS computed in X-direction at the RV stick top and bottom locations (Nodes 16235 and 16239) show that by introducing the 3D isolation devices at the RV beam supports drastically reduces the RV system horizontal acceleration responses.

ISRS Below Surface, El. -18 ft (N2280) in X and Z Directions



The ISRS computed in X and Z directions at an isolated SMR basement location at low elevation, El. -16 ft (Node 2280). The ISRS show that for other locations within the isolated SMR structure, the inclusion of the 3D isolation devices have only a very small influence, practically negligible.

5. PRELIMINARY SENSITIVITY STUDIES FOR SSI RESPONSES

Preliminary Seismic SSI Sensitivity Studies

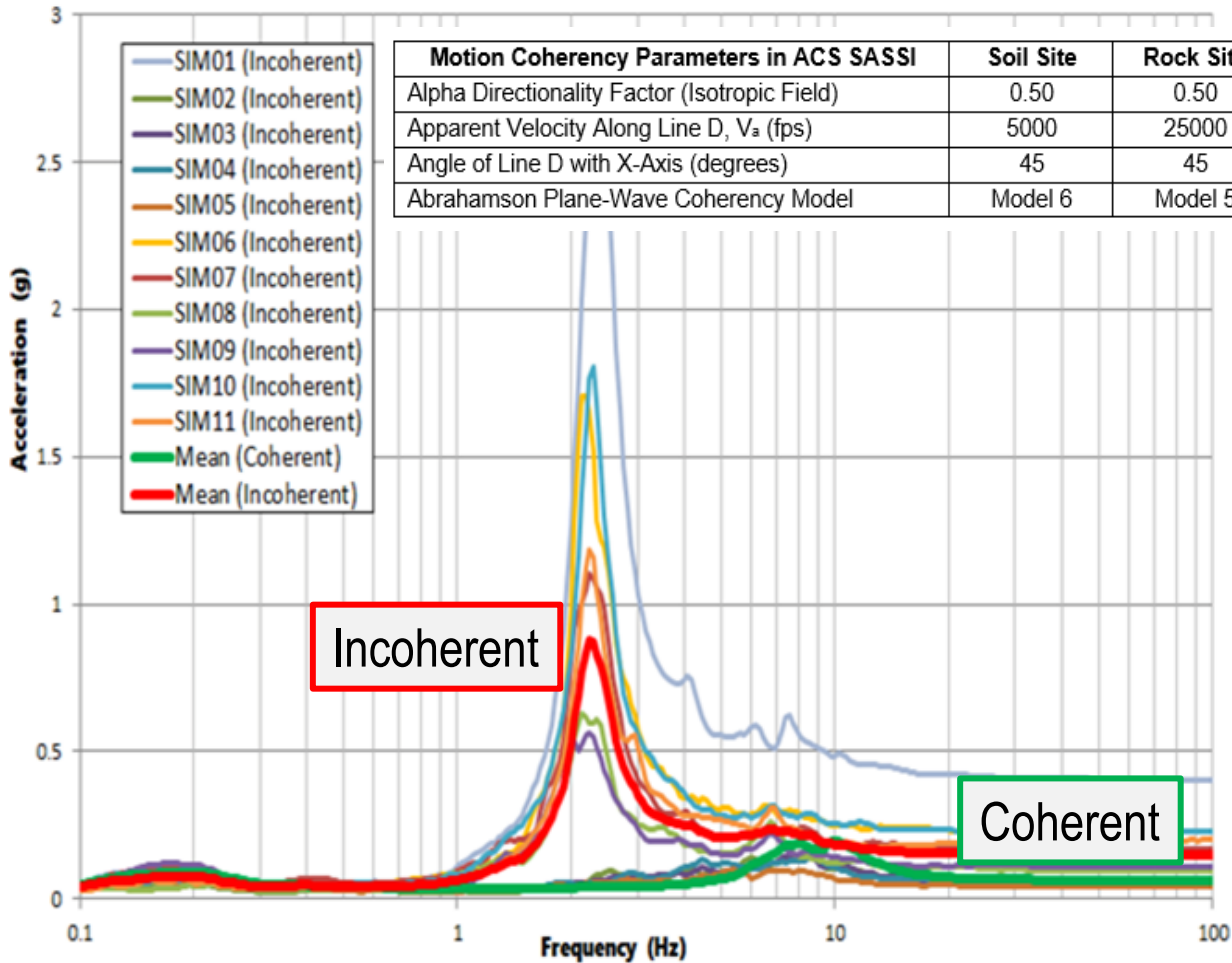
The preliminary SSI sensitivity studies were limited to some key influential effects due to:

1. DBE spectral amplitude variations, including component-component variations
2. FP isolation system stiffness random variation
3. Mass eccentricity variations due to the FP isolation system stiffness spatial variation
4. *Single FP isolator failure assuming scenarios for different locations*
5. *Seismic motion spatial variation due to soil deformation under non-vertically propagating waves*

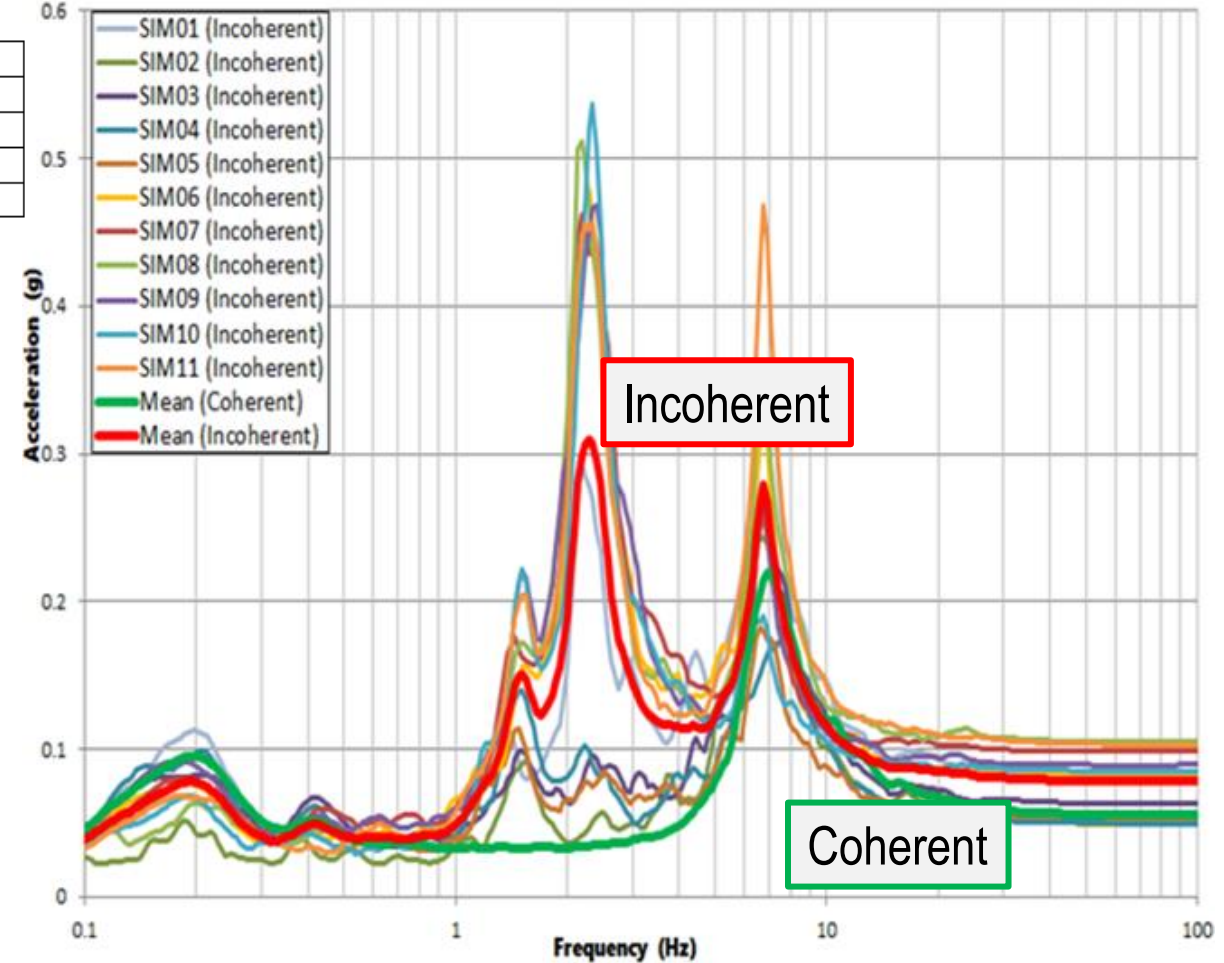
From these preliminary SSI sensitivity studies, items 4 and 5, appeared to have the largest influence on ISRS responses with spectral amplifications above 100%.

Coherent and Incoherent Mean ISRS at El. -16 ft for Soil Site

ISRS (5% Damping) for Node 2280 - Direction X
at Location (19.875, 0, -16) - Middle-InnerCylinder-Edge



ISRS (5% Damping) for Node 2280 - Direction Y
at Location (19.875, 0, -16) - Middle-InnerCylinder-Edge



Mean ISRS at Elevation -16 ft (N2280) for Coherent (green) and Incoherent (red) Motions

6. SUMMARY REMARKS

Main Conclusions and Actions for Isolation Improvements

1-The established seismic SSI analysis methodology provides a reasonable and affordable seismic SSI methodology for performing the design-basis seismic analysis for the base-isolated ARC-100 SMR design. Based on the SSI sensitivity study results, few additional SSI methodology adjustments are required to be considered in the following final design stages of the isolated structure.

2-It was shown that the SMR base-isolation system efficiency can be significantly enhanced by using a *hybrid* isolation system by adding a local 3D BCS isolation system placed at the RV beam supports. The local 3D isolation system for the RV system *avoids the potential dynamic coupling* between the SMR superstructure and the RV system SSI responses, especially for the soil sites.

3-A *global 3D* base-isolation using BCS devices for the entire SMR structure could provide a substantial isolation system improvement especially for acceleration in *vertical direction*. The *global 3D* base-isolation requires only a *one-step SSI methodology which will be more cost-effective and safer* from seismic analysis point of view.

Thank you!