Seismic SSI Analysis of ARC-100 SMR Plant

Summary of
Seismic Isolation Results,
Dynamic Responses,
Building Design Evaluations, and
Probabilistic Risk Assessment

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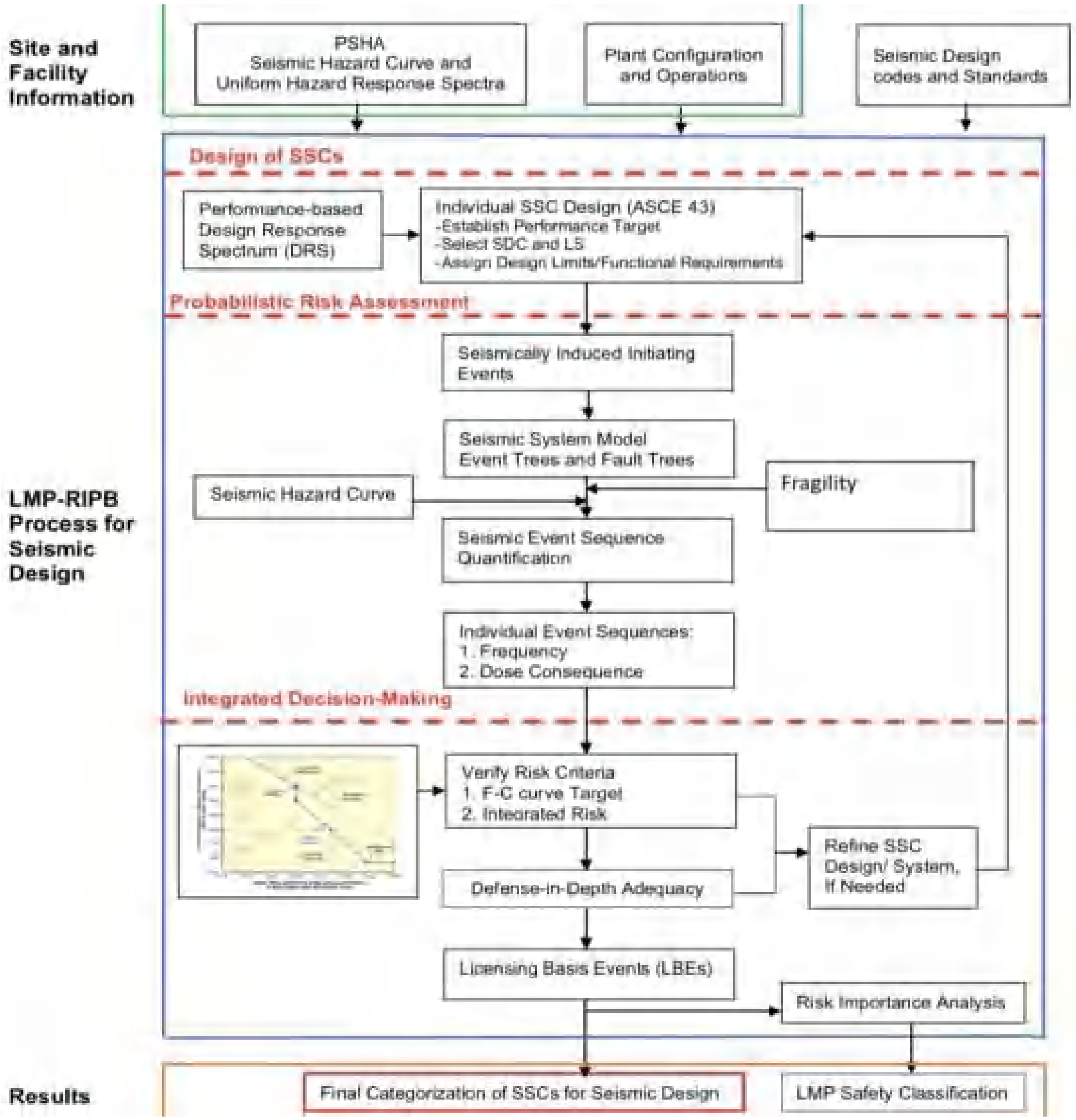
Contents

Introduction and Objectives

- Describe the Seismic Isolation System for the ARC 100 Reactor Building as originally envisioned and the technical implementation of Regulatory and Code Requirements
- Provide technical insights of the seismic SSI/SSSI analysis of the base-isolated deeply embedded ARC-100 SMR structure for the standard baseline plant.
- Describe why the results obtained from the analyses of the presently isolated reactor building, the associated system and their fragilities. have caused the rethinking of a more appropriate system that will also isolate in the vertical direction
- Present the results of the initial seismic probabilistic risk assessment, reinforcing the need to have 3-D isolation
- Inform the NRC of the next step to be taken to demonstrate that a choice of 3-D building with possibly selected individual component isolation will resolve the limitation of the present design



RIPB Seismic Design and LBE Selection Process (from RIL 2021-04)

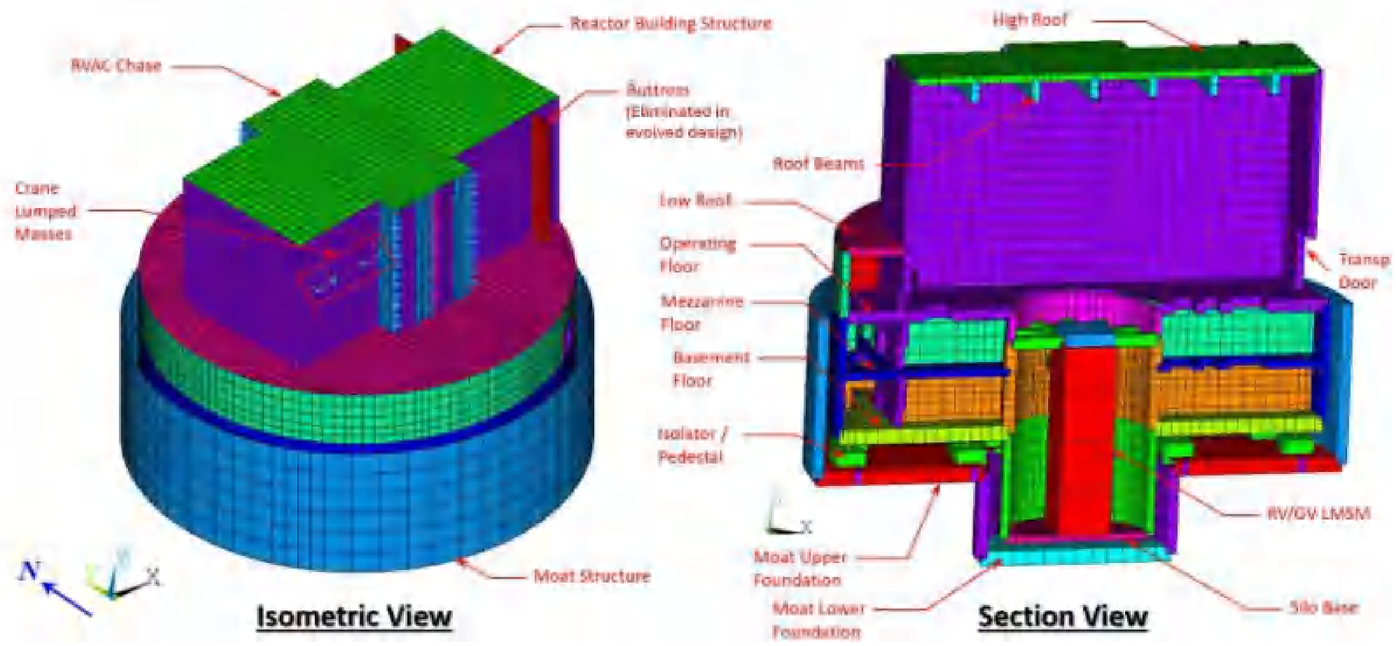
Isolated Building Description and Regulatory/Code Applicability

Enver Odar (ARC Clean Technology)

Building Description including Seismic Isolation System

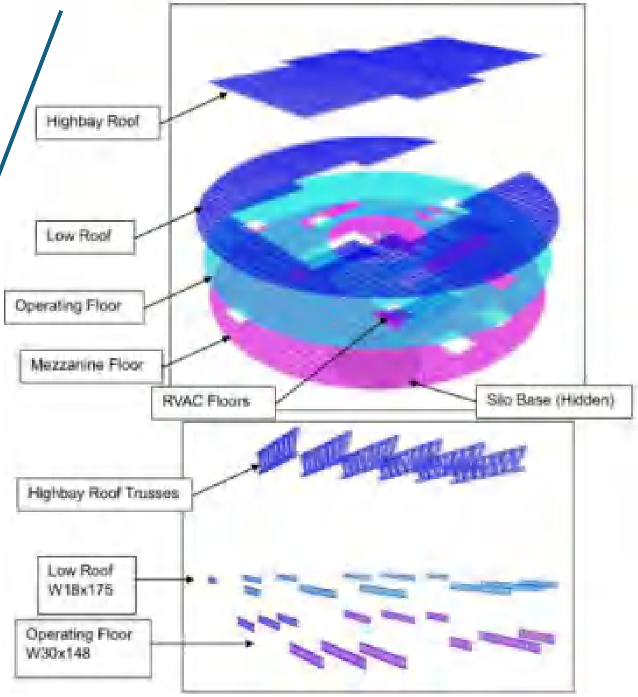
- Top of moat at grade level, 0’
  - Moat upper fdn at -43’
  - Moat lower fdn at -66’
- Reactor Building
  - Aprox. 134’ diameter
  - Basement floor at -32’
  - Mezzanine floor at -16.5’
  - Operating floor at 0’
  - Low roof at +17.5’
  - High roof at +57’

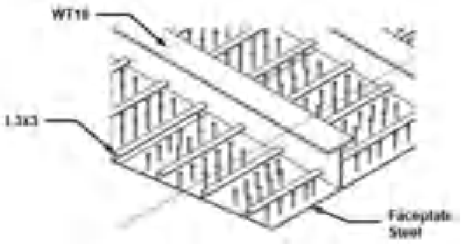
Reactor Building (RB) – Preliminary Design ANSYS Model – Isometric View

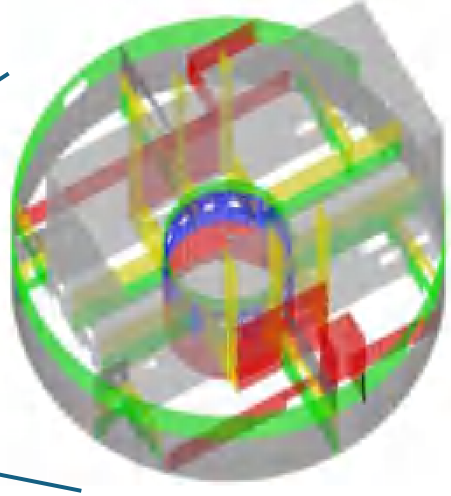


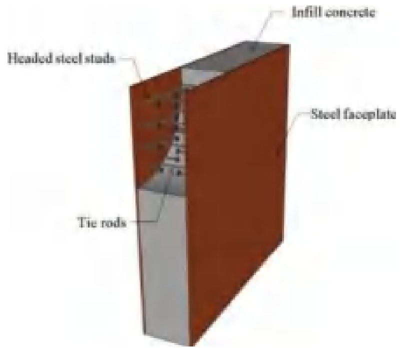
General Construction

- Moat substructure and basement floor reinforced concrete.
- All other horizontal floors and roofs are partial steel-concrete composite: Bottom steel faceplate (with studs, stiffeners) and traditional deformed bar reinforcing on top layer
  - WF beams are also embedded within the SC floors where required to support construction loading
  - Highbay roof slab is supported by steel trusses
- All vertical walls are full steel-concrete composite construction (two steel faceplates with studs and tie rods, concrete infill)





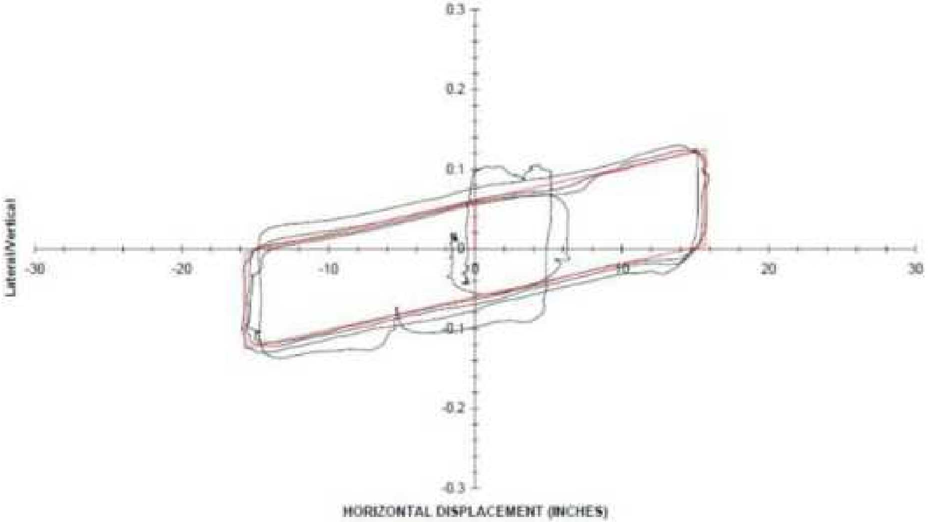




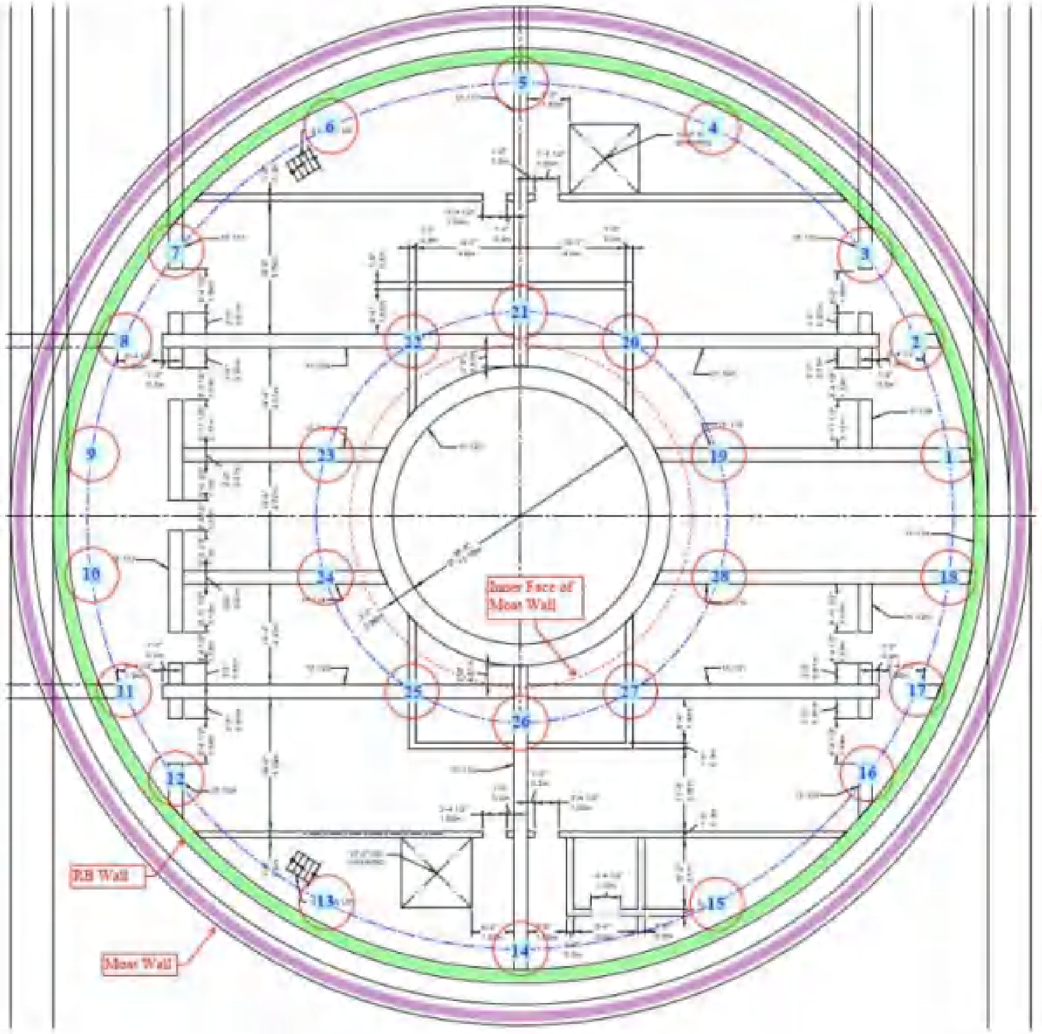
Friction Pendulum Seismic Isolators

- 28 identical seismic isolators between superstructure and moat upper foundation
- Single-pendulum type
  - Constant friction, lateral stiffness, and dynamic period
- Dynamic properties, friction factors and stiffness developed by Prof. Constantinou based on existing prototype test data

Images from Earthquake Protection Systems



Isolator Layout



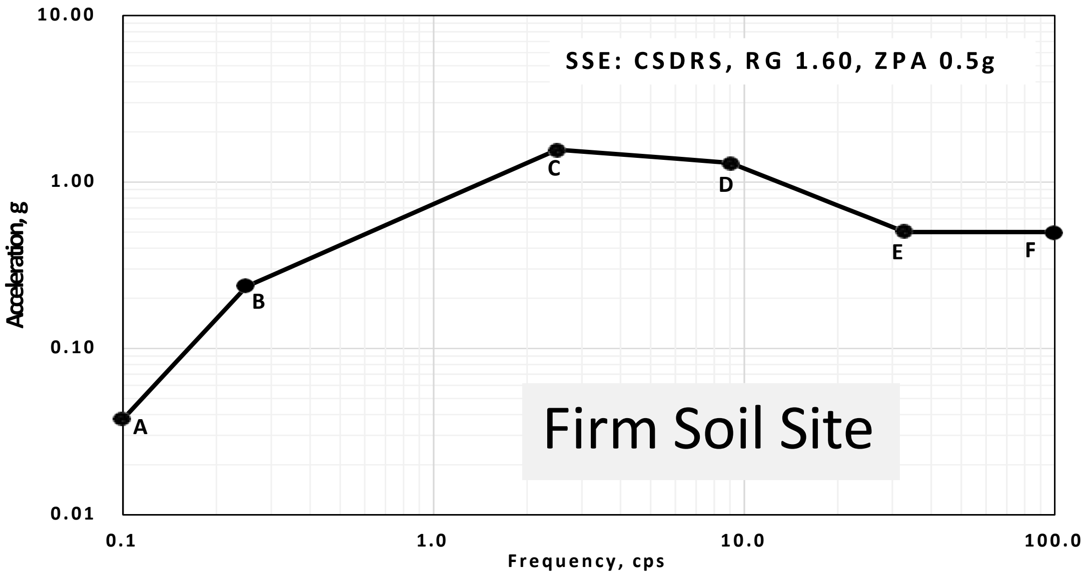
Regulatory and Code Basis

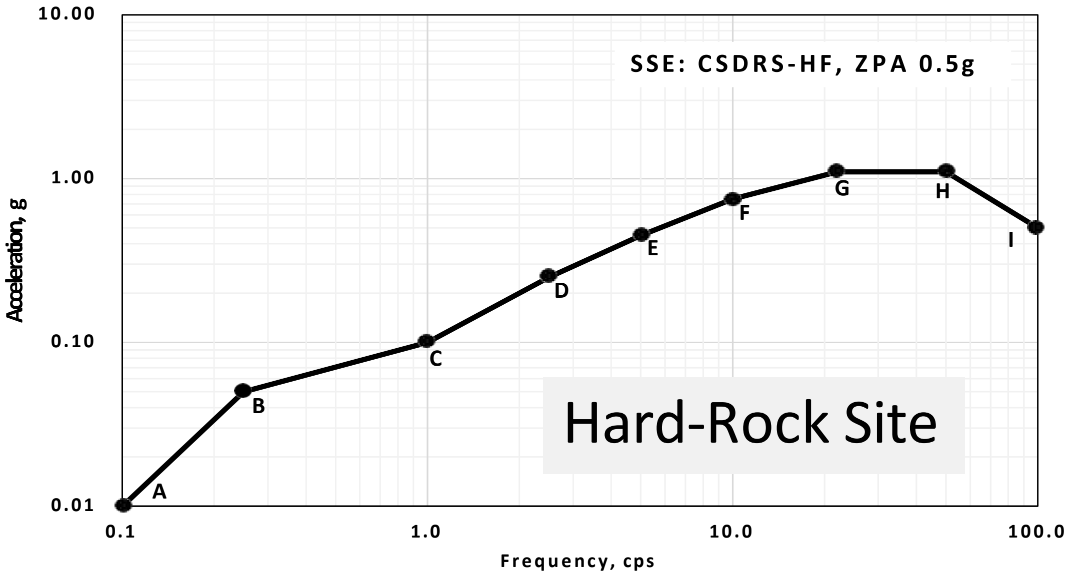
- RG. 1.60 for design response spectra (not in CEUS)
- RG. 1.61 damping
- RG 1.92 combination of modal responses and spatial components
- RG 1.22 floor spectra
- RG 1.208 performance-based approach to define the site-specific earthquake ground motion
- DC/COL ISG-01 seismic issues associated with high frequency ground motion
- DC/COL ISG-017 hazard-consistent seismic input
- SRC 2.5.2 development of design ground motion
- SRC 3.7.1 development of design parameters for SSI
- SRP 3.7.2 SSI analysis of safety related structures
- SRP 3.7.3 seismic subsystem analysis.
- ASCE 4-16 seismic analysis of safety-related nuclear structures
- ASCE 7-22 minimum design loads for buildings
- ASCE 43-19 seismic design criteria

Generic site seismic design parameters
Seismic modeling

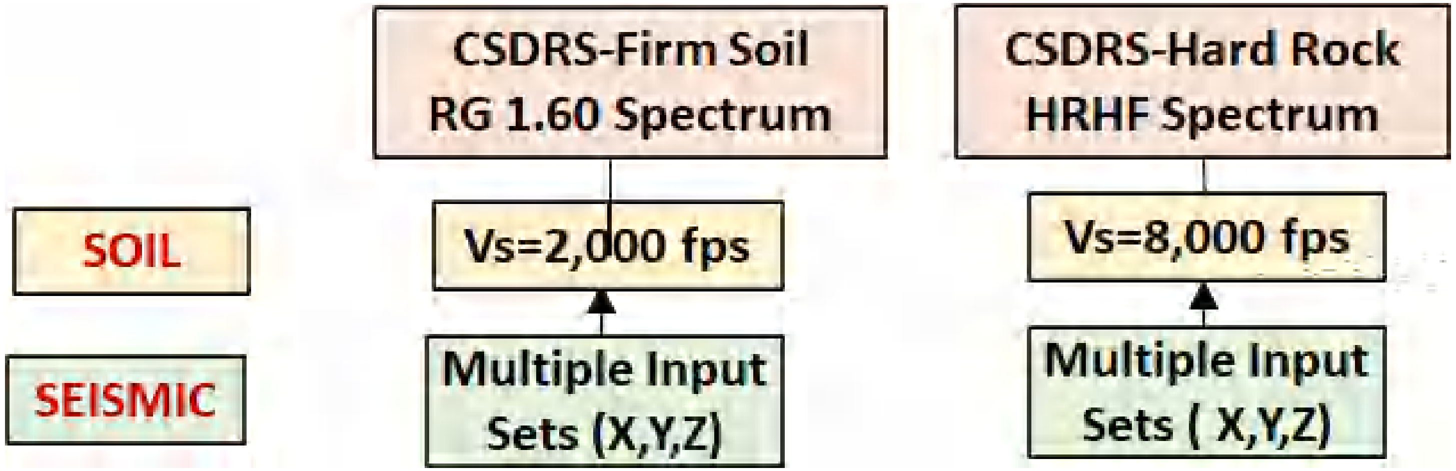
Jeff Pieper (UECI/Hopper Engineering)

Postulated SSE For DBE Shaking (for 0.50g)





Generic Soil Site Conditions



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

The ASCE 4-16 Chapter 12 applicable to base-isolated structures requires for the DBE shaking to compute the 80^{th} percentile seismic responses, and for the 150% DBE shaking to compute the 90^{th} 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 80^{th} percentile DBE responses and for each of the two generic site conditions, a set of 33 seismic SSI simulations were considered (33 = 11 input sets x 3 soil variations, BE, LB and UB soils).

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

Seismic Soil-Structure Interaction (SSI) Modeling and Analysis

Dr Dan Ghiocel (Ghiocel Predictive Technologies)

• Objective of this part of the presentation

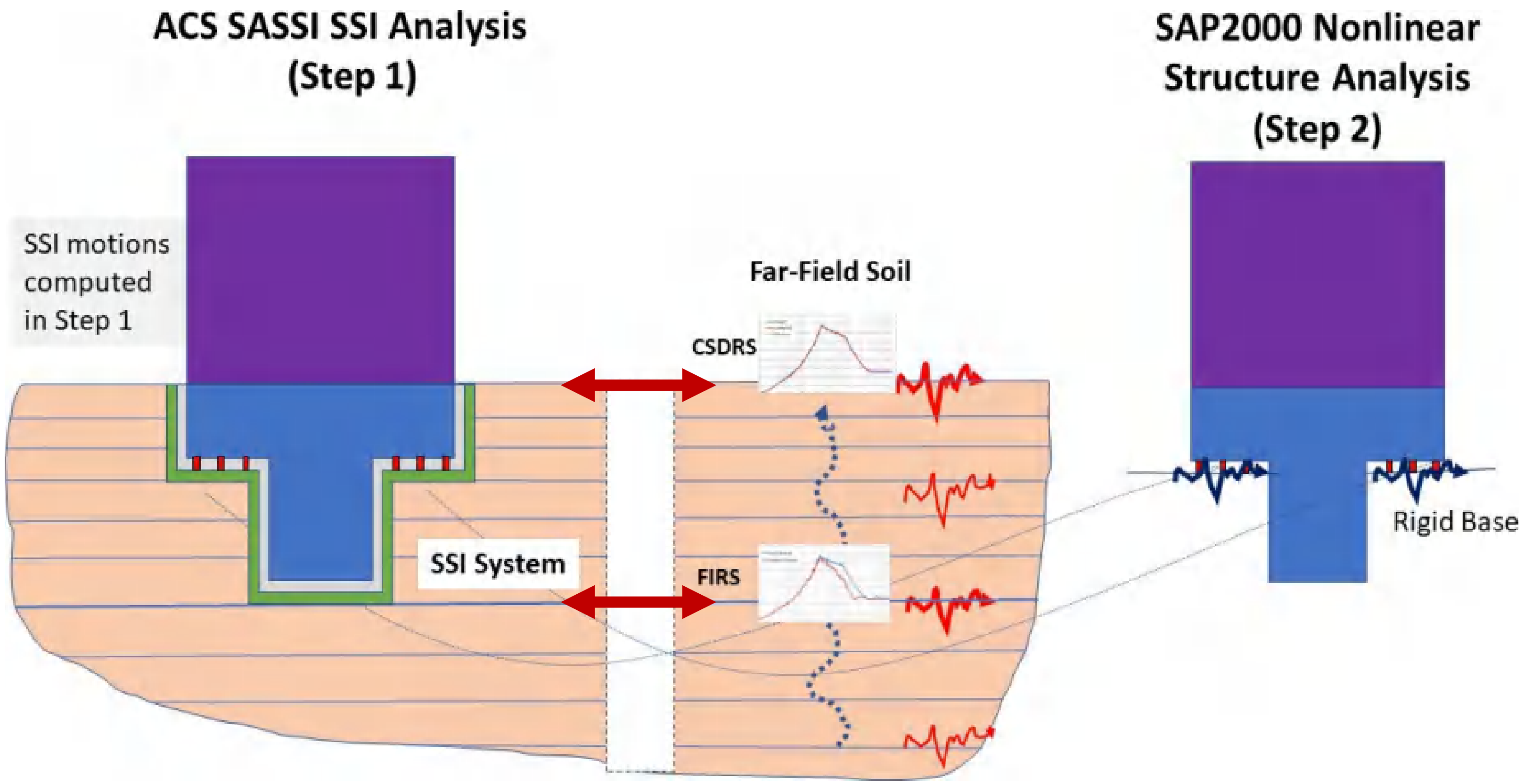
The objective of this presentation is to provide technical insights of the seismic SSI analysis of the base-isolated deeply embedded ARC-100 SMR structure for the standard baseline plant.

The SMR embedment depth is 66.5 ft. The investigated base-isolation system solution for Advanced Conceptual Study ARC-100 SMR 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.

More recently, a hybrid base-isolation system was also considered as a potential technology improvement. The hybrid isolation system consists of including in addition to the 2D global FP isolation system, a 3D local isolation system with springs and dampers placed at the RV system supports.

Although the report focuses on the initial 2D global base-isolation solution using FP isolators, it also makes few comparisons between the seismic SSI response results using the two isolation systems.

Seismic SSI Analysis Methodology



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

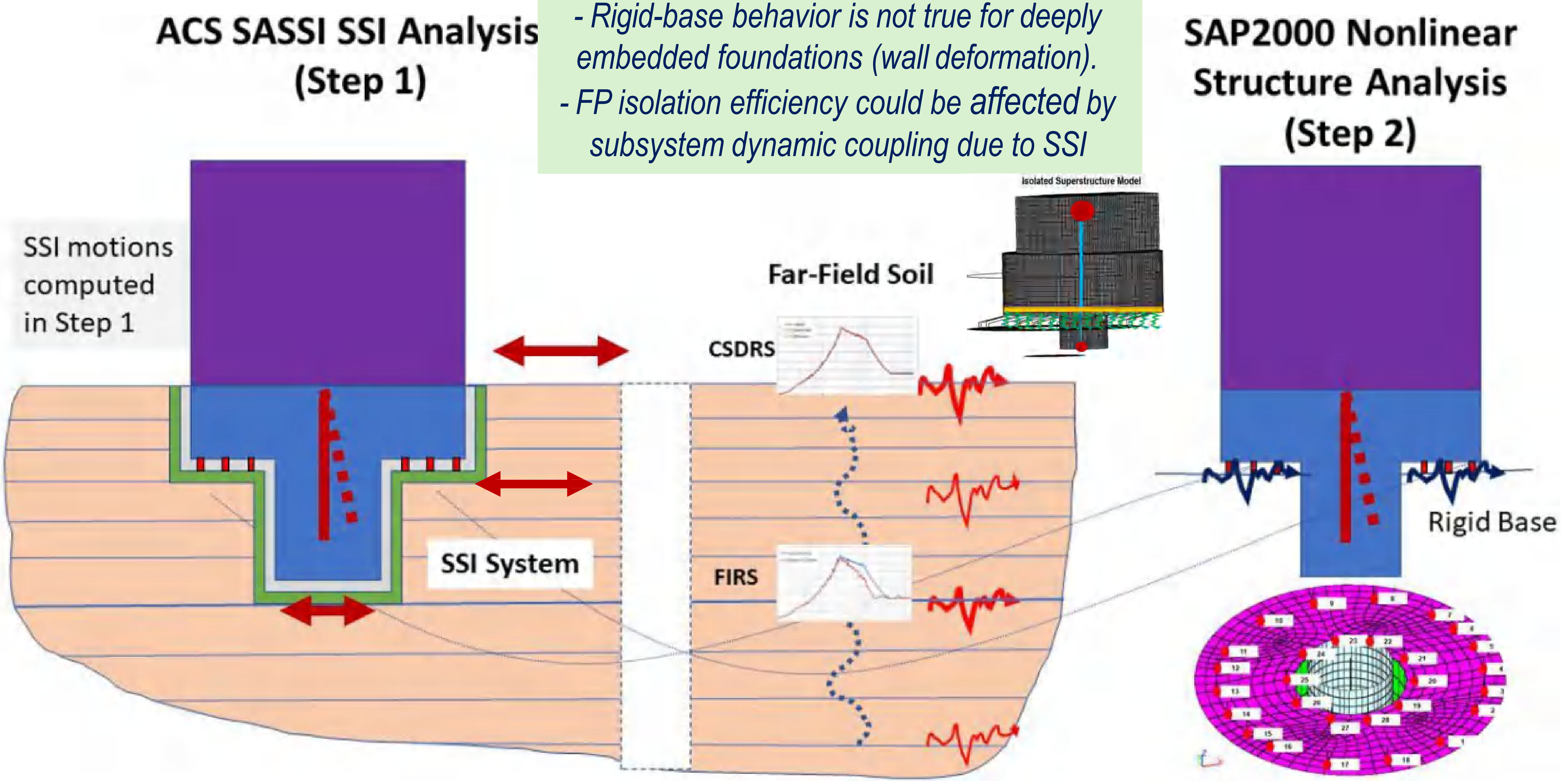
In *Step 1*, an iterative seismic linearized SSI analysis is performed in complex frequency domain to determine the SSI foundation response motion for the iterated equivalent-linear FP isolator properties.

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

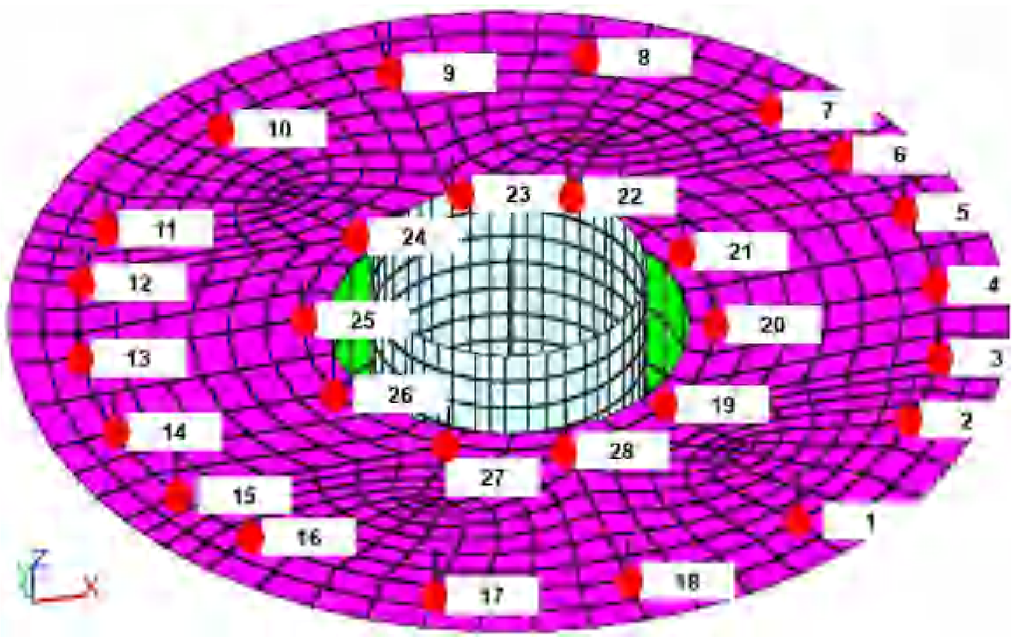
Specific SSI Modeling Aspects for Deeply Embedded Base-Isolated ARC-100 SMR Structure

- *Rigid-base behavior is not true for deeply embedded foundations (wall deformation).*
- *FP isolation efficiency could be affected by subsystem dynamic coupling due to SSI*



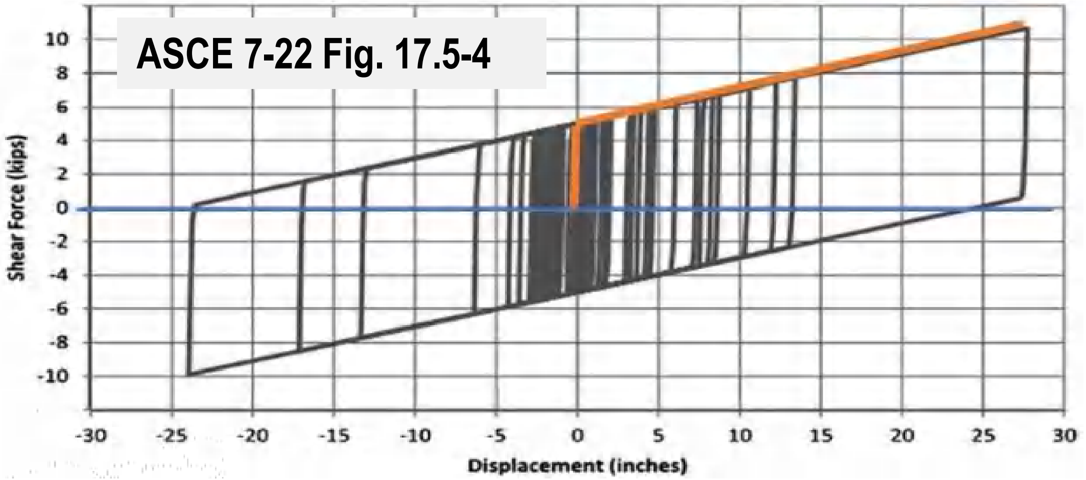
28 FP Isolator Distributed at the Foundation Upper Level;
18 FPI on Outer Circle (1-18) & 10 FPI on Inner Circle (19-28)

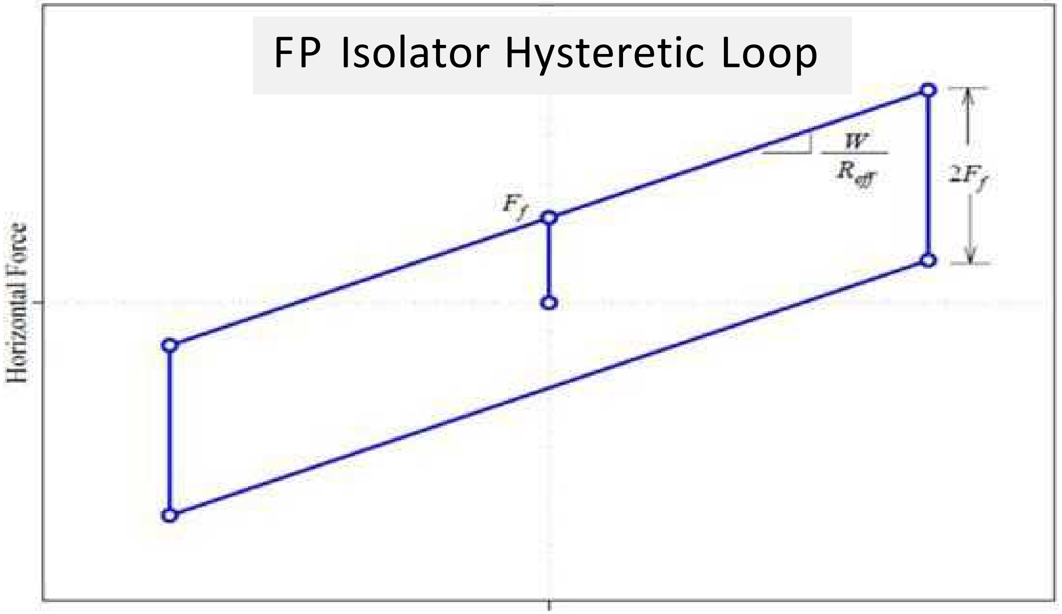
FPI 15680-26 Type with Different Gravity Vertical Axial Forces (from 1373 to 3371 kips)



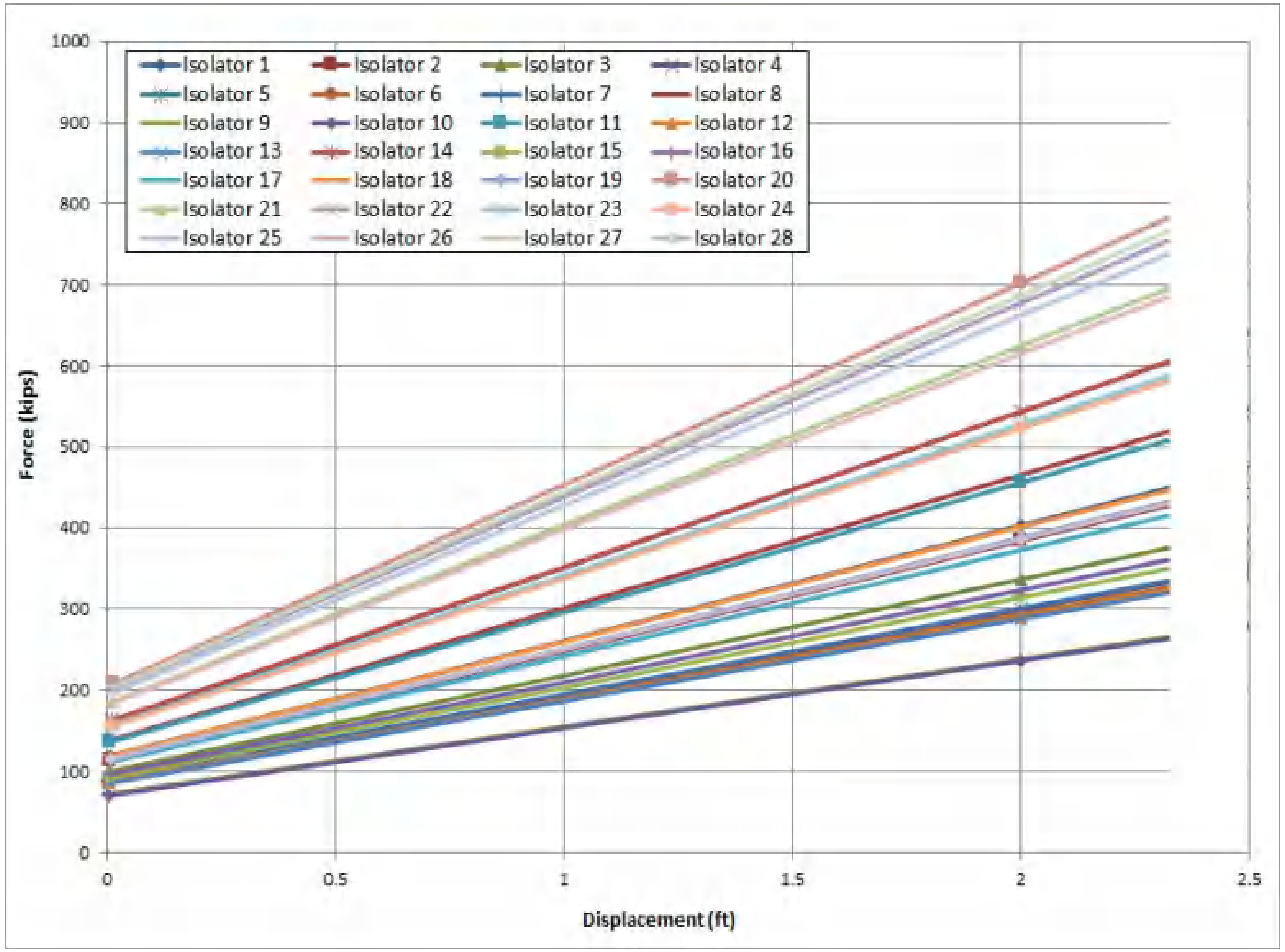
Isolator Number (BBC #)	Friction Pendulum Isolator Type	Isolator Vertical Stiffness (k/in)	Isolator Axial Force (kips)	Isolator Bottom Node No.	Coordinates			μ Average	Effective Radius (in)
					X-Coor. (ft)	Y-Coor. (ft)	Z-Coor. (ft)		
1	FPI 15680-26	200000	1935	16064	61.082	8.75	-38	0.062	163
2	FPI 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



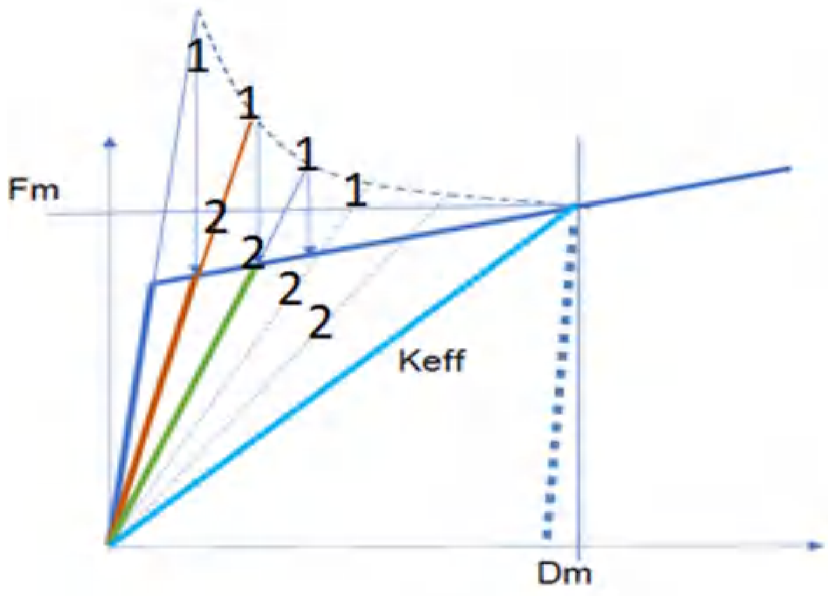


28 FP Isolator Back-Bone Curves (BBC)

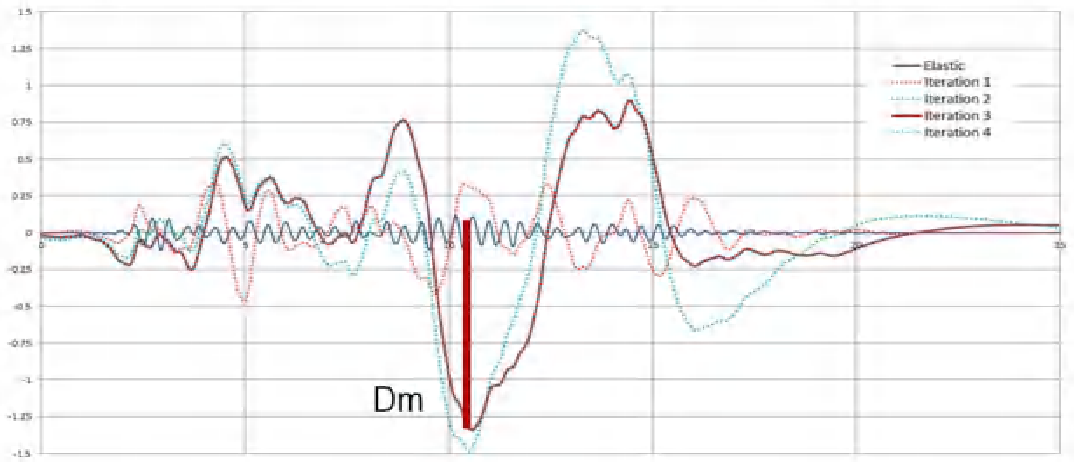


ACS SASSI NON Fast-Convergent Iterative SSI Analysis Procedure for Modeling FP Isolator Hysteretic Behavior

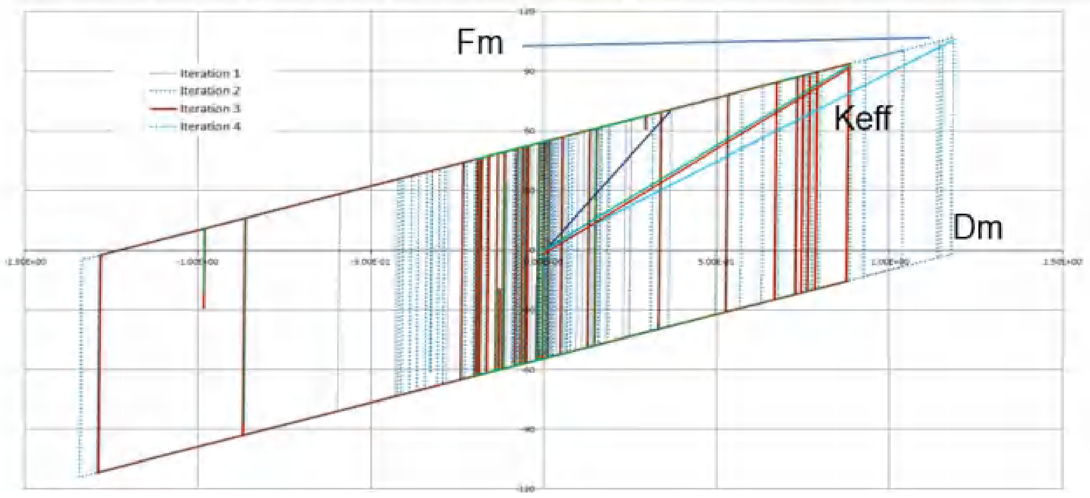
Iterative procedure couples the equivalent-linear SSI analysis to compute FPI sliding displacements in substep 1, with fast local hysteretic cyclic analyses in time domain to compute nonlinear forces in each FP isolator using bilinear models in substep 2. Then, compute Keff = f (Dm, Fm).



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

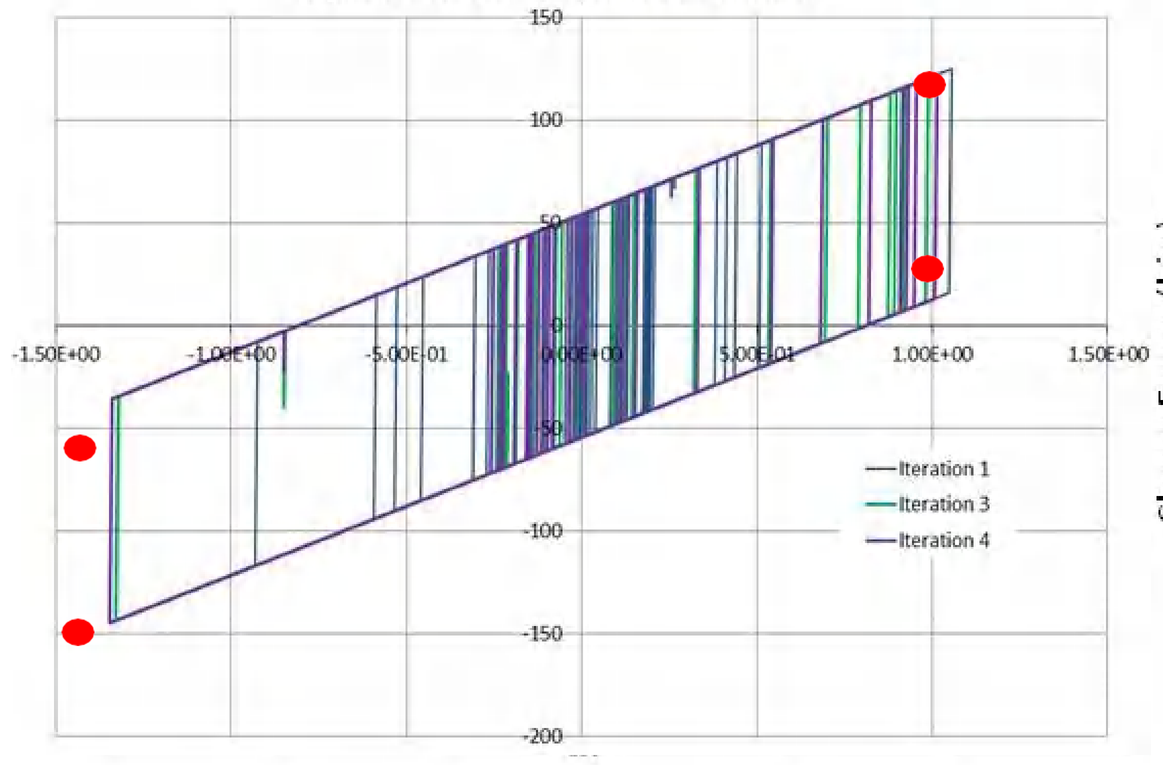


Substep 2: Hysteretic cyclic analysis to get nonlinear isolator forces

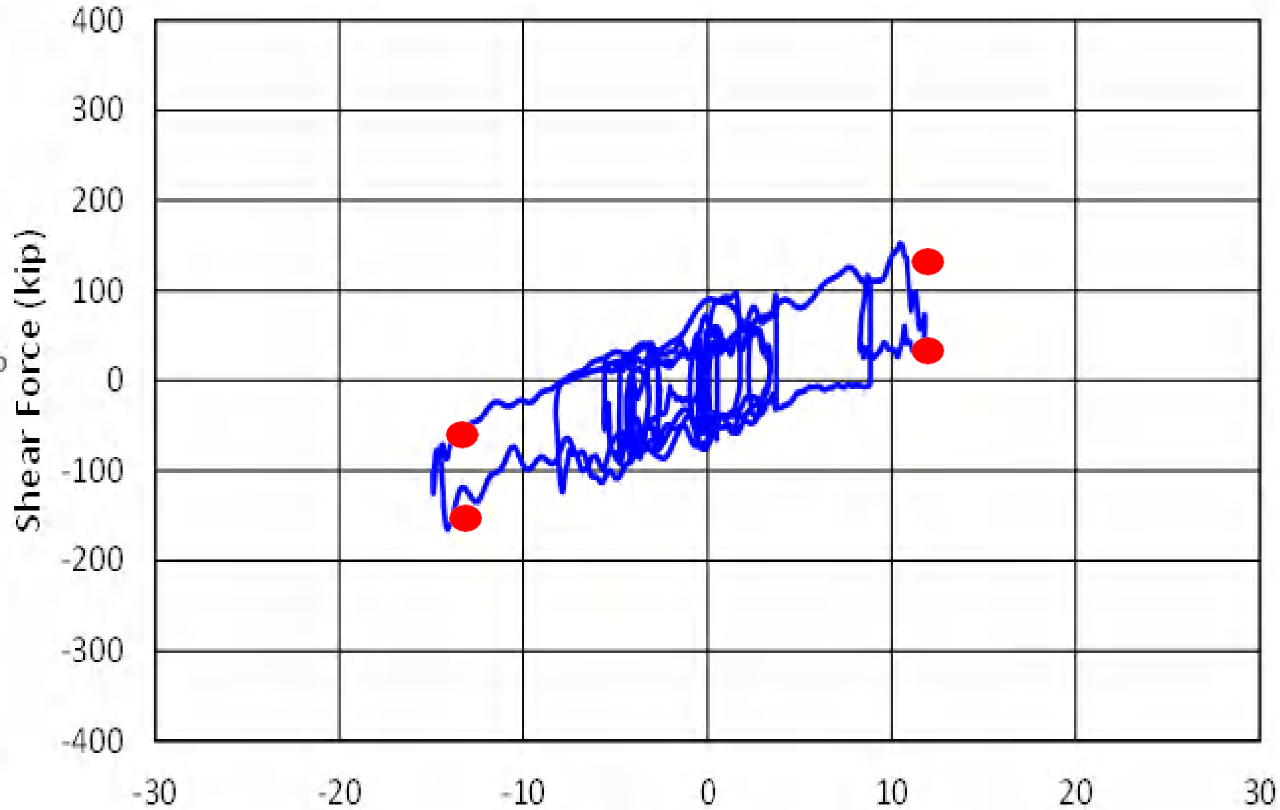


Verification of Equivalent-Linear FP Isolator Properties Against SAP2000 Nonlinear Analysis Results. Diff < 10%

ACS SASSI NON Using Iterative SSI Analysis (Step1)

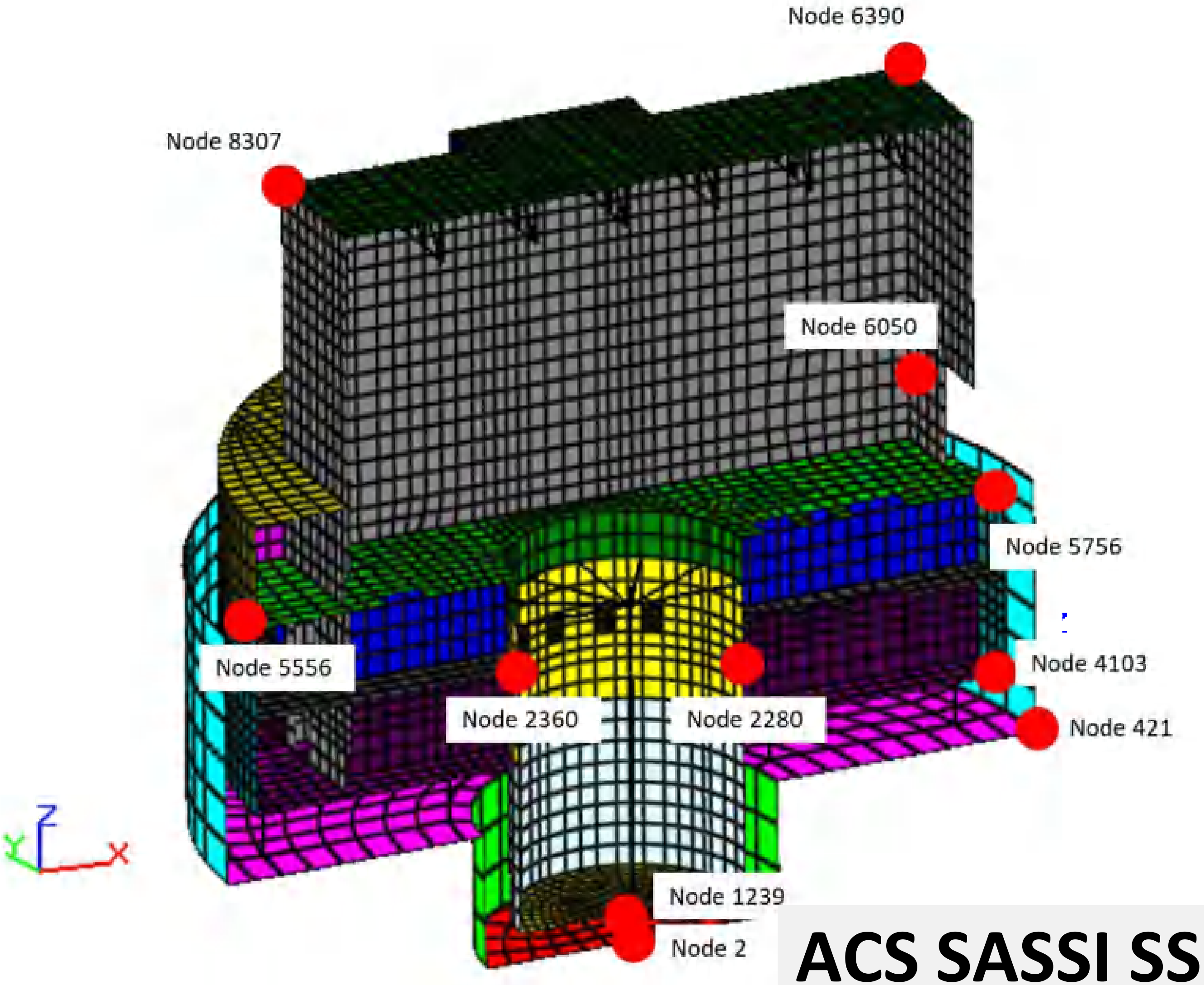


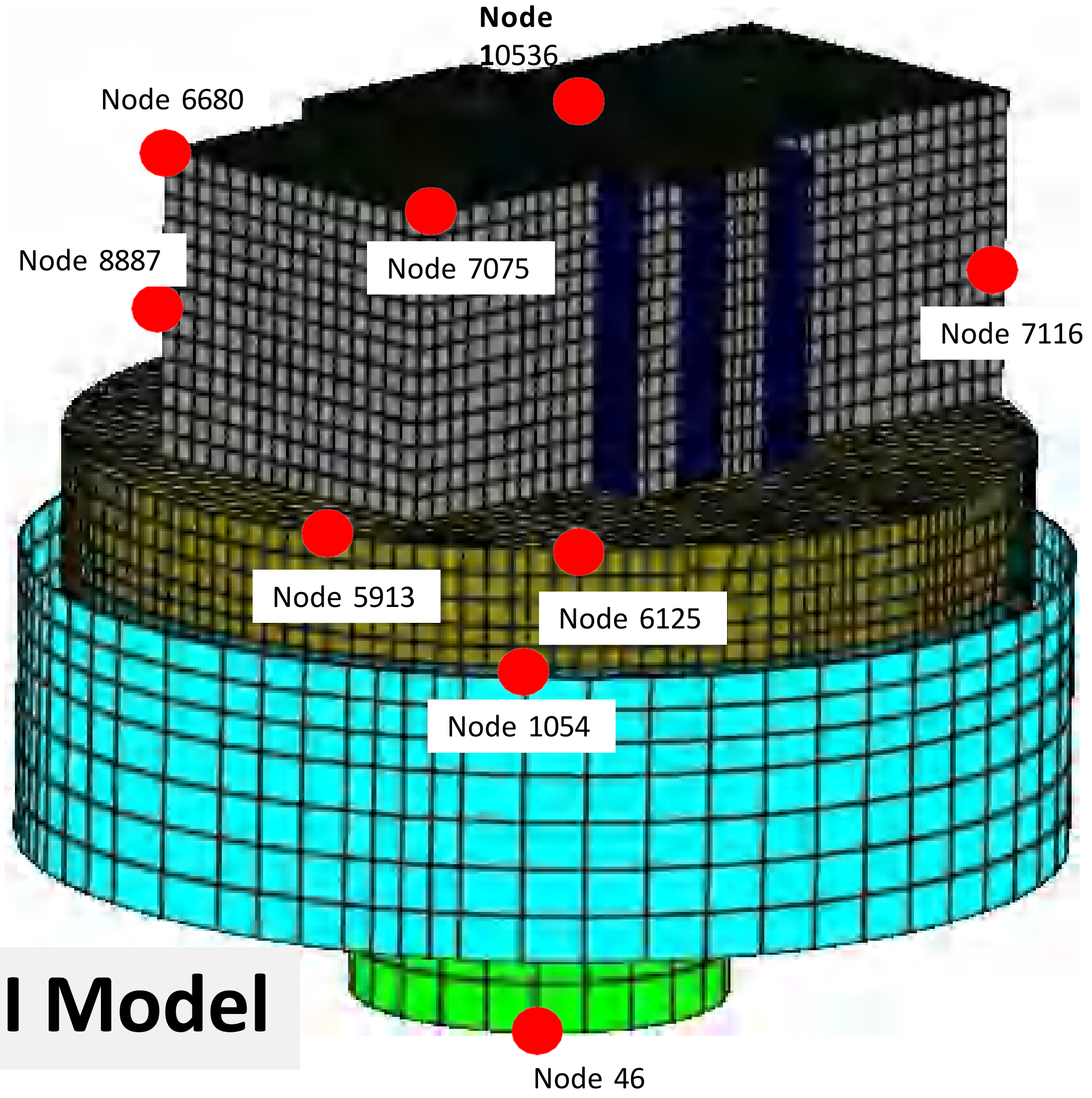
SAP2000 Using Nonlinear Analysis (Step 2)



ACS SASSI NON assumes that the FP isolator vertical axial forces are equal with the static gravity forces. The FP isolator equivalent-linear modeling neglects the nonlinear behavior due to the vertical seismic motions; it can’t model potential FP isolator uplift effects.

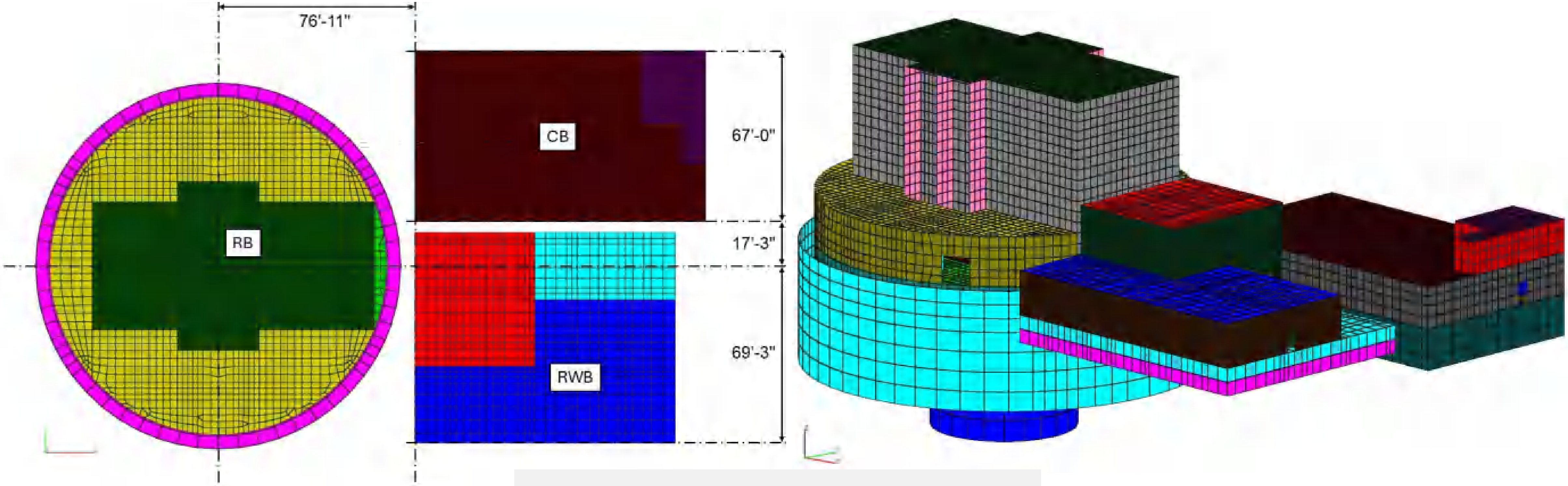
ARC-100 SMR SSI (Rock) And SSSI (Soil) Models





ACS SASSI SSI Model

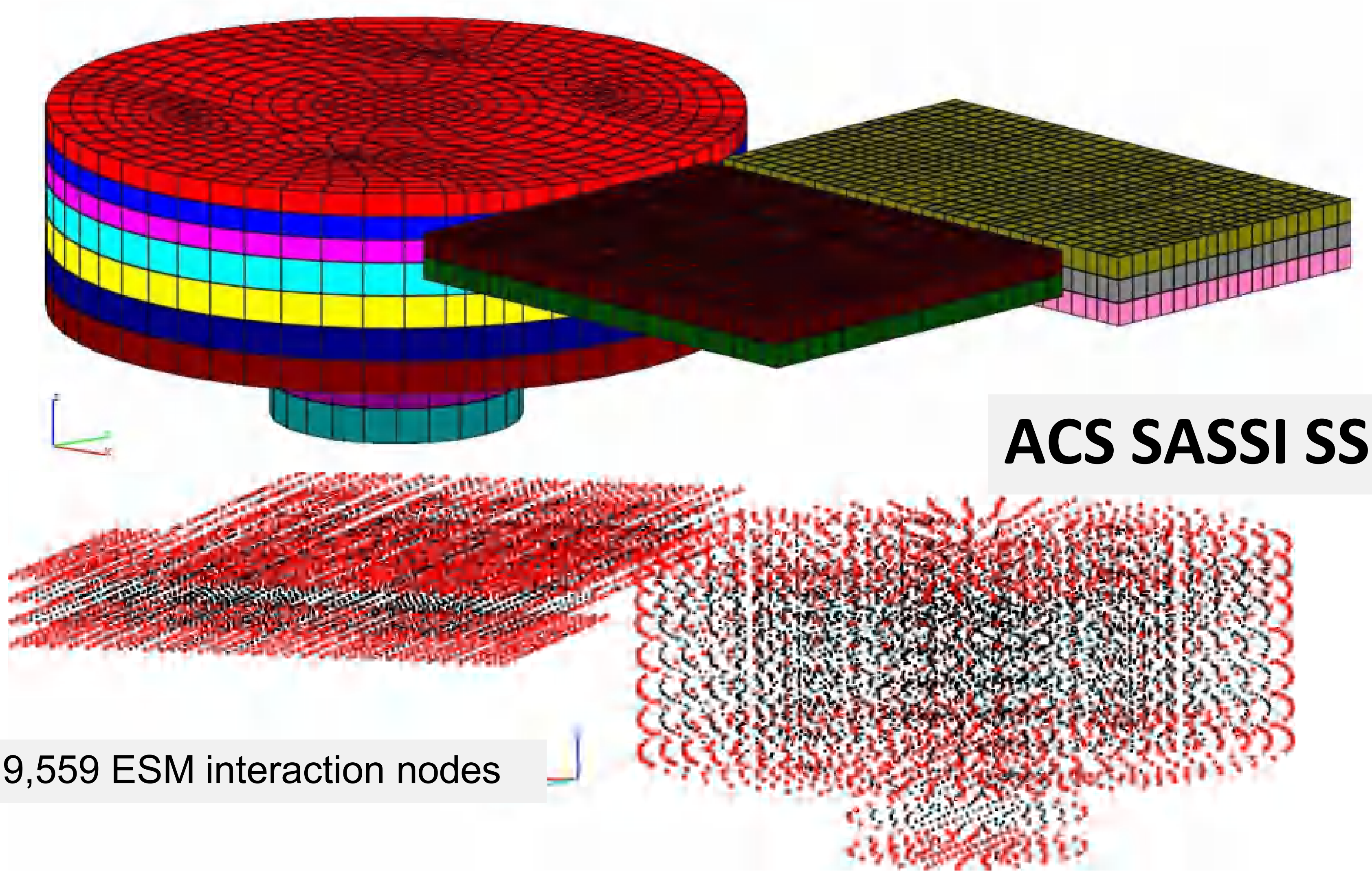
Seismic ARC-100 RB-RWB-CB Structure SSSI Model (Soil)



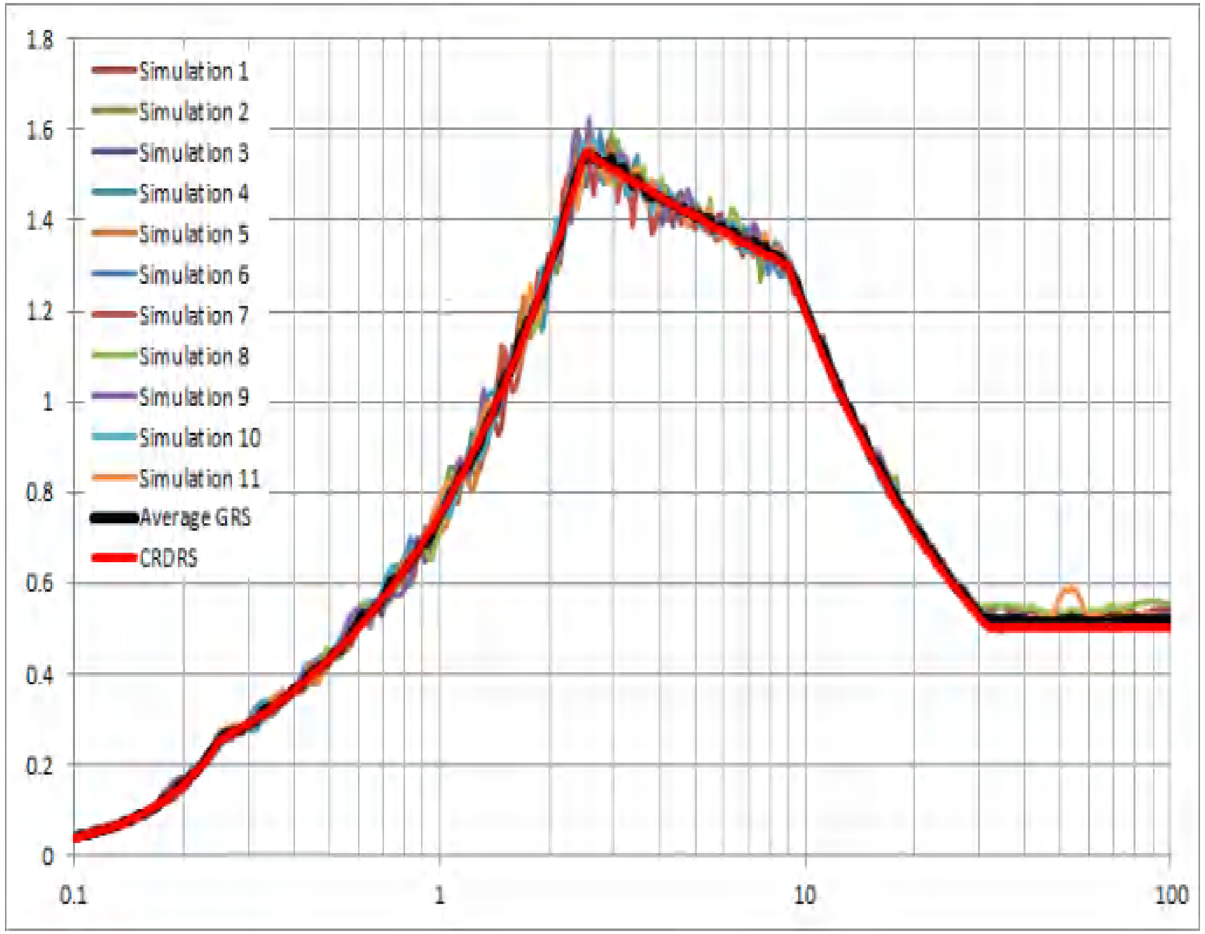
ACS SASSI SSSI Model

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.

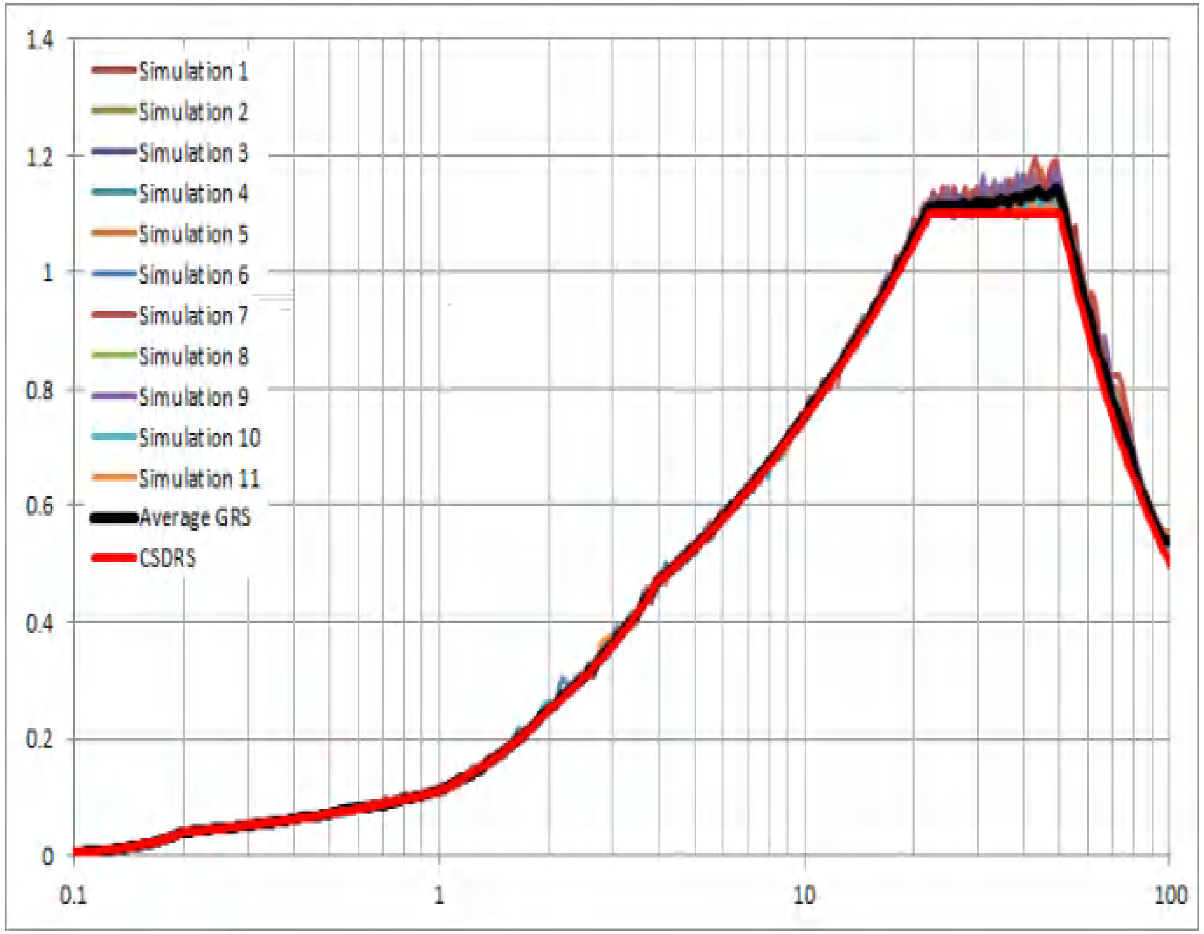
Seismic ARC-100 RB-RWB-CB Excavated Soil SSSI Model



Generation of Spectrum Compatible Acceleration Input Sets (11 inputs for each soil profile, LB, BE and UB)



CSDRS Firm Soil Site



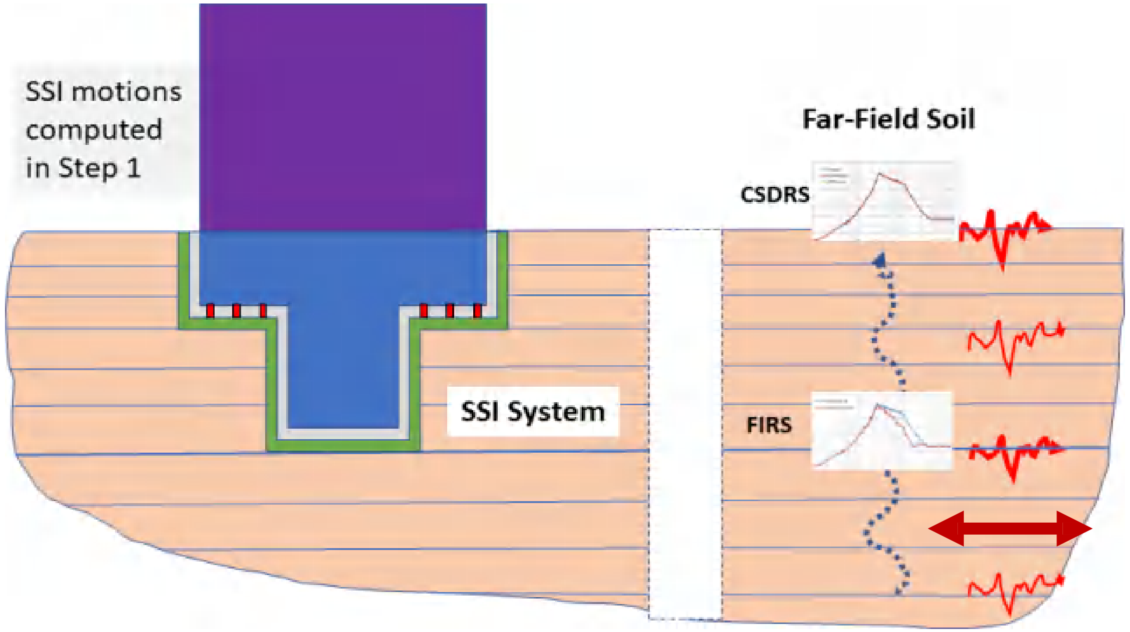
CSDRS Hard-Rock Site

Defining FIRS Input Motion for SSI Analysis

The in-column FIRS soil motions at the foundation level required for the SSI analysis were computed from the outcrop FIRS motions using the ACS SASSI SOIL module based on the SHAKE methodology.

The computed in-column FIRS were computed for the six soil variations (6 = 2 generic site conditions and 3 soil variations, BE, LB UB) and 11 seismic input sets for each soil variation.

A total of 66 FIRS input sets (= 2 x 33) were simulated.

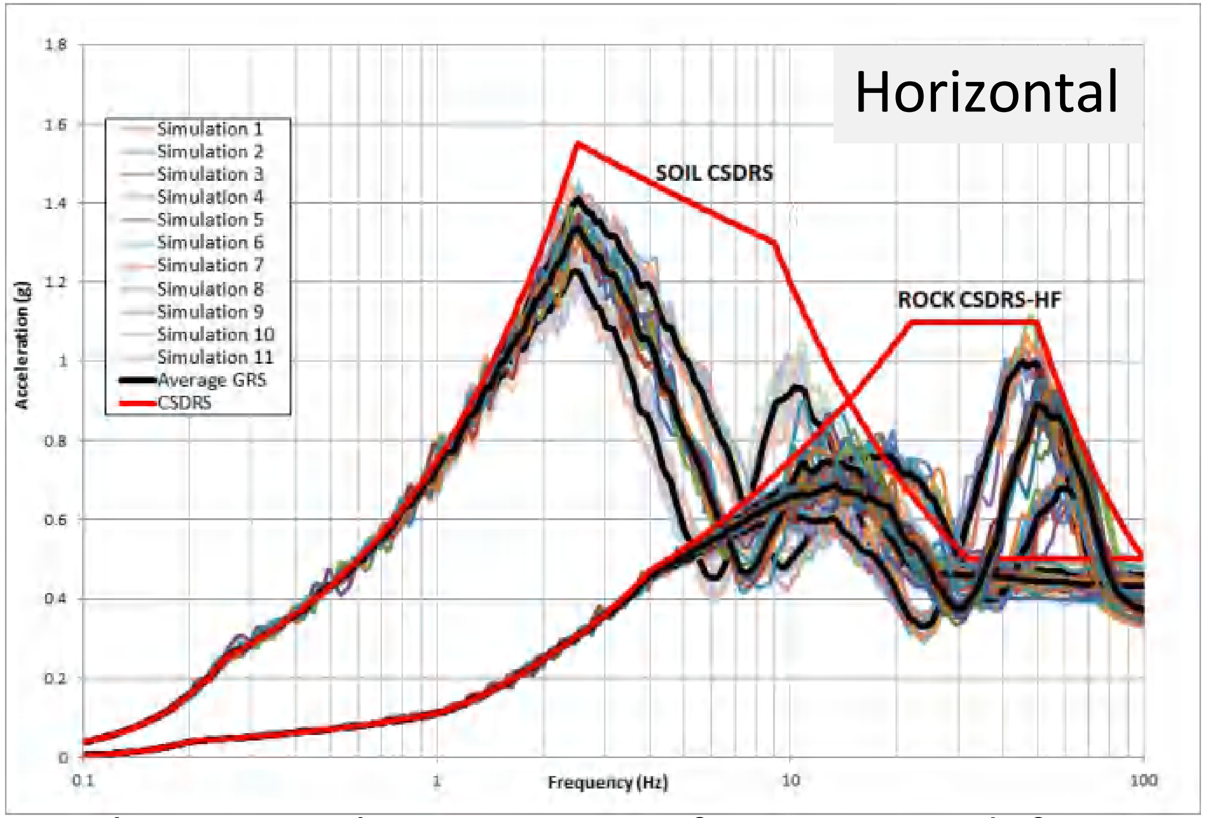


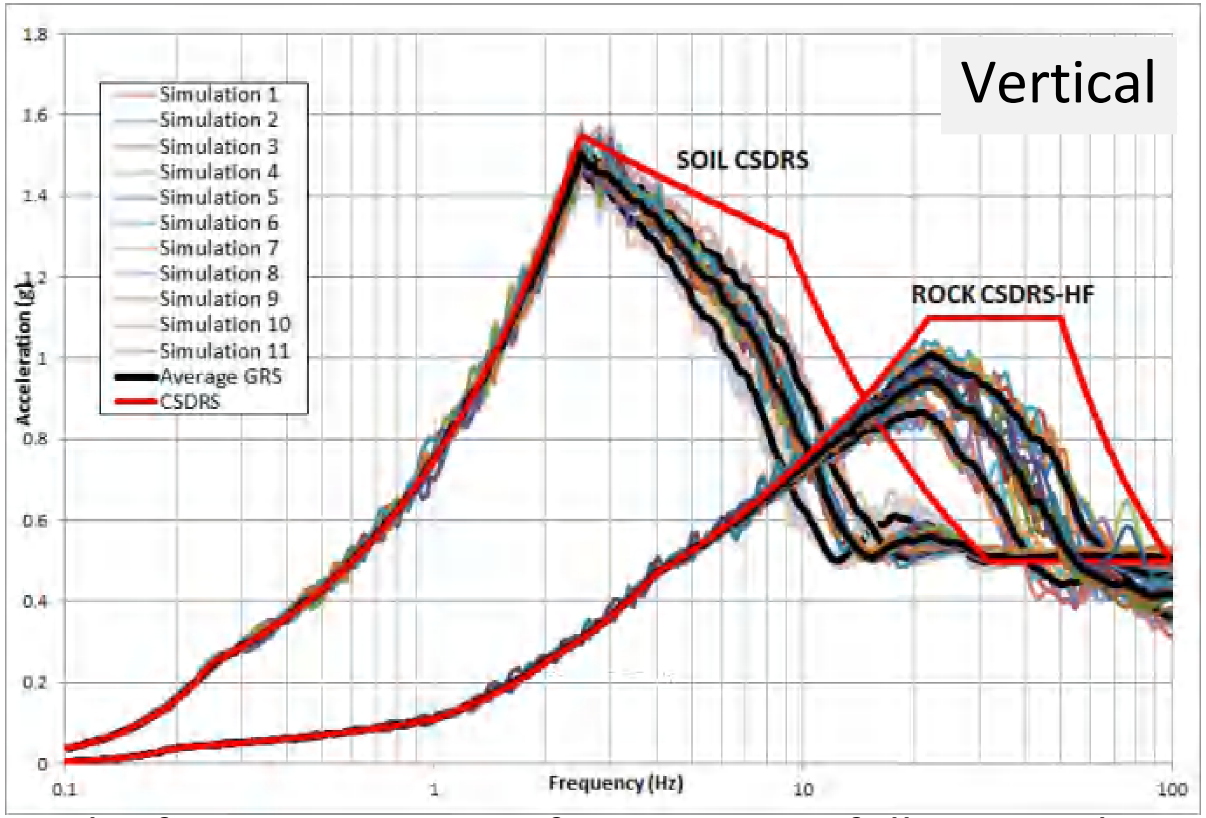
Generic Site Soil Properties including LB and UB Soil Bounding Variations

No.	Generic Soils (BE, LB, UB)	Specific Weight (kcf)	S-Wave Velocity (fps)	P-Wave Velocity (fps)	S-wave Damping	P-wave Damping
1	Firm Soil, BE	0.13	2000	4000	0.03	0.03
2	Firm Soil, LB	0.13	1633	3266	0.03	0.03
3	Firm Soil, UB	0.13	2450	4900	0.03	0.03
4	Hard Rock, BE	0.15	8000	16000	0.01	0.01
5	Hard Rock, LB	0.15	6530	13060	0.01	0.01
6	Hard Rock, UB	0.15	9800	19600	0.01	0.01

Considering Soil Dynamic Property Bounding Variations, LB and UB, assuming a 50% coefficient of variation for soil shear modulus. Well investigated sites.

Defining FIRS Motions for SSI Analysis (66 FIRS Sets)

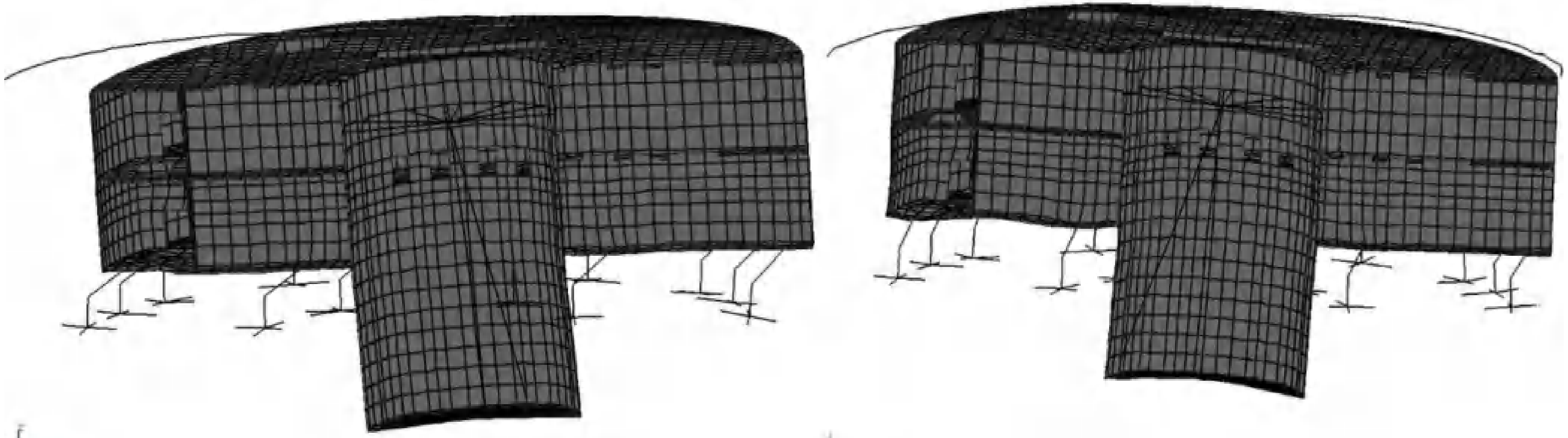




In-column FIRS show some significant power deficiencies in the frequency range of interests. To fully cover the noted frequency range deficiencies, additional soil sites should be considered.

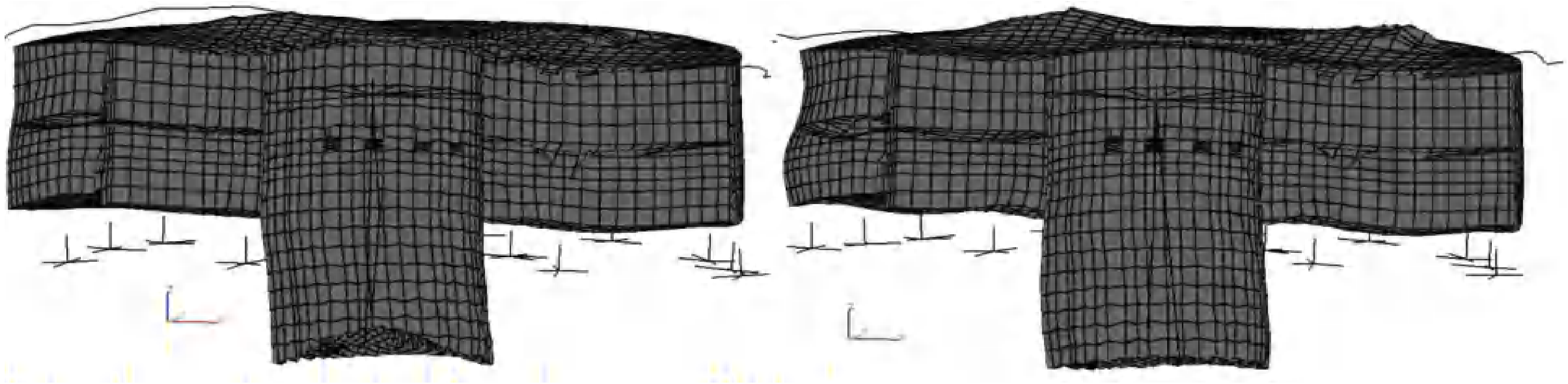
It was agreed that for the Advanced Conceptual Design study using only two generic site conditions is sufficient for demonstrating the appropriateness of the applied seismic SSI design-basis methodology for the deeply embedded base-isolated ARC-100 SMR structure for both the firm soil type and the rock type of sites.

Isolated Structure SSI Acceleration Response (Below Ground Surface Level) For Soil and Rock Sites



Underground Superstructure Acceleration at Two Instants for BE Soil Site

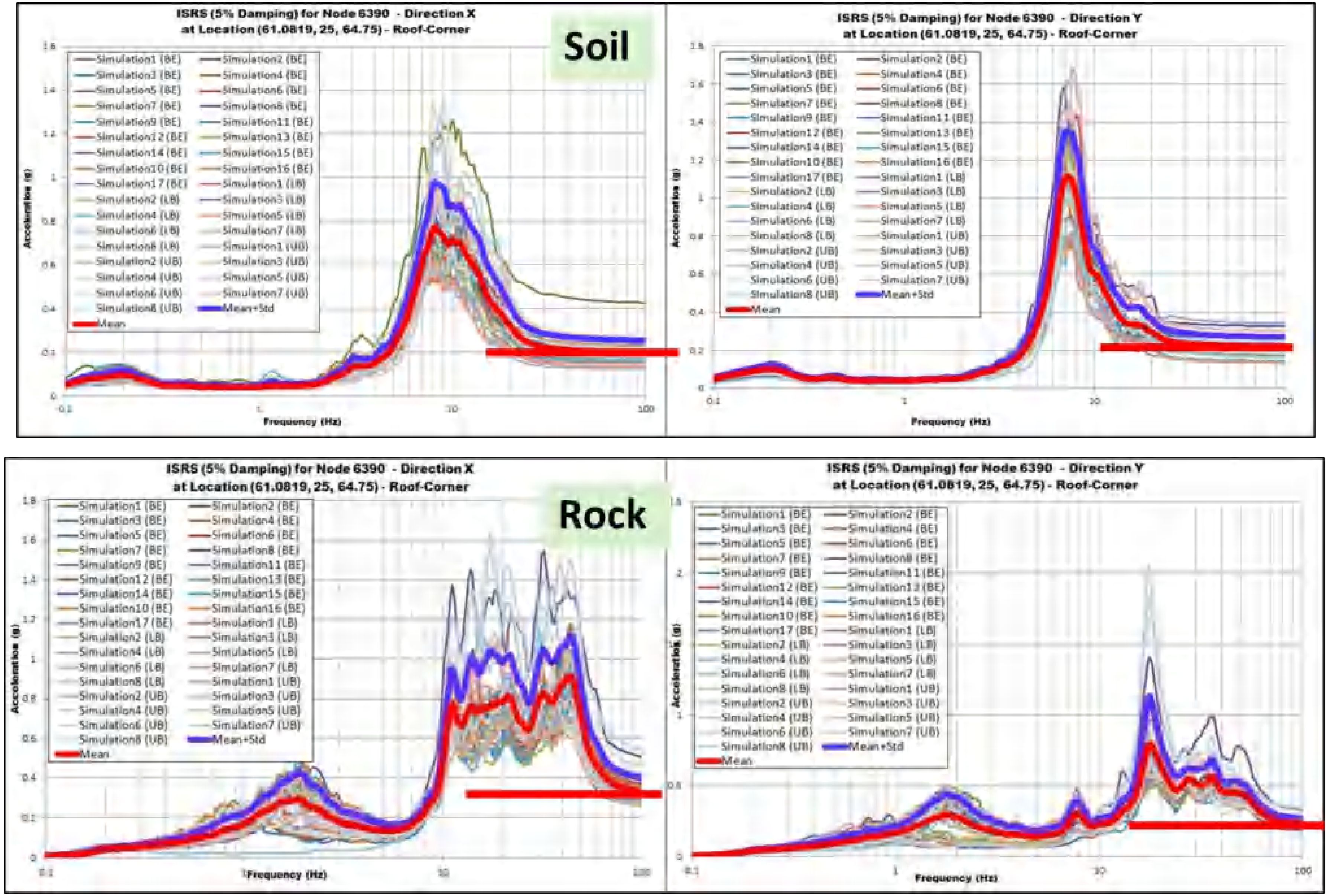
Soil Site



Underground Superstructure Acceleration at Two Instants for BE Rock Site

Rock Site

Mean and 80 NEP ISRS at Top of SMR Structure (El. 64.75 ft)



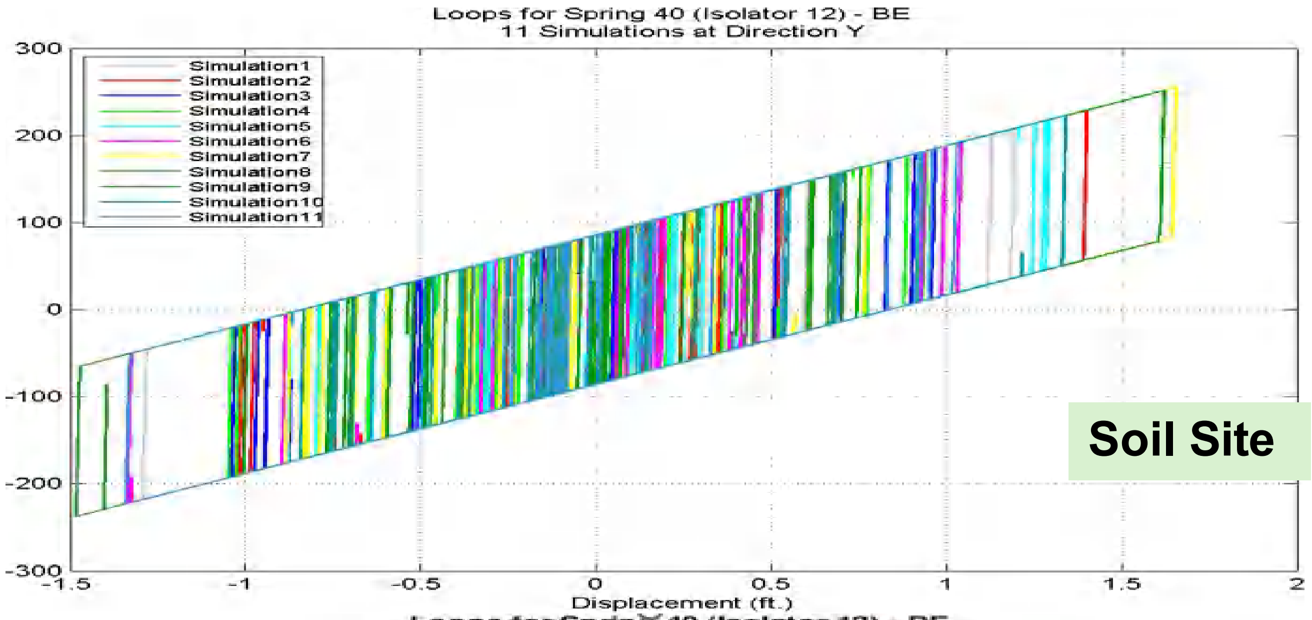
Mean and 80 NEP ISRS at SMR structure roof level (Node 6390) at Elevation 64.75 ft.

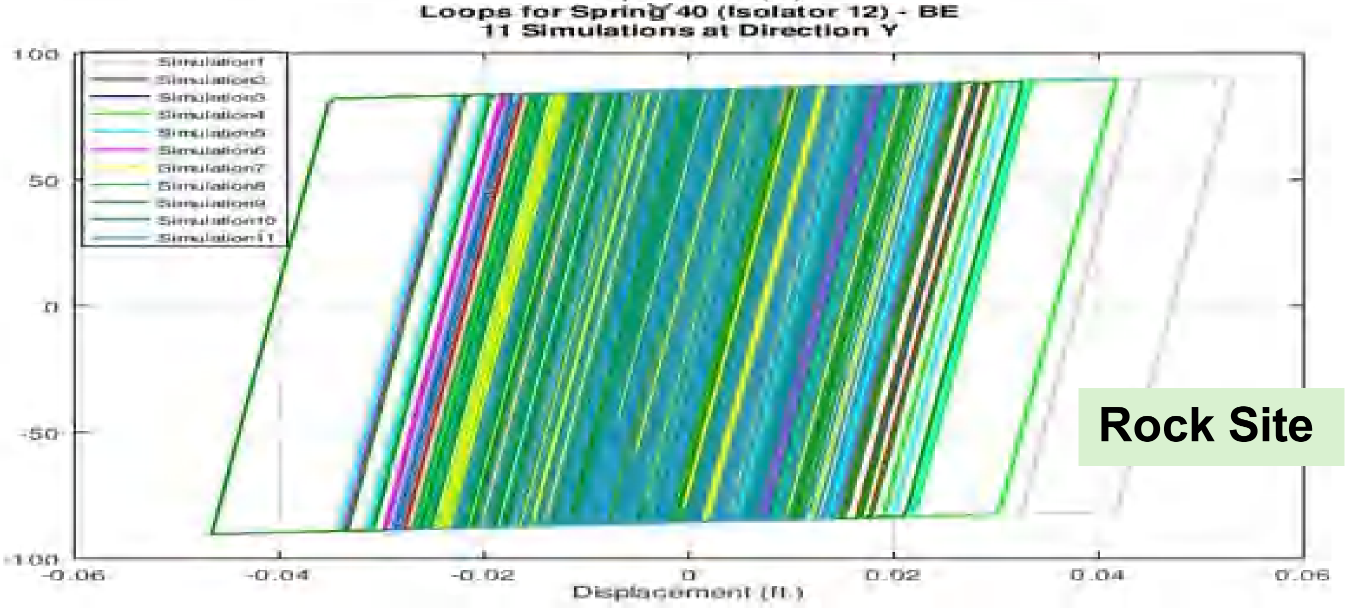
Based on 33 SSI simulations (11 inputs x 3 soil variations).

The maximum SSI accelerations are quite low, being only 0.20-0.25g for soil and 0.25-0.35g for rock, well below the 0.50g free-field ground surface acceleration.

(per SS24)

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 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.

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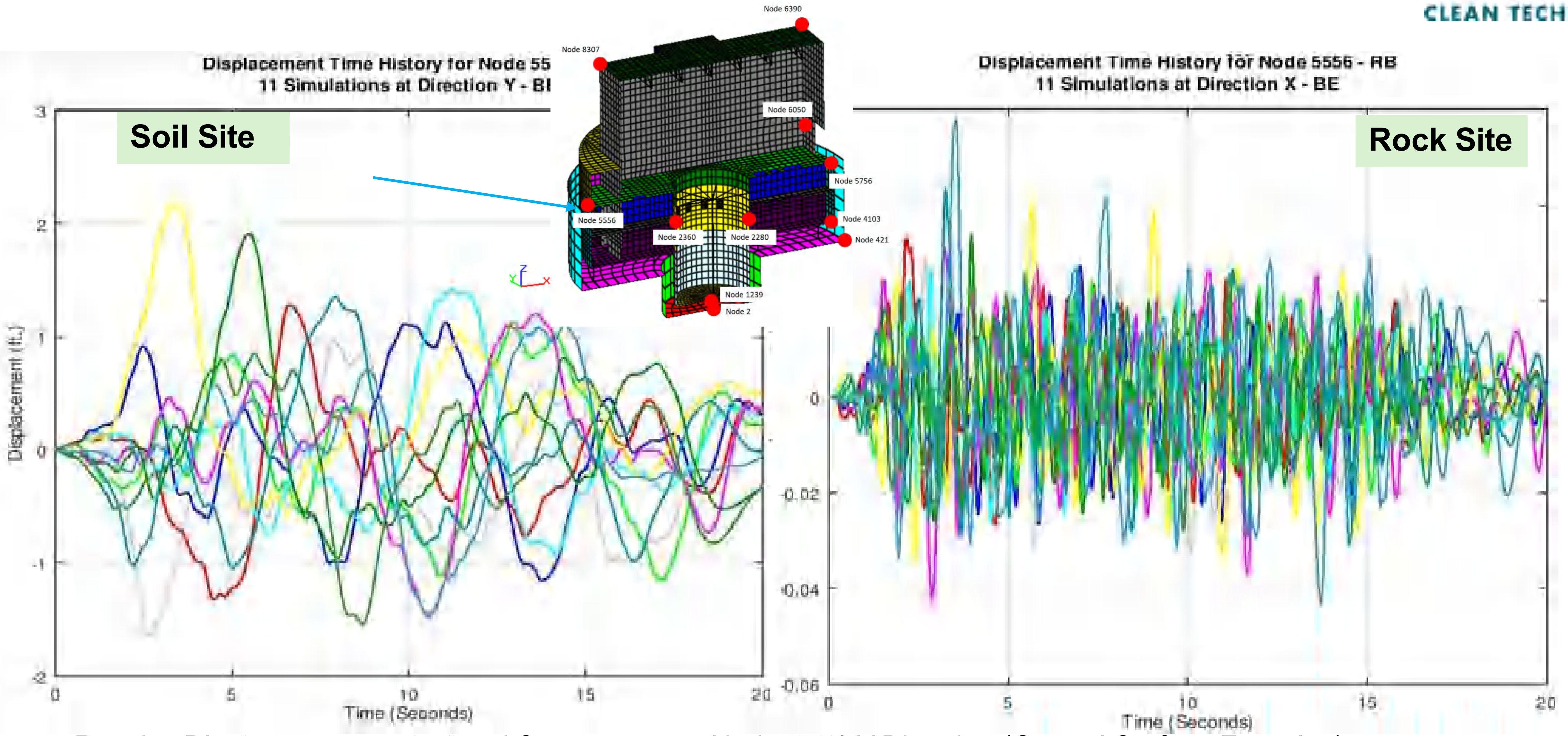
Relative Displacements at Ground Surface Level (Node 5556)



Relative Displacements at Isolated Superstructure Node 5556 Y-Direction (Ground Surface Elevation)

DETRIMENTAL DYNAMIC COUPLING BETWEEN RV SYSTEM AND ISOLATED STRUCTURE SSI RESPONSES FOR SOIL SITE AND REMEDIAL ACTIONS

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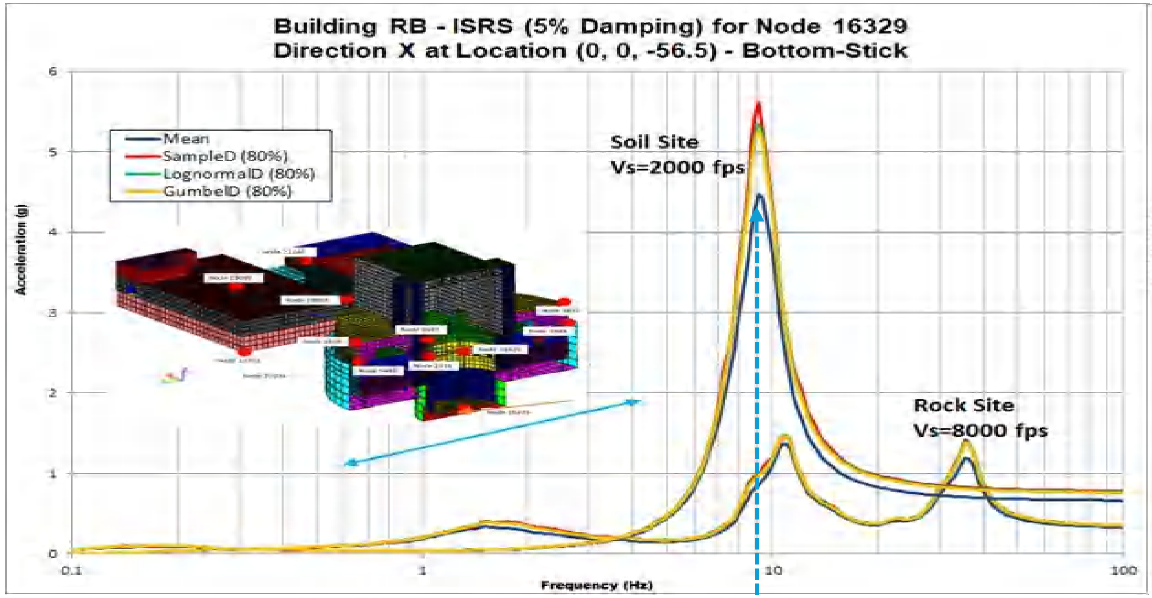
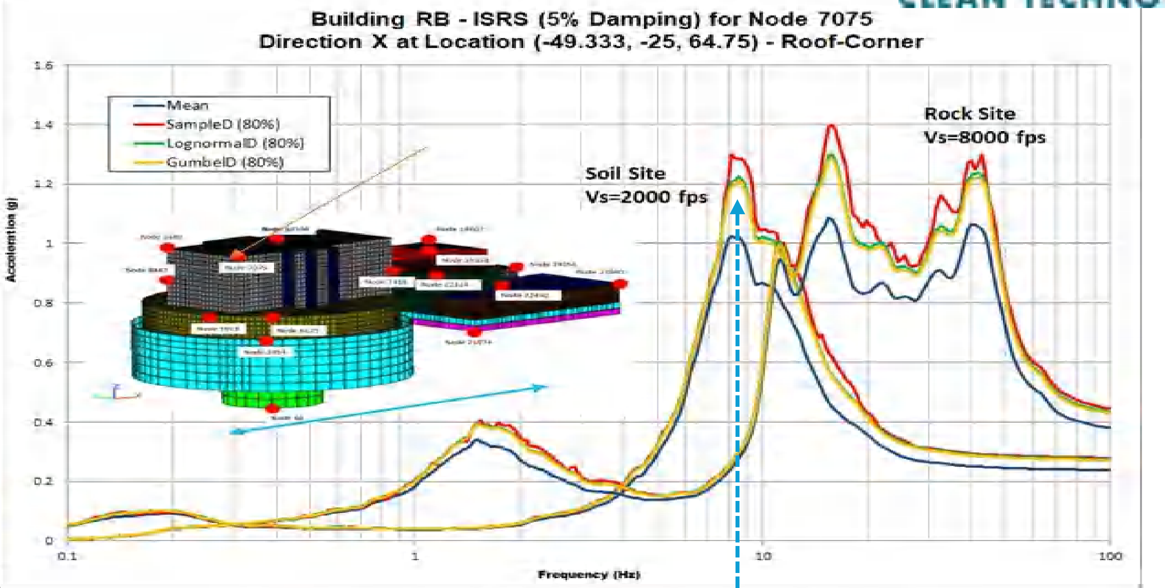
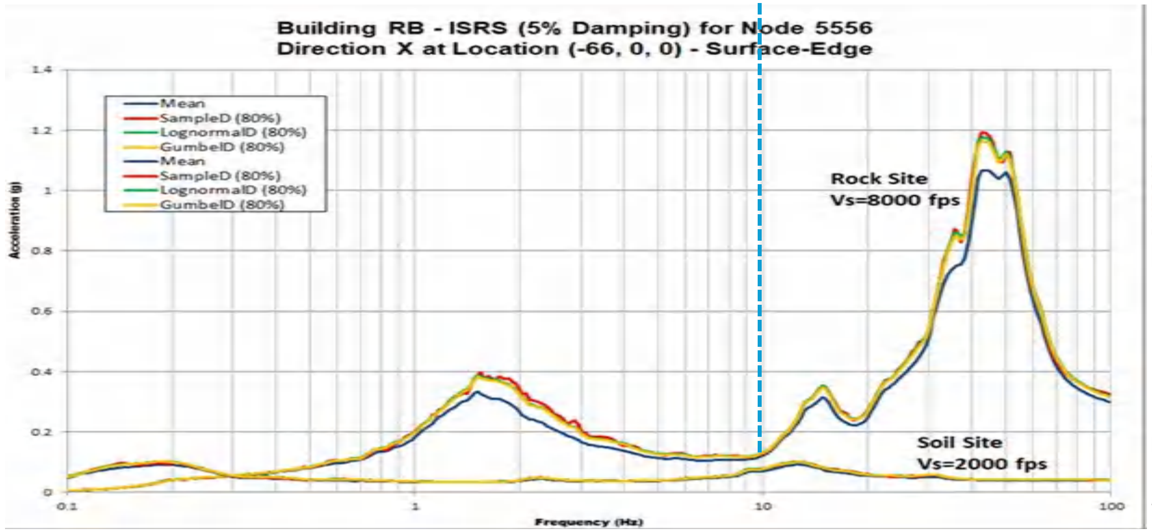
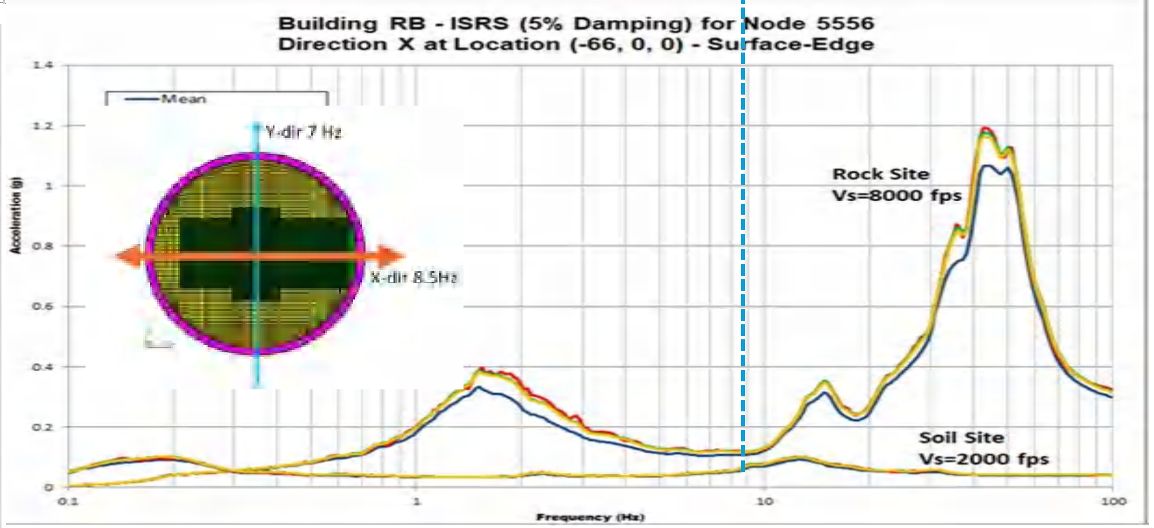
Mean and 80 NEP X-Dir ISRS at RV Stick Bottom and Roof



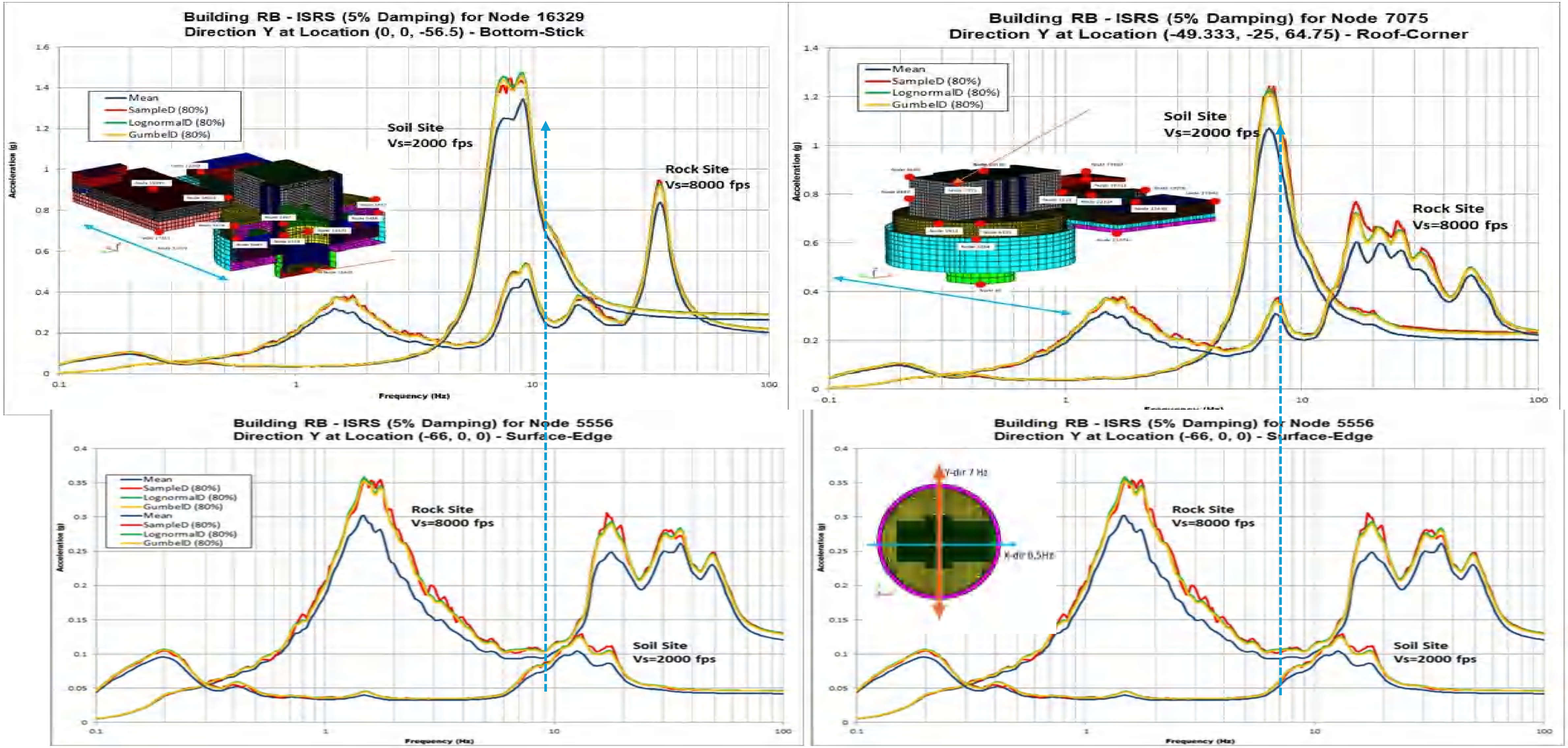






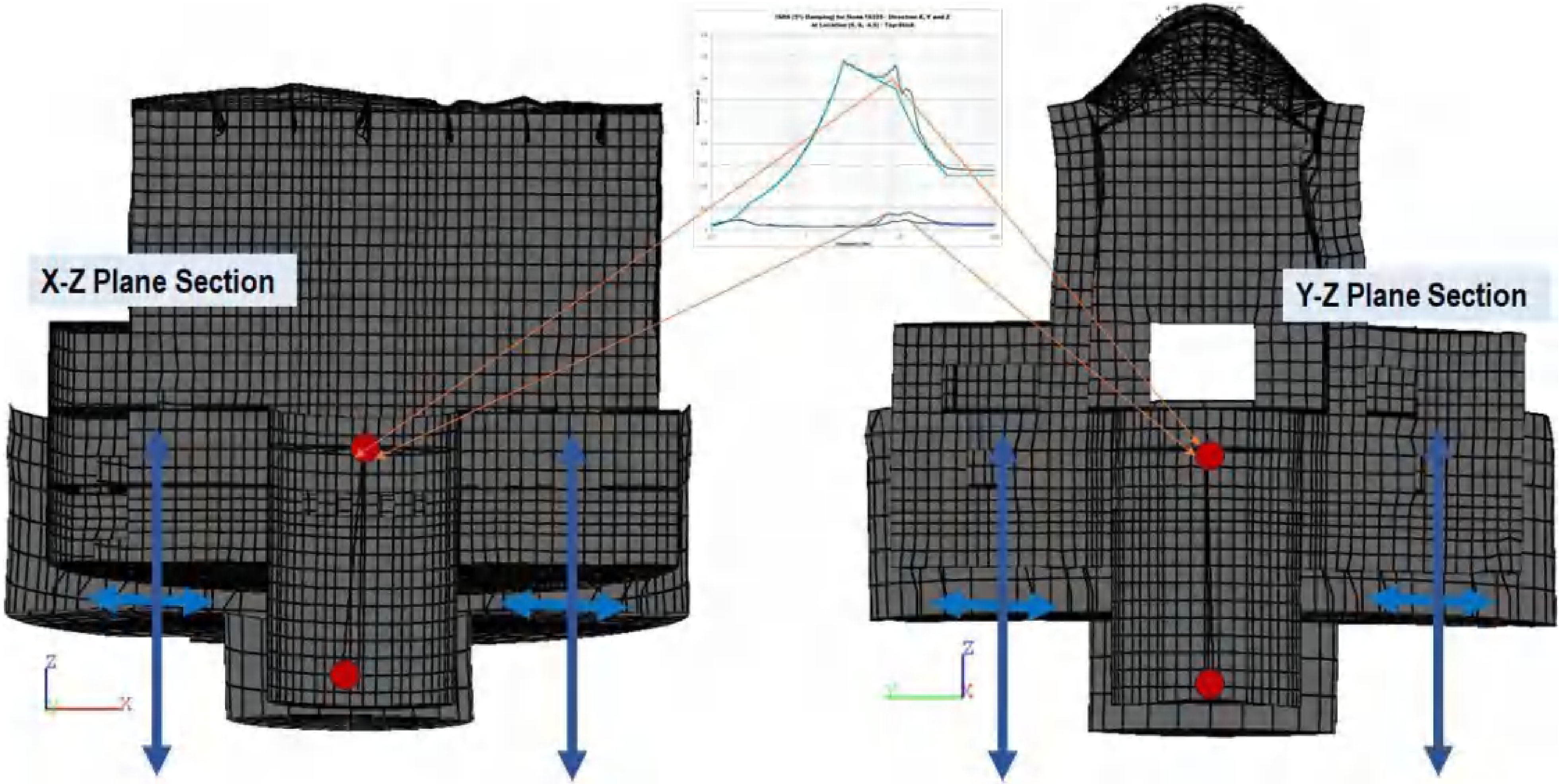
33

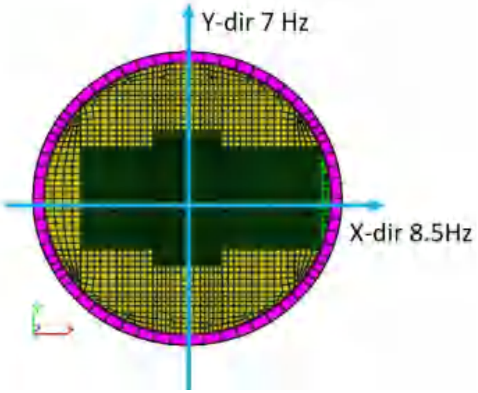
Mean and 80 NEP Y-Dir ISRS at RV Stick Bottom and Roof

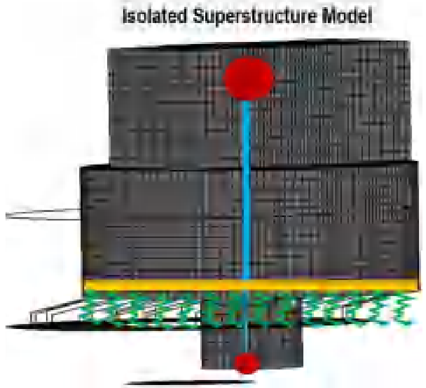


34

SMR Structural Accelerations in X and Y Directions for Soil







X-SMR Longitudinal

Y-SMR Transversal

RV Stick
X-dir 9 Hz
Y-dir 8.5 Hz
Z-dir 9 Hz

 35

Multiple Mode Frequency Tunning Produces A Severe Dynamic Coupling Between RV and Isolated Structure

The lack of perfect symmetry for the SMR structure in the X-Z plane produces a very small SSI rocking motion which for the soil site stiffness creates a certain condition for a large vibration energy transfer from the vertical response to the horizontal response due to a multiple SSI mode tunning.

It should be noted that this dynamic coupling is less visible for the Y-direction responses which appear totally independent of the vertical motion response. This dynamic coupling in X-direction due to multiple mode frequency tunning is strictly related to the SSI effects for the soil site stiffness corresponding to a soil shear wave velocity of 2,000 fps.

The dynamic mode coupling is also due to the limitation of the 2D FP isolators that are efficient only for the horizontal responses but have no effect on the vertical responses which remain large with large amount of vibration energy.

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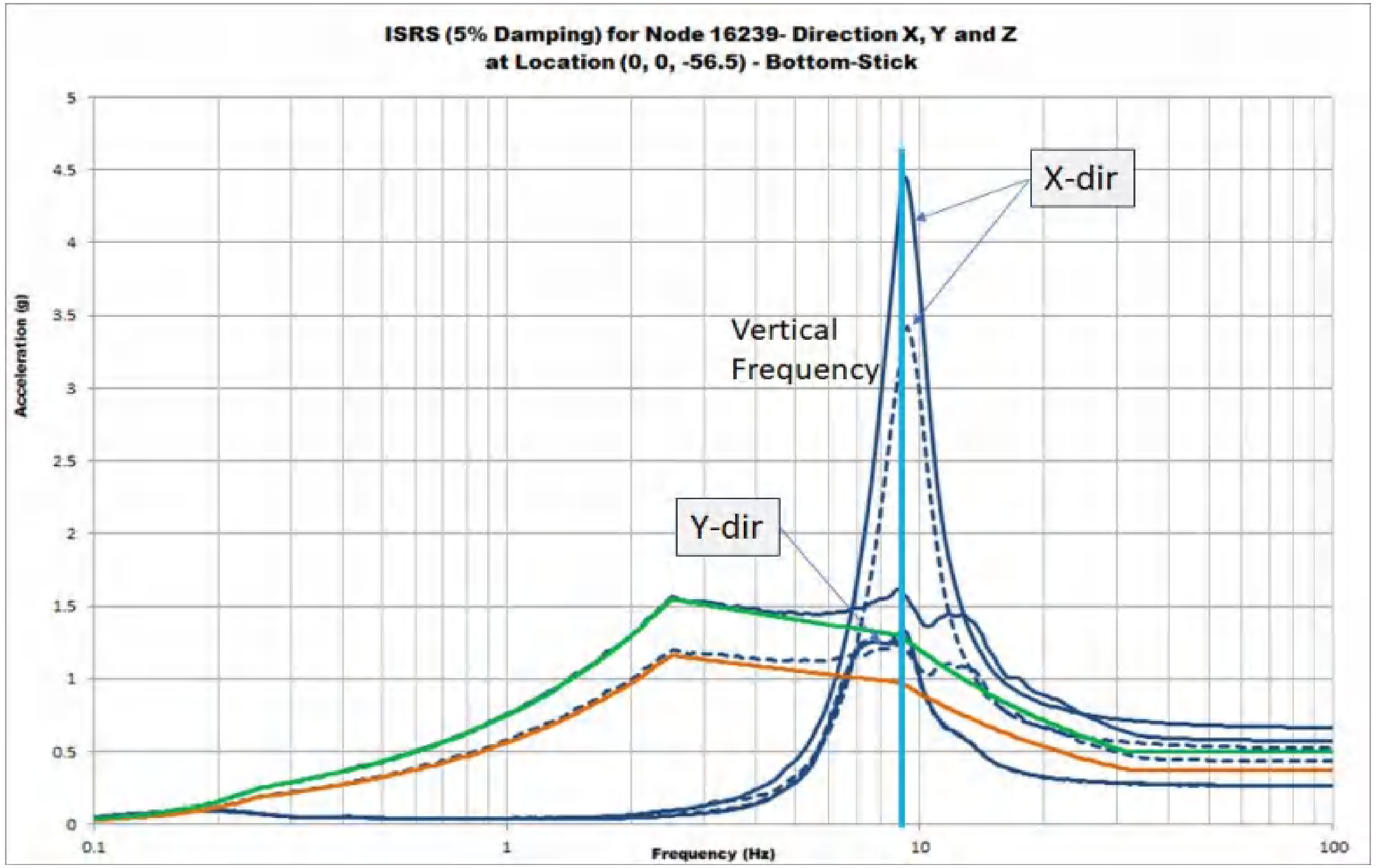
Quantitative Checking for Dynamic Coupling Effects

To add a quantitative checking measure for evaluating the dynamic coupling effects, we compared the ISRS computed at the RV stick bottom and at the top of SMR structure locations for the vertical input acceleration of 0.5 g and a 25% reduced vertical input acceleration, specifically 0.375g = 0.75 x 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).

Remedial Actions to Avoid Dynamic Coupling Effects

Due to these unacceptably high seismic responses of the RV and their effects on the Reactor Vessel and the internals which occurred for the soil site, some remedial actions have to be considered. Remedial actions could be based on either by adding a *local isolation for RV system*, or by considering a *global 3D isolation of the entire structure.*

So far, we included some preliminary calculations based on adding a local isolation for the RV system vibration. To reduce the large RV acceleration responses for the soil site in the X-direction, a *local 3D isolation system* was introduced at the RV stick beam supports.

Therefore, a *hybrid* isolation system was created by integrating the *global* isolation system using the 2D FP bearings with a *local* isolation system using the 3D GERB BCS devices (combined 3D Spring blocks, SB, and 3D high-viscosity dampers, HVD) placed at the RV top beam supports.

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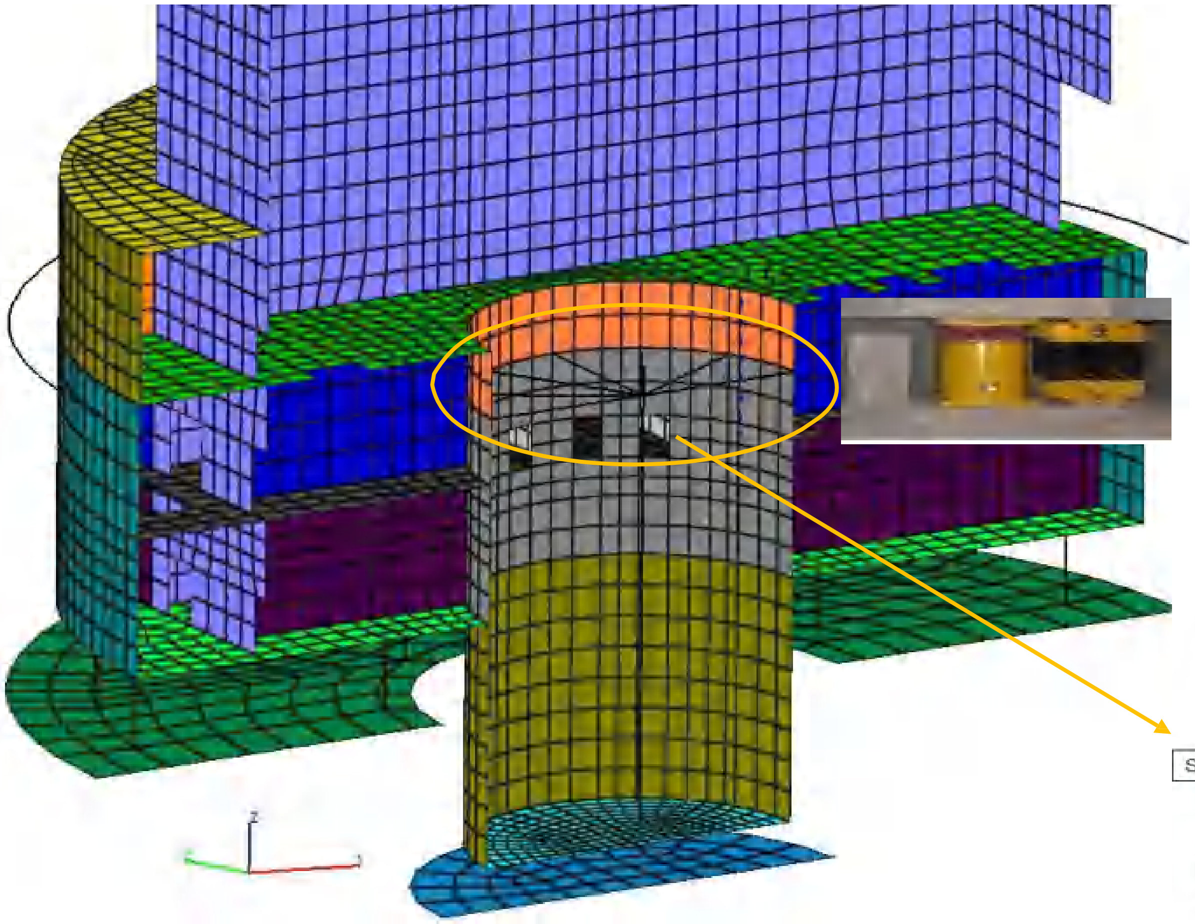
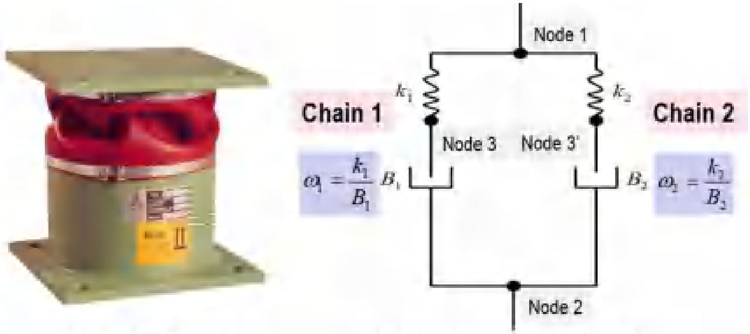
Adding BCS 3D Spring Blocks and 3D High-Viscosity Dampers

GERB BCS 3D Spring Block (SB) and 3D High-Viscosity Damper (HVD) Unit Deformation Under 120 mm Relative Lateral Displacements (TINCE 2018 Presentation Slides)

Remedial solution by creating a hybrid isolation system of the ARC-100 SMR structure by maintaining the global 2D FP-based isolation system and adding a local 3D BCS isolation system for the RV system Added BCS devices (SB and HVD units) at the RV beam supports avoid detrimental dynamic coupling .

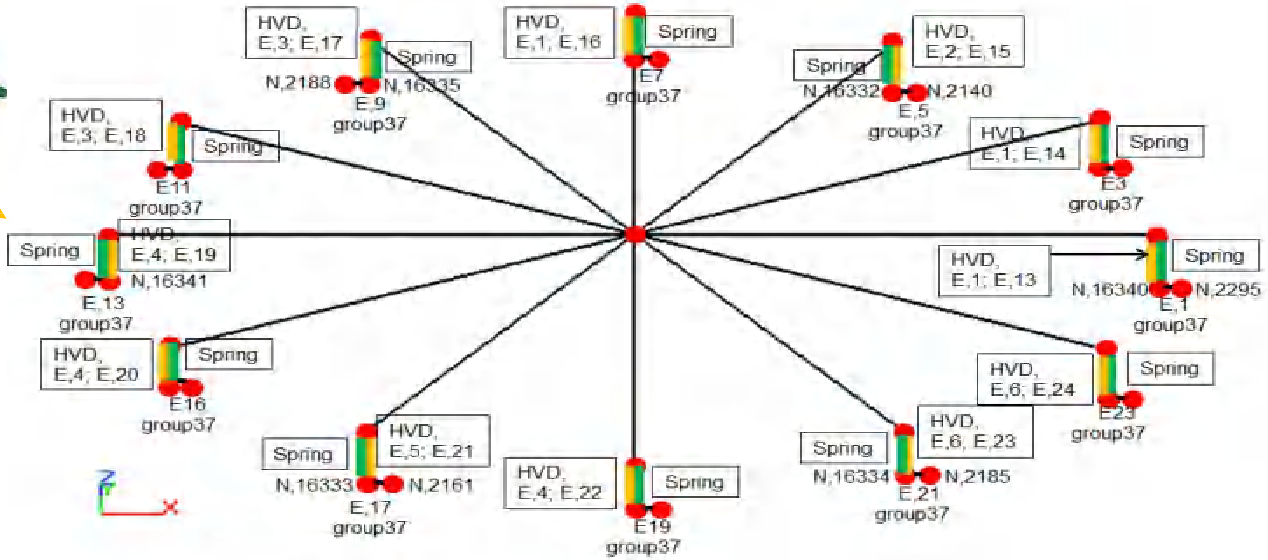
Adding GERB BCS 3 Isolation Devices at RV Beam Supports





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 (Kh, Kv, Bh, Bv) for each Maxwell chain. Total eight parameters for HVD unit.



40

SSI Models Including BCS 3D Local Isolation for RV System

The SSI results were compared for three models:

1) Model 0, the original FP base-isolated SMR model with no BCS devices
2) Model 1 and 2, hybrid isolation including the FP base-isolated SMR model and BCS devices for the local RV system base-isolation.

Models 1 and 2 have with slightly different BCS unit models.

For the preliminary calculations, only a single DBE seismic input set for the BE soil profile (Vs=2,000 fps) was considered.

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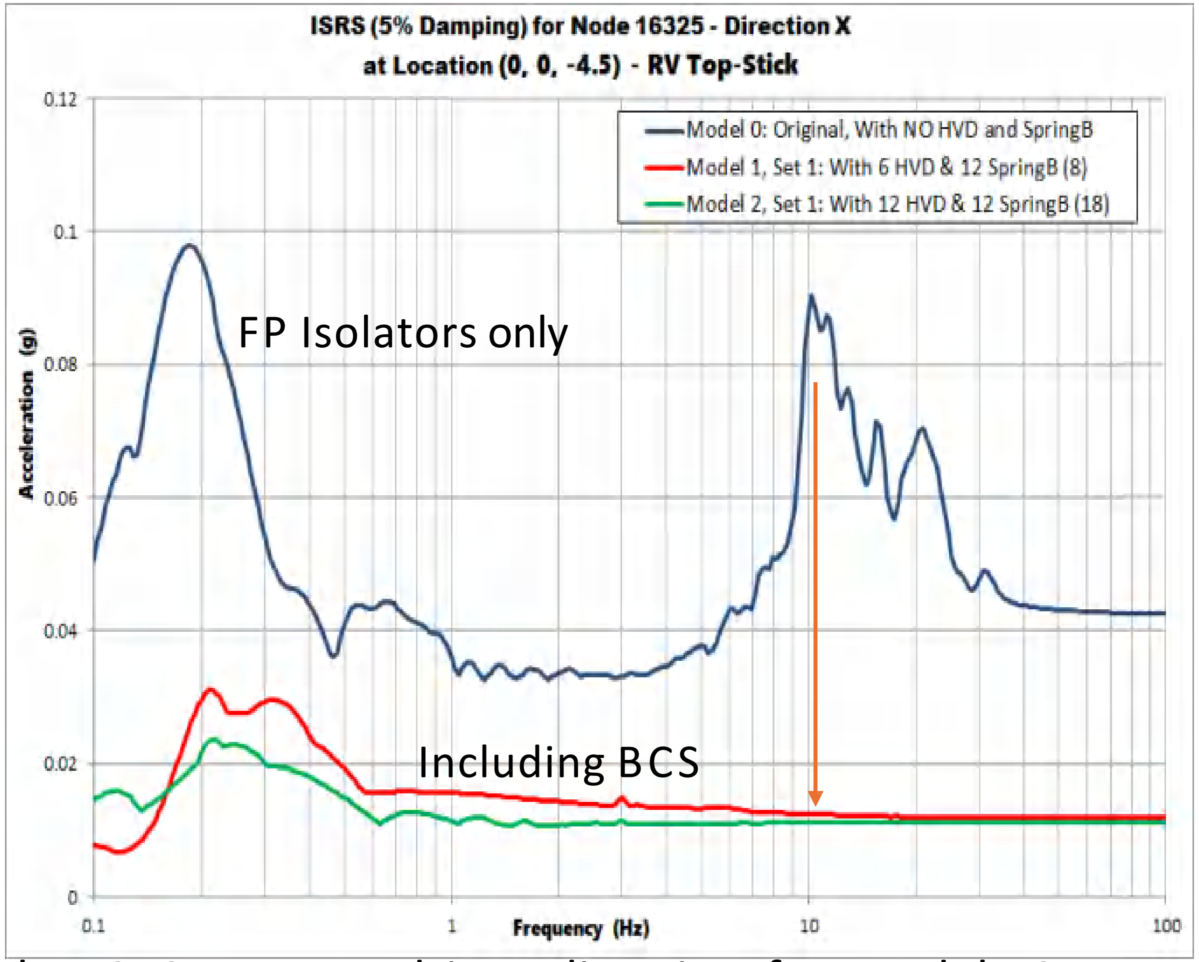
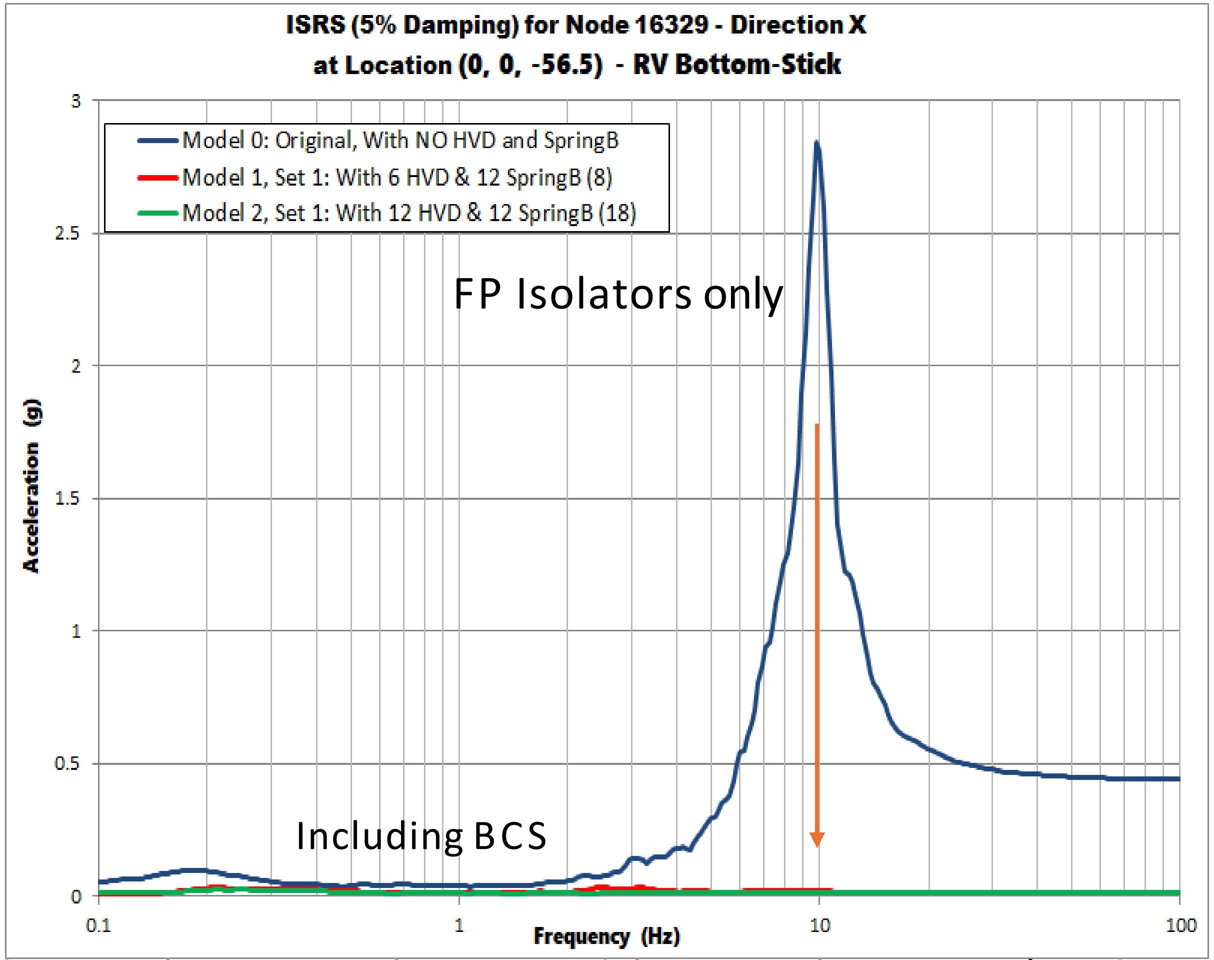
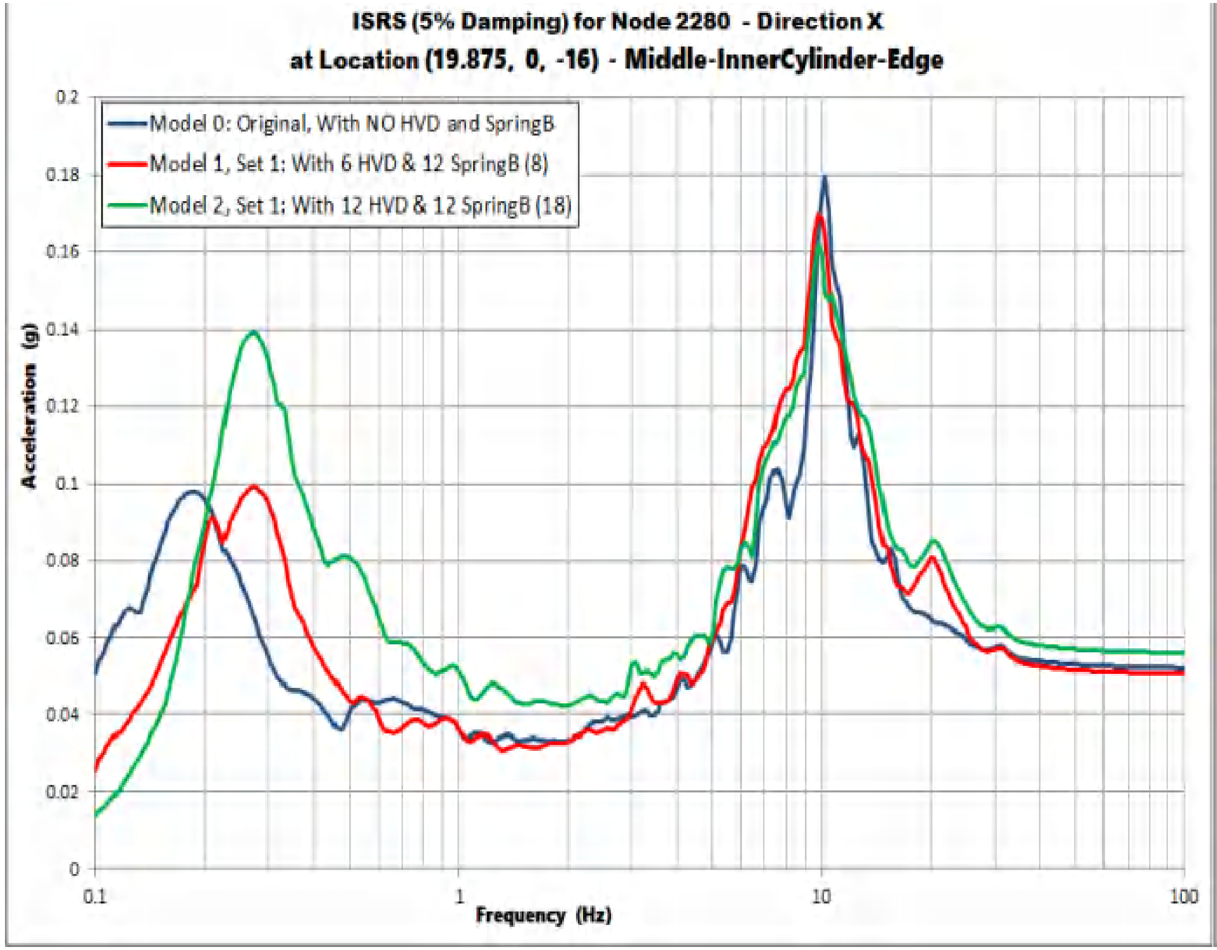
ISRS at RV Stick Top and Bottom Locations in X Direction

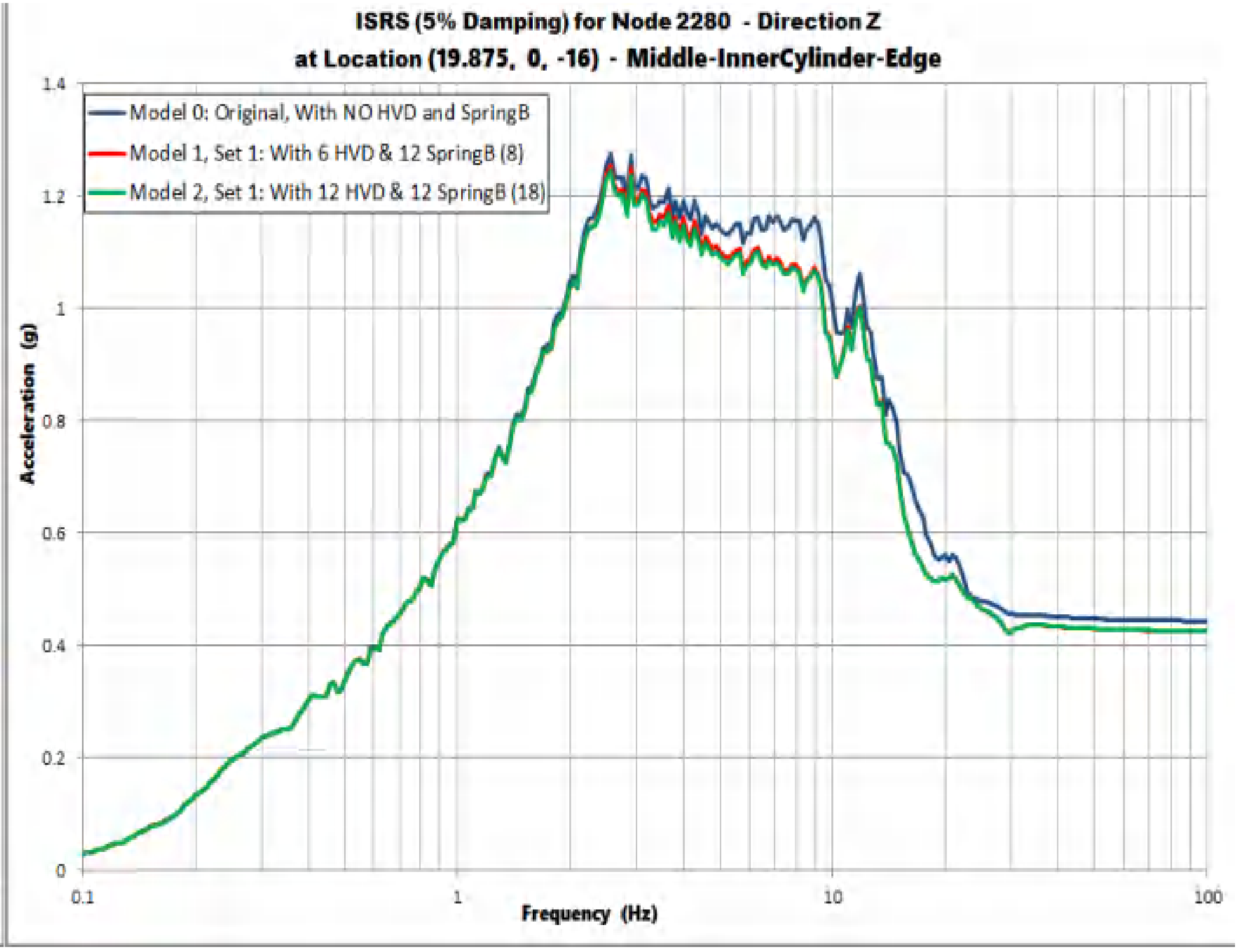




The ISRS computed in X-direction for Models 0, 1 and 2 at the RV stick top and bottom locations (Nodes 16235 and 16239) show that by introducing the 3D isolation devices at the RV beam supports (for Models 1, 2) drastically reduces the RV system horizontal acceleration responses.

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.

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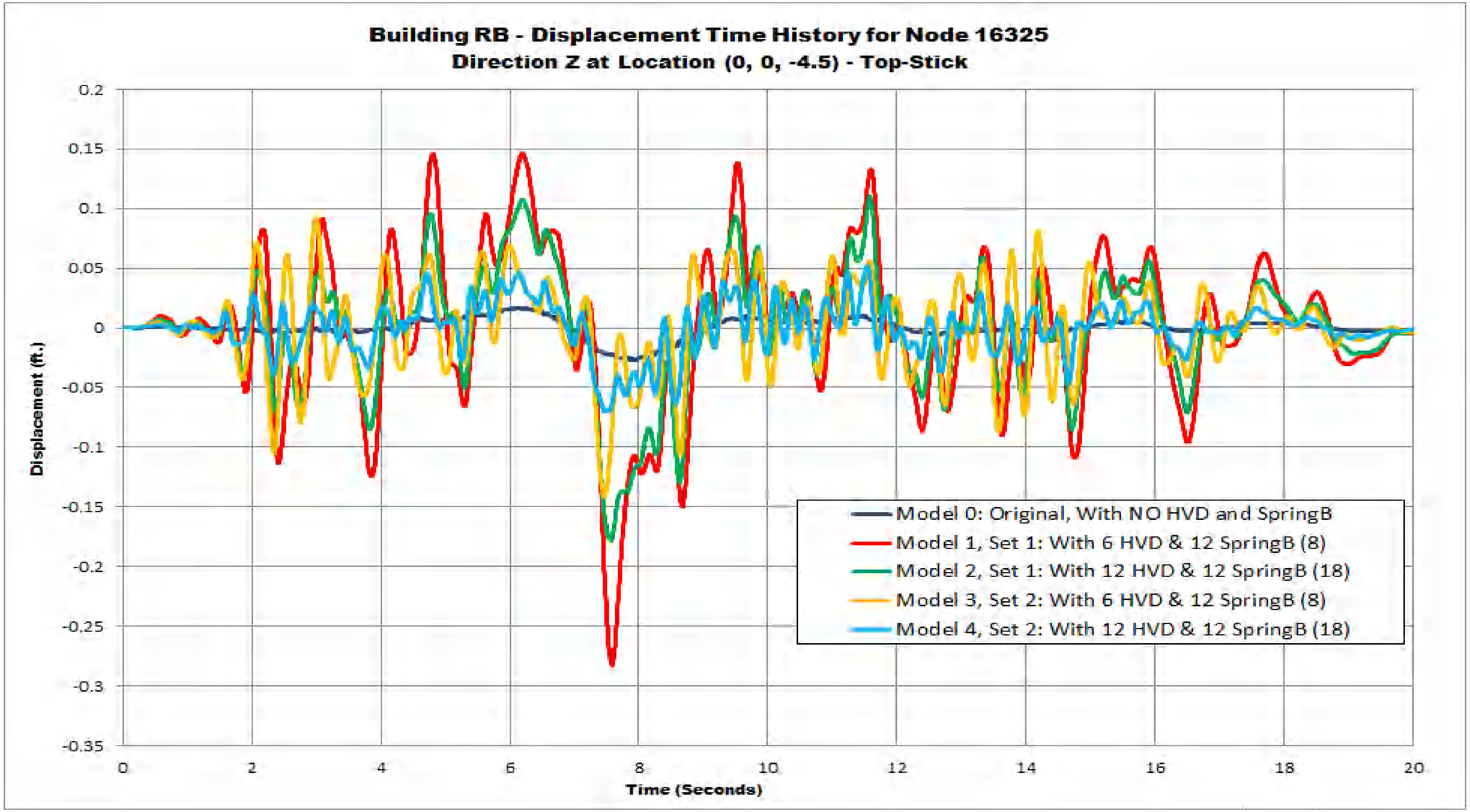
RV Stick Top Vertical Displacements for Different BCS Units



Remedial Solution Using A Hybrid Isolation System

These preliminary calculations show that the BCS devices are extremely efficient for the *local* 3D base-isolation of the RV system by reducing its lateral acceleration responses and have only a negligible impact on the *global 2D* base-isolation of the SMR superstructure.

At the same time, the ISRS results for all three models, Models 0, 1 and 2, show very close results. As expected, the ISRS in the vertical direction show that the local 3D isolation devices placed at the RV supports do not bring any isolation improvement in the vertical direction.

These preliminary results indicate that a *hybrid* isolation system for ARC-100 SMR could be desirable for avoiding potential dynamic coupling between the superstructure and the RV system responses.

Remedial Solution Using A Global 3D Isolation System

A *global 3D* base-isolation using BCS devices for the entire SMR structure could provide a substantial isolation system improvement for the vertical direction.

The *global 3D* base-isolation will need only one step SSI methodology (linearized SSI analysis) which will be much more cost-effective since the BCS devices have a time-invariant linear behavior, not a nonlinear hysteretic behavior.

The BCS 3D viscous dampers are frequency-dependent, but they have linear behavior.

- Cut seismic SSI analysis time by 50% or more (use restart for same soil profile).
- Avoids difficulties in defining the interface between Step 1 and Step 2.
- More accurate results (no simplification assumption for foundation stiffness)
- Simpler to check by peer reviewers and NRC staff.
- The DBE and BDBE SSI results are linear and can be scaled for same soil profile.

Seismic SSI Sensitivity Studies for Establishing Final Design-Basis Seismic Methodology for ARC-100 SMR

Some preliminary sensitivity investigations were performed based on the overall seismic SSI analysis using the ACS SASSI NON software.

Per the ASCE 4-16 standard requirement, if a sensitivity investigation indicates that the DBE demand increase by more than 10% from the design-basis modeling due to an input parameter modification to cover an inherent variability, then that the input parameter modification becomes an intrinsic part of the design-basis analysis.

The final design-basis SSI analysis methodology and procedures shall consider all DBE response sensitivity effects that can significantly affect the SMR design safety margins. The design-basis model parameters and the SSI inputs should be adjusted accordingly, based on sensitivity study results to properly capture the effects of all significant input variations and modeling uncertainties.

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.

Detailed results are available and can be provided.

Reactor Building structural design

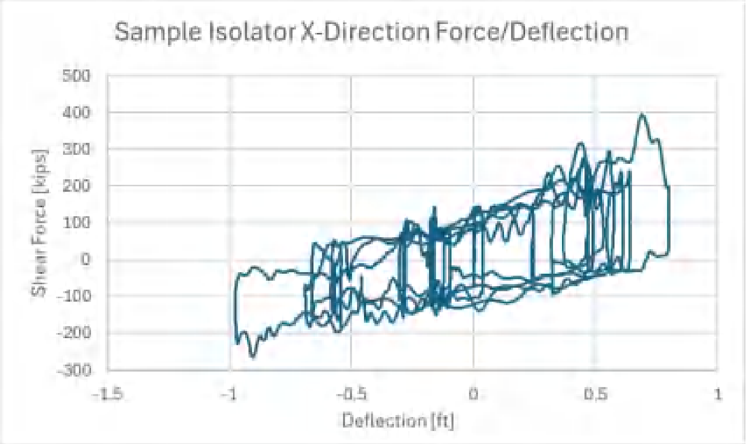
Jeff Pieper (UECI/Hopper Engineering)

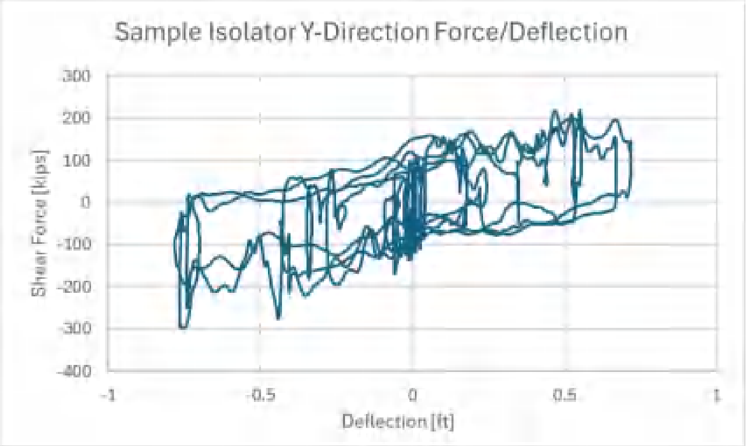
Nonlinear Time-Domain Analysis of Reactor Building

- “Step 2” of the ASCE 4-16 multi-step solution.
- Performed in SAP2000 which includes nonlinear element specifically for Friction Pendulum isolators.
- Isolator properties developed by Prof. Constantinou are applied in the model.
- Base of isolators is fixed. Loading is by acceleration time histories output from SSI analyses.
- Note: SAP2000 model for “Step 2” includes an updated Reactor Vessel Lumped Mass Stick Model – minor deviation from SSI model.
- (15) soils site DBE cases have been run using pedestal base time histories directly from SSI.

Selected Representative Responses

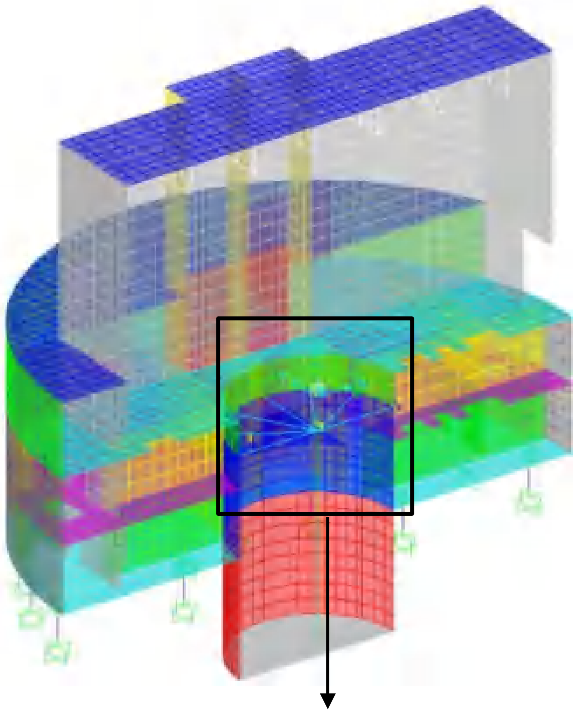
Soil Variation	Iteration No.	Max. Isolator Displ. (Polar) [in]	X-Dir. Base Shear		Y-Dir. Base Shear		Peak ISRS Spectral Accelerations at RV Support (3% of Critical Damping)			Peak ISRS Spectral Accelerations at Pedestal Base (SIDRS) (5% of Critical Damping)			Peak ISRS Spectral Accelerations at Operating Floor / Silo Wall (5% of Critical Damping)		
			Base Shear [kip]	Ratio to Total Weight	Base Shear [kip]	Base Shear to Weight Ratio	X-Dir. (g)	Y-Dir. (g)	Z-Dir. (g)	X-Dir. (g)	Y-Dir. (g)	Z-Dir. (g)	X-Dir. (g)	Y-Dir. (g)	Z-Dir. (g)
BE	1	18.4	11,904	0.192 g	12,337	0.198 g	0.46	0.57	2.20	1.32	1.31	1.48	0.38	0.54	1.68
BE	2	24.2	10,844	0.175 g	9,510	0.153 g	0.42	0.58	2.19	1.33	1.31	1.47	0.38	0.60	1.60
BE	3	19.5	9,371	0.151 g	10,062	0.162 g	0.40	0.45	2.22	1.32	1.33	1.52	0.34	0.41	1.57
BE	4	21.5	11,477	0.185 g	9,451	0.152 g	0.44	0.53	2.07	1.33	1.34	1.51	0.40	0.50	1.64
BE	5	14.3	10,077	0.162 g	8,322	0.134 g	0.45	0.64	2.34	1.32	1.31	1.48	0.38	0.50	1.75
LB	1	18.1	11,408	0.184 g	11,693	0.188 g	0.40	0.57	2.04	1.25	1.25	1.46	0.34	0.48	1.50
LB	2	24.3	7,619	0.123 g	10,601	0.171 g	0.42	0.55	2.12	1.25	1.24	1.45	0.38	0.47	1.56
LB	3	19.4	9,310	0.15 g	9,969	0.16 g	0.40	0.45	2.16	1.25	1.25	1.49	0.34	0.39	1.54
LB	4	21.4	11,362	0.183 g	9,203	0.148 g	0.43	0.51	2.07	1.26	1.27	1.48	0.38	0.43	1.52
LB	5	14.2	9,905	0.159 g	8,083	0.13 g	0.44	0.61	2.12	1.24	1.25	1.46	0.37	0.47	1.49
UB	1	18.3	12,346	0.199 g	12,433	0.2 g	0.45	0.57	2.38	1.37	1.37	1.50	0.38	0.61	1.80
UB	2	24.6	8,396	0.135 g	11,148	0.179 g	0.43	0.61	2.74	1.40	1.36	1.50	0.38	0.70	1.96
UB	3	19.5	9,255	0.149 g	10,342	0.166 g	0.40	0.47	2.26	1.37	1.39	1.55	0.34	0.53	1.60
UB	4	21.8	11,655	0.188 g	9,526	0.153 g	0.50	0.57	2.32	1.38	1.40	1.54	0.45	0.53	1.59
UB	5	14.6	10,443	0.168 g	8,362	0.135 g	0.45	0.68	2.44	1.37	1.38	1.51	0.38	0.52	1.86
80th %-tile (D_D)		**22.3**	11,513	0.185 g	11,257	0.181 g	**0.45**	**0.61**	**2.35**	**1.37**	**1.37**	**1.51**	**0.38**	**0.55**	**1.76**
50th %-tile (D_{50})		***19.5***	*10,443*	*0.168 g*	*9,969*	*0.16 g*	***0.43***	***0.57***	***2.20***	***1.32***	***1.31***	***1.49***	***0.38***	***0.50***	***1.60***
Mean		***19.6***	*10,358*	*0.167 g*	*10,069*	*0.162 g*									

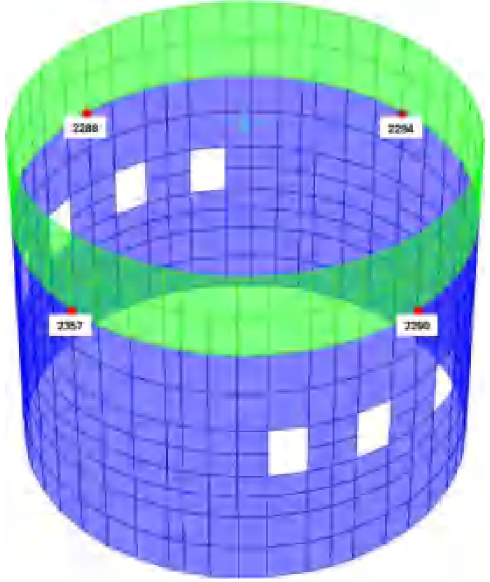


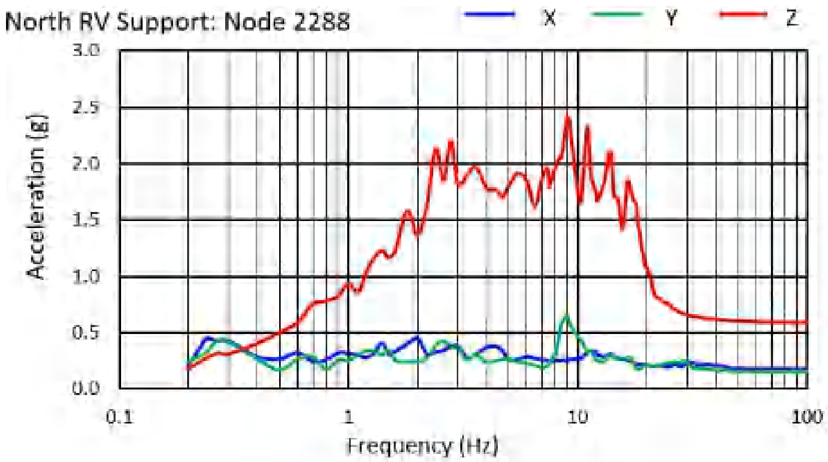


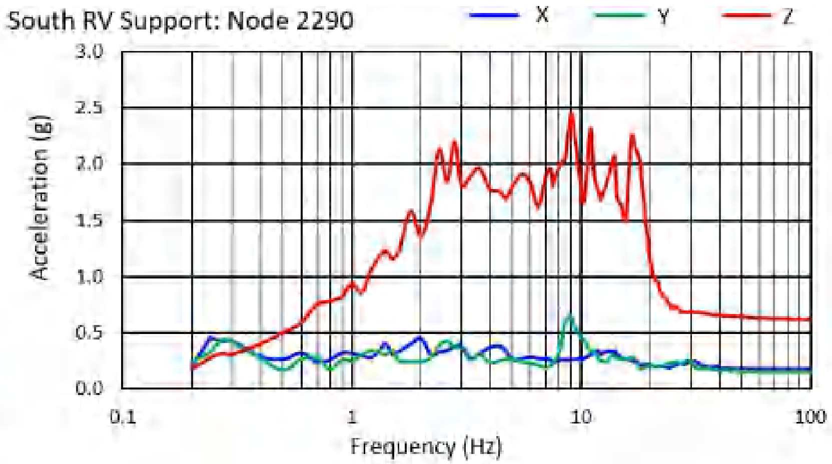
ISRS at RV Supports

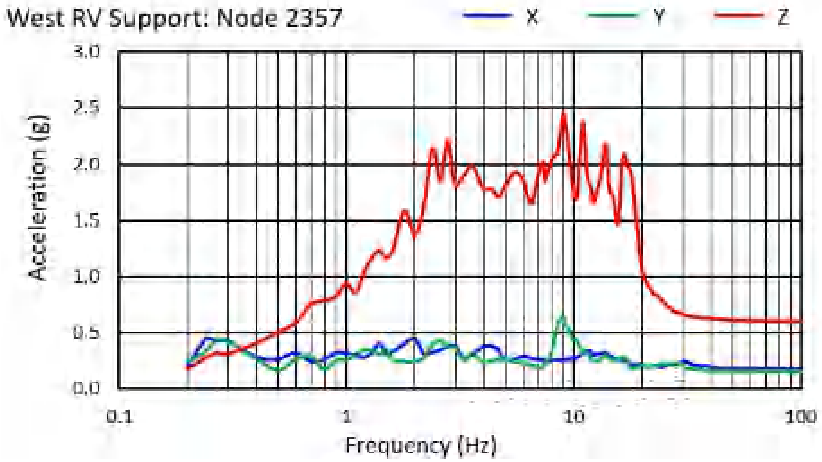
Raw, 3% Damping

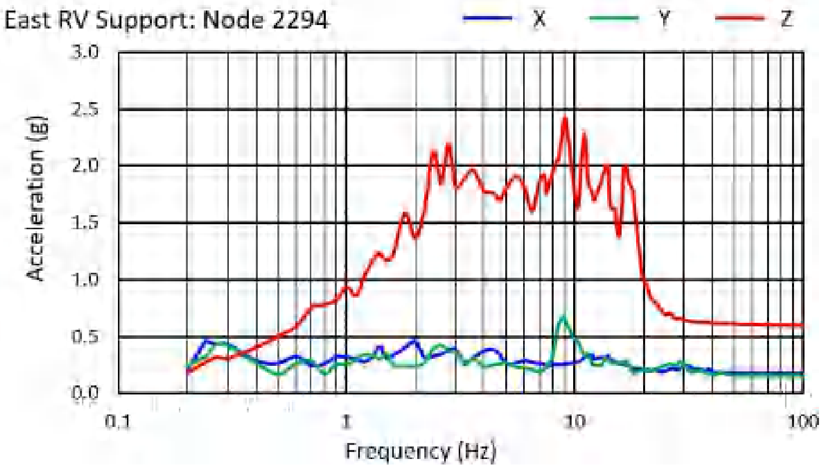






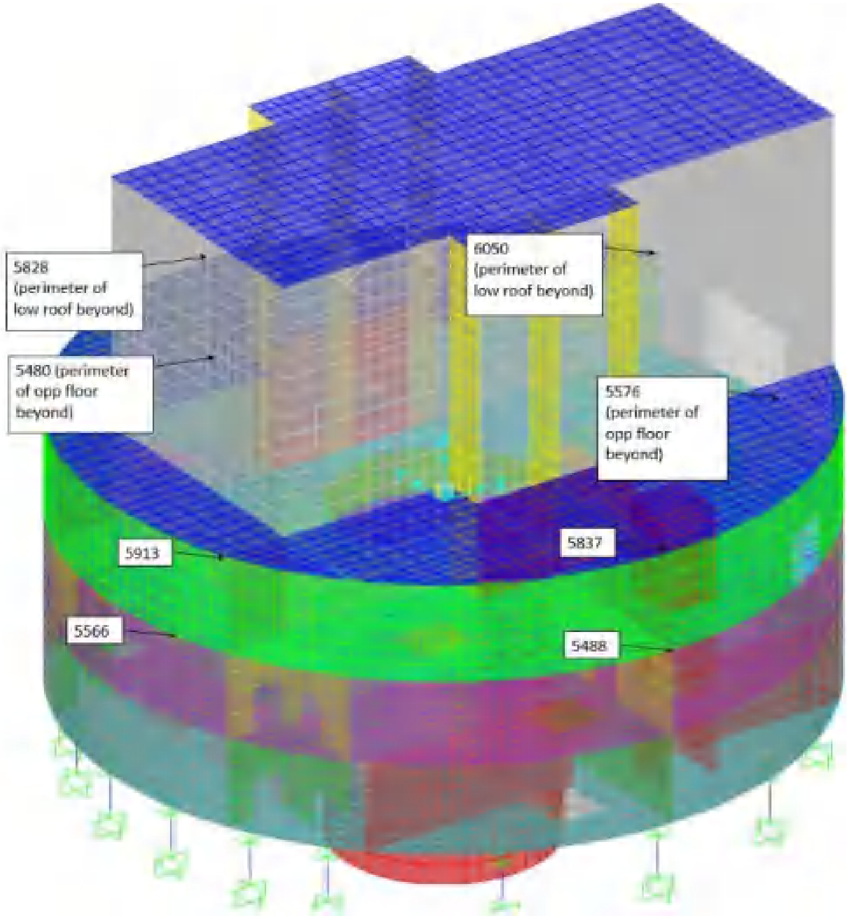






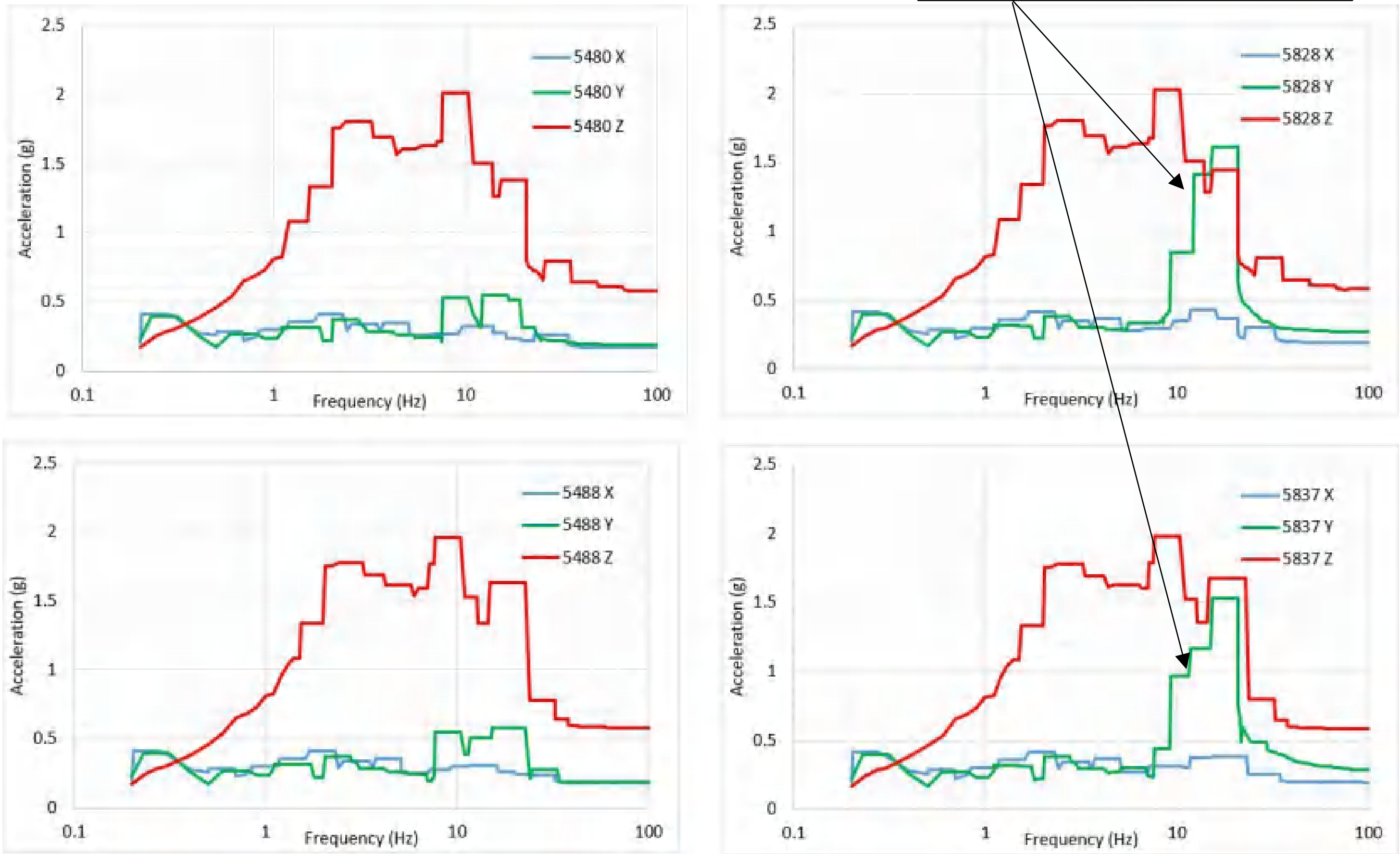
DRACS Supports

15% Broadening, 4% Damping



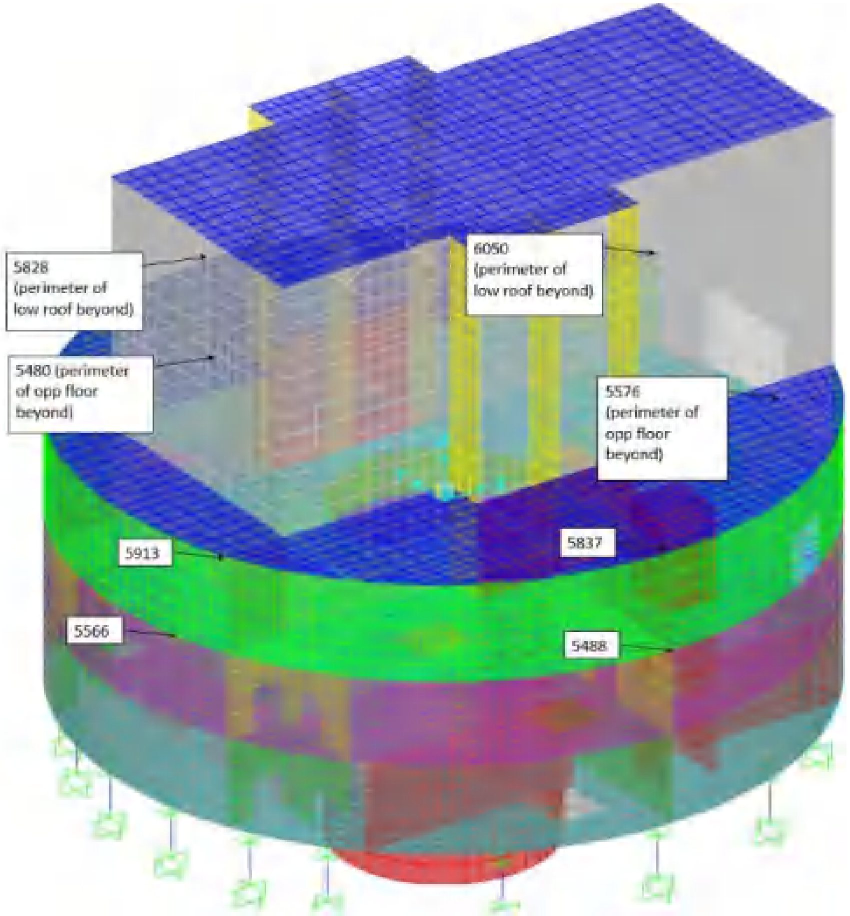
Along Building NS Axis

Increased Y-direction response

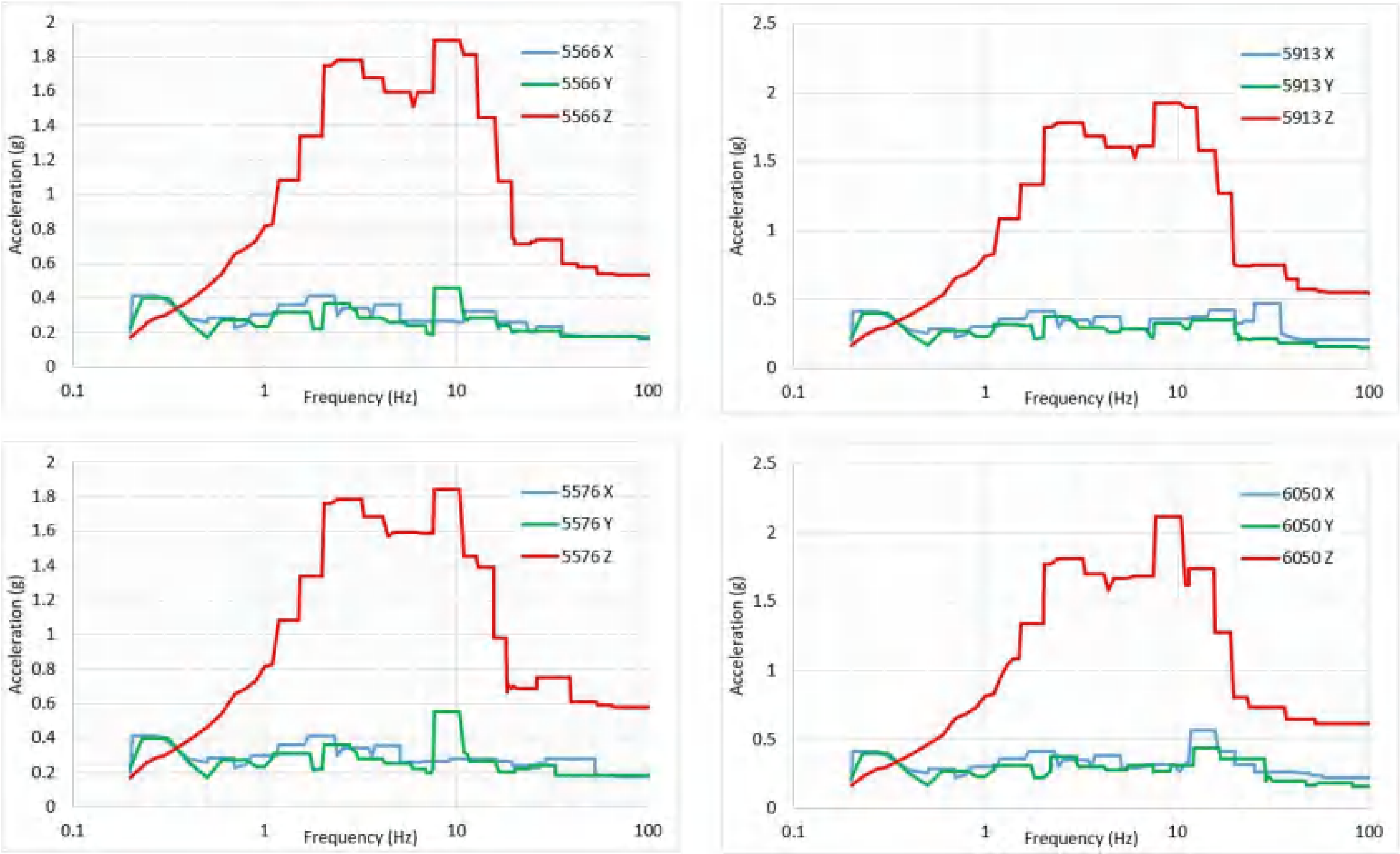


DRACS Supports

15% Broadening, 4% Damping



Along Building EW Axis



RVACS Supports

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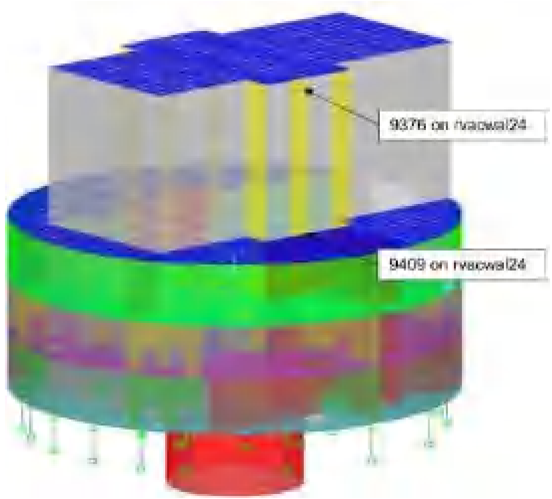
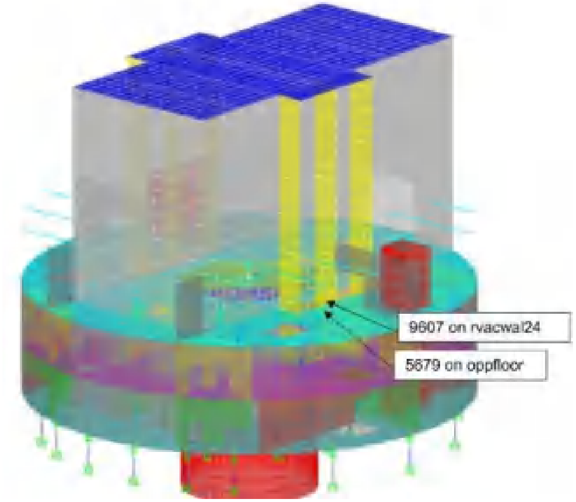
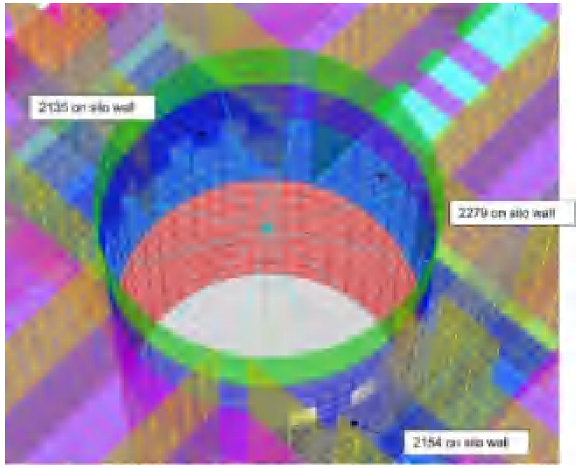
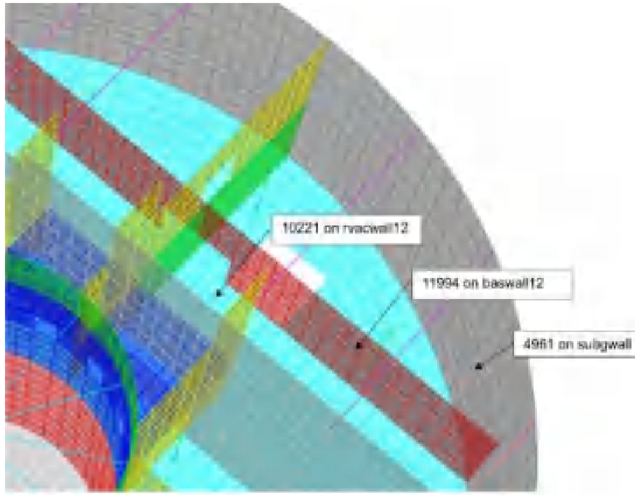
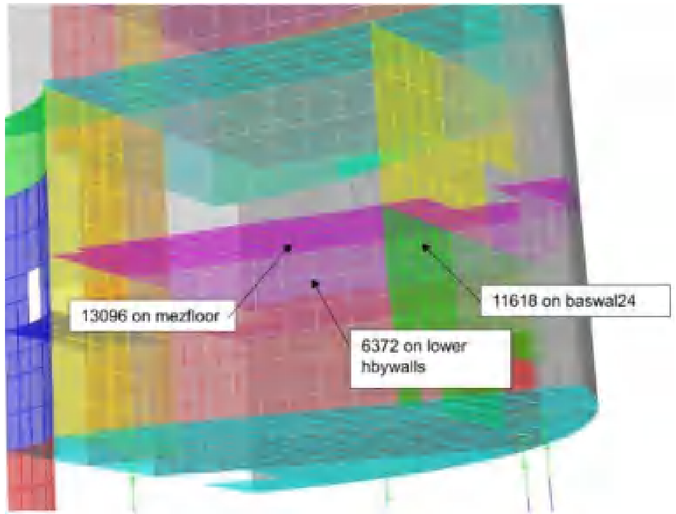
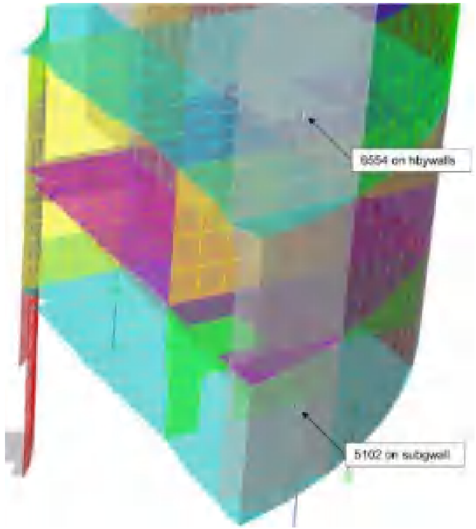








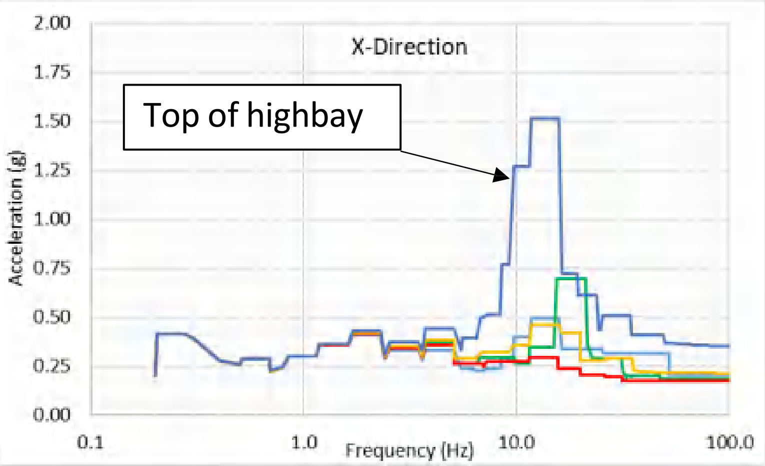


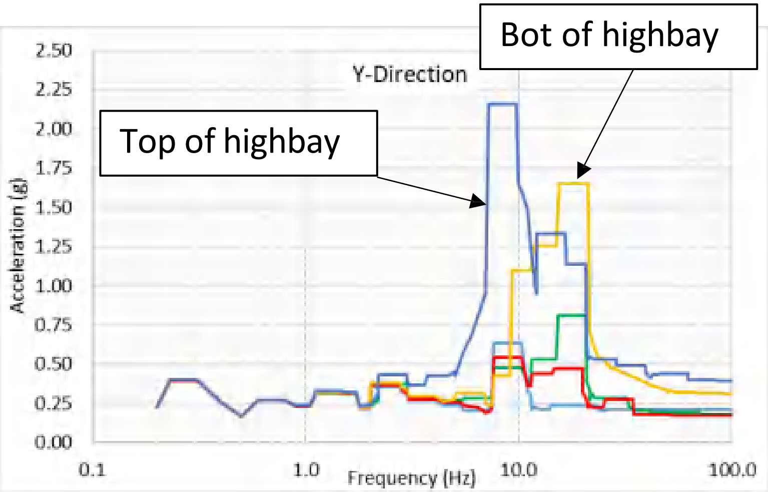


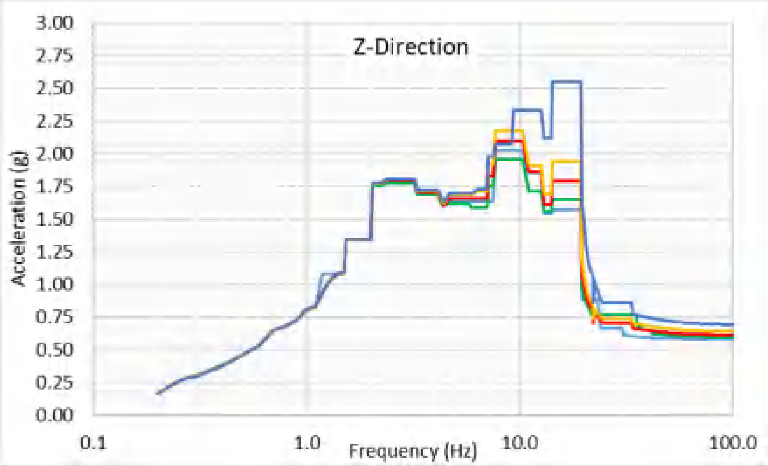
RVACS Supports

15% Broadening, 4% Damping

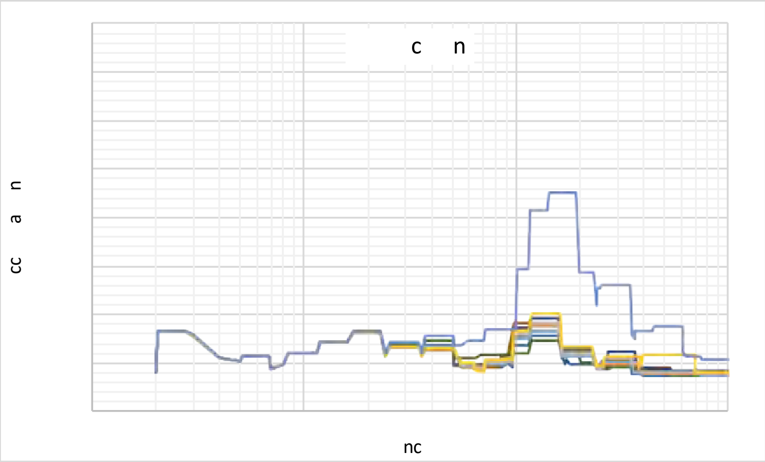
Outlet Ducts

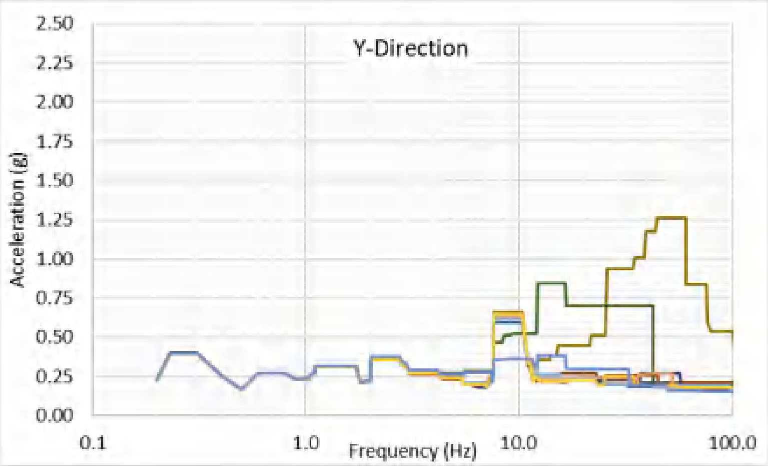


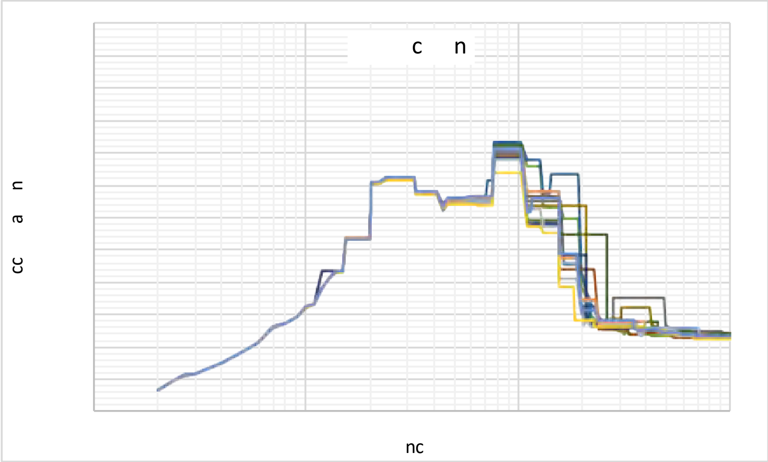




Inlet Ducts







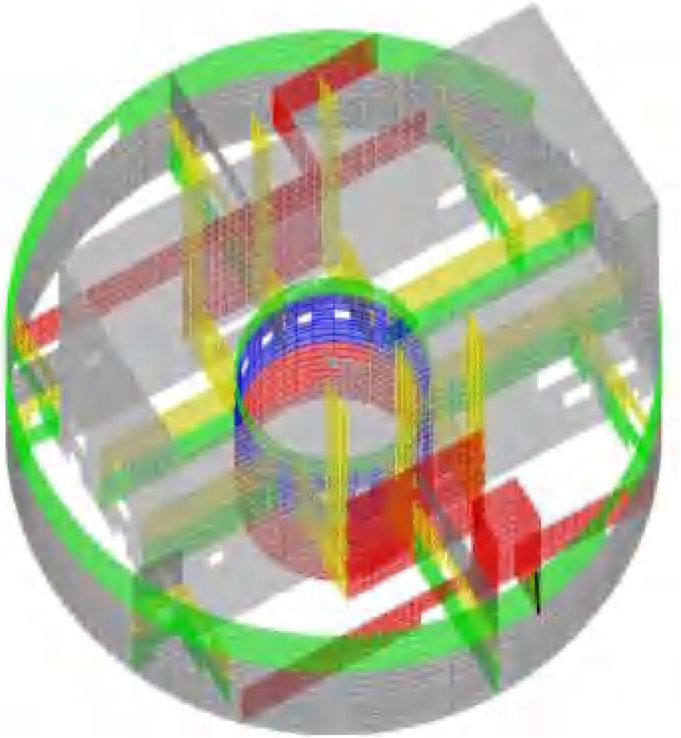
Structural Design Evaluations of the Reactor Building

- Based on Soil Upper Bound Iteration 5
- Single Load Combination: 1.0D+1.0L+1.0E
  - Moat structure evaluation includes additional combinations

- Reactor Building Vertical Walls (SC)
- Reactor Building Floors (Partial SC)
- Reactor Building Basement Floor (RC)
- Seismic Isolator Pedestals (RC)
- Moat Substructure (RC)
- Reactor Vessel Support (SC/Steel)

Reactor Building Vertical Walls

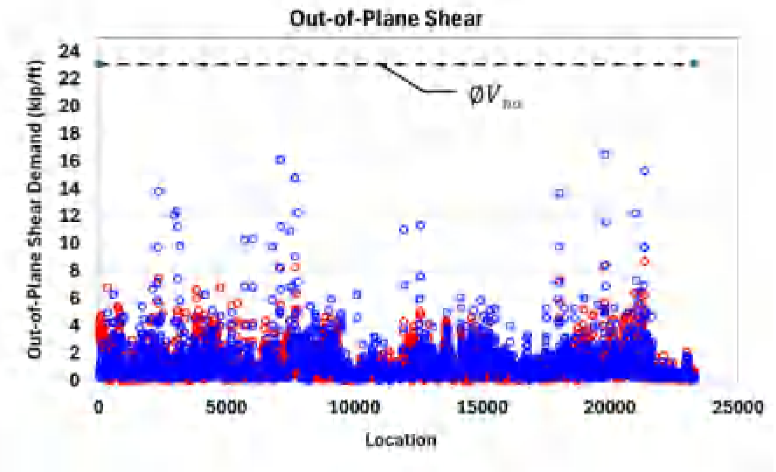
- Steel Concrete Composite Construction
- Analysis and Design per AISC N690-18 Appendix N9
- Fy = 50 ksi, Fu = 65 ksi for steel faceplates, studs and ties
- 5,000 psi concrete infill

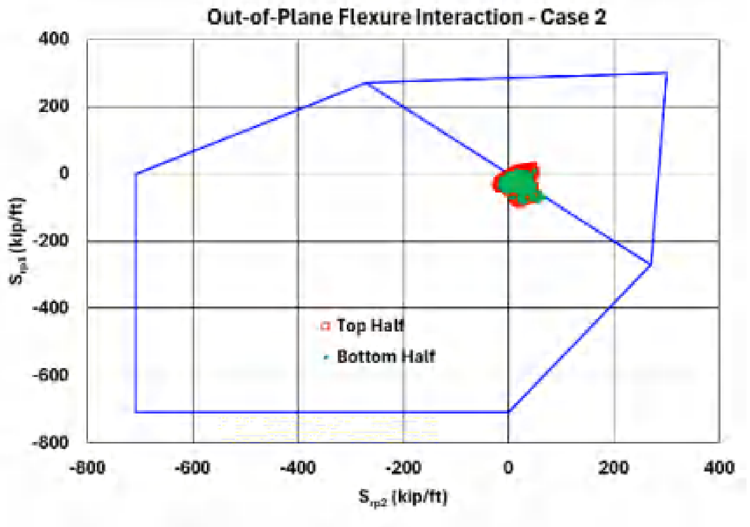


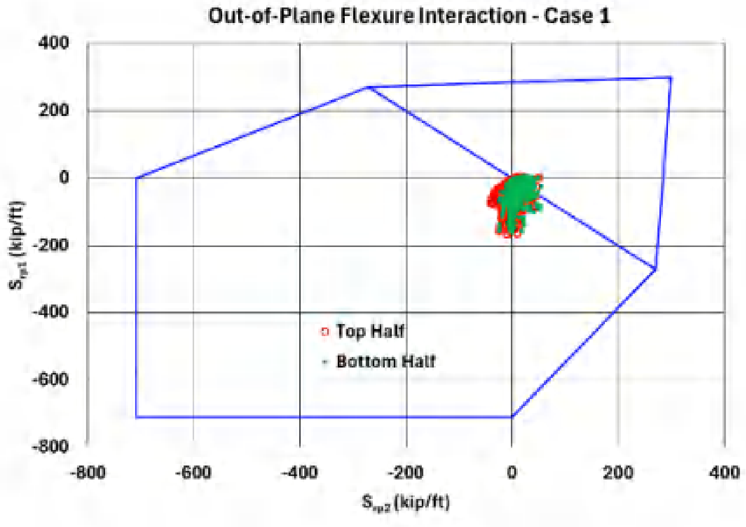
Location	Total Thickness [in]	Steel Faceplate Thickness [in]	Wall Height [ft]	Maximum Demand-to-Capacity Ratio	Design Margin (%)	Governing Case
abgrwall	24	0.5	18	0.246	75.4	Out-of-Plane Shear
baswal12	12	0.25	16.5	0.151	84.9	Uniaxial Comp.
baswal24	24	0.5	16.5	0.501	49.9	Out-of-Plane Shear
grdwal12	12	0.25	18	0.158	84.2	In-Plane Interaction
grdwal24	24	0.5	18	0.178	82.2	Out-of-Plane Shear
hbywalls	24	0.5	97.25	0.698	30.2	Out-of-Plane Shear
mezwall12	12	0.25	16	0.086	91.4	Out-of-Plane Shear
mezwall24	24	0.5	16	0.223	77.7	Out-of-Plane Shear
rvacwl12	12	0.25	50.5	0.359	64.1	Out-of-Plane Shear
rvacwl24	24	0.5	97.25	0.388	61.2	Out-of-Plane Shear
subgwall	24	0.5	32.5	0.177	82.3	Out-of-Plane Shear
swallcan	24	0.5	29	0.421	57.9	Out-of-Plane Shear
swallhgh	24	0.5	8	0.506	49.4	Out-of-Plane Shear
swalllow	36	0.5	24.5	0.422	57.8	Out-of-Plane Shear

Reactor Building Vertical Walls

- Sample interaction diagrams and out-of-plane shear plot.







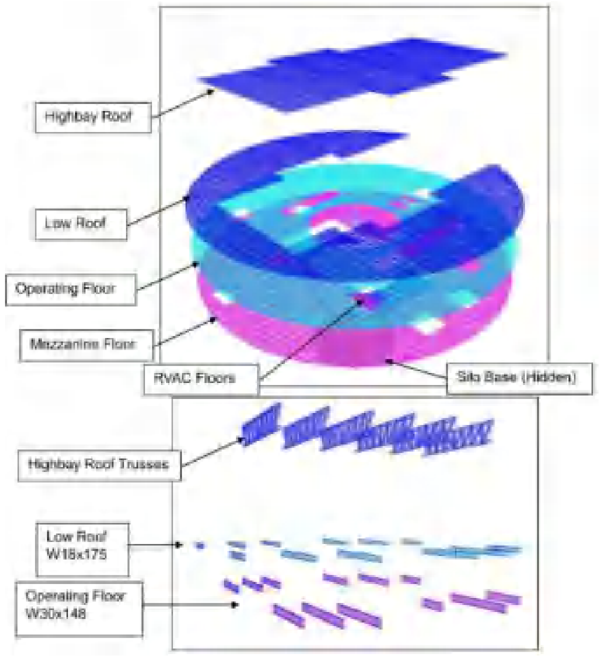
- Summary of wall design including studs and ties.

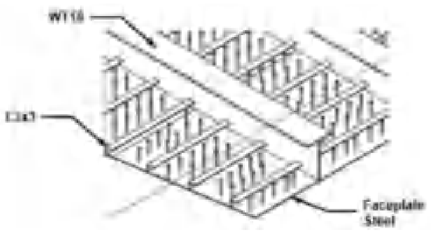
Component Name	t_{sc} (in)	t_p (in)	t_c (in)	Stud Spacing s (in)	Tie Spacing s_{tt} (in)	Tie Spacing s_{tl} (in)	d_s (in)	d_{tie} (in)	$F_{y,stud}$ (ksi)	$F_{u,stud}$ (ksi)	$F_{y,tie}$ (ksi)	$F_{u,tie}$ (ksi)
SCWALL12	12	0.25	11.5	6	12	12	0.63	1.0	50	65	50	65
SCWALL24	24	0.50	23	7.25	18	18	0.75	1.0	50	65	50	65
SCWALL36	36	0.50	35	8.75	24	24	0.75	1.0	50	65	50	65

Reactor Building Floors

- Partial Steel Concrete Composite Construction
- Analysis and Design per AISC N690-18 and ACI 349-13
- Effects of construction loading included
- 5,000 psi concrete
- 0.50” thick bottom steel plate, Fy = 50 ksi and Fu = 65 ksi
- Typical #11@12 Gr. 60 reinforcing each way at top with additional #8@12 at highbay roof edges

Section	Tension	Compression	Strong-Axis Shear (Web)	Weak-Axis Shear (Flanges)	Interaction	Design Margin (%)
W18x175 (lowroofs)	0.082	0.024	0.047	0.002	0.422	57.8
W30x148 (oppfloor)	0.048	0.007	0.018	0.001	0.222	77.8

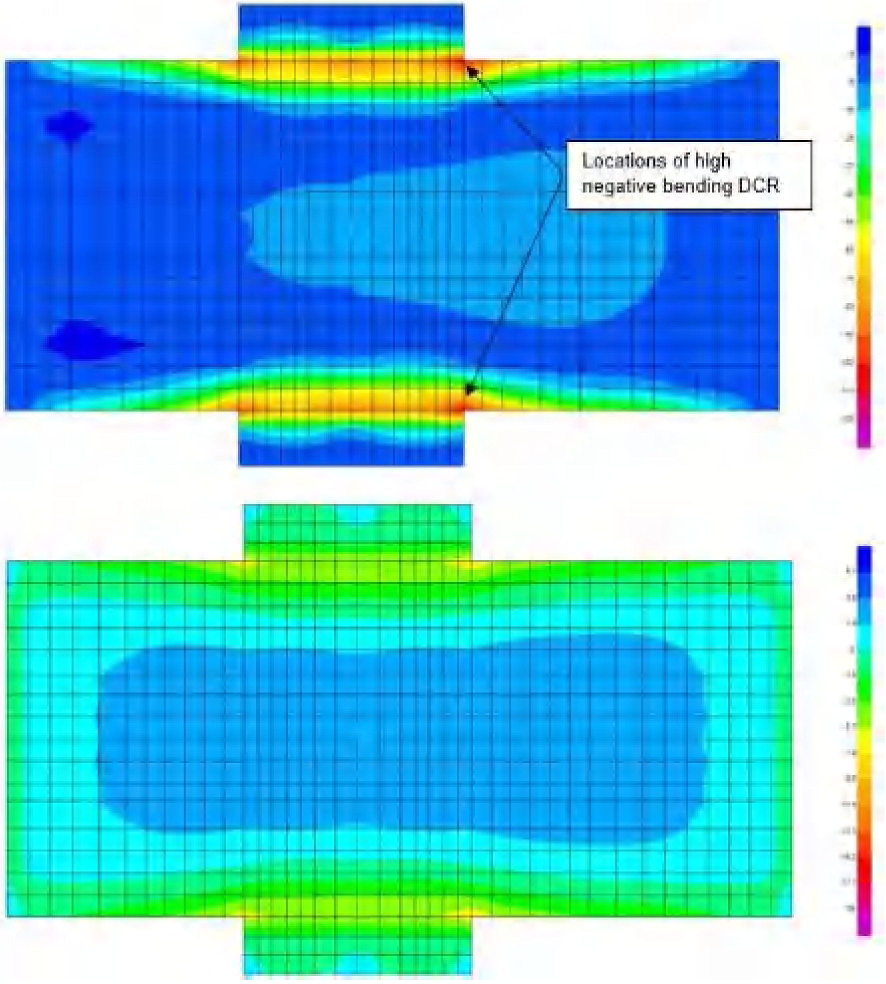




Name	Total Thickness [in]	Bottom Plate Thickness [in]	Maximum Demand-to-Capacity Ratio	Design Margin (%)	Governing Case
silobase	24	0.5	0.21	79.0	Combined Positive Flexure
rvacflrs	24	0.5	0.863	13.7	Out-of-Plane Shear
mezfloor	24	0.5	0.42	58.0	Out-of-Plane Shear
oppfloor	36	0.5	0.9	10.0	Out-of-Plane Shear
lowroofs	24	0.5	0.9	10.0	Out-of-Plane Shear
Hbyroofs	24	0.5	0.94	6.0	Out-of-Plane Shear

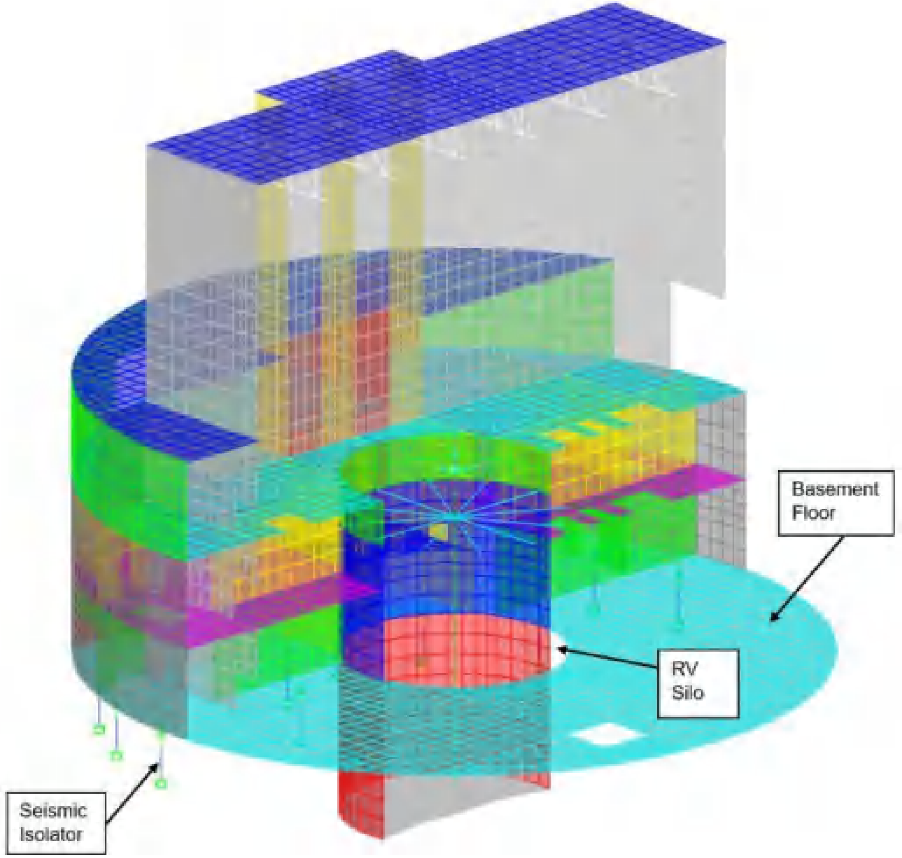
Reactor Building Floors

- Example plot of bending moments. Large negative bending at highbay roof.



Reactor Building Basement Floor

- 4 feet thick, Reinforced Concrete
- Analysis and Design per ACI 349-13
- 5,000 psi concrete
- #11@9” Gr. 60 reinforcing each way, bottom of slab
- Typical #11@9” Gr. 60 reinforcing each way, top of slab with additional #11@9” within 6-foot radius of each isolator.
- Out-of-Plane shear reinforcing
  - 7/8” diameter headed shear studs on a 9” square grid within 6.5’ radius of each outer perimeter isolator
  - ¾” diameter headed shear studs on 9” square grid within 6.5’ radius of each inner perimeter isolator
- Also evaluated for BDBE loading (150% of DBE)
- Capacity based on phi-factors (ϕ) set to 1.0 and dynamic strength increases per ACI 349 Apx. F

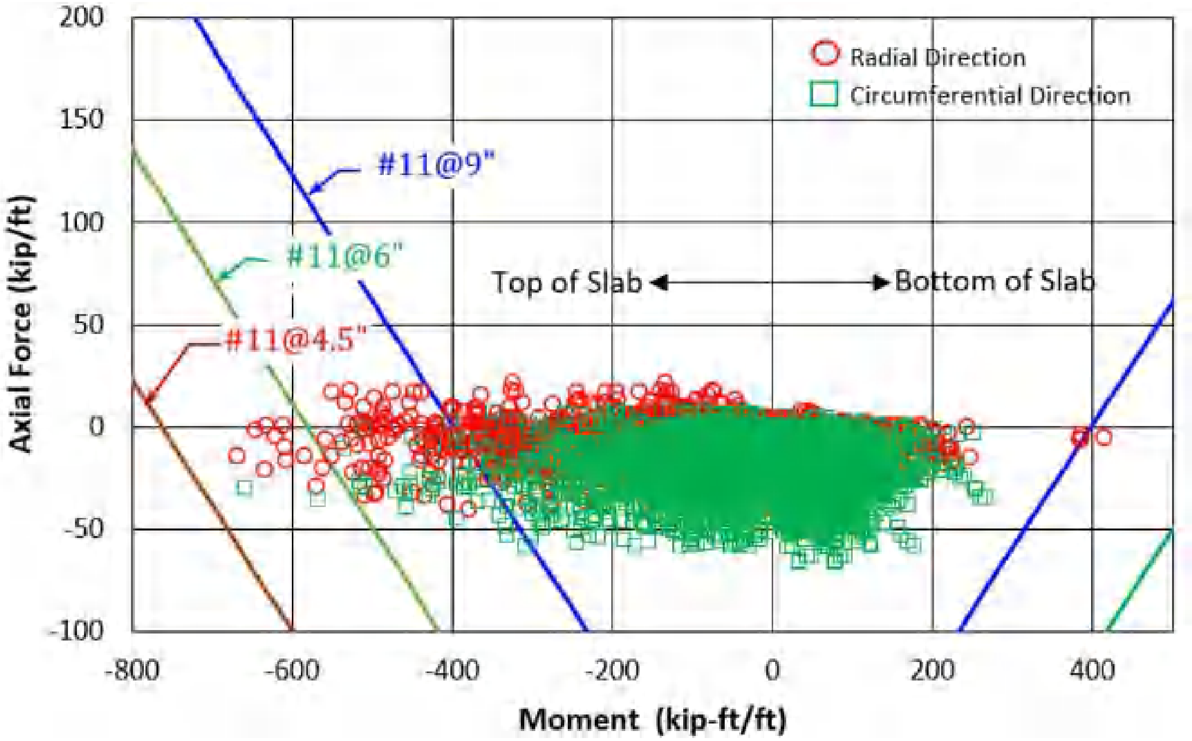


Reactor Building Basement Floor

DBE				
Stress Type	Location	Reinforcing	DCR	Design Margin
Axial + Bending Interaction	Bottom of Slab	#11@9 each way	0.66	34%
	Top of Slab	#11@9 each way except additional #11@9 each way within 6-foot radius of isolators	0.91	9%
Out-of-Plane Shear	N/A	0.75 in^2/ft w/in radius of 6.5 ft of each outer perimeter isolator 0.5 in^2/ft w/in radius of 6.5 ft of each inner perimeter isolator	<0.9	>10%
In-Plane Shear	N/A	Inherent in longitudinal bars	0.41	59%

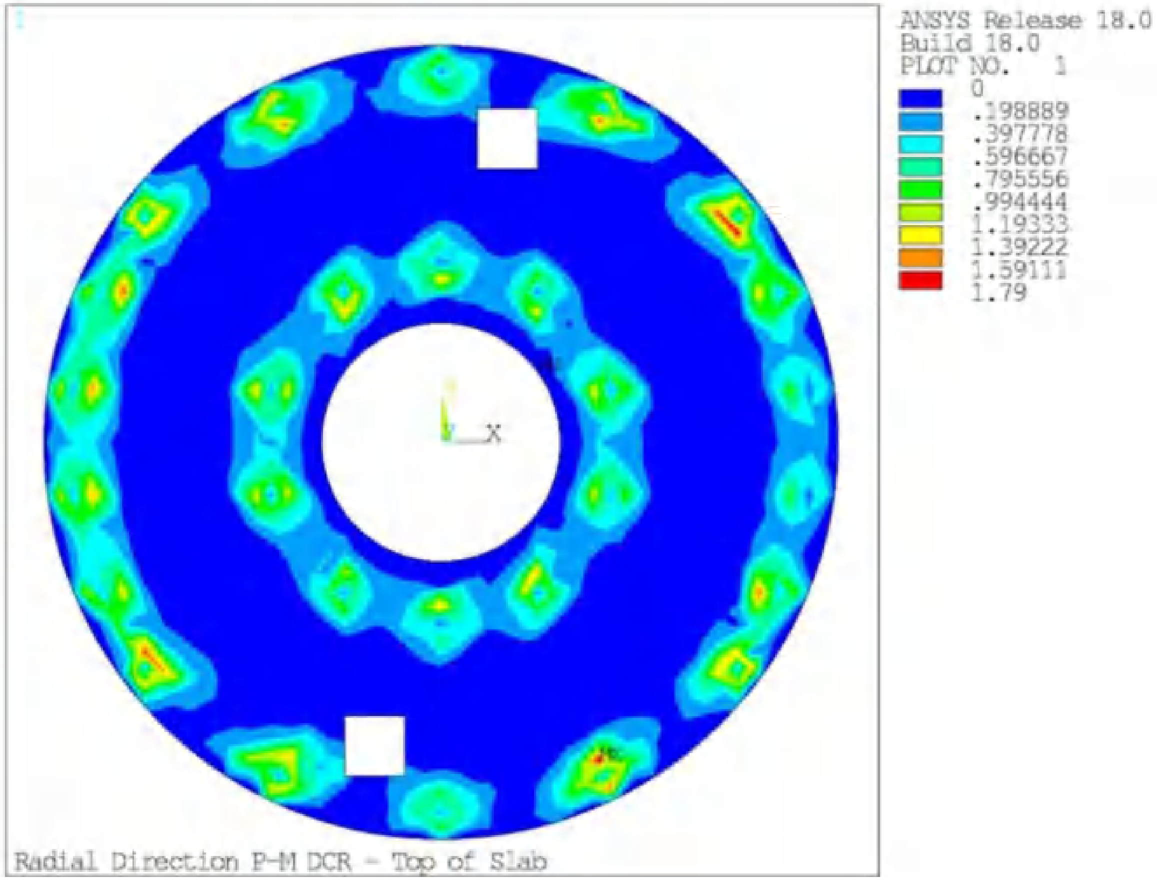
BDBE				
Stress Type	Location	Reinforcing	DCR	Design Margin
Axial + Bending Interaction	Bottom of Slab	#11@9 each way	0.962	4%
	Top of Slab	#11@9 each way except additional #11@9 each way within 6-foot radius of isolators	0.9	10%
Out-of-Plane Shear	N/A	0.75 in^2/ft w/in radius of 6.5 ft of each outer perimeter isolator 0.5 in^2/ft w/in radius of 6.5 ft of each inner perimeter isolator	<0.9	>10%
In-Plane Shear	N/A	Inherent in longitudinal bars	0.53	47%

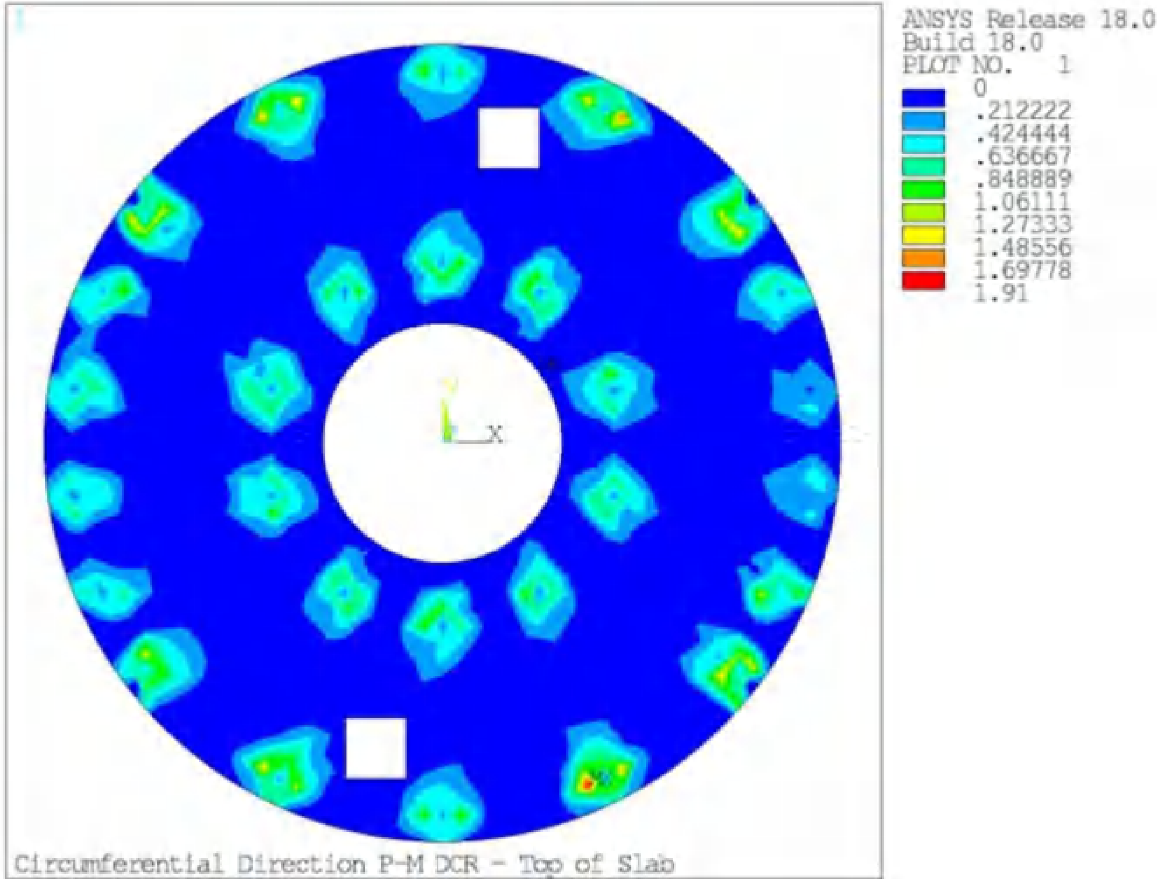
- P-M Diagram



Reactor Building Basement Floor

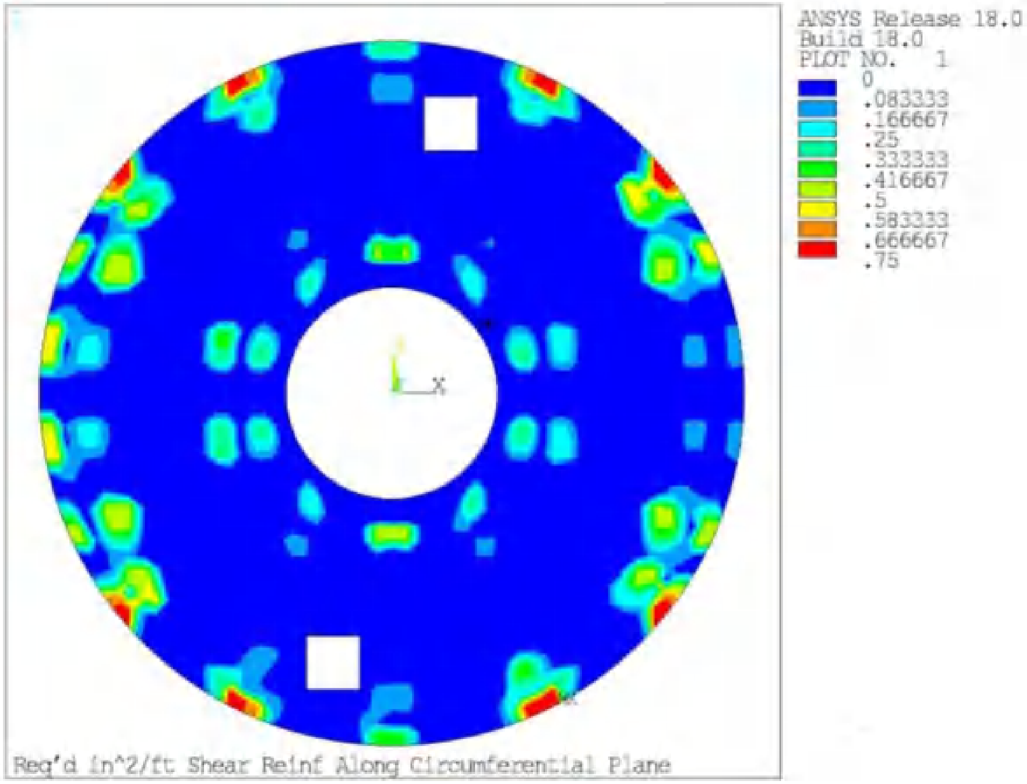
- Top-of-Slab DCRs with basic #11@9 reinforcing

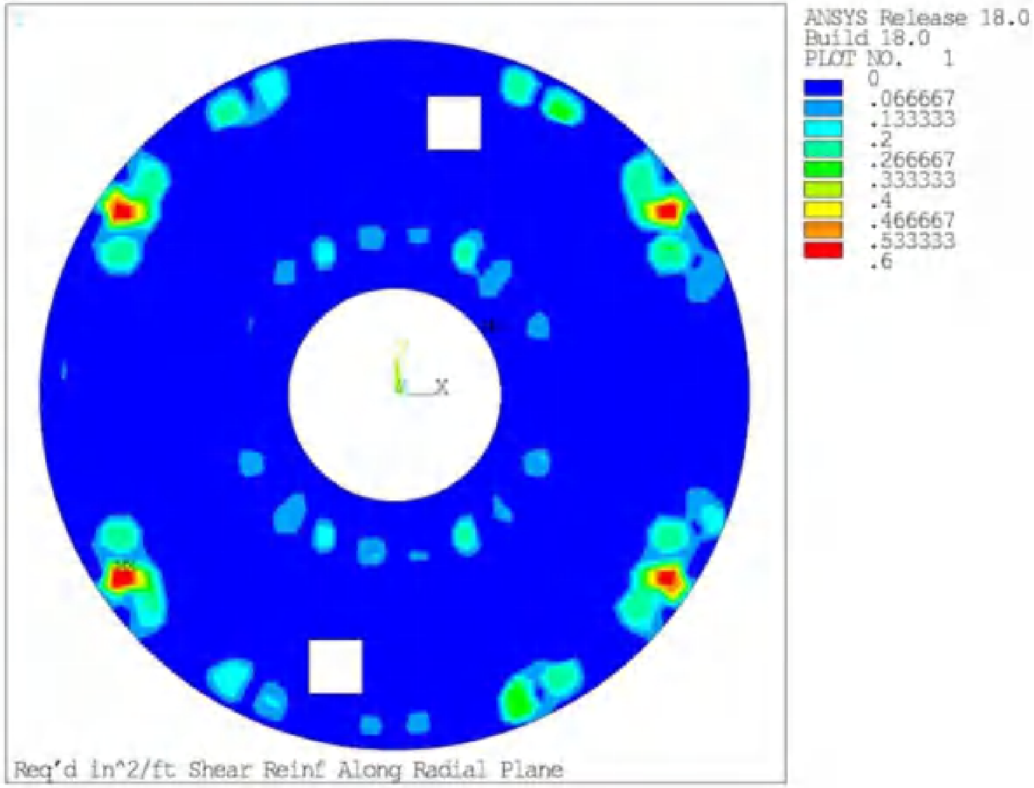




Reactor Building Basement Floor

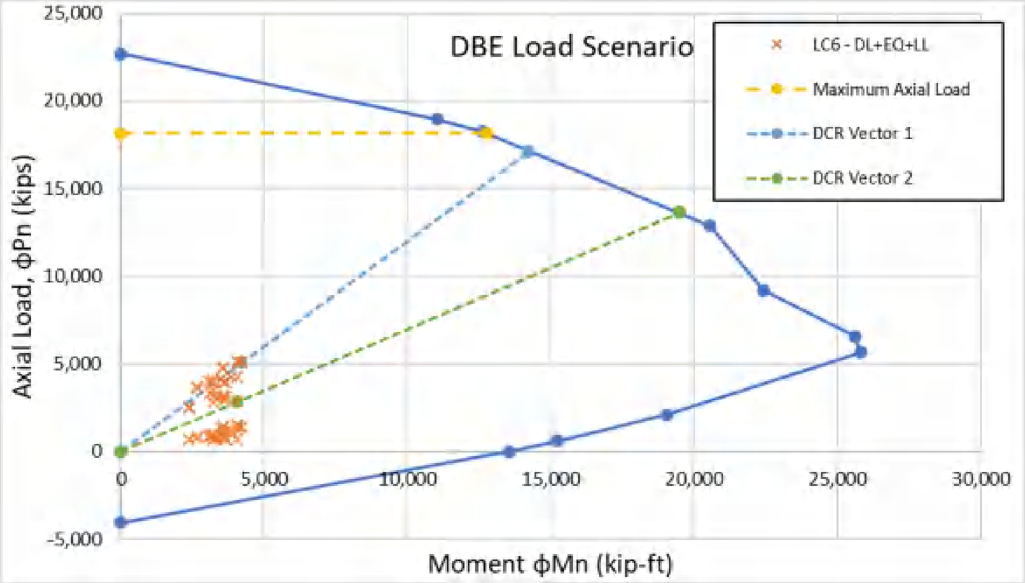
- Required Shear Reinforcing





Seismic Isolator Pedestals

- 8 ft diameter, 5.5 ft tall above moat TOC
- Design per ACI 349-13
  - BDBE uses ϕ-factors set to 1.0 and ACI-349 Apx. F DIFs
- (48) #11 vertical bars around perimeter
- #11@9" reinforcing each way, top of slab except
  - #11@4.5" reinforcing within 6-foot radius of each isolator
- #6 hoops with (6) cross ties @ 6" vertical spacing

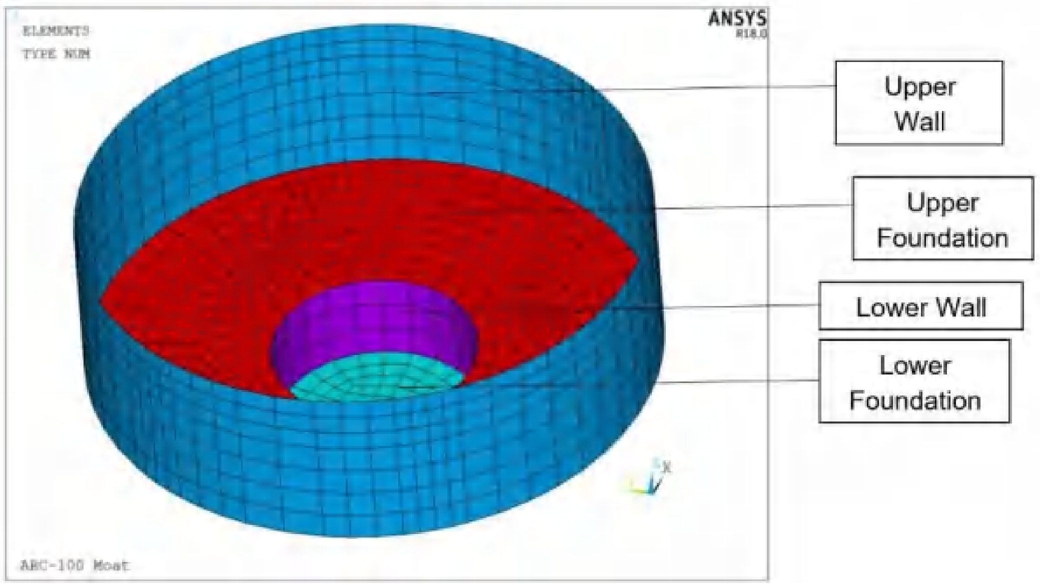


DBE Loading					
Capacity Check	Demand	Capacity	Demand-to-Capacity Ratio	Design Margin (%)	Comment
Flexure	4216.8 k-ft	14210.6 k-ft	0.297	70.3	Based on vector found on P-M interaction curve
Shear	689.1	782.0 k	0.753	24.7	Capacity using concrete shear only. Conservative.
Punching Shear	163.7	212.1 psi	0.772	22.8	No additional mat reinforcement needed for 6 ft thick mat
Bearing	114.24 k/in	233.8 k/in	0.489	51.1	
BDBE Loading					
Capacity Check	Demand	Capacity	Demand-to-Capacity Ratio	Design Margin (%)	Comment
Flexure	10110.4 k-ft	13244.6 k-ft	0.763	23.7	Based on vector found on P-M interaction curve
Shear	1873.2 k	4120.6 k	0.455	54.5	Use #6 hoops at 6 in O.C. with (6) crossties
Punching Shear	214.12 psi	311.1 psi	0.688	31.2	No additional mat reinforcement needed for 6 ft thick mat
Bearing	143.21 k/in	396.7 k/in	0.361	63.9	

Reactor Building Moat Substructure

- Stepped cylindrical structure
- Reinforced Concrete construction
- Evaluated in ANSYS using element forces and moments directly from SSI analysis
- Additional loads applied in ANSYS
  - Soil active/passive pressure
  - Groundwater loading
- Load Combinations
  - Combination 1 1.0D + 1.0H + 1.0E
  - Combination 1A 1.0D + 1.0H + 1.0E (No GW, No OB, Low Density Soil)
  - Combination 2 1.0D + 1.0H – 1.0E
  - Combination 2A 1.0D + 1.0H – 1.0E (No GW, No OB, Low Density Soil)
  - Combination 3 1.2D + 1.6H
- SSI Results from
  - i. Firm Soil (Vs=2000 fps), Best Estimate (BE) properties.
  - ii. Firm Soil (Vs=2000 fps), Lower Bound (LB) properties.
  - iii. Firm Soil (Vs=2000 fps), Upper Bound (UB) properties.
  - iv. Hard Rock (Vs=8000 fps), Best Estimate (BE) properties.
- Design per ACI 349-13
- General minimum design margin is 10%

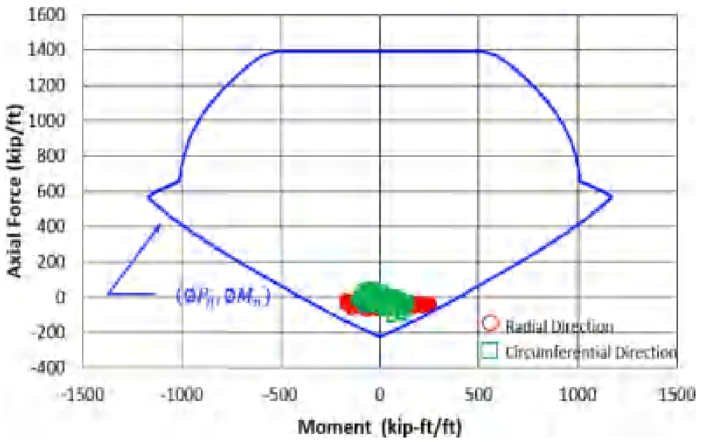
Item	Diameter [ft]	Depth [ft]	Thickness [ft]
Upper Cylindrical Wall	143	Top: 0 Bottom: -43.5	3.0
Upper Foundation	Outer: 143 Inner: 51.75	-43.5	6.0
Lower Cylindrical Wall	51.75	Top: -43.5 Bottom: -66.5 (Overall: 23.0)	3.0
Lower Foundation	51.75	-66.5	4.0

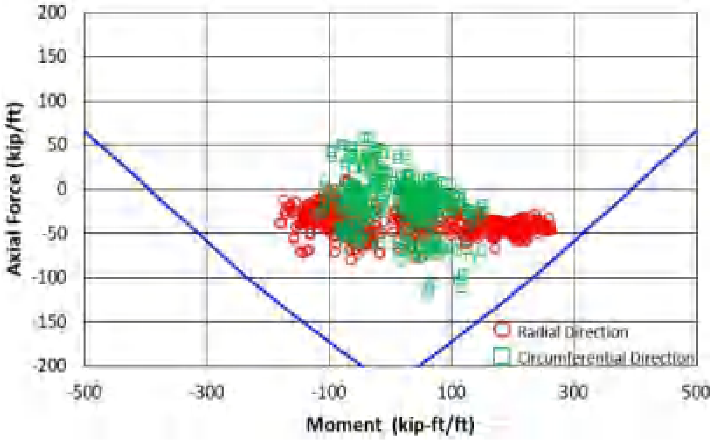


Reactor Building Moat Substructure

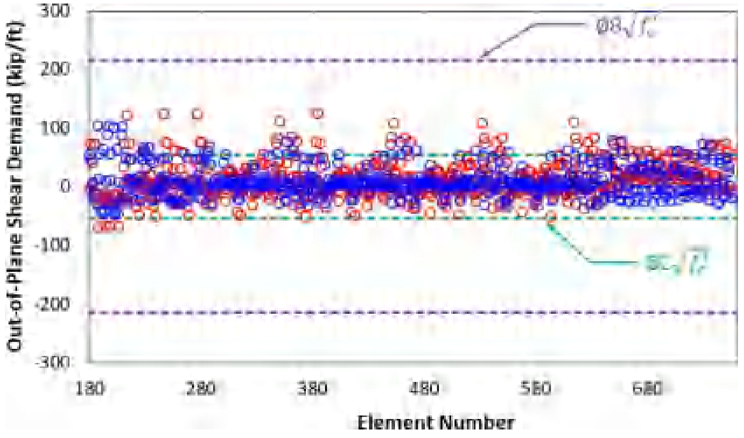
Example evaluations performed for each portion of the structure (upper wall, upper foundation, lower wall, lower foundation) and for each Analysis Case (Soil UB, Soil BE, Soil LB, Rock BE) and for each Load Combination

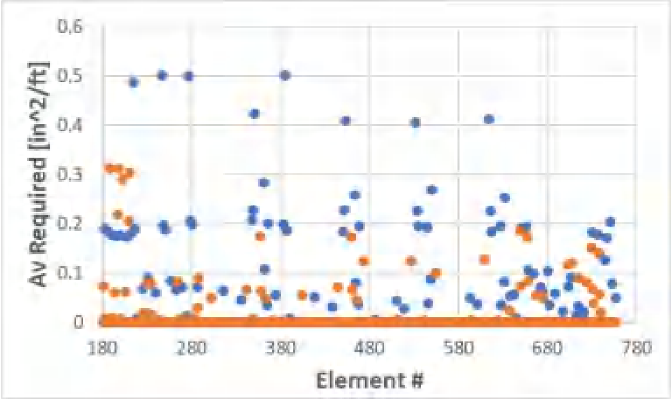
P-M Diagrams



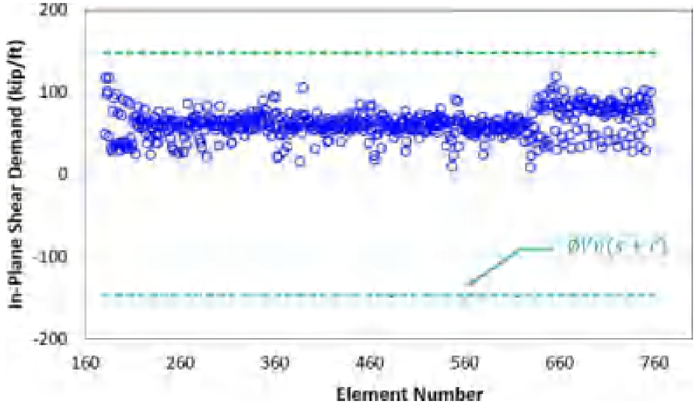


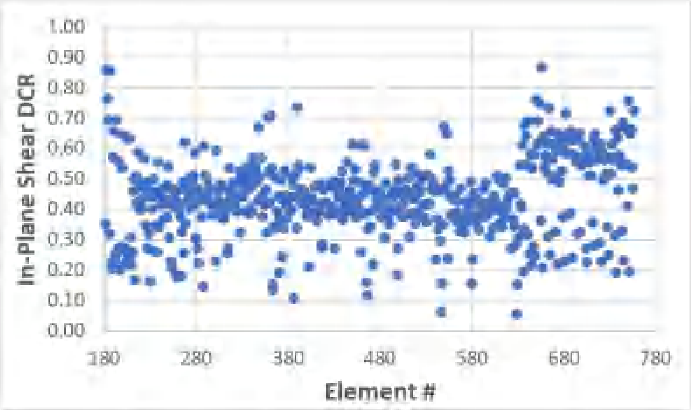
Out-of-Plane Shear





In-Plane Shear



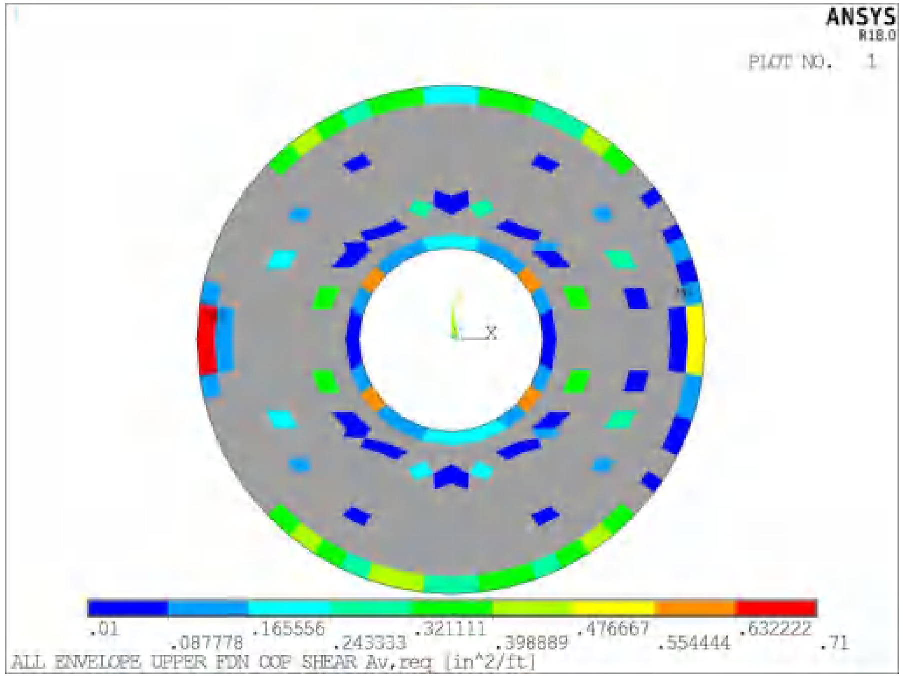


Reactor Building Moat Substructure

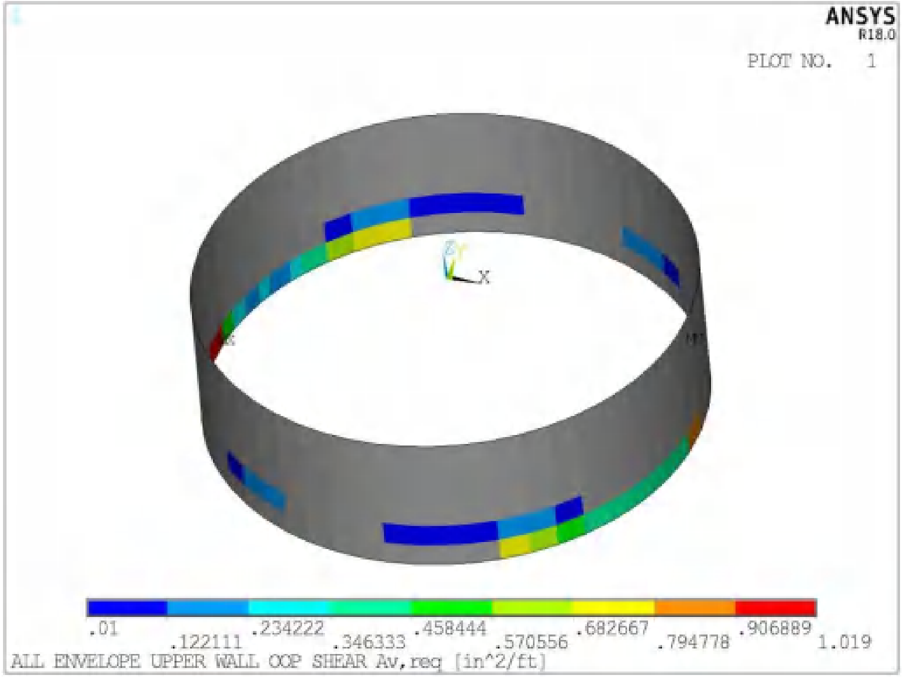
- General reinforcing is #11@9, each way, each face
- Moat Lower Foundation:
  - Axial and Flexure: #11@6 each way, each face
  - Out-of-Plane Shear: Reinforcing equivalent to 0.424 in^2/ft between the outer perimeter to a distance inward from the perimeter of 9.5 ft
- Moat Lower Wall:
  - Axial and Flexure: #11@9 each way, each face
  - Out-of-Plane Shear: Reinforcing equivalent to 0.55 in^2/ft for the bottom 7.67 feet of the lower wall and 0.03 in^2/ft for the top 7.67 feet of the lower wall
- Moat Upper Foundation:
  - Axial and Flexure: #11@9 each way, each face, with additional #11@9” bars, each face, in the radial direction, extending from the inner perimeter outward 4 feet
  - Out-of-Plane Shear: Reinforcing starting within 2.75 feet of the walls and seismic isolator pedestal perimeters with values and spatial requirements as shown on next slide
- Moat Upper Wall:
  - Axial and Flexure: #11@9 each way, each face
  - Out-of-Plane Shear: Reinforcing equivalent to the values required as shown on next slide. Shear reinforcement is required only in the bottom 14.4 feet of the wall – each layer of elements is 7.2 feet high.
  - In-Plane Shear: Additional longitudinal reinforcing equivalent to 0.2 in^2/ft in the lower half of the upper wall to resist in-plane shear

Reactor Building Moat Substructure

Required shear reinforcing in upper foundation

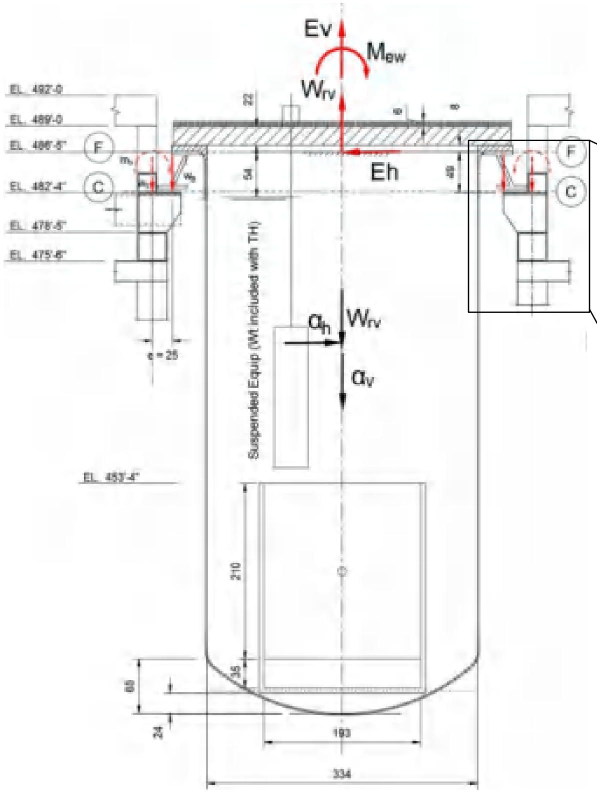


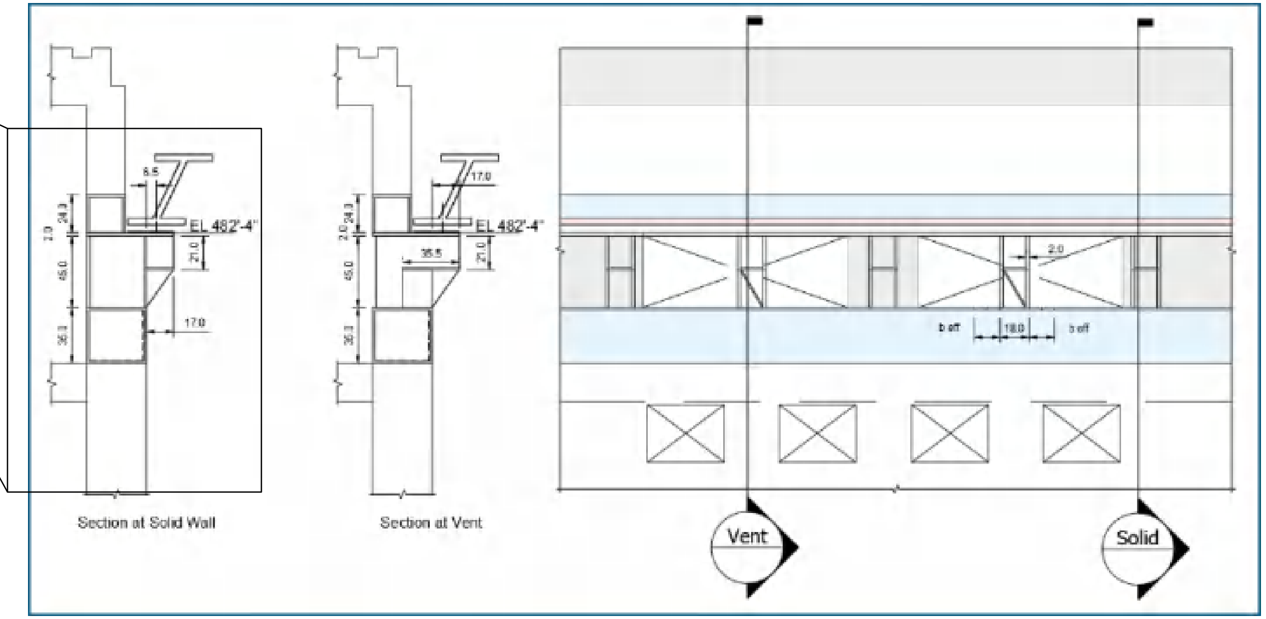
Required shear reinforcing in upper wall



Reactor Vessel Support

- Integral portion of the Steel-Concrete composite Silo Walls
- Provides support to the RV Support Conical Frustrum being design by IHI along with the RV and GV
- Accommodates passage of (4) large RVACS ducts





Reactor Vessel Support

- Design per AISC N690 using manual calculations
- Deadweight + Seismic Load using peak 3% damped ISRS accelerations at the RV support locations.
- The vertical and overturning loads are resolved into uniform loading on the corbel.
- The eccentric force on the corbel results in torsion of the assembly.
- The upper 24” square and lower 36” square portion of the assembly, which are connected by (16) pairs of gusset plates, comprise a torsion beam assembly.
- Maximum calculated Design Capacity Ratio (DCR) is 0.8.

Seismic PRA Results

Kurt Vedros (Idaho National Laboratory)

ARC-100 Seismic Hazard Curve Selection

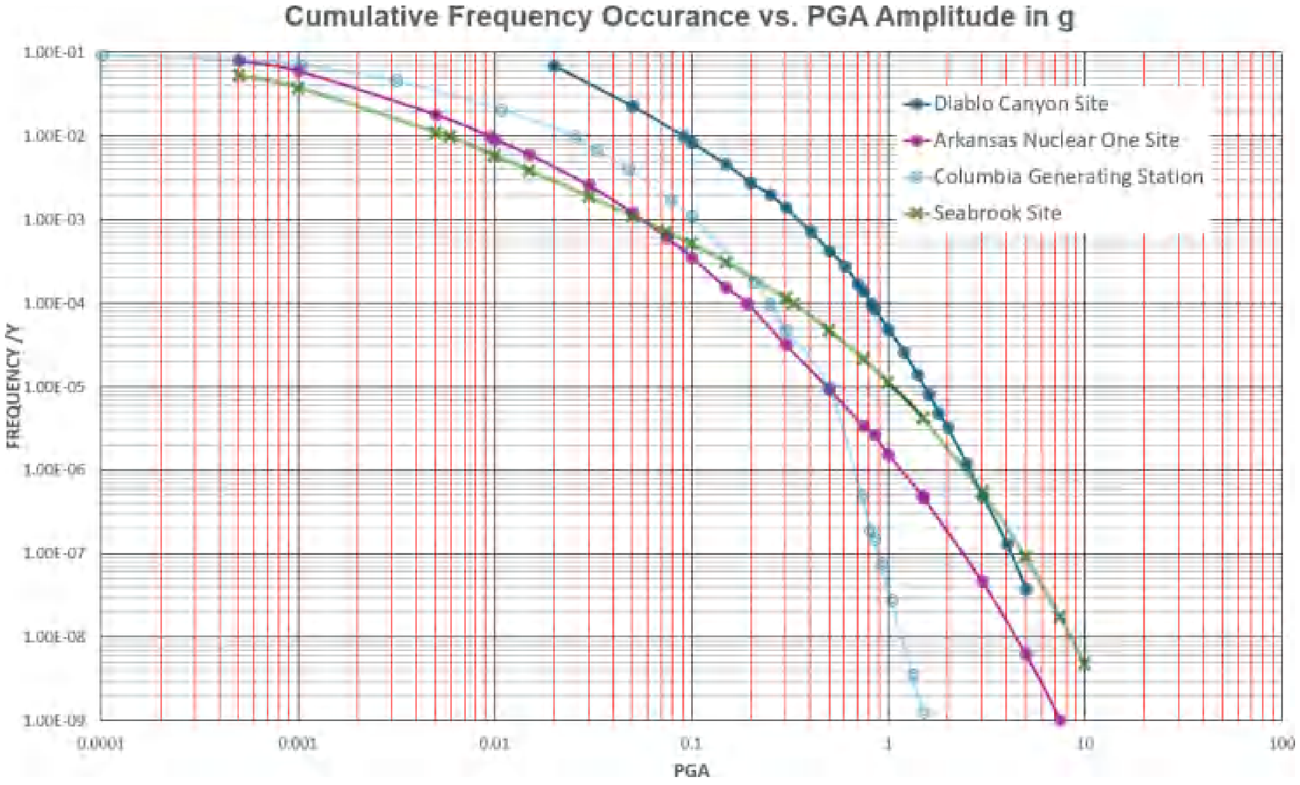
The ARC-100 Design is proposed for the majority of the lower 48 continental United States locations

Four sites with publicly available tabular seismic hazard curve data were selected to represent these locations

1. Arkansas One
2. Columbia Generating Station
3. Diablo Canyon
4. Seabrook

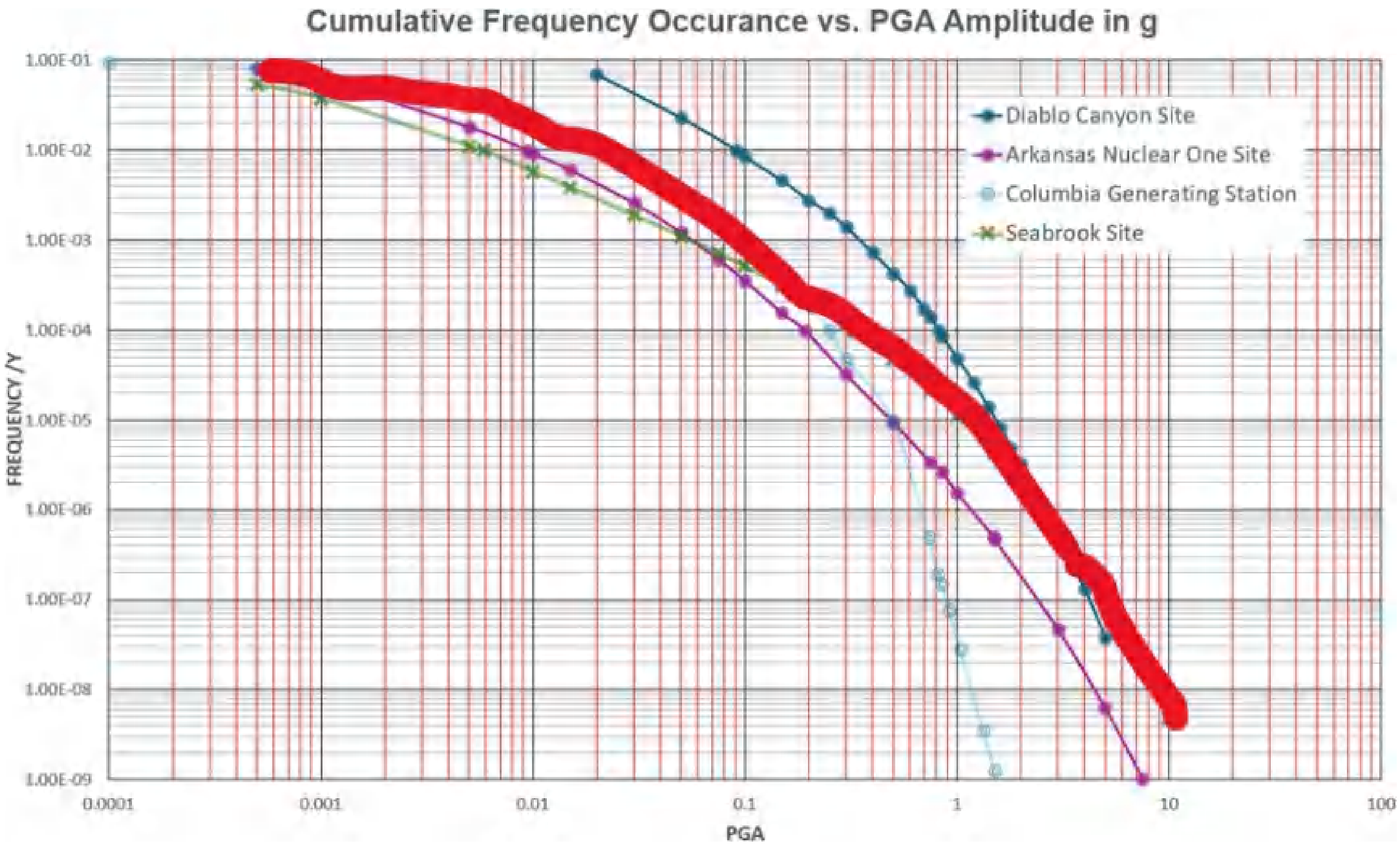
Diablo Canyon was screened out because the ARC-100 design excludes placement in such high acceleration

Bounding seismic hazard curve was selected by the envelope of the remaining three sites.



ARC-100 Seismic Hazard Curve Selection

The bounding curve was built by including the higher frequencies at lower peak ground accelerations of Columbia site up to 0.209 PGA and the higher frequencies of Seabrook site from 0.300 PGA to 10 PGA



ARC-100 Bounding Seismic Hazard Curve Construction Goals

The ARC-100 building is designed to survive the PGA of the seismic design basis event

- Advantageous to use the SDBE PGA of 0.5g and the extended 1.5X PGA of 0.75g as bin PGAs to provide results useful for iterative design
- Allows minimal seismic spectral analysis runs to save funds in the initial design

ARC-100 wants to follow NEI 18-04 guidance

- Bin thresholds not determined by design criteria were chosen based on NEI 18-04 target anchors

The bins should not over-estimate or under-estimate seismic risk

- Care was taken to analyze the results to determine if the discrete number of bins was appropriate

ARC-100 Bounding Seismic Hazard Curve Bin Construction

arc CLEAN TECHNOLOGY

- Where UT = Upper Threshold and LT = Lower Threshold
- Bin 1 UT and Bin 2 LT used the NEI 18-04 AOO LT frequency
- Bin 2 UT was determined by Bin 3's LT selection
- Bin 3 LT and UT were selected to make Bin 3's PGA = ARC-100's SDBE PGA of 0.5g
- Bin 4 UT was selected to make Bin 4's PGA = 1.5X ARC-100's SDBE (0.75g)
- Bin 5 LT was determined by Bin 4's UT
- Bin 5 UT was determined by the closest bin to the NEI 18-04 BDBE lowest frequency (the QHO)
- Bin 6 UT was determined by the highest evaluated Seabrook index of 10.0g

Bin	Index from Site Seismic Data and/or Thresholds	Index PGA (g)	Index Mean
	Columbia index 1	0.0001	9.36E-02
	Columbia index 2	0.0005	8.26E-02
	Columbia index 3	0.0010	7.12E-02
1	Columbia index 4	0.0032	4.63E-02
	Columbia index 5	0.0108	2.08E-02
	NEI 18-04 AOO LT, Bin 1 UT, Bin 2 LT	0.0253	1.00E-02
	Columbia index 6	0.0329	6.81E-03
	Columbia index 7	0.0476	4.04E-03
	Columbia index 8	0.0779	1.76E-03
2	Columbia index 9	0.0997	1.11E-03
	Columbia index 10	0.2089	1.80E-04
	Seabrook Bin 11	0.3000	1.15E-04
	Seabrook Bin 12	0.3318	1.00E-04
	Bin 2 UT, Bin 3 LT	0.4175	7.34E-05
3	ARC-100 DBE	0.5000	4.78E-05
	Bin 3 UT, Bin 4 LT	0.6000	3.72E-05
4			
	1.5 * ARC-100 DBE	0.7500	2.14E-05
	Bin 4 UT, Bin 5 LT	0.9370	1.39E-05
	Seabrook index 14	1.0000	1.14E-05
5	Seabrook index 15	1.5000	4.19E-06
6	Seabrook index 16/NEI 18-04 BDBE LT, Bin 5 UT, Bin 6 LT	3.0000	5.55E-07
	Seabrook index 17	5.0000	9.15E-08
	Seabrook index 18	7.5000	1.76E-08
	Bin 6 UT	10.0000	4.84E-09

Standard Calculation Methods Used in Seismic PRA.

- Bin frequency is the frequency of the higher PGA frequency subtracted from the frequency of the lower PGA frequency

- Bin PGA is used as the bin median acceleration (A_m) for probability of failure determination of safety SSCs in the two parameter seismic lognormal distribution. This is determined by the geometric mean:

$$\text{Seismic bin PGA for fragilities} = \text{Geometric Mean} = \sqrt{lower\ bin\ threshold\ PGA * upper\ bin\ threshold\ PGA}$$

- Binning is done by utilizing NEI 18-04 as guidance and for which the lower range leads to a bin PGA (mean) that cannot be compared directly to the ARC 100 DBE and BDBE , or with bins selected so the PGA of bins 3 and 4 correspond **exactly** to the ARC 100 SSE and BDBE

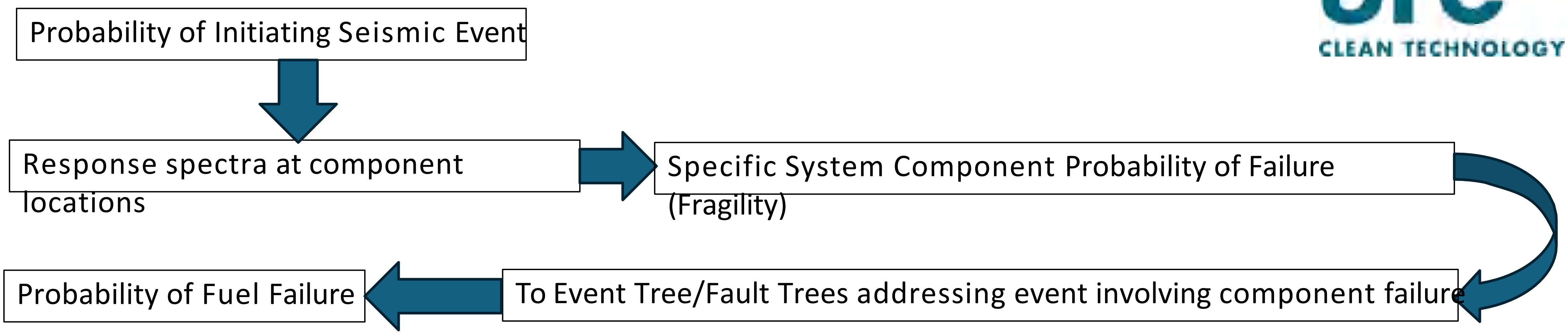
ARC-100 Seismic Bin Annual Frequencies and PGAs

Seismic Bin	EQ1 (0.0 - 0.0059g)	EQ2 (0.0059 - 0.4175g)	EQ3 (0.4175 - 0.6g)	EQ4 (0.6 - .937g)	EQ5 (.937 - 3.0g)	EQ6 (> 3.0g)
Bin Freq	8.36E-02	9.93E-03	3.62E-05	2.33E-05	9.73E-06	5.55E-07
Bin PGA	0.002	0.103	0.500	0.750	1.677	5.477

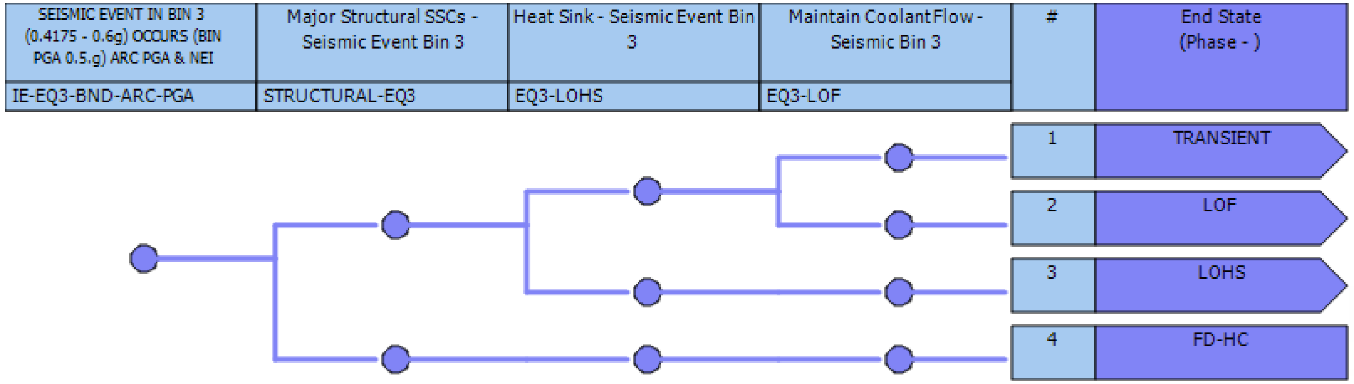
Seismic Bins and SSC Seismic Parameters in ARC-100 PRA

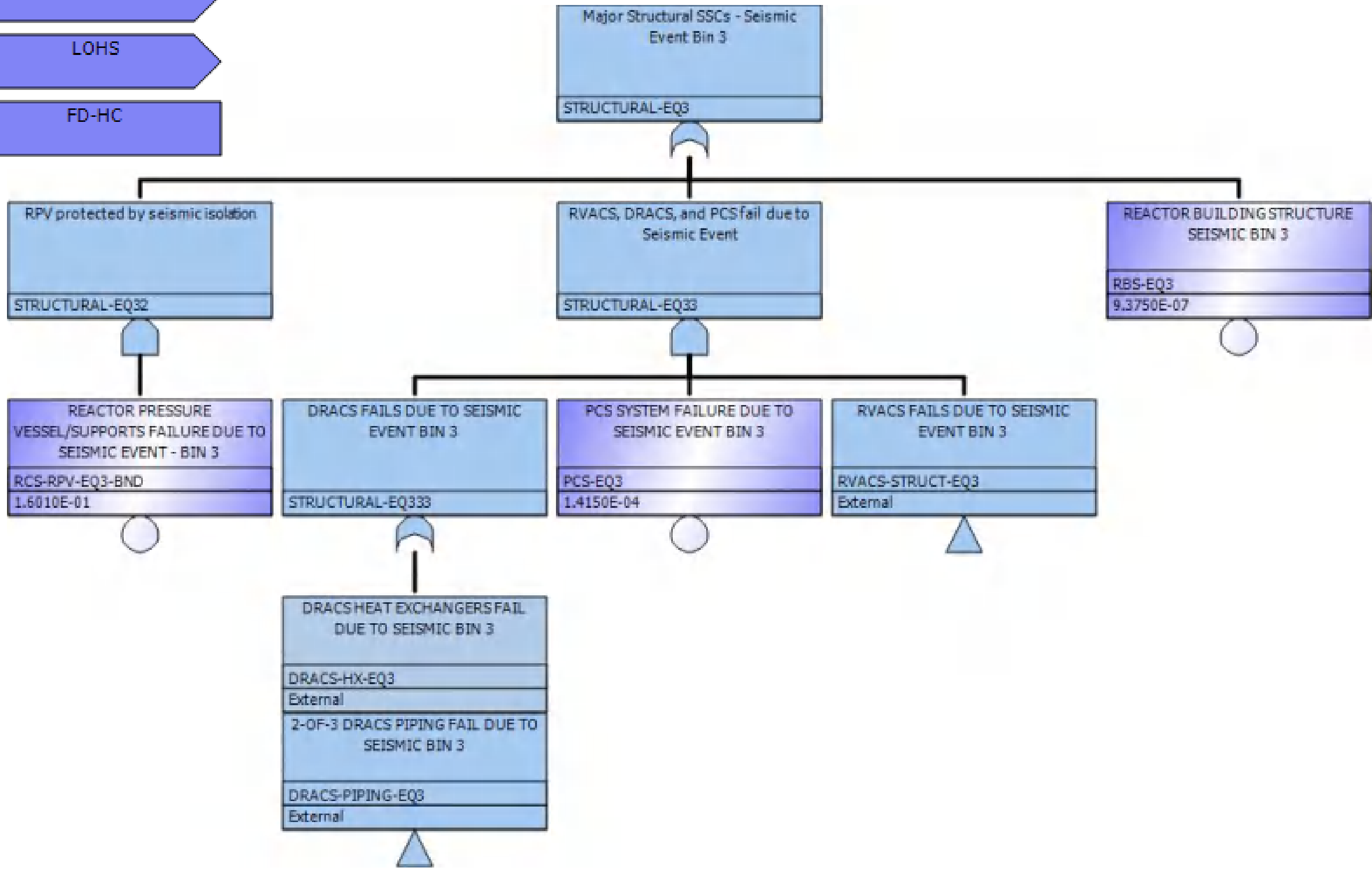
- The bins beyond Bin 3 (the DBE) are representative of seismic isolation that is beyond the currently designed horizontal isolator's displacement limit, after which the building would be unstable, and the spectral analysis may not follow the results presented in the following slides.
  - The current horizontal isolators are limited to 28.2 inches of travel
  - The free field PGA that would exceed the travel limit is approximately 0.69g
  - All PRA results beyond 0.69g in the current design are only useful as a representative goal to inform future design
- Median acceleration (A_m) used for safety SSCs use results of seismic analysis of the design, where available
- Beta R and Beta U parameters from Table 6-1 of NUREG/CR-6544 are used for the SSCs.

Seismic PRA Present results



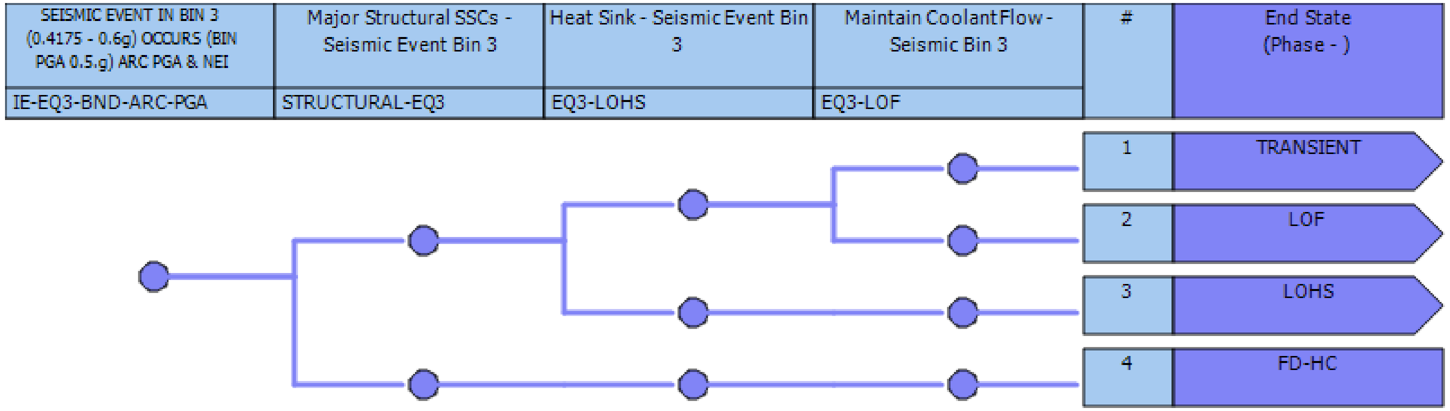
Seismic Safety SSC Selection and Usage





- The Seismic PRA Event Trees first question major safety structures
- The reactor building, pressure vessel, and major passive heat removal systems are questioned for failure due to the seismic event.
- Any of these major SSC failures can lead to fuel damage

Seismic Safety SSC Selection and Usage



- A seismic initiator enables the logic for all seismic and internal basic events for the transferred event trees
- If the major structural damage is avoided, the Seismic Heat Sink fault tree top event is checked which consists of the PCS System
- If PCS System fails due to seismic event, the LOHS event tree is entered
- If the PCS is successful, the coolant pumps are checked in the LOF fault tree top
    - A success transfers to the TRANSIENT tree
    - A failure transfers to the LOF event tree
- Fuel failure cut sets can consist of any combination of seismic and/or random basic event failures

Bins used for Assessment of Fragilities and Pre-Screening

- Chose this approach to binning, because the mean free field accelerations coincide with the ARC 100 SSE (0.5g) at which structural evaluation have been conducted, and local response spectra in the various structures have been developed. Enables direct comparison with responses (SRSS of Horizonal and Vertical components) at locations where components have been analyzed for their fragilities
  - e.g., Reactor building structure, Reactor Vessel and supports, and Safety related Heat Removal Systems (RVACS and DRACS)

- Prescreening was performed on the safety SSCs to determine the modeled capacity versus the NUREG/CR-6544, Table 6-1 HCLPF for the most similar SSCs listed. The results are listed in the following slide.

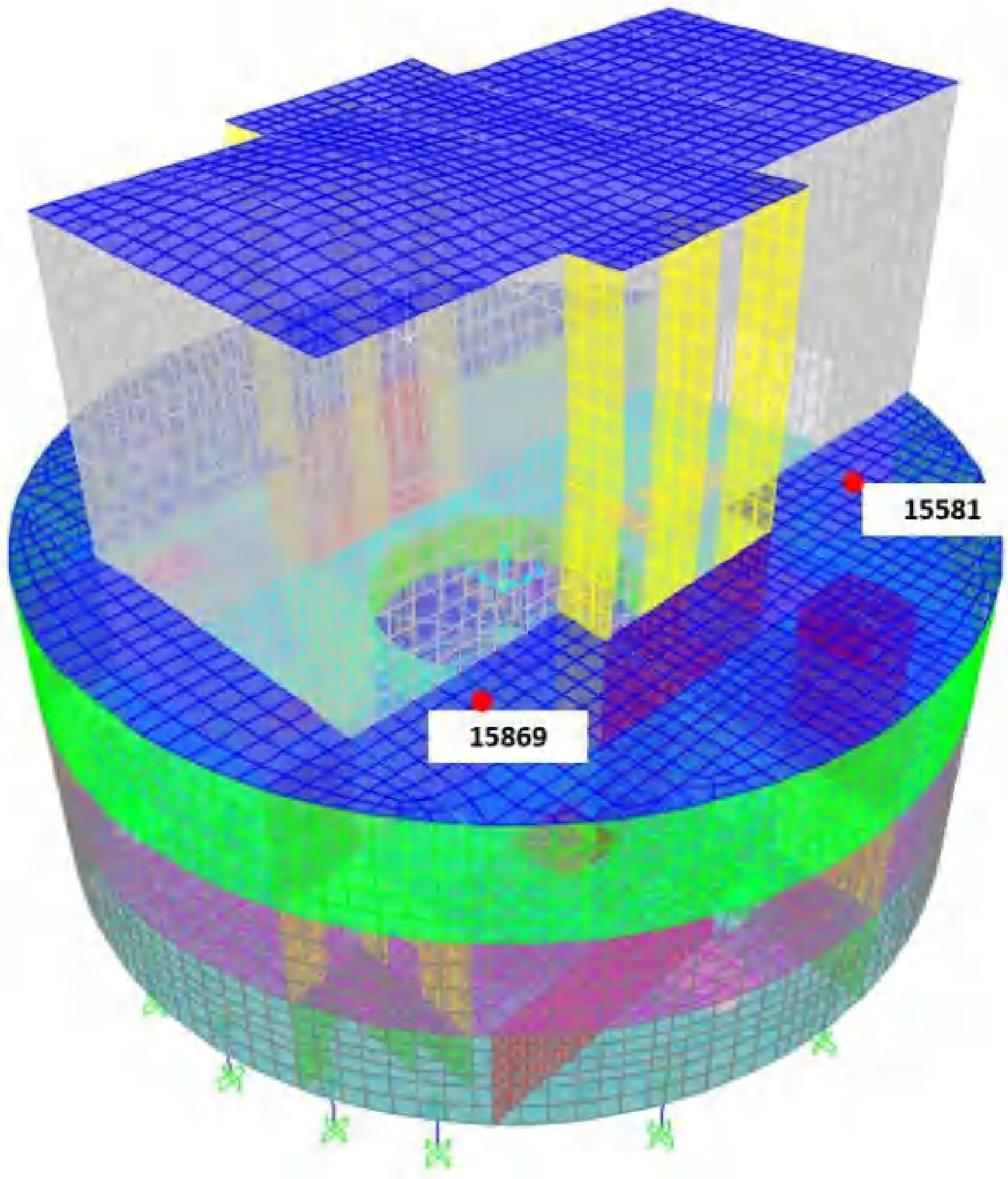
Prescreening per Generic Modeled Mean and HCLPF Capacity of NUREG/CR-6544, Table 6-1

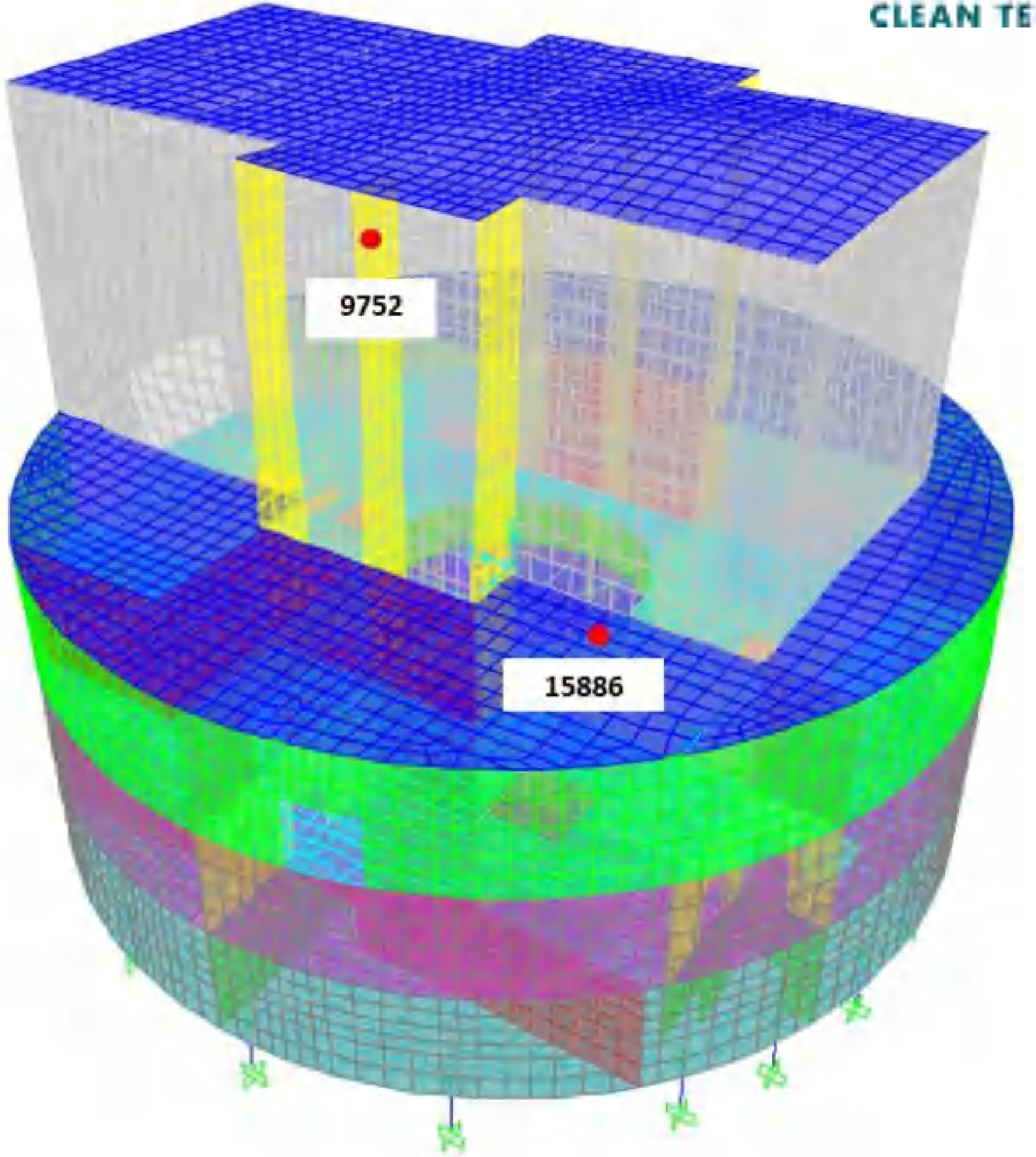
ARC Safety Related Component	NUREG/CR-6544, Table 6-1 Component: Seismic Fragilities Equivalent Component	Elevation (Grade is El. 492'-0")	Tested Capacity	Mean Capacity from Actual SSC structural/stress analysis SRSS (XYZ) Peak SSE Response	Mean Capacity per NUREG/CR-6544, Table 6-1 PGA_{SSE} (1)	HCLPF Capacity per NUREG/CR-6544, Table 6-1 (g)
Reactor Isolation Valves	Air-Operated Valves	492'-0"		1.61	3.8	0.93
Batteries and Battery Racks	Batteries and Battery Racks	457'-0"		1.66	3.8	1.30
Cable Trays****	Cable Trays	489'-0"		1.61	2.5	0.61
Control Rod Drive Motors	Control rod drive and hydraulic drive units	489'-3"		1..61	2.5	0.76
Diesel Generator and support systems**	Diesel generator and support systems	492'-0"		2.72	3.1	1.06
Diesel Generator Exhaust Pipe**	Piping	508'-0"		3.13	3.8	0.93
DRACS Heat Exchangers	Heat exchangers and small tanks	509'-5"	Will be specified to meet Am of DRACS piping (2.72)		1.9	0.65
DRACS Head Tanks	Heat exchangers and small tanks	549'-9"	2.72		1.9	0.65
DRACs Piping (Highest Elevation)	Piping	549'-9"	2.72		3.8	0.93
Reactor Internals	Reactor Internals and Core Assembly	@ RV Bottom	1.26-1.4 w vertical isolators		1.8	0.55
				3.39 w/o vertical isolators	1.8	0.55
Reactor Vessel	Reactor pressure vessel	482'-4"***	1.61		2.0	0.68
RVACS Ducts (Outlet elevations)	HVAC ducts	554'-4"	3.23		2.5	0.61
RVACS Ducts (Inlet elevations)	HVAC Ducts		2.22		2.5	0.61
VFDs	Electrical Equipment - Function during = 0.34g - Function after = 0.77g	457'-0"		1.66	1.0 or 2.5	See NUREG / CR-6544, Table 6-1
Primary EM Pumps	Recirculation Pumps	@ RV Bottom	1.26-1.4 with vertical isolators		1.9	0.65
				3.39 w/o vertical isolators	1.9	0.65
DCS Cabinets	Panelboards and Instrumentation panel	477'-0"		2.71	3.8	1.30
MCR Operator Panels	Panelboards and Instrumentation panel	477'-0"		2.71	3.8	1.30
ASP Room Operator Panels	Panelboards and Instrumentation panel	507'-0"		3.07	3.8	1.30
Notes:						
(1) Per SRP 19.0, the Target HCLPF is considered as 1.67 x PGA of the Safe Shutdown Earthquake						
*Consider No Safety-Related Cable Trays Located Higher than the Mezzanine Floor						
** RTNSS						
*** Only Available ISRS at RV Head and D Supports						

Assessment of fragilities for RVACS and DRACS using Spectral Response

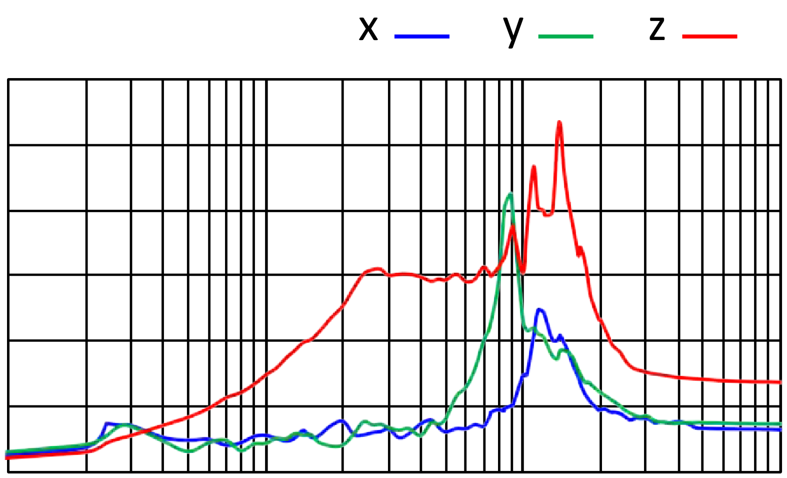
- Horizontally seismic isolated response spectra at RVACS (9752) and DRACS (15581, 15869, 15886) support points and the SRSS of XYZ peak accelerations are shown in following slides for 0.5 PGA (SSE) and 0.75PGA (BDBE)
- Horizontally seismic isolated response spectra for RVACS outlet and inlets ducts (many nodes there for only few examples are shown) in subsequent slides
  - Structural analysis of RVACS and stress analysis of DRACS piping indicate
    - No deformation of RVACS ductwork
    - Stresses in DRACS piping are acceptable
    - DRACS heat exchangers will be a unique design and will be specified to meet the DRACS piping fragilities

RVACS and DRACS Nodes

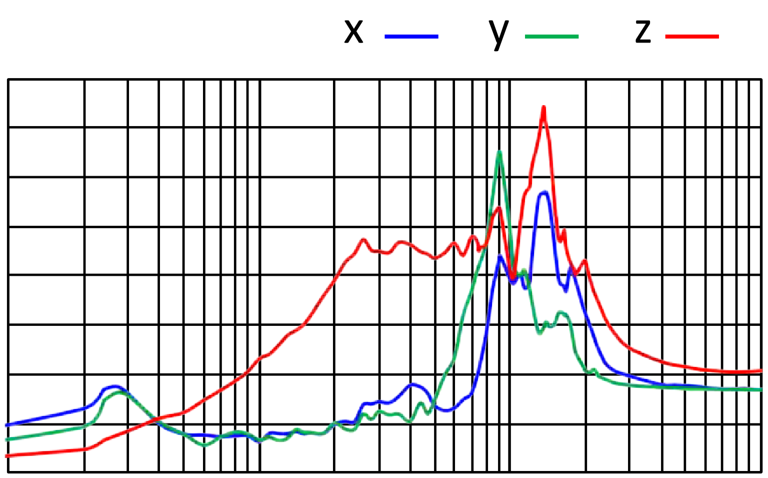




Response of RVACS Outlets to DBE and BDBE (0.75 PGA 4% damping)

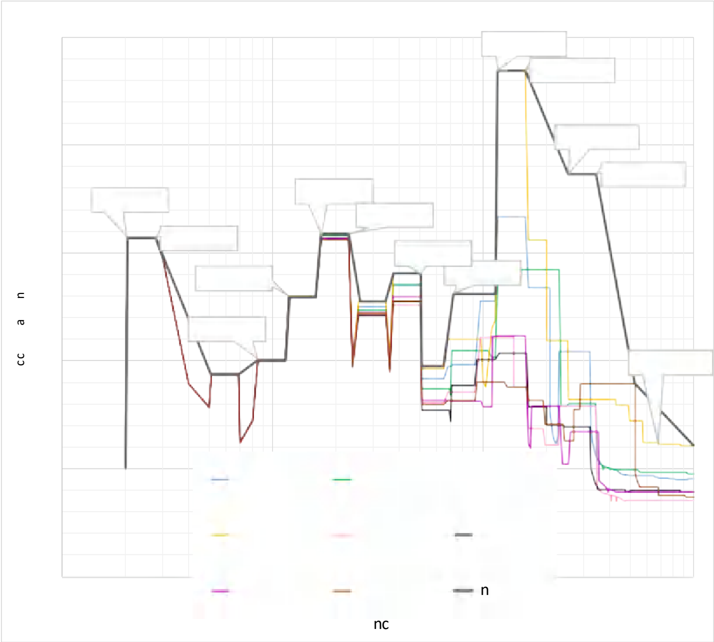


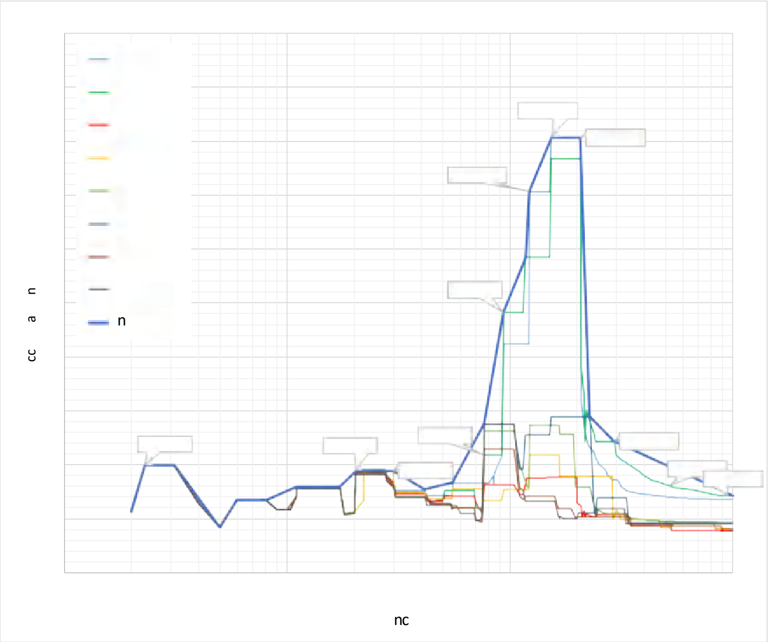
DBE

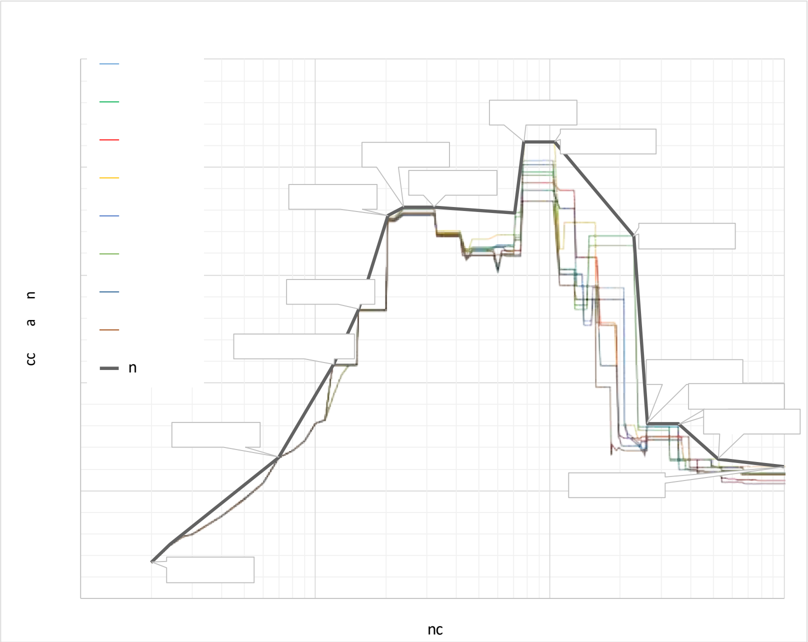


BDBE

DRACS Piping Stress analyses under DBE (SSE) conditions
RB Horizontal Isolators Only







1. Individual SSE X, Y and Z, response spectra at the RB operating floor and lower level roof have been developed with 4% damping for piping systems per NRC R.G 1.61
2. The response spectra in each direction is broadened by 15% per NRC R.G 1.122 Section C
3. the broadened and enveloped spectra have been applied to the piping finite element model via s Uniform Support Motion response spectra analysis – individual support stiffnesses and mass were not considered in this preliminary AutoPIPE analysis
4. The total modal response in a single direction is then calculated by the CQC method per RG 1.92 Rev1.Section 1.2.3 considering missing mass.
5. The overall response is then computed by the square meet the stress criteria the ASME Section III Div 1 NB-3650

DRACS Piping SRSS Calculation for use in PRA Effective PGA in Seismic Lognormal Distribution

- This is an example of the use of the spectral analysis results to determine the modified bin PGA parameter used in the seismic lognormal distribution
- The equation used is the square root of the sum of the squares, for all three axes this is:

$$\sqrt{X^2 + Y^2 + Z^2}$$

Node	X Direction	Y Direction	Z Direction	SRSS
DRACS Piping and Heat Exchangers	0.569	1.613	2.118	2.722

Scaling of Spectral Response

- We received spectral responses for the DBE (0.5g) and BDBE (0.75g) for the DRACS and RVACS nodes
- This was used to test the validity of the scaling based on the 0.5g spectral results for all SSCs
- In the vertical direction scaling can be approximated by a ratio ~ 1.0
- In horizontal direction scaling cannot reliably be used, but an approximation of 1.0 is nominally conservative for most locations and frequencies.
- The conclusion is that to properly assess fragilities for BDBE, responses need to be generated from full modeling of RB (with SSSI) with BDBE free field PGA. The BDBE ISRS have been generated under the assumption that the isolator still performs.
    - Scaling from these two points can be approximately linearly for the higher bins, where initiating event frequency becomes increasingly the major driver in sequence results

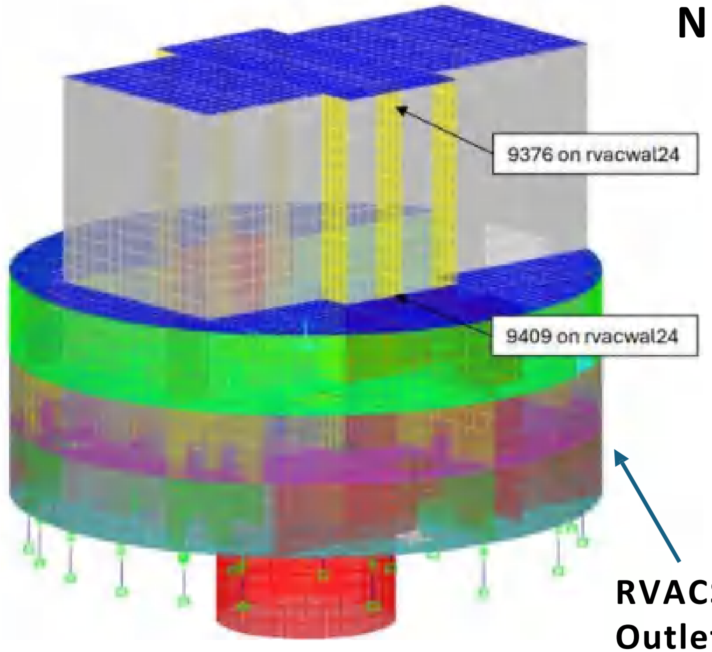
Scaling of Responses to Free Field Peak Ground Accelerations

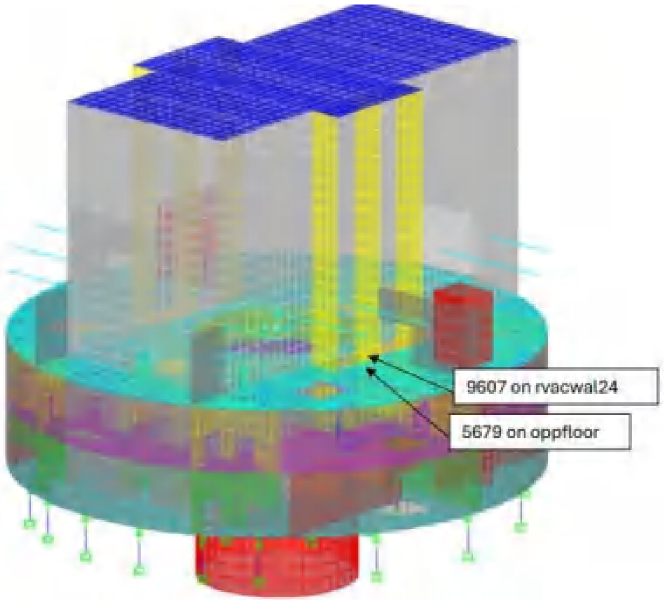
Nodes	Frequency Range	X				Y				Z			
		SSE	1.5xSSE	BDBE	Ratio	SSE	1.5xSSE	BDBE	Ratio	SSE	1.5xSSE	BDBE	Ratio
9752 RVACS	50	0.3	0.45	0.8	0.562	0.35	0.525	0.8	0.656	0.7	1.05	1.1	0.95
	10-20	1.25	1.875	2.8	0.7	1.1	1.65	1.7	0.62	2.7	4.05	3.7	1.09
	9-10	0.7	1.05	2.15		2.1	3.15	3.25	0.97	1.8	2.7	2.7	1.0
	2-8	0.3-0.5	0.45-0.75	0.9-1.5	0.5	0.3-1.5	0.45-2.25	0.45-2.25	1.0	1.5	2.25	2.3	0.98
	0.2-0.4	0.3	0.45	0.9	0.5	0.3	0.45	0.9	0.5	0.25-0.35	0.375-0.525	0.25-0.51	0.94
15881 15869 DRACS	50	0.2	0.3	0.45	0.66	0.2	0.3	0.45	0.66	0.90	1.35	1.3	1.04
	10-20	0.4	0.6	0.75	0.8	0.55	0.825	1.0	0.82	3.75	5.62	4.75	1.14
	9-10	0.3	0.45	0.75-1	0.45-0.75	0.3-0.5	0.45-0.75	0.75-1	0.6-1.0	2.1	3.15	2.55-3	1.05-1.3
	2-9	0.25	0.375	0.5-0.8	0.47-0.75	0.25-0.5	0.375-0.75	0.50-.75	0.75-1.0	1.5	2.32	2.35	0.99
	0.2-0.4	0.4	0.6	0.5-0.8	0.75-1.2	0.4	0.6	0.5-0.8	0.75-1.2	0.39	0.585	0.55	1.06
15886 DRACS	50	0.2	0.3	0.5	0.6	0.2	0.3	0.5	0.6	0.8	1.2	1.2	1.0
	10-20	0.45	0.675	1.05	0.64	1.2	1.8	2.05	0.88	1.2-1.6	1.9-2.4	1.95	0.97-1.2
	9-10	0.85	1.275	1.1	1.15	0.3-0.5	0.45-0.75	0.75	0.6-1.0	2.5	3.75	3.75	1.0
	2-8	0.375	0.562	0.75	0.75	0.2-0.4	0.3-0.6	0.5-0.75	0.6-0.8	1.5	2.25	2.3	0.978
	0.2-0.4	0.39	0.585	0.85	0.69	0.375	0.562	0.8	0.70	0.38	0.57	0.55	1.03

Table compares accelerations scaled from the SSE to the BDBE (SSR x 1.5) to the responses obtained directly from a 0.75g PGA

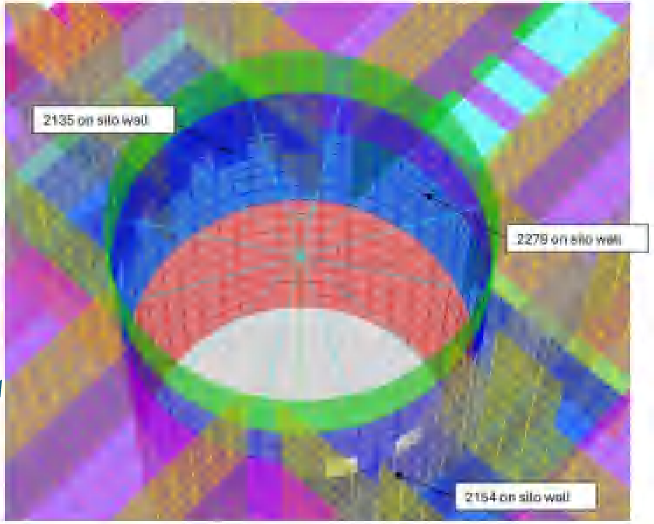
- However, the table assumes isolator displacement can be greater than the present limit (~ 28.2 inches), and this is done solely to determine what probability of failure would be if that limit would not be the case in the future seismic isolation

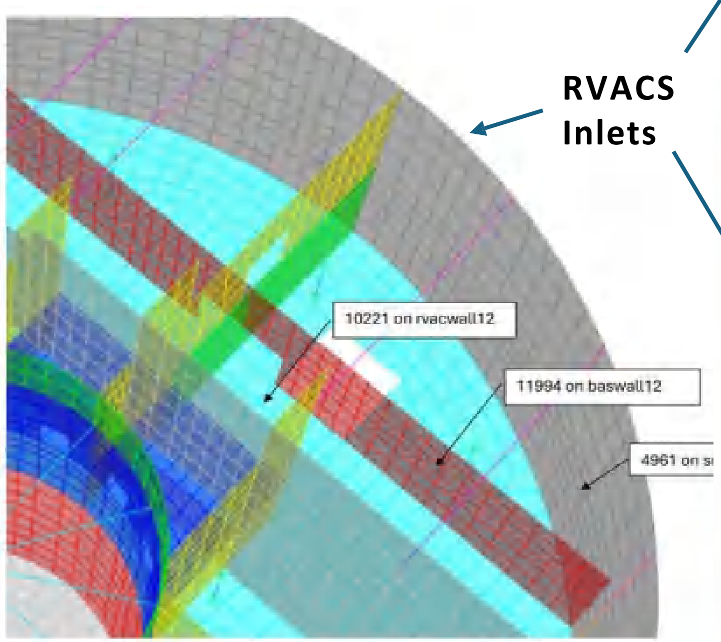
RVACS Nodes



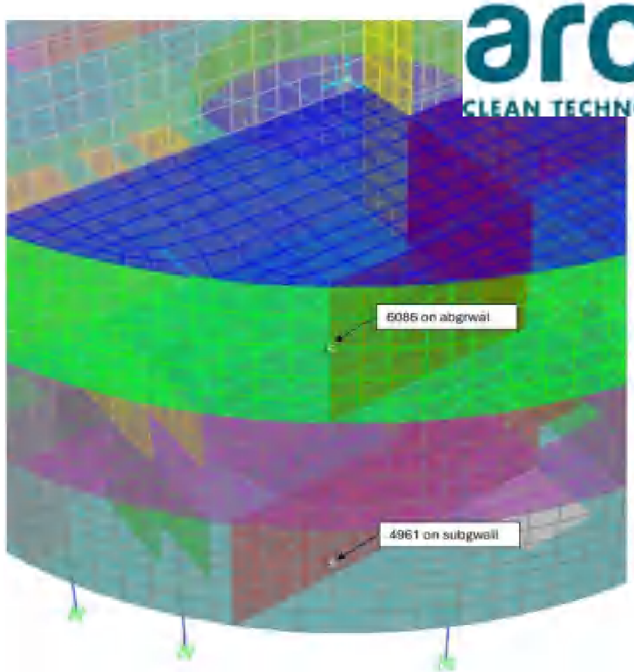


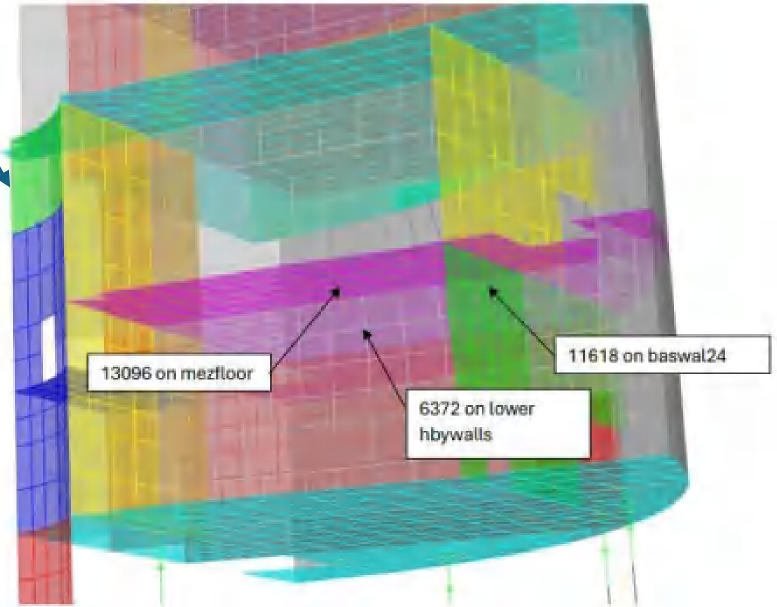
RVACS Outlets



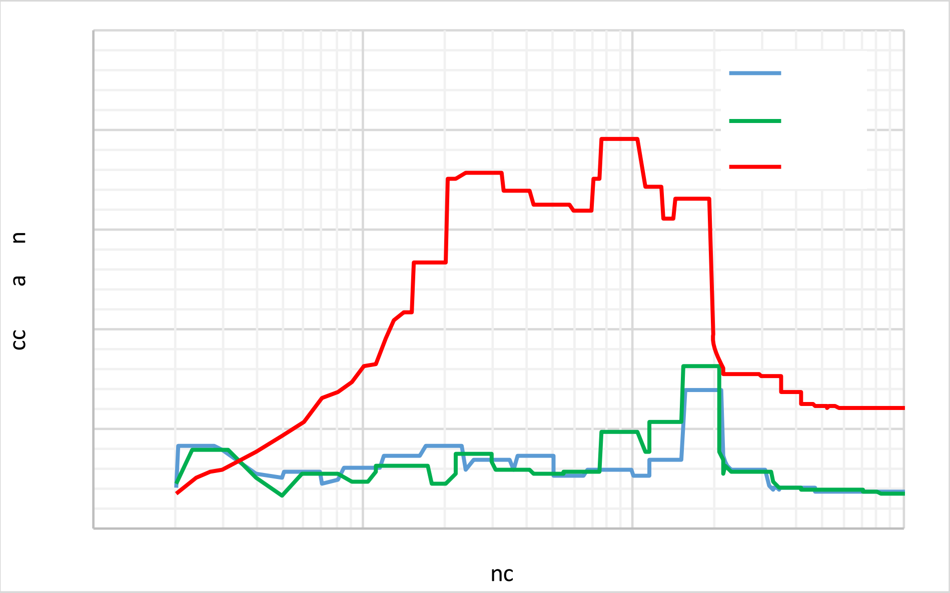


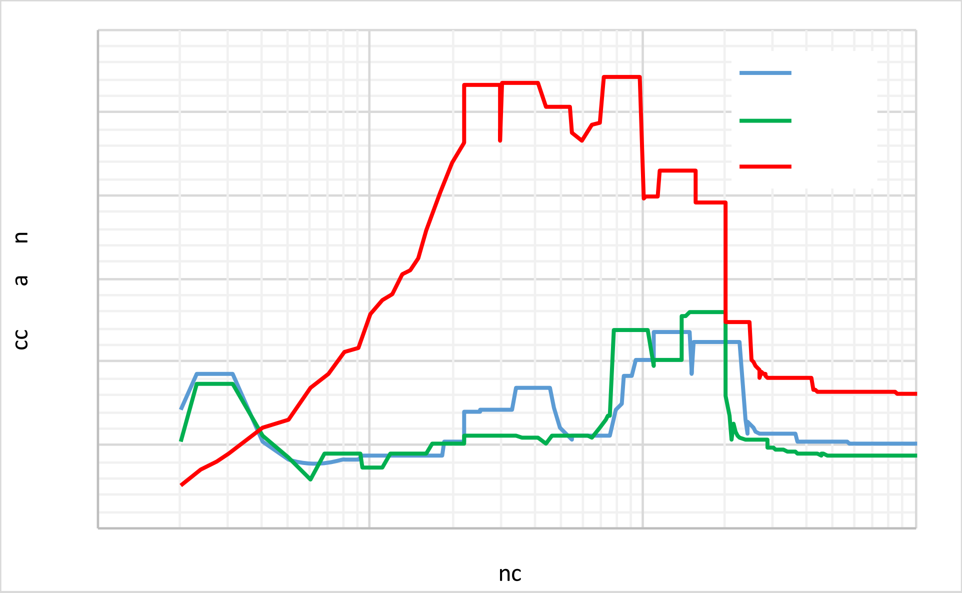
RVACS Inlets



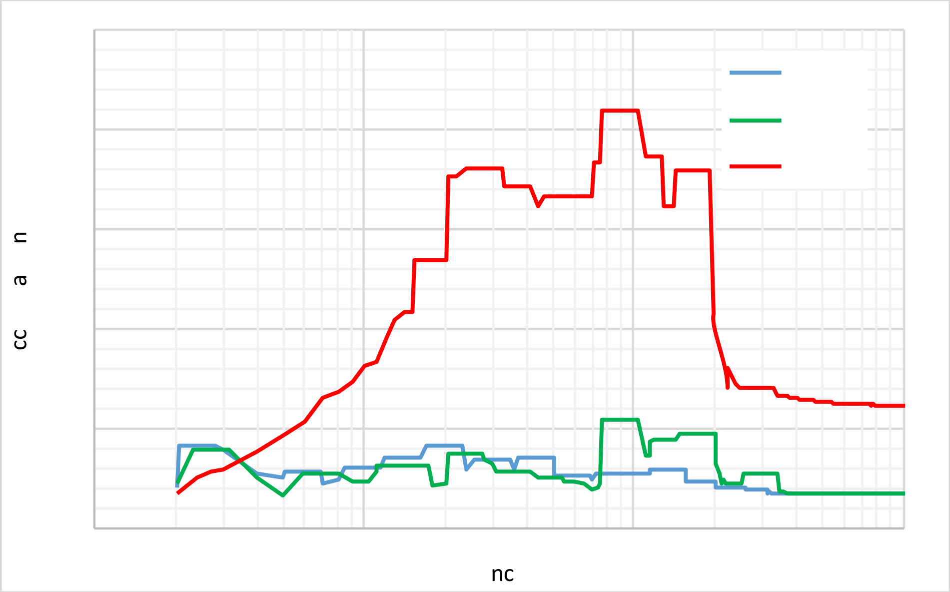


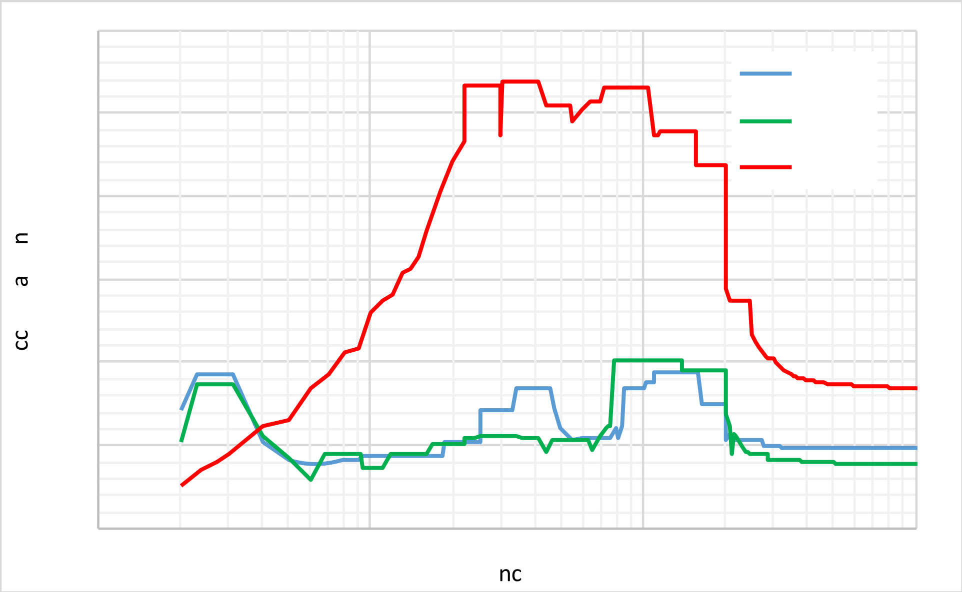
RVACS Typical ISRS Broadened Spectra Outlets & Inlets (DBE (left)and BDBE (right)





Outlets (typical)



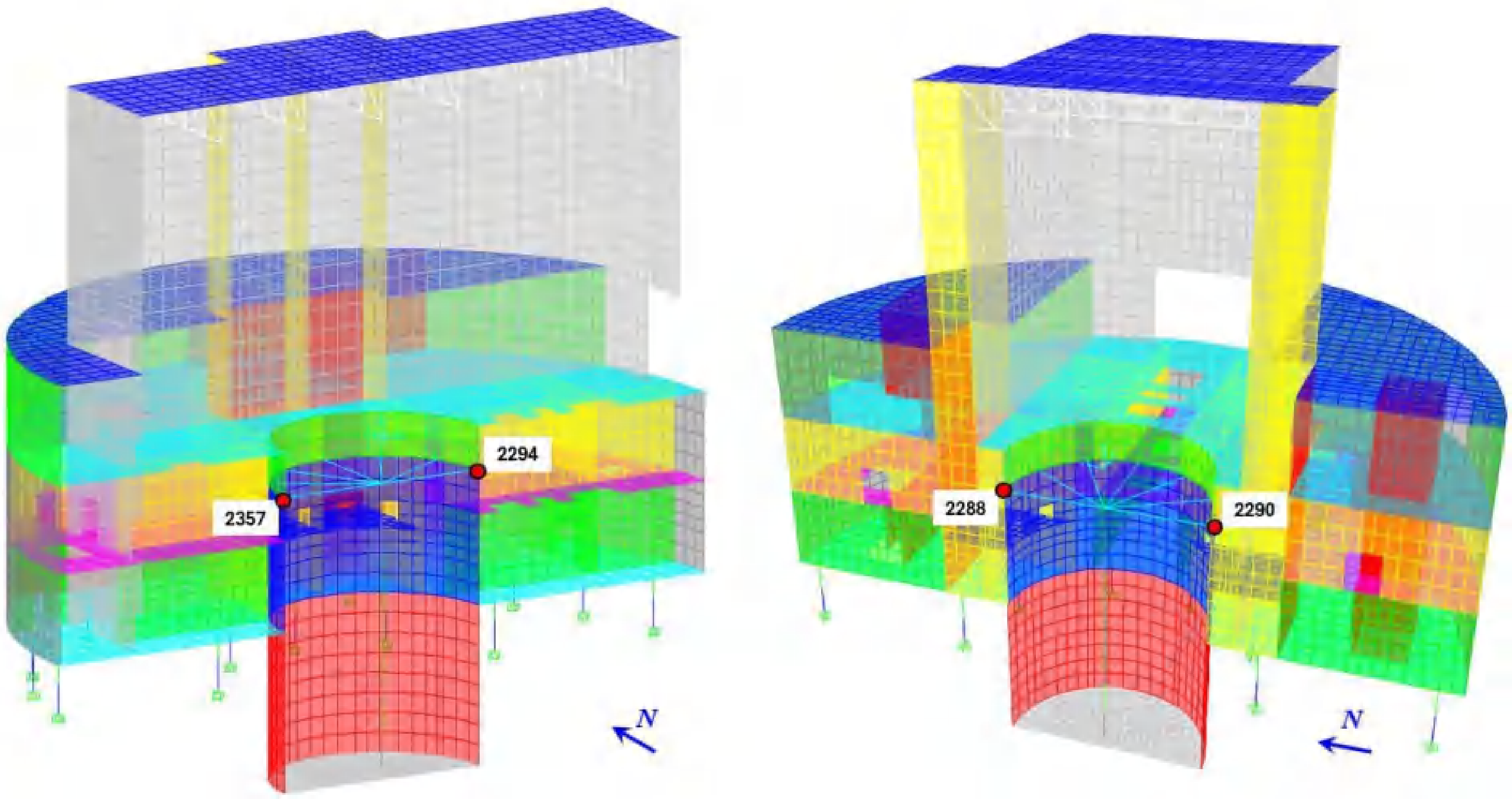


Inlets (typical)

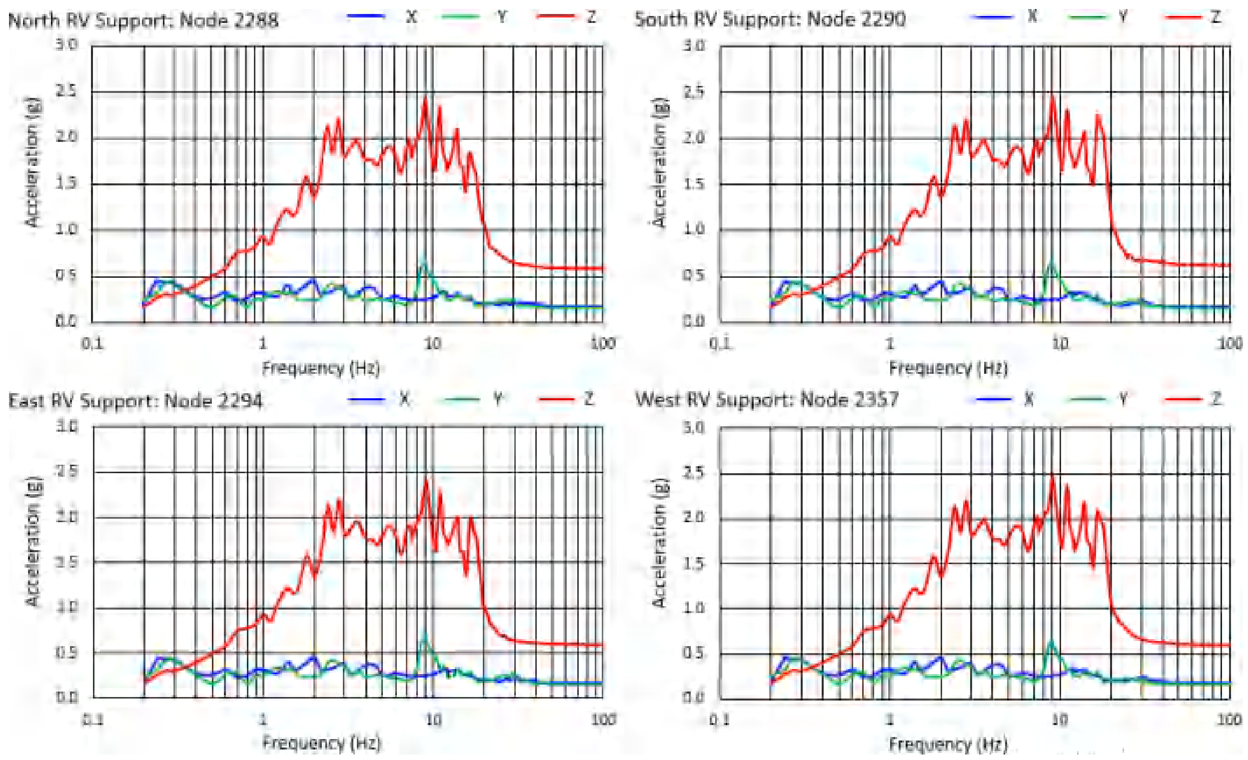
Assessment of fragilities using spectral response

- Horizontally seismic isolated response spectra at reactor vessel support points and the SRSS of XYZ peak accelerations are shown in next slide for 0.5 PGA (SSE)
  - IHI initial seismic analysis of reactor vessel, using those spectra, with a 15% envelope, indicated vessel meets the Code, meaning there will not be a structural failure at the SSE.
  - Mean responses exceed mean fragilities of common LWR reactor vessels in NUREG/CR 6544 Table 1, but preliminary analysis shows reactor and guard vessels meet the Code and will not be damaged.
    - The reactor vessel Am was adjusted to 2.722g to more accurately represent this fragility

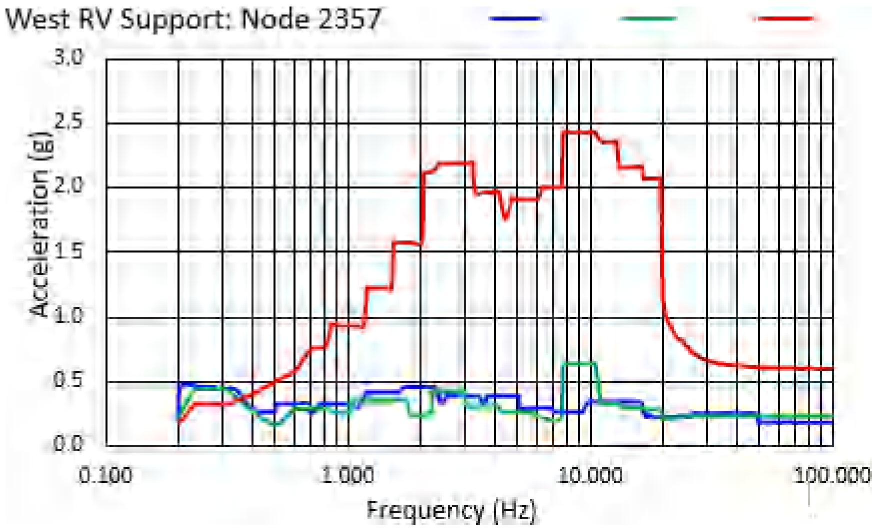
Reactor Vessel Supports Nodes in FE of Horizontally Isolated Reactor Building



Acceleration Spectra at Reactor Vessel Supports Nodes of Horizontally Isolated Reactor Building



Broadened spectra at reactor supports used by IHI. Node 2357

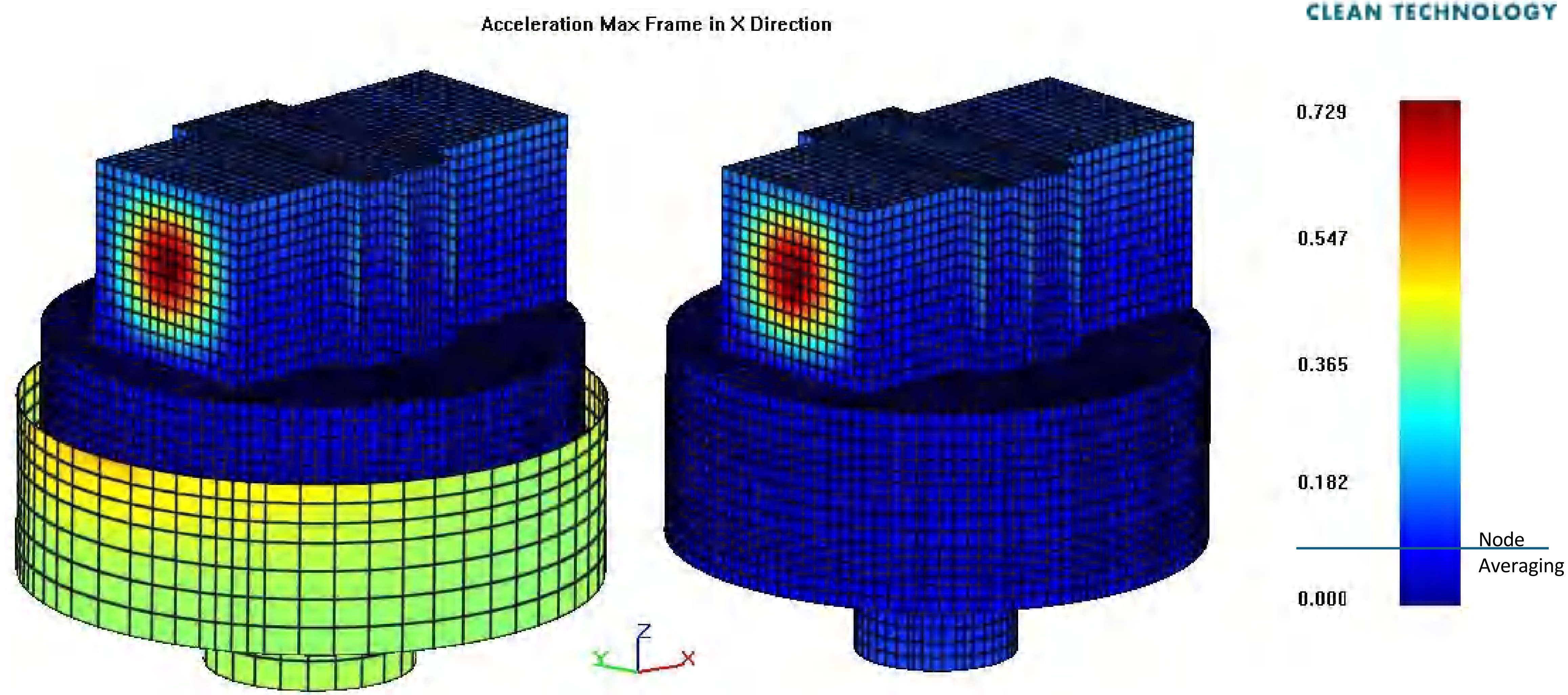


Modeling issues: 1. Reactor modeled as supported at 4 orthogonal points, but in reality, continuously supported
2. SRSS of(XYZ) Peak acceleration= 2.54g

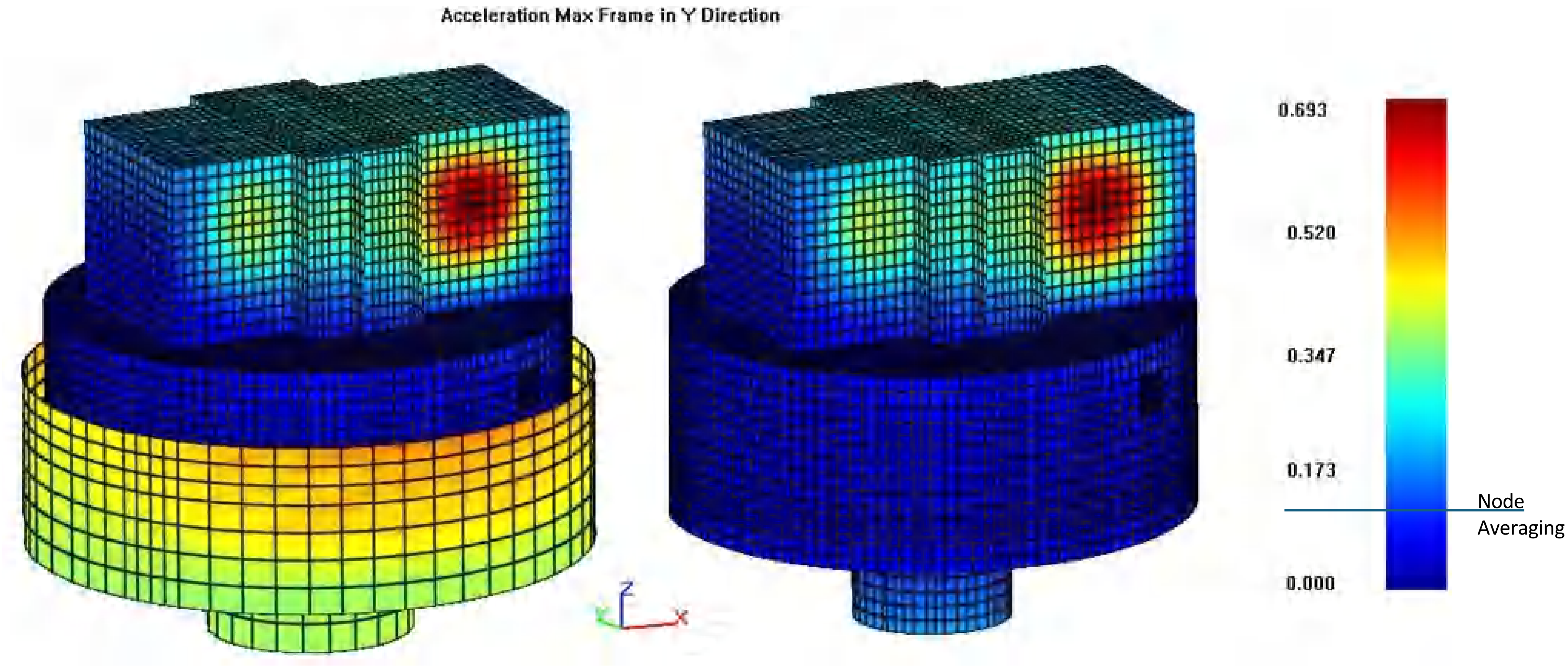
Reactor Building Spectral Response

- The reactor building was modeled, and spectral analysis results indicate that it will pass code with no significant damage at DBE and minimal non-catastrophic damage at BDBE
- There are “hot spots” of increased spectral acceleration in the middle of the roof and walls of the building, as shown in the following slides, but none that affect the SSCs anchored to the walls (e.g., RVACS ducts)

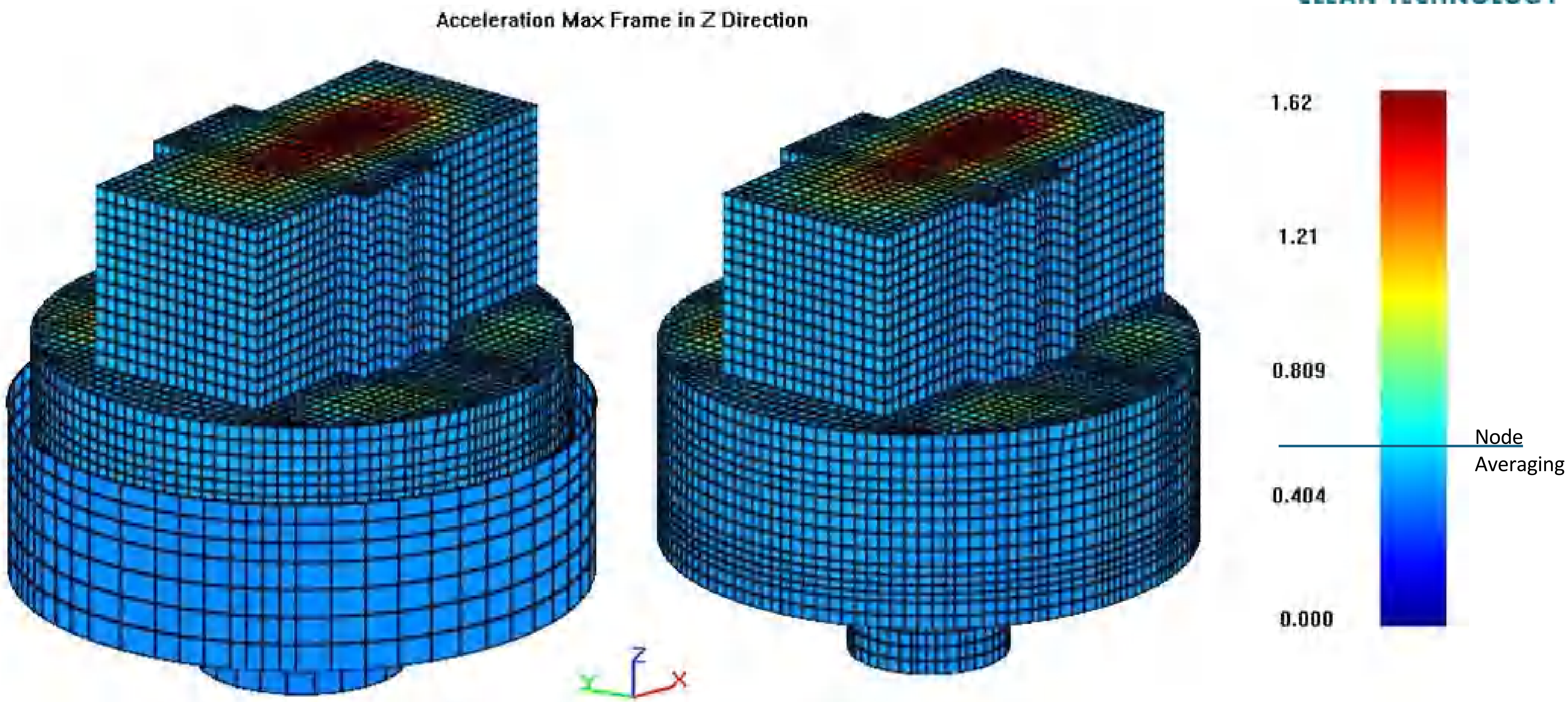
Maximum SMR Structure Accelerations in X-Direction



Maximum SMR Structure Accelerations in Y-Direction



Maximum SMR Structure Accelerations in Z-Direction



Reactor Building Fragility for PRA

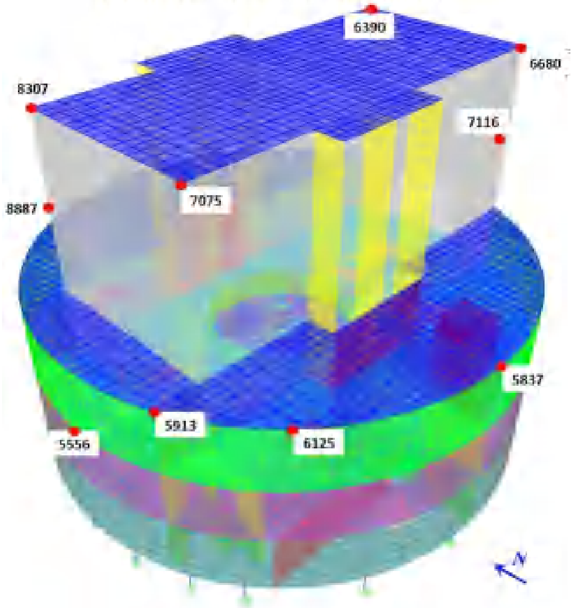
- The reactor building was modeled, and spectral analysis results indicate that it will pass code with no significant damage at DBE and minimal non-catastrophic damage at BDBE
- The expert opinion of the seismic experts estimated the Am at 4.5g,
  - This value lies between the common LWR reactor containment building Am = 1.1g and Diablo Canyon = 9.0g
- The following fragilities were calculated using this information, along with the Beta R and Beta U listed for reactor containment buildings

Reactor Building Fragilities					
	Bin PGA	Am	Br	Bu	Probability of Failure
EQ1	0.002	4.5	0.3	0.35	3.12E-63
EQ2	0.103	4.5	0.3	0.35	1.27E-16
EQ3	0.5	4.5	0.3	0.35	9.38E-07
EQ4	0.75	4.5	0.3	0.35	5.08E-05
EQ5	1.677	4.5	0.3	0.35	1.61E-02
EQ6	5.477	4.5	0.3	0.35	6.65E-01

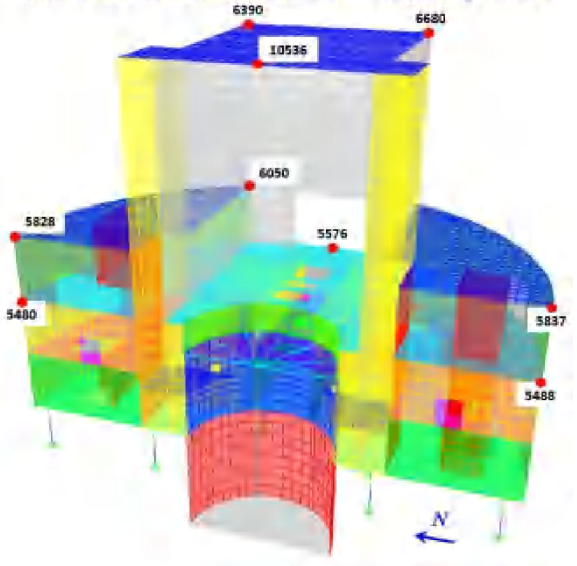
arc CLEAN TECHNOLOGY

Examples of Nodes at which DBE and BDBE responses are provided

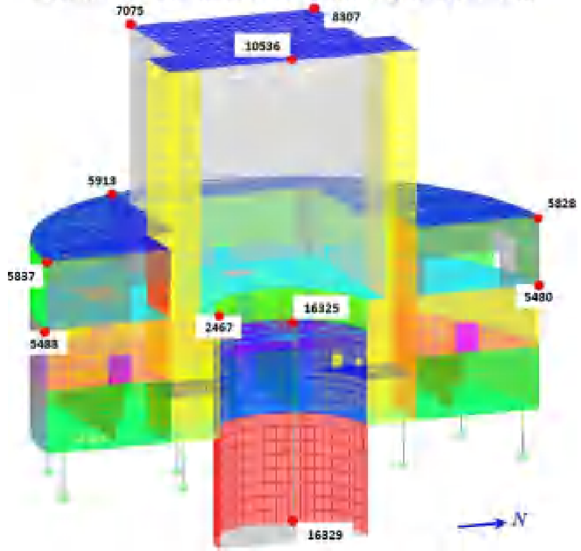
SAP2000 Model: Isometric View Looking North-East



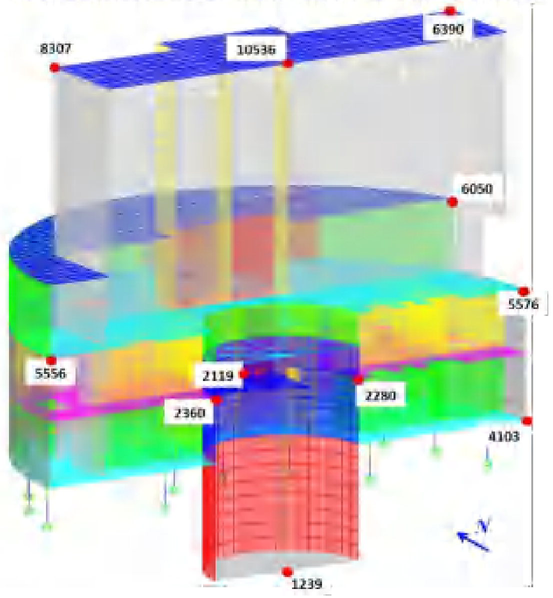
SAP2000 Model: Partial Isometric View - Cut at Y = 0-ft, Looking North-East



SAP2000 Model: Partial Isometric View - Cut at X = 0-ft, Looking North-West



SAP2000 Model: Partial Isometric View - Cut at Y = 0-ft, Looking North-East



Spectral Analysis Results and Current Seismic Isolator Limitations

- Seismic events dominate the risks that could lead to fuel damage unless the reactor is properly seismically isolated.

- Initial nominal results for internal events are in the fuel damage frequency range of 10^{-6}-10^{-7}/yr. Horizontally isolated seismically initiated events run in the $5x10^{-5}$/yr range.

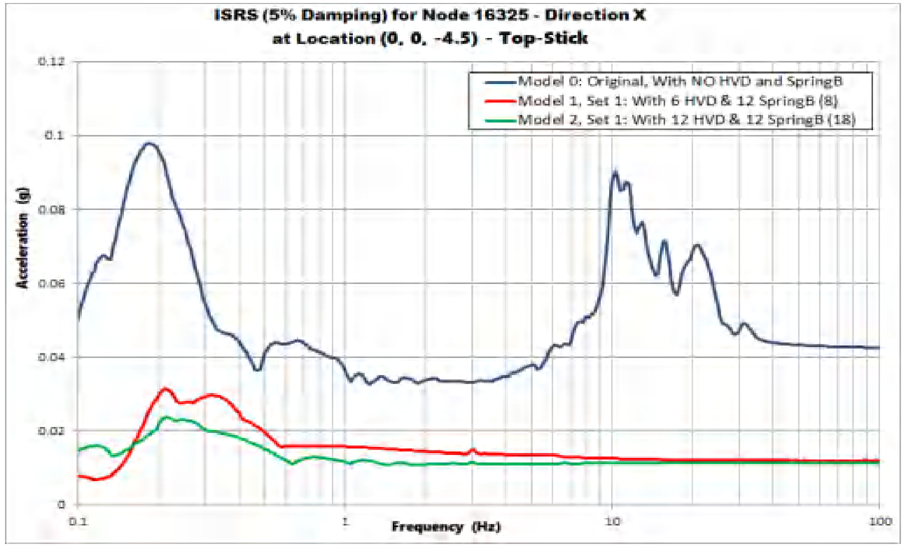
- We have spectral analysis results for horizontally isolated RB up to 0.5g (bin 3), and limited results for 0.75 g (bin 4)- We have no results that can be relied upon at the 0.75 g or above

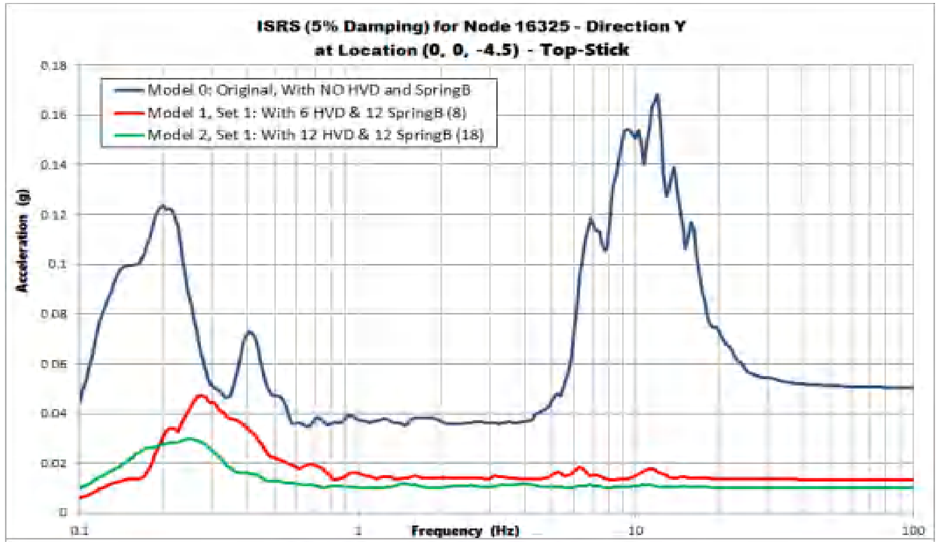
- Fragility of building/structures can be determined up to some acceleration as part of the ongoing effort the assess the structures
  - Reactor building Structure has been verified to meet Code for the response to the SSE

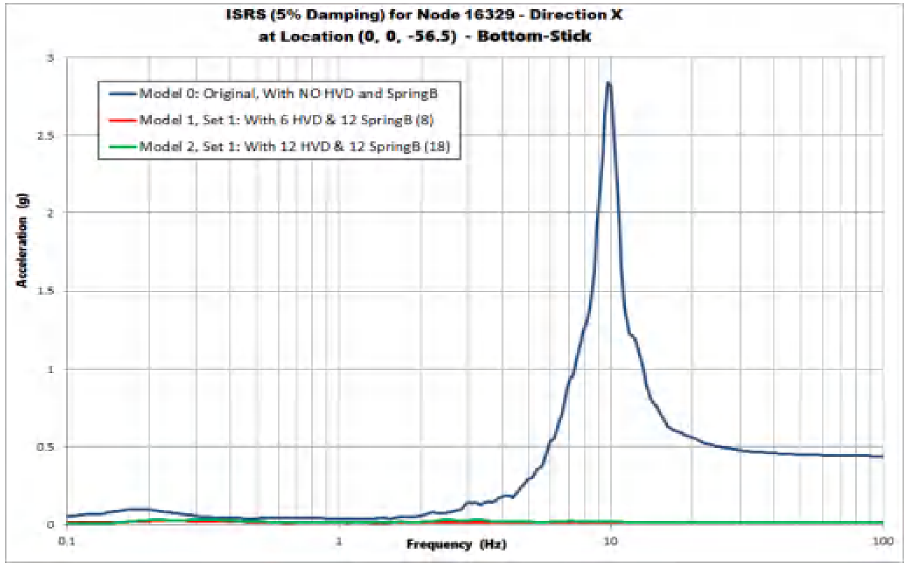
- Fragility of RB is limited to a free field accelerations up to about 0.69-0.7 because displacement at horizontal isolators exceed isolator capability (28.2 inches)

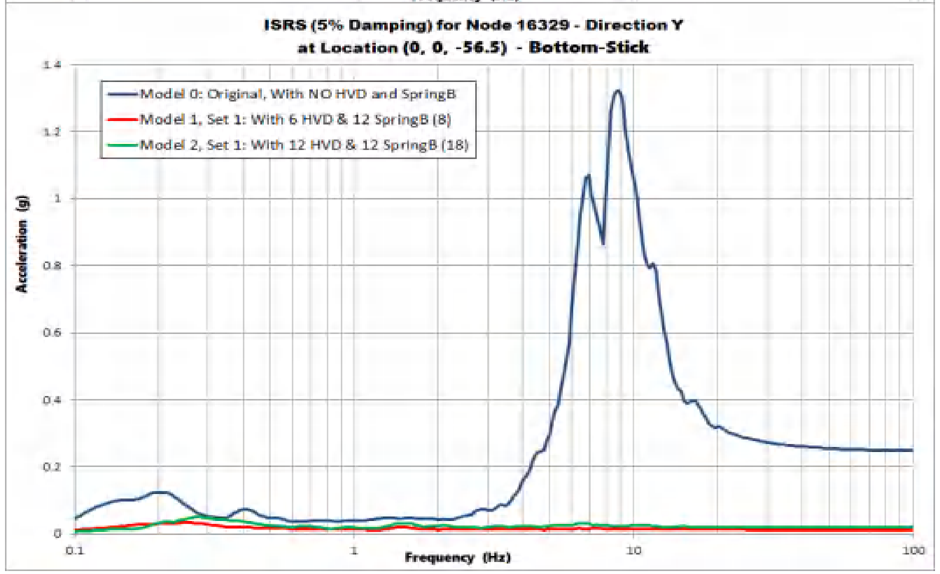
- Any structural analyses of isolated RB at free field PGAs exceeding 0.69-0.7 g is only useful as a planning tool for when more capable isolators are installed, as local responses are no longer valid for these isolators

Horizontal Seismic Response at Top and Bottom of Vessel with and w/o Vertical Isolator





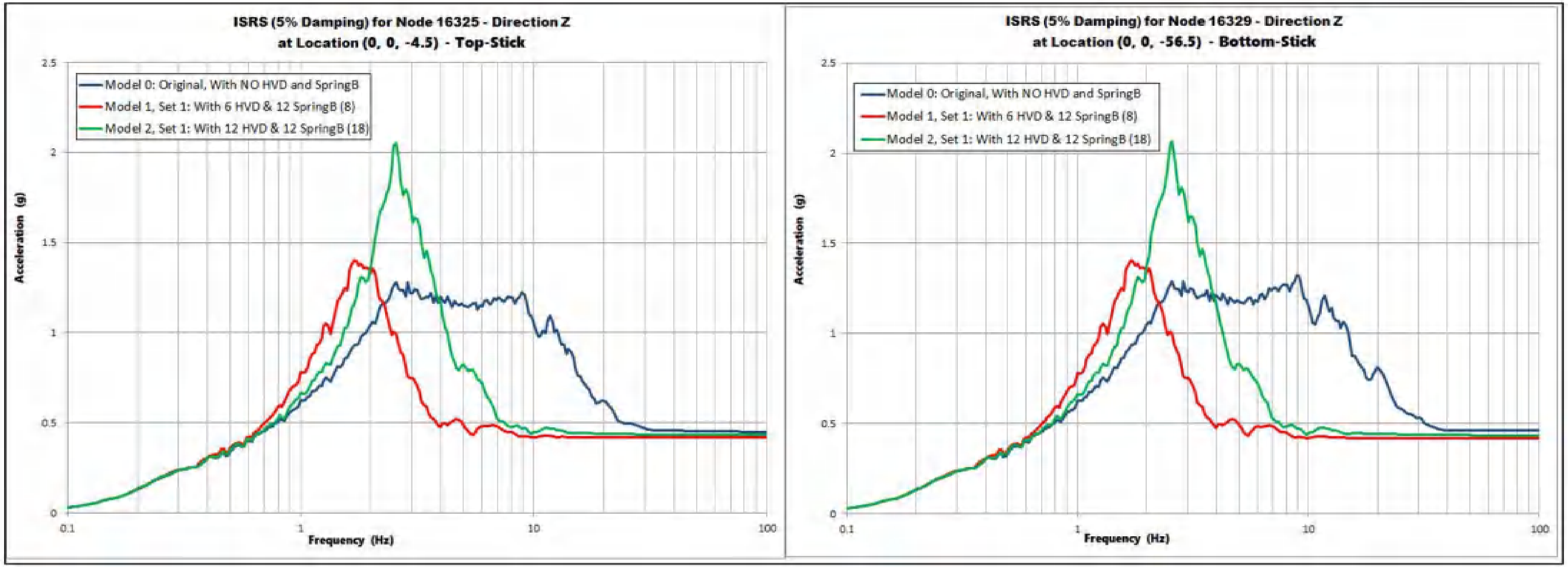




Vertical Seismic Response at Top and Bottom of Vessel with and w/o Vertical Isolator

Top of reactor Vessel

Bottom of reactor Vessel



Peak Seismic Acceleration Top (SRSS XYZ) w/o vertical isolation-1.26g
Peak Seismic Acceleration Top (SRSS XYZ) w.12 vertical isolators-1.25g
Peak Seismic Acceleration Bottom(SRSS XYZ) w/o vertical isolation-3.39g
Peak Seismic Acceleration Bottom(SRSS XYZ) w. 12 vertical isolators-1.4g

Seismic PRA Results with Theoretical Unlimited Isolator Displaceme n

Name	Point Estimate	% Contribution	Bin PGA	Cut Set Count
Totals	2.24E-05	100		48203
EQK-BND-PGA-BIN-1	9.84E-16	< 0.01	0.002	1
EQK-BND-PGA-BIN-2	1.43E-08	0.06	0.103	2
EQK-BND-PGA-BIN-3	3.81E-06	17	0.500	38
EQK-BND-PGA-BIN-4	8.30E-06	37.03	0.750	12050
EQK-BND-PGA-BIN-5	9.73E-06	43.43	1.677	18056
EQK-BND-PGA-BIN-6	5.55E-07	2.48	5.477	18056

- Results are for any fuel damage experienced, regardless of severity
- Results beyond Bin 3 are not reliable because the exceedance the horizontal isolator’s displacement limit is reached beyond 0.69 PGA
- Overall results are two orders of magnitude above the internal events fuel damage frequency

Conclusion, Open Items and Future Investigations

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Conclusions

- Horizontally Isolated Reactor Building is capable of withstanding the SSE (0.5 PGA) without damage
  - In the opinion of structural experts, the horizontally isolated RB would also be capable of withstanding an earthquake (BDBE) 1.5 time greater (0.75 PGA)
  - However presently chosen horizontal isolators are limited to 28.2inch displacements. BDBE in excess of 0.69 PGA will likely cause exceedance of displacement capacity
  - Seismic PRA predictions for BDBE assume isolators continue to function at increasingly greater accelerations
    - Assumption made to indicate results obtainable when accelerators are replaced in future design work
  - Different isolator with increased displacement capacity are necessary

Conclusions (Continued)

- Most components housed in RB as well as in Control and Diesel Generator building have fragilities that are better than the **mean** fragilities indicated by the NRC (NUREG/CR 6544 Table 6-1); but not the **HCLPF** values
  - Fragilities indicated by conservatively estimated SRSS of XYZ responses spectra at components locations
  - Critical components, e.g. Reactor Vessel Internals may not meet , unless vertically isolated
  - More work remains to be done to compare additional systems /components

- Combination of isolator limitation and necessity to isolated vertically drives future design toward Full 3D isolation of RB, plus possibly local additional vertical isolation
  - Two analyses planned to help select 3D isolators with requisite displacement capacities
    - 3D isolated RB subjected to full SSSI under SSE (0.5 PGA) in soil of 2000 fps shear velocity
    - 3D isolated RB subjected to full SSSI under BDBE (0.75 PGA) in soil of 2000 fps shear velocity
  - Results will be communicated to NRC as soon as available (see open Items and Near-Term Investigation slide)

Open Items and Near-Term Investigation

- Open Items
  - Identify limits of validity for assumption of linear behavior in PRA space
  - ISRS for BDBE assumed isolators function properly, but displacment limits are exceeded at accelerations lesser than the BDBE PGA
  - Resolution of inconsistencies that have crept into the various parallel calculations performed during the analysis documented in this report.
    - Response of the building, including the model of the reactor vessel incorporates the change in vessel weight.
    - Parallel study of the effect on adding vertical isolators to the support of the reactor vessel, has not yet included that change
- Near-Term Investigation
  - Identify 3-D isolator with increased horizontal displacement capacity
  - Apply isolators to RB model developed for SSI/SSSI under DBE and BDBE
  - Report results to NRC (and DOE)