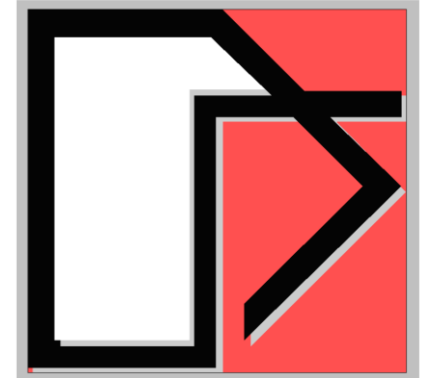


Response to NRC Staff Feedback on ARC-100 SMR Seismic Isolation Meeting on February 18, 2026 Related to Preliminary SSI Analysis Studies



D. M. Ghiocel
Ghiocel Predictive Technologies



Ghiocel Predictive Technologies Inc.

**NRC Meeting on ARC-100 Seismic Isolation
Rockville, MD, October 8, 2026**

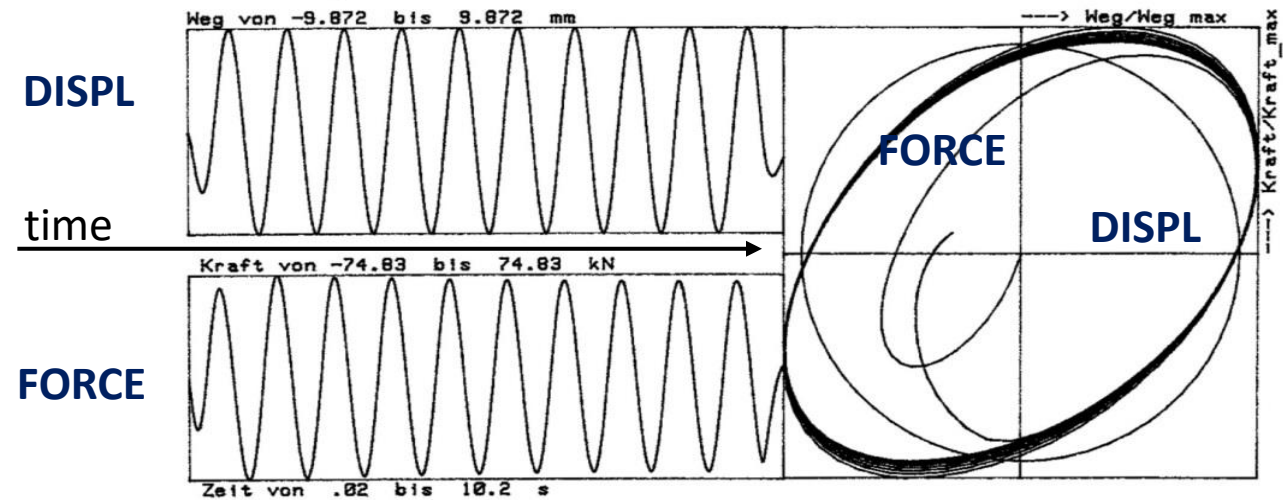
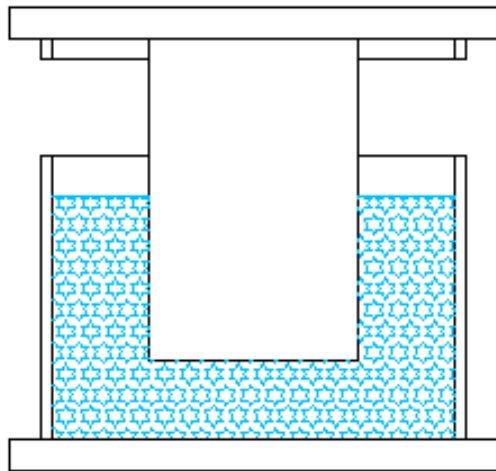
1. Clarifications on the GERB 3D Base Control System (BCS) Viscous-Elastic Linear Behavior and Explanation of BCS Modeling and Assumed Input Parameters

A Foreword... Before Presenting Details on Visco-Damper Modeling

Experimental tests confirmed that the viscous-damper force-displacement hysteresis behavior is primarily governed by the high viscosity internal fluid properties. Damping forces are produced by the shearing and displacement of the high viscosity fluid and are severely dependent on the excitation frequency.

The viscous-damper has a viscous-elastic dynamic behavior governed by the high viscosity fluid material deformation which is basically independent of motion amplitude and highly dependent on motion frequency.

Experimental tests indicate that viscous-dampers have linear hysteretic behavior under harmonic motions:



The above damping force-displacement hysteretic curve shows *a nice elliptical hysteresis loop which is typical to the linear damped dynamic system behavior.*

1.1 Brief Background on BCS Applications to NPP Structures

Since the early '90s, more than 10,000 units of GERB viscous-elastic dampers have been installed around the world at nuclear and conventional power plants, and industrial facilities for dynamic restraints of piping systems and critical vibrating equipment base-isolation (Barutzki et al, 2020). In the United States, GERB viscous-elastic dampers were applied for Eastern US NPPs for dynamic restraining the vibration of nuclear piping systems. An example is the Cooper NPP in Nebraska.

It should be noted that the use of GERB HVD units for the base-isolation of piping systems and nuclear components in the United States was already accepted in accordance with ASME B&PVC Section III - Subsection NF, and the ASME QME-1 “Qualification of Active Mechanical Equipment Used in Nuclear Facilities”.

In the last few decades, the application of GERB BCS has been extended from equipment to structures, including NPP structures. The IAEA-TECDOC-1905, 2020, pages 72-78, refers to the application of the GERB 3D BCS for the 3D base-isolation of nuclear building structures.

The GERB HVD designs are also covered by German Nuclear Code KTA and European Nuclear Code for Light Water and currently they have been accepted by Nuclear Authorities of all Nuclear States in Europe, Asia, and America, including US, Russia, Japan, China and India, and others.

1.2 GERB BCS Isolation Design is An Iterative Process Using from Simple to Refined HVD Models Based on Experimental Test Data

It should be noted that GERB BCS are not sold as off-the-shelf products since they do not have standard properties. They are manufactured in various ranges of properties for specific problems, analyzed on a case-by-case basis. The BCS design involves a complex iterative process until the final, optimal BCS configuration is established.

The BCS unit properties and placements in space should be optimized from a structural dynamics point of view to get the best seismic isolation efficiency for specific input excitations of interest.

Initially, in the preliminary design stage of BCS isolation, usually, there is no specific information on either the base-isolated structure seismic responses or the HVD unit dynamic behavior based on experimental tests.

Therefore, preliminary seismic analyses, as recommended by GERB experts, should be based on simpler, ideal viscous-damper models with assumed input parameters based on past experiences (Nawrotzki and Siepe, 2014, Barutzki et al., 2024, TerraPower, 2024)

BCS Isolation Design is An Iterative Process

The HVD unit has a viscous-elastic behavior governed by the high viscosity fluid material deformation which is highly dependent on excitation frequency, similar with a viscous-elastic fluid material behavior. The availability of the test data in the unit operating range is essential to calibrate refined analytical models.

The frequency-dependent HVD modeling is conveniently done in complex frequency domain, not time domain.

Importantly, the preliminary seismic SSI analyses of the BCS base-isolated structures should cover all possible critical seismic load scenarios, including BDBE (Beyond Design Basis Earthquake), and even CS (Clearance to the Stop) and FM (Failure Mode), in addition to the DBE (Design Basis Earthquake).

Based on the preliminary SSI analysis results, the required experimental tests and the quality assurance measures for the BCS units should be decided. Qualification tests are one of several important topics to be addressed at an early stage.

The final experimental test scenarios should be decided for HVD units based on the final BCS configuration and seismic HVD forces and relative displacements in the 3D space directions

BCS Isolation Design is An Iterative Process

Preliminary SSI analyses should ensure that the BCS units operate in the experimental test-validated range for any critical seismic scenario required for a safe design. For this, several BCS unit key response parameters should be determined from seismic SSI analysis to ensure that their effective values are smaller than their allowable values.

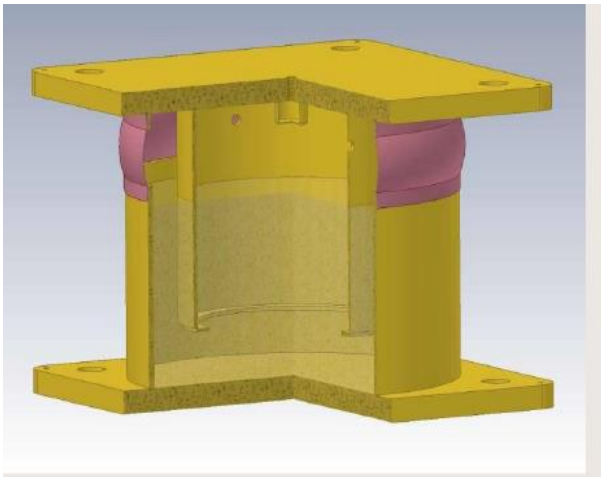
If the BCS unit parameter allowable limits are reached, then larger capacity BCS unit types, or a larger number of the same BCS type should be considered. These BCS unit key limiting response parameters include the relative displacements and/or nominal loads under combination of seismic and non-seismic loads. The limiting parameters provided by the BCS vendor include:

- 1) for SB units, the allowable horizontal and vertical displacements to avoid closing the coil space under compression (clearance to stop, CS), and the allowable tension force to avoid or limit uplift displacements (limited uplift forces can be handled by including anchorages).
- 1) for HVD units, the allowable horizontal and vertical displacements are the maximal relative “housing-piston” displacements from the nominal center position, to avoid malfunctioning of the viscous-damper outside the test-validated operating range. This is ensured by checking the HVD forces against the nominal loads.

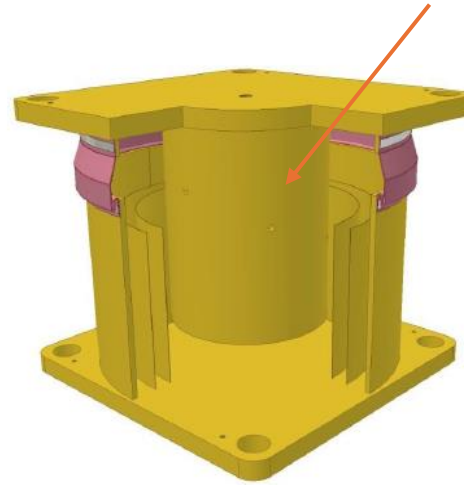
1.3 HVD Experimental Tests for Calibrating Refined Models

Experimental tests performed by GERB confirmed that the HVD force-displacement hysteresis behavior is primarily governed by the high viscosity internal fluid properties. Since the high viscosity fluid behavior is dominant, *HVD behavior is linear in time-domain and highly frequency dependent.*

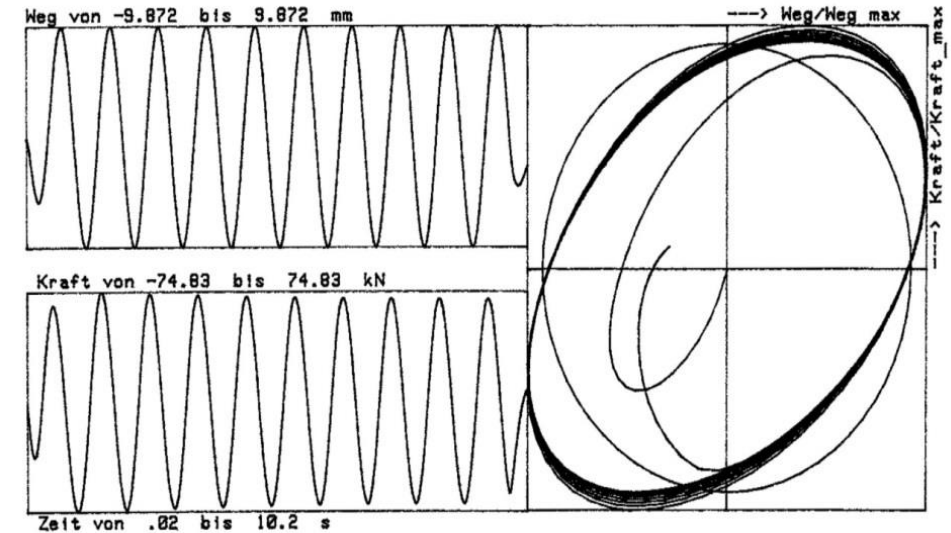
Therefore, tests are performed in the 1- 40/50 Hz range using harmonic excitation inputs.



VES with Bituminous Fluid



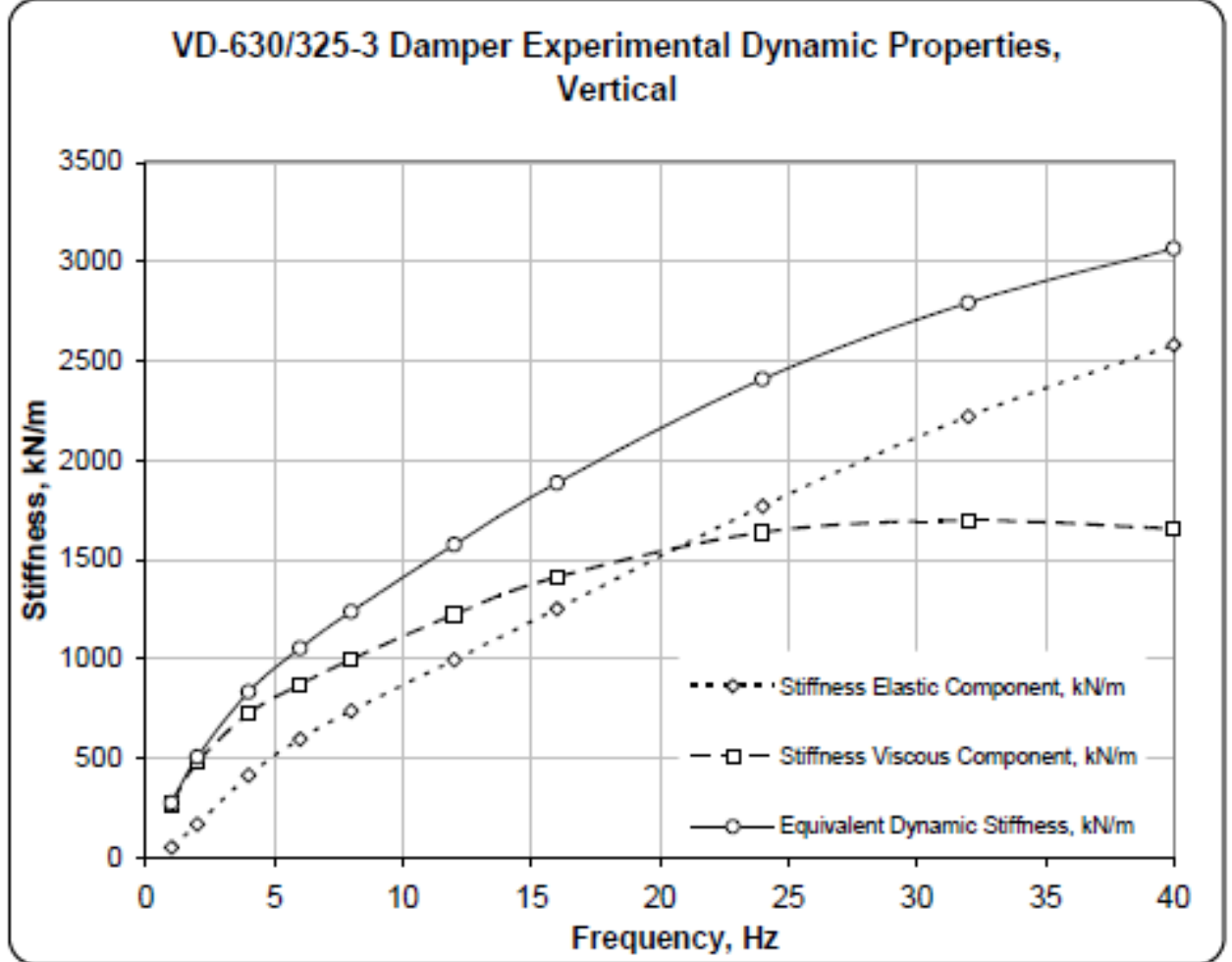
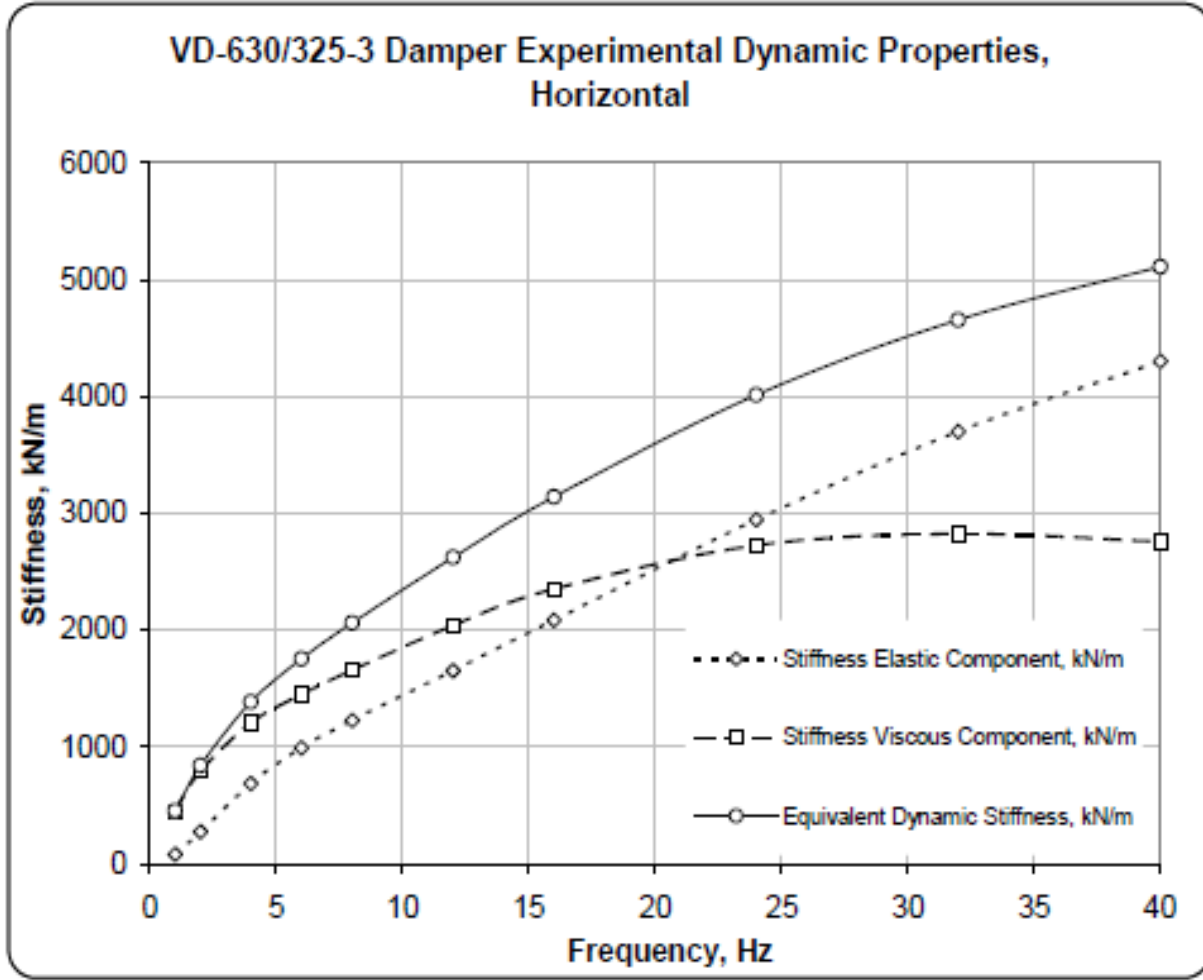
VD with Silicon-based Fluid



Test curves address the HVD dynamic stiffness variation with frequency. The HVD dynamic stiffness is defined in complex frequency by two component: elastic or storage stiffness, K_e (real part), and the viscous or loss stiffness, K_v (imaginary part).

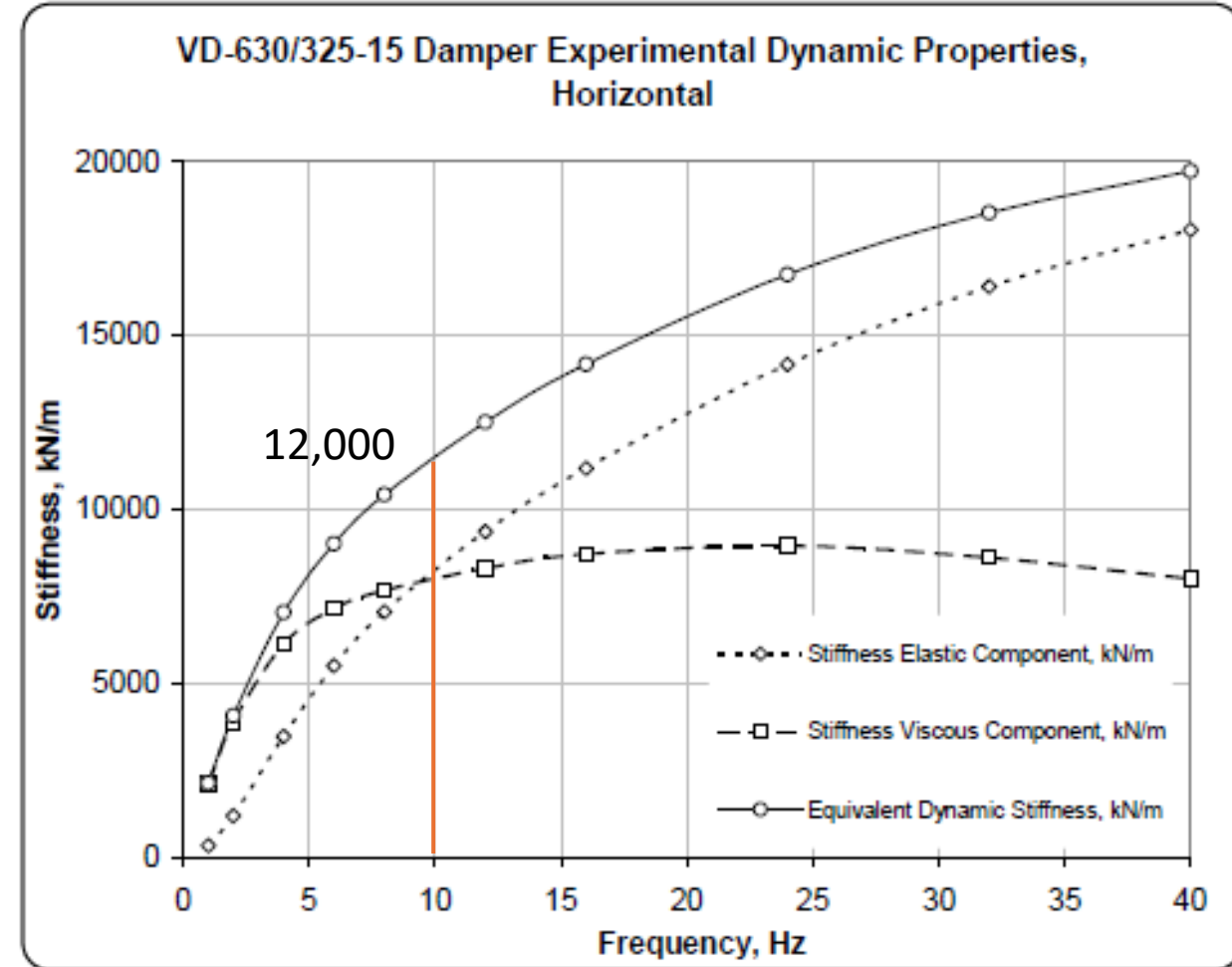
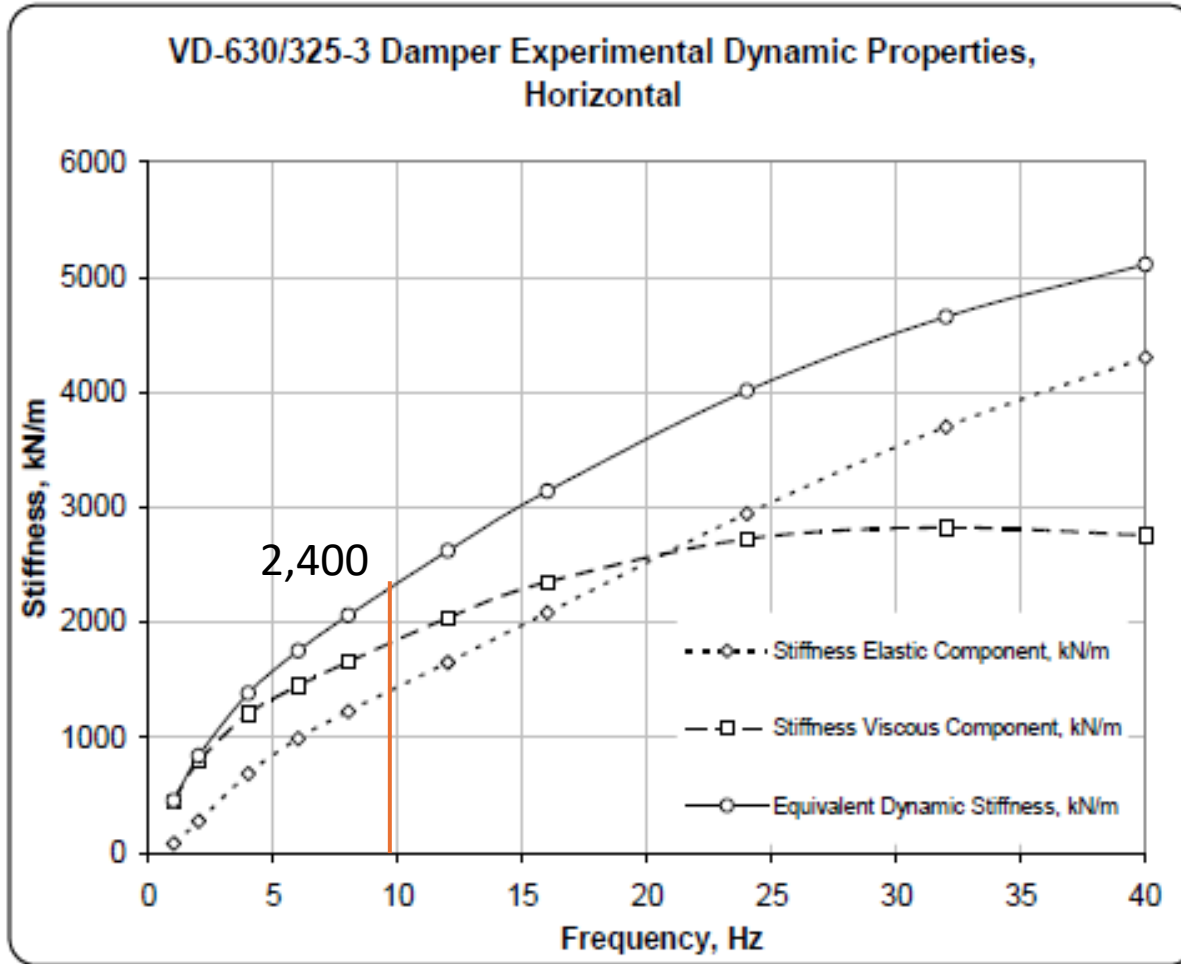
VD-630/325-3 Visco-Damper Typical Experimental Test Results

The two VD dynamic stiffness component variations in complex frequency are the elastic or storage stiffness component (real part) and the viscous or loss stiffness component (imaginary part), respectively. The total equivalent stiffness is shown with solid line.



VD Internal Steel Pipe Wall Structure Effects

The VD internal wall structure is indicated by index numbers, as 3 or 15, at the end of VD type names.

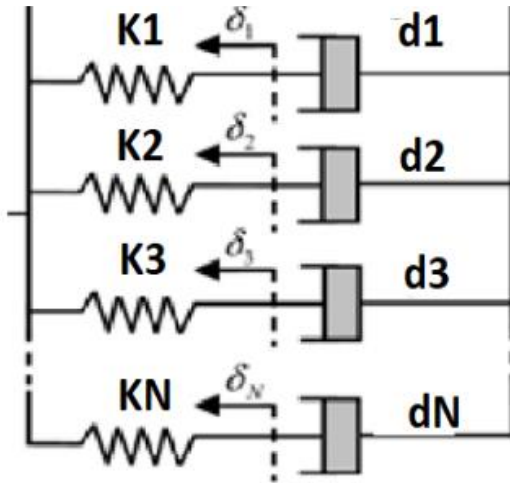


VD-630/325-3 vs. VD-630/325-15 Horizontal Stiffness Curves

4. HVD Dynamic Behavior Modeling Based on Test Data

Based on the HVD experimental test data, analytical models are fitted using the least-square method to minimize deviations between the analytical model and test data. To accurately capture the HVD viscous-elastic behavior in complex frequency, the Generalized Maxwell Model (order N) based on the Prony series can be fitted on test data (Baumgaertel and Winter, 1989).

For each Maxwell Chain or Prony series term, two input parameters (elastic stiffness, k_i , and characteristic frequency, k_i/d_i) should be defined based on test data fitting.



$$K = \sum_{i=1}^N k_i \left(\frac{(\omega/\omega_i)^2}{1+(\omega/\omega_i)^2} + j \frac{(\omega/\omega_i)}{1+(\omega/\omega_i)^2} \right)$$

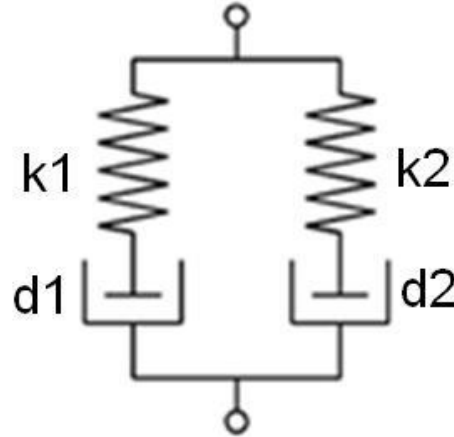
$$\text{where: } \omega_i = \frac{k_i}{d_i} ; \omega = 2\pi f$$

Generalized Maxwell Chain (GM, order N)

Based on experimental tests by GERB and CVS, it was shown that a two Maxwell Chains or two term Prony expansion model with only 4 parameters for the model calibration ($K1$, $K2$, $d1$, $d2$) provides an accurate analytical model for each direction and frequency.

Double Maxwell Chain Model Based on Test Data

The two-chain Maxwell model is also called the Two or Double Maxwell Chain model (Barutzki et al., 2020, TerraPower, 2024), or 4-Parameter Maxwell model (Kostarev, 1993, Tamura et al., 2016) in different publications.



Double Maxwell Chain (DMC) Model

When detailed HVD experimental tests are available, the more refined Double Maxwell Chain model should be applied for final verification.

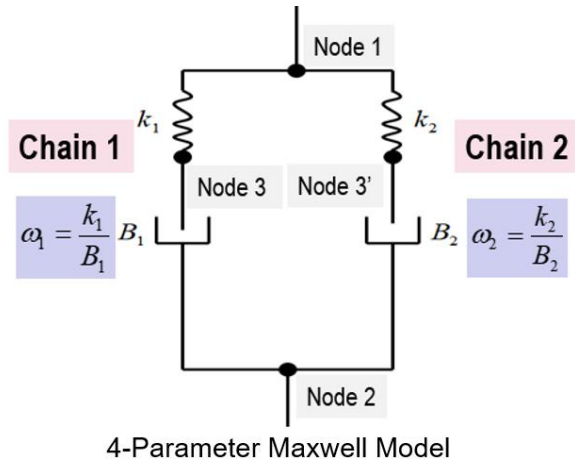
.The TerraPower NAT-8922 Rev. 0 TR, 2024, at page 73, states:

“Tests on seismic isolation units demonstrate good correlation between measurement and numerical models using ideal springs and dampers. One such model is the Double Maxwell-Model... The relevant constitutive (or mathematical) model is linear, and available by default in most finite element software used in NPP design”.

ACS SASSI HVD Element with Frequency-Dependent Dynamic Stiffness



GERB HVD Device



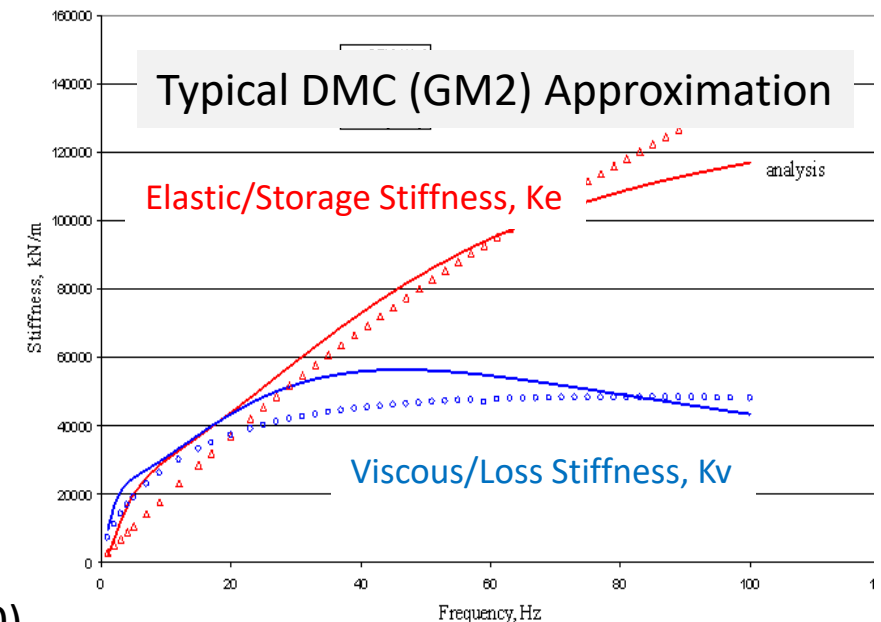
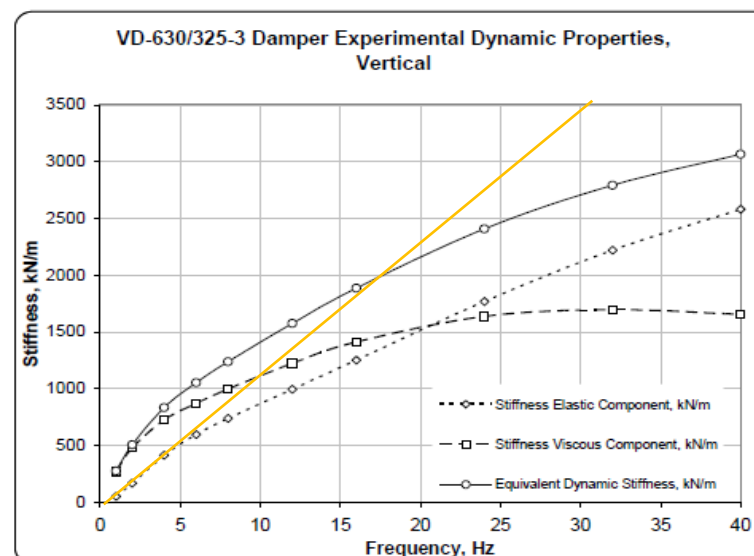
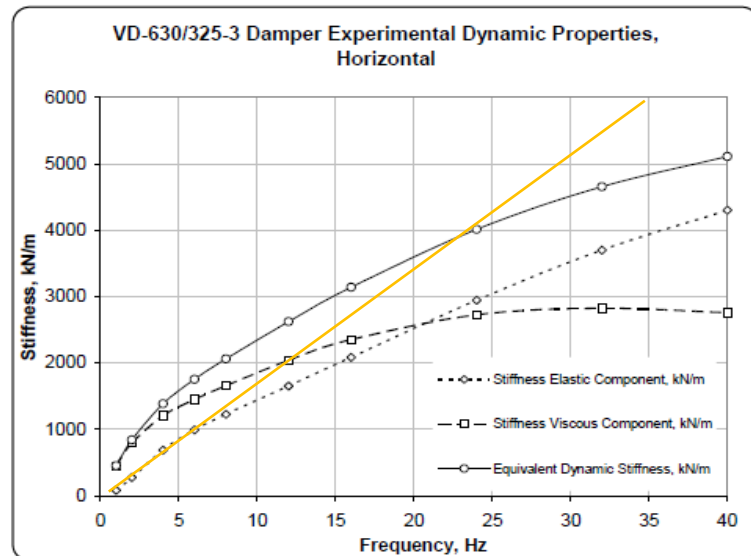
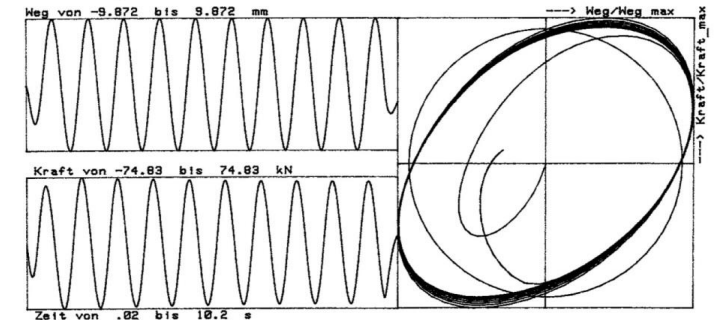
ACS SASSI HVD Modeling Options ($K = K_e + j K_v$):

- Ideal Viscous Damper (HVDLIN) (no real stiffness, preliminary)
- Generalized Maxwell model (GM n) (HVDCEQ) (2 parameters/chain)
- Using Experimental Curves directly (HVDEXP) (no approximation)

2 Prony series terms

Double Maxwell Model (4p/dir);
Recommended by GERB and CVS

$$K = \sum_{i=1}^2 k_i \left(\frac{(\omega/\omega_i)^2}{1+(\omega/\omega_i)^2} + j \frac{(\omega/\omega_i)}{1+(\omega/\omega_i)^2} \right)$$



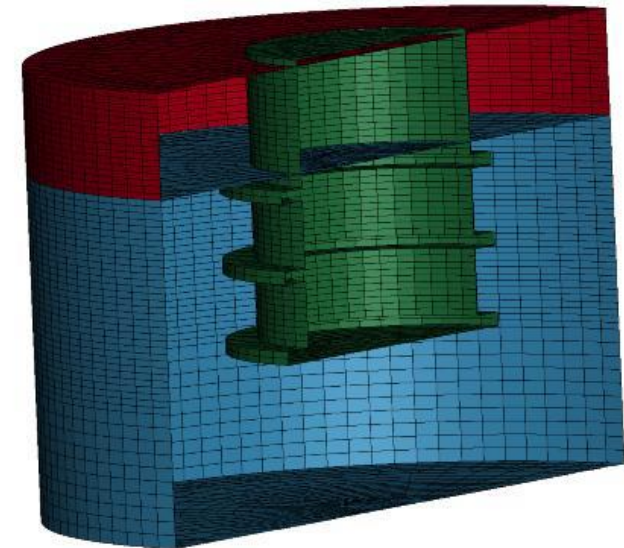
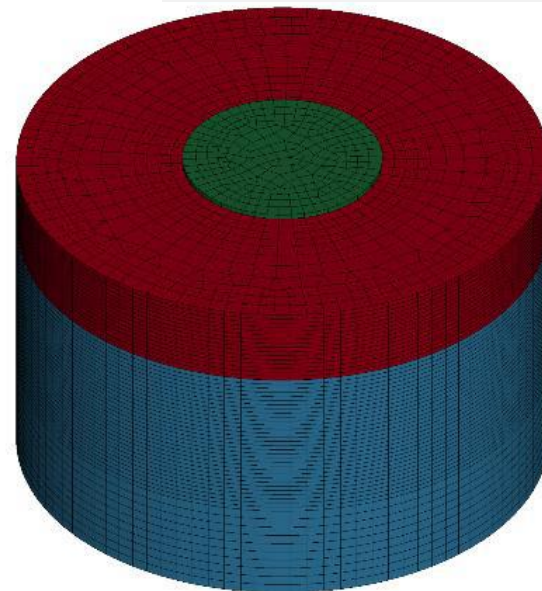
(CVS, 2021, Barutzki et al., 2020)

LS-DYNA Modeling of Fluid Viscous-Elastic Material

Patel (Patel et al., 2025,2026) analyzed an HVD using a **LS-DYNA** FE model with an extremely refined mesh for internal fluid modeling using the **MAT_GENERAL_VISCOELASTIC (MAT_076)** viscous-elastic fluid material model that uses an analytical modeling based on Prony expansion (same in ACS SASSI).

Patel showed through a computationally intensive analysis via LS-DYNA that the 3rd Prony series term contribution to the data-fitted model accuracy *is less than 8% for the fluid elastic modulus/stiffness, and only 2.1% for the characteristic frequency*. The 4th Prony series term contribution is basically negligible, i.e. *1.4% for the fluid elastic modulus/stiffness and 0.3% for the characteristic frequency*

LS-DYNA VD Refined VD Model



(Patel et al., 2025, 2026)

HVD Behavior Modeling Should Include Uncertainties

Special tests are required to consider the influence of different *temperature conditions, humidity, corrosion and/or radiation*. For nuclear reactors, it is essential to choose a suitable damper working under significant radiation effects.

Therefore, for preliminary seismic SSI analyses, including the base-isolated ARC-100 SMR SSI analysis, it is important to consider BCS unit stiffness and damping parameter *uncertainties* to be able to evaluate the sensitivity of base-isolated structure SSI responses due to the BCS isolator property variations. Bounding variations should be established.

For preliminary analysis, in the absence of detailed test data, the BCS isolation stiffness and damping variations can be considered by BCS unit property variations, but also by assuming different SB and HVD types or numbers. BCS configuration should be also optimized.

Local BCS Isolation for RV System (GPT-UNITED-WA006-2024-7-31)

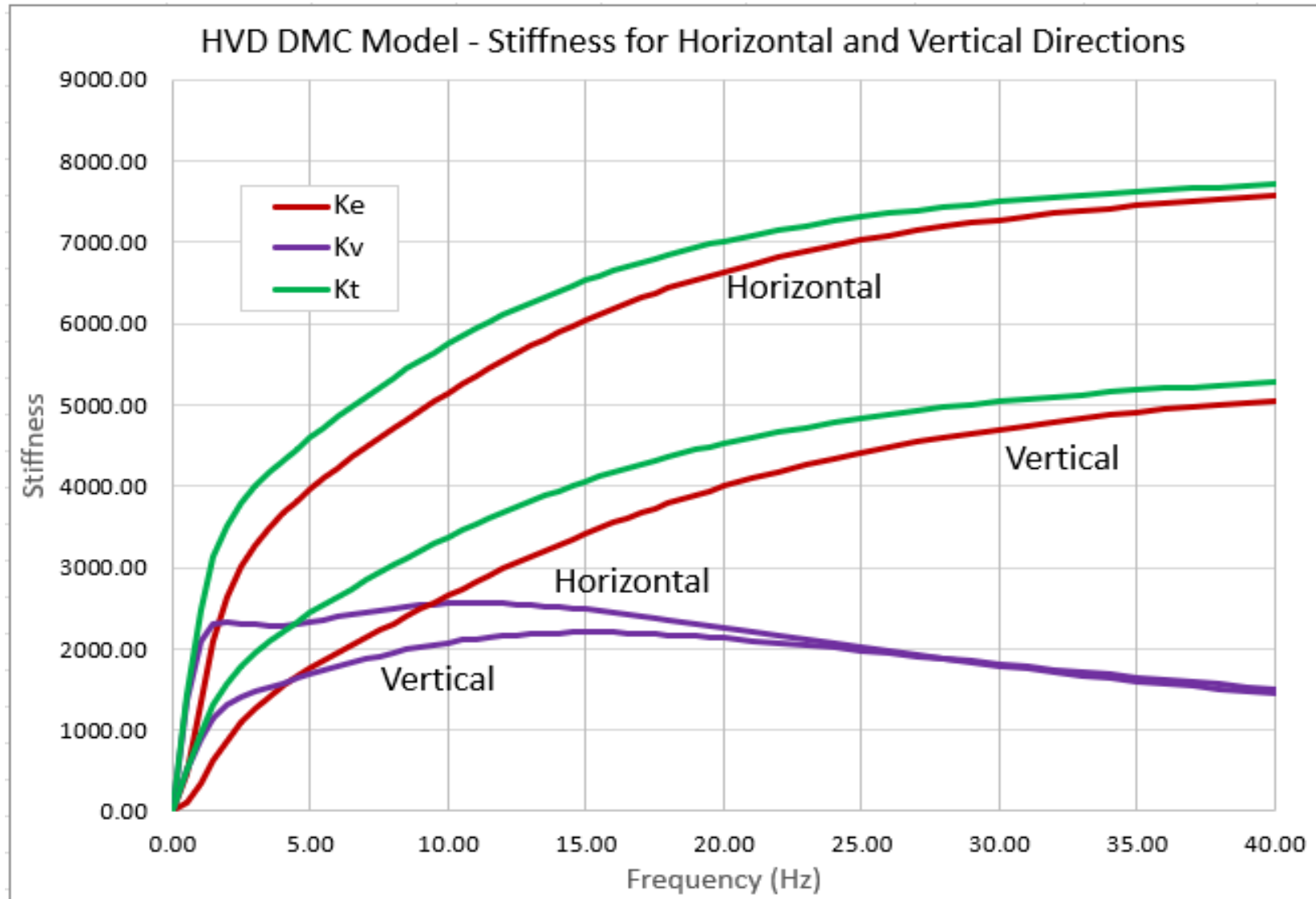
To reduce the large RV system acceleration responses, some GERB BCS isolation units were included under the RV system spider beam supports. The improved efficiency of the ARC-100 SMR base-isolation system is based on a *hybrid isolation system* obtained by integrating the *global* isolation system using the 2D FP bearings with a *local* isolation system using 3D BCS units for the RV system vibration.

Two BCS configurations were considered by applying the BCS isolation devices under the 12 spider beams supporting the RV system:

- 1) Model 1, including 12 SB (green) and 6 HVD (yellow) units, and
- 2) Model 2, including 12 SB (green) and 12 HVD (yellow) units.

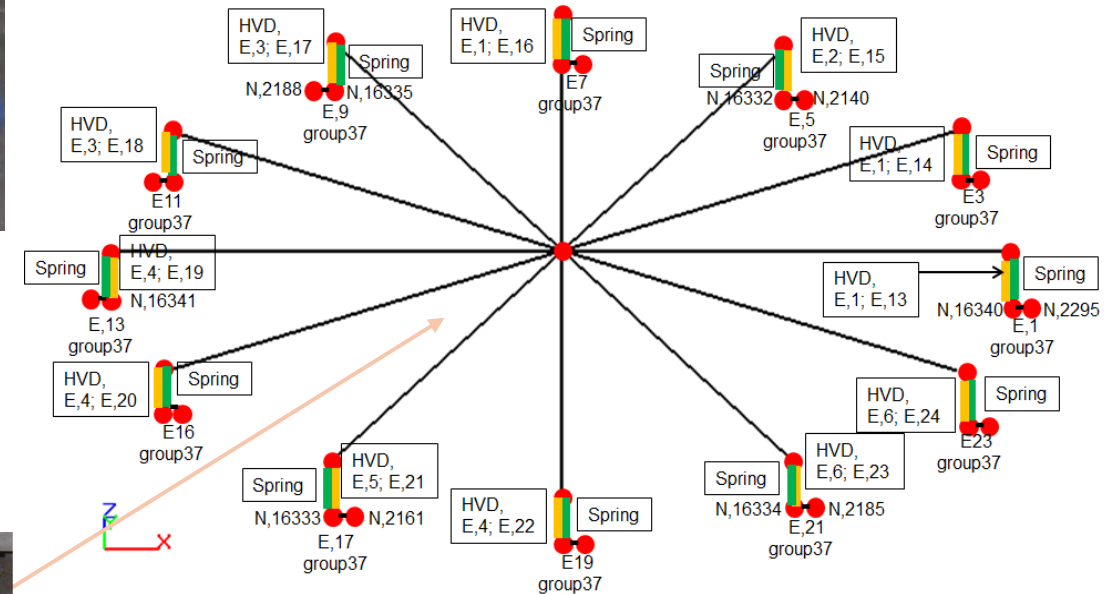
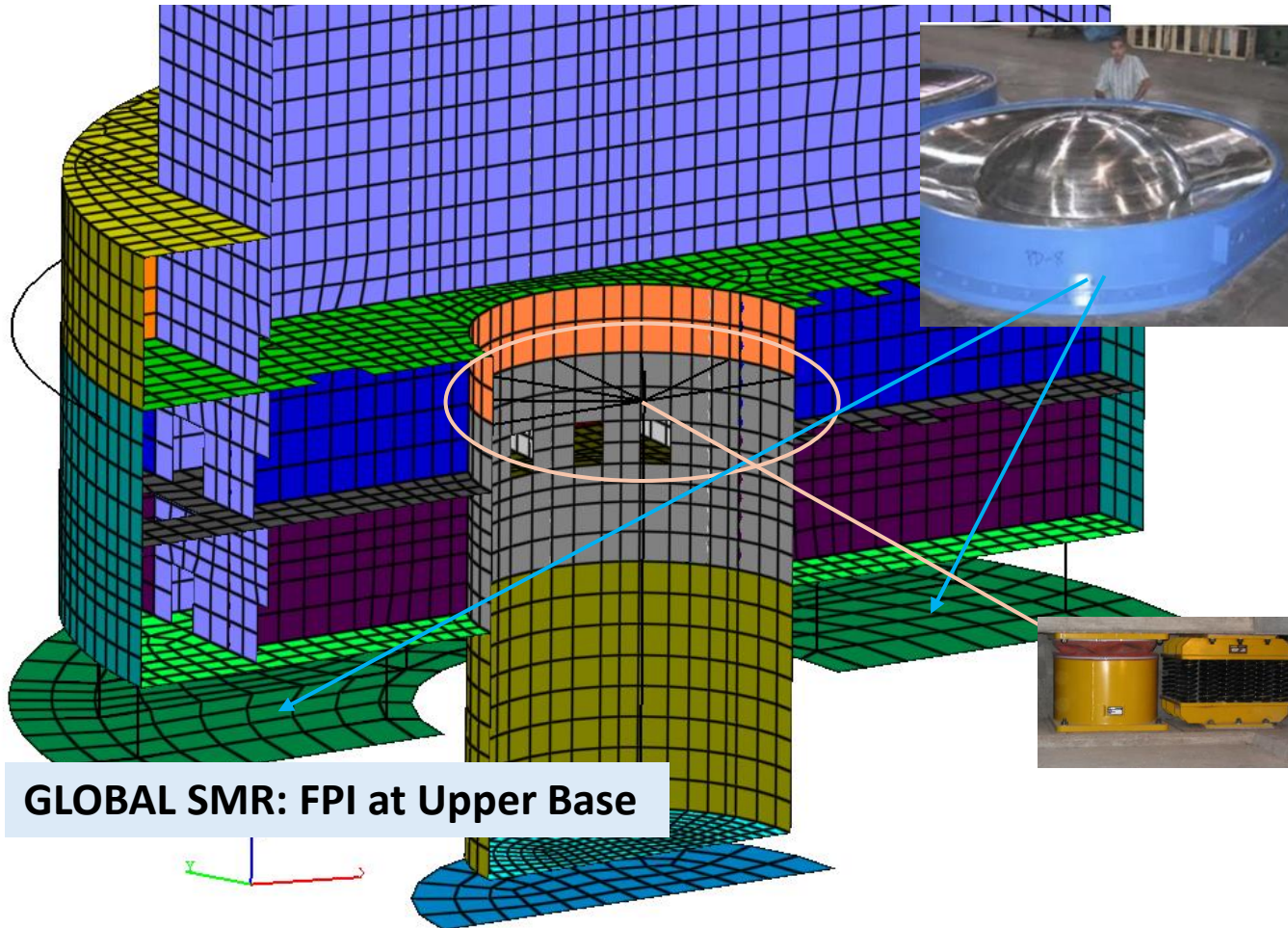
The hybrid isolation system is described in detail in the GPT-UNITED-WA006-2024-7-31 report. For the HVD modeling, the Double Maxwell Chain model (HVDCEQ option in ACS SASSI) was considered for both Models 1 and 2.

Double Maxwell Chain (DMC) Model for HVD Units

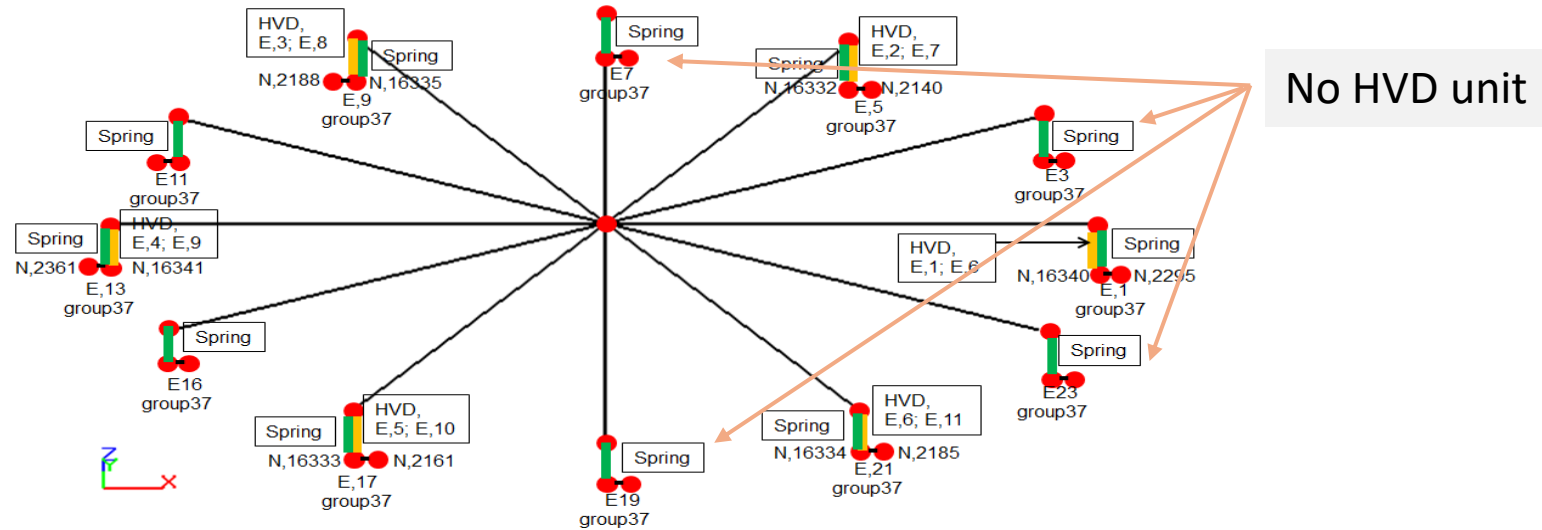


Hybrid SIS: Global 2D FP Isolators and Local 3D BCS Isolators

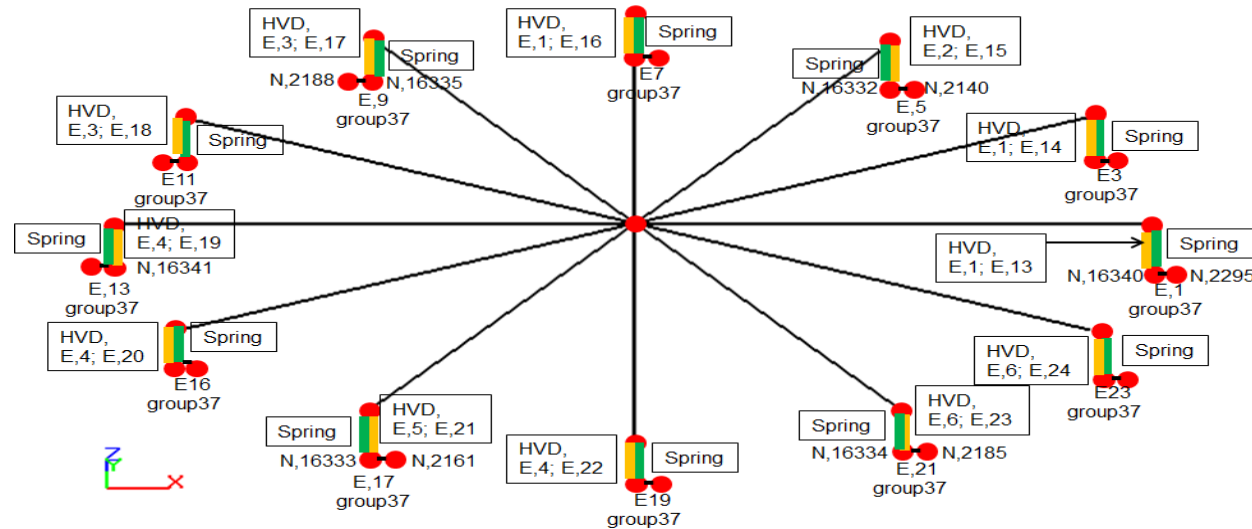
Hybrid Global FP - Local GERB BCS Isolation System



BCS Model 1 (12 SB8 and 6 HVD) BCS Model 2 (12 SB18 and 12 HVD)



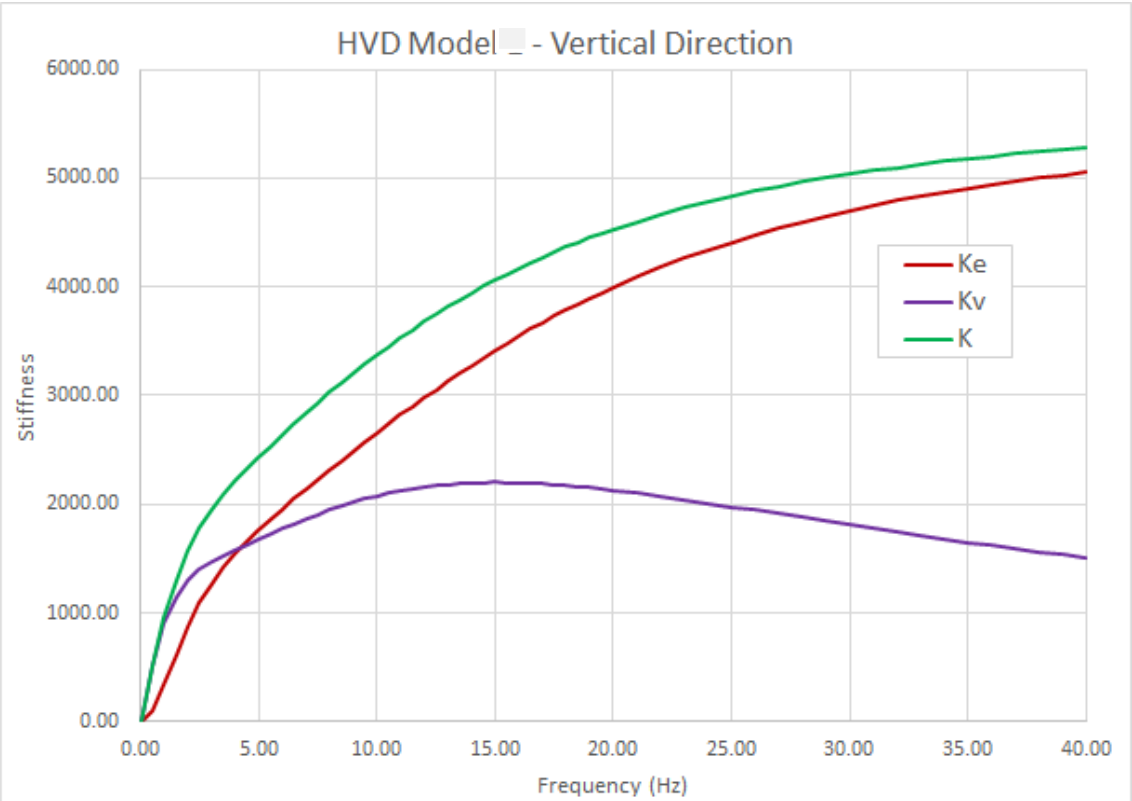
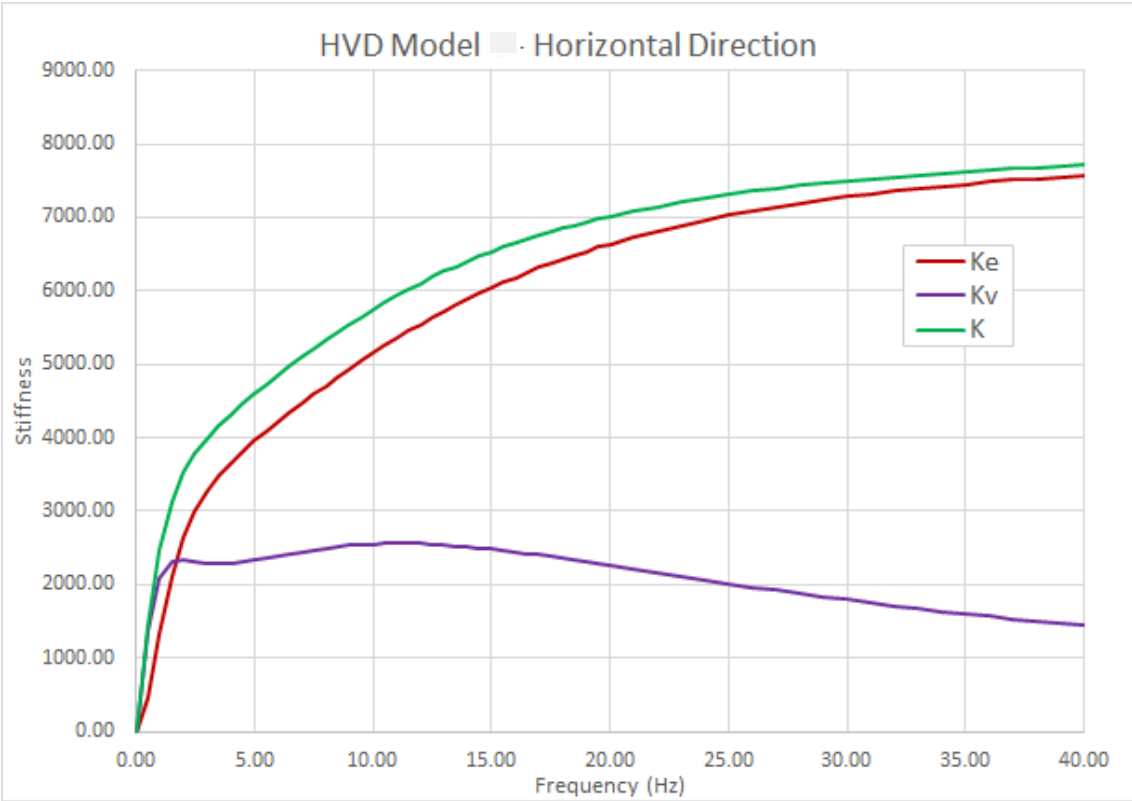
Model 1: 12 SB (8) and 6 HVD Units (Fig. 2.51 in GPT-UNITED-WA006-2024-7-31)



Model 2: 12 SB (18) and 12 HVD Units (Fig. 2.52 in GPT-UNITED-WA006-2024-7-31)

SB and HVD Input Parameters (Using Double Maxwell Chain Model)

BCS	HVD Chain 1				HVD Chain 2				Spring Block	
	Kh (k/ft)	Kv (k/ft)	Bh (ks/ft)	Bv (ks/ft)	Kh (k/ft)	Kv (k/ft)	Bh (ks/ft)	Bv (ks/ft)	Kx=Ky (k/ft)	Kz (k/ft)
Model 1	4326.52	3974.28	50.58	37.63	3700.2	1685.6	436.62	130.15	91.134	973.02
Model 2	4326.52	3974.28	50.58	37.63	3700.2	1685.6	436.62	130.15	227.84	2432.6



Global BCS Isolation for SMR Structure (GPT-UNITED-WA009-2025-10-15)

For preliminary SSI analysis of the ARC-100 SMR superstructure with BCS base-isolation, larger capacity SB units (FE-02.01/EKZ-49) with 49 spring per block (7x7) and larger capacity HVD units (VD850/VD1000) were considered. The SB unit axial force capacity is 11,400 kN in compression.

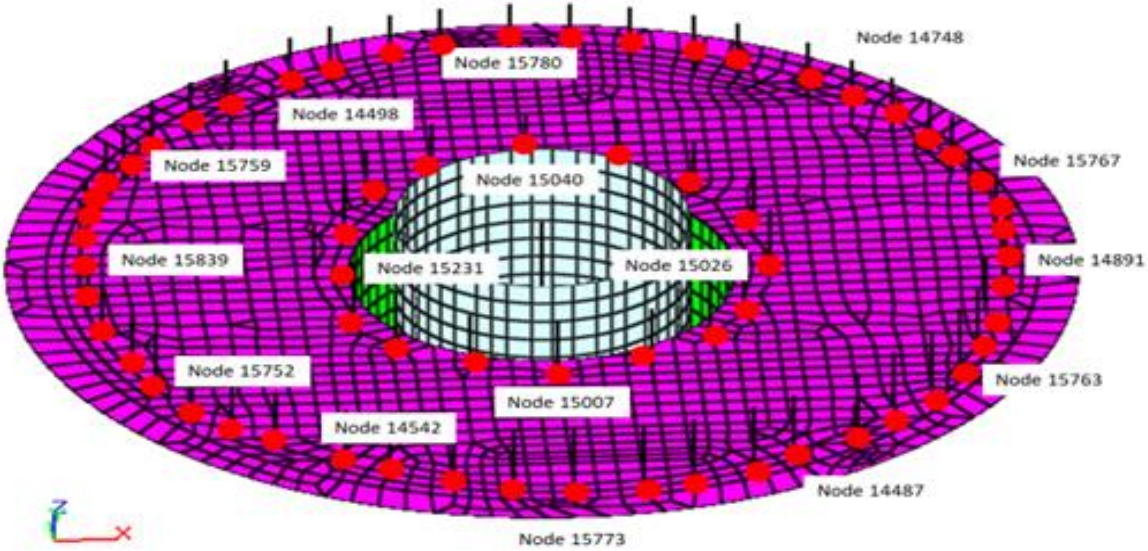
The VD850/VD1000 types have been manufactured by GERB GmbH specifically for CVS projects for the BCS application to the VVER 600/640 reactor building (Kostarev et al., 2015).

For the preliminary SSI analysis of the ARC-100 SMR structure with global BCS isolation, it was assumed that HVD units behave as ideal viscous dampers (HVDLIN option in ACS SASSI) per GERB expert recommendations (Nawrotzki and Siepe, 2014, TerraPower, 2024, Barutzki et al., 2024).

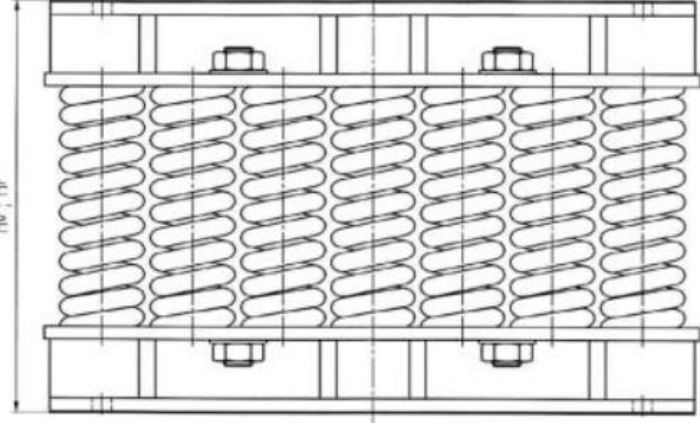
To cover uncertainties in the BCS configuration, modeling and/or in dynamic stiffness properties, four BCS models with different configurations were applied, assuming a reference BCS with a baseline configuration having 64 SB and HVD pair locations.

Four BCS Models for Preliminary SSI Studies for ARC-100 SMR

2025 ARC100 SMR BCS Pedestal Nodes Location



Large Spring Blocks (EQZ-49)



Large HVD (VD850/VD1000)



ACS SASSI HVD HVDLIN Modeling Option

For preliminary SSI analysis, we used four ideal viscous damper models with different dynamic properties using different BCS configurations to capture modeling uncertainties. No test curves used/available for large VD850/1000. Bh and Bv values recommended by GERB.

BCS SIS	Unit	Type	HVD Elastic Stiffness (K) and Viscous Dashpot (B) *			
	SB	HVD	Kh (k/ft)	Kv (k/ft)	Bh (ks/ft)	Bv (ks/ft)
MODEL1	64	96	685.22	8912	113.12	56.56
MODEL2	42	160	447.5	5820.4	188.55	94.25
MODEL3	54	128	566.35	7365.8	150.81	75.41
MODEL4	42	128	447.5	5820.4	150.81	75.41

* Parameters are for 64 SB and HVD reference locations

The assumed BCS dynamic property variations were almost twice from lower-bound (LB) values to the upper bound (UB) values.

Or +/- 25% property variations from the mean property.

2. Seismic Input Simulation for Rock CSRDS-HF. Explain Target PSD Checking Procedure

Generation of Input Accelerations for Given CSDRS-HF

For the target CSDRS-HF, a total of *11 input sets of spectrum compatible acceleration triplets* for each of the X, Y and Z directions were generated (33 sets = 11 sets x 3 directions).

The 11 sets of seismic input acceleration triplets were generated in accordance with the NRC SRP 3.7.1 requirements for Option 1 (for single set of time histories) with Approach 2 applied to each of the generated acceleration time histories.

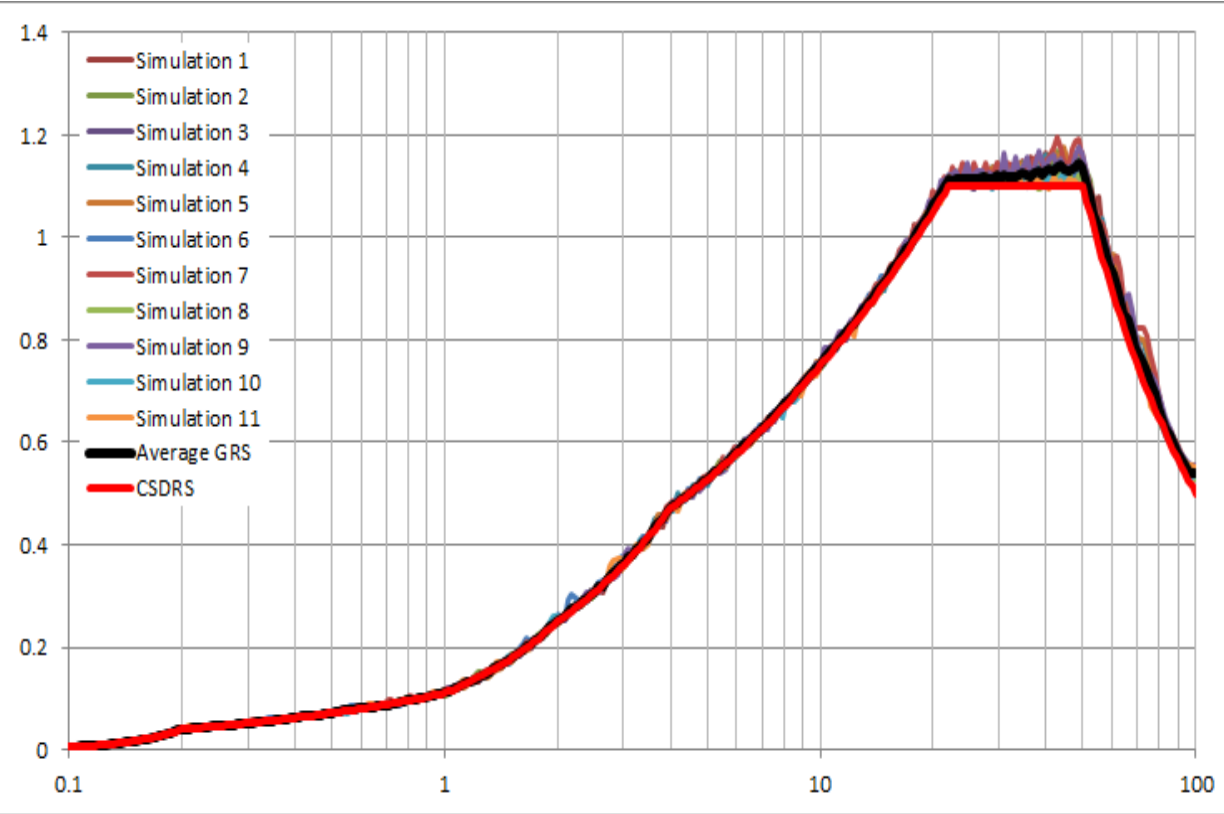
The applied Option 1 is more restrictive than Option 2 (for multiple sets of time histories), since imposes the Approach 2 requirements to each simulated time history, rather than per the ensemble of simulated time histories.

For the CSDRS-HF Rock site input, the acceleration time steps were 0.0025 sec. This time step size for the generated time histories ensured that the Nyquist frequencies were 200 Hz.

Per the ASCE 43-19 Section C2.4, the acceleration Fourier transform cut-off frequency should be about 1/3 of Nyquist frequency to maintain the numerical approximations of computed response spectra (RS) at 50 Hz be below 10% error. This suggests a 66 Hz or less for the SSI cut-off frequency for the hard-rock site.

Simulated Acceleration Parameters (per Sample & Ensemble)

Computed Sample RS and Target CSDRS-HF



Motion Parameters Per 11 Simulation Set

Parameters for Rock CSDRS-HF Spectrum 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	0.5	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	34.2	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
HARD ROCK SITE	0.0503	0.0428	0.0696

Computation of Target PSD for Rock CSDRS-HF

In addition to Option 1 Approach 2 requirements included in NRC SRP 3.7.1, an extra PSD checking was performed to compare the strong-motion PSD computed for each generated acceleration (and for ensemble average) against a “Target PSD”.

It should be noted that for a site-independent CSDRS-HF RS input, there is no Target PSD directly available. The CSDRS-HF design RS input is not associated with a particular site location in the Central-Eastern US (CEUS) area. Therefore, the PSHA-PSRA approaches used for site-specific applications are not directly applicable to site-independent CSDRS-HF design RS.

The NRC SRP 3.7.1 Appendix B guidance is applicable to site-specific applications for given site locations. For site-specific applications, PSHA disaggregated characteristic earthquakes are defined using Magnitude-Fault Distance (M,D) interval ranges or bins for given MAFE.

To compute the Target PSD for the site-independent CSDRS-HF spectra, based on NRC SRP 3.7.1 Appendix B, we *assumed* different site locations to cover most of the CEUS area.

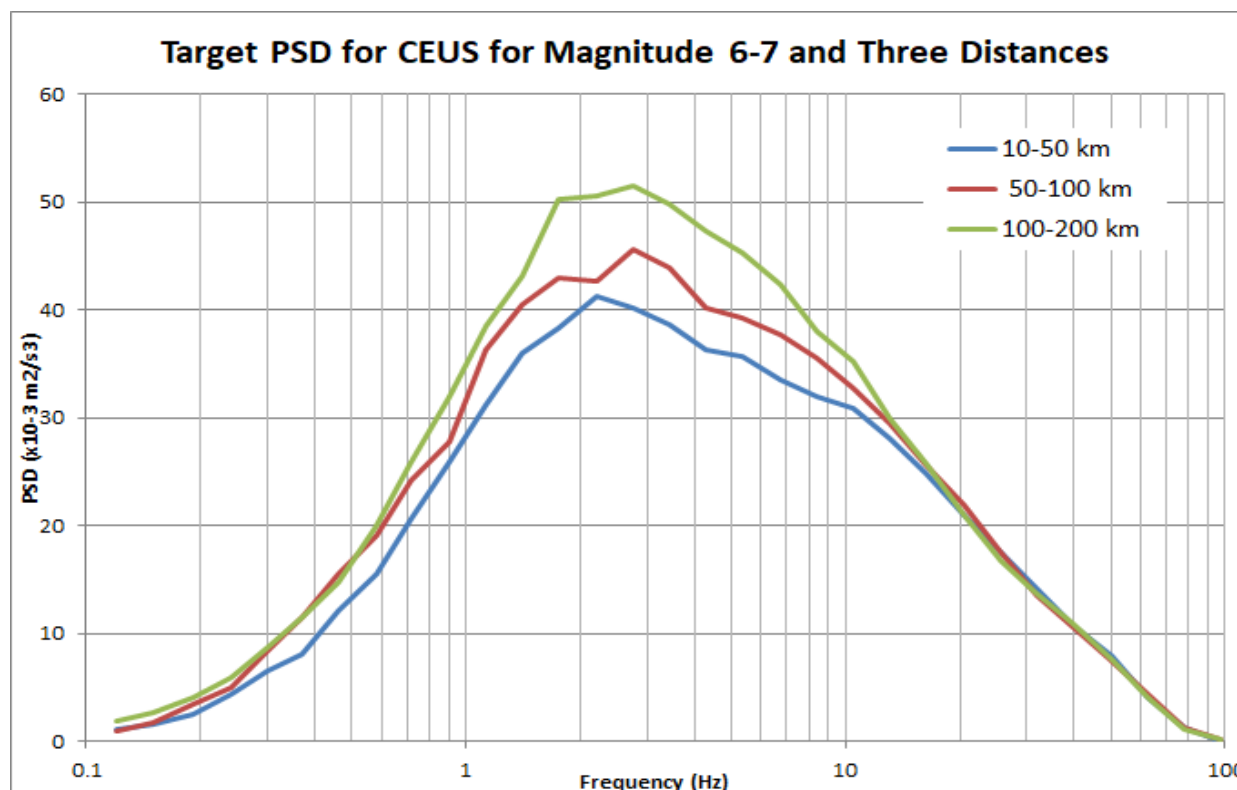
We *arbitrarily* considered three CEUS locations with given M, D bins for the Magnitude bin, $\text{BinM} = 6-7$. Specifically, the three locations were defined by $\text{BinD} = 10-50 \text{ km}$, $\text{BinD} = 50-100 \text{ km}$ and $\text{BinD} = 100-200 \text{ km}$. By arbitrarily selecting the three (M,D) bins, most of the site locations in EUS area with Magnitudes 6-7 and fault distances $D > 10 \text{ km}$ were basically covered.

Computation of Target PSD Per NRC SRP 3.7.1 Appendix B Guidance

The NRC SRP 3.7.1 Appendix B *equation 3 for CEUS* was used to compute the *bin representative design RS* for given (M,D) bins. Then, to compute the *target PSD* for the three assumed locations using the *bin representative design RS*, the Appendix B1 guidance was followed.

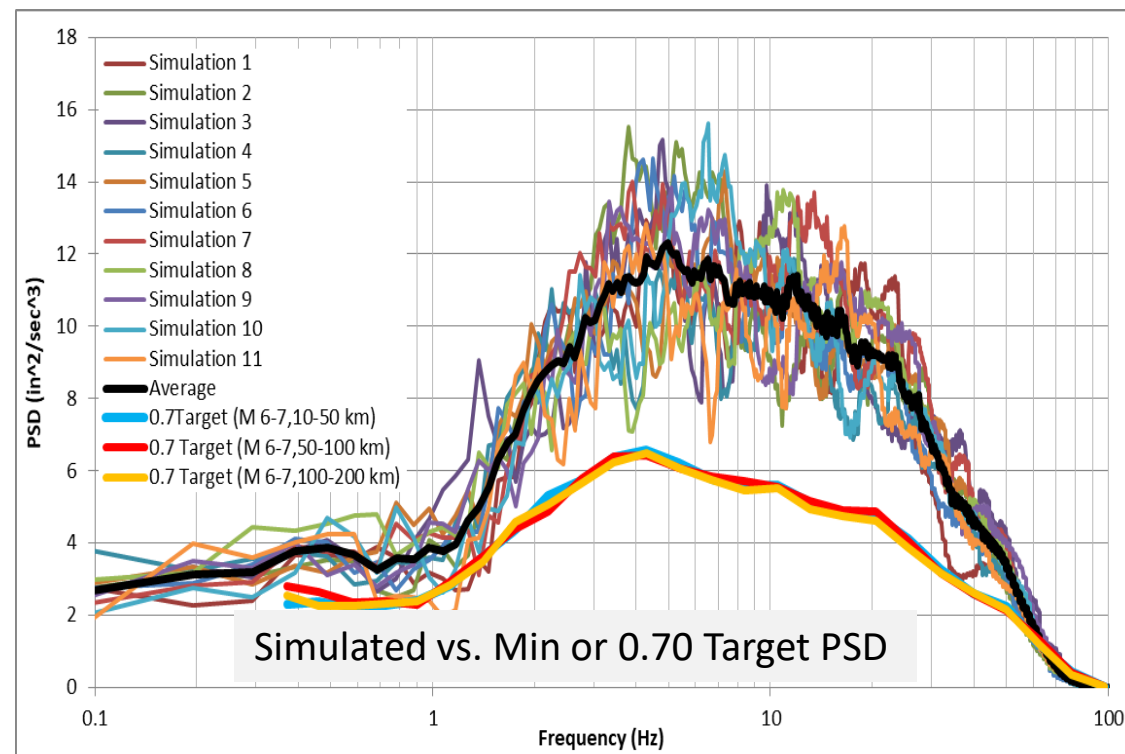
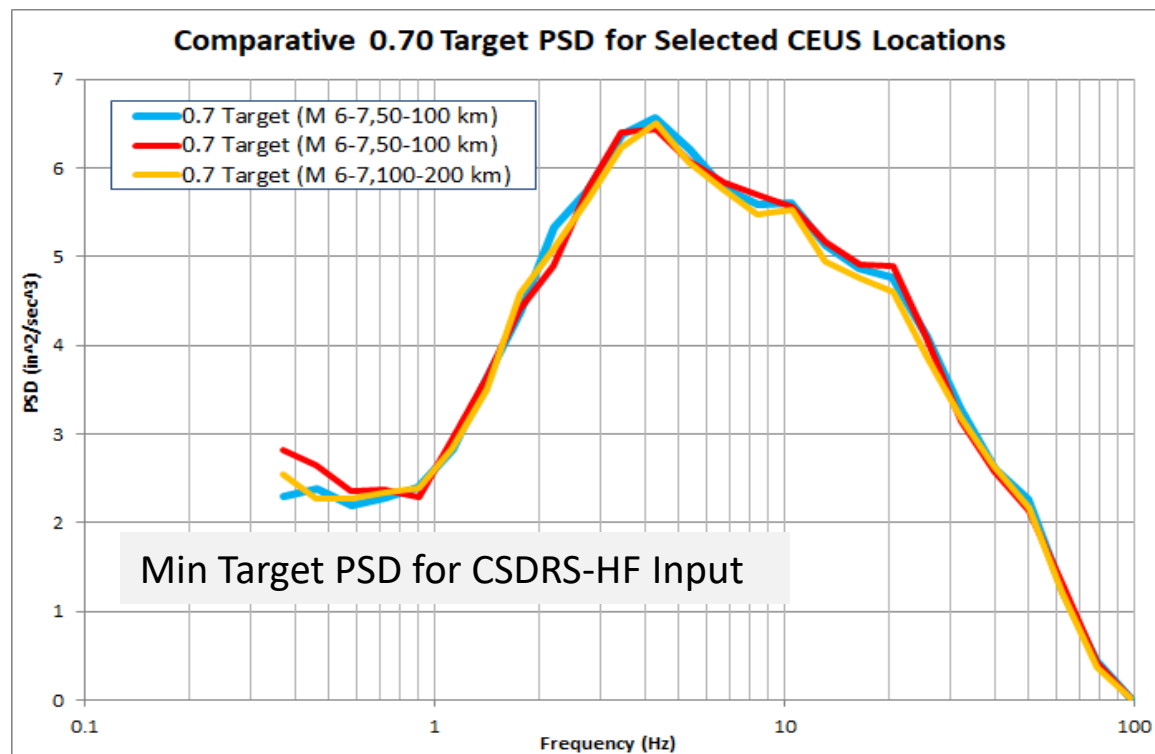
For each of the three assumed site location (M, D) bins, the computed frequency-by-frequency *square ratios of the CSDRS-HF RS amplitudes over the bin average RS amplitudes* (provided in Appendix B2 Table 7 for Bin Average RS for CEUS rock sites) were used to scale the Target PSD (also provided in Appendix B1 Table 1 for Target PSD for CEUS rock sites).

Target PSD for Selected
Three Locations (Table 1)



Unique Solution Target PSD for CSDRS-HF RS Input

The consistency of the applied approach for getting the Target PSD associated with the CSDRS-HF RS, based on the three arbitrarily selected (M, D) bins, is indicated by the unique solution obtained for Target PSD. It should be noted that the three Target PSD curves computed using the three assumed locations are completely overlapped, showing, as expected, unique single Target PSD corresponding to the CSDRS-HF RS input.



The computed CSDRS-HF PSD curves show smooth variations in frequency with their amplitudes being well above the minimum Target PSD.

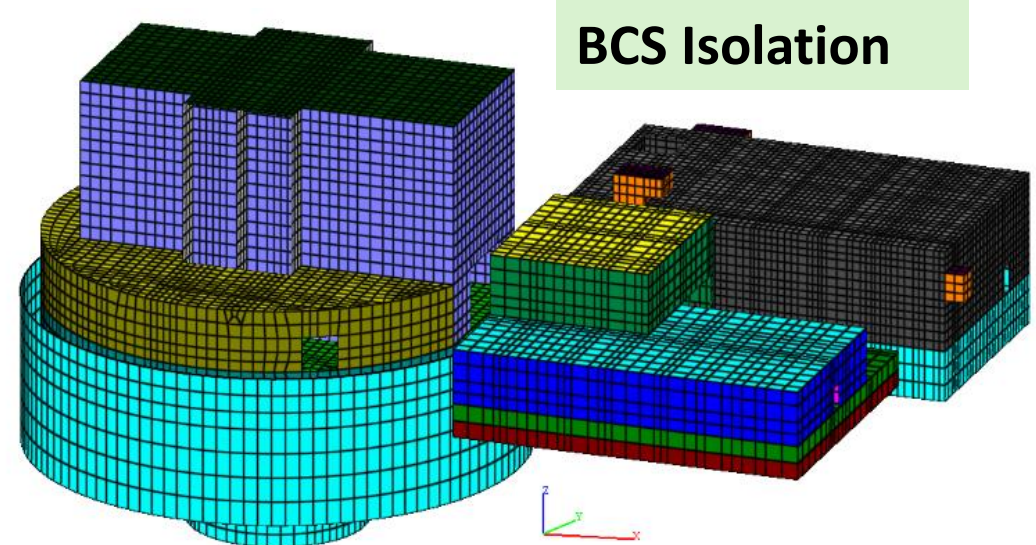
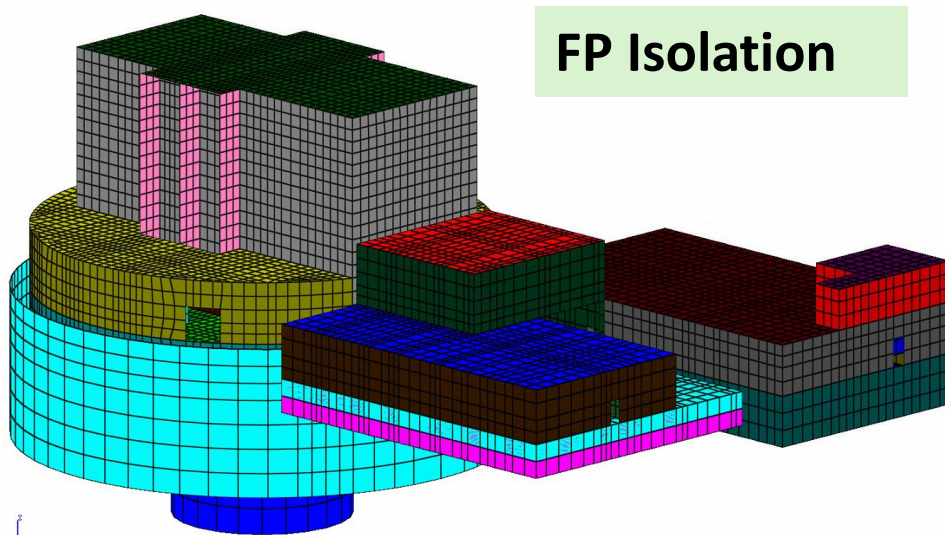
3. Comparative Seismic Responses for Non-Isolated and Base-Isolated ARC-100 SMR

Building Non-Isolated ARC-100 SMR SSSI Models

To simulate the non-isolation condition without changing the ARC-100 RB finite element (FE) models, we assumed that the FP or BCS isolators are modeled by *rigid springs* in all three space directions (having a directional stiffness, $K=1.0 \text{ E}10 \text{ k/ft}$).

The new seismic SSSI analyses were performed for a single input set of three CSDRS spectrum compatible acceleration inputs for X, Y and Z directions. Only the uniform soil BE profile with $V_s=2,000 \text{ fps}$ was considered.

For comparisons, the SSI responses included structural accelerations and displacements, ISRS at several selected locations, and maximum RV system stick forces/moments

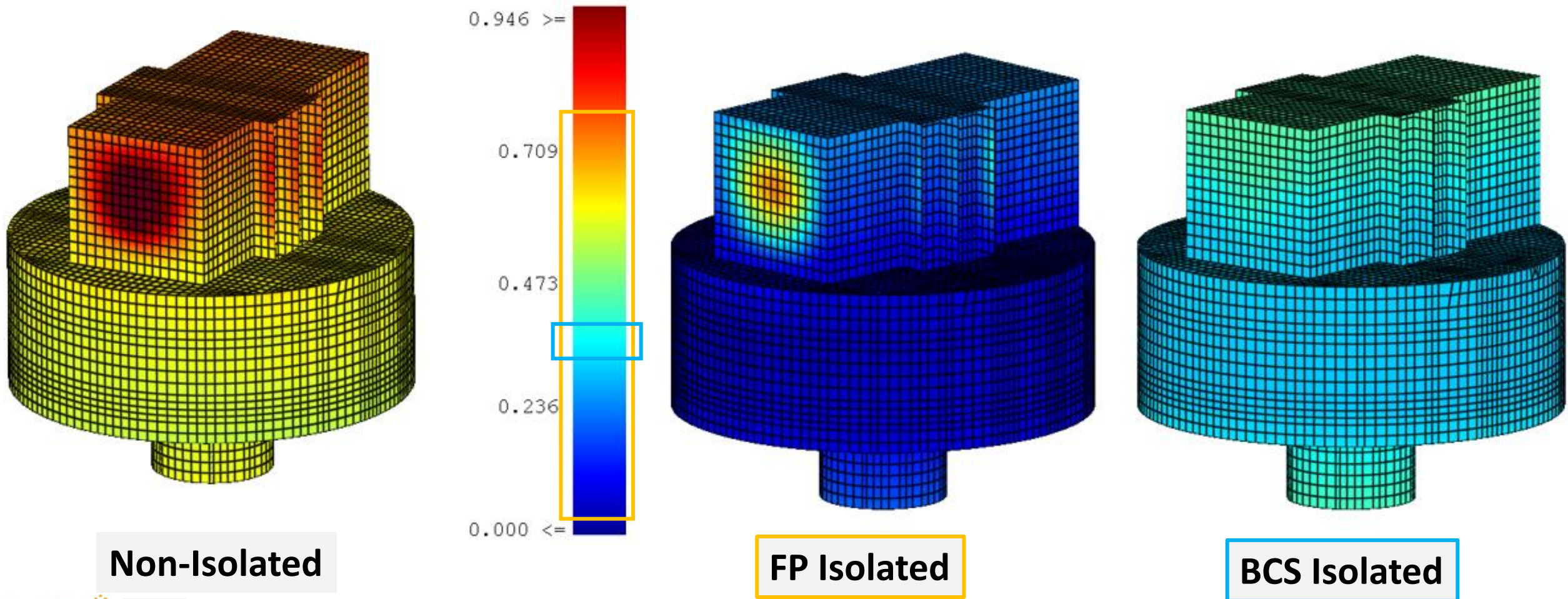


DBE Maximum Structural Accelerations in Horizontal X Direction Non-Isolated and Base-Isolated SMR Superstructure

Rigid Springs in X-Direction

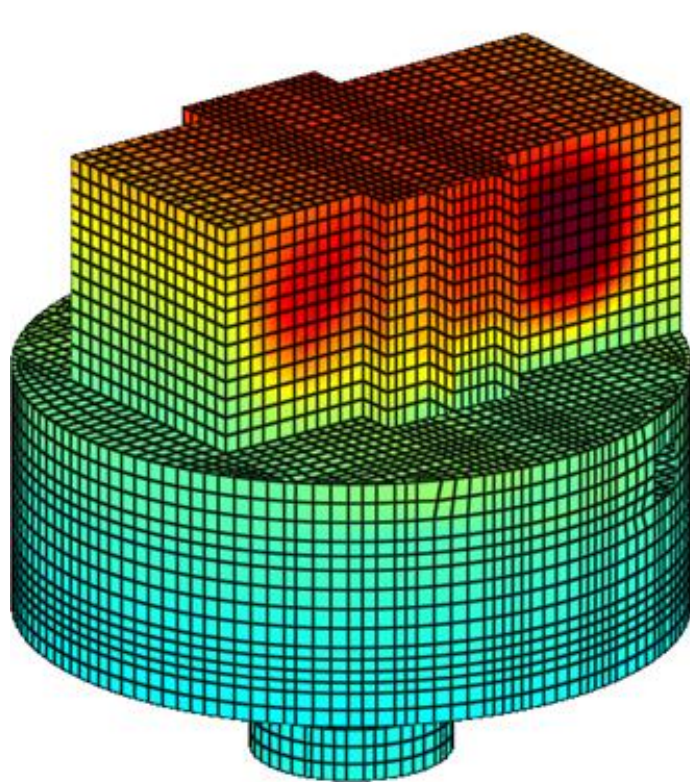
ARC FP 2024 in X-Direction

ARC BCS 2025 in X-Direction



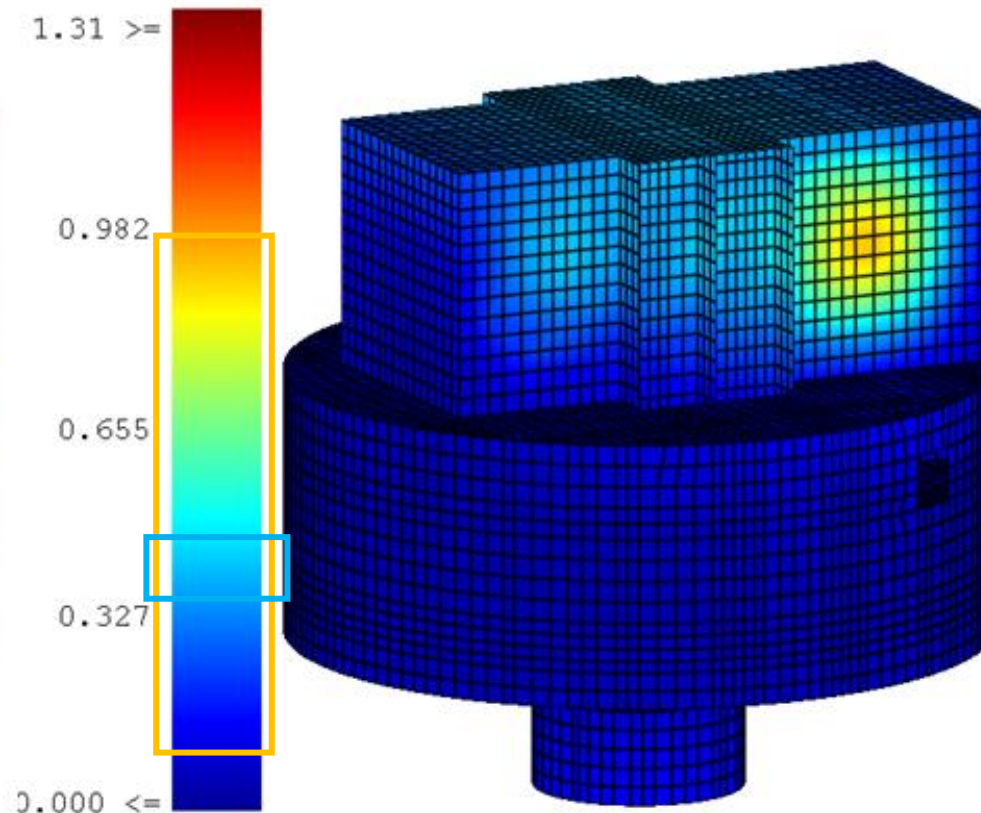
DBE Maximum Accelerations in Horizontal Direction for Non-Isolated and Base-Isolated SMR Superstructure

Rigid Springs in Y-Direction



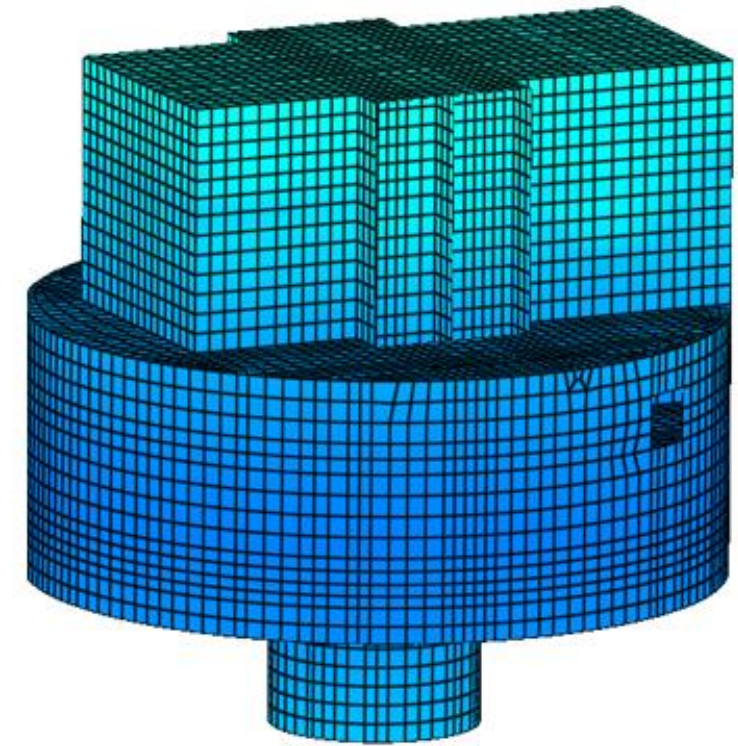
Non-Isolated

ARC FP 2024 in Y-Direction



FP Isolated

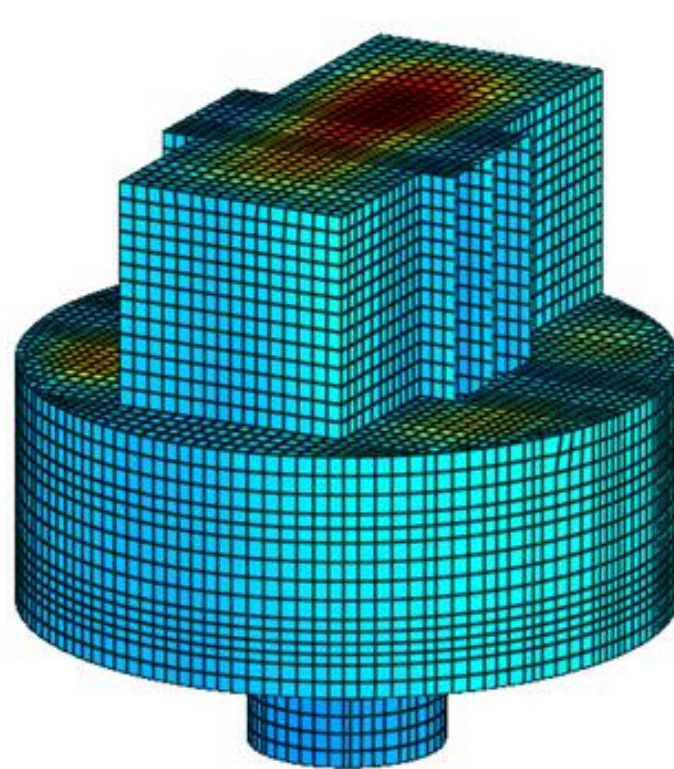
ARC BCS 2025 in Y-Direction



BCS Isolated

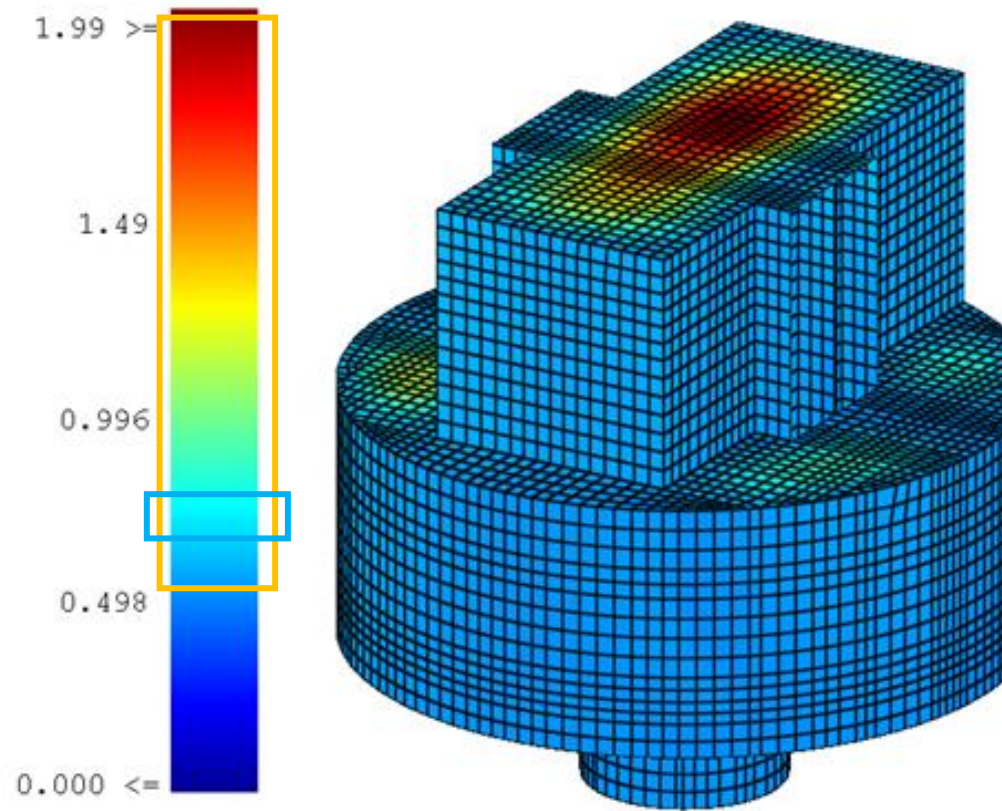
DBE Maximum Accelerations in Vertical Direction Non-Isolated and Base-Isolated SMR Superstructure

Rigid Springs in Z-Direction



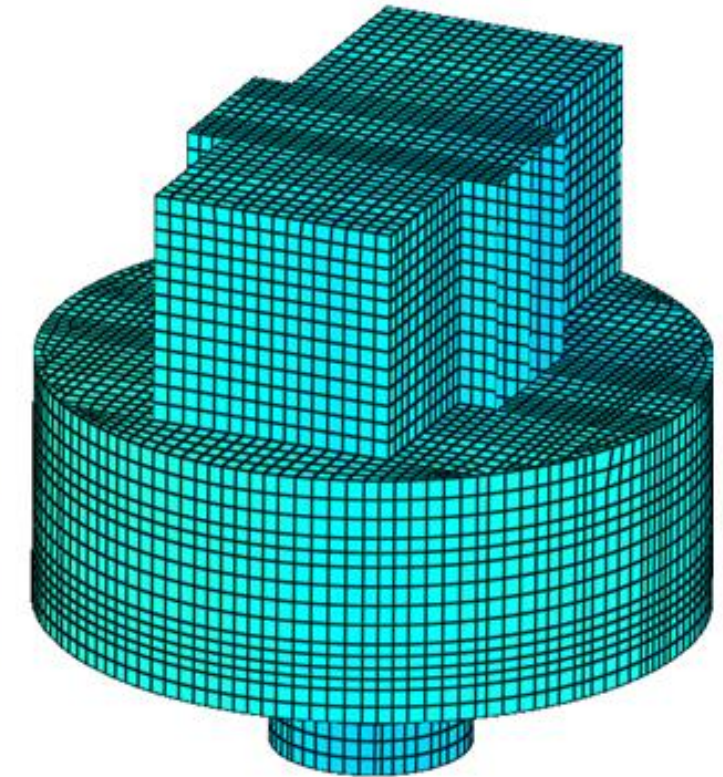
Non-Isolated

ARC FP 2024 in Z-Direction



FP Isolated

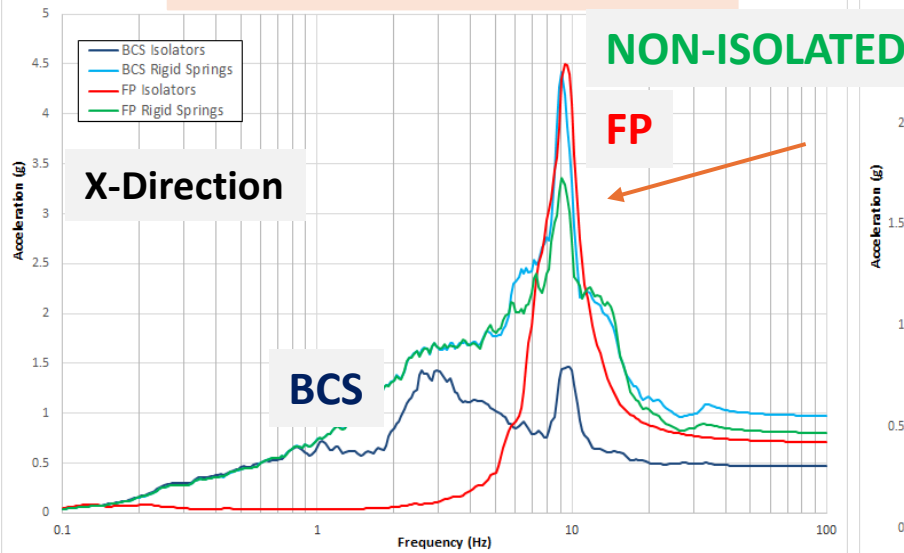
ARC BCS 2025 in Z-Direction



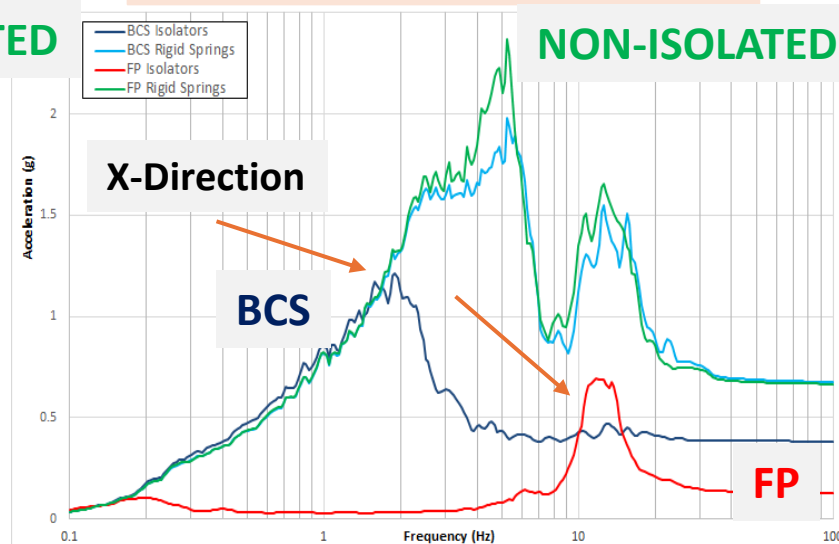
BCS Isolated

ISRS for Isolated (FP, BCS) and Non-Isolated SMR Structure

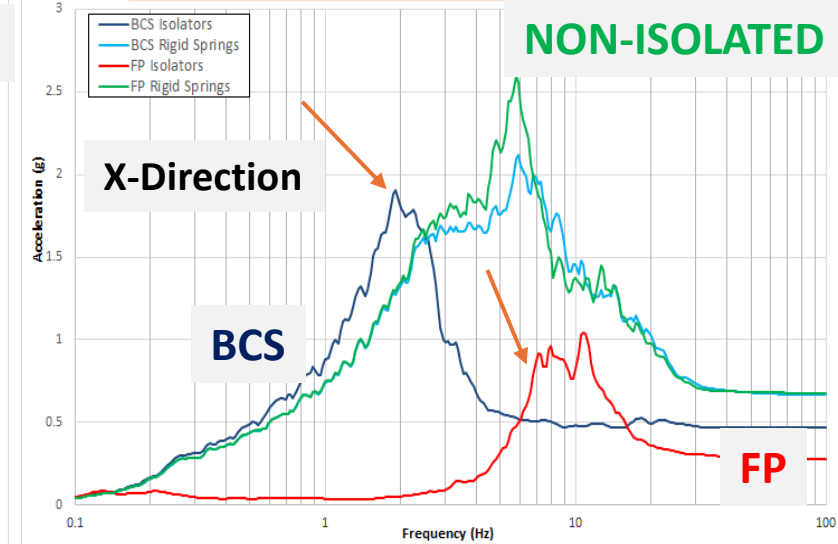
RV Stick Bottom, El.-56.5ft



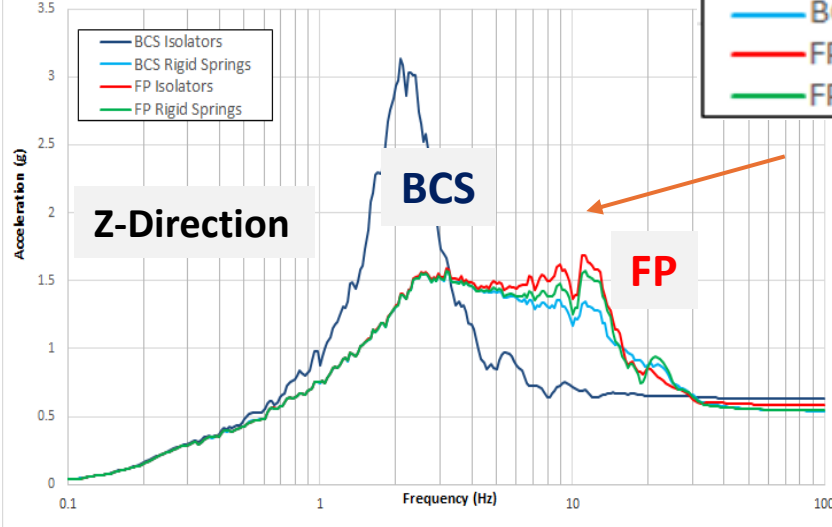
SMR Structure Edge, El.+18 ft



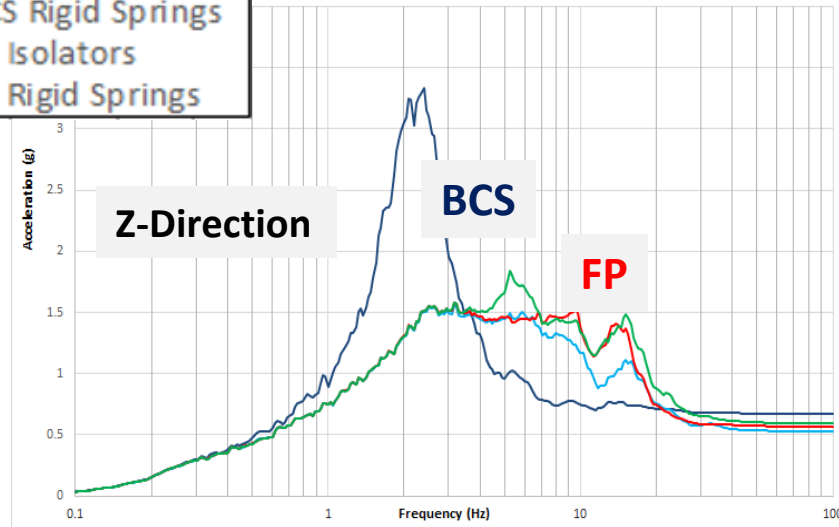
SMR Roof Center, El.+64.75 ft



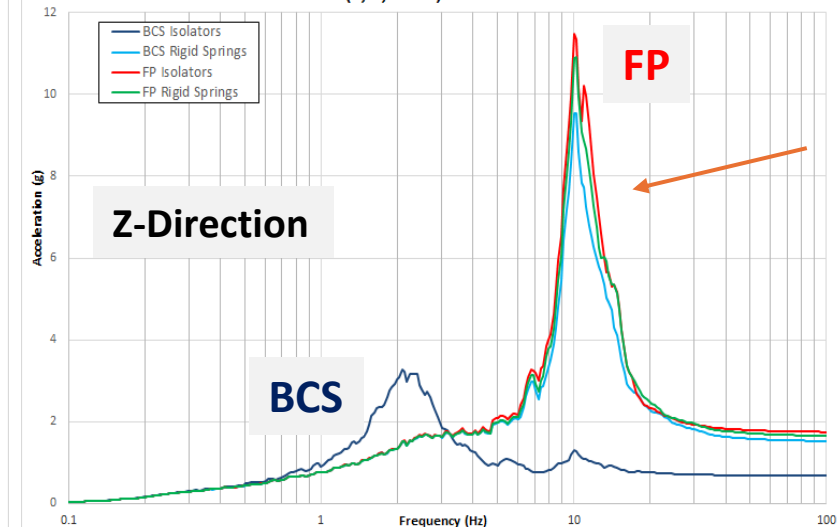
ARC - ISRS (5% Damping) for Node 18792 - Direction Z
at Location (0, 0, -56.5) - Bottom-Stick of RB



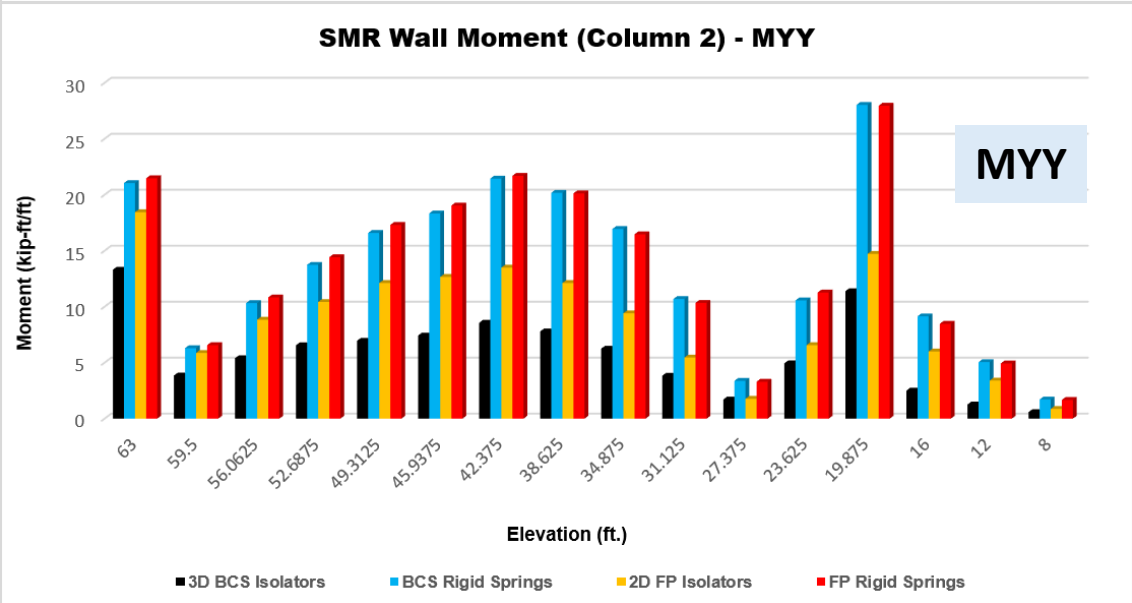
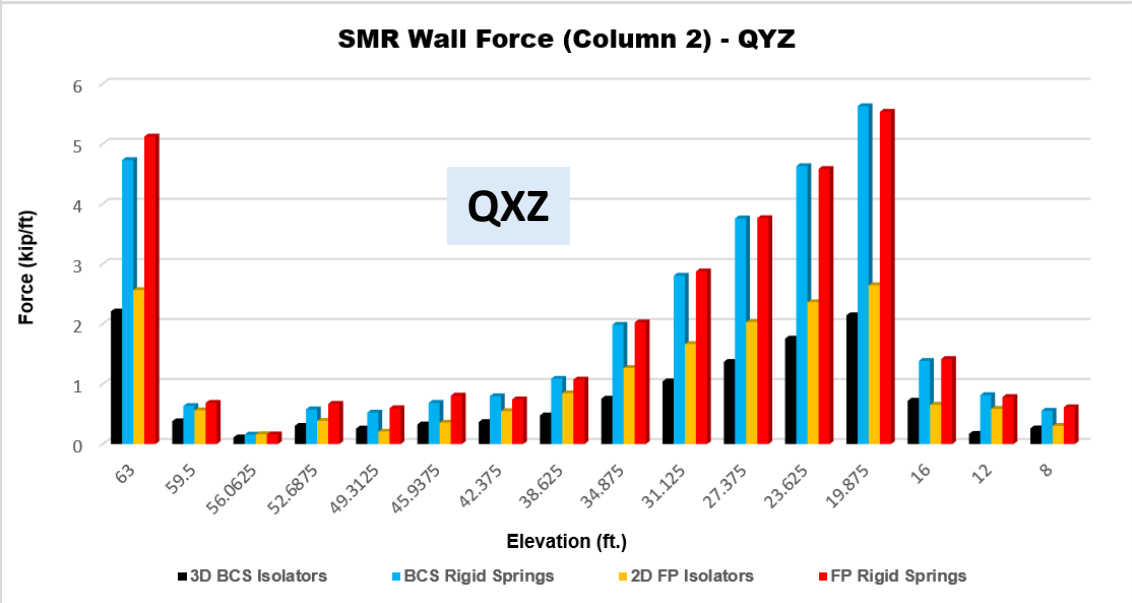
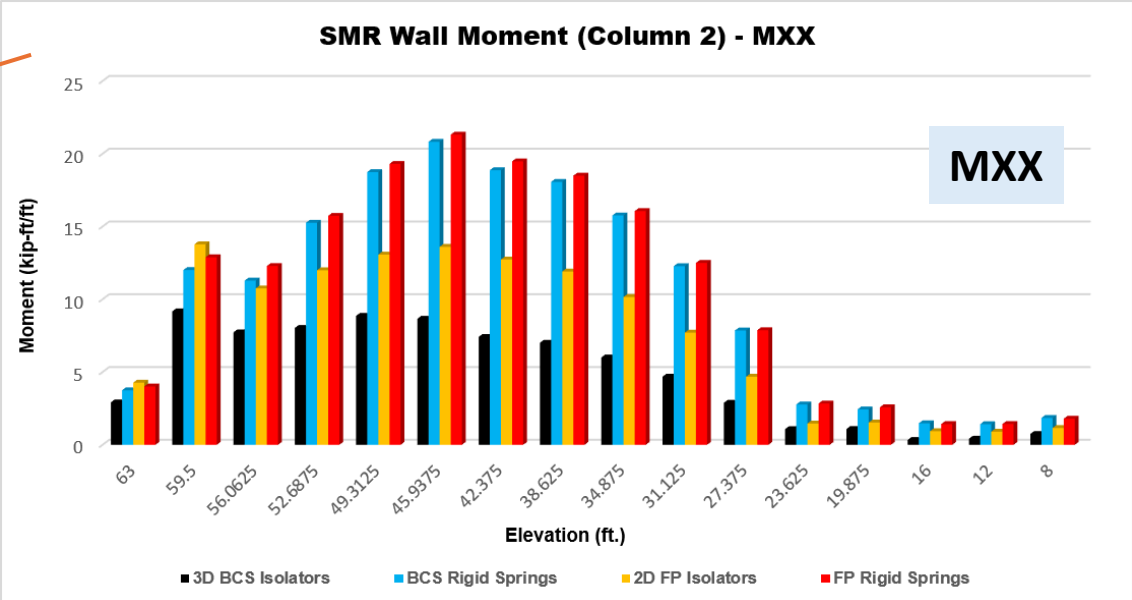
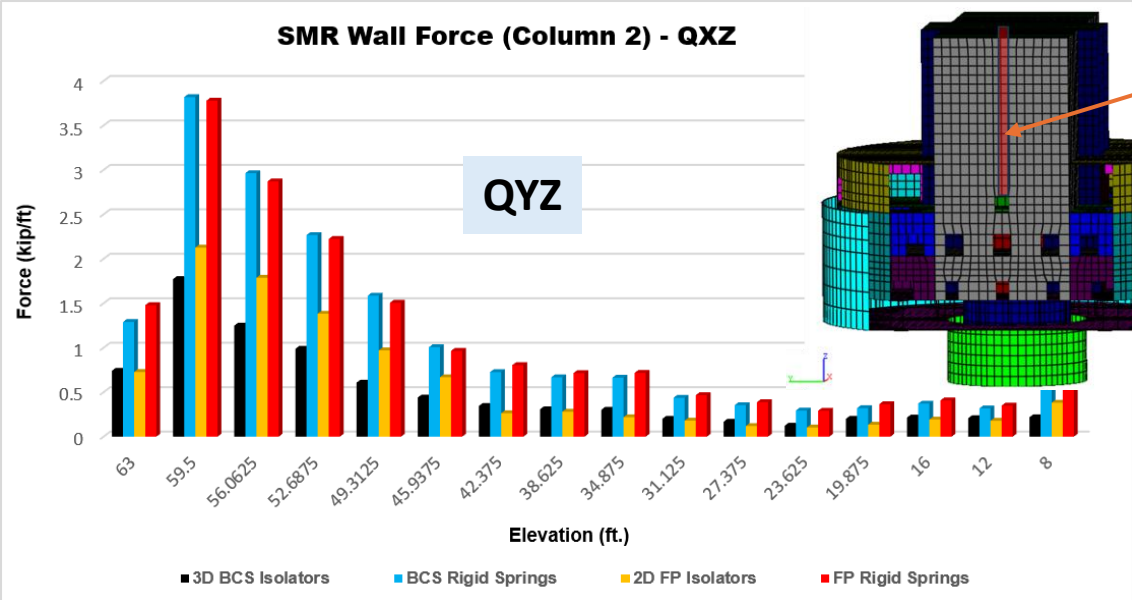
SRS (5% Damping) for Node 4499 - Direction Z
at Location (0, -66, 18) - Edge of RB



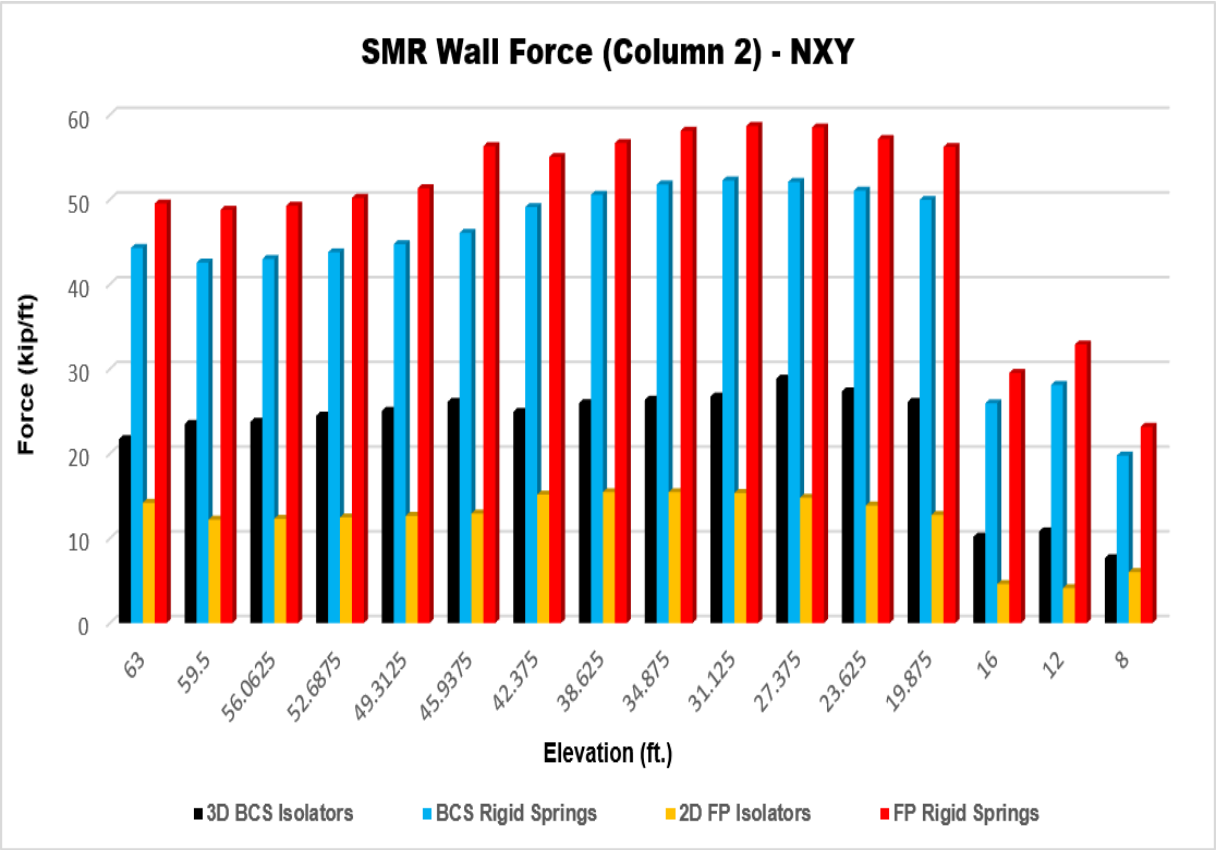
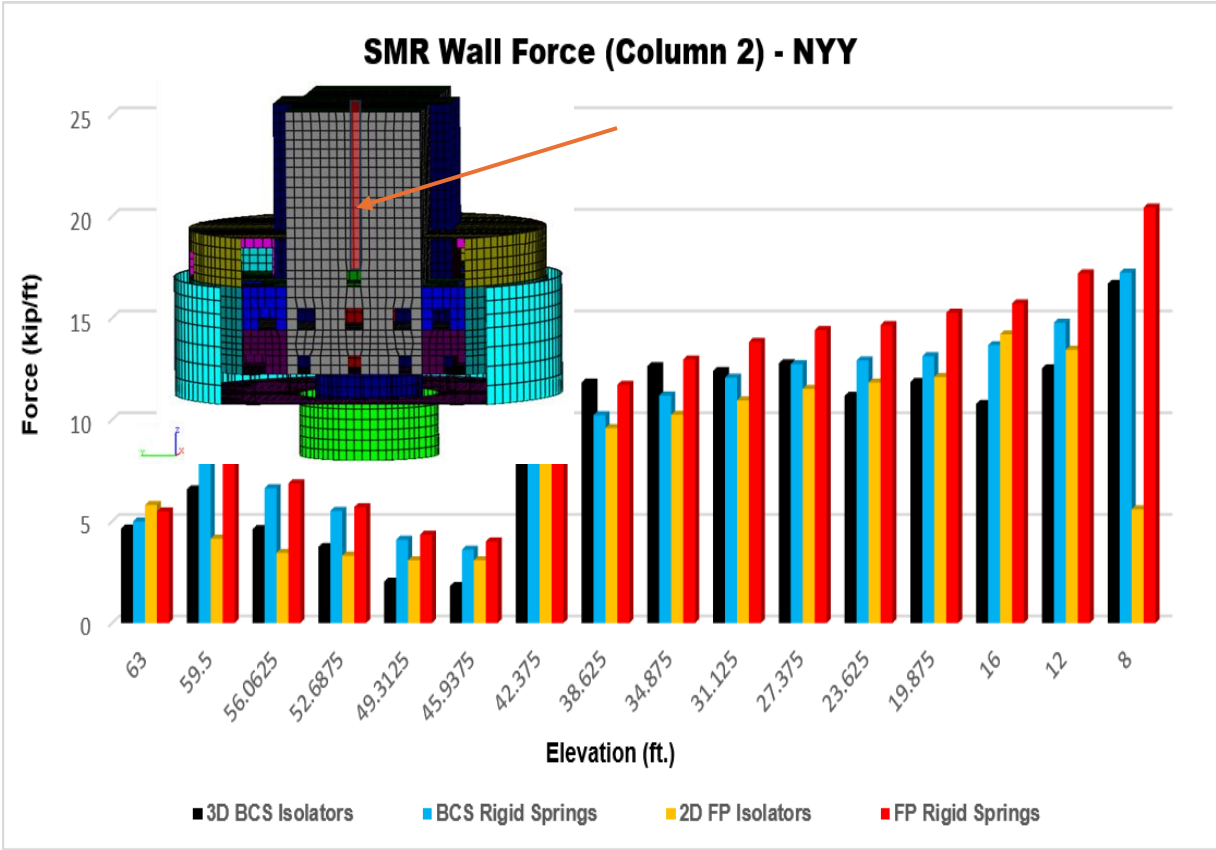
ARC - ISRS (5% Damping) for Node 9044 - Direction Z
at Location (0, 0, 64.75) - Roof-Center of RB



SMR Wall Mean Max DBE Transverse Forces/ Moments



SMR Wall Mean DBE In-Plane Forces/Moments

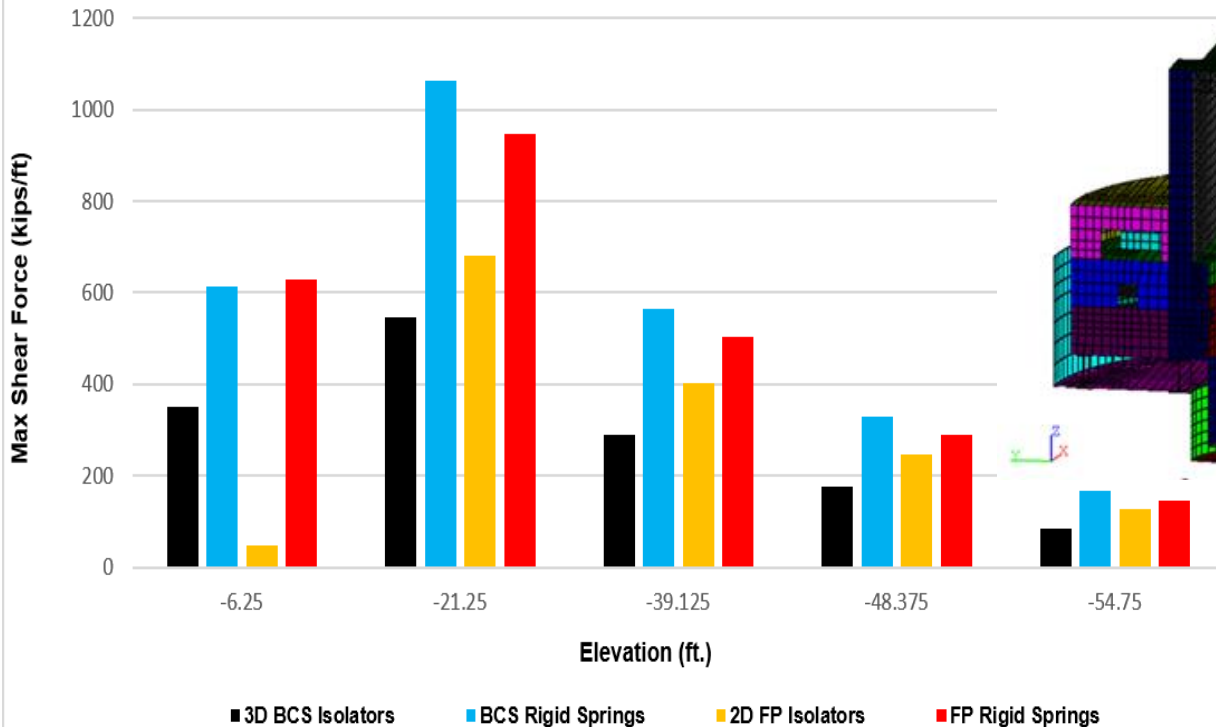


3D BCS Isolators
 BCS Rigid Springs
 2D FP Isolators
 FP Rigid Springs

RV Stick Mean Max Shear DBE Forces/Moments

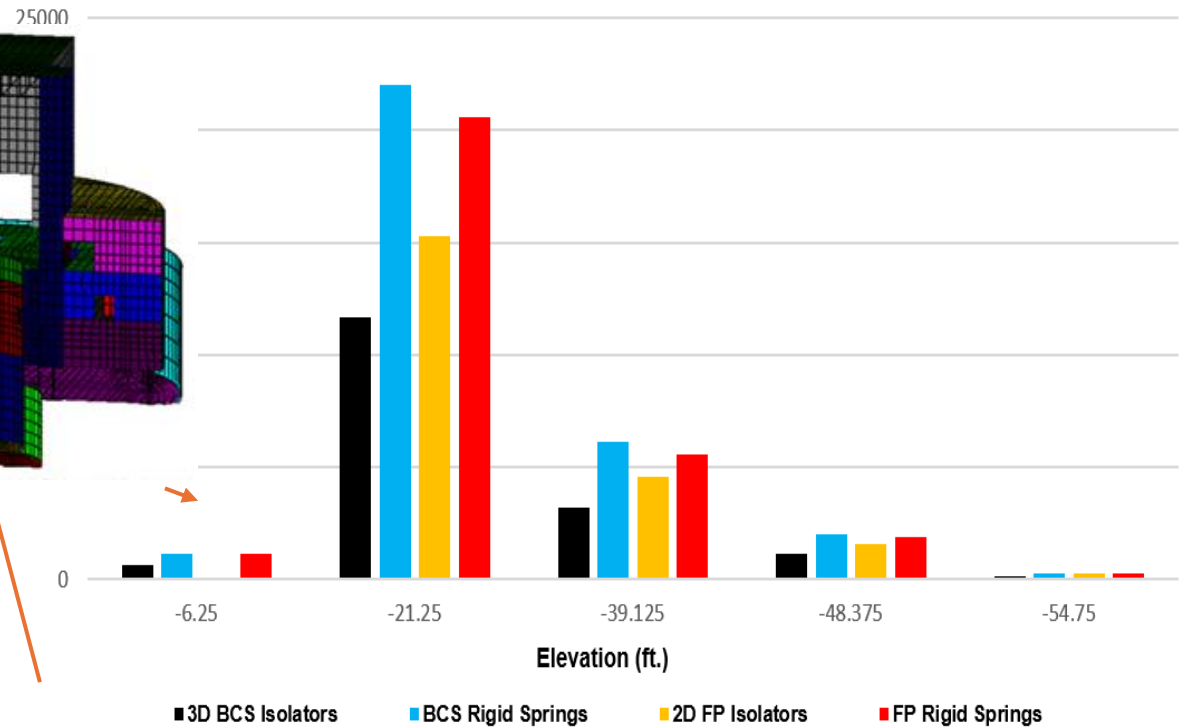
MAX SHEAR FORCE

ARC-100 RB - Max Shear Force in RV System Stick - PY



MAX BENDING MOMENT

ARC-100 RB: Max Bending Moments In RV System Stick - MZ



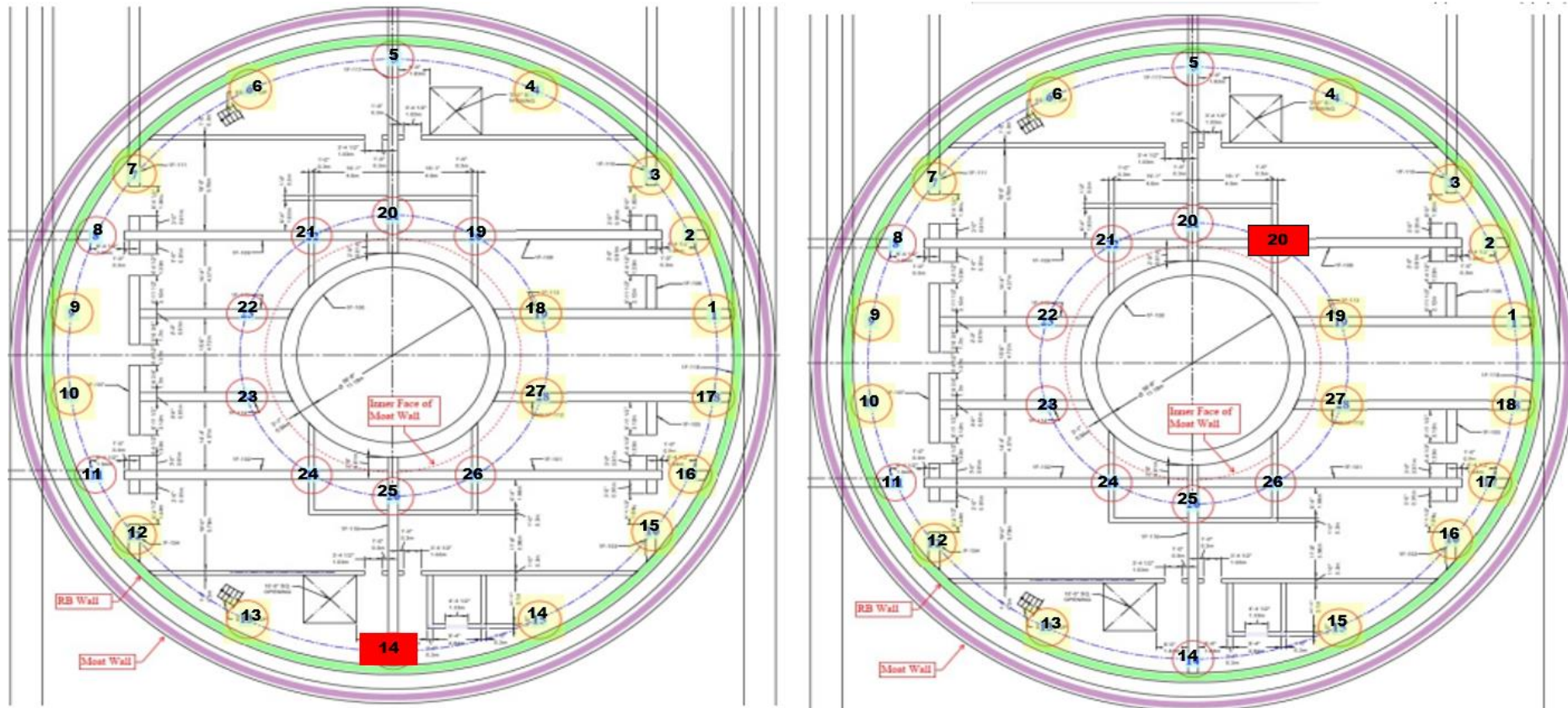
3D BCS Isolators BCS Rigid Springs 2D FP Isolators FP Rigid Springs

4. Effects of Single FP Isolator Failure for SMR Response for Soil and Rock Sites

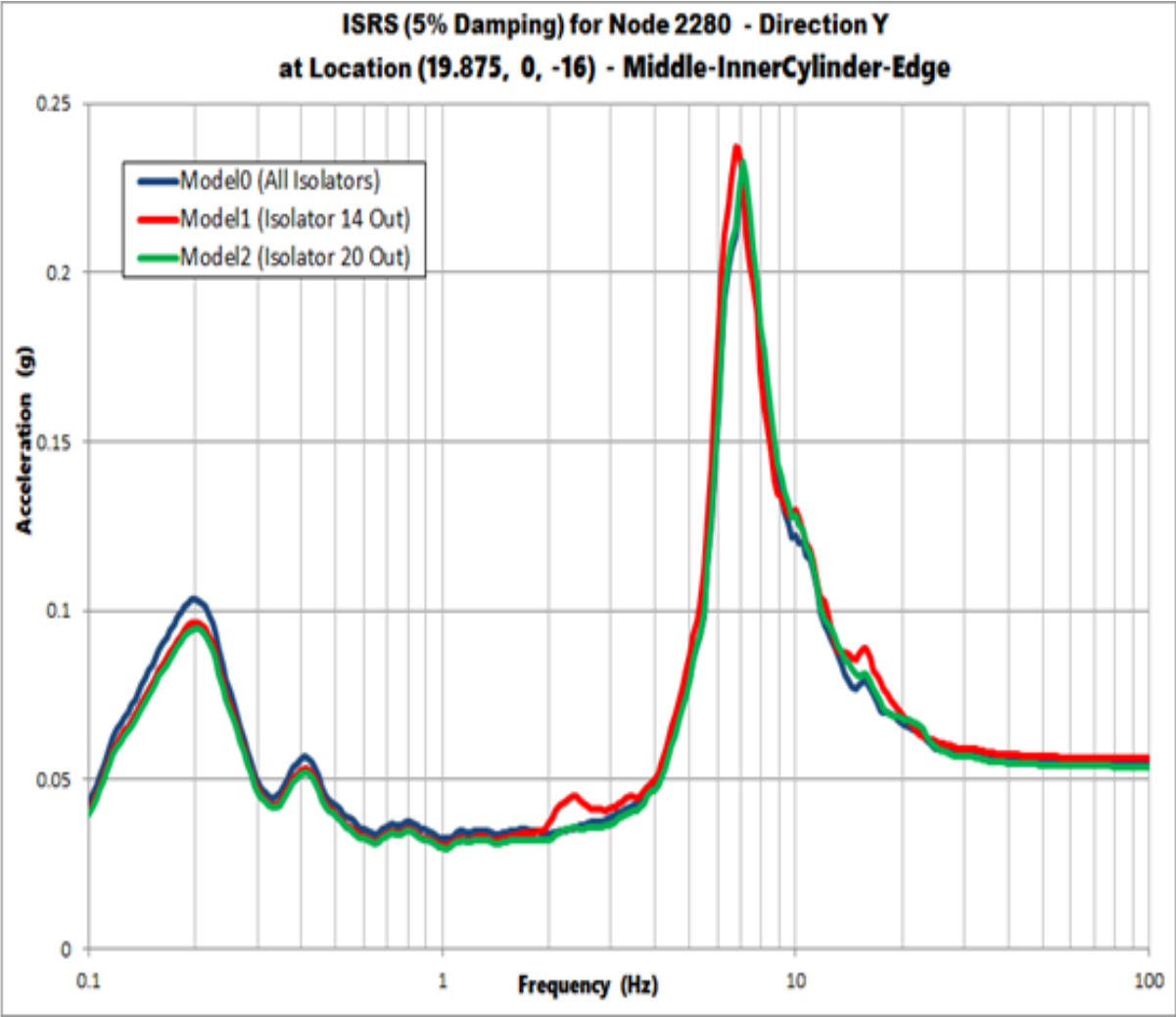
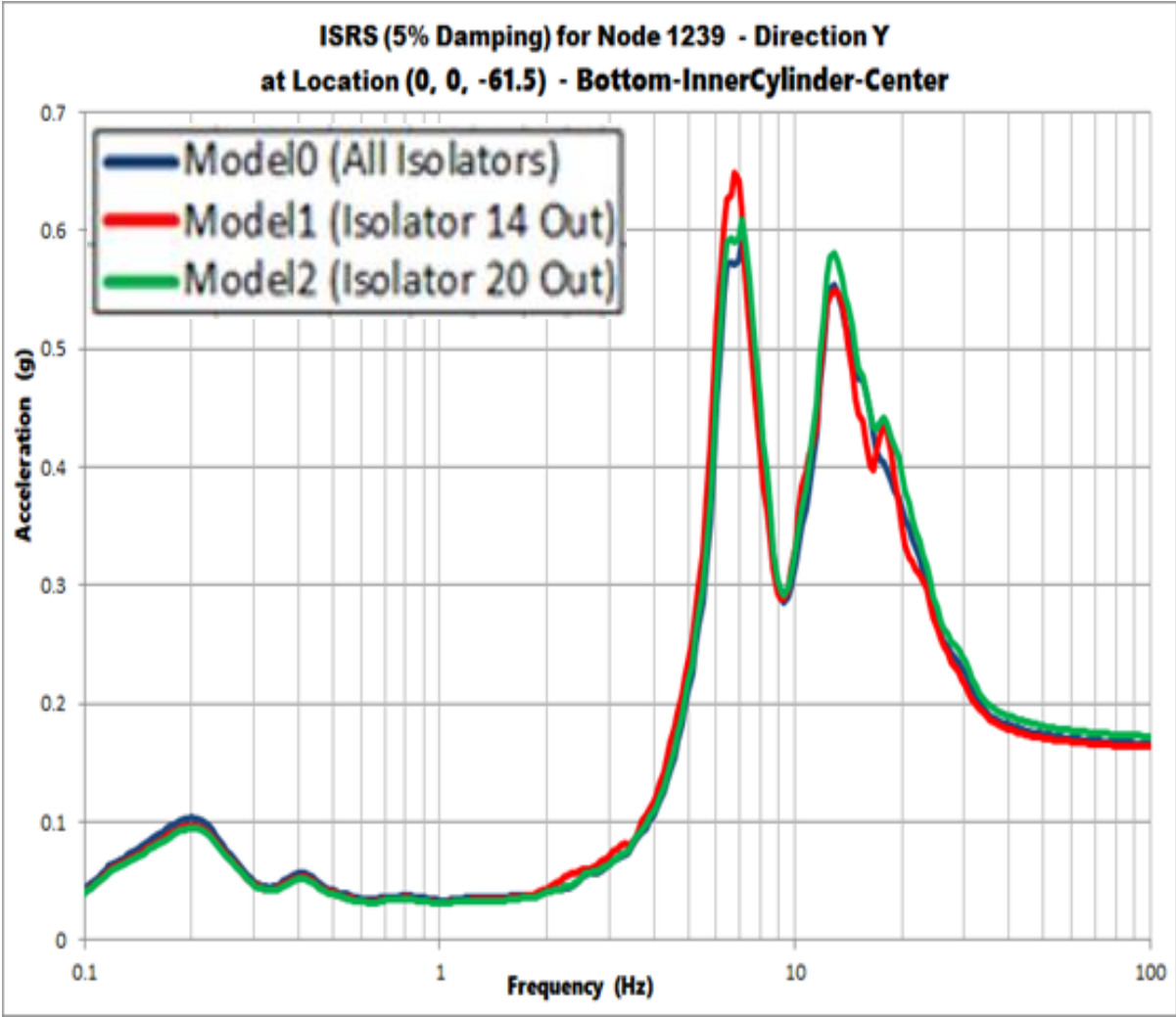
Two Isolator Failure Scenarios for Soil Site and Rock Site

The two selected FP isolator failure scenarios, which correspond to the failure of the isolators with the largest gravity axial loads placed on the outer isolator circle, **isolator #14**, and the inner isolator circle, **isolator #20**. The two failed isolators are at two different locations within SMR upper base.

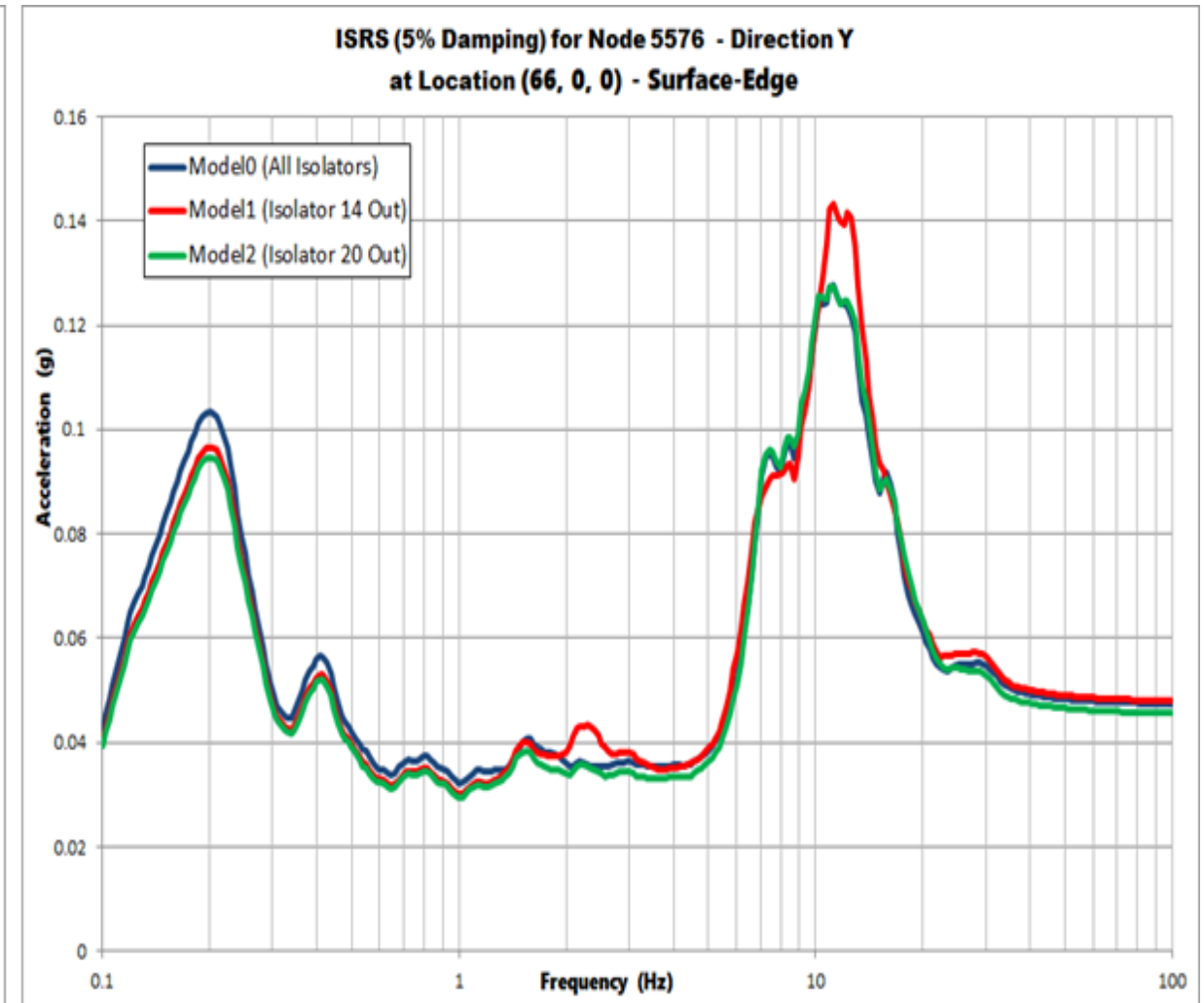
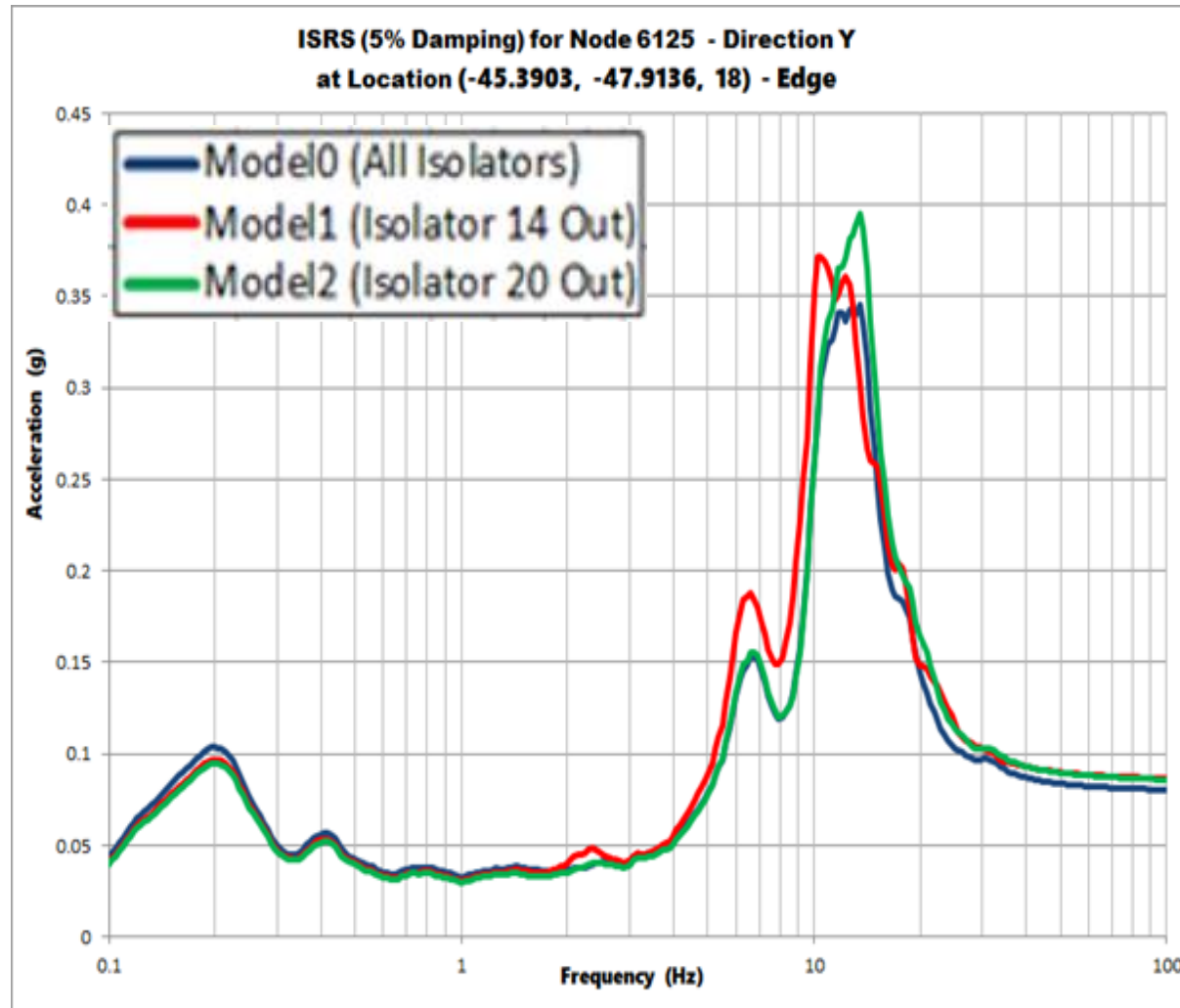
The seismic input was defined by 5 sets of spectrum compatible acceleration triplets for CSDRS for soil site and CSDRS-HF for rock site, while the soil stiffness was defined by the BE soil profiles, $V_s=2,000$ fps for soil site and $V_s=8,000$ fps for the rock site.



ISRS at Below Ground Surface (-61.5ft & -16ft) for Soil Site

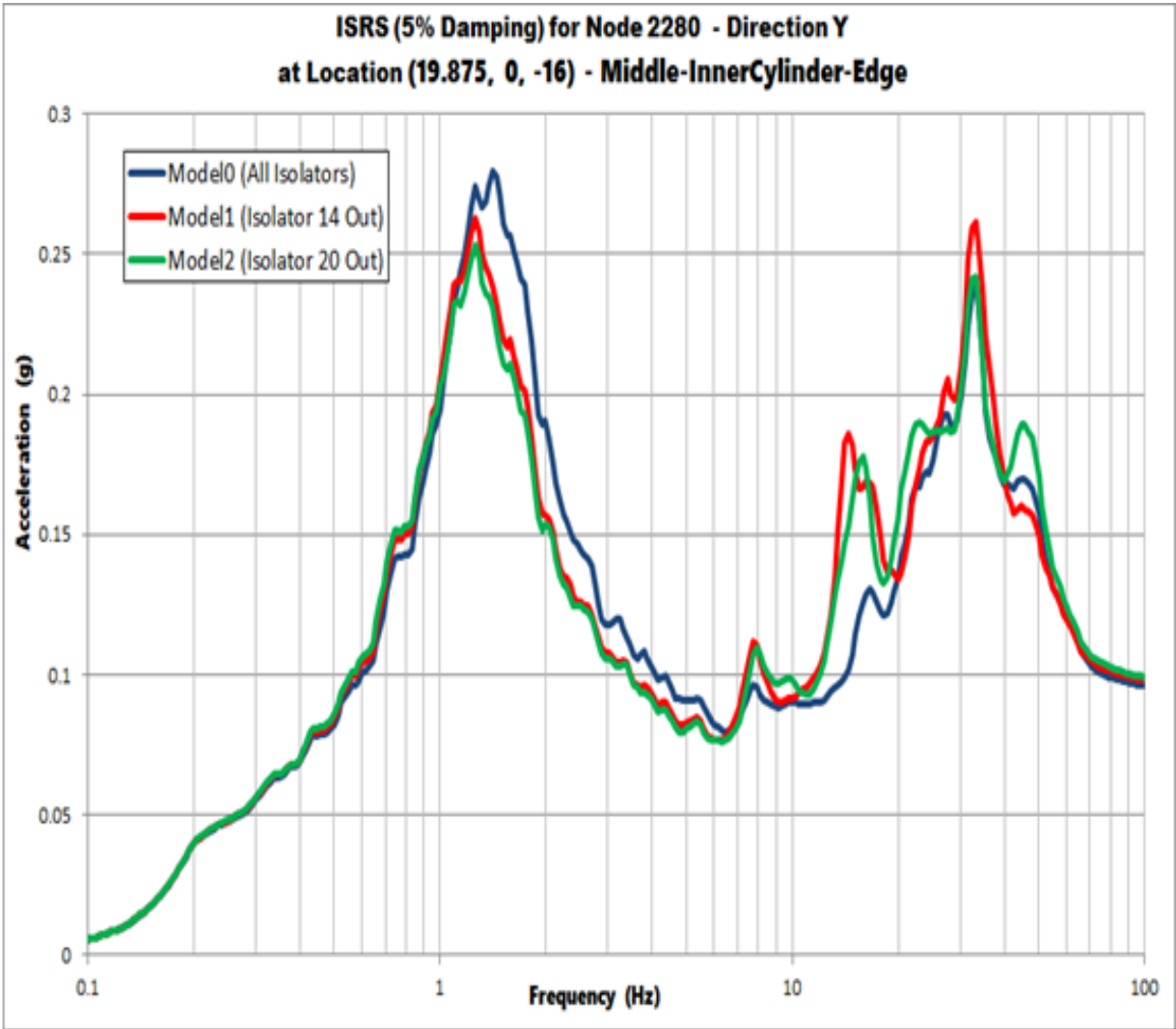
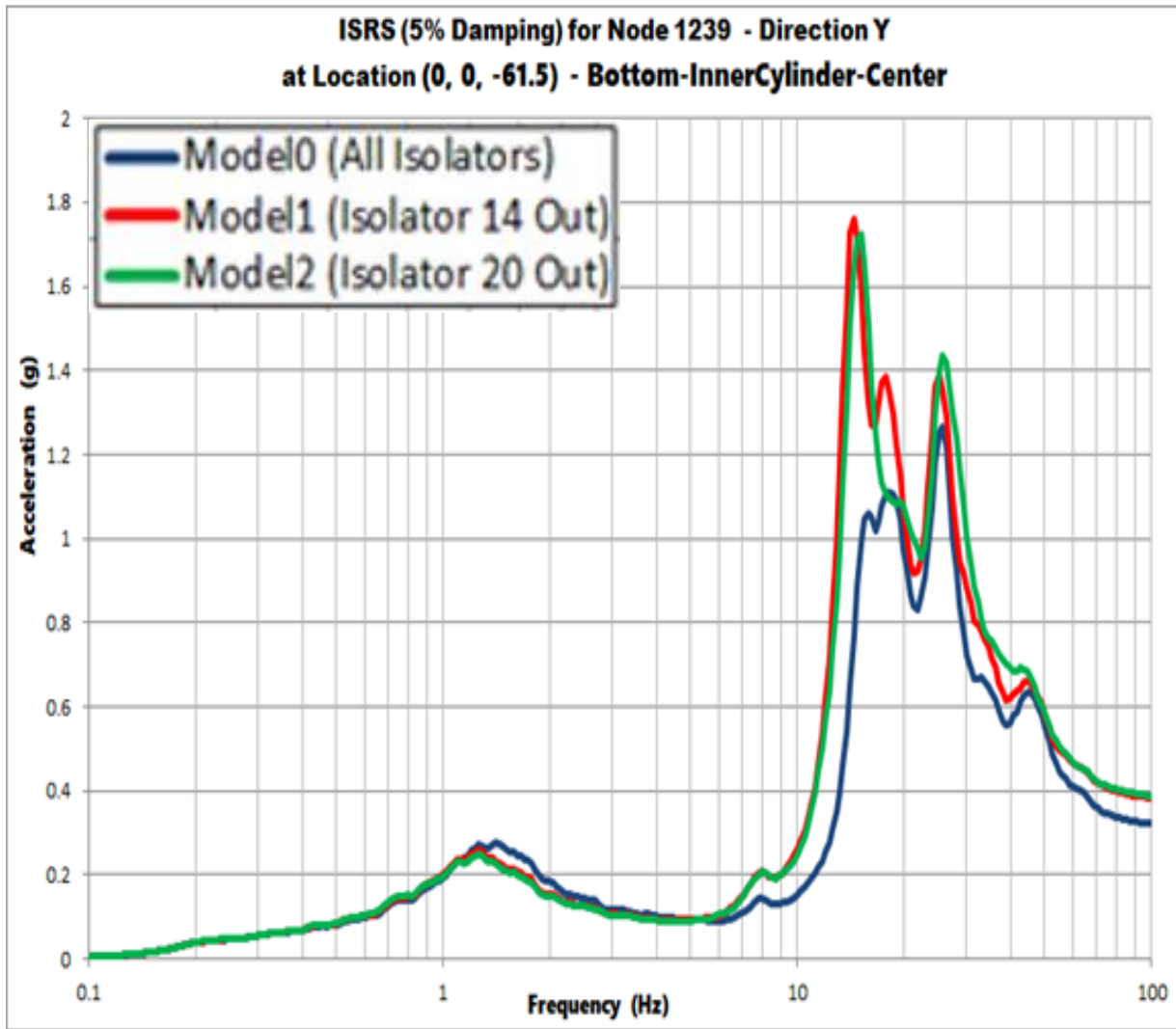


ISRS Above Ground Surface (0 ft & 18 ft) for Soil Site

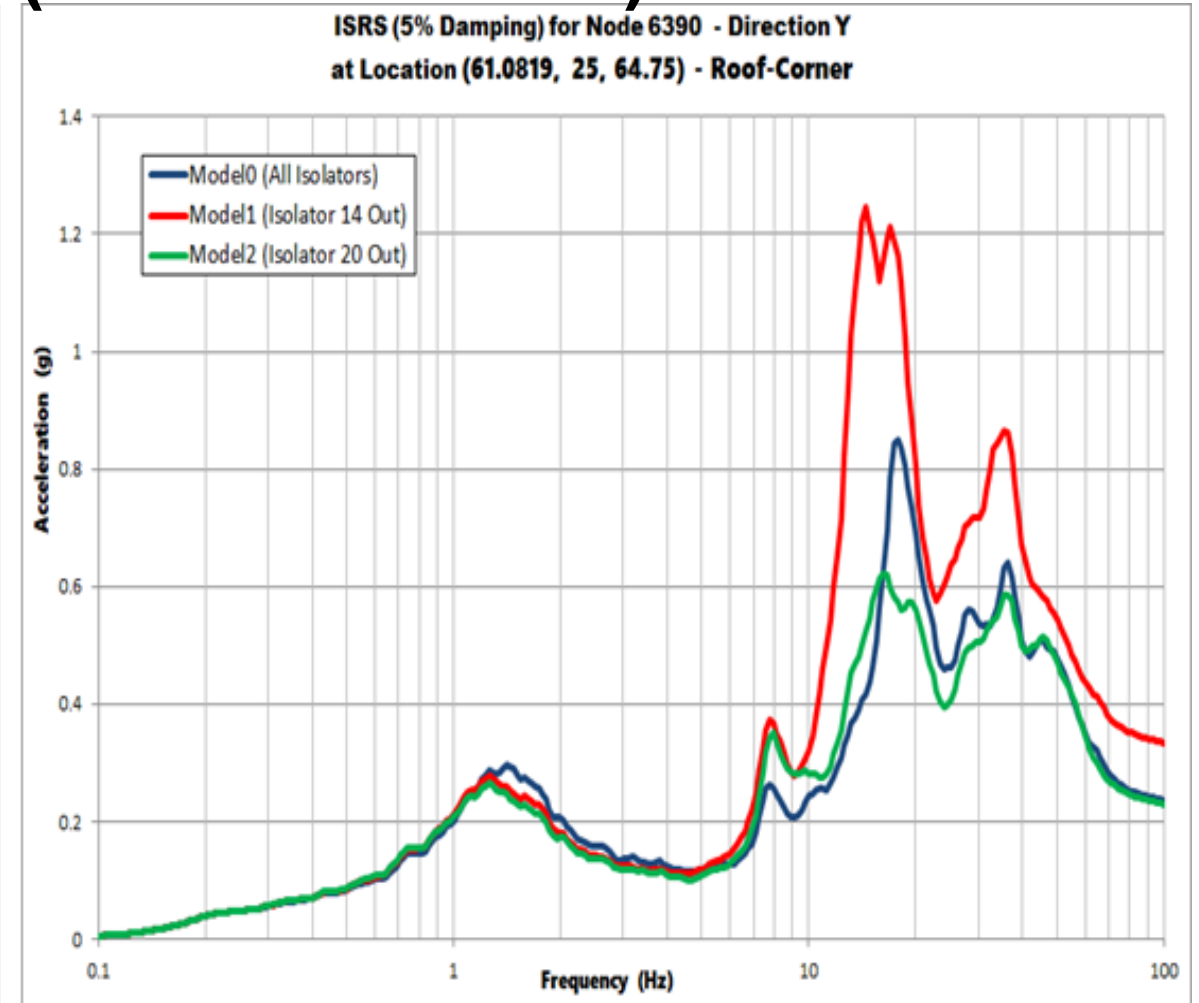
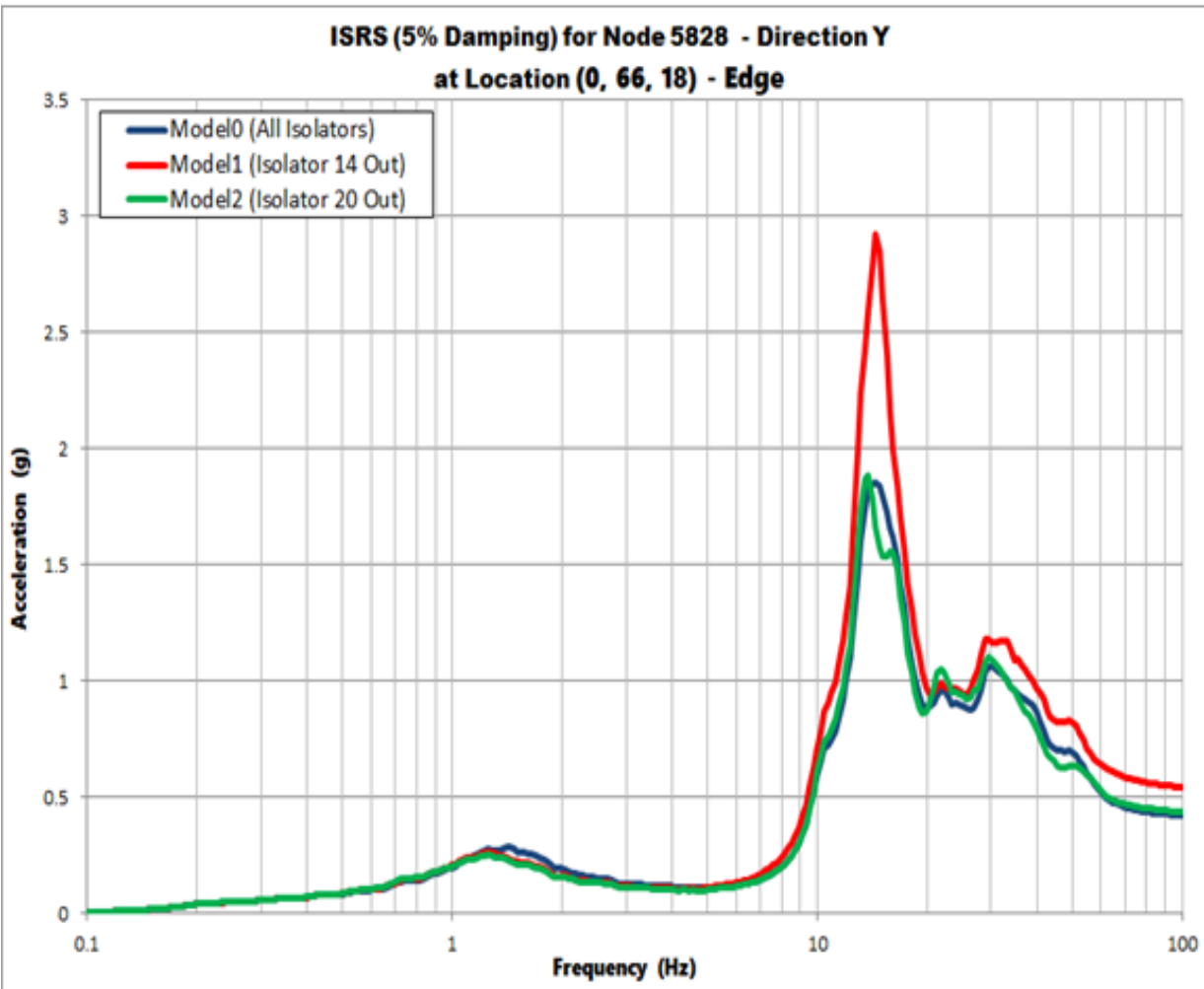


For the **soil site** the ISRS differences due to single isolator failures go up to 15-20% at higher elevation levels.

ISRS at Below Ground Surface (-61.5ft & -16ft) for Rock Site



ISRS Above Ground Surface (18 ft & 64.75 ft) for Rock Site



For the **rock site**, the ISRS differences due to the single isolator failures go up to 100% at higher elevation levels. It appears that the single FP isolator failure could affect the boundary conditions for some local high-frequency structural vibration modes excited in the 15-30 Hz frequency range.

For the two investigated single FP isolator failure scenarios, it appears that the failure of the heavy loaded *isolator #14* which is a part of the outer FP isolator circle *is more critical* than the failure of the heavy loaded *isolator #20* which is a part of the inner FP circle.

5. References for GERB BCS

References for GERB BCS

- Barutzki, F., Kostarev, V., Pavlov, D., Evzikova, I. (2020). "Vibration Elimination Using Viscodamper Technology", Enrgiforsk Technical Report 2020:677, Stockholm
- Barutzki, F., Nawrotzki, P. and Siepe, D. (2024). "GERB Vibration Control Systems Seismic Control Systems – BCS", Private Communication with Dan M. Ghiocel, Berlin
- Baumgaertel, M., and Winter, H. H. (1989). "Determination of Discrete Relaxation and Retardation Time Spectra from Dynamic Mechanical Data", Rheologica Acta, Vol. 28(6), 511-519.
- CVS or CKTI-Vibroseism (2021). "Viscoelastic Damper Series VD", Technical Specification, TS 4192-001-20503039-01, Akkuyu NPP, St. Petersburg
- GERB (2022) "Elastic Support of Power Plant Structures, Machinery and Equipment", GERB Online Brochure, EN-2022-08-1
- GERB (2019). "BCS Numerical Description", GERB-CVS-GPTech Two-Days Private Workshop, Berlin
- Ghiocel, D.M., Kostarev, V. and Nawrotzki, P. (2022). "Seismic SSI Analysis of A Base-Isolated Storage Structure Founded on Firm Soil", " SMiRT26 Conference, Div. III, Berlin
- Ghiocel Predictive Technologies (2024a) "Seismic SSI Analysis of Base-Isolated Deeply Embedded ARC-100 SMR Structure on Different Site Conditions", Technical Report GPT-UNITED-WA005-2024-1-31, Rev 1, May 13
- Ghiocel Predictive Technologies (2024b) "SSI Sensitivity Studies for Supporting the Design-Basis Modeling of Base-Isolated Deeply Embedded ARC-100 SMR", Technical Report GPT-UNITED-WA006-2024-7-31, Rev 0, July 31
- Ghiocel Predictive Technologies (2025). "Preliminary Study on Seismic SSI Analysis of Deeply Embedded Base-Isolated ARC-100 SMR Using 3D-Space BCS Isolation", Technical Report GPT-UNITED-WA009-2025-10-15, Rev 0, October 15

References for GERB BCS

- Kostarev, V., Bercovsky, A., Kireev, B., Vasiliev, P.(1993). "Application of Mathematical Model for High Viscous Damper to Dynamic Analysis of NPP Piping Systems", SMIRT-12, Division K, paper K20/6
- Kostarev, V., Nawrotzki, P. and Vasiliev, P. (2015). "3D Base Isolation of Reactor Building Using BCS Concept, Post-SMIRT23 Seminar, Istanbul
- Makris, N. and Constantinou, M. (1990). "Viscous Dampers: Testing, Modeling and Application in Vibration and Seismic Isolation", NCEER, SUNY at Buffalo Technical Report, NCEER-90-0028, Buffalo
- Nawrotzki, P. and Siepe, D. (2014). "Structural Challenges of Power Plants in High Seismic Areas", 2nd European Conference on Earthquake Engineering and Seismology, ECEES, Istanbul, 2014
- Nawrotzki, P., Kostarev, V., Siepe, D, Barutzki, F. and Salcedo, V. (2022)."3D Seismic Isolation Systems for Nuclear Industry Layout, Design and Qualification", SMIRT26, Division V, Berlin-Postdam
- Patel, A.D., Parsi, S.S., Whittaker, A. and Constantinou, M. (2025). " 3D Viscoelastic Dampers: Age Effects and Validation of FSI-based Numerical Models", 19WCSI, Berkeley
- Patel, A.D., Whittaker, A. and Constantinou, M. (2026). "Experimental and Numerical Characterization of 3D Fluid Viscous Dampers for Application to Seismically Isolated Nuclear Structures and Safety-Related Equipment" DOE/NRC Natural Phenomena Hazards (NPH) Workshop, D2-A-5, US NRC Headquarters, Rockville, MD
- Tamura, I.,Kuramasu, M., Barutzki, F., Fiisher, D., Kostarev, V., Berkovsky, A., Vasiliev, P., Inoue, T., Okita, S. and Namiita, Y. (2016). "Dynamic Analysis of NPP Piping Systems and Components with Viscoelastic Dampers Subjected to Severe Earthquake Motions", Proceedings of the ASME 2016 Pressure Vessels and Piping Conference, PVP2016-64029, Vancouver
- TerraPower (2024). Reactor Seismic Isolation System Qualification Topical Report, Doc. No. NAT-8922, Released in March

BACK UP SLIDES

SUPPLEMENTARY INFORMATION ANIMATIONS

Key Behavioral Aspects of 2D and 3D Isolation Systems

The **2D FP isolation** produces the largest overall reduction of the SMR structural accelerations, it does not solve the issue with the large amplifications due to local vibration modes, some largely amplified due to the vertical-horizontal mode couplings.

The large sliding displacements of few feet are critical for BDBE. Uplift can be an issue for BDBE.

The **3D BCS isolation** produces a smaller overall reduction of the SMR structural accelerations but completely solves the issue with the large amplifications due to local vibration modes.

All local SMR vibration mode responses above 2.5 Hz frequency are completely filtered out.

It has much smaller horizontal displacements, fraction of a foot, acceptable for BDBE.

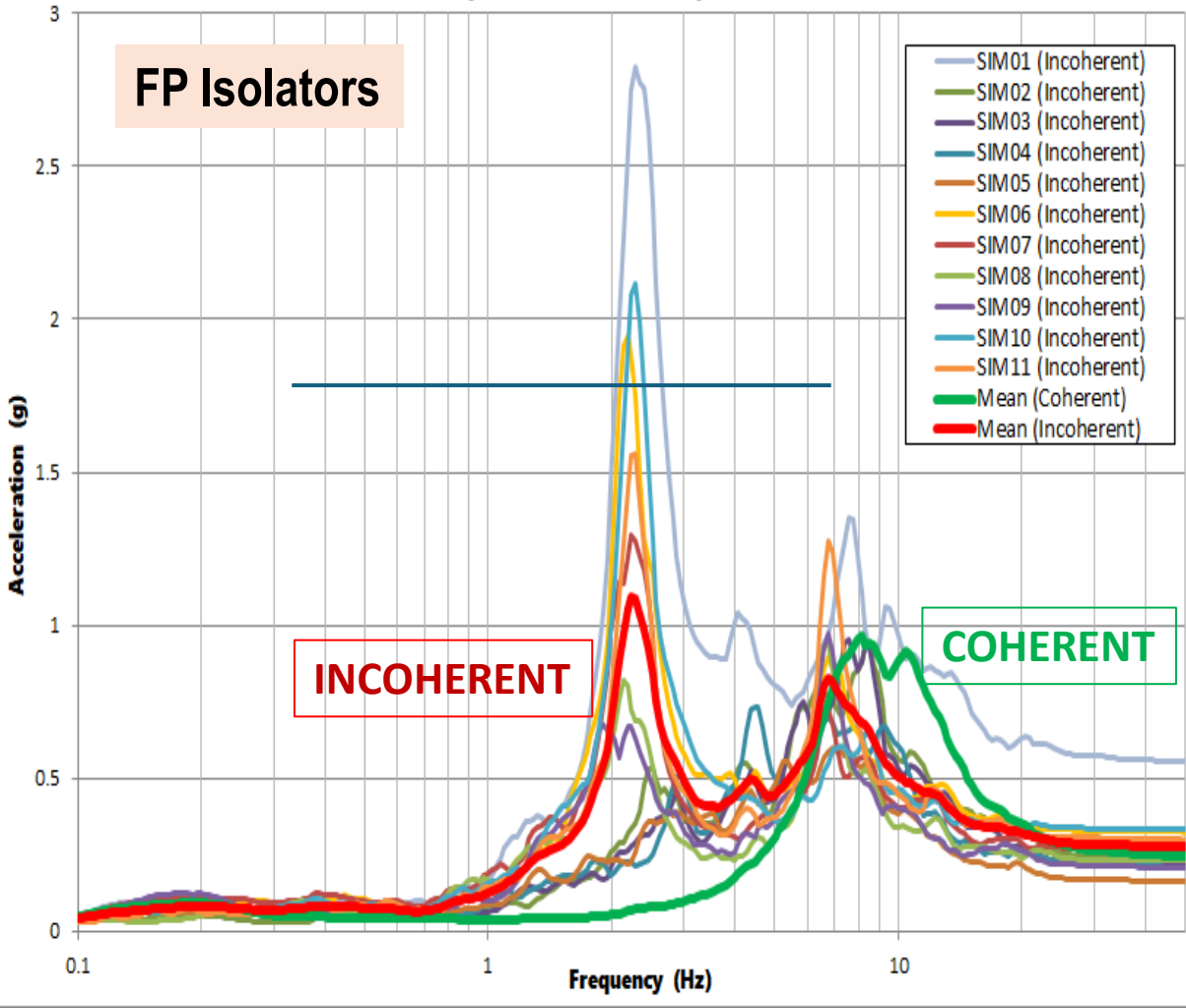
Motion incoherency, which simulates realistic 3D-space seismic waves based on real dense array records, could *significantly affect the 2D FP isolation efficiency by amplifying ISRS* due to significant increase of the vertical-horizontal response motion couplings produce by the presence of non-vertically propagating wave components.

Motion incoherency effects are less significant for 3D BCS isolation due to the total decoupling of the vertical-horizontal motions.

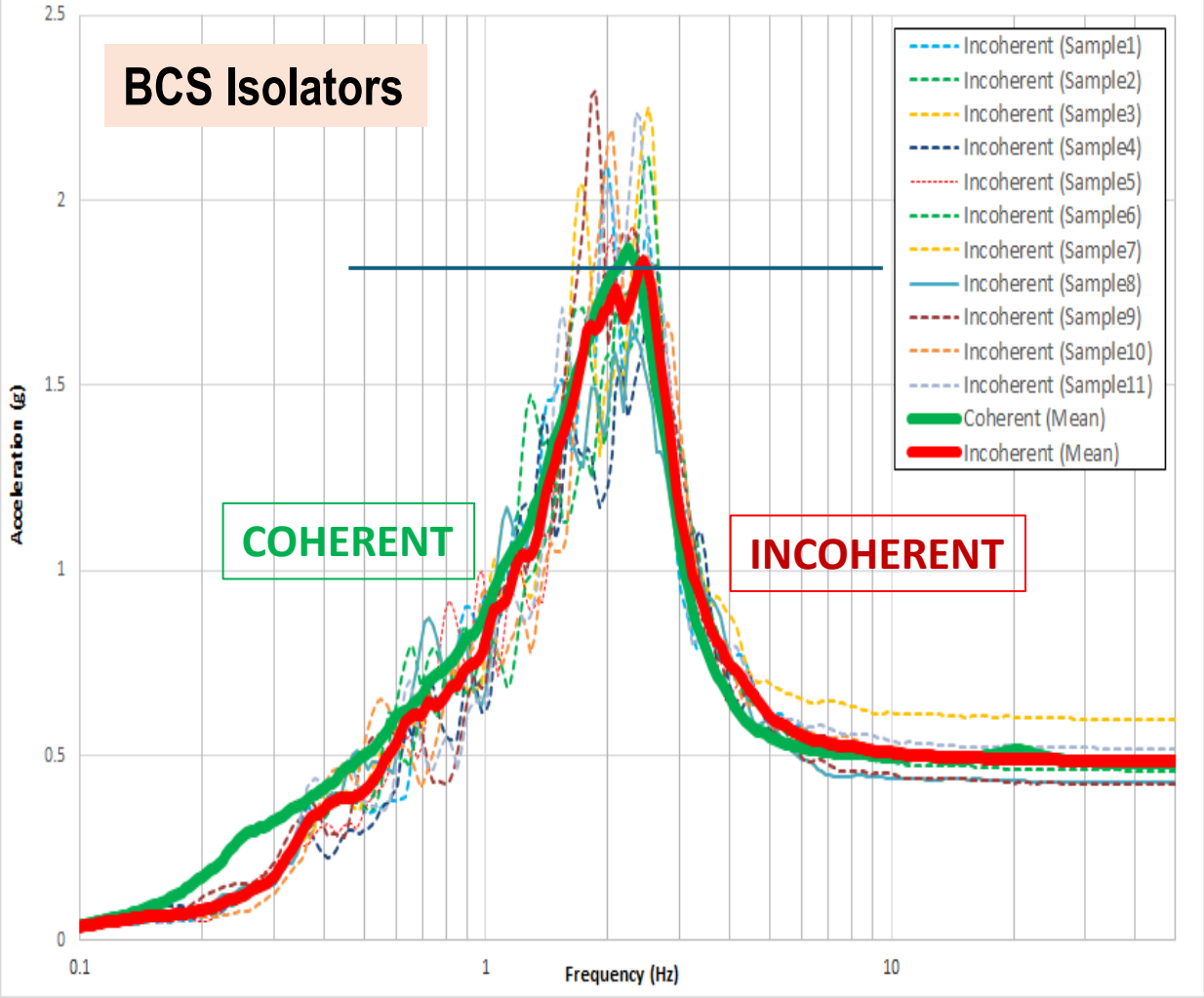
Motion Incoherency Effects on ISRS for FP and BCS Isolations

RB Roof Corner

ISRS (5% Damping) for Node 6390 - Direction X
at Location (61.0819, 25, 64.75) - Roof-Corner



ARC - ISRS (5% Damping) for Node 5046 - Direction X
at Location (61.0819, 25, 64.75) - Roof-Corner of RB

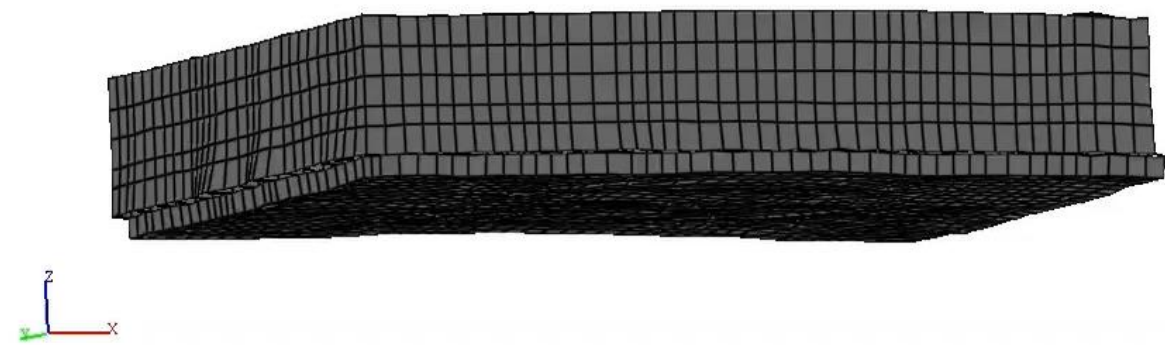
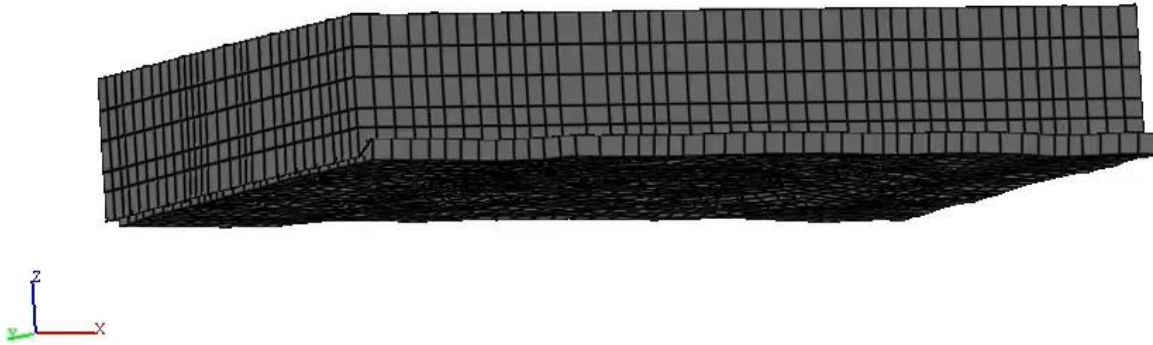


RB Complex on 3D BCS & 2D LRB Hysteretic Isolators

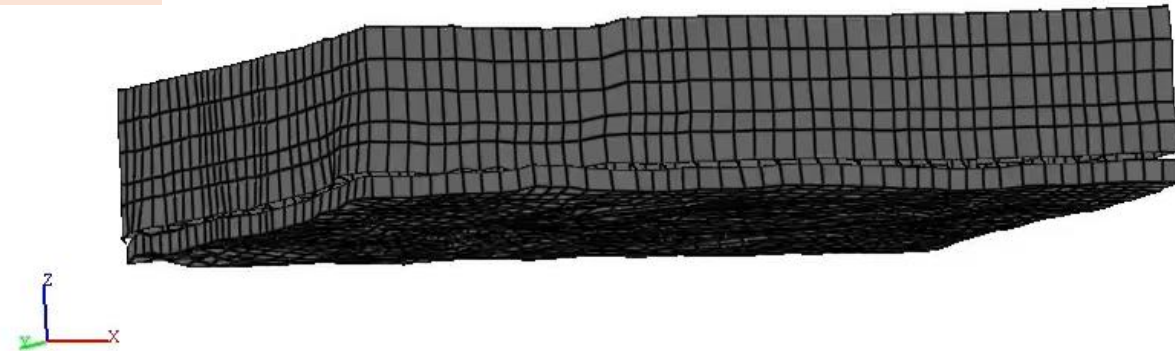
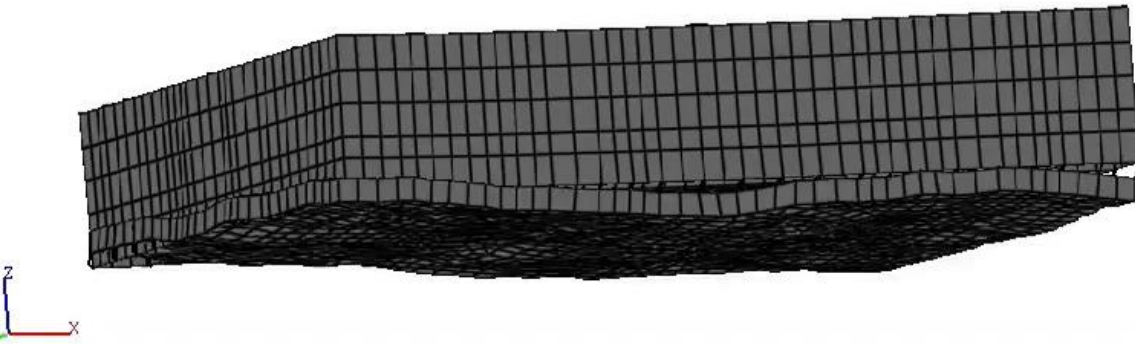
BCS Isolators

Coherent

LRB Isolators



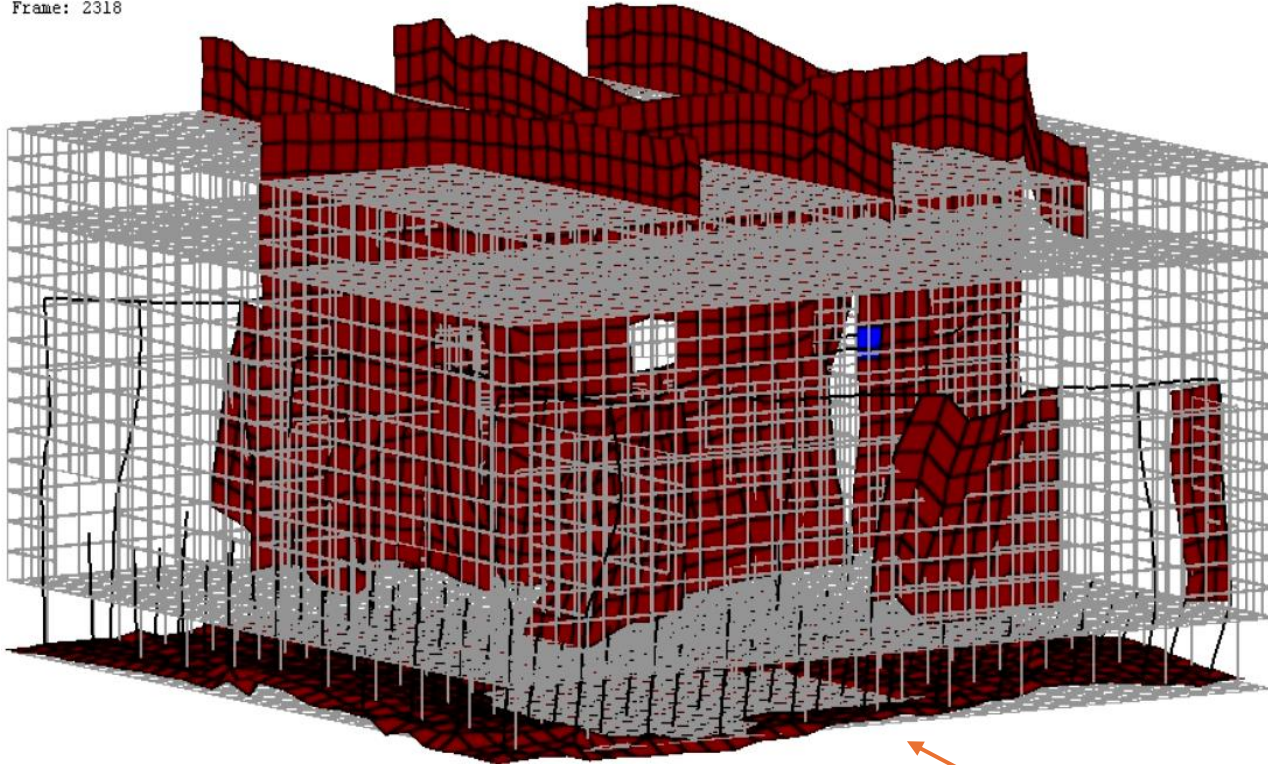
Incoherent



Nuclear Storage Building on 3D BCS & 2D LRB Isolators

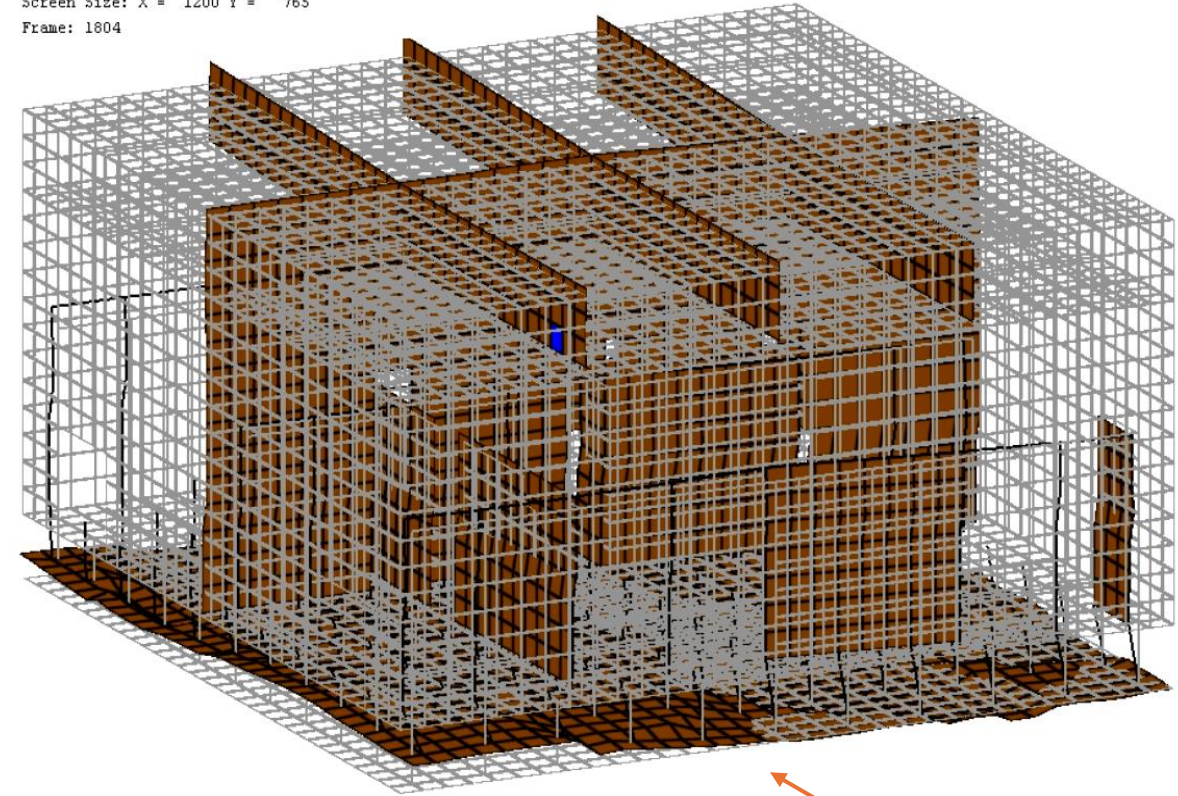
LRB Isolators

Rot: X = 82.500000 Y = 0.000000 Z = -33.000000 LRB-INCOH-ACC
Zoom: 0.532000 Pan: X = 0.000000 Y = 0.000000
Screen Size: X = 1198 Y = 764
Frame: 2318



BCS Isolators

Rot: X = 74.500000 Y = 0.000000 Z = -26.000000 BCS-INCOH-ACC
Zoom: 0.558000 Pan: X = 0.000000 Y = 0.000000
Screen Size: X = 1200 Y = 765
Frame: 1804



Incoherent

(Ghiocel et al., 2022, SMiRT26)

**Initial 120 mm Horizontal Displacement.
Constrained suddenly released.**





**Initial 120 mm Horizontal Displacement.
Constrained suddenly released.**

SSI Analysis for Hybrid SIS Includes Both FP and BCS Isolators

