Update on Seismic Isolation Design

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Seismic Analyses Work Subsequent to Meeting on Nov 12, 2024

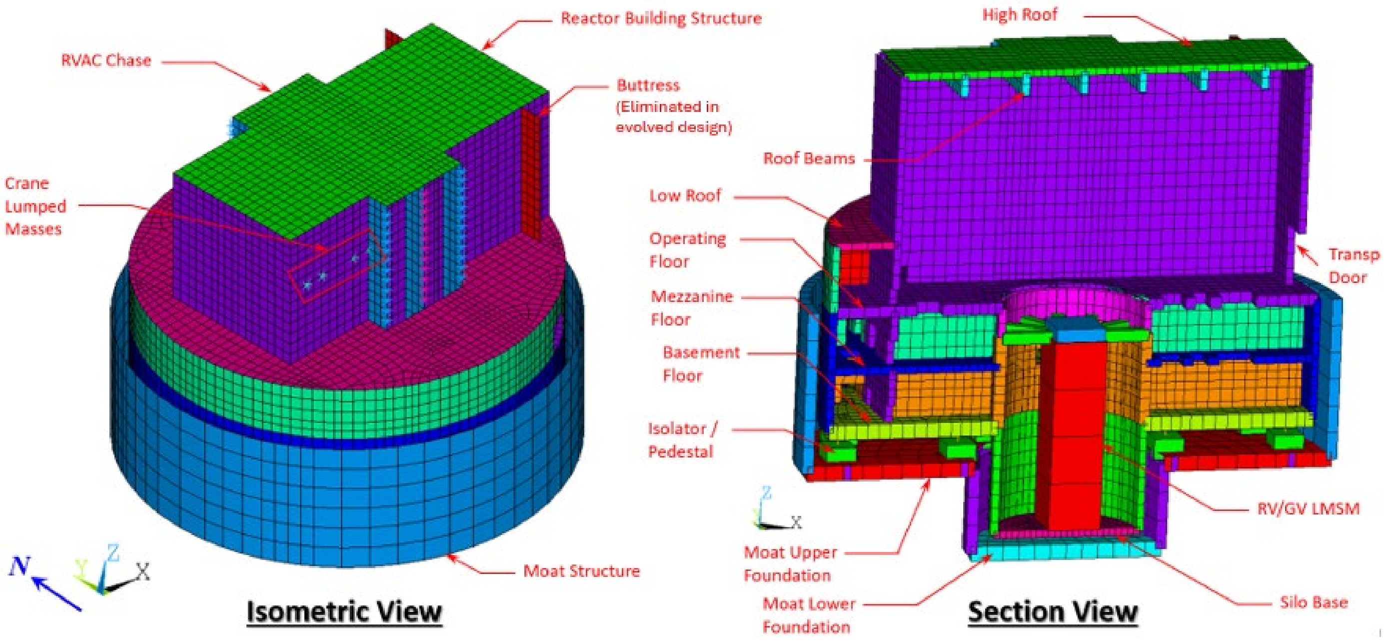
- Meeting held on NOV 12, 2O24 reported results of:
  - Reactor building 2D seismic isolation, with additional effect or local 3D isolators under reactor vessel supports
  - Initial Probabilistic Seismic Analysis based on initial Seismic Hazards
- Results for the design basis earthquake (0.5 PGA) showed:
  - significant feedback from the vertical to horizontal in-structure response spectra (ISRS) (due to a combination of building asymmetry and nonlinearity of 2D friction pendulum isolators;
  - Despite large horizontal acceleration at certain locations due to the feedback, the Code analysis by IHI, using the generated seismic input at the vessel supports confirmed the reactor vessel, the guard vessel and their supports meet the code allowables; and the reactor building analysis confirmed the building meets its code
- Results for the beyond design basis earthquake (0.75 PGA) showed
  - Non-linearity of the response at different PGAs
  - Displacement at the accelerator exceeding the isolator capacity
  - Assessment of fragilities in Seismic PRA space proceeded assuming the isolator as working beyond its capacity
    - Fragility results therefore no reliable except for DBE
- Committed to study effect of isolating the RB with 3D Isolators and report to the NRC
- Purpose of this meeting is to communicate :
  - The results of the 3D isolation in the structural responses vs. those obtained with 2D isolation
  - The linearity of 3D responses enabling establishment of fragilities to any magnitude earthquakes, and its effect on seismic hazards
  - The very severe earthquakes cause the worst consequences to be considered in design for BDBEs, i.e. frequencies above 5 x 10-7 per year

Structural Modeling and Seismic SSI Analysis Methodology

Building Description including Seismic Isolation System

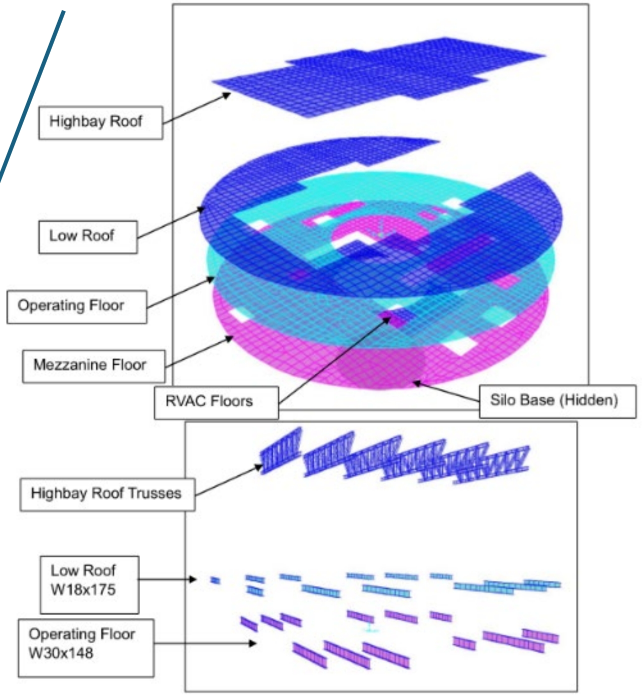
- Top of moat at grade level, 0’
  - Moat upper fdn at -43’
  - Moat lower fdn at -66’
- Reactor Building
  - Aprox. 134’ diameter
  - Basement floor at -32’
  - Mezzanine floor at -16.5’
  - Operating floor at 0’
  - Low roof at +17.5’
  - High roof at +57’

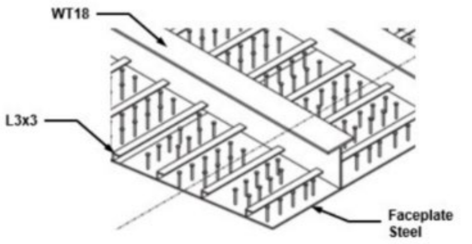
Reactor Building (RB) – Preliminary Design ANSYS Model – Isometric View

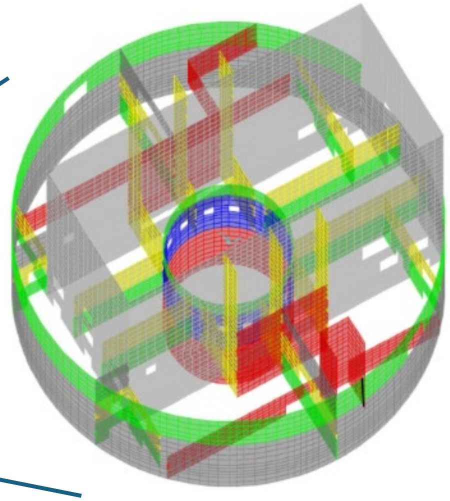


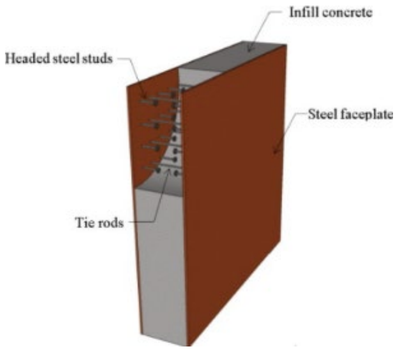
General Construction

- 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)

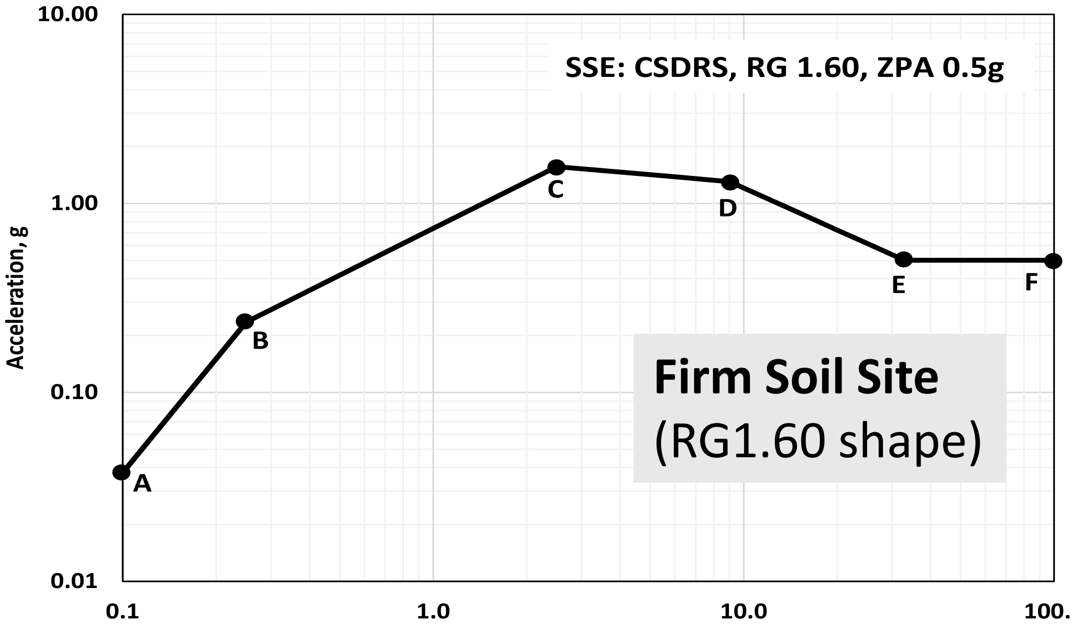


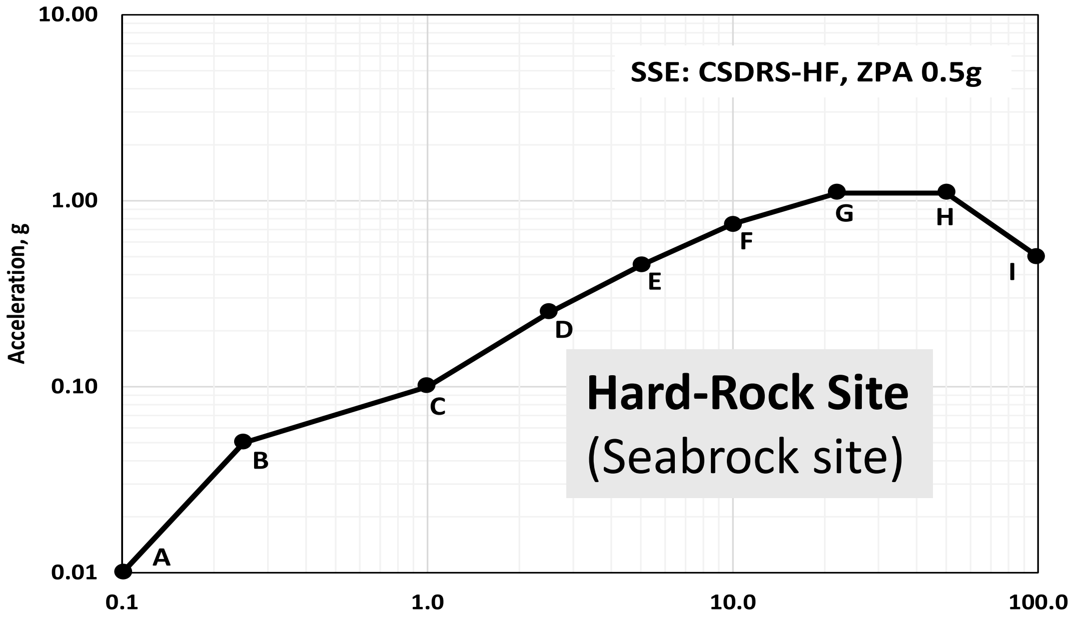


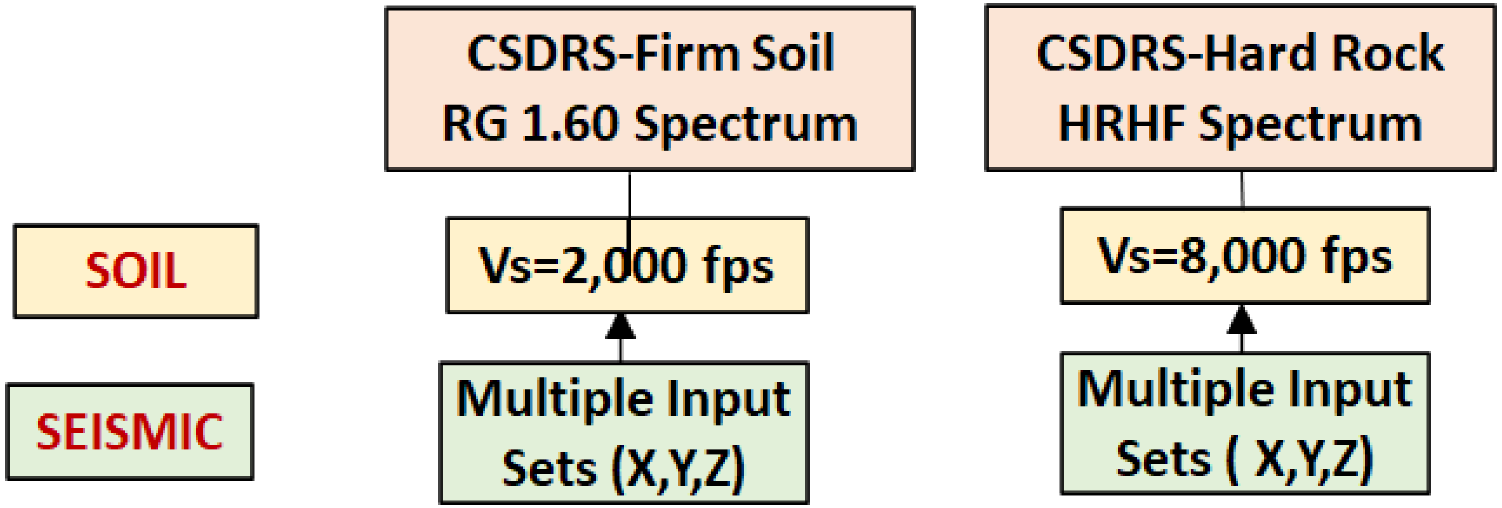




Two Generic Site Conditions with 0.5g CSDRS, Same for X, Y and Z Input Directions







CSDRS-Firm Soil RG 1.60 Spectrum

CSDRS-Hard Rock HRHF Spectrum

SOIL

Vs=2,000 fps

Vs=8,000 fps

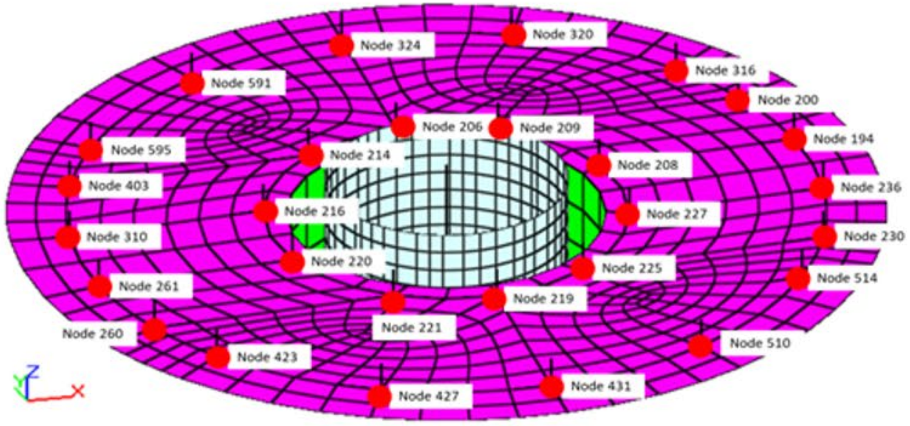
SEISMIC

Multiple Input Sets (X,Y,Z)

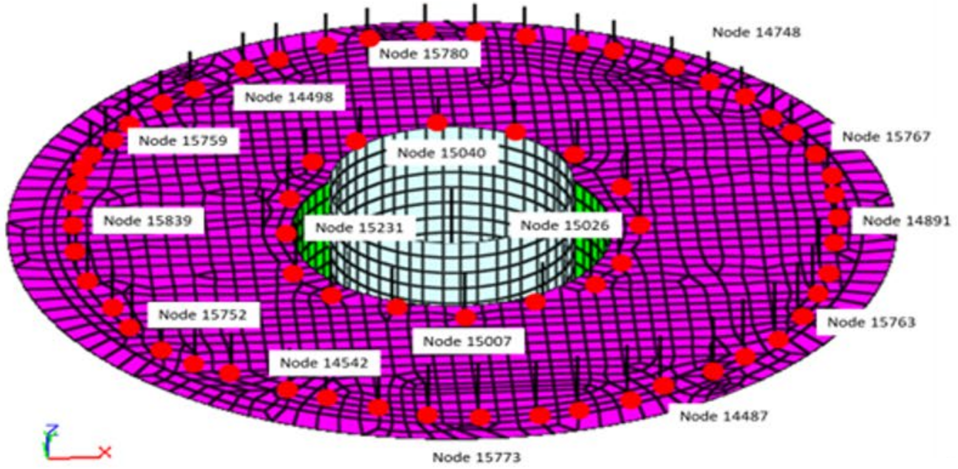
Multiple Input Sets (X,Y,Z)

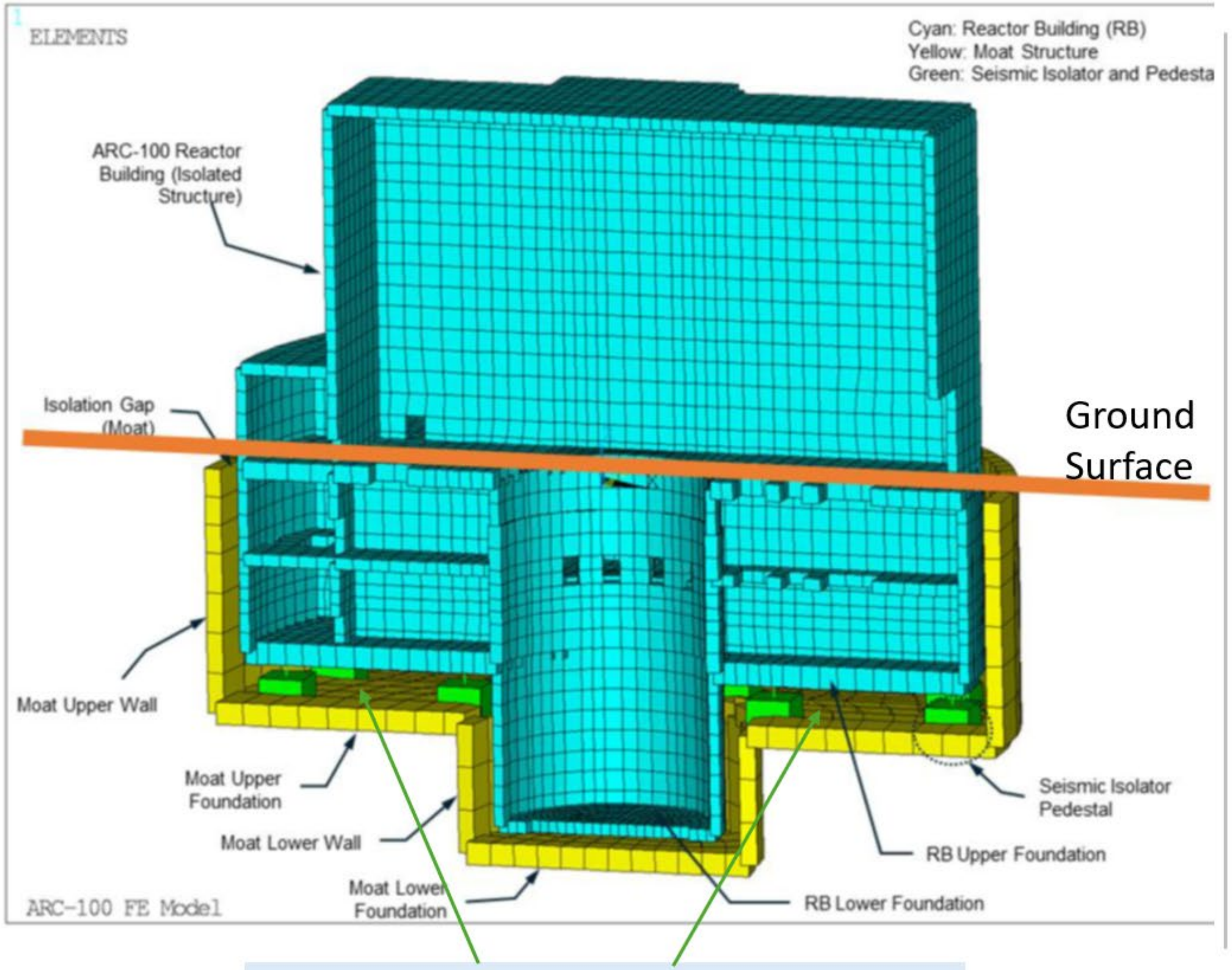
Global SIS Isolator Locations at SMR Upper-Base Level

2D SIS: 28 FP Type Isolator SIS



3D SIS: Variable 42-64 SB and 96-160 HVD





SIS at SMR Upper-Base Level

Summary of 2023-2025 Studies Using Different Seismic Isolation Systems (SIS) for ARC-100 SMR

1) 2D SIS: Global 2D Friction Pendulum Base-Isolation System (2023)

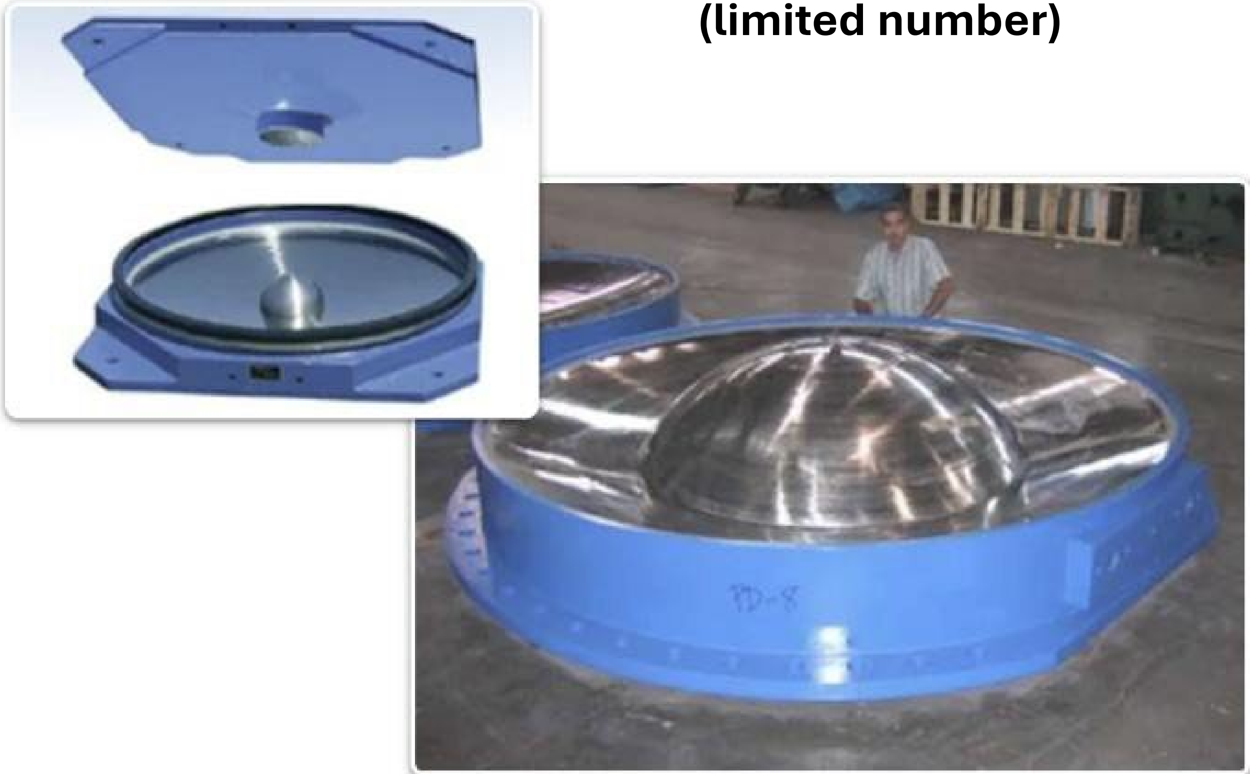
2) 2D-3D Hybrid SIS: Global 2D Friction Pendulum Base-Isolation System,
Plus A Local 3D Spring-Damper Isolation System for RV System Vibration (2024)

3) 3D SIS: Global 3D Spring-Damper Base-Isolation System (2025)

Comparative Studies Using 2D Friction Pendulum (FP) and 3D Spring-Damper (GERB BCS) Isolators

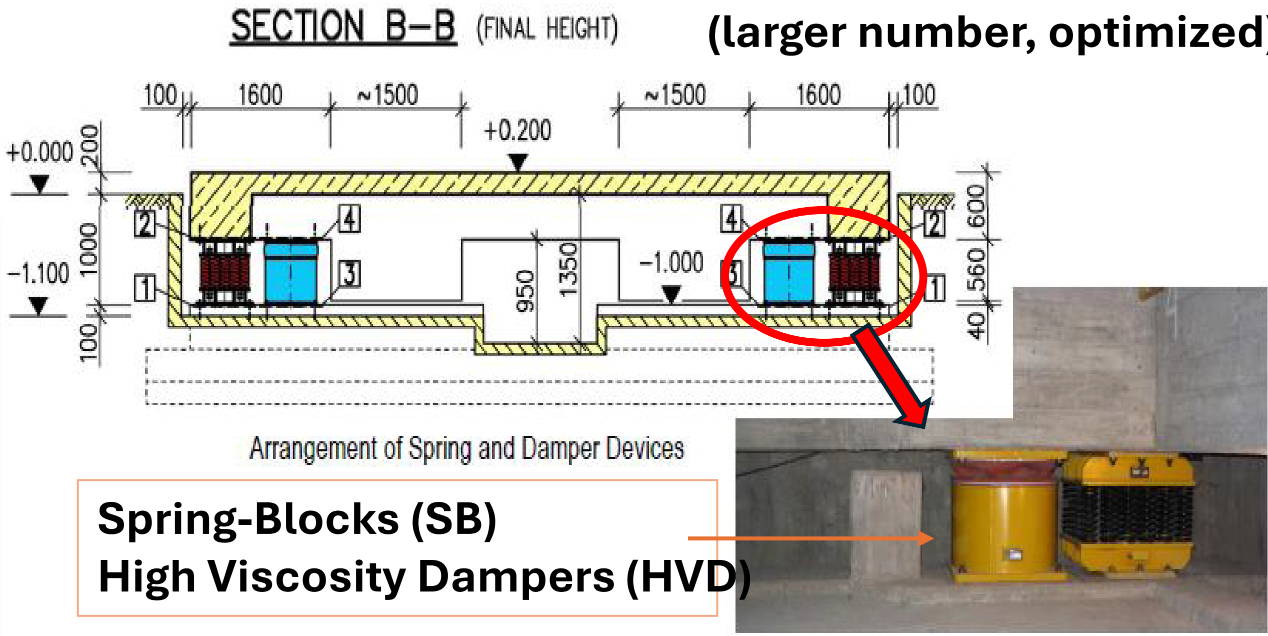
- 2D-space **Friction Pendulum (FP)**

Large-size isolators (limited number)



GERB **3D-space Base Control System** (BCS

Smaller-size isolators
(larger number, optimized



Arrangement of Spring and Damper Devices

Spring-Blocks (SB)
High Viscosity Dampers (HVD)

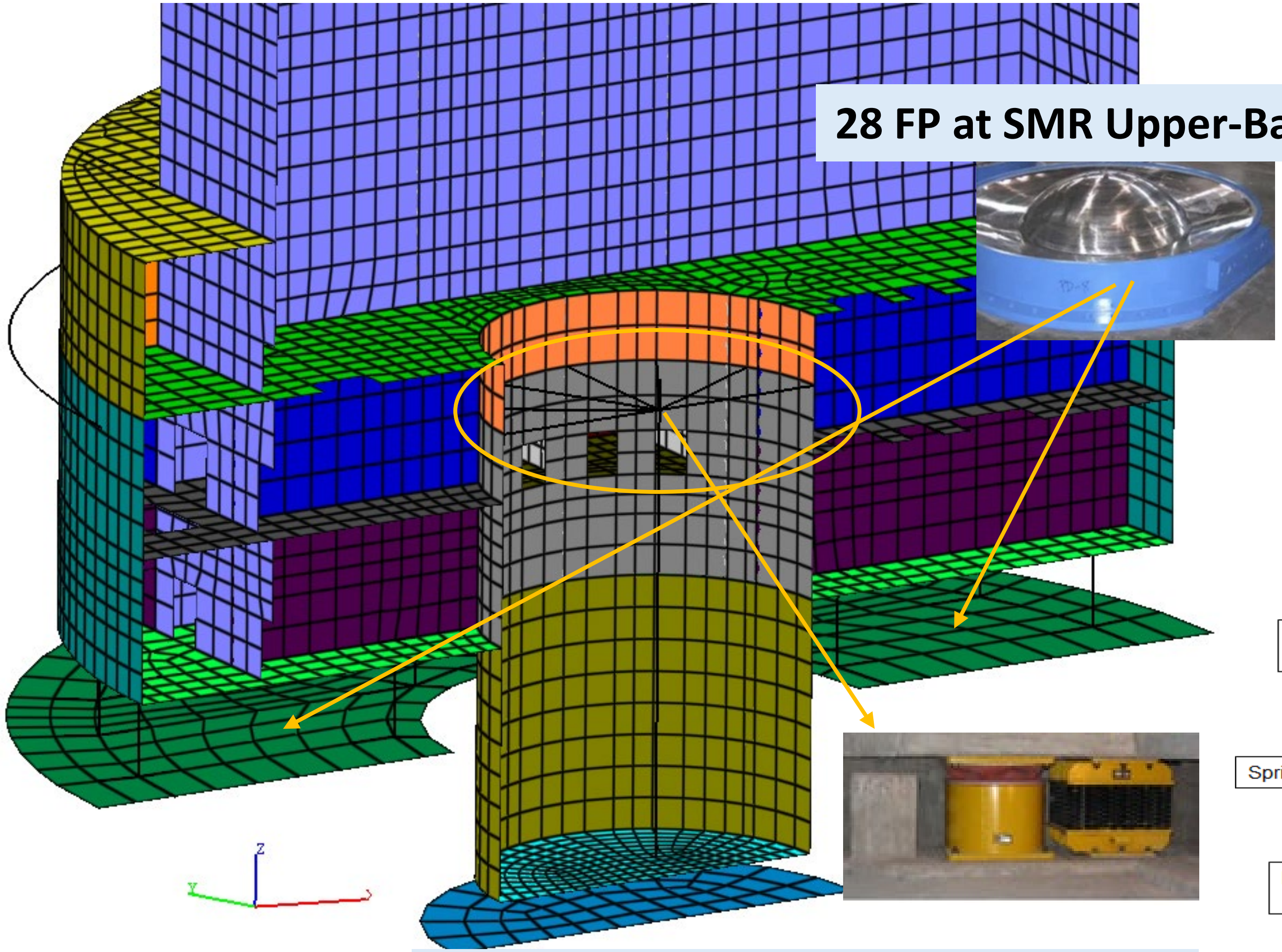
Two separate BCS isolation system applications:

1) Local Isolation: Initially used together with FP isolator
for local isolation of the reactor vessel (RV)

2) Global Isolation: Replace completely the FP isolators

Hybrid 28 FP Plus 12 BCS for Local RV System

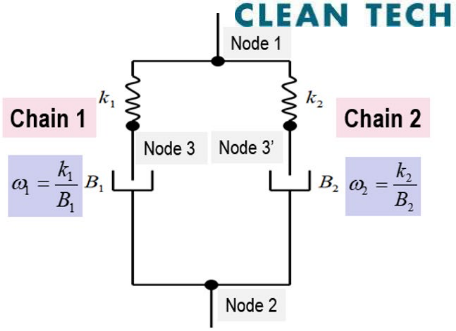
Hybrid Global-Local Isolation System



28 FP at SMR Upper-Base

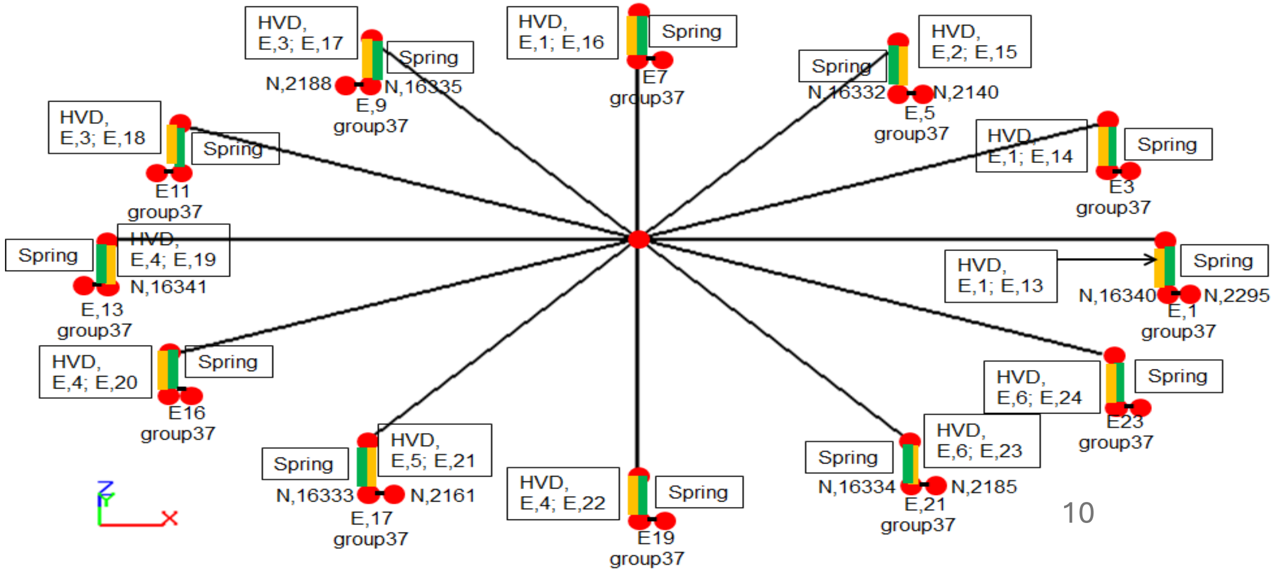
12 BCS Isolators at RV Support Beams

GERB HVD Device



4-Parameter Maxwell Model

ACS SASSI includes linearized frequency-dependent HVD (based on GERB recommendations). Uses four frequency-dependent complex stiffnesses (Kh, Kv, Bh, Bv) for each Maxwell chain. Total eight parameters for a HVD unit.



SIS Dynamic Behavior Affects Complexity of Seismic SSI Analysis Per ASCE 4-16/7-22 Standards

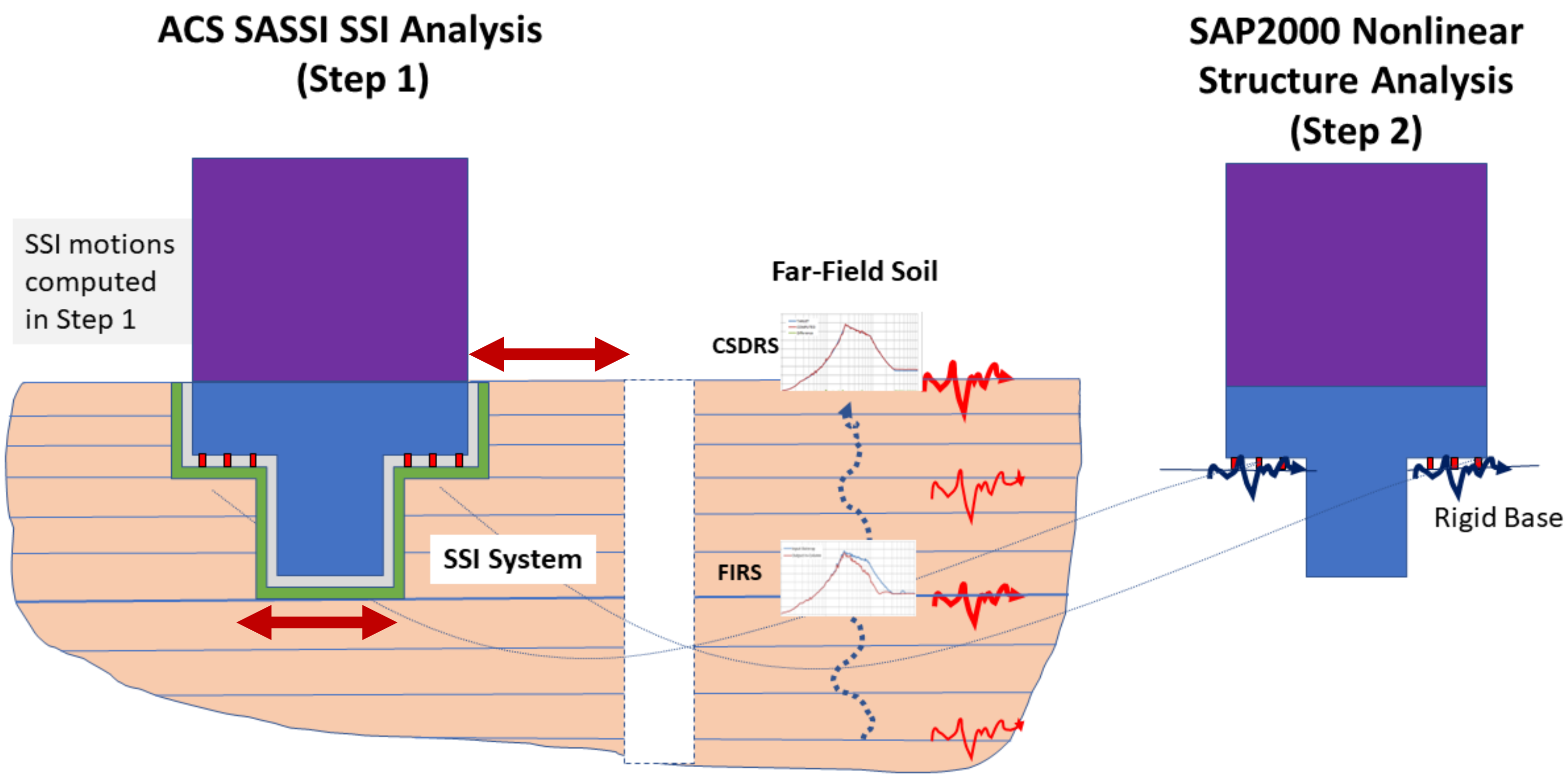
1) 2D Friction Pendulum Isolators have nonlinear geometric (sliding) behavior

   - Requires *nonlinear* time-domain analysis of isolated structure
     COMPLEX ANALYSIS; including a multistep SSI analysis

2) 3D Spring-Damper Isolators have linear behavior

   - Requires *linear* frequency or time-domain analysis of isolated structure
     STANDARD DYNAMIC ANALYSIS; including a standard SASSI analysis

For 2D FP SIS: Seismic SSI Analysis Methodology Using Multistep (Two) Approach Per ASCE 4-16 Chapter 12



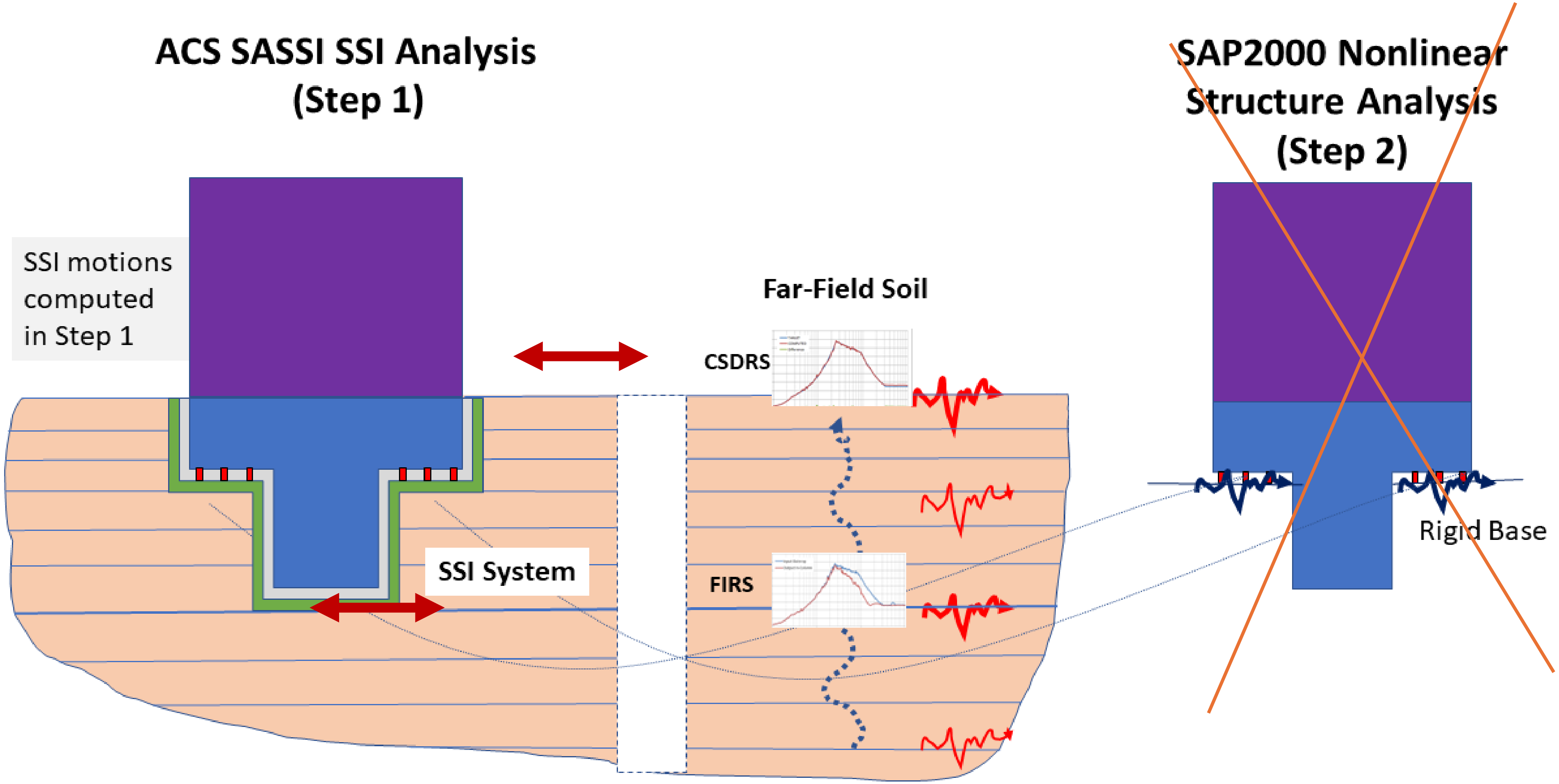
The multistep seismic SSI analysis solution was performed in two (cascaded) steps as recommended in the ASCE 4-16 Section 12:

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

For 3D SB-HVD SIS: Seismic SSI Analysis Methodology Using Standard SASSI SSI Analysis Per ASCE 4-16 Chapter 12



ACS SASSI SSI Analysis
(Step 1)

~~SAP2000 Nonlinear Structure Analysis (Step 2)~~

SSI motions computed in Step 1

Far-Field Soil

CSDRS

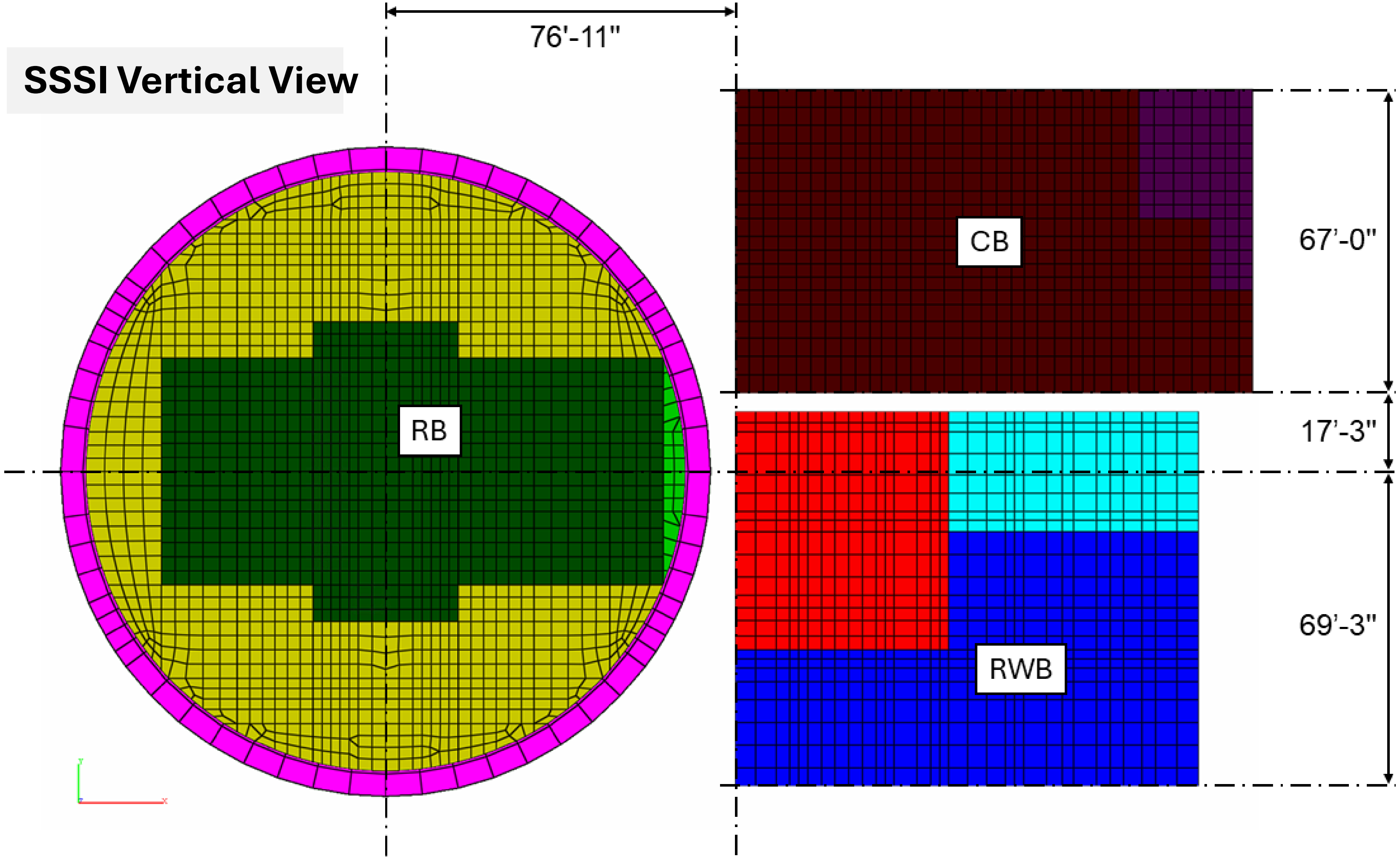
SSI System

FIRS

~~Rigid Base~~

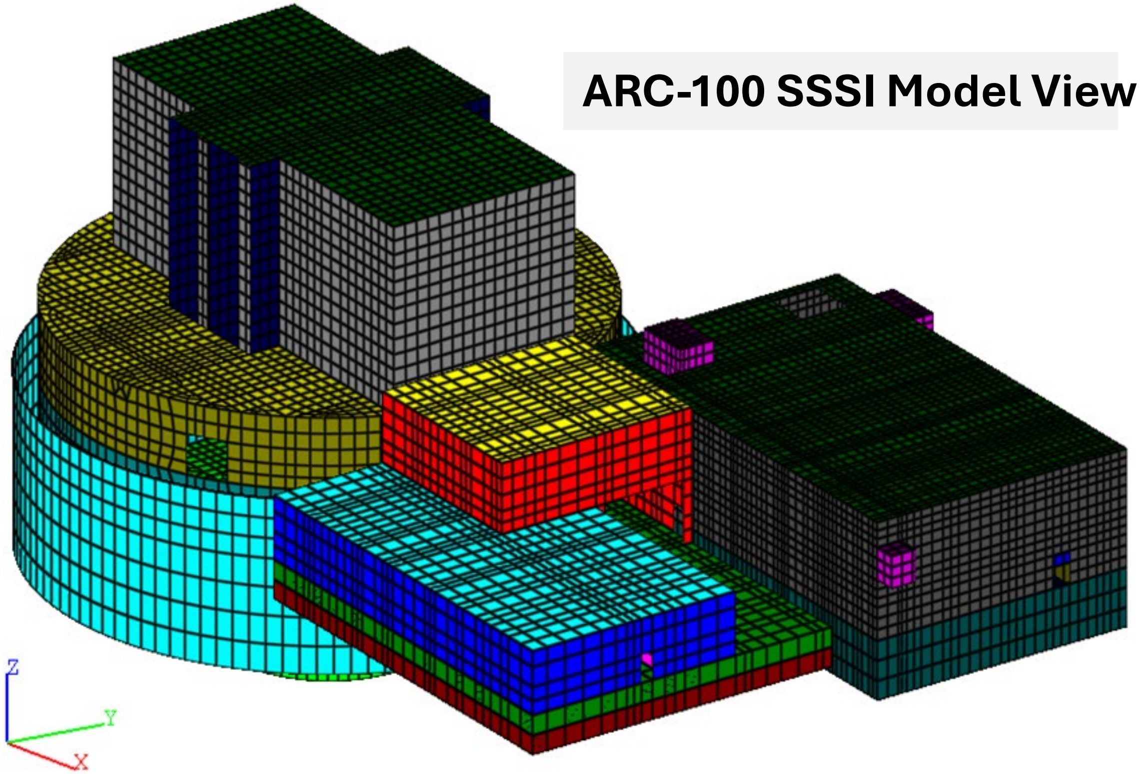
One Step SSI Analysis; ACS SASSI was applied for standard linear SSI analysis

Including Seismic SSI Coupling Effects with Neighboring ARC-100 NPP Standard Plant Buildings

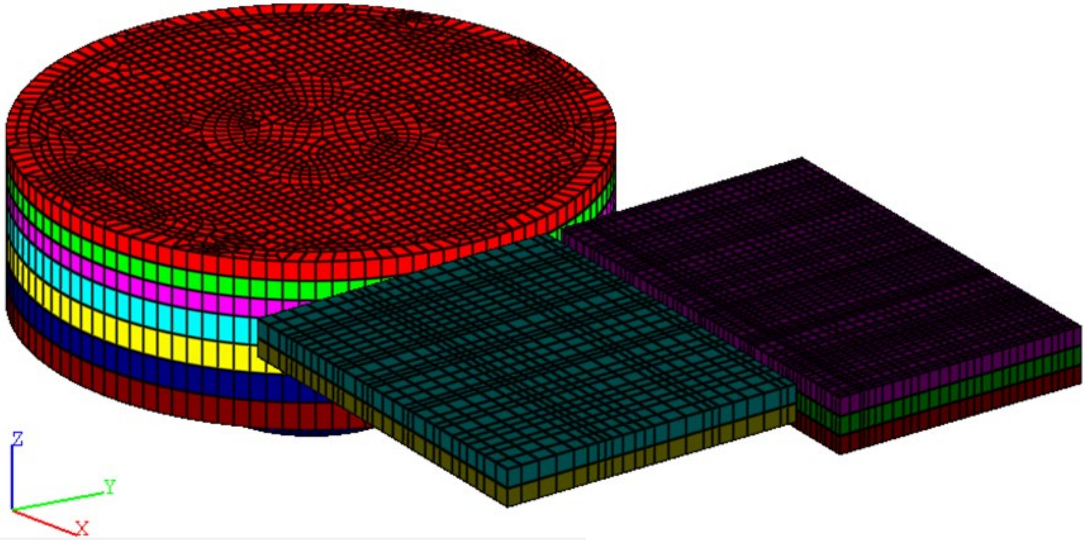


The SSSI structure FE models contain about aa total of 25,000 nodes and 69 groups with about 26,000 elements. The SSSI excavated soil model had a total of about 11,000 nodes.

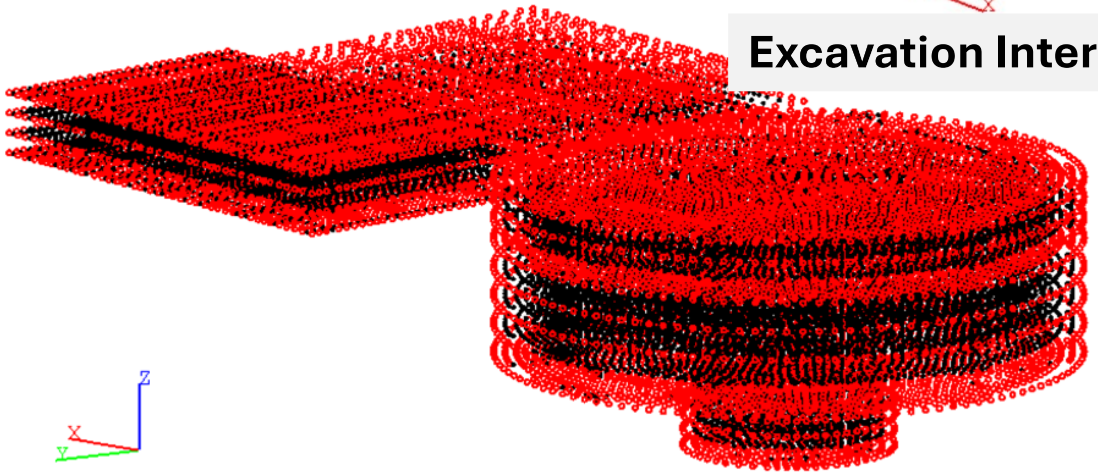
ARC-100 NPP ACS SASSI Seismic SSSI Model View



ARC-100 SSSI Model View



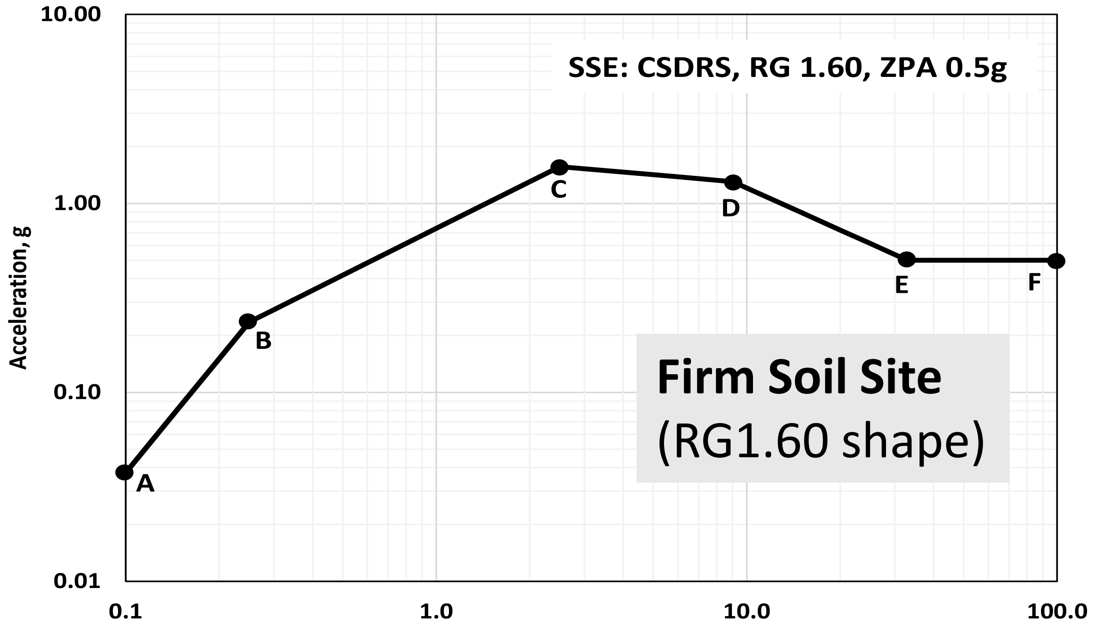
SSSI Excavation Model View

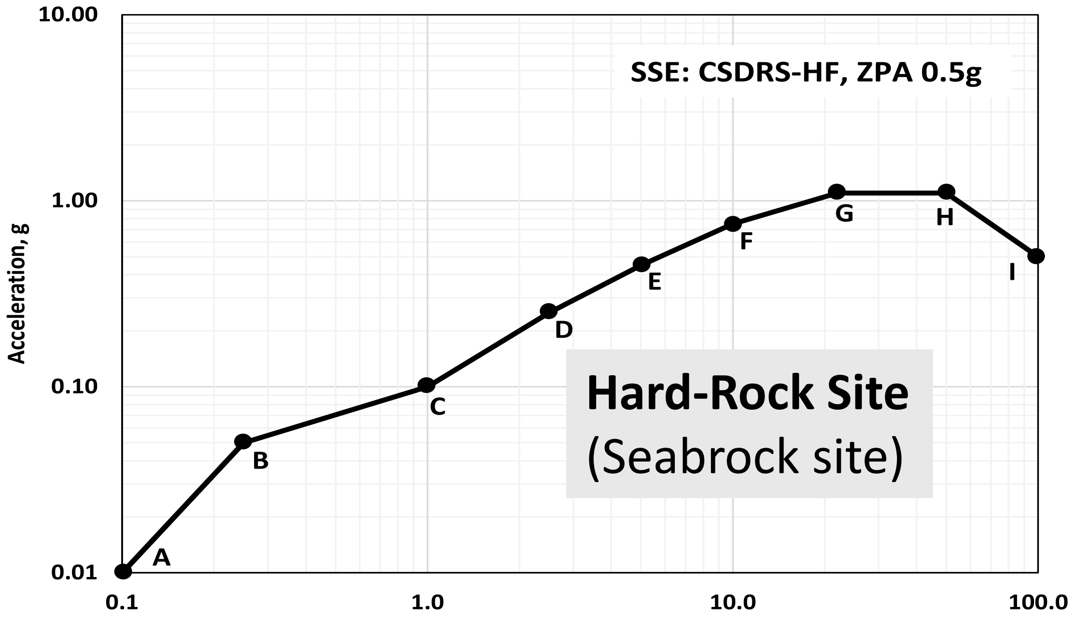


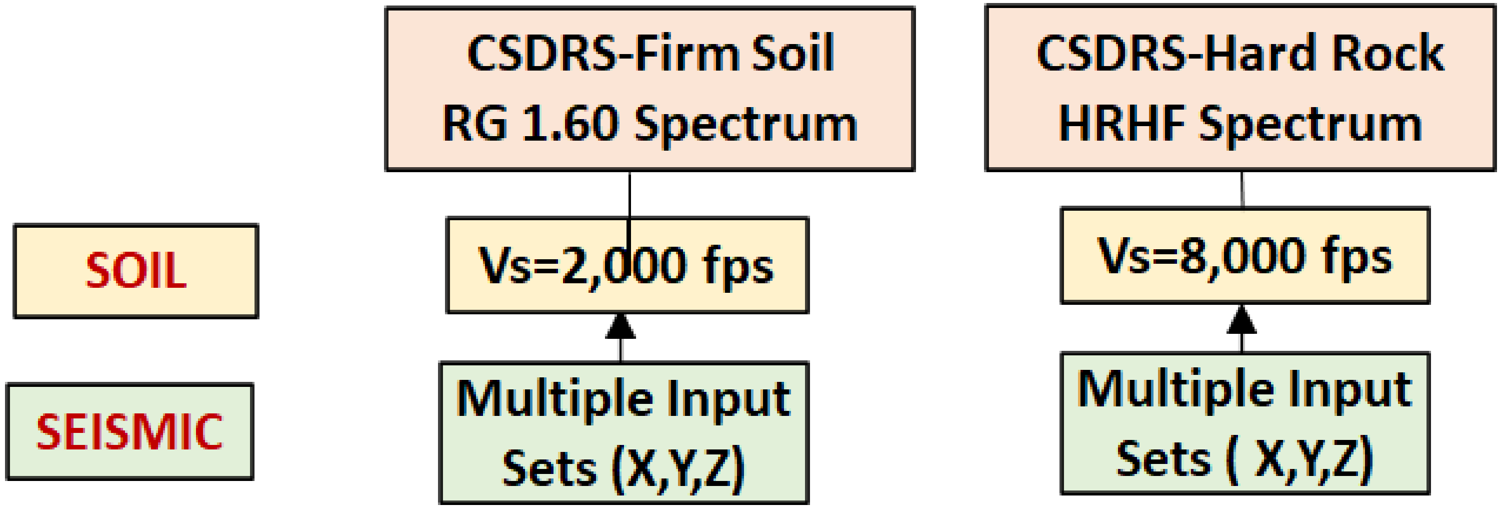
Excavation Interaction Nodes (Red)

Generic Seismic Site Conditions

Two Generic Site Conditions with 0.5g CSDRS, Same for X, Y and Z Input Directions







SOIL

SEISMIC

CSDRS-Firm Soil
RG 1.60 Spectrum

Vs=2,000 fps

Multiple Input
Sets (X,Y,Z)

CSDRS-Hard Rock
HRHF Spectrum

Vs=8,000 fps

Multiple Input
Sets (X,Y,Z)

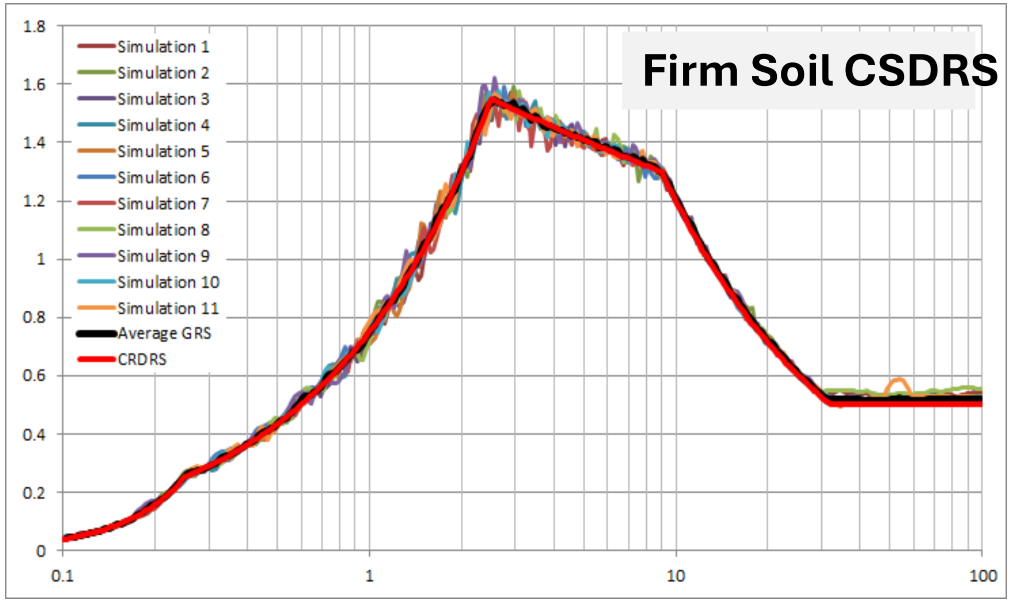
Specific Requirements for Seismic SSI Analysis of Base-Isolated Structures for Computing Mean & 80th Percentile DBE Responses

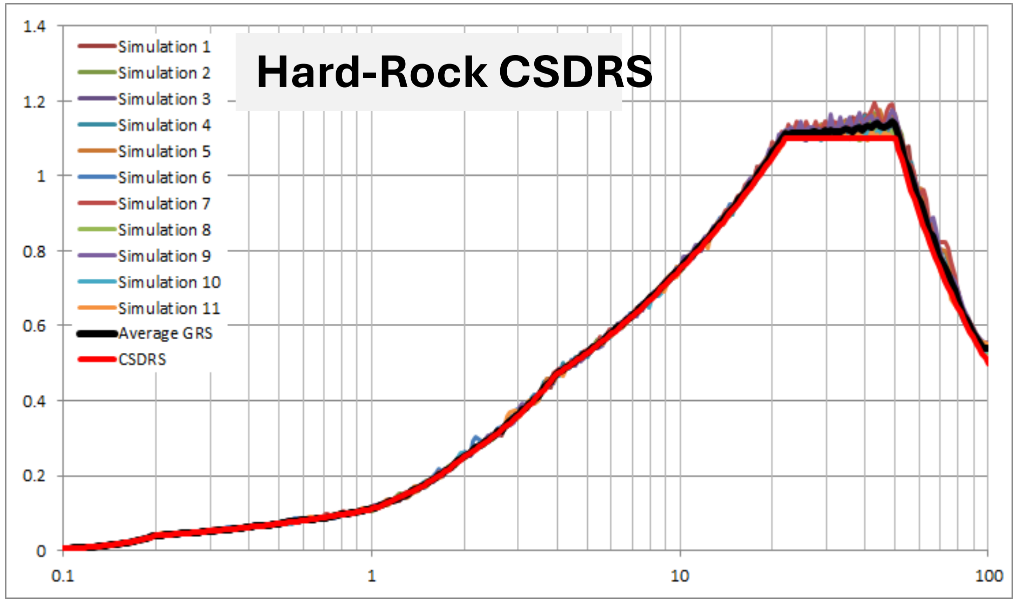
To be compliant with the latest requirements for the DBE shaking, including ASCE 4-16, and also ASCE 21 Chapter 12 draft, Rev 13, and ASCE 7-22 Chapter 17, to compute the 80th percentile DBE responses a set of 33 seismic SSI simulations was considered for each generic site condition including 3 soil variations, LB, BE and UB soil profiles.

We used: 33 SSI case simulations were considered: 11 seismic input sets compatible with CSDRS at 0.50g (in H and V directions) and 3 soil variations, BE, LB and UB soil profiles.

The LB and UB bounding variation soil profiles were defined assuming a 50% coefficient of variation of the shear soil moduli.

11 Simulated Sets of Acceleration Triplets (X,Y,Z) for 0.50g





Parameters for Soil CSDRS Compatible Acceleration Histories for X, Y and Z

Average for 11 Simulations				
Seismic Input Direction		X	Y	Z
S.M. Duration	(s)	9.171	9.348	9.642
PGA	(g)	0.509	0.513	0.516
PGV	(cm/s)	82.857	84.183	83.605
PGD	(cm)	56.311	55.859	52.804
PGV/PGA	(cm/s/g)	162.999	164.289	162.049

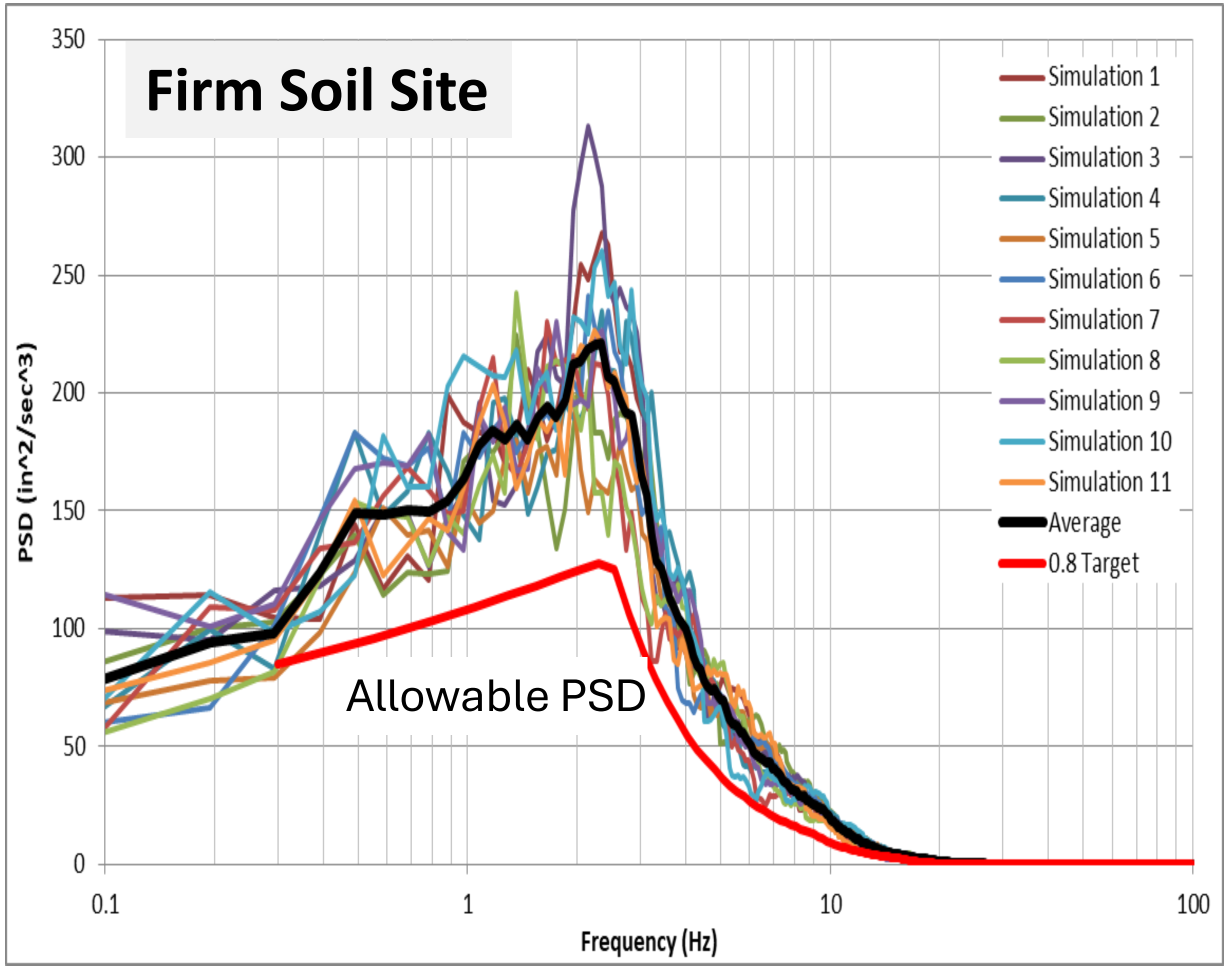
Parameters for Rock CSDRS-HF Compatible Acceleration Histories for X, Y and Z

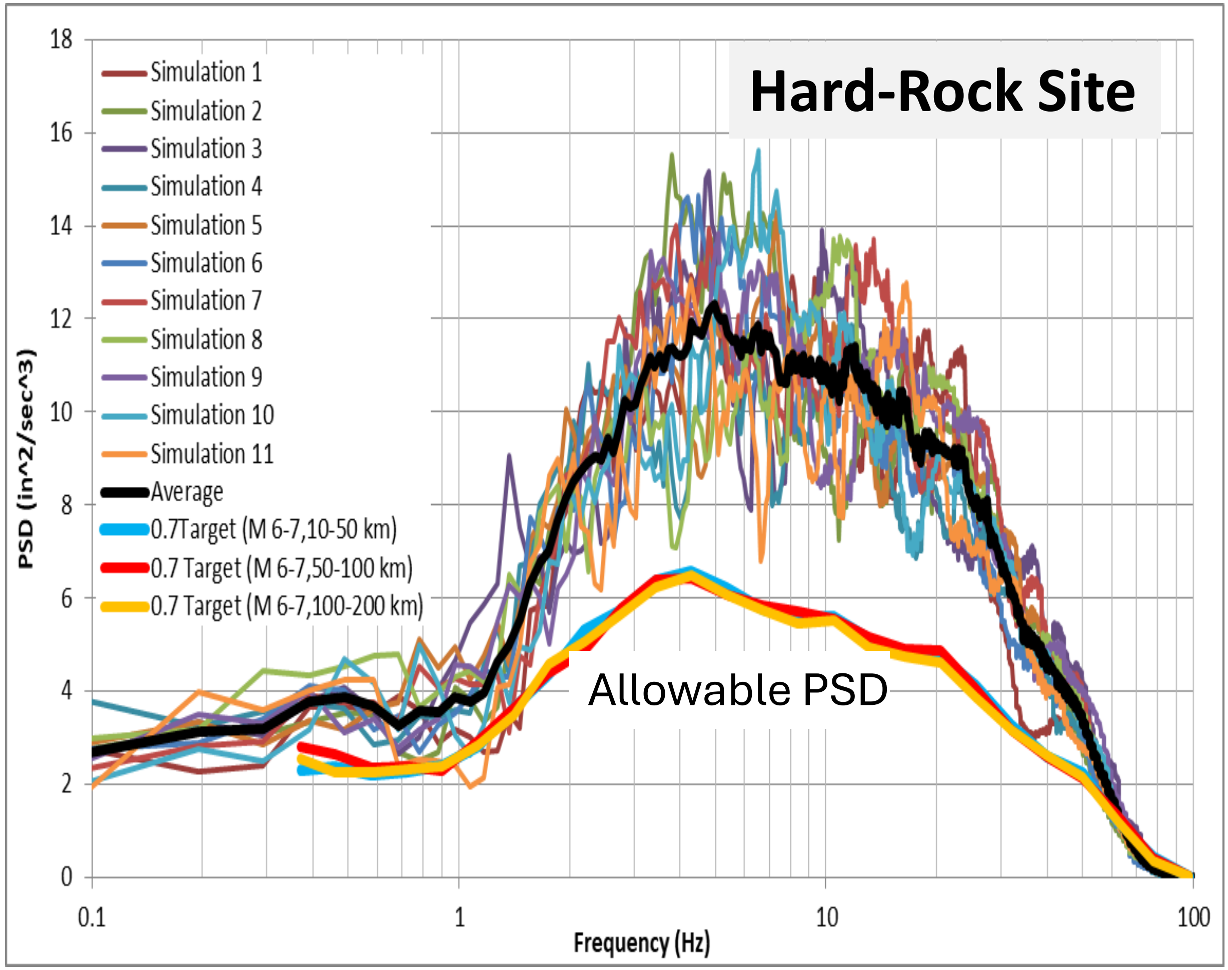
Average for 11 Simulations				
Seismic Input Direction		X	Y	Z
S.M. Duration	(s)	8.823	8.874	8.807
PGA	(g)	0.502	0.500	0.505
PGV	(cm/s)	16.004	17.099	16.714
PGD	(cm)	8.385	9.302	8.056
PGV/PGA	(cm/s/g)	31.929	34.200	33.084

Statistical Correlation Coefficients Between Acceleration Components X, Y and Z

Average of 11 Simulations (Absolute Values)			
Correlation Coefficient	X,Y	X,Z	Y,Z
FIRM SOIL	0.0227	0.0420	0.0568
HARD ROCK	0.0503	0.0428	0.0696

Checking PSD Frequency Content for Acceleration Motions



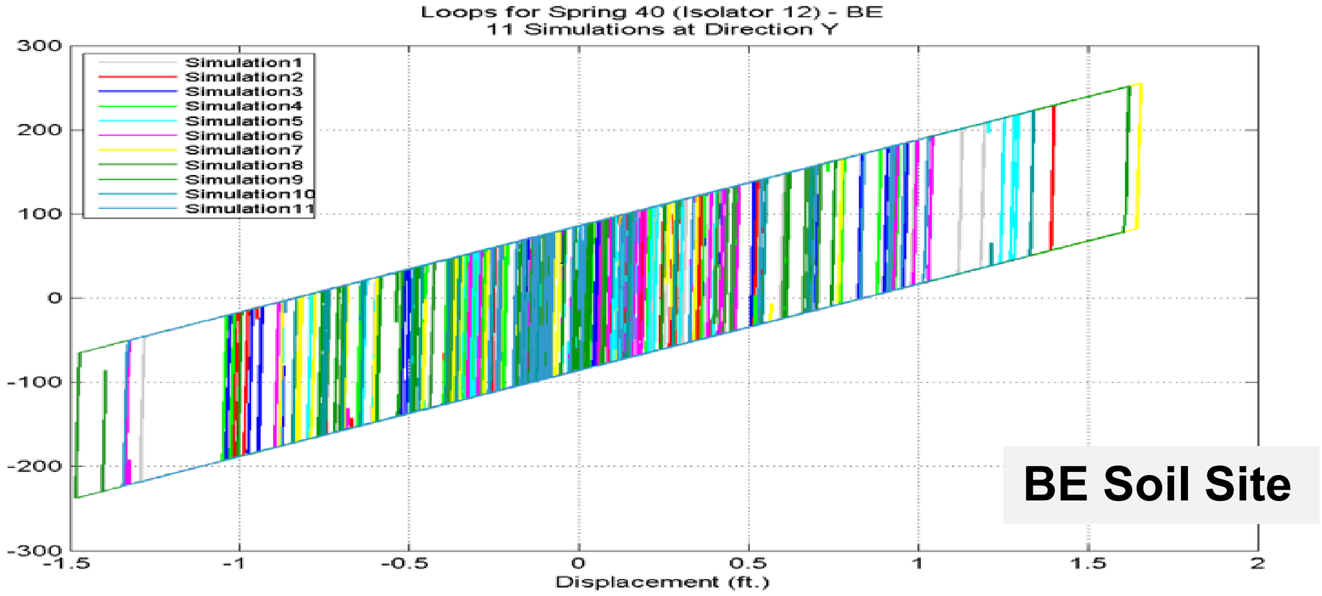


The computed PSD curves indicated smooth variations with conservative frequency contents against the required minimum target PSD per the NUREG SRP 3.7.1 Appendix A (Soil) and B (Rock).

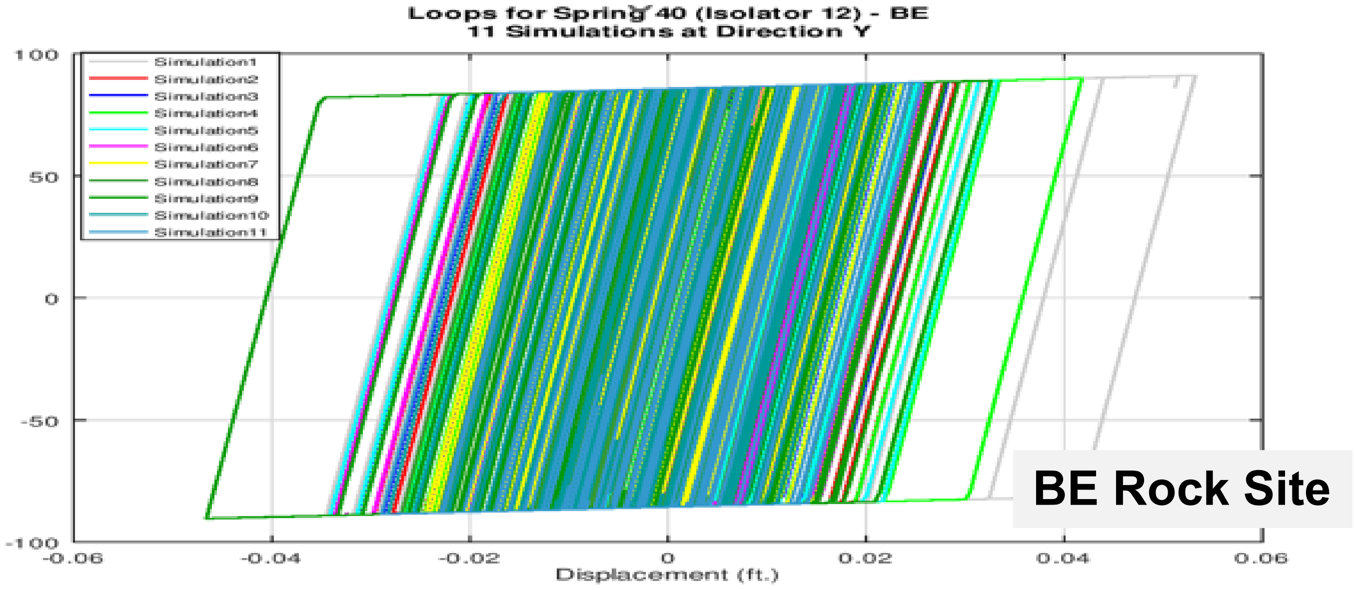
SMR Dynamic SSI Responses
For Investigated Base-Isolated Systems

(Initial) Global 2D FP Isolation System Results (2023-2024)

SMR FP Isolator SSI Sliding Simulations for Soil and Rock Sites



BE Soil Site



BE Rock Site

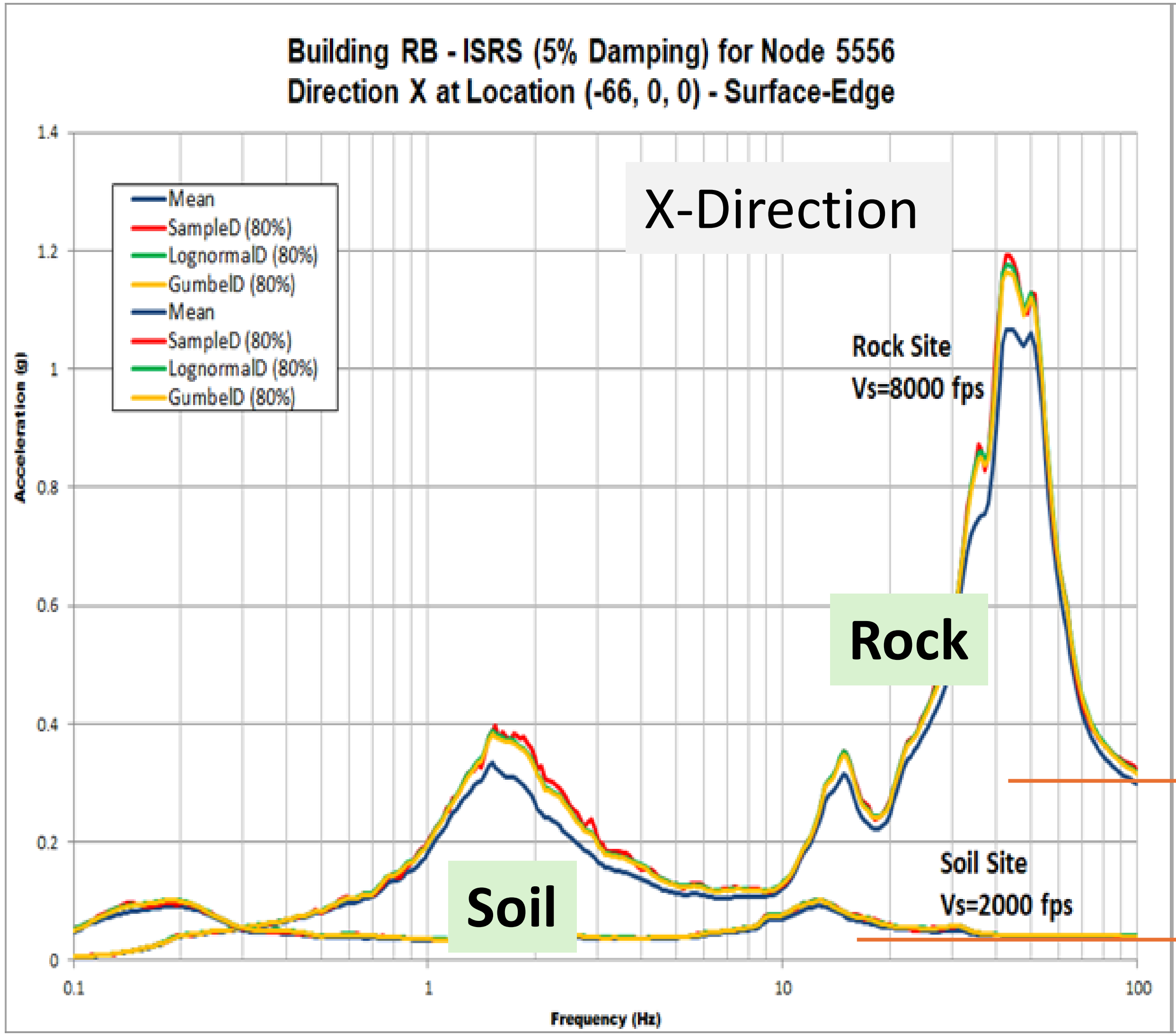
It should be noted that for the BE soil and CSDRS input, the 11 simulated FP isolator displacements ***are up 1.7 ft***,

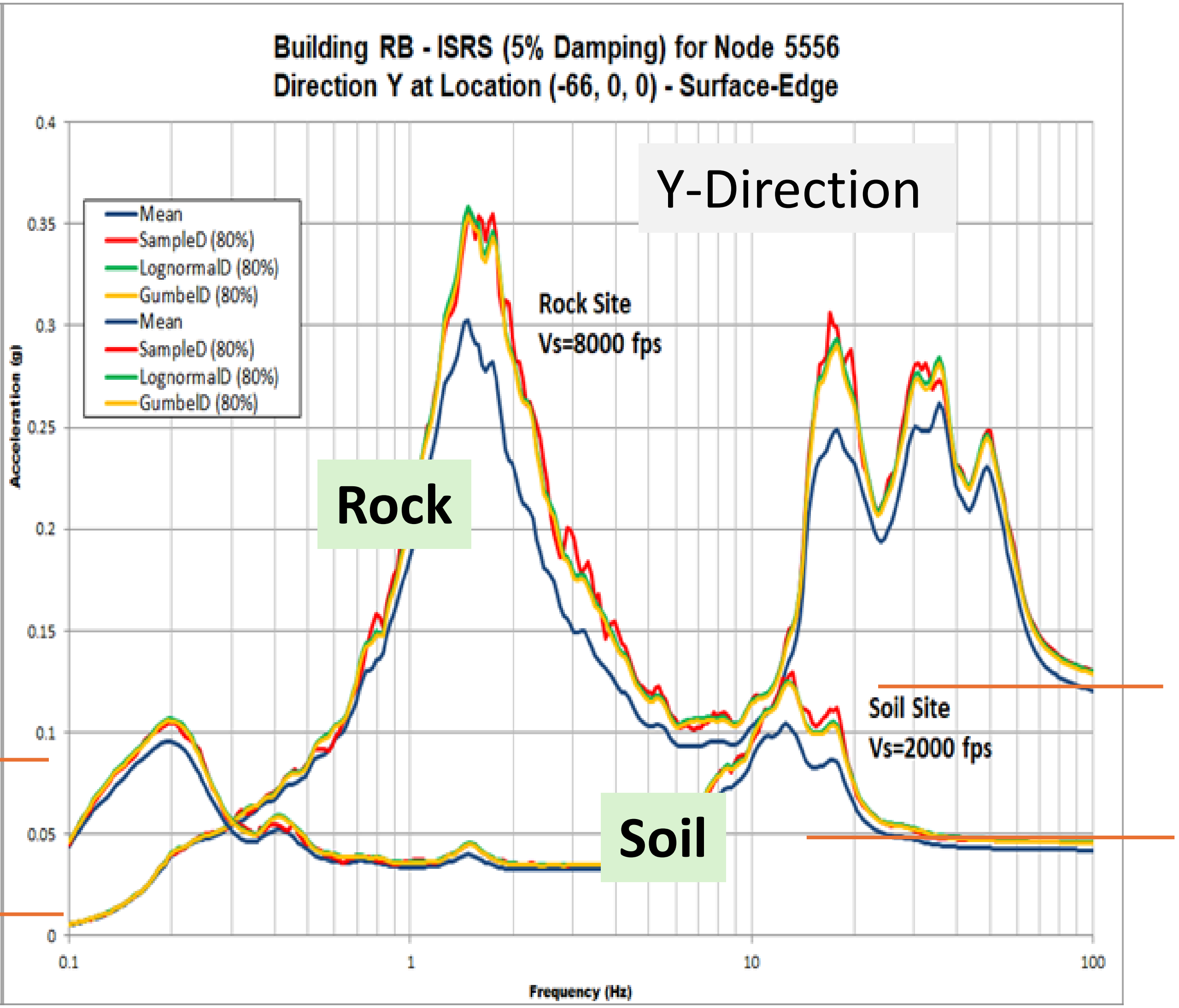
while for the BE rock and CSDRS-HF input, the 11 simulated FP isolator displacements are ***up to only 0.05 ft***.

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

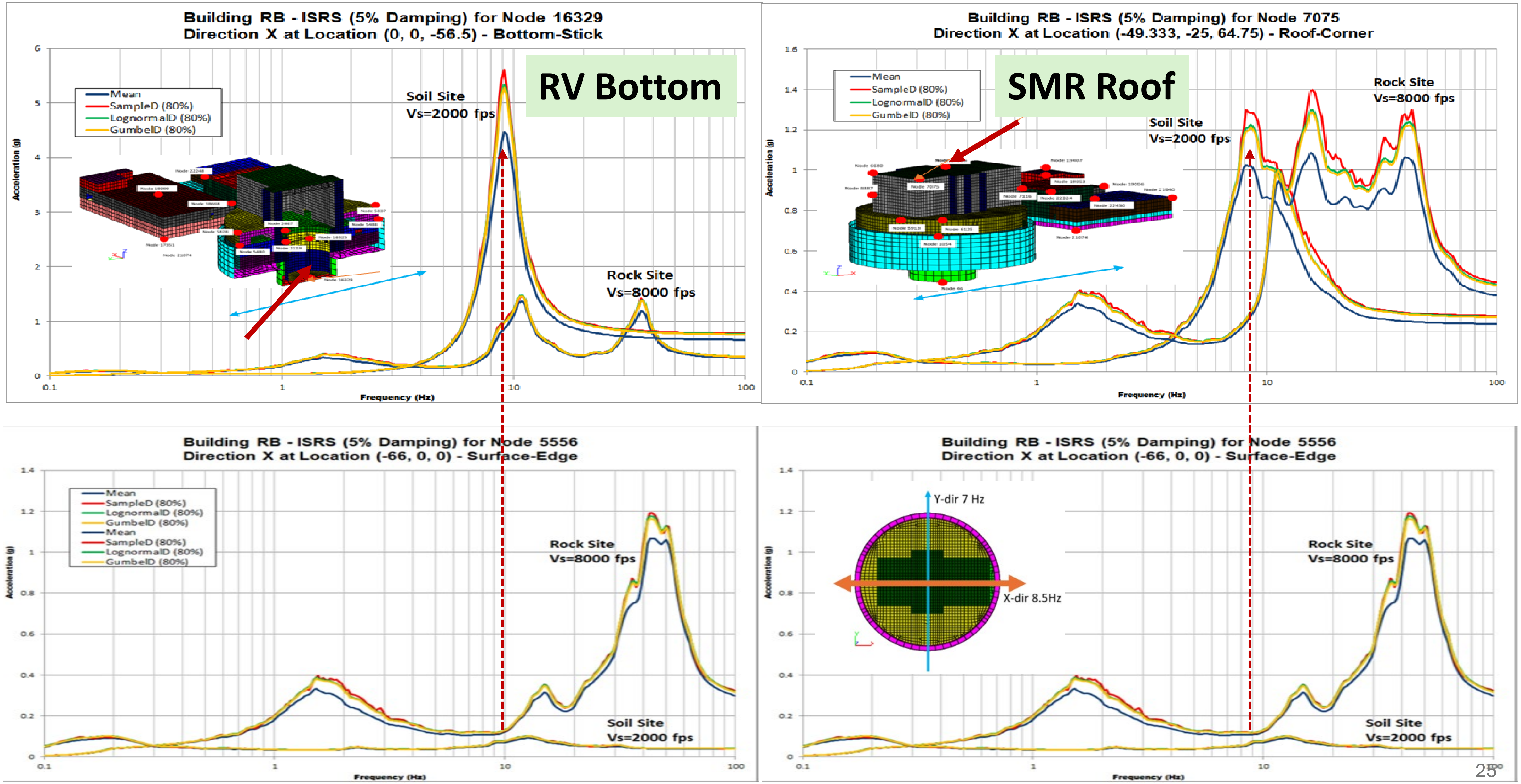
The larger reduction of the isolator displacements for the rock site is due to the high-frequency input with a fast sign-switching acceleration motion for the CSDRS-HF.

DBE Mean and 80 NEP SMR ISRS at Ground Surface (N5556)


Building RB - ISRS (5% Damping) for Node 5556
Direction X at Location (-66, 0, 0) - Surface-Edge


Building RB - ISRS (5% Damping) for Node 5556
Direction Y at Location (-66, 0, 0) - Surface-Edge

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



Building RB - ISRS (5% Damping) for Node 16329
Direction X at Location (0, 0, -56.5) - Bottom-Stick

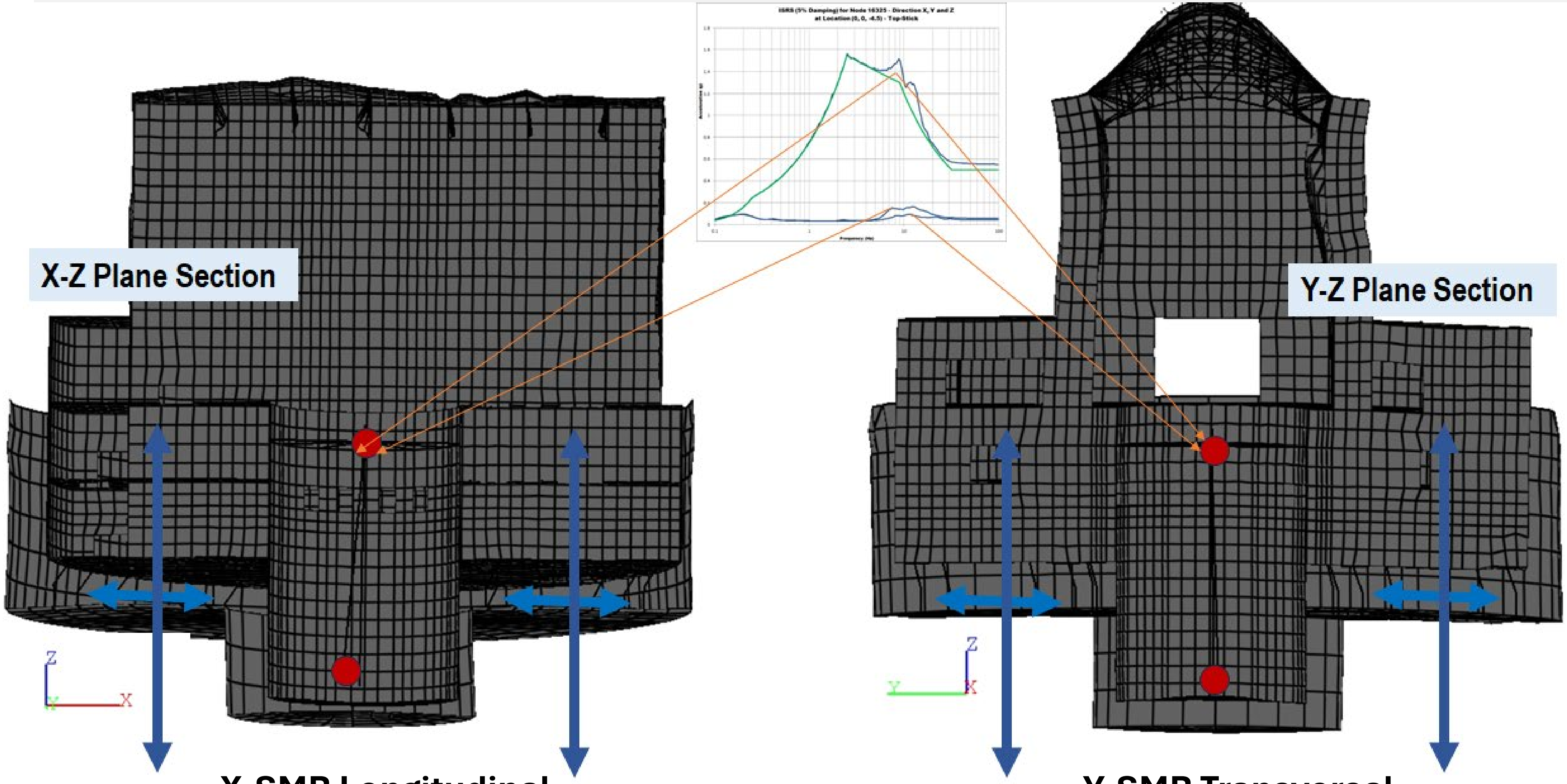
Building RB - ISRS (5% Damping) for Node 7075
Direction X at Location (-49.333, -25, 64.75) - Roof-Corner

Building RB - ISRS (5% Damping) for Node 5556
Direction X at Location (-66, 0, 0) - Surface-Edge

Building RB - ISRS (5% Damping) for Node 5556
Direction X at Location (-66, 0, 0) - Surface-Edge

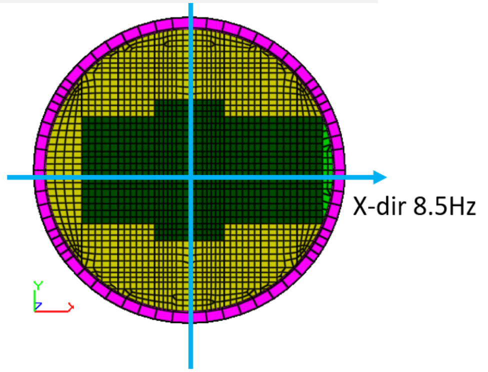
Slight Structural Asymmetry Produced Large Dynamic Coupling

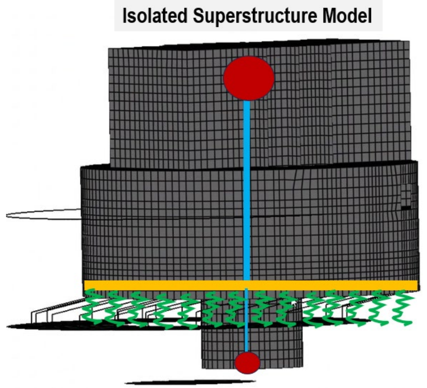
Dynamic coupling between SMR SSI vertical vibration with two horizontal structure modes



X-SMR Longitudinal

Y-SMR Transversal

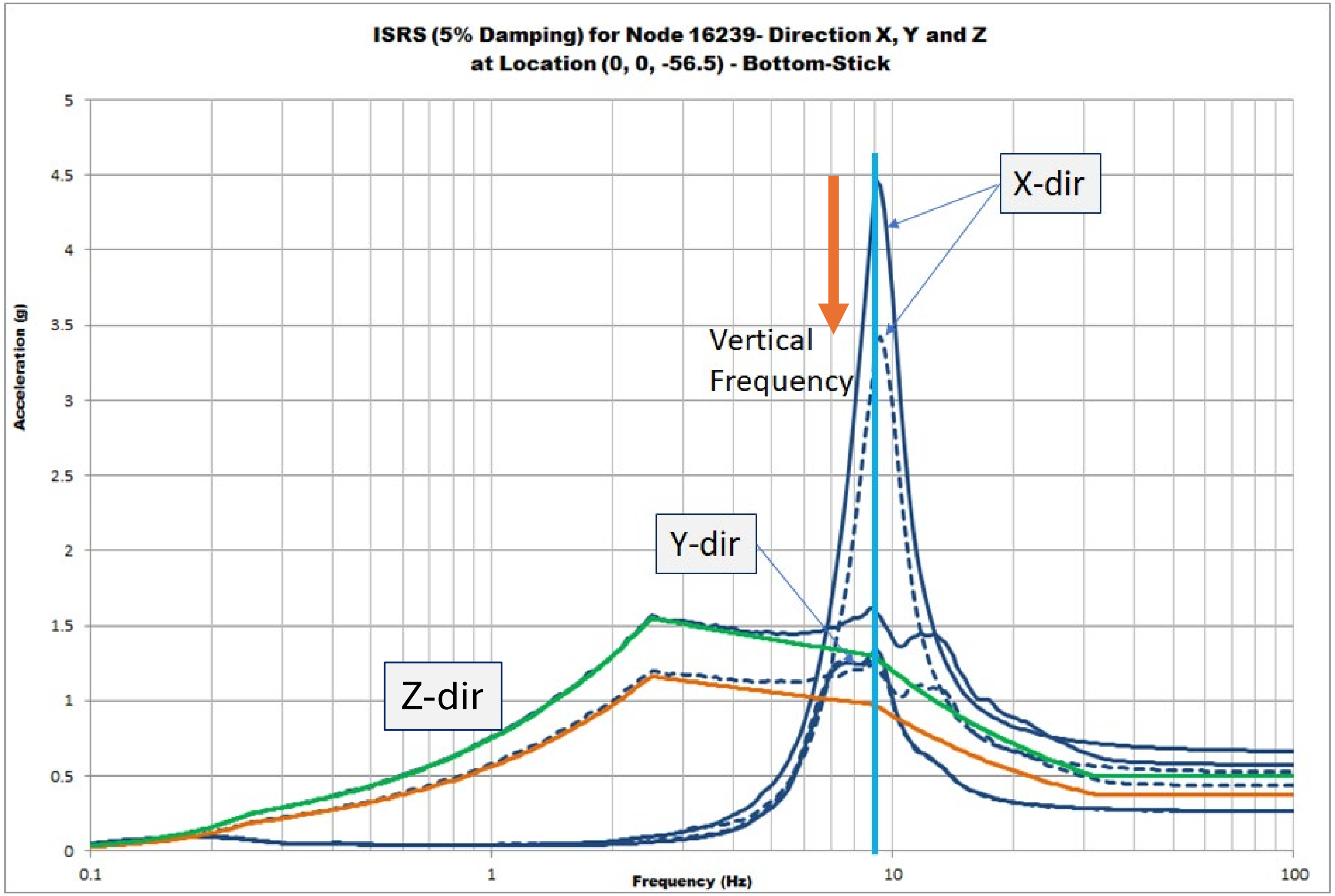




RV Stick
X-dir 9 Hz
Y-dir 8.5 Hz
Z-dir 9 Hz

Quantitative Checking for V-H Dynamic Coupling Effects

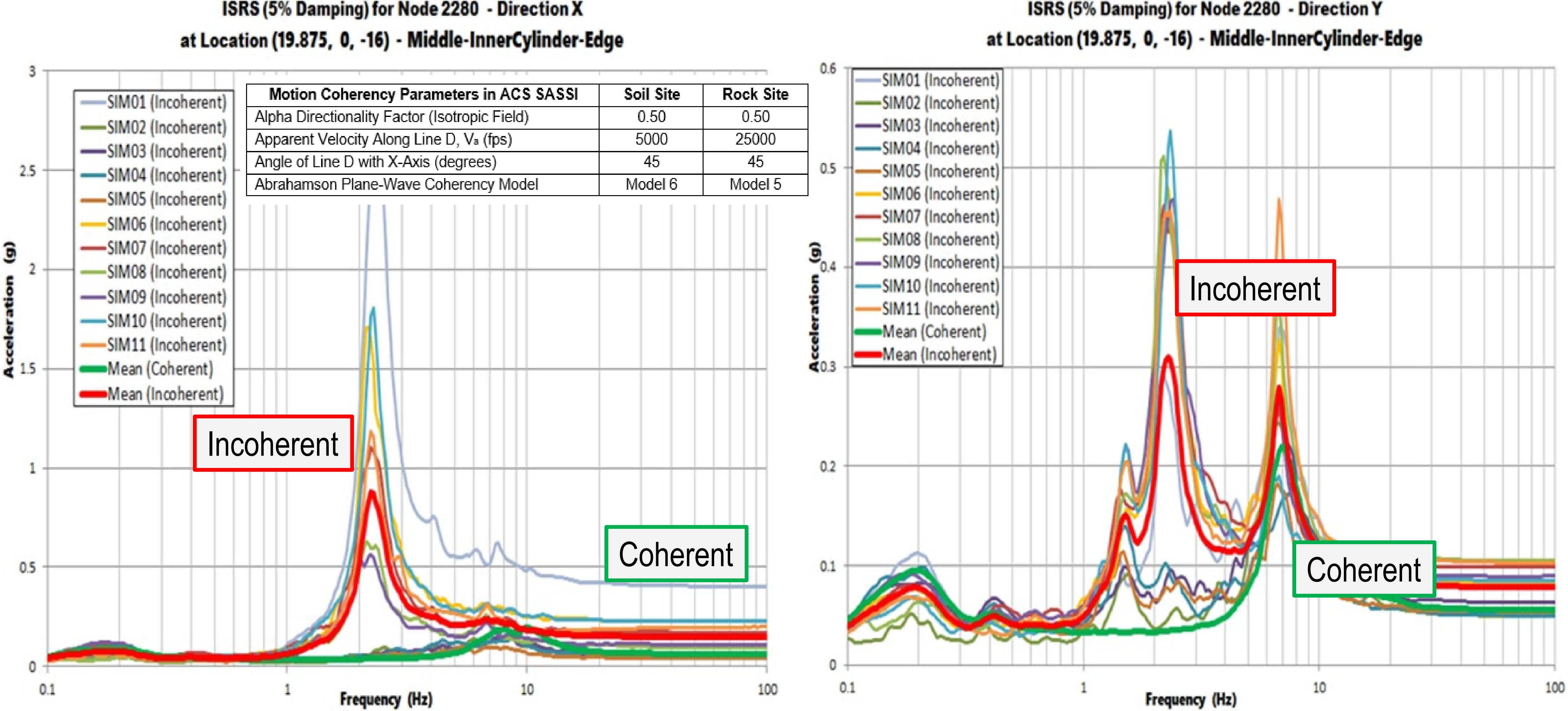
We compared the ISRS X, Y, Z computed at the RV stick bottom location for the vertical input acceleration of 0.5 g and a 25% reduced vertical input acceleration, 0.375g = 0.75 x 0.50g.



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).

FP Isolated SMR Response to Motion Incoherency for Soil



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

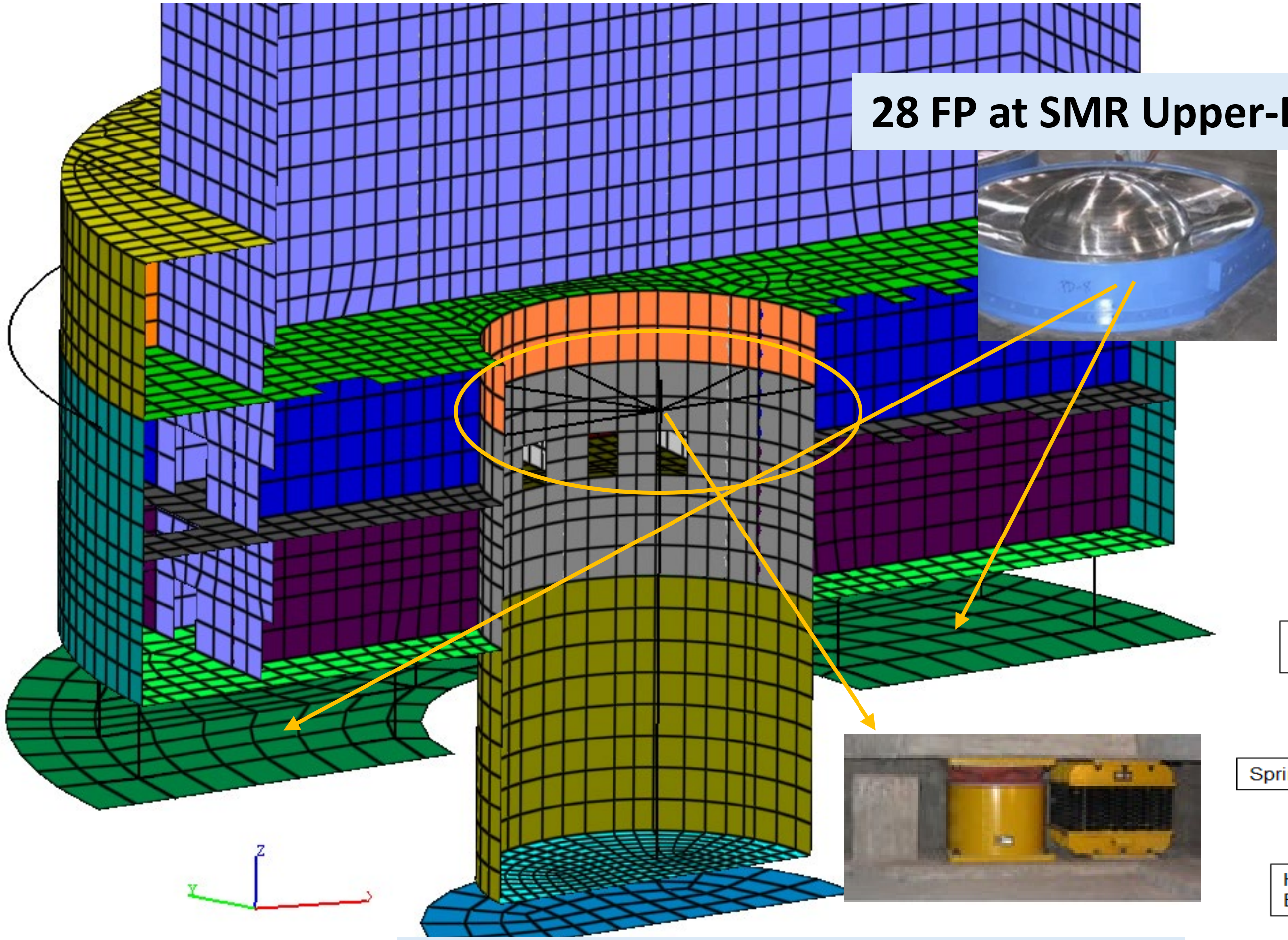
Motion Coherency Parameters in ACS SASSI	Soil Site	Rock Site
Alpha Directionality Factor (Isotropic Field)	0.50	0.50
Apparent Velocity Along Line D, V_a (fps)	5000	25000
Angle of Line D with X-Axis (degrees)	45	45
Abrahamson Plane-Wave Coherency Model	Model 6	Model 5

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

Hybrid Global 2D FP - Local 3D BCS Isolation System Results

Hybrid 28 FP Plus 12 BCS for Local RV System

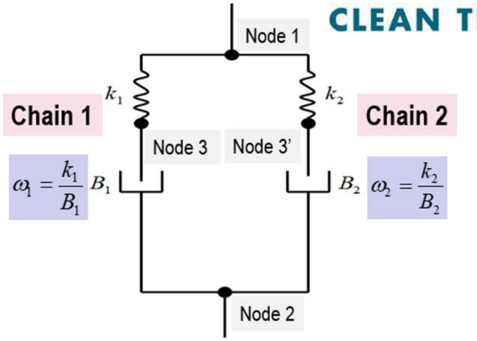
Hybrid Base-Isolation System



28 FP at SMR Upper-Base

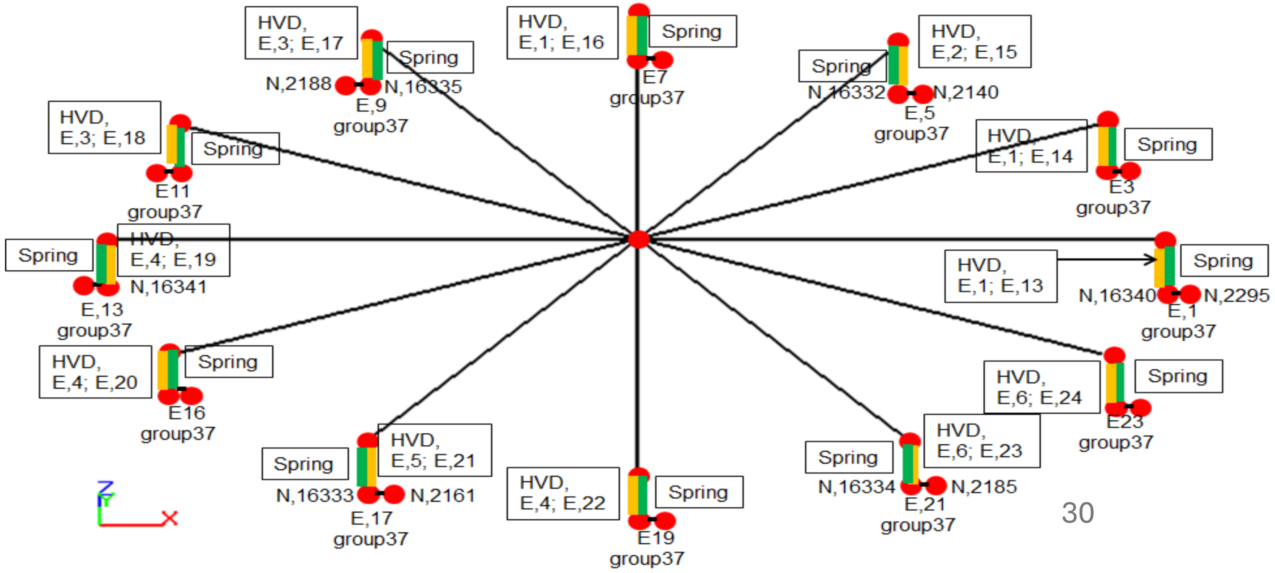
12 BCS Isolators at RV Support Beams

GERB HVD Device

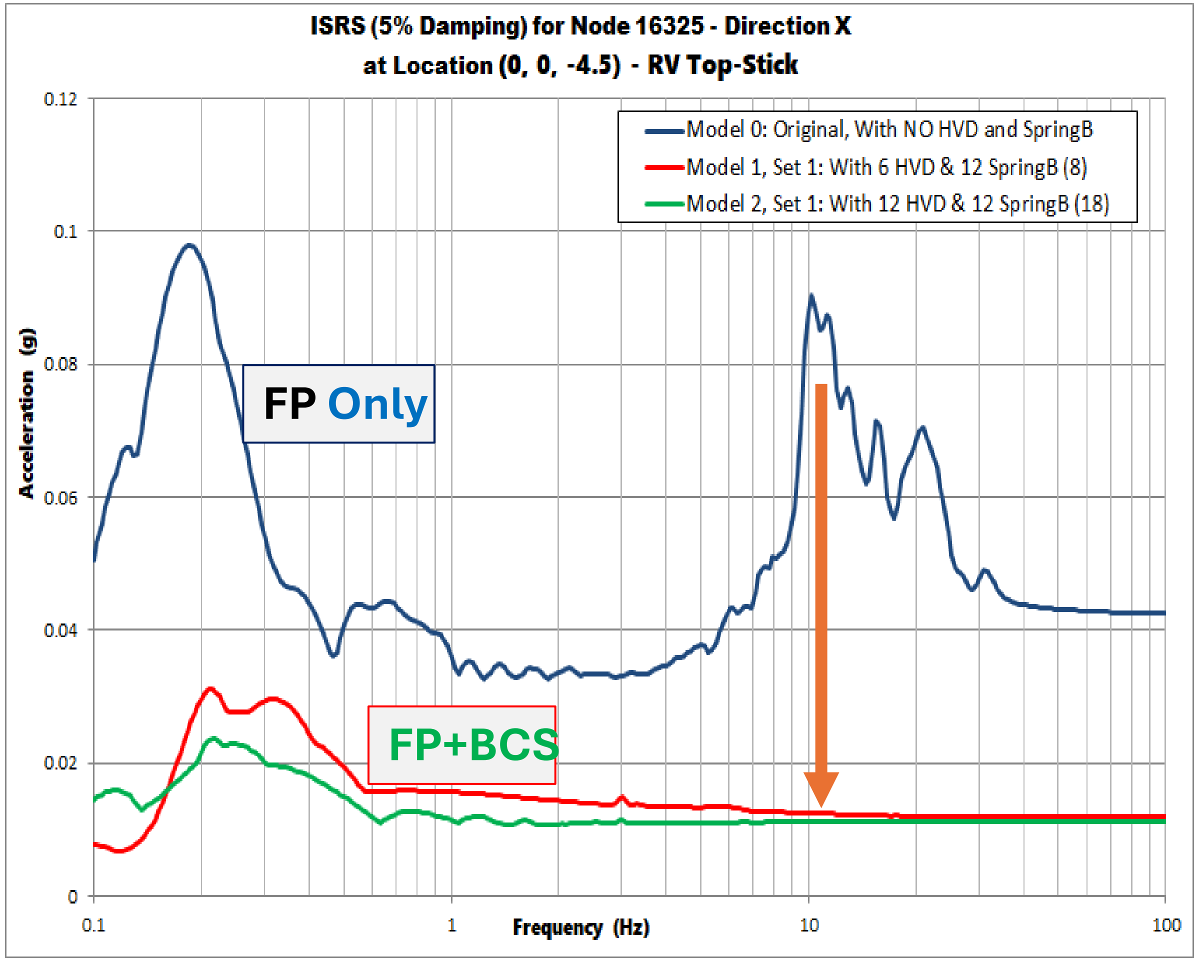


4-Parameter Maxwell Model

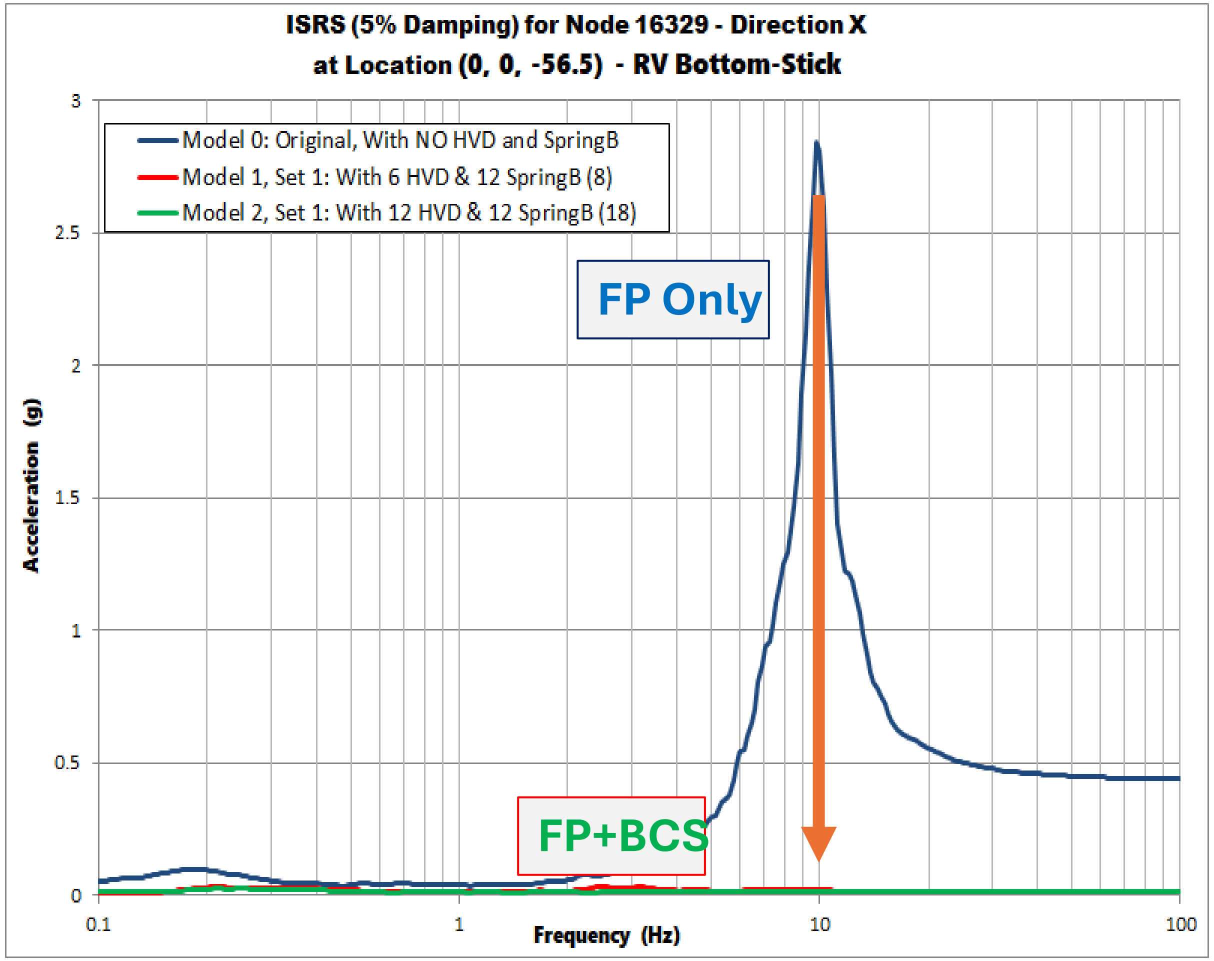
ACS SASSI includes linearized frequency-dependent HVD (based on GERB recommendations). Uses four frequency-dependent complex stiffnesses (Kh, Kv, Bh, Bv) for each Maxwell chain. Total eight parameters for a HVD unit.



ISRS at RV Top and Bottom Locations in X Direction



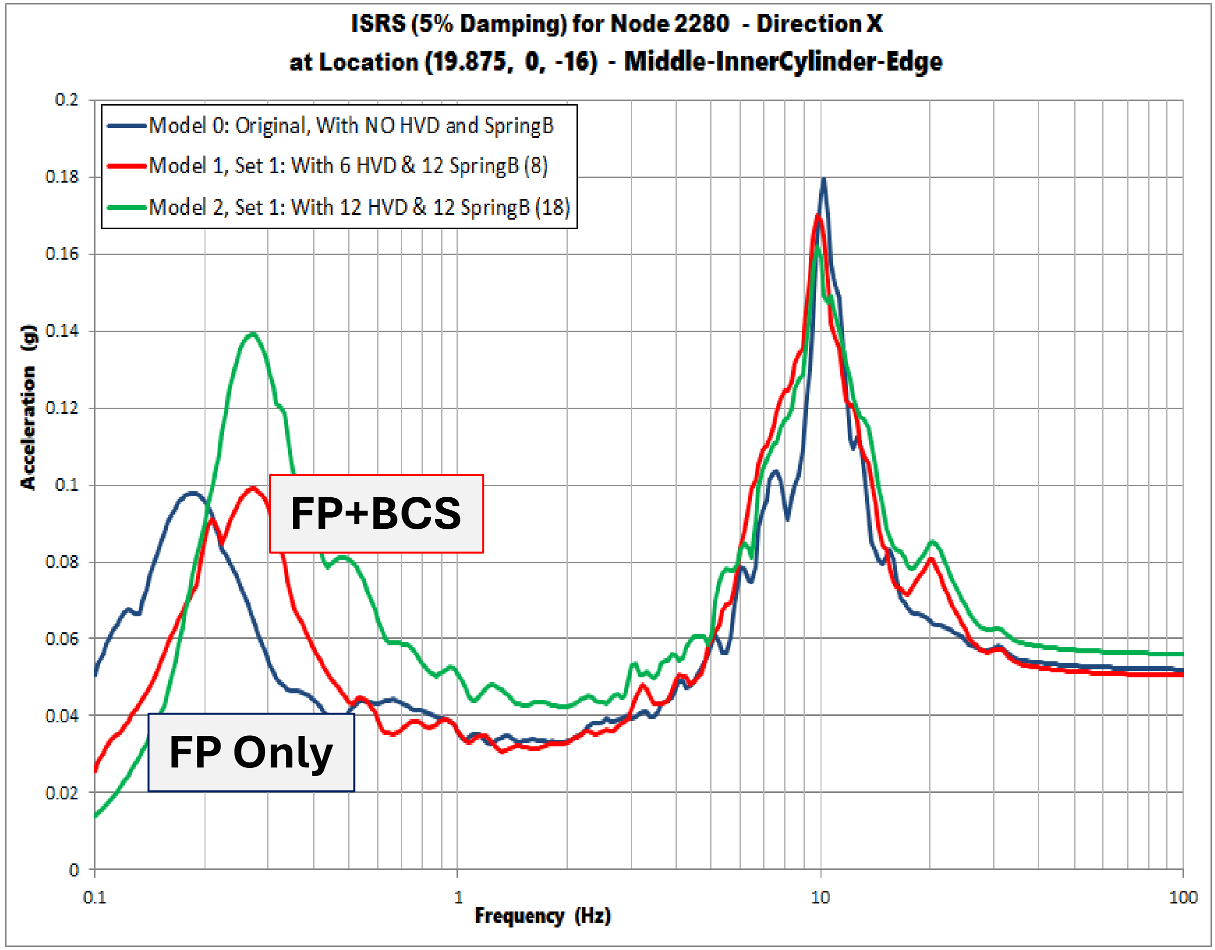
ISRS (5% Damping) for Node 16325 - Direction X
at Location (0, 0, -4.5) - RV Top-Stick

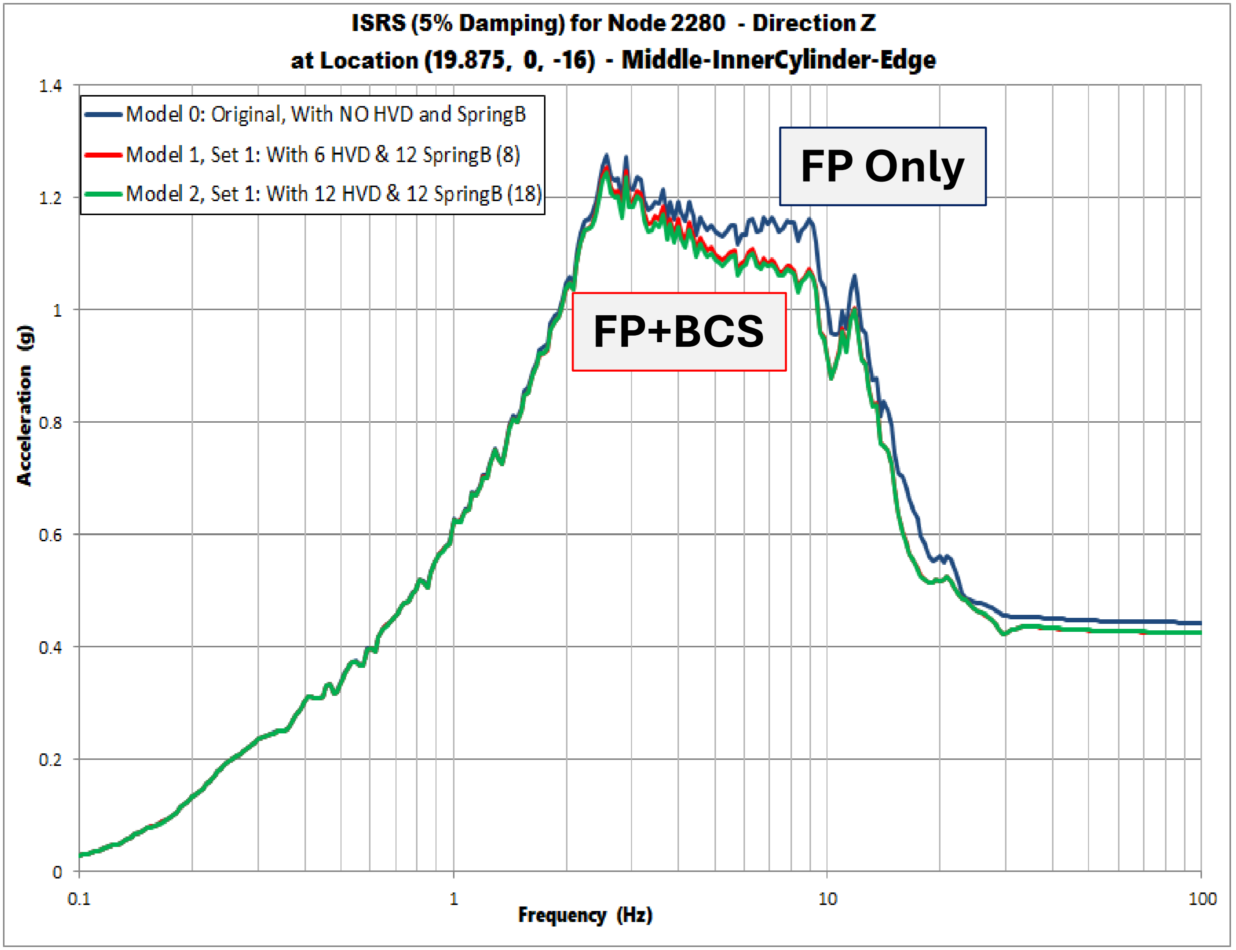


ISRS (5% Damping) for Node 16329 - Direction X
at Location (0, 0, -56.5) - RV Bottom-Stick

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


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

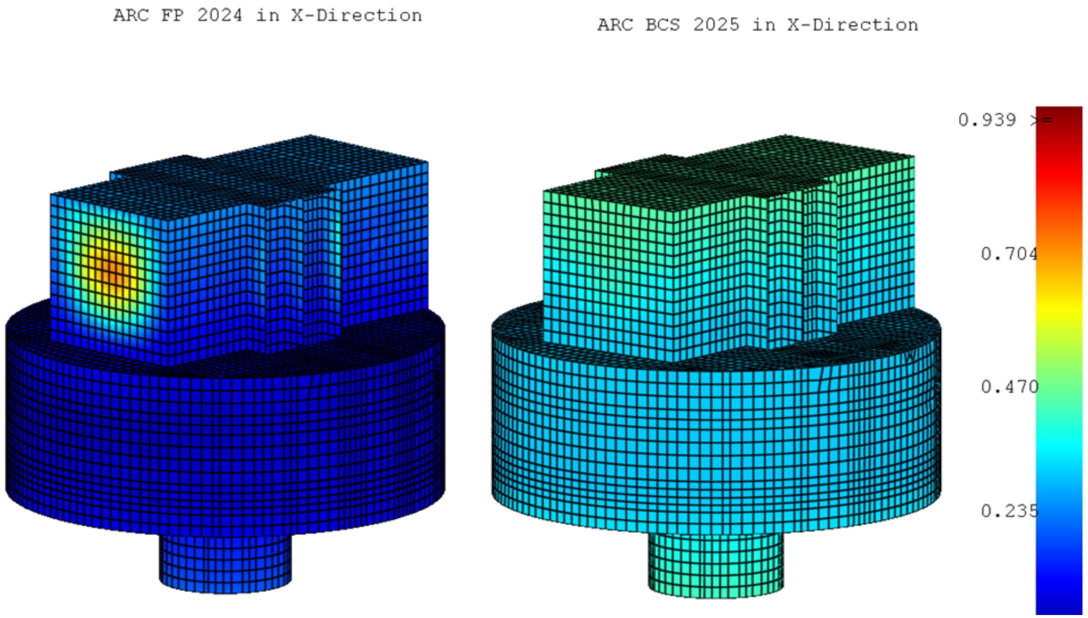

ISRS (5% Damping) for Node 2280 - Direction Z
at Location (19.875, 0, -16) - Middle-InnerCylinder-Edge

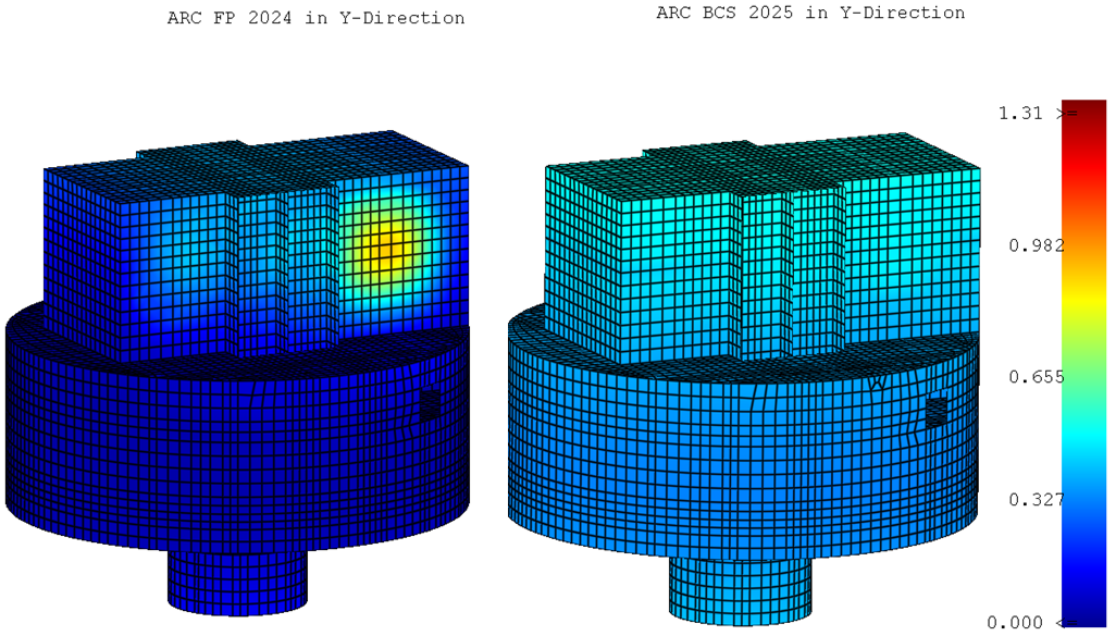
The ISRS computed in X and Z directions at an isolated SMR basement location at low elevation, El. -16 ft (Node 2280). The ISRS show that for other locations within the isolated SMR structure, the inclusion of the 3D isolation devices have only a very small influence, practically negligible.

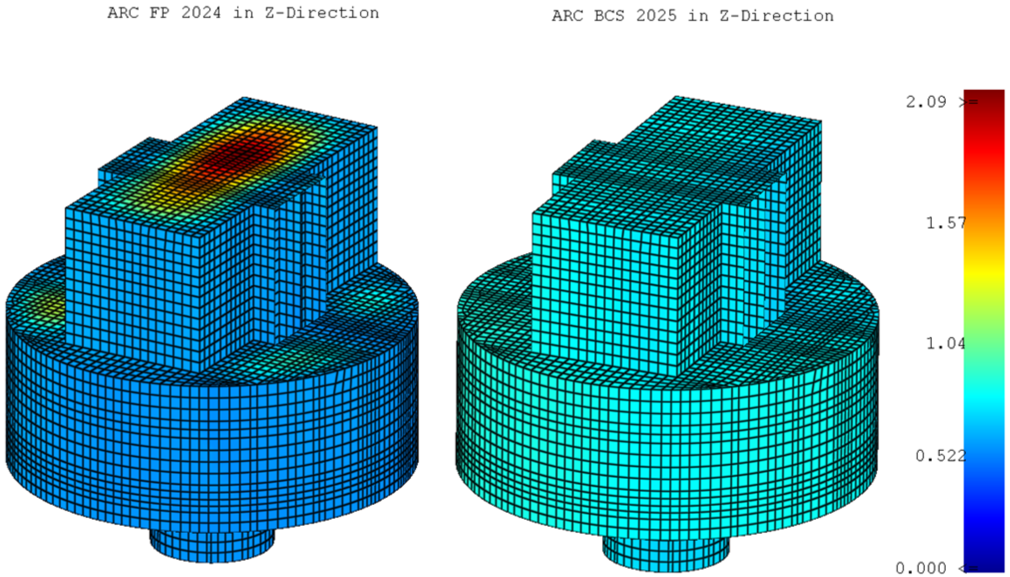
Global 3D BCS Isolation System Results
(In Comparison with Global 2D FP Isolation System)

DBE Responses

Distribution of Max Accelerations in SMR Structure

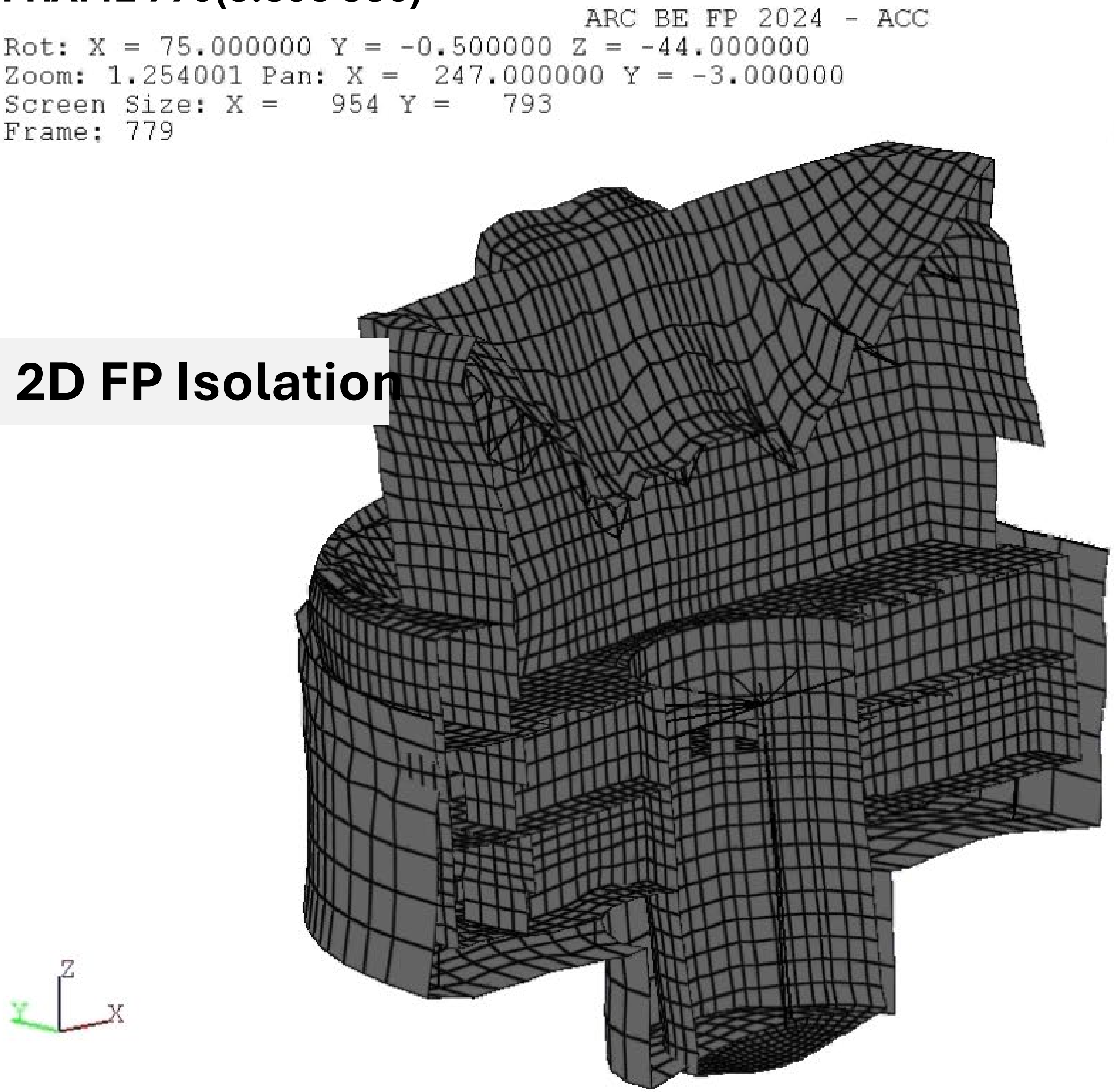






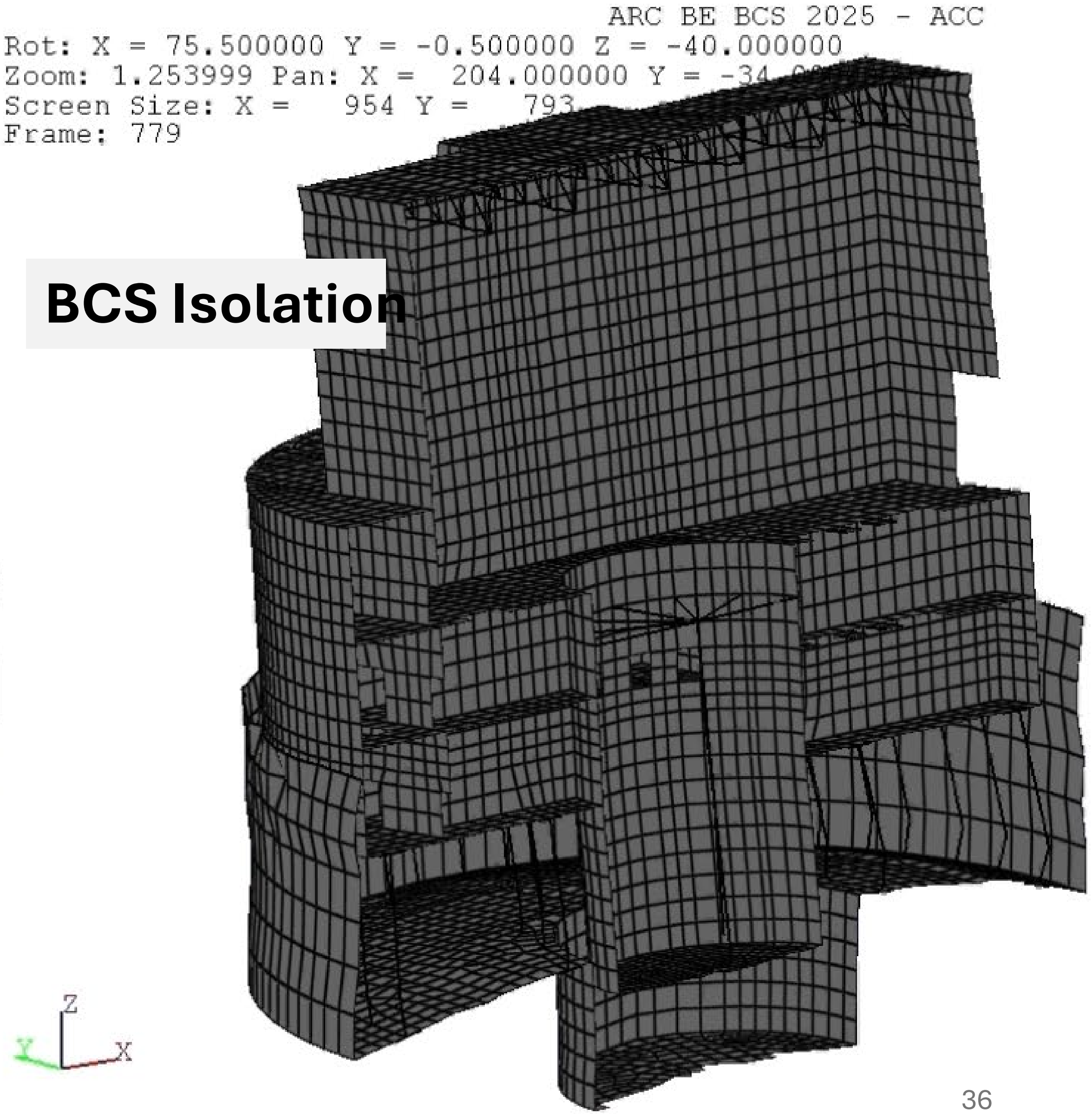
DBE Structural Accelerations for FP and BCS

FRAME 779(3.895 sec)



```
ARC BE FP 2024 - ACC
Rot: X = 75.000000 Y = -0.500000 Z = -44.000000
Zoom: 1.254001 Pan: X =  247.000000 Y = -3.000000
Screen Size: X =    954 Y =    793
Frame: 779
```

2D FP Isolation



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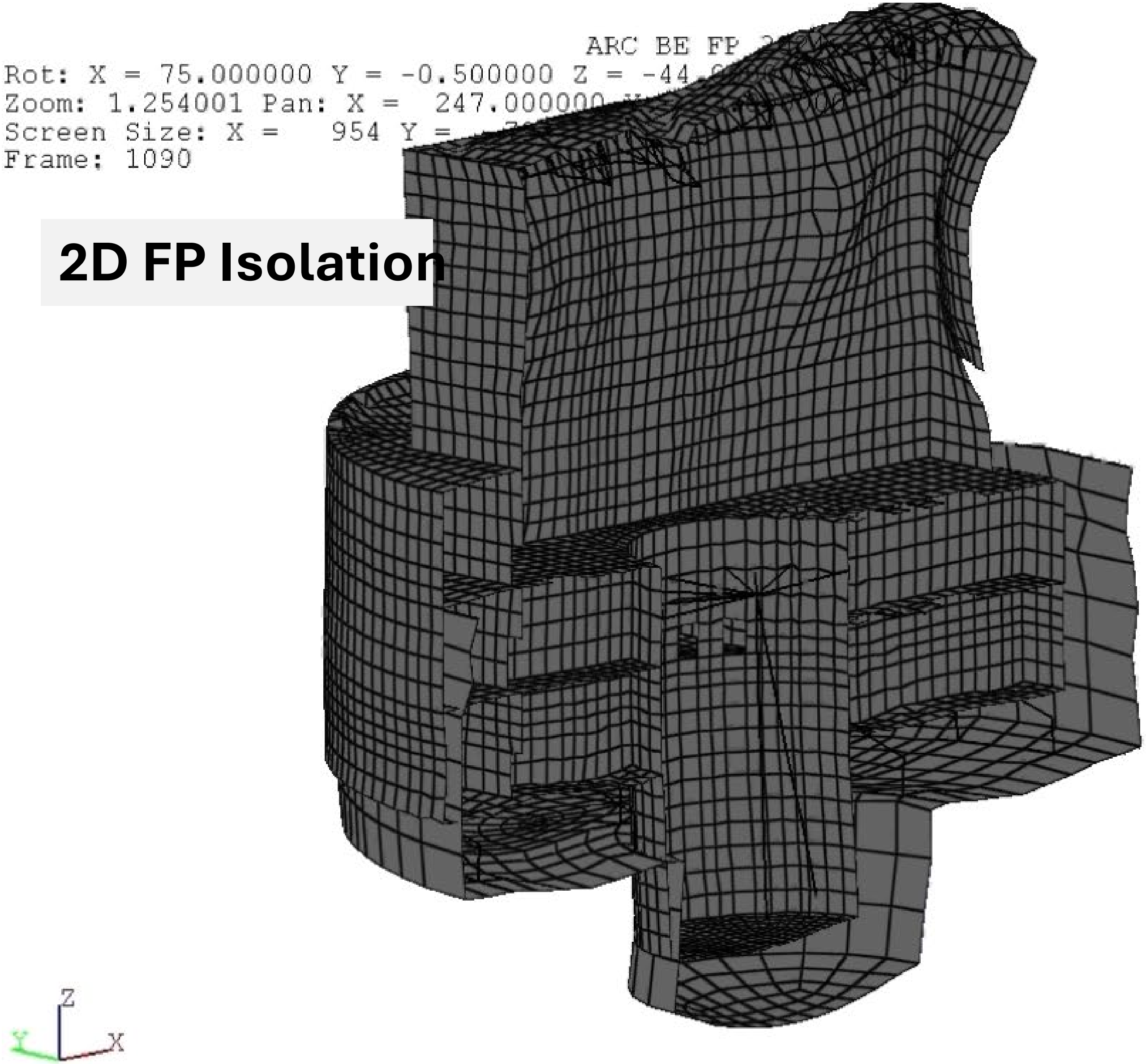
ARC BE BCS 2025 - ACC
Rot: X = 75.500000 Y = -0.500000 Z = -40.000000
Zoom: 1.253999 Pan: X =  204.000000 Y = -34
Screen Size: X =    954 Y =    793
Frame: 779
```

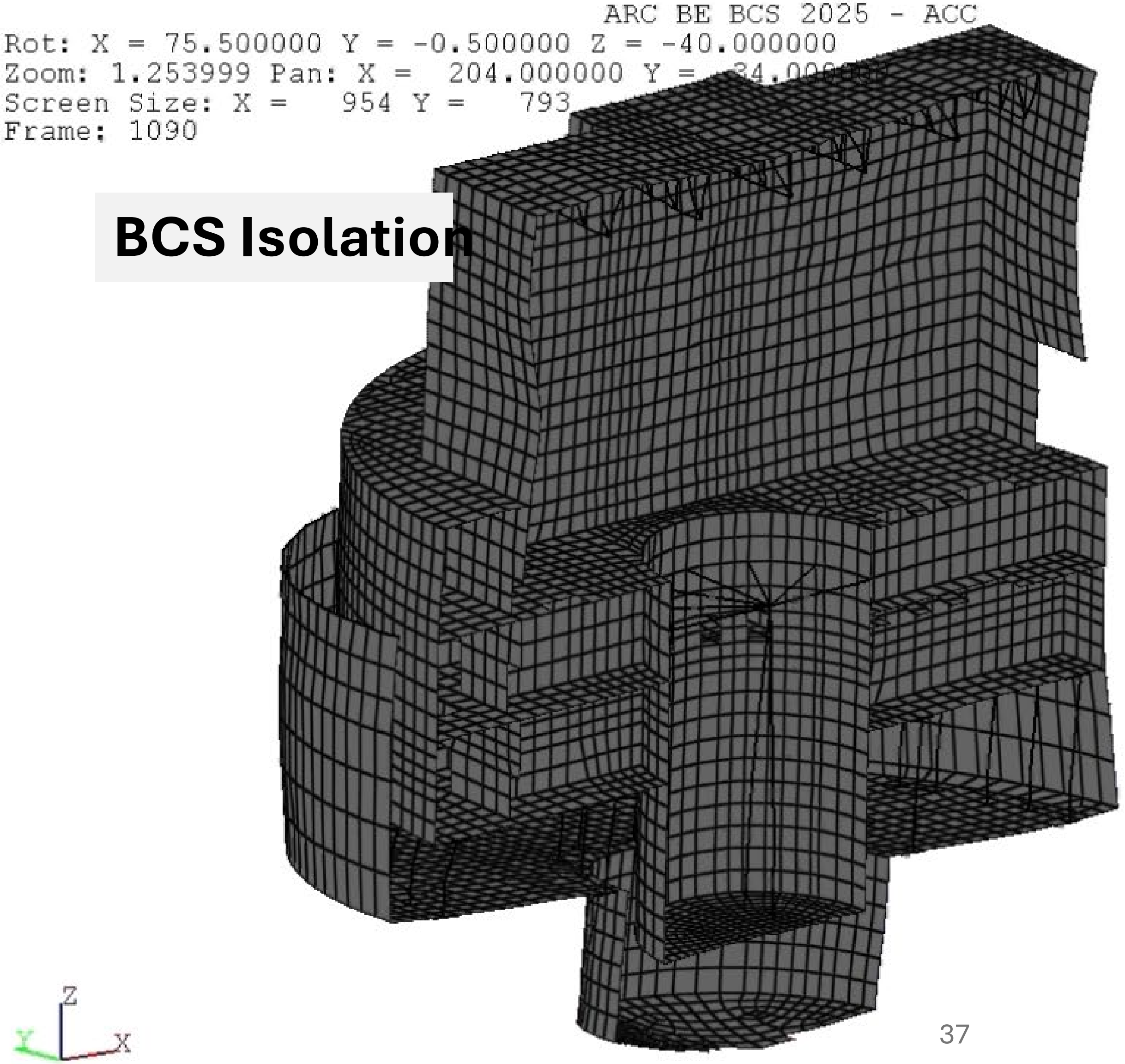
BCS Isolation

DBE Structural Accelerations for FP and BCS

FRAME 1090 (5.45 sec)



2D FP Isolation



BCS Isolation

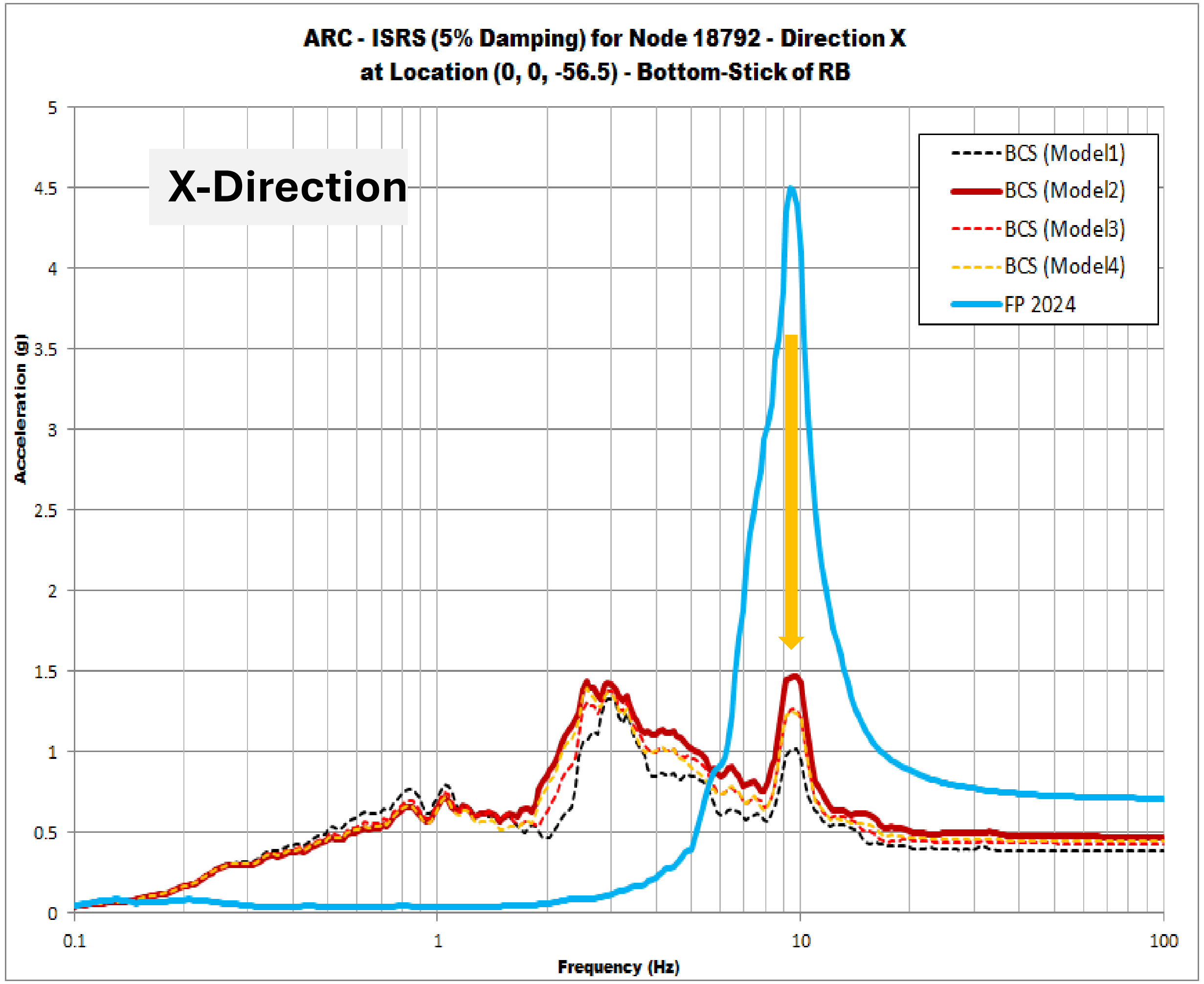
Remarks Based on Structural Acceleration Plots

The shown acceleration contour plots have the same legend scale for the two isolation systems.

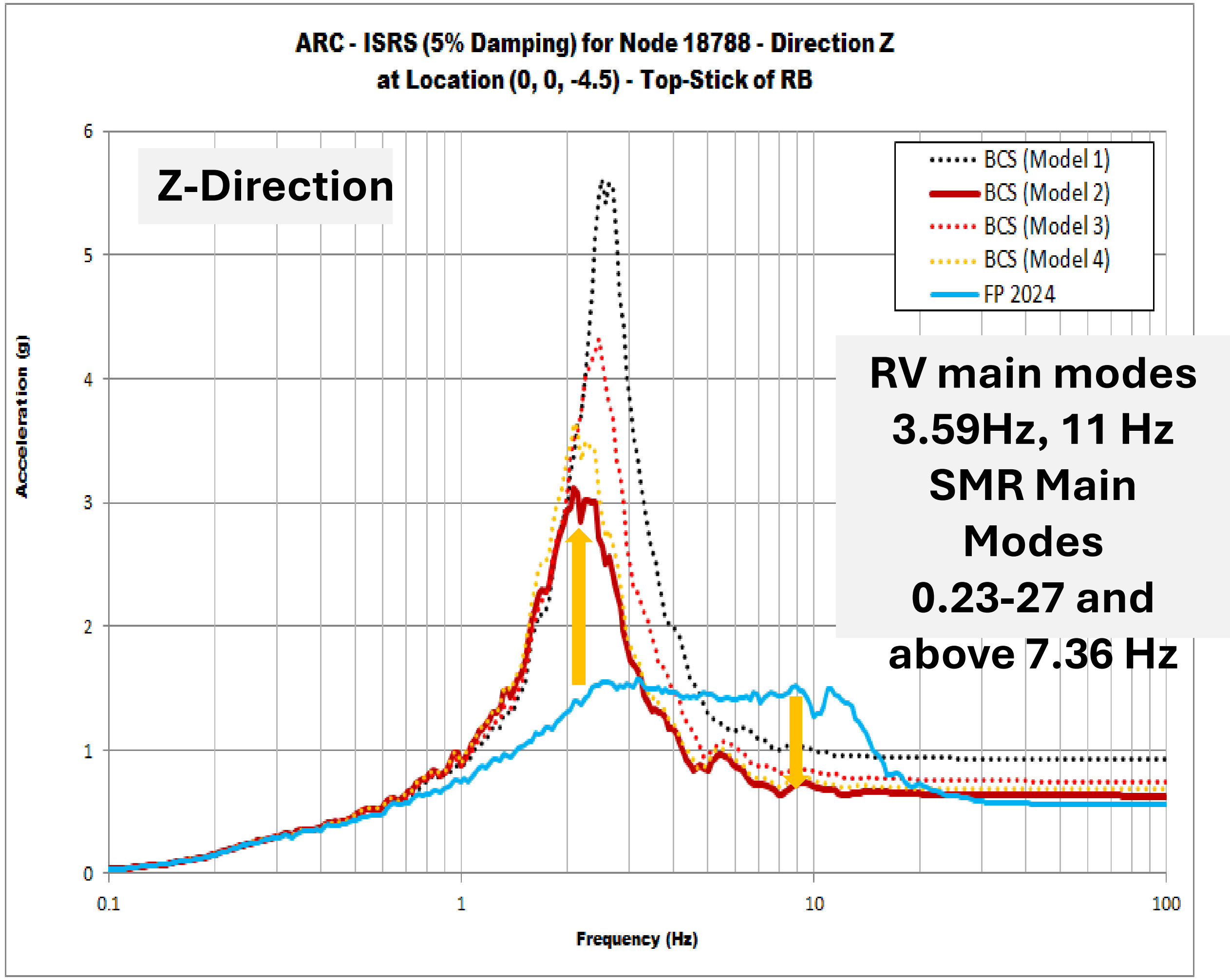
It should be noted that the **FP isolation**, although it produces highly reduced accelerations at lower elevations, significantly excites the out-of-plane local vibration modes of the SMR walls (for X and Y direction) and floors (for Z direction). This amplification of the local transverse vibration modes is due to lack of vertical isolation by the FP isolation system.

In contrast to the FP isolation effects, the **BCS isolation** produces highly uniform accelerations without exciting any structural local vibration modes in X, Y or Z direction. This result is due to the 3D-space BCS isolation that fully decouples the motions in X, Y and Z directions. Therefore, no transfer of energy can happen between the SMR SSI vertical mode and horizontal modes.

Comparison of FP and BCS ISRS at RV Bottom Location


ARC - ISRS (5% Damping) for Node 18792 - Direction X
at Location (0, 0, -56.5) - Bottom-Stick of RB

X-Direction

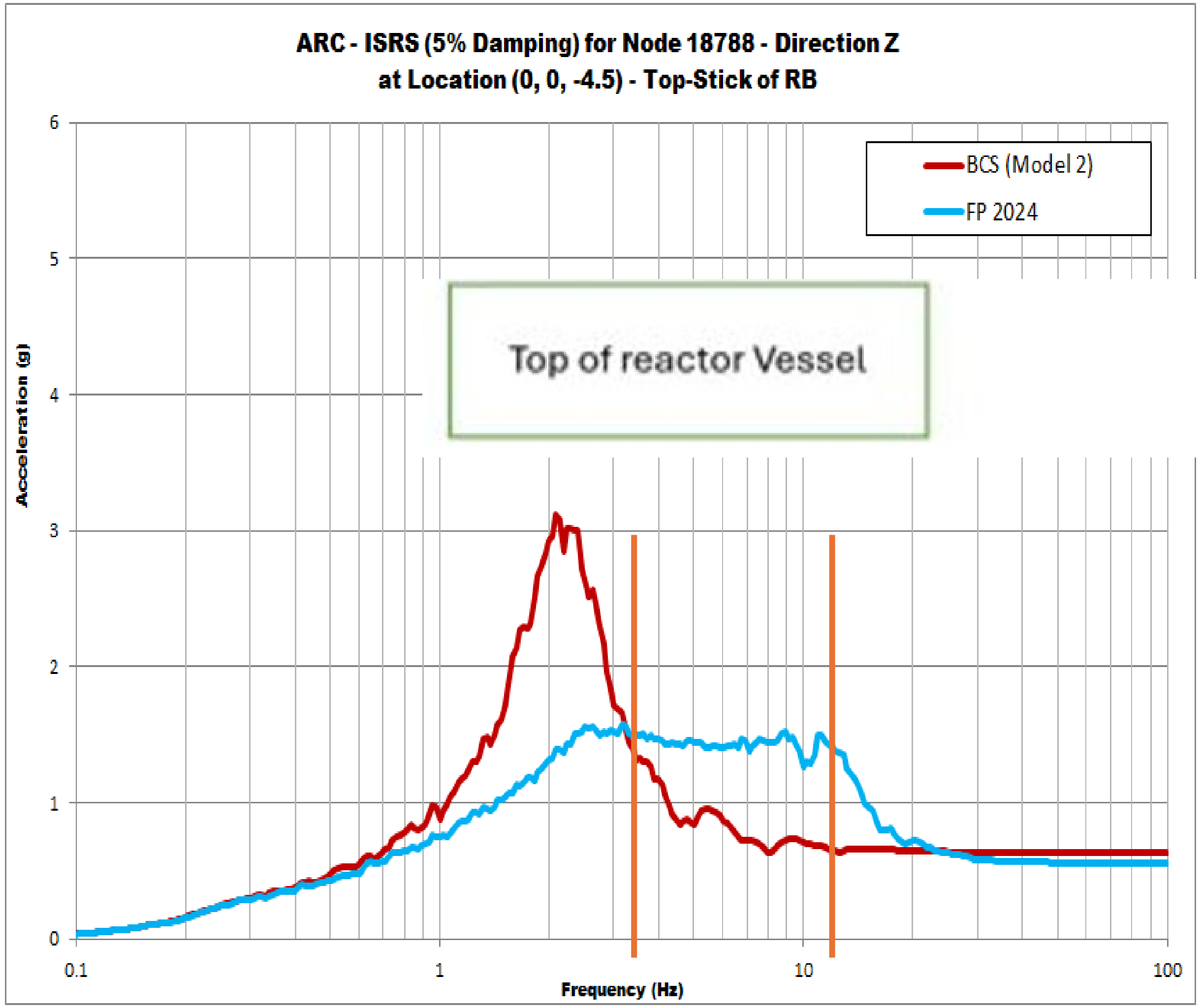

ARC - ISRS (5% Damping) for Node 18788 - Direction Z
at Location (0, 0, -4.5) - Top-Stick of RB

Z-Direction

RV main modes 3.59Hz, 11 Hz
SMR Main Modes 0.23-27 and above 7.36 Hz

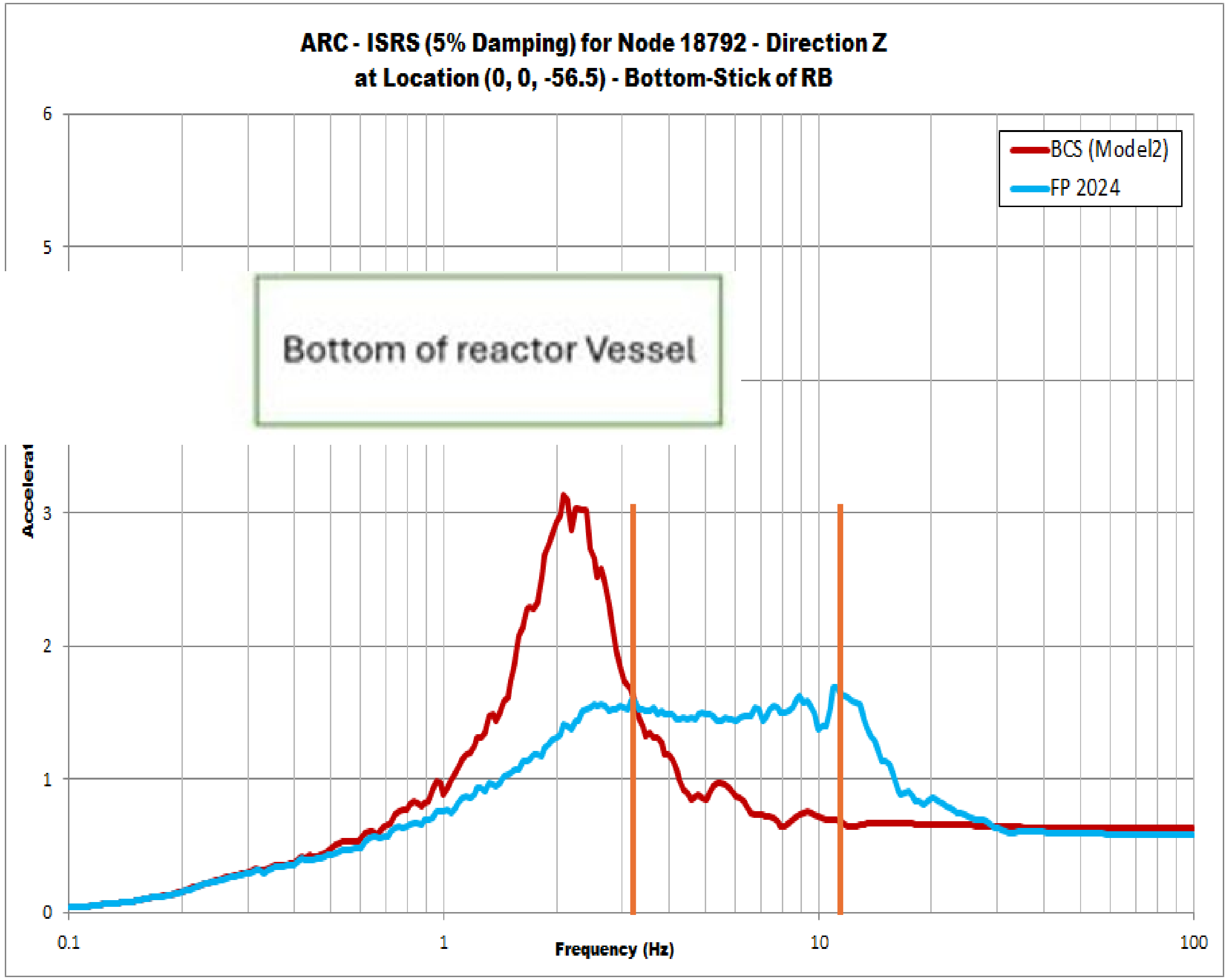
- 3D BCS isolation decouples the SSI response motions in X, Y and Z directions, and, therefore, no transfer of energy can happen between the SMR SSI vertical mode and the RV stick horizontal modes
- 3D BCS isolation reduces vertical ISRS response in 3-20 Hz range, and amplifies in the 1-3 Hz range

Comparison of FP and BCS Vertical ISRS at RV Bottom and Top



ARC - ISRS (5% Damping) for Node 18788 - Direction Z at Location (0, 0, -4.5) - Top-Stick of RB

Top of reactor Vessel

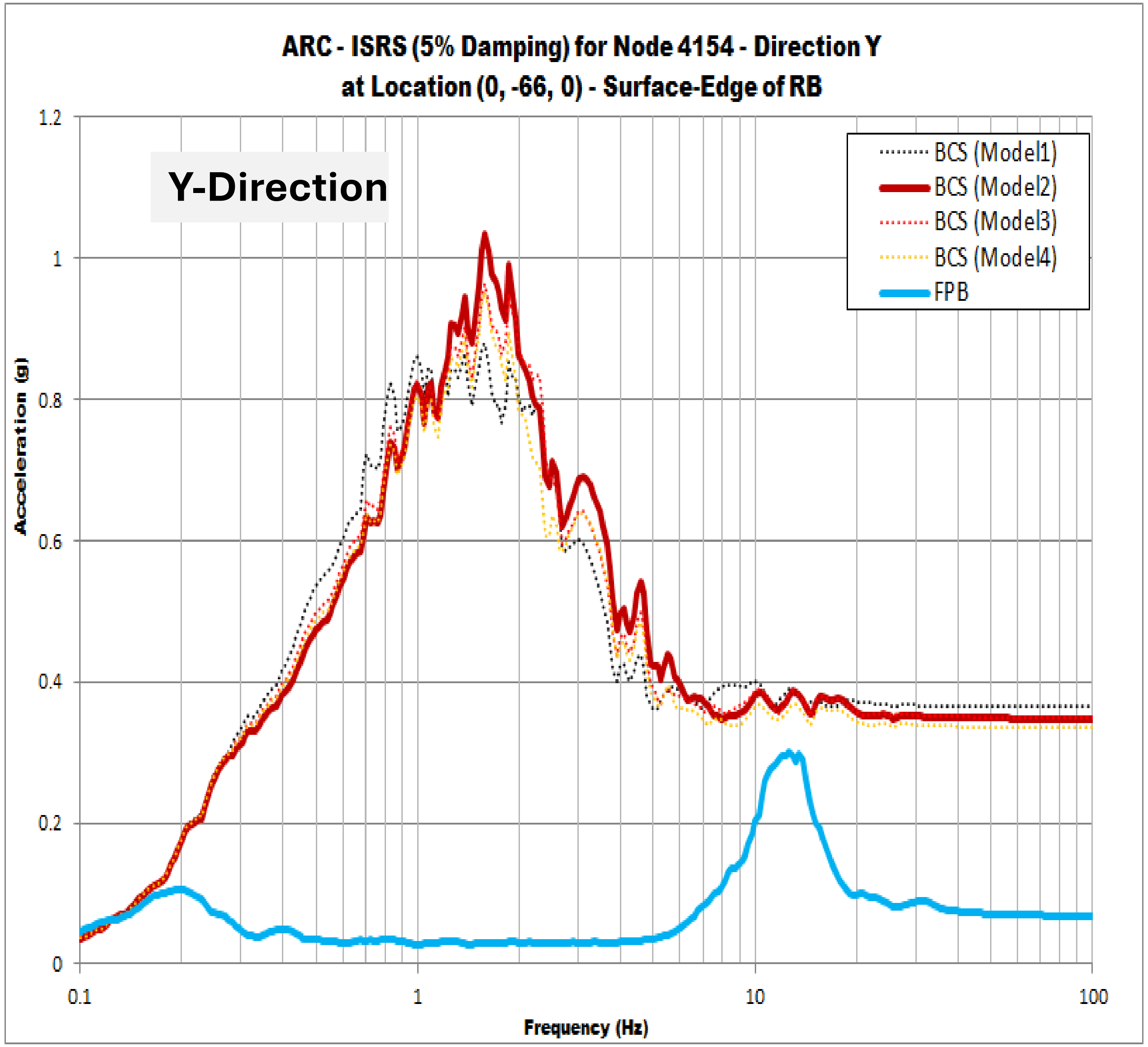


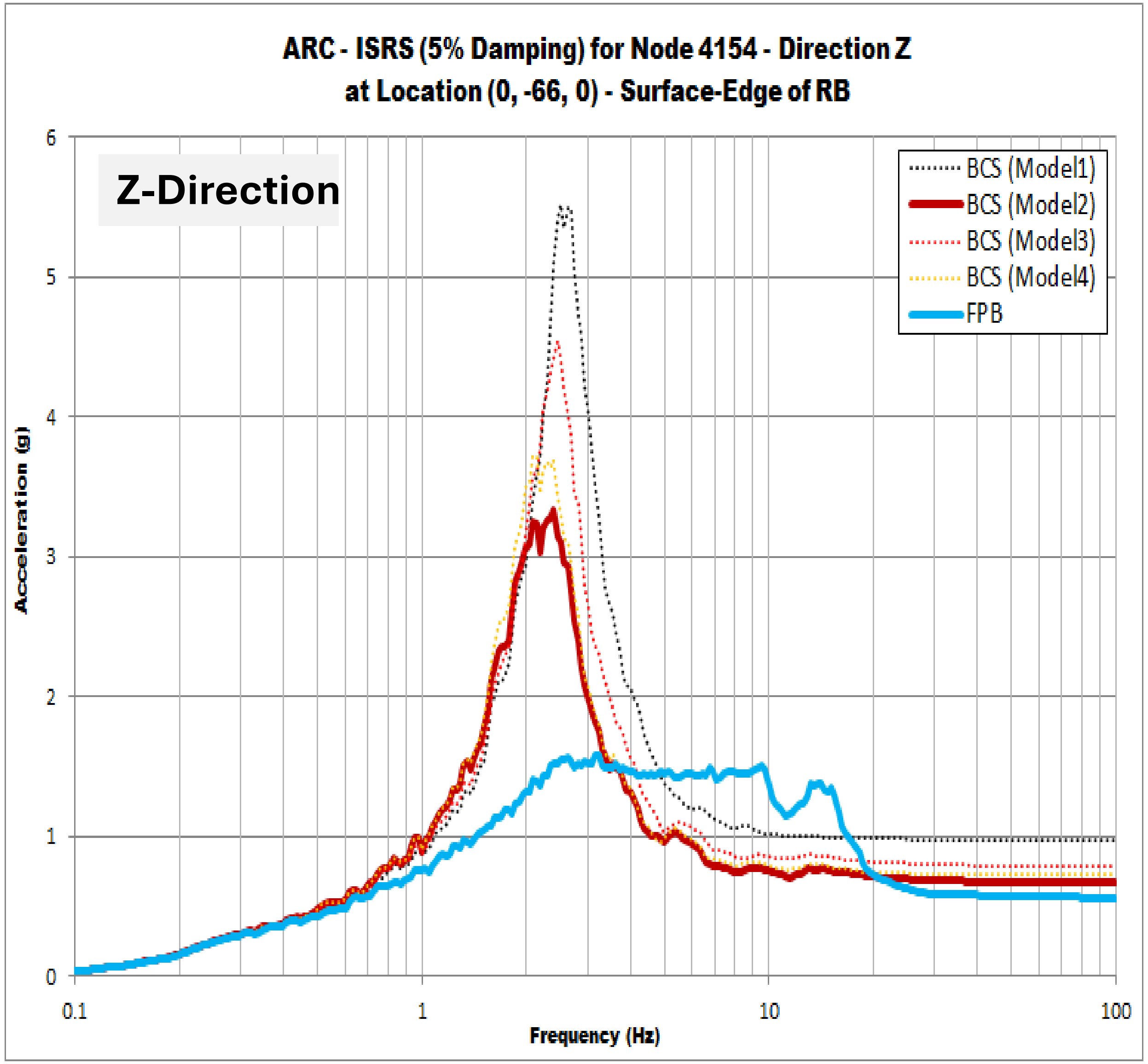
ARC - ISRS (5% Damping) for Node 18792 - Direction Z at Location (0, 0, -56.5) - Bottom-Stick of RB

Bottom of reactor Vessel

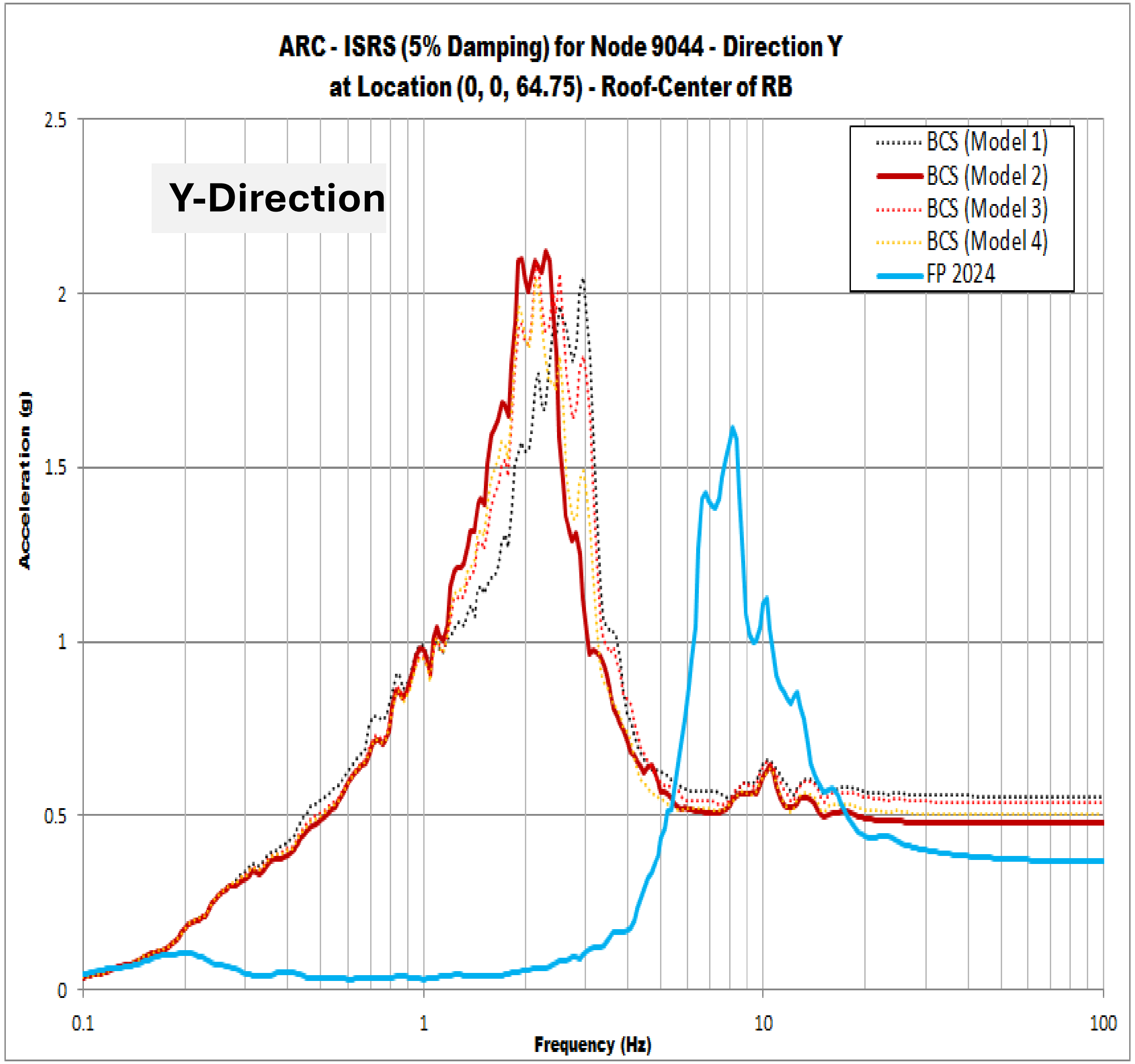
- 3D BCS isolation reduces vertical ISRS response in 3-20 Hz range, and amplifies in 1-3 Hz range. This is due to the BCS vertical flexibility which is larger than the FP isolator flexibility (almost rigid)
- The RV vertical modes are at 3.59 Hz and 11. Hz; ISRS lower response for BCS vs. FP isolation

Comparison of FP and BCS ISRS at Ground Surface Level



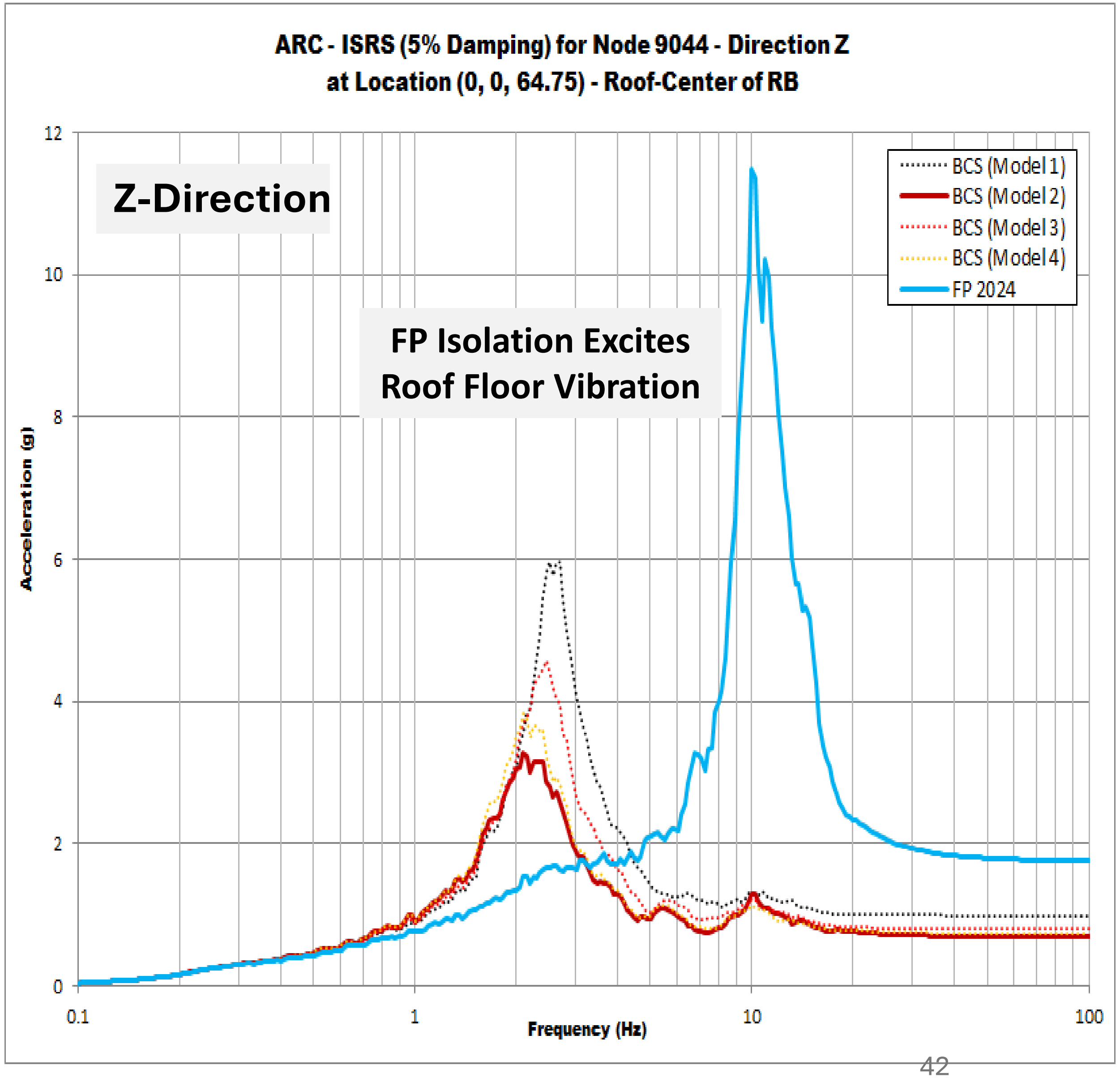


Comparison of FP and BCS ISRS at Roof Center



ARC - ISRS (5% Damping) for Node 9044 - Direction Y at Location (0, 0, 64.75) - Roof-Center of RB

Y-Direction

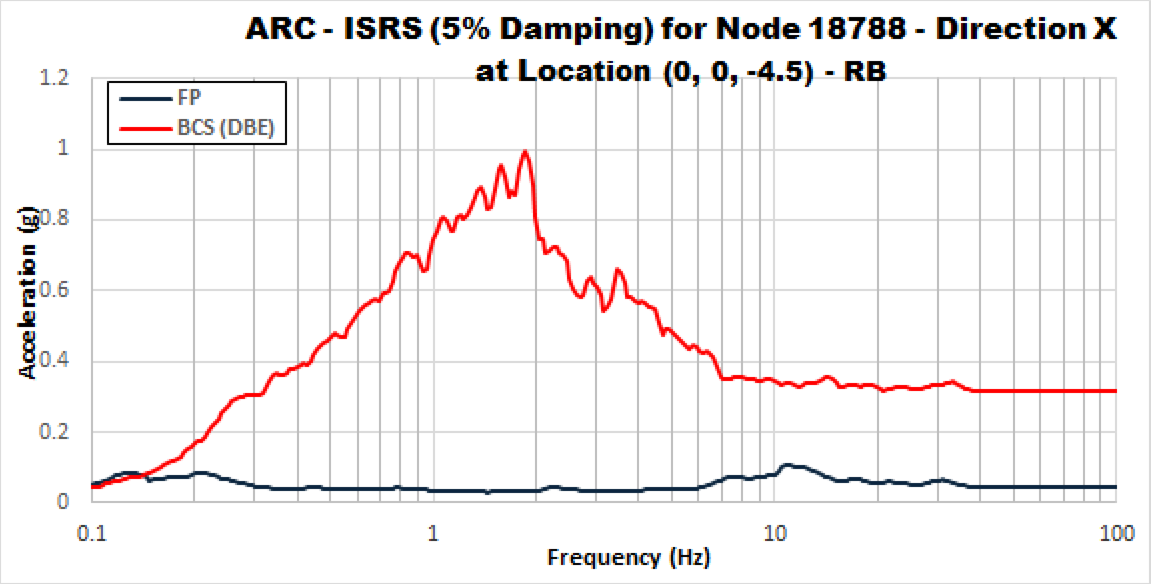


ARC - ISRS (5% Damping) for Node 9044 - Direction Z at Location (0, 0, 64.75) - Roof-Center of RB

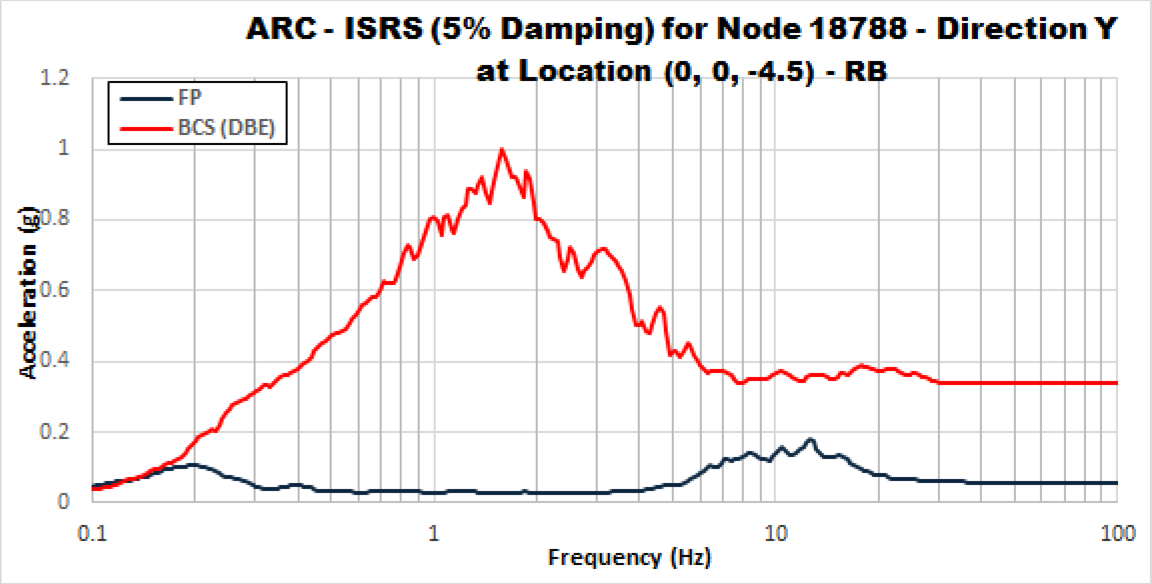
Z-Direction

FP Isolation Excites Roof Floor Vibration

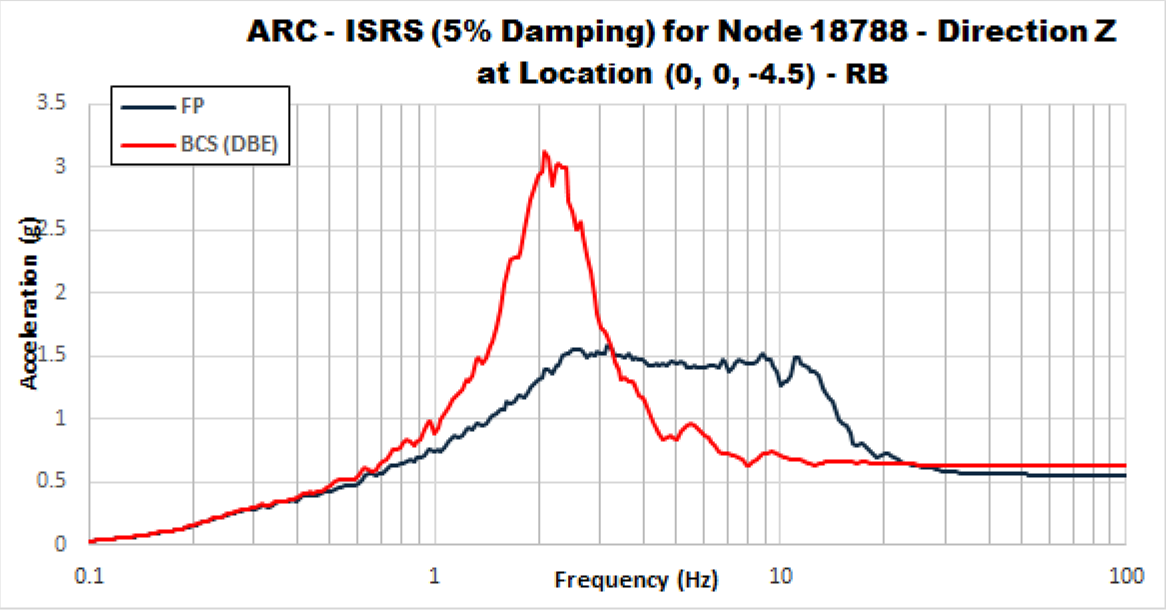
Vessel Support Location ISRS for FP and BCS Isolation



ARC - ISRS (5% Damping) for Node 18788 - Direction X at Location (0, 0, -4.5) - RB

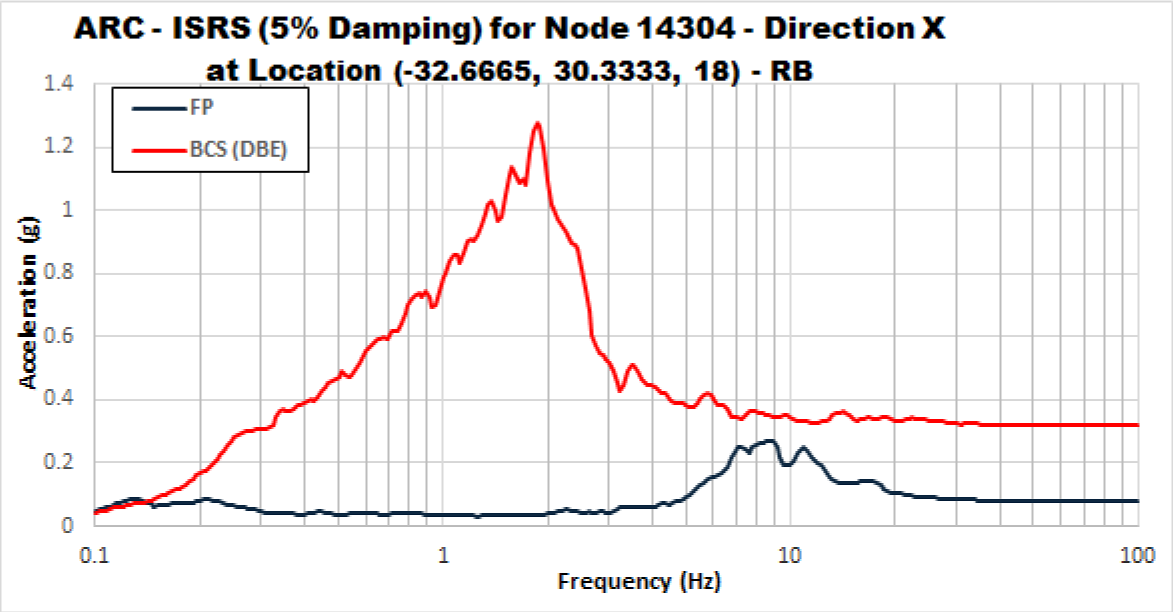


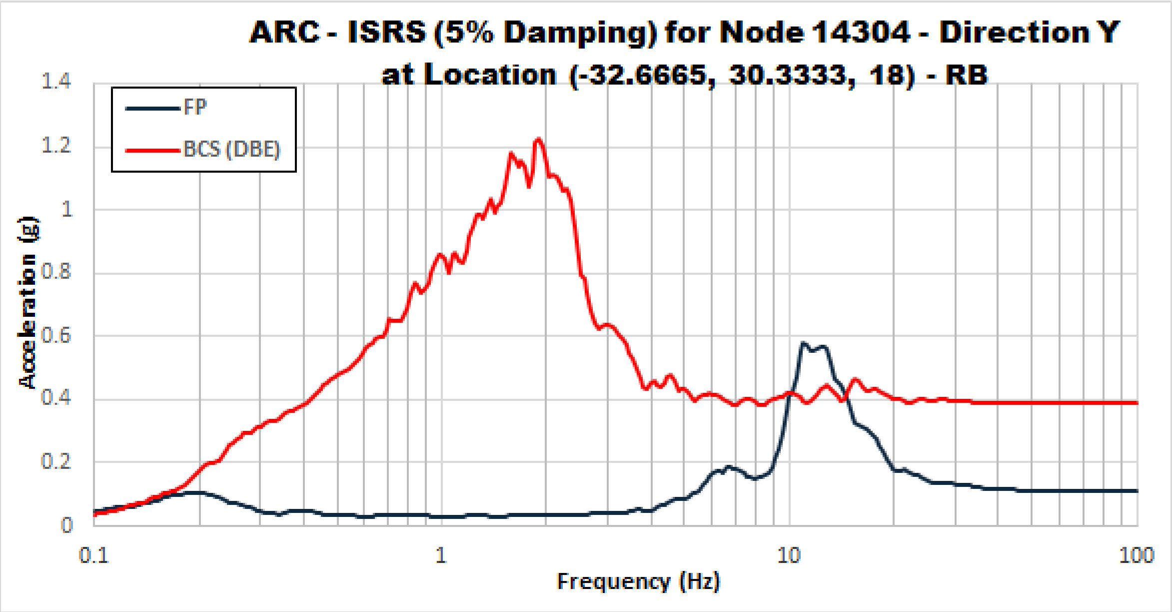
ARC - ISRS (5% Damping) for Node 18788 - Direction Y at Location (0, 0, -4.5) - RB

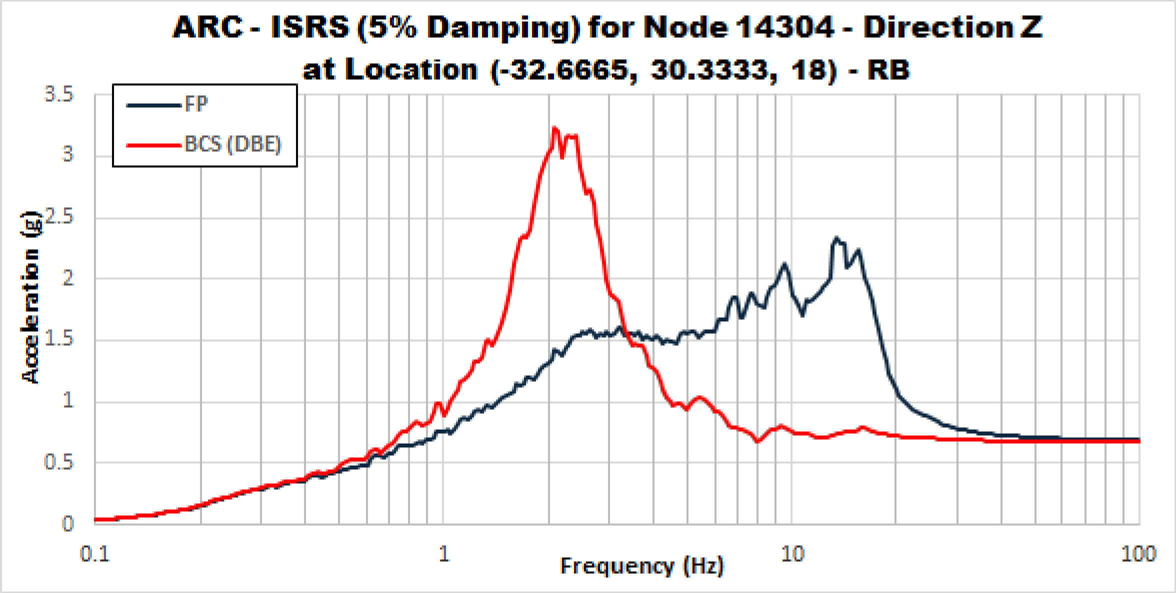


ARC - ISRS (5% Damping) for Node 18788 - Direction Z at Location (0, 0, -4.5) - RB

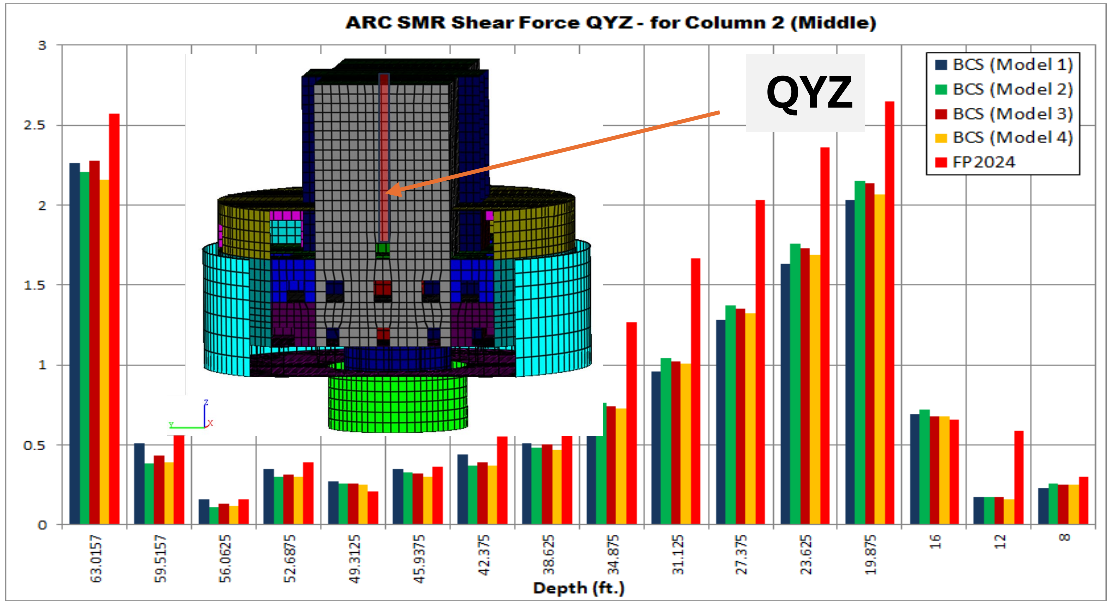
Comparative DRACS ISRS with FP and BCS Isolators

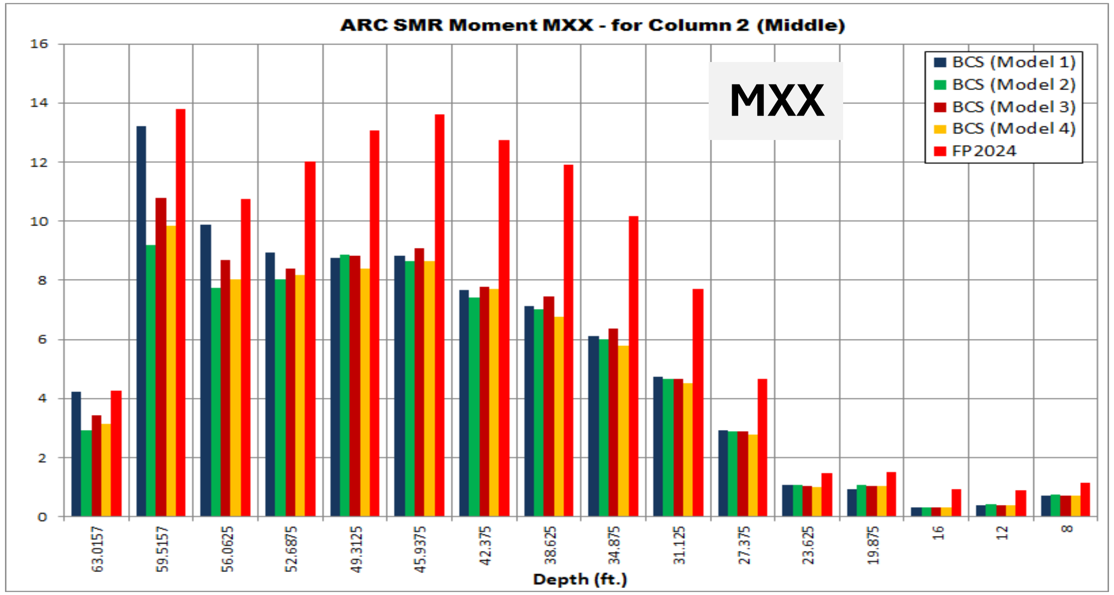

ARC - ISRS (5% Damping) for Node 14304 - Direction X at Location (-32.6665, 30.3333, 18) - RB

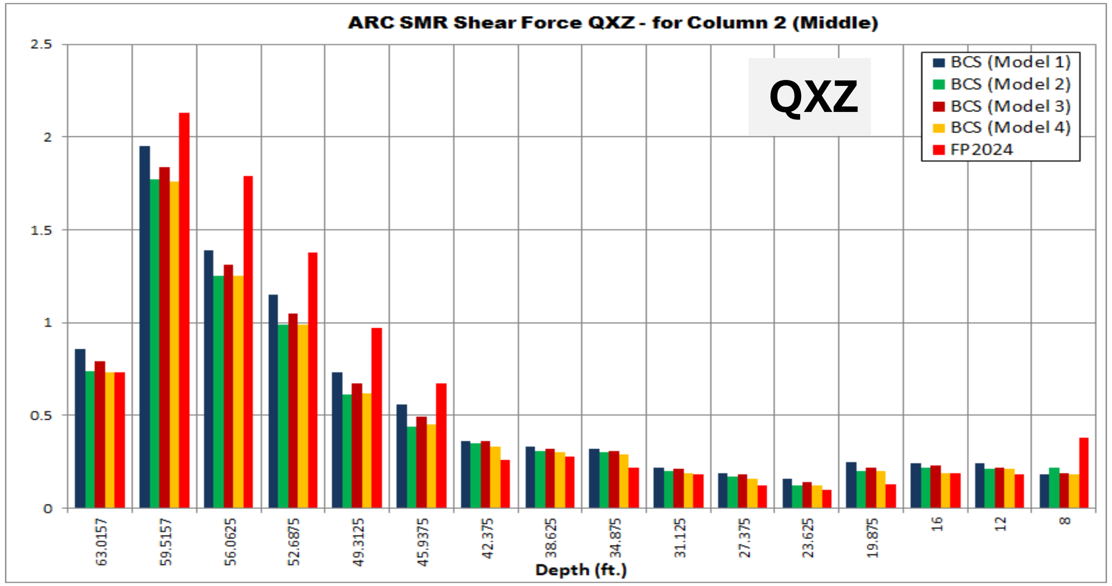

ARC - ISRS (5% Damping) for Node 14304 - Direction Y at Location (-32.6665, 30.3333, 18) - RB

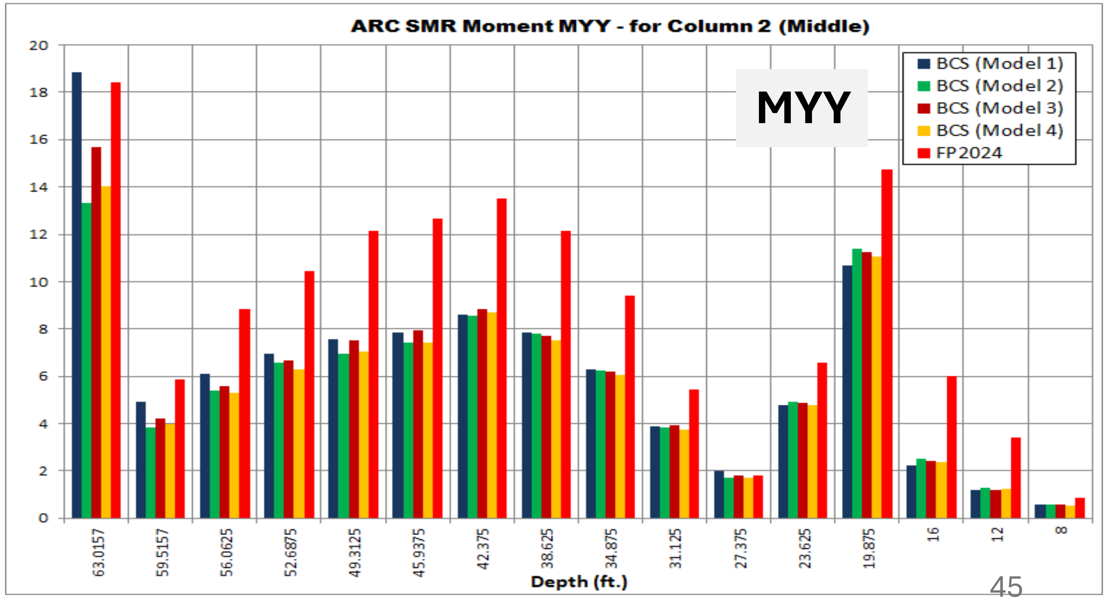

ARC - ISRS (5% Damping) for Node 14304 - Direction Z at Location (-32.6665, 30.3333, 18) - RB

Comparative SMR Wall DBE Mean Max Transverse Forces/Moments

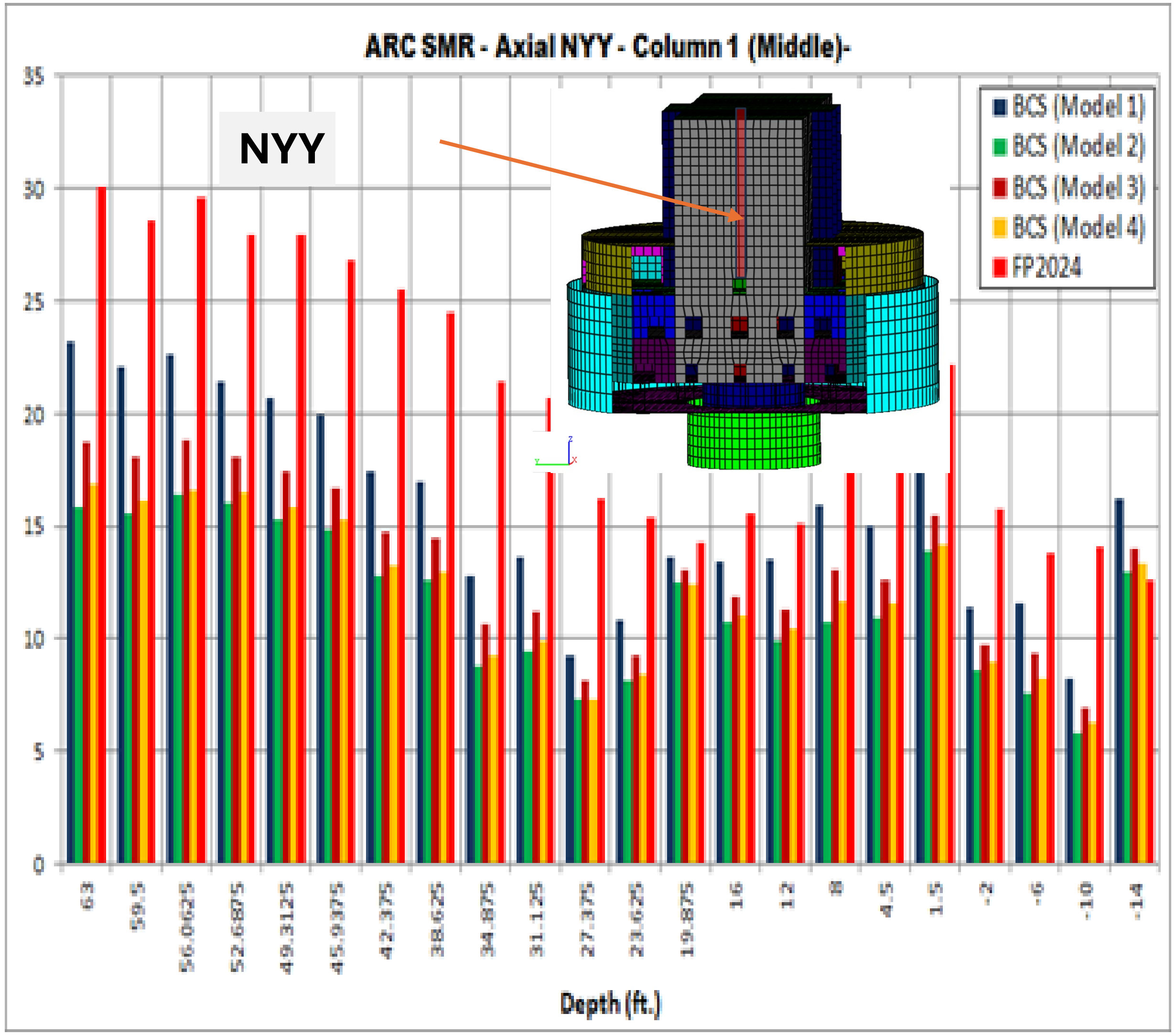

ARC SMR Shear Force QYZ - for Column 2 (Middle)

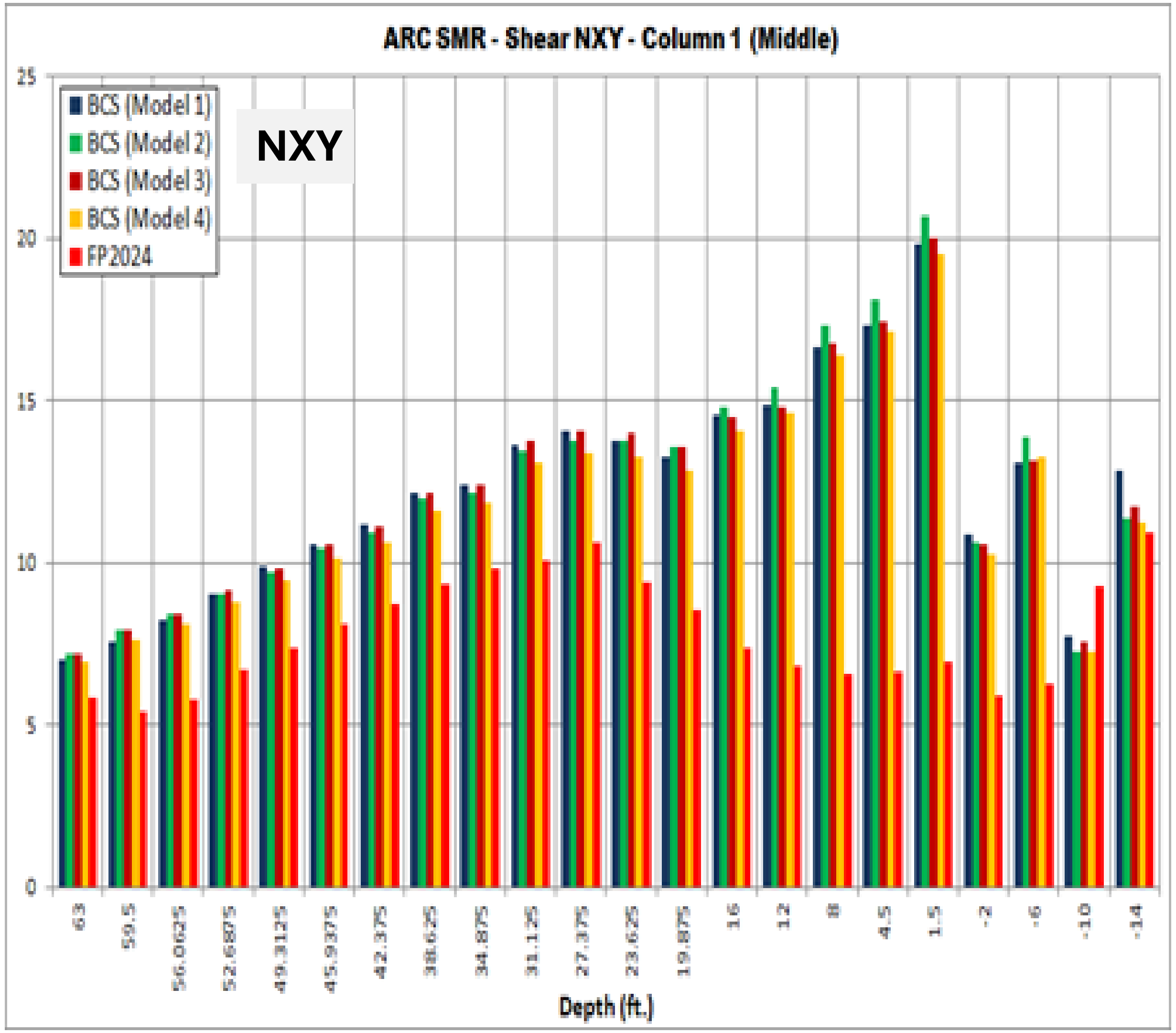

ARC SMR Moment MXX - for Column 2 (Middle)


ARC SMR Shear Force QXZ - for Column 2 (Middle)

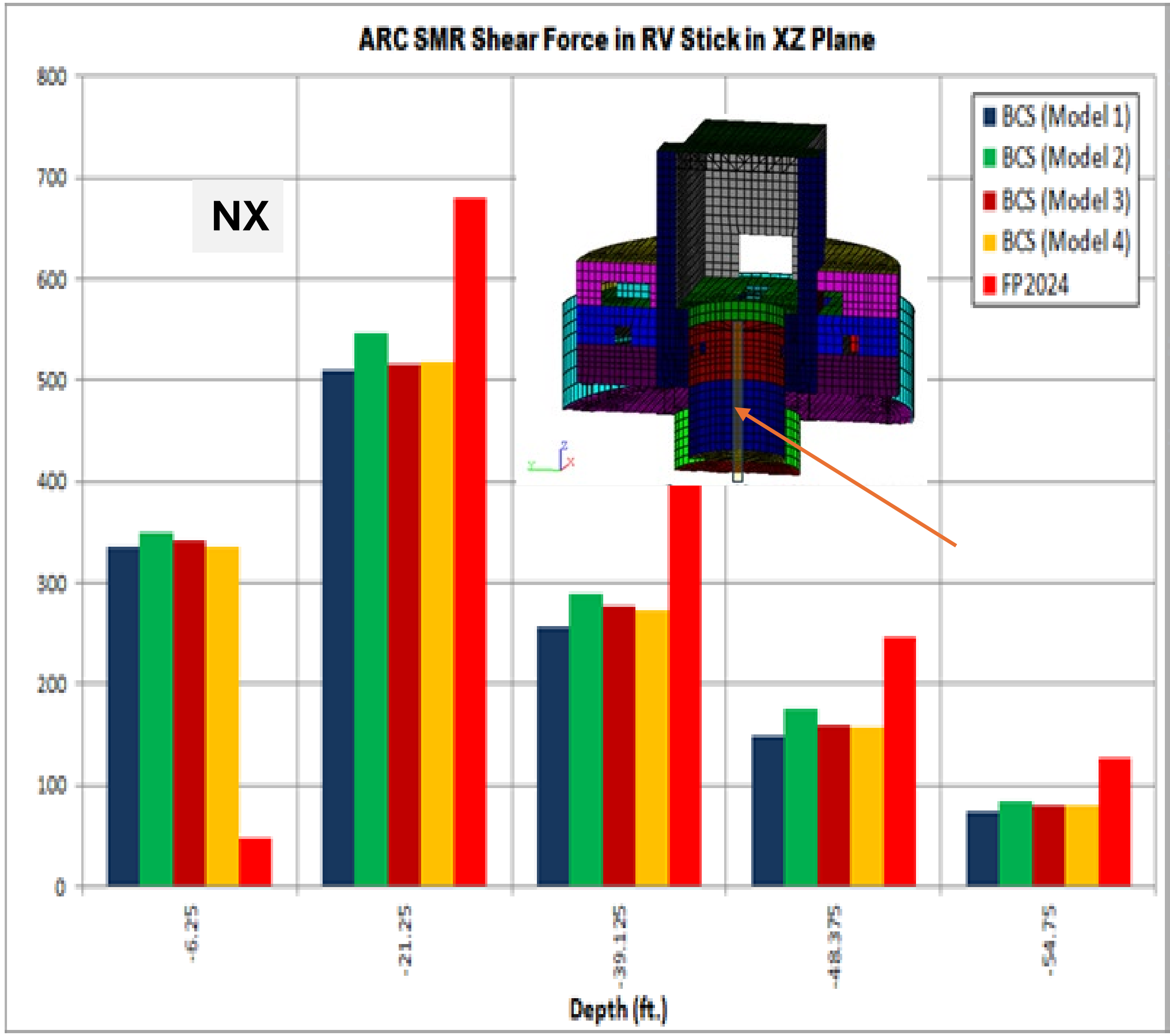

ARC SMR Moment MYY - for Column 2 (Middle)

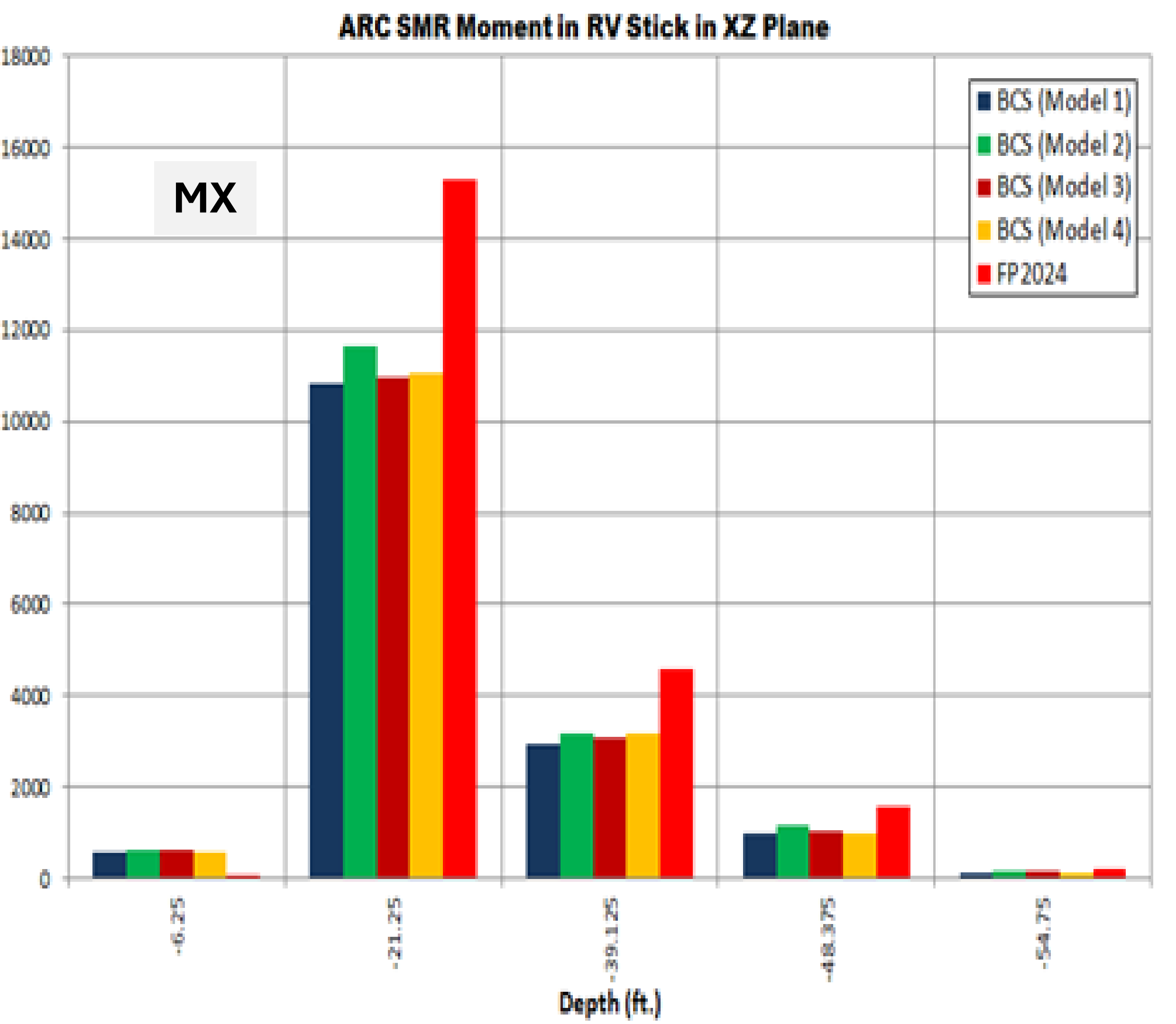
SMR Wall DBE Mean Longitudinal Forces/Moments for FP and BCS





RV Stick DBE Mean Max Shear Forces/Moments for FP and BCS





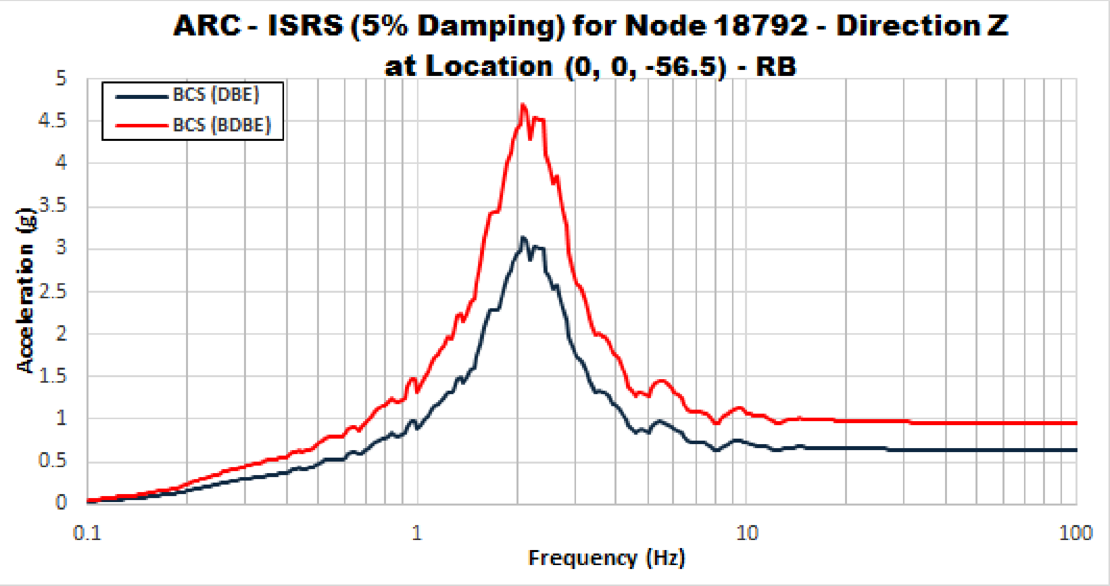
BDBE (or 1.5 DBE) Responses

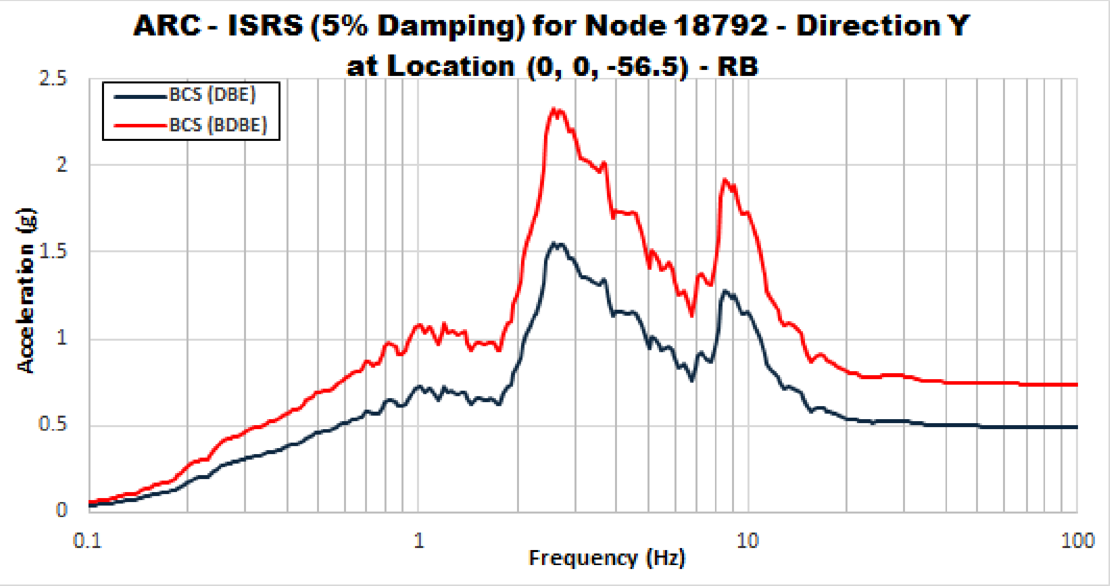
Scaling DRACS and RVACS Responses for BDBE Responses for 2D FP Isolation

Nodes – 2D	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 – **nearly linear in Z, but not in X-Y**
- Moreover, 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

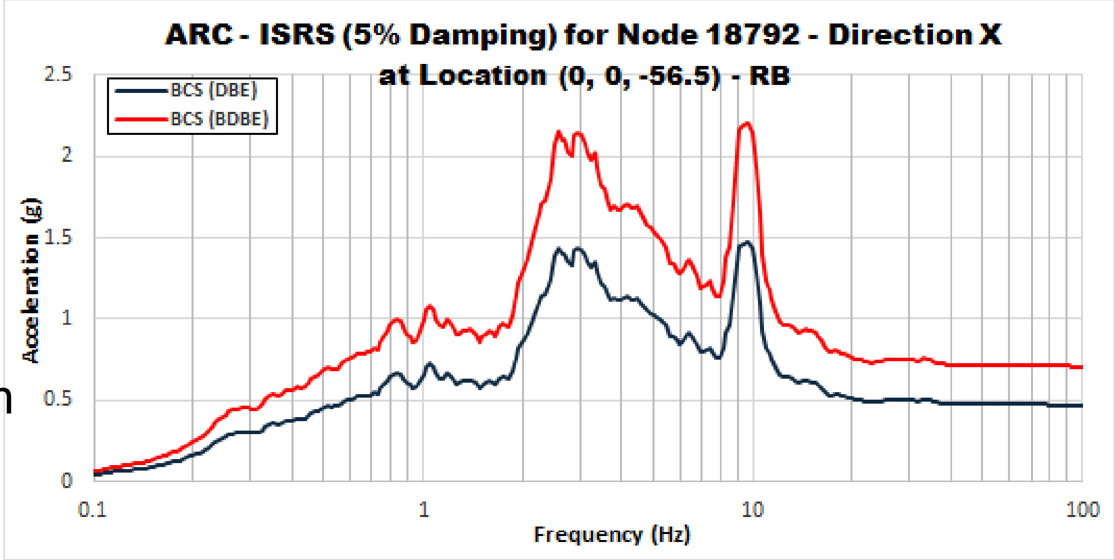
Scaling RV DBE Responses for RV BDBE Responses for 3D BCS



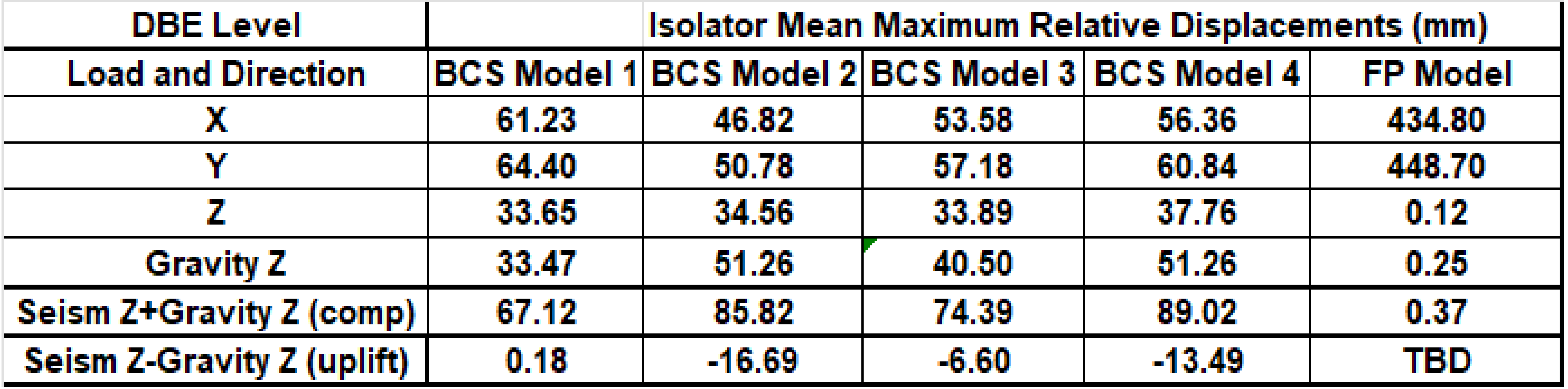


- Linear response of 3D BCS isolator facilitate assessment of fragilities at different PGAs

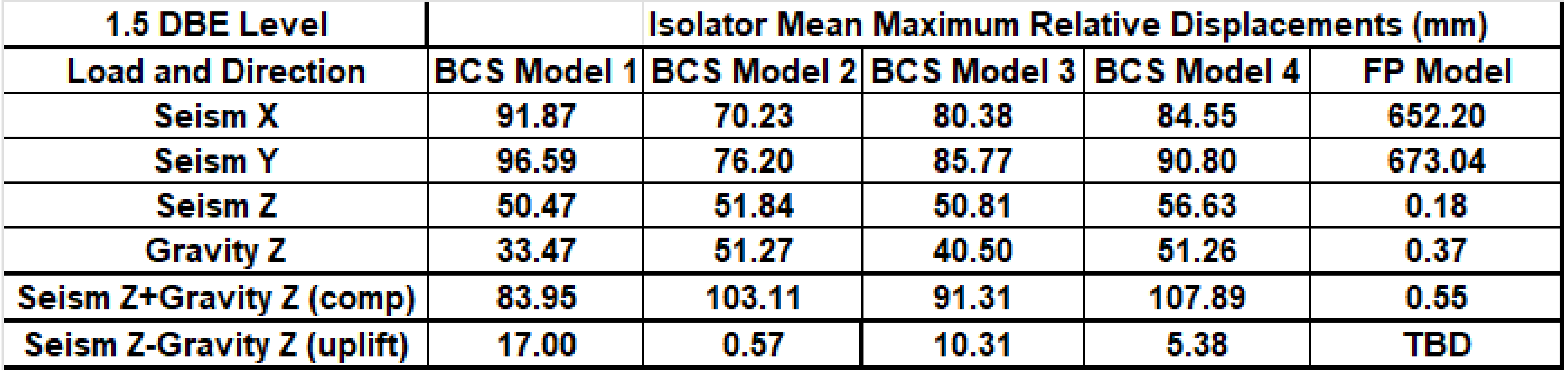
- Very high confidence in scaling ISRS for different PGA is crucial to F-C assessment in Seismic PRA.



DBE and BDBE Mean Max. Relative Displacements (mm)



DBE Level		Isolator Mean Maximum Relative Displacements (mm)			
Load and Direction	BCS Model 1	BCS Model 2	BCS Model 3	BCS Model 4	FP Model
X	61.23	46.82	53.58	56.36	434.80
Y	64.40	50.78	57.18	60.84	448.70
Z	33.65	34.56	33.89	37.76	0.12
Gravity Z	33.47	51.26	40.50	51.26	0.25
Seism Z+Gravity Z (comp)	67.12	85.82	74.39	89.02	0.37
Seism Z-Gravity Z (uplift)	0.18	-16.69	-6.60	-13.49	TBD



1.5 DBE Level		Isolator Mean Maximum Relative Displacements (mm)			
Load and Direction	BCS Model 1	BCS Model 2	BCS Model 3	BCS Model 4	FP Model
Seism X	91.87	70.23	80.38	84.55	652.20
Seism Y	96.59	76.20	85.77	90.80	673.04
Seism Z	50.47	51.84	50.81	56.63	0.18
Gravity Z	33.47	51.27	40.50	51.26	0.37
Seism Z+Gravity Z (comp)	83.95	103.11	91.31	107.89	0.55
Seism Z-Gravity Z (uplift)	17.00	0.57	10.31	5.38	TBD

Linearly Scaled x 1.5

Comparative 90th Percentile BDBE Isolator Deformations (mm)

1.5 DBE Level		Isolator 90% Maximum Relative Displacements (mm)			
Load and Direction	**BCS Model 1**	**BCS Model 2**	**BCS Model 3**	**BCS Model 4**	**FP Model**
Seism X	102.89	78.65	90.02	94.70	730.46
Seism Y	108.18	85.34	96.06	101.70	753.81
Seism Z	56.53	58.06	56.91	63.43	0.20
Gravity Z	33.47	51.27	40.50	51.26	0.37
Seism Z+Gravity Z (comp)	90.01	109.33	97.41	114.68	0.57
Seism Z-Gravity Z (uplift)	23.06	6.79	16.41	12.17	TBD

Good

- **FP isolation** sliding displacements of 753.81 mm which are beyond the FP **sliding limit *of 716 mm*** (28.2 in). Potential of isolator uplift not considered
- GERB **BCS isolation** devices per manufacturer's recommendation work up to ***150 mm lateral*** displacements and up to ***110 mm vertical*** compressive displacements.
- It should be noted that the SB units can be designed to handle large uplift tension forces corresponding to a spring tension displacement up to ***40mm (uplift)*** by including a cable anchorage system (for a SB unit cost increase up to 20% per manufacturer's estimate).
- BCS Model 2 has significant safety margins for 90th percentile BDEB SSI displacement response

Differences Between 2D FP and 3D BCS Isolation

2D FP Isolation

- Very flexible in horizontal direction. Provides generally lower global accelerations because of large horizontal flexibility .
- Lateral displacement exceed capability of isolator at PGA less than 1.5 DBE .
- Potential of isolator uplift not considered in SSI studies. It may occur at 1.5 DBE.
- Sensitive to coupling of vertical to horizontal due to mode frequency tuning of global structure large mass vertical modes to local structure horizontal modes (smaller mass)
- SMR spectral acceleration distribution is highly nonuniform, and FP nonlinear behavior renders extrapolation of response at different PGAs difficult and questionable – i.e. for high confidence separate analyses need to be conducted for each PGA
- FP isolation produces transverse forces and moments generally significantly greater and in-plane shear forces significantly lower than those produced by 3D BCS.

Differences Between 2D FP and 3D BCS Isolation (cont.)

3D BCS Isolation

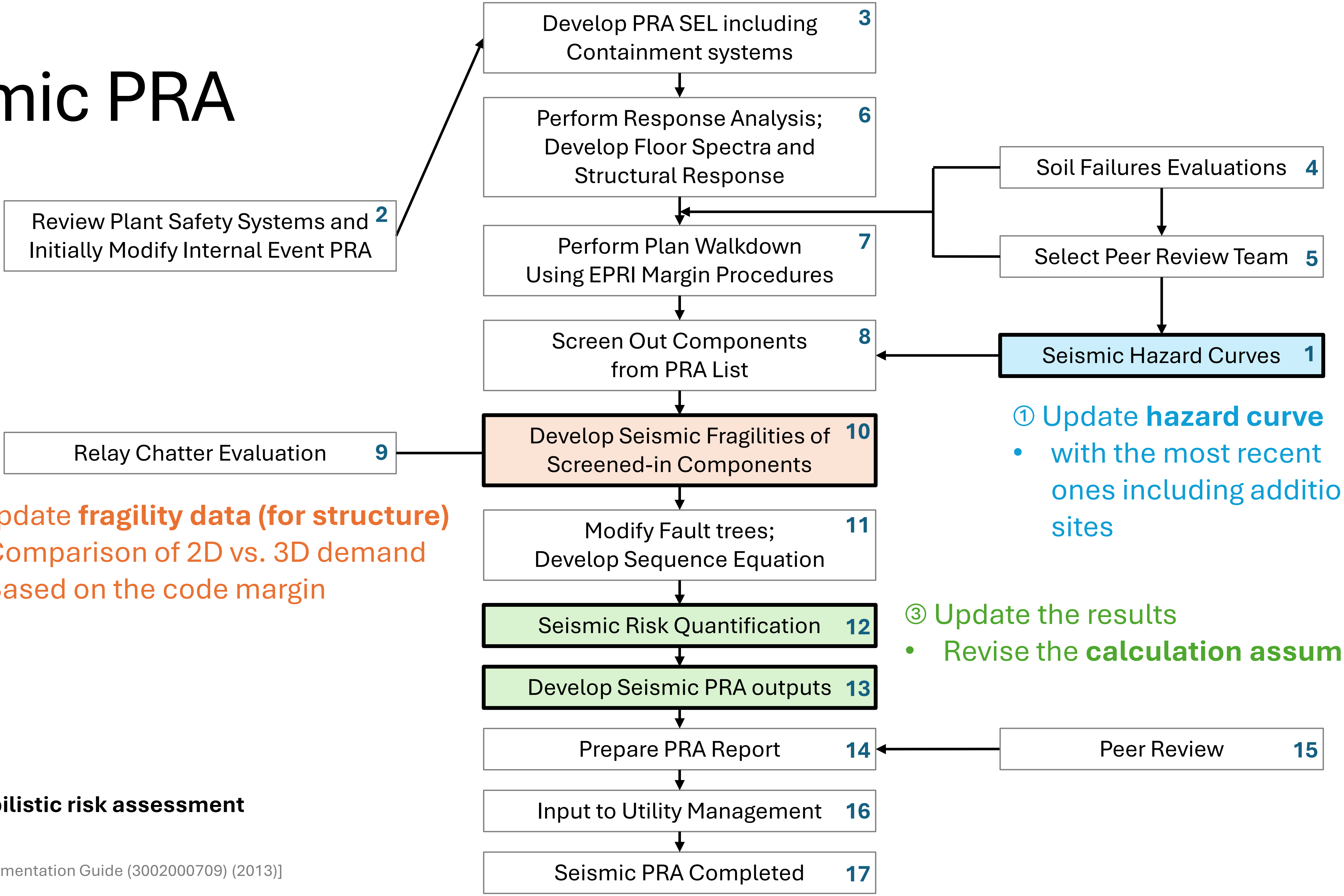
- Much stiffer in horizontal direction, so lateral displacements are much smaller than for FP isolation. Provides generally higher global accelerations because of smaller horizontal flexibility .
- Horizontal and vertical displacements of isolator are not a concern at PGA equal to 1.5 DBE and higher still – We have not yet investigate how large a PGA can be accommodated by BCS type isolators .
- Spectral acceleration distribution is highly uniform and linearity renders extrapolation of response at different PGAs very reliable (within displacement limits)– i.e. does not require separate nonlinear analyses need to be conducted for each PGA (see next slide)
- The 3D BCS isolation fully decouples the vertical motion and the horizontal motions. BCS isolation ensures complete avoidance of dynamic coupling due to mode frequency tunning which are occurring for 2D FP isolation.
- Produces transverse forces and moments generally significantly smaller and in-plane shear forces higher than those produced by 2D FP isolation

Conclusion for structural adequacy

- There are advantages and disadvantages to both systems, and perhaps use of both will offer best solution
- BCS was chosen because of ready availability of isolator properties, having been used to isolated the reactor vessel within the 2D isolated Reactor building .
    - BCS is not necessarily the optimal 3D isolator –more study needed of other potential 3D isolators
- FP large horizontal displacement significantly reduces horizontal accelerations, provided coupling of vertical to horizontal modes is avoided. Behavior at PGA significantly greater than DBE would require detailed analyses of behavior at the specific PGA
- 3D Isolation appears to have a number of advantages over 2D.
    - Decoupling of vertical and horizontal modes - however isolator is likely not sole contributor to coupling, asymmetry of building also contributes
    - Uniformity of ISRS distribution
    - Linearity of response with PGAs facilitates Seismic Hazard analysis
- Present design of RB (and other buildings) and safety systems has been demonstrated to be adequate for Design Basis Earthquake, with RB 2D isolated.
- Based on margins to Codes the system with the least margin is the reactor vessel support (low margin caused by thermal stresses). 3D does not appear to substantially increase the margin

Seismic PRA

Seismic PRA



Develop PRA SEL including Containment systems 3

Perform Response Analysis; Develop Floor Spectra and Structural Response 6

Soil Failures Evaluations 4

Review Plant Safety Systems and Initially Modify Internal Event PRA 2

Select Peer Review Team 5

Perform Plan Walkdown Using EPRI Margin Procedures 7

Screen Out Components from PRA List 8

Seismic Hazard Curves 1

Relay Chatter Evaluation 9

Develop Seismic Fragilities of Screened-in Components 10

Modify Fault trees; Develop Sequence Equation 11

Seismic Risk Quantification 12

Develop Seismic PRA outputs 13

Prepare PRA Report 14

Peer Review 15

Input to Utility Management 16

Seismic PRA Completed 17

① Update **hazard curve**
- with the most recent ones including additional sites

② Update **fragility data (for structure)**
- Comparison of 2D vs. 3D demand
- Based on the code margin

③ Update the results
- Revise the **calculation assumptions**

Seismic probabilistic risk assessment task flowchart

[Ref. EPRI, SPRA Implementation Guide (3002000709) (2013)]

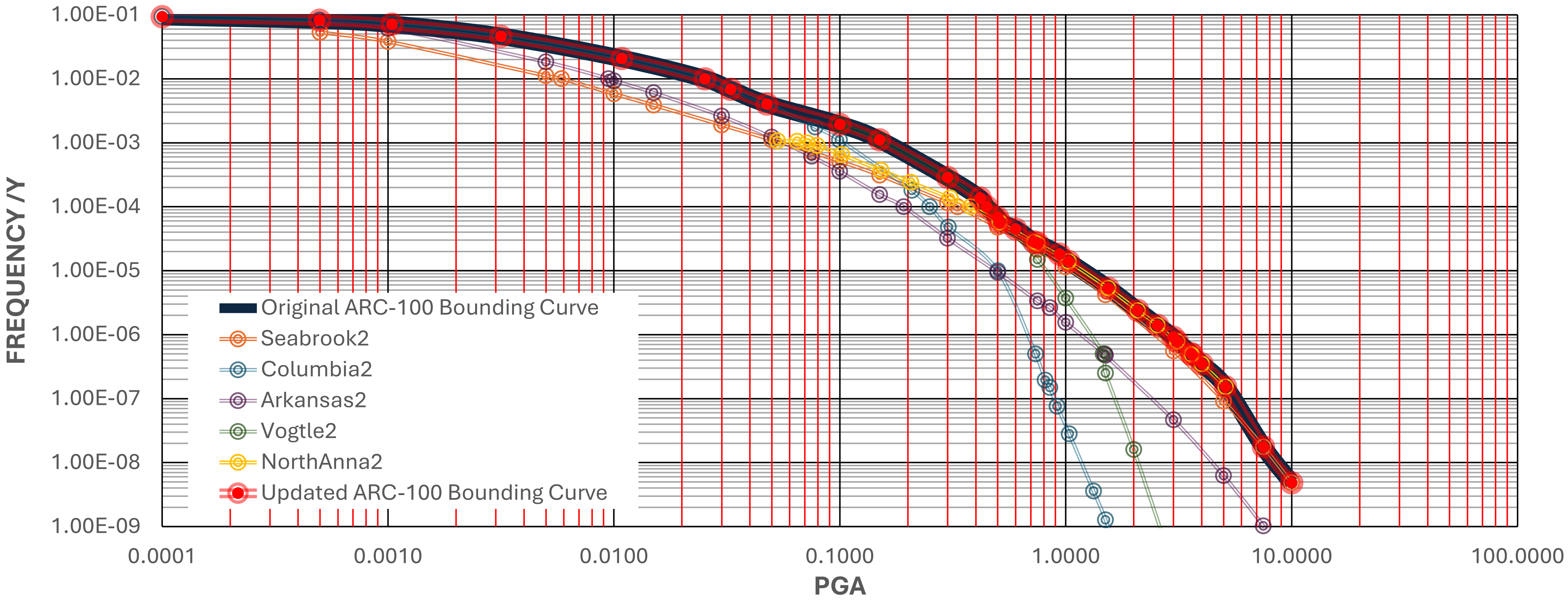
1. Update Seismic Hazard Curve

PGA range	Site
– 0.048 PGA	Columbia site
0.100 – 0.500 PGA	Vogtle site
0.509 – 5.10 PGA	North Anna site
7.500 – 10.00 PGA	Seabrook site

The bounding curve was built by including the higher frequencies of each site:

- Original: Seabrook, Columbia (Dec.2024)
- Updated: Seabrook, Columbia, Arkansas, Vogtle, North Anna

ARC-100 Bounding Seismic Curve



1. Update Seismic Hazard Curve

- Binning unchanged
  - Bin PGA = geometric mean
  - Binning is done by utilizing NEI 18-04 as guidance and for which the lower range leads to a Bin PGA 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
- Initiating frequencies are updated for each bin to reflect the revised hazard curve.
- For the final bin, the initiating frequency is based on PGA ≥ 3 g (hazard at 3 g), while the bin PGA is represented by the geometric mean of 3–10 g.

Seismic Bin		**Bin 1 (0 – 0.025 g)**	**Bin 2(0.025 – 0.418 g)**	**Bin 3 (0.418 – 0.6 g)**	**Bin 4 (0.6 – 0.937 g)**	**Bin 5 (0.937 – 3 g)**	**Bin 6 (> 3 g)**
Bin PGA		0.002 g	0.103 g	0.5 g	0.75 g	1.677 g	5.477 g
Bin Freq	Original	8.36E-02/yr	9.93E-03/yr	3.62E-05/yr	2.33E-05/yr	9.73E-06/yr	5.55E-07/yr
	Updated	**8.36E-02/yr**	**9.86E-03/yr**	**9.18E-05/yr**	**2.67E-05/yr**	**1.73E-05/yr**	**9.09E-07/yr**

2. Update Seismic Fragility Data

- SEL unchanged from Dec.2024 PRA model
- Original fragility data: expert judgement, generic data(NUREG/CR-6544)
- Updated fragility: median ground motion capacity(Am) for structure estimated via code-based margins

System	SEL	Failure mode	A_m	β_r	β_u	Data source
RB	Reactor building	Structural failure	4.5	0.3	0.35	Expert opinion (INL report Dec.2024)
RV	Reactor vessel	Structural failure	2.85	0.3	0.35	Expert opinion
RX internal	Reactor internals and core assembly	Structural failure	1.8	0.3	0.4	Generic (Reactor internals and core assembly)
RVACS	RVACS Inlet Ducts	Support failure	2.5	0.3	0.35	Generic (HVAC ducts)
	RVACS outlet Ducts	Support failure	2.5	0.3	0.35	Generic (HVAC ducts)
DRACS	DRACS AIR Heat Exchanger	Rupture	1.9	0.3	0.35	Generic (Heat exchangers)
	DRACS Submerged Heat Exchanger	Rupture	1.9	0.3	0.35	Generic (Heat exchangers)
	DRACS pipe	Loss of support	3.8	0.3	0.5	Generic (Piping)
	DRACS head tank	Rupture	1.9	0.3	0.35	Generic (Small tanks)
UPS	UPS	Functional failure	2.5	0.3	0.4	Generic (Electrical equipment function - after)
Primary EM Pump	NCF PUMP BATTERY	Structural failure of supports	3.8	0.35	0.5	Generic (Batteries and battery racks)
	NCF Pump Coast down failure	Functional failure	0.5	0.5	0.31	Enigeering judgement (NOTE in PRA model)
	Primary EM Pump Rupture	Loss of support	3.8	0.3	0.5	Generic (Piping)
	Primary EM Pump Fail to Run	Chatter	1	0.3	0.35	Generic (Electrical equipment function - during)
	Primary EM Pump Fail to Trip	Chatter	1	0.3	0.35	Generic (Electrical equipment function - during)
PCS	Power conversion system fail	Structural failure of support	2.5	0.3	0.4	Generic (Steam generator)

- Generic data in green
- Expert opinion in Orange

2. Update Seismic Fragility Data

$$A_m = F_C\, F_{RS}\, PGA_{RE} = \frac{\textbf{Capacity (C)}}{\textbf{Demand (D)}} F_{RS}\, PGA_{RE}$$

A_m: median capacity
F_C: Capacity factor
F_{RS}: Response factor
PGA_{RE}: Reference earthquake

- Structural Demand (D) is evaluated using median-centered ISRS
- **Structural Capacity (C)** is evaluated by applying **ACI/AISC code-based margins** to the 2D isolator seismic demand (ISRS).
  - Margin between seismic demand and code allowable
  - Code conservatism: additional margin inherent in the codes
- Structural Capacity (C) is a property of the structure and is independent of isolation type
- The response factor, F_{RS}, is assumed to be unity.
- PGA_{RE} is 0.5 g for ARC.
- The uncertainty parameters (β_r, β_u) are assumed based on generic data

Updated A_m

- w/2D isolator: $\frac{Capacity}{Demand_{w/2D}} (F_{RS})\, PGA_{RE} = \frac{D_{w/2D} * Margin}{D_{w/2D}} (1)\,(0.5)$
- w/3D isolator: $\frac{Capacity}{Demand_{w/3D}} (F_{RS})\, PGA_{RE} = \frac{D_{w/2D} * Margin}{D_{w/3D}} (1)\,(0.5)$

An example of Reactor Building

(1) Top of the center of vessel stick

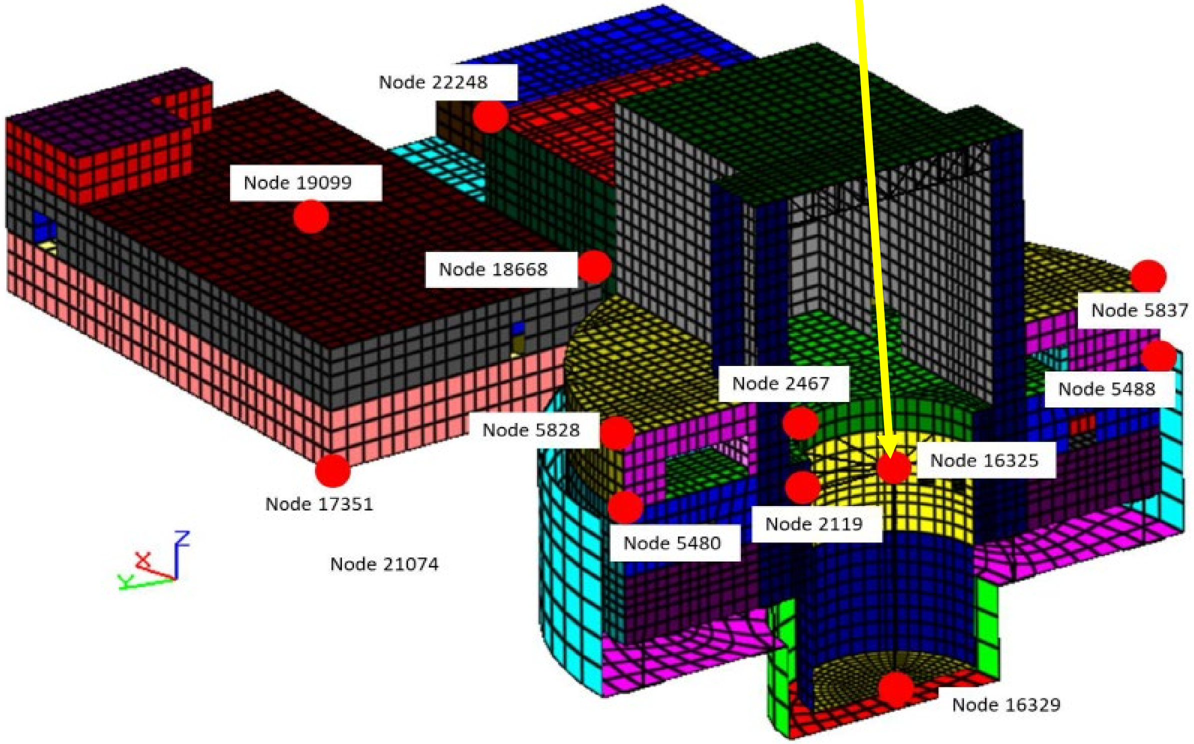


Figure D2.2: Locations of Selected Nodes for ARC-100 SSSI Model

(3) Corner of high roof

(2) Center of high roof

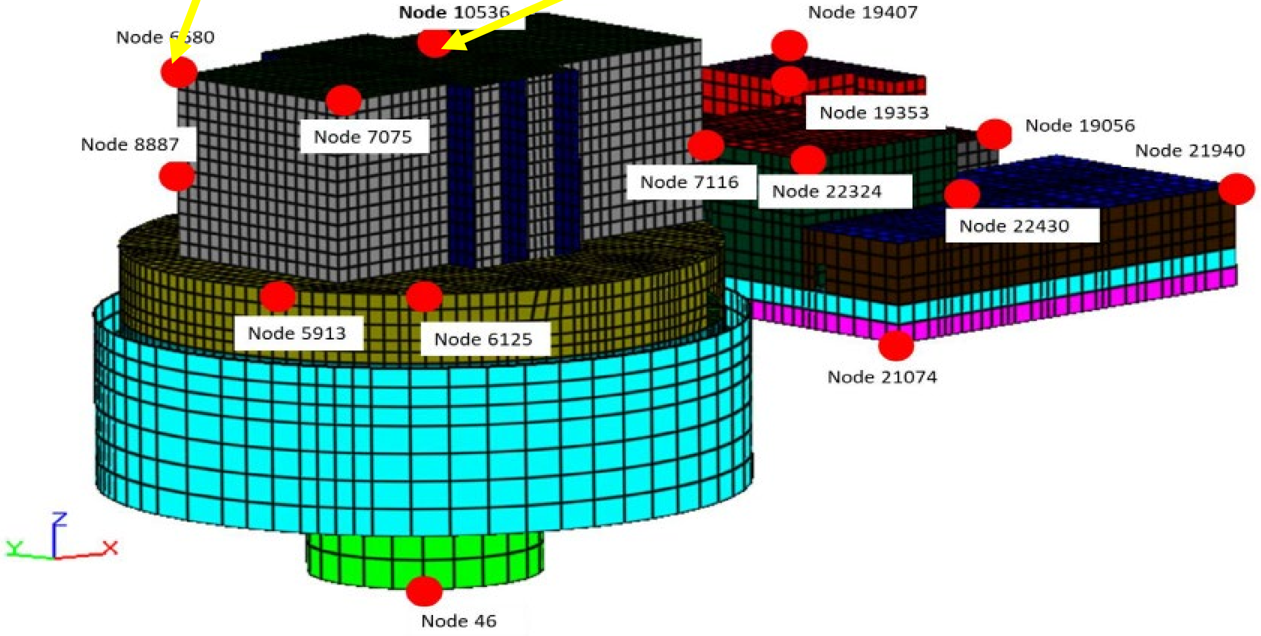
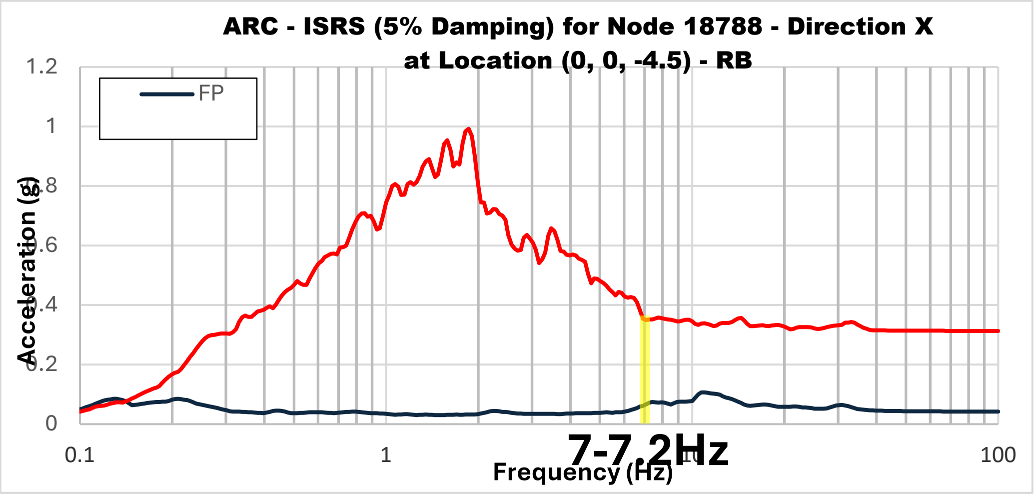
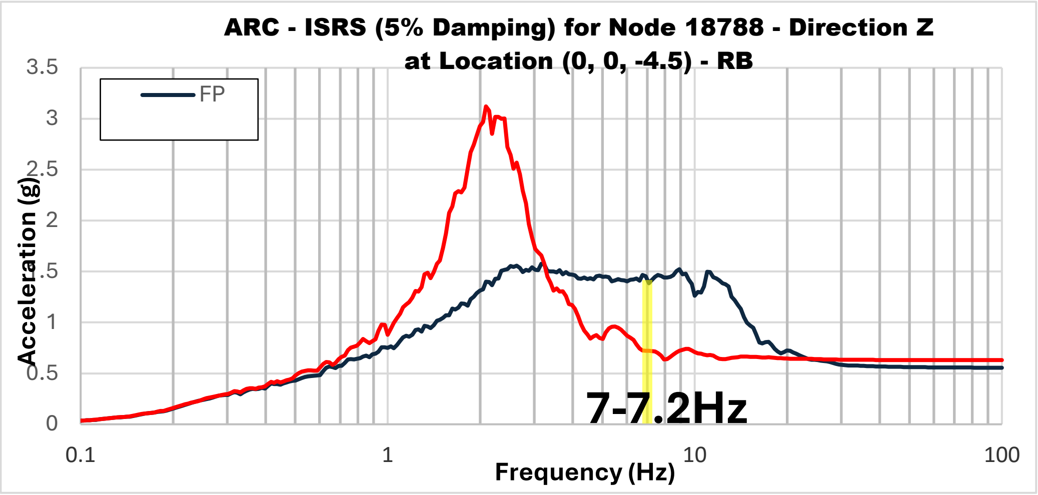
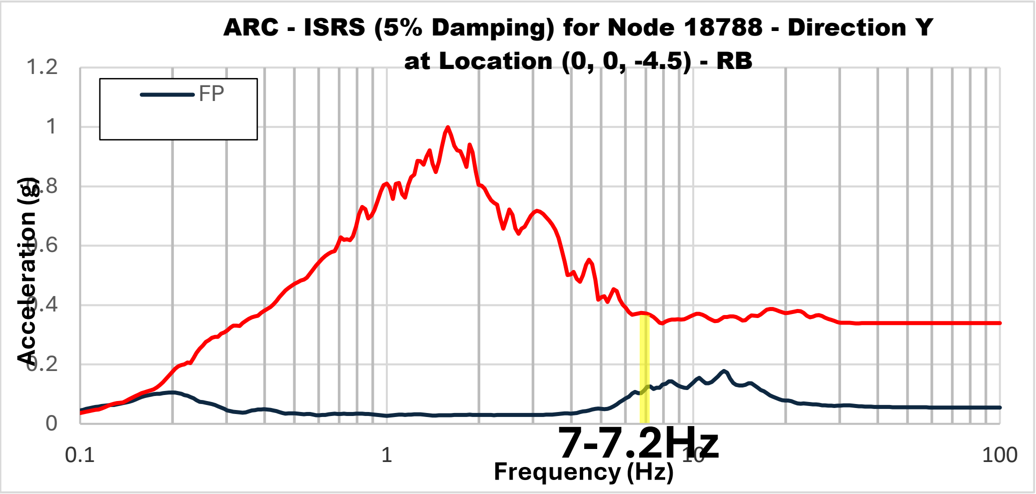


Figure D2.3: Locations of Selected Nodes for ARC-100 SSSI Model

An example of Reactor Building







- **Top of the center of vessel stick**

An example of Reactor Building

- $Capacity = D_{w/2D} * Margin$
- $A_m = \frac{Capacity}{D_{w/2D}} F_{RS} PGA_{RE} = \frac{Capacity}{D_{w/2D}} (1)\,(0.5)$

Structure	Location	Isolator	Node	Hz	ISRS (=demand)				Margin	Capacity	Am
					x	y	z	SRSS			
Reactor building	**(1) The top of the center of reactor vessel**	2D (FP)	16325	7.2	0.07	0.13	1.41	1.42	60% (58-66%)	2.27	0.80
		3D (BCS)	18788		0.35	0.4	0.72	0.89		2.27	1.27
		2D (FP)	16325	**3.59**	0.034	0.033	1.49	1.49		2.39	0.80
		3D (BCS)	18788		0.62	0.63	1.33	1.60		2.39	0.75
	(2) Center of high roof	2D (FP)	10356	7.2	0.91	1.38	3.01	3.43	40%	4.81	0.70
		3D (BCS)	9044		0.51	0.51	0.75	1.04		4.81	2.31
	(3) Corner of high roof	2D (FP)	6680	7.2	0.915	0.915	1.47	1.96	40%	2.74	0.70
		3D (BCS)	5336		0.51	0.51	0.793	1.07		2.74	1.28

- We need to define which modal frequency is being used for the evaluation.
- Since the frequency mode with a high participation factors of reactor building is 7 – 7.2 Hz, the 3.59 Hz case, which is for reactor vessel, is excluded.
- 3D isolation reduces ISRS demand compared to those of the 2D isolation for Reactor building.

- The 2D result in green
- The 3D result in Orange
- Exclusion in Grey

An example of Reactor Building

- Reactor building $\boldsymbol{A_m}$
    - w/ 2D isolator
        - Min: 0.7
        - Max: 0.8
    - w/ 3D isolator
        - Min: 1.27
        - Max: 2.31
- Reactor building $\boldsymbol{\beta_r, \beta_u}$
    - Generic data (NUREG/CR-6544) assumed
    - $\beta_r = 0.3, \beta_u = 0.35$

Bins	**Bin PGA (a)**	**Failure probability (fuel damage frequency)**			
		2D (FP)		3D (BCS)	
		w/ Min $\boldsymbol{A_m}$	w/ Max $\boldsymbol{A_m}$	w/ Min $\boldsymbol{A_m}$	w/ Max $\boldsymbol{A_m}$
Bin1 (0.00-0.025g)	0.002 g	2.68E-37 (2.24E-38 /yr)	6.34E-39 (5.30E-40 /yr)	7.81E-45 (6.53E-46 /yr)	3.97E-53 (3.31E-54 /yr)
Bin2 (0.025-0.418g)	0.103 g	1.61E-05 (1.59E-07 /yr)	4.36E-06 (4.30E-08 /yr)	2.53E-08 (2.49E-10 /yr)	7.54E-12 (7.43E-14 /yr)
Bin3 (0.418-0.600g)	0.500 g	2.33E-01 (2.14E-05 /yr)	1.54E-01 (1.41E-05 /yr)	2.16E-02 (1.98E-06 /yr)	4.50E-04 (4.13E-08 /yr)
Bin4 (0.600-0.937g)	0.750 g	5.60E-01 (1.49E-05 /yr)	4.44E-01 (1.19E-05 /yr)	1.27E-01 (3.38E-06 /yr)	**7.34E-03** (1.96E-07 /yr)
Bin5 (0.937-3.000g)	1.677 g	9.71E-01 (1.68E-05 /yr)	9.46E-01 (1.64E-05 /yr)	7.27E-01 (1.26E-05 /yr)	2.44E-01 (4.21E-06 /yr)
Bin6 (3.000-10.00g)	5.477 g	1.00E+00 (9.09E-07 /yr)	1.00E+00 (9.09E-07 /yr)	9.99E-01 (9.08E-07 /yr)	9.70E-01 (8.81E-07 /yr)

- Note that reactor building structural failure represents local failures (e.g. location at reactor vessel, center of high roof, corner of high roof), not necessarily global building collapse.

2. Update Seismic Fragility Data

- Generic data in green
- New approach in Pink

System	SEL	Failure mode	A_m	β_r	β_u	Data source
RB	Reactor building	Structural failure	1.27-2.31 w/ 3D isolator	0.3	0.35	**Based on structural analysis (ISRS)** and **code-based margins**
RV	Reactor vessel	Structural failure	2.85	0.3	0.35	Expert opinion
RX internal	Reactor internals and core assembly	Structural failure	1.8	0.3	0.4	Generic (Reactor internals and core assembly)
RVACS	RVACS Inlet Ducts	Support failure	1.42-1.46 w/ 3D isolator	0.3	0.35	**Based on structural analysis (ISRS)** and **code-based margins**
	RVACS outlet Ducts	Support failure	1.91-2.25 w/ 3D isolator	0.3	0.35	**Based on structural analysis (ISRS)** and **code-based margins**
DRACS	DRACS AIR Heat Exchanger	Rupture	1.9	0.3	0.35	Generic (Heat exchangers)
	DRACS Submerged Heat Exchanger	Rupture	1.9	0.3	0.35	Generic (Heat exchangers)
	DRACS pipe	Loss of support	1.21-1.43 w/ 3D isolator	0.3	0.5	**Based on structural analysis (ISRS)** and **code-based margins**
	DRACS head tank	Rupture	1.9	0.3	0.35	Generic (Small tanks)
UPS	UPS	Functional failure	2.5	0.3	0.4	Generic (Electrical equipment function - after)
Primary EM Pump	NCF PUMP BATTERY	Structural failure of supports	3.8	0.35	0.5	Generic (Batteries and battery racks)
	NCF Pump Coast down failure	Functional failure	0.5	0.5	0.31	Enigeering judgement (NOTE in PRA model)
	Primary EM Pump Rupture	Loss of support	3.8	0.3	0.5	Generic (Piping)
	Primary EM Pump Fail to Run	Chatter	1	0.3	0.35	Generic (Electrical equipment function - during)
	Primary EM Pump Fail to Trip	Chatter	1	0.3	0.35	Generic (Electrical equipment function - during)
PCS	Power conversion system fail	Structural failure of support	2.5	0.3	0.4	Generic (Steam generator)

3. Update the results

Changed Assumptions

- Previous assumption (Dec. 2024):
  - **A given ground motion level** for failure probability of an SSC's event, $\boldsymbol{a}$, was defined using **the ISRS value**.
- Current assumption:
  - $\boldsymbol{a}$ is defined as the **bin PGA**
  - ISRS is treated as the seismic demand, and capacity is evaluated using ISRS with margin.

$$F(a) = \Phi\left(\frac{\ln(a) - \mathbf{ln}(\boldsymbol{A_m})}{\sqrt{(\beta_r)^2 + (\beta_u)^2}}\right)$$

F(a) : Failure probability of component at a given ground motion level a.

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.

3. **Update the results (fuel damage frequency)**

BDD result

Bins		Bin PGA	2D (FP) isolator		3D (BCS) isolator	
			w/ Min A_m	w/ Max A_m	w/ Min A_m	w/ Max A_m
Bin 1	0.000- 0.025 g	0.002 g	9.838E-16/yr	9.838E-16/yr	9.838E-16/yr	9.838E-16/yr
Bin 2	0.025 - 0.418 g	0.103 g	1.588E-07/yr	4.297E-08/yr	2.492E-10/yr	7.737E-14/yr
Bin 3	0.418 - 0.600 g	0.500 g	2.137E-05/yr	1.414E-05/yr	1.988E-06/yr	4.866E-08/yr
Bin 4	**0.600 - 0.937 g**	**0.750 g**	**1.497E-05/yr**	**1.190E-05/yr**	**3.424E-06/yr**	**2.460E-07/yr**
Bin 5	0.937 - 3.000 g	1.677 g	1.695E-05/yr	1.665E-05/yr	1.371E-05/yr	7.028E-06/yr
Bin 6	3.000	5.477 g	9.090E-07/yr	9.090E-07/yr	9.090E-07/yr	9.090E-07/yr
Total			**5.436E-05/yr**	**4.365E-05/yr**	**2.003E-05/yr**	**8.232E-06/yr**

BDD (Binary decision diagram): more accurate quantification method

Summary

- Hazard curves have been updated using the latest available data.
- Fragility data update
  - Updated fragility parameter Am is grounded in **structural analysis (ISRS)** and **code-based margins**, rather than expert opinion.
- Result Update
  - Ground motion parameter, a, has been redefined under revised assumptions.
  - Comparison between 2D and 3D isolation configurations has been performed.
  - **3D isolation for structures** reduces ISRS levels, resulting in a reduction in fuel damage frequencies.
  - When applying more refined quantification methods (e.g., BDD), there is 63% ~ 81% reduction from the 2D result to the 3D result.
- 3D isolation is generally effective in reducing seismic demand (structure-only consideration), but **it does not provide universally optimal performance across all frequency ranges.**

Summary

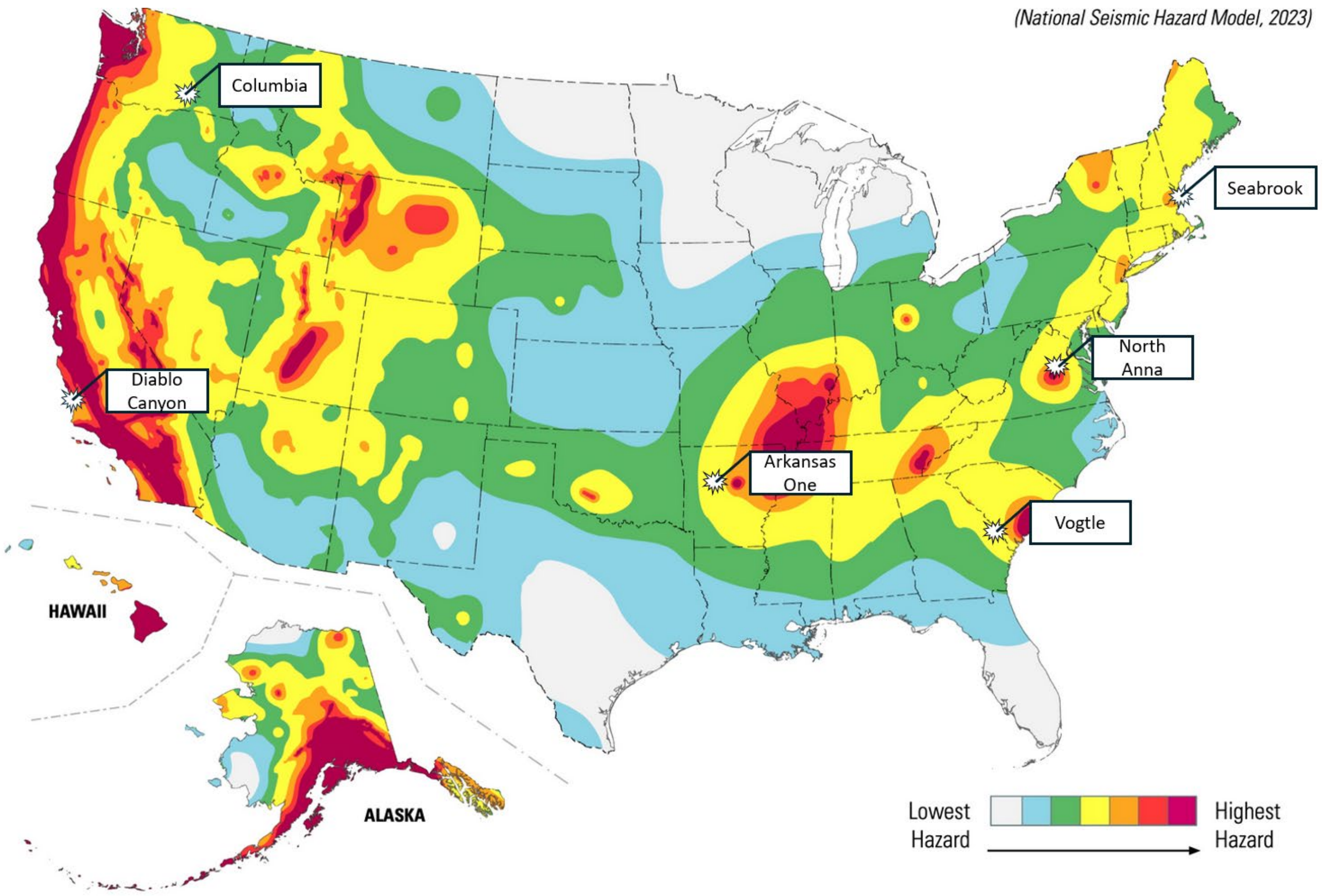
Future works

- Current updates focus on **structure failure only** **(Reactor building, RVACS pipe, DRACS pipe)**
- Equipment response, which may differ significantly from building response, will be addressed in a subsequent phase.
  - Support conditions should be explicitly evaluated.
  - Structure response should be included.
  - Different frequency between structural response and equipment response should be considered.
- Generic data will continue to be used for uncertainty parameters (β_r, β_u) in the interim.

Backup

The slides used in the last meeting

Bounding hazard curve



Represent the higher seismically active zones in the southern mid-west, northeast, eastern seaboard, southeast, and northwest

- Arkansas Nuclear One, Arkansas
- Columbia Generating station, Washington
- North Anna power station, Virginia
- Seabrook station, New Hampshire
- Vogtle, Georgia

Exclude areas of the highest seismic activity

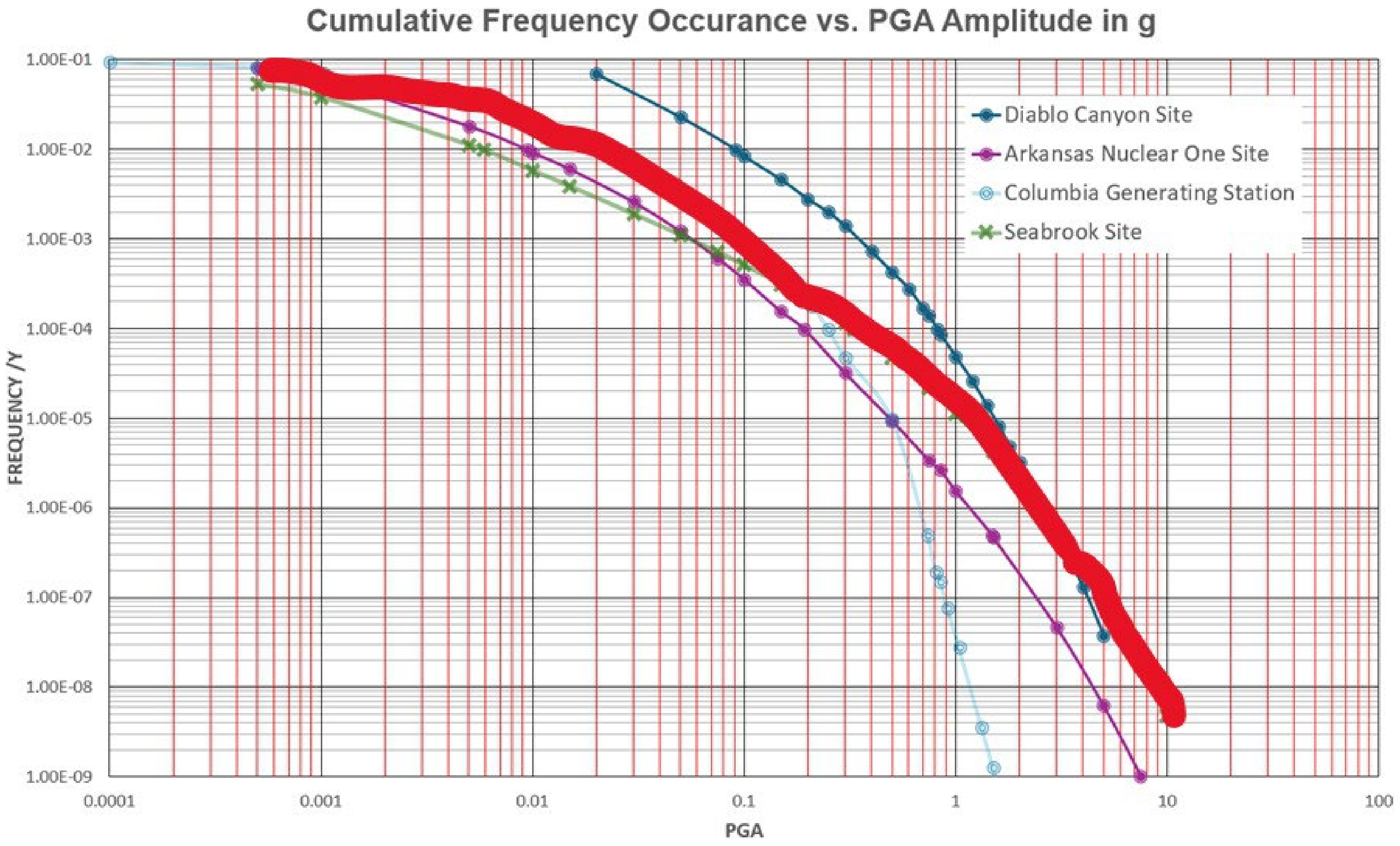
- Diablo Canyon

Most recent seismic curves were all taken from the responses to the near-term task force review of insights from the Fukushima Daiichi accident

PGA (g)	Exceedance frequency (Previous bounding hazard)	Reference	Exceedance frequency (Updated bounding hazard)	Reference
1.00E-04	9.36E-02	Columbia	9.36E-02	Columbia
4.97E-04	8.26E-02	Columbia	8.26E-02	Columbia
1.04E-03	7.12E-02	Columbia	7.12E-02	Columbia
3.16E-03	4.63E-02	Columbia	4.63E-02	Columbia
1.08E-02	2.08E-02	Columbia	2.08E-02	Columbia
2.53E-02	1.00E-02	Columbia	1.00E-02	Columbia
3.29E-02	6.81E-03	Columbia	6.81E-03	Columbia
4.76E-02	4.04E-03	Columbia	4.04E-03	Columbia
1.00E-01			1.93E-03	Vogtle
1.50E-01			1.11E-03	Vogtle
3.00E-01	1.15E-04	Seabrook	2.87E-04	Vogtle
4.18E-01	7.34E-05	Seabrook	1.37E-04	Vogtle
4.46E-01			1.00E-04	Vogtle
5.00E-01	4.78E-05	Seabrook	6.78E-05	Vogtle
5.10E-01			5.70E-05	North Anna
6.00E-01	3.72E-05	Seabrook	4.49E-05	North Anna
7.25E-01			2.81E-05	North Anna
7.50E-01	2.14E-05	Seabrook	2.67E-05	North Anna
9.37E-01	1.39E-05	Seabrook	1.82E-05	North Anna
1.03E+00			1.39E-05	North Anna
1.54E+00			5.34E-06	North Anna
2.08E+00			2.39E-06	North Anna
2.55E+00			1.40E-06	North Anna
3.00E+00	5.55E-07	Seabrook	9.09E-07	North Anna
3.12E+00			7.83E-07	North Anna
3.59E+00			5.04E-07	North Anna
3.62E+00			4.84E-07	North Anna
4.01E+00			3.48E-07	North Anna
5.10E+00			1.53E-07	North Anna
7.50E+00	1.76E-08	Seabrook	1.76E-08	Seabrook
1.00E+01	4.84E-09	Seabrook	4.84E-09	Seabrook

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



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

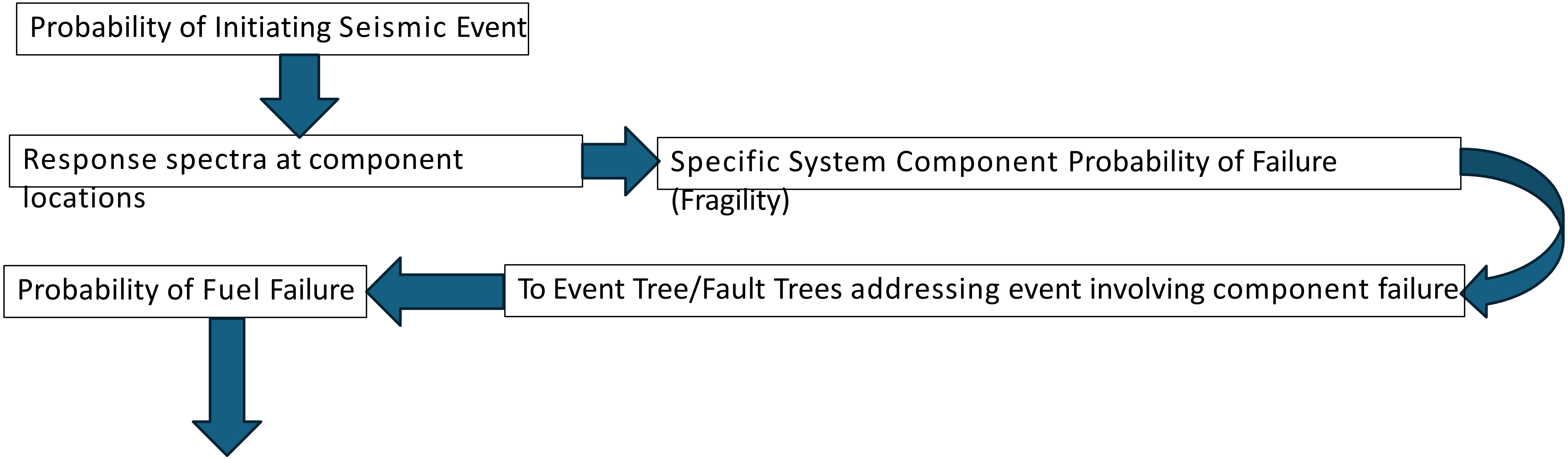
ARC-100 Seismic Bin Annual Frequencies and PGAs

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



Probability of Initiating Seismic Event

Response spectra at component locations

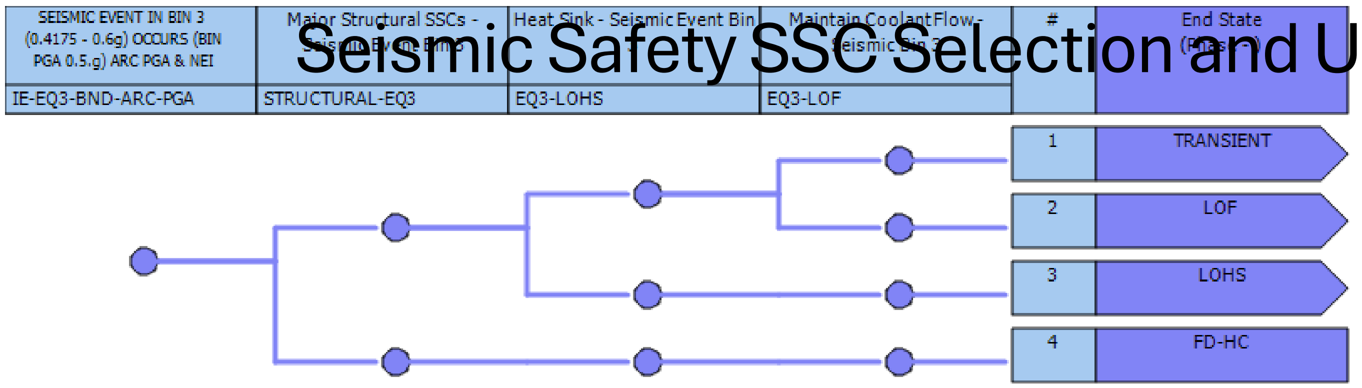
Specific System Component Probability of Failure (Fragility)

To Event Tree/Fault Trees addressing event involving component failure

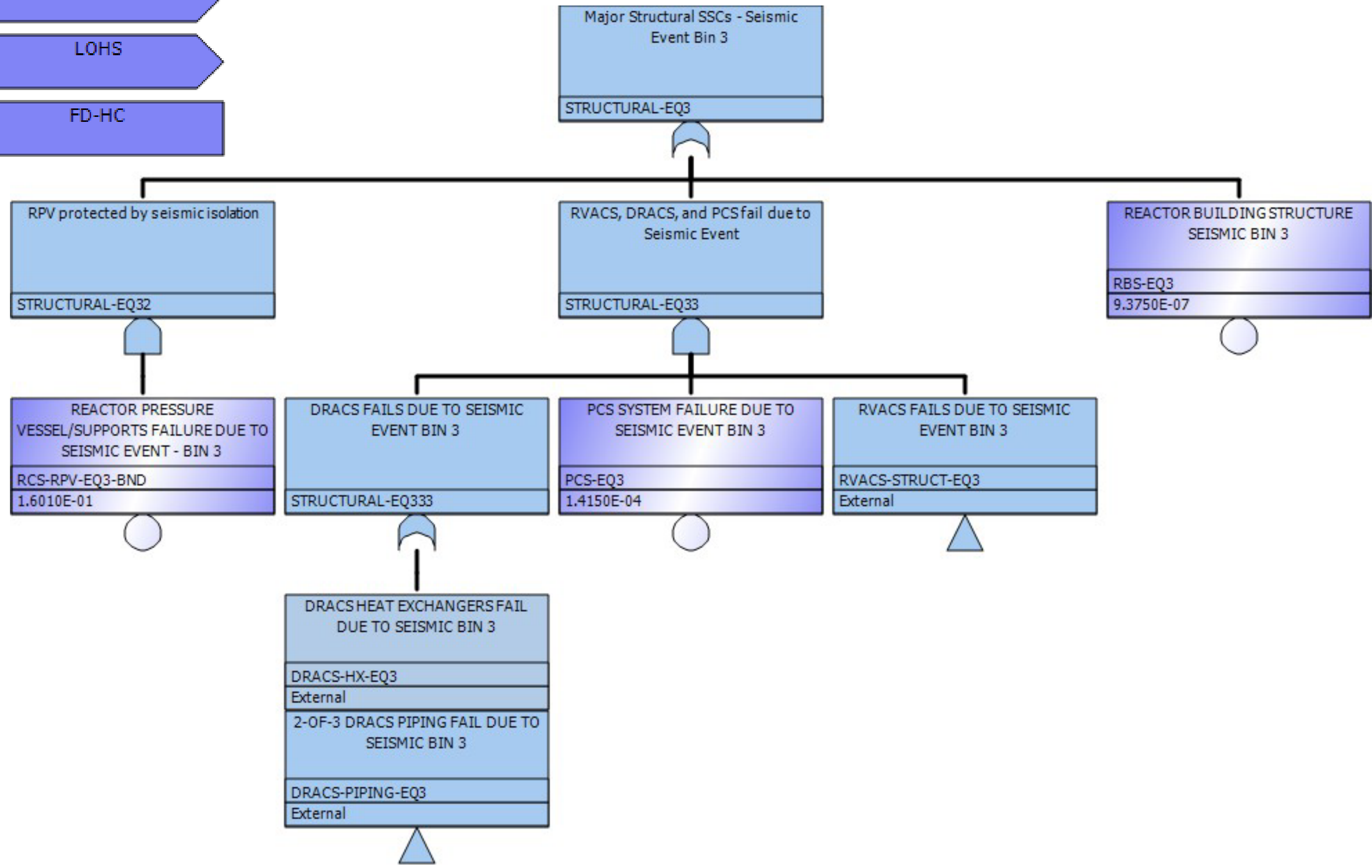
Probability of Fuel Failure

Slide 20 has 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



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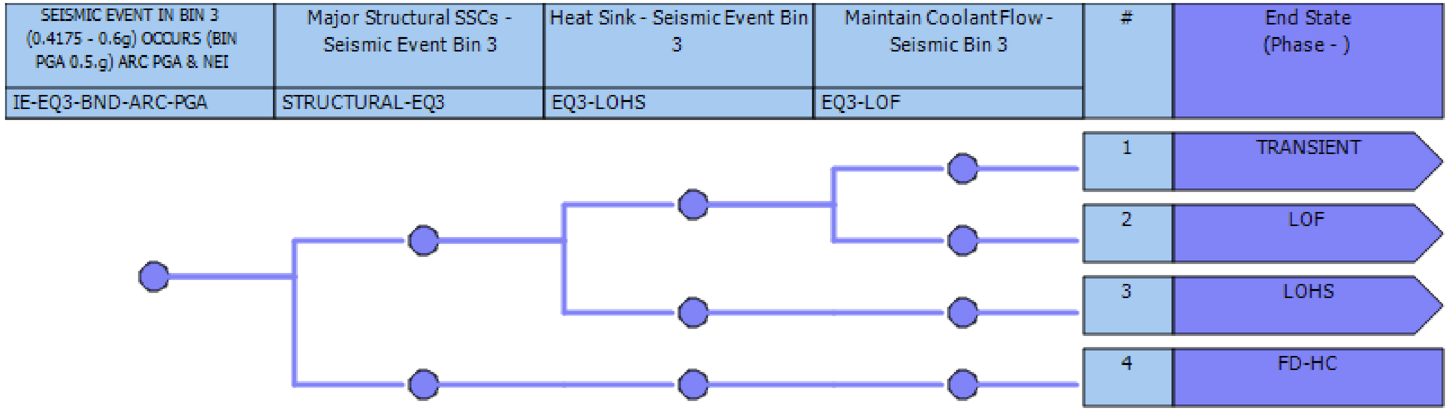


- A seismic initiator enables the logic for all seismic and internal basic events for the transferred event trees
- If the major structural damage is avoided, the Seismic Heat Sink fault tree top event is checked which consists of the PCS System
- If PCS System fails due to seismic event, the LOHS event 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.

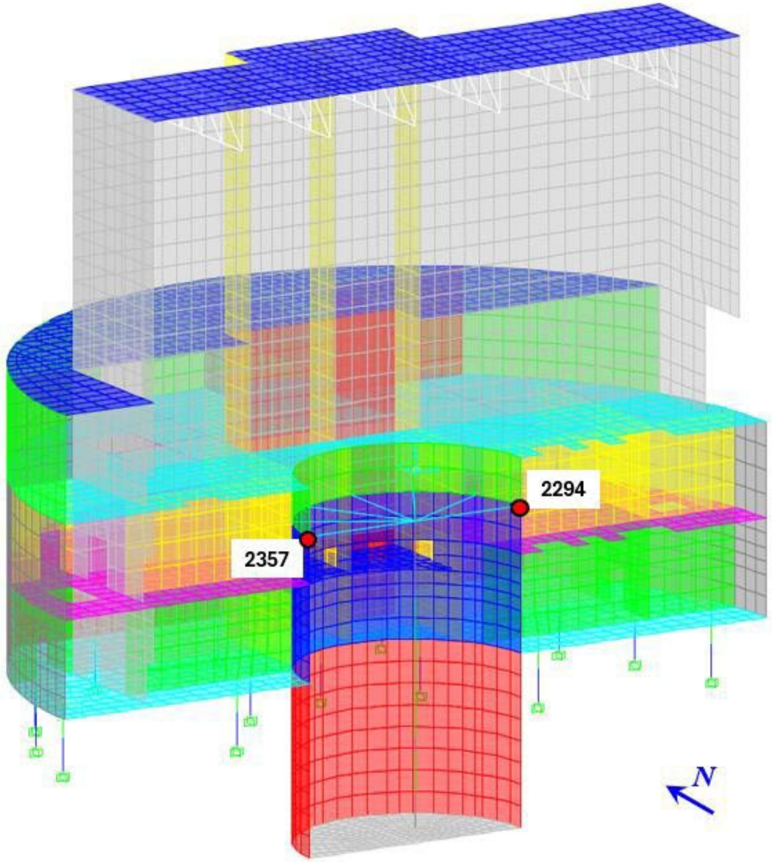
Prescreening per Generic Modeled Mean and HCLPF Capacity of NUREG/CR-6544, Table 6-1

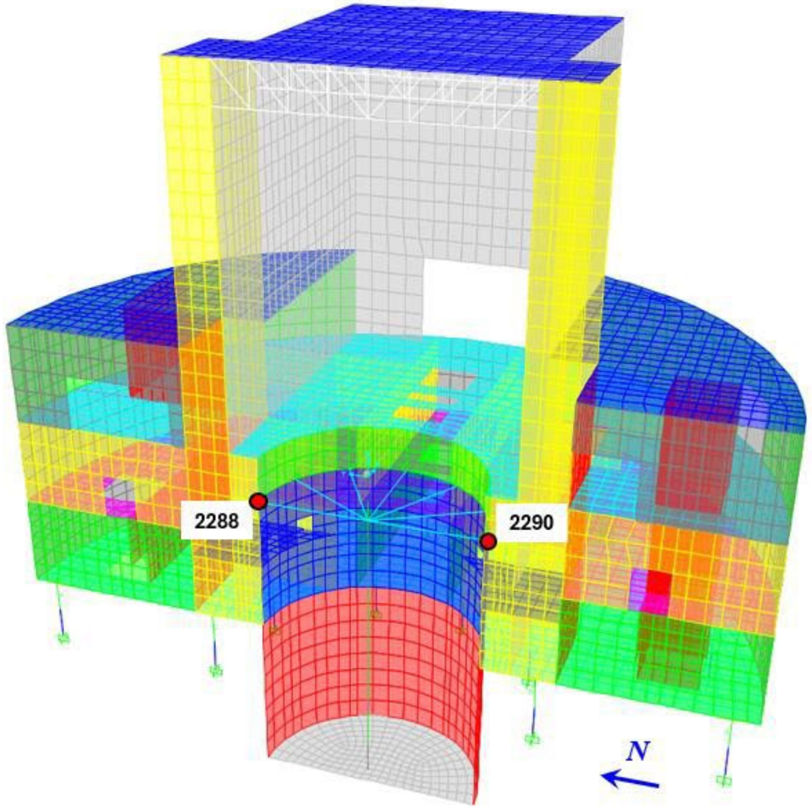
ARC Safety Related Component	NUREG/CR-6544, Table 6-1 Component: Seismic Fragilities Equivalent Component	Elevation (Grade is El. 492'-0")	Tested Capacity	Mean Capacity from Actual SSC structural/stress analysis SRSS (XYZ) Peak SSE Response	Mean Capacity per NUREG/CR-6544, Table 6-1 PGA_{SSE} (1)	HCLPF 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 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 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





Seismic PRA Results with Theoretical Unlimited Isolator Displacement

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

Conclusions

- Horizontally Isolated Reactor Building is capable of withstanding the SSE (0.5 PGA) without any 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 the presently chosen horizontal isolators are limited to 28.2inch displacements. BDBE in excess of 0.69 PGA will likely cause exceedance of its displacement capacity
  - Moreover the prior conclusion were based on the SRSS of the responses that could not be scaled linearly to greater PGAs, and hence limited to only 1.5 time DBE under the assumption the 2D isolator would continue to work after exceeding it maximum displacement.

- In Nov 12 2024, ARC committed to communicate to NRC as soon as 3D isolation of RB results would be available..

- The 3D results are encouraging, but not entirely conclusive.

- 3D isolation decouples vertical from horizontal responses, but vertical resposes are significantly greater, so it is difficult to establish whether the capacities of equipment that is sensitive to vertical accelerations are sufficient at the different PGAs in the seismic hazard curve. On the other hand the responses can be scaled linearly, so a more credible assessment can be made of the magnitude of earthquake the facility could withstand without damage to the fuel large enough to cause exceed the F-C target