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New Plant Seismic Issues Resolution Program – Follow-Up Discussion of S2.1 Incoherence Project

December 20-21, 2006

Stephen Short
Jim Johnson
Greg Hardy

New Plant Seismic Program Task S2.1(a)

- New Report – "Effect of Seismic Wave Incoherence on Foundation and Building Response" EPRI No. 1013504, November 2006
- Meeting Topics
  - Progress Report on S2.1a Actions from October 24-25 NRC Meetings (9 Action Items Resulting from Meeting)
    - Coherent-Incoherent Response
    - Important Fixed-Base Modes
    - Validation
    - CLASSI and SASSI Comparison Studies
- NRC Comments to New Material

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October S2.1a Action Items

- **Action #1 -** The EPRI Project Team will review the implications of a change in the coherency function to address the low values at depths between 10 and 20 m (see Topic 1 task list). EPRI will develop a recommendation on how to address a potential variation in the coherency function with depth. Assuming that a change to the coherency function with depth is determined, new foundation and structure responses will be analyzed to demonstrate the effects of the changes as appropriate.

- **Status**
  - New coherency function at depth defined on December 9th
  - Project team recommends using this new function for embedded structures at all elevations
  - Starting the review of the effects of the new coherency function for comparison to original (surface) function, mid January completion
  - Recommendation for surface founded structures pending results of study

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October S2.1a Action Items

- **Action #2** - Greg Hardy will arrange a conference call with Dr. Abrahamson and interested parties to discuss the following questions: If the basic site seismic hazard is defined from recorded ground motions using the entire strong motion window, why does the coherency evaluation consider only the plane S-wave contribution? Does the wave passage effect in the SSI calculation induce response in excess to that caused by the consideration of the plane wave coherency only?
- **Status**
  - Requested call conducted 11/6/06
  - Clarification of several issues
  - NRC consultants agreed to send written questions to clarify remaining items

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October S2.1a Action Items: #2 Cont.

- Follow up Questions from Aspa Zerva and Carl Costantino sent by NRC (11/7/06)
- "The following questions are posed to NEI/EPRI regarding the use of plane wave coherency in the SSI calculations
  a) If the basic site seismic hazard is defined from recorded ground motions using the entire strong motion window, why does the coherency evaluation consider only the plane S-wave contribution?
  b) Does the wave passage effect in the SSI calculation induce response in excess to that caused by the consideration of the plane wave coherency only?"
- Response to Questions via email on 12/10/06 from Norm Abrahamson and Jim Johnson

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October S2.1a Action Items

- **Action #3** - Changes to the report will be made by ARES:

a. To address a number of editorial items that were identified

b. Wording will also be changed to state that the coherency function “was assumed to be independent of depth” not “was independent of depth”.

c. Reference will be made to Dr. Veletsos’ earlier study on incoherency that describes the “approximate deterministic” approach and a descriptive comparison of the ARES and Veletsos approaches will be made.

d. Chapter 4 will be amended to address the translation and rotation combination.

e. The use of random vibration theory in addition to SRSS to determine the combination of translation and rotation for edge translations will be considered (ARES) and changes to figures may be incorporated.

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October S2.1a Action Items

- **Action Item #3 - Status**
  - All items requested have been completed and were incorporated into the recent November EPRI report

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October S2.1a Action Items

- **Action #4** - Dr. Costantino will schedule a discussion with Bechtel on SASSI details relative to the input motion power spectral density (PSD) preservation and on load vectors.
- **Status**
  - Believe this discussion was conducted? Dr. Costantino to provide summary of results of conversation.

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October S2.1a Action Items

- **Action #5 -** ARES will provide additional information on the main structural model results (frequencies, mode shapes, eigenfunctions and participation factors up to about 30 Hz) in order for the NRC consultants to fully understand the responses.
- **Status**
  - Studies completed to provide requested information
  - Presented in following section of presentation

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October S2.1a Action Items

- **Action #6** - ARES to discuss with EPRI a path generating documentation and a version of CLASSI (can be kept proprietary) with incoherency to the NRC for specific use in reviews on this project.
- **Status**
  - Cleared the legal hurdles
  - In process of documenting code for use/understanding by others
  - Portions to be sent at the end of December
  - Complete package in late January

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October S2.1a Action Items

- **Action #7** - Discuss and resolve the issue of whether both versions of SASSI and CLASSI get the increase in the low-frequency region due to the rotations. There should be a problem that is done consistently with all codes. The resolution will be communicated to the NRC.
- **Status**
  - Evaluation in process
  - Preliminary results presented in following section
  - Still have work to do to complete study

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October S2.1a Action Items

- **Action #8** - Discuss/implement ways for industry to participate in an effort to generate an NRC/Industry consensus on elements of the seismic qualification process that have not been finalized, e.g., :

a. Convolution for soil, rock and deep soil sites
b. Site profile properties uncertainty usage for SSI analyses
c. Minimum seismic design levels
d. Site response assessment methods

- **Status**
  - NEI meeting held Dec 13 to generate industry input/recommendations
  - NRC meeting held Dec 14 with industry
  - Further interactions requested relative to draft SRP sections

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October S2.1a Action Items

- **Action #9** - Plots of the free-field ground motion, SSI coherent and SSI Incoherent Fourier Spectra for figures such as 5-80 and 5-81 of the EPRI Report 1013504 to help demonstrate the effects of SSI (coherent or incoherent) on the seismic response of foundations and structures.
- **Status**
  - Evaluations completed and will be presented in the following presentation sections

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Coherent – Incoherent Foundation Response

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Foundation Response: Review of Free-Field, Coherent, and Incoherent Response

- Objective: Demonstrate the characteristics of the foundation response for coherent and incoherent assumptions
- Rock site profile and high frequency ground motion
- Kinematic interaction – response of a rigid, massless foundation subjected to the free-field ground motion - also called foundation input motion (FIM)
  - Coherent wave assumption – FIM = free-field ground motion
  - Incoherent wave assumption – FIM = (free-field ground motion) * Incoherency Transfer Functions (ITFs)
- SSI response
  - Structure model supported on 150 ft square foundation
  - Coherent wave assumption – Inertial interaction
  - Incoherent wave assumption – Kinematic and inertial interaction

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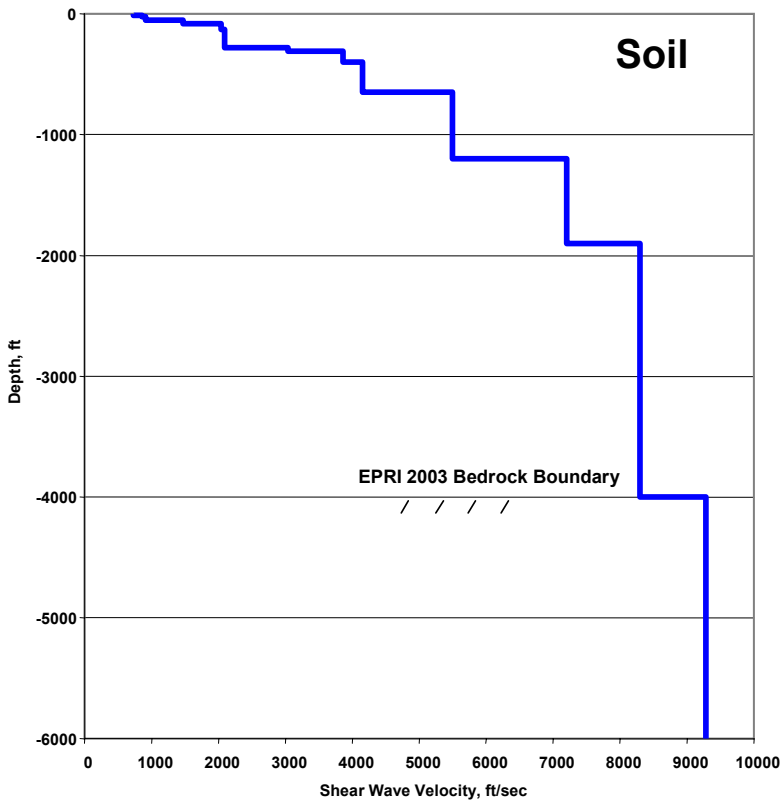
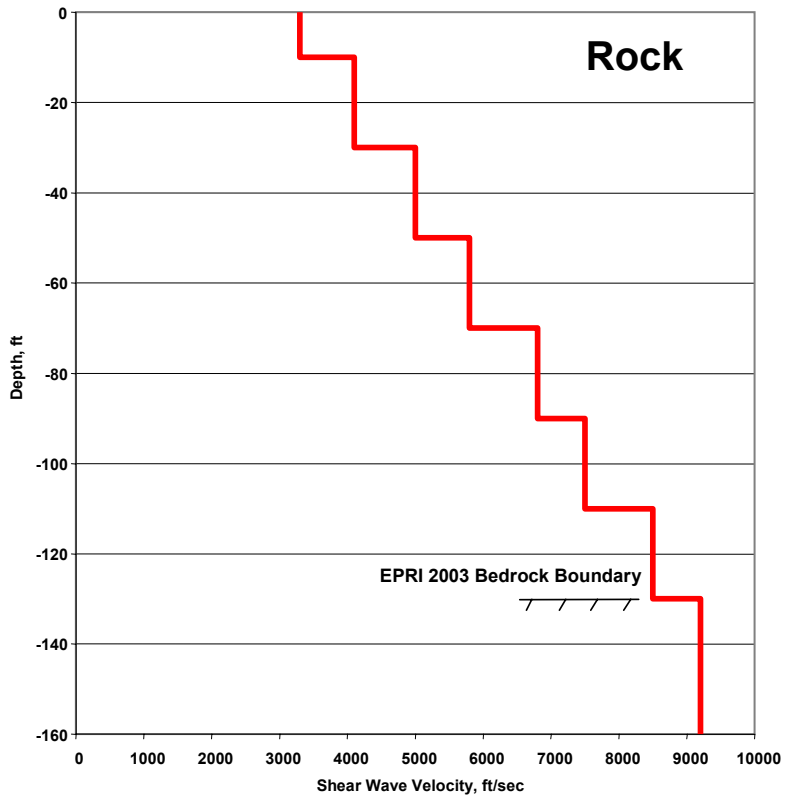
Rock and Soil Site Profile
Shear Wave Velocities vs. Depth





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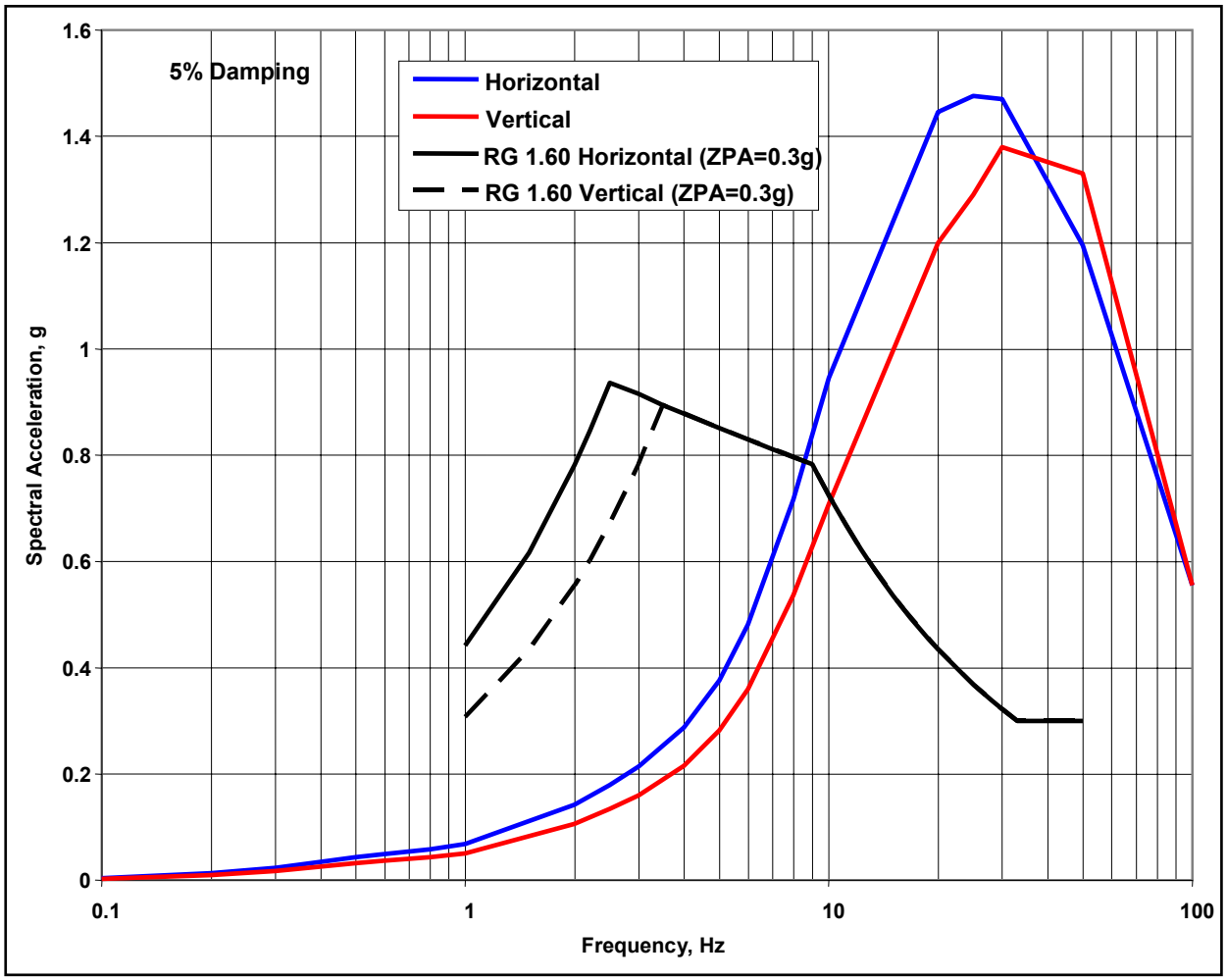
Site-Specific Response Spectra for Rock Site at Ground Surface (Depth 0-ft)



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Free-Field vs. Foundation Input Motion (FIM) (Kinematic interaction)

- Response of a **rigid, massless foundation** subjected to the incoherent wave field defined by the Abrahamson ground motion coherency functions
- Free-field ground motion defined by acceleration time histories (horizontal and vertical)
- Foundation is square - 150 ft on a side
- Rock site profile
- FIM calculated by applying the Incoherency Transfer Functions to the Fourier transform of the free-field ground motions – Inverse Fourier transform to obtain time histories on foundation
- Response spectra (5% damped) and Fourier Amplitude Spectra calculated

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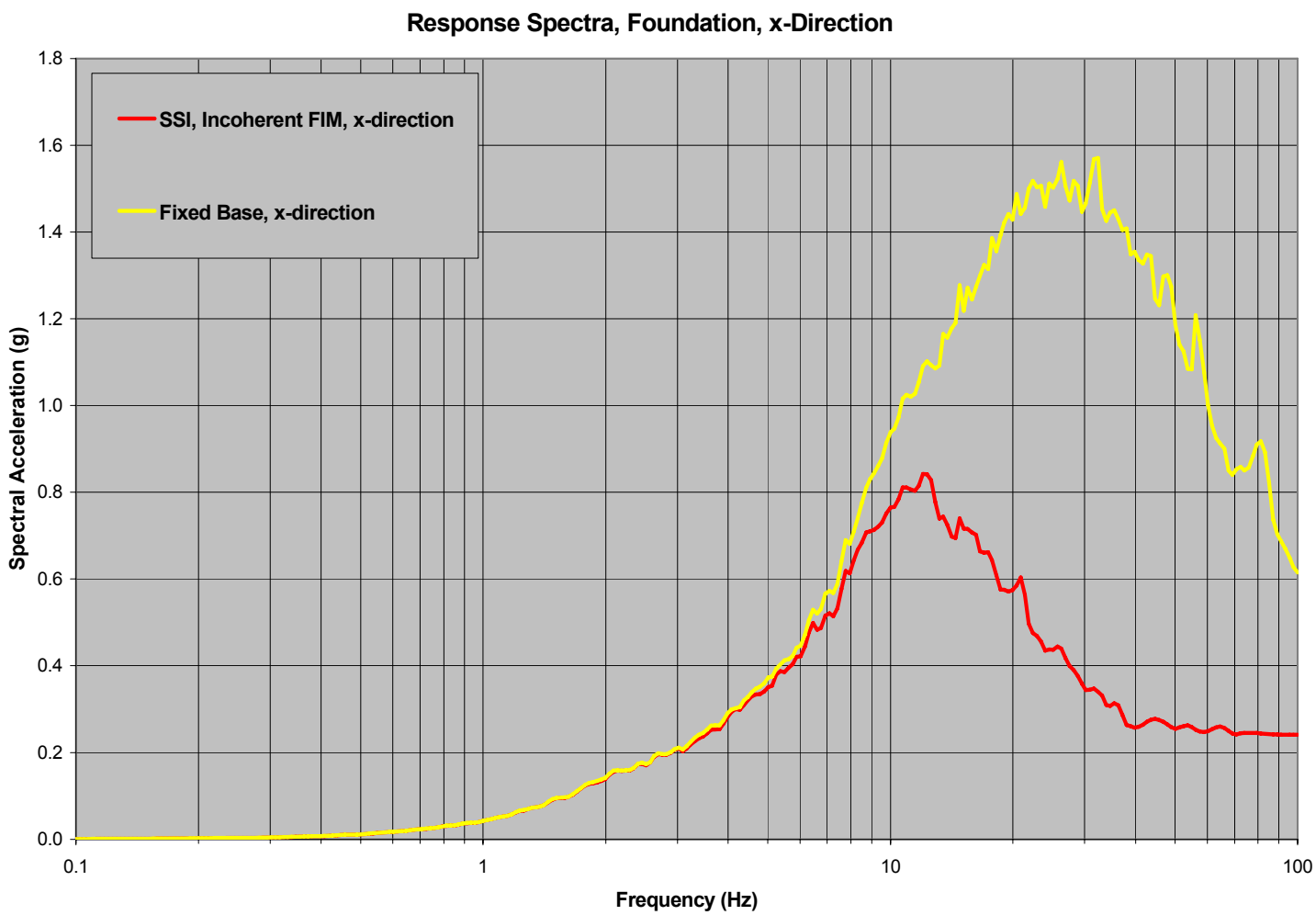
Response Spectra: Free-Field vs. Foundation Input Motion (Incoherent wave assumption) – Horizontal



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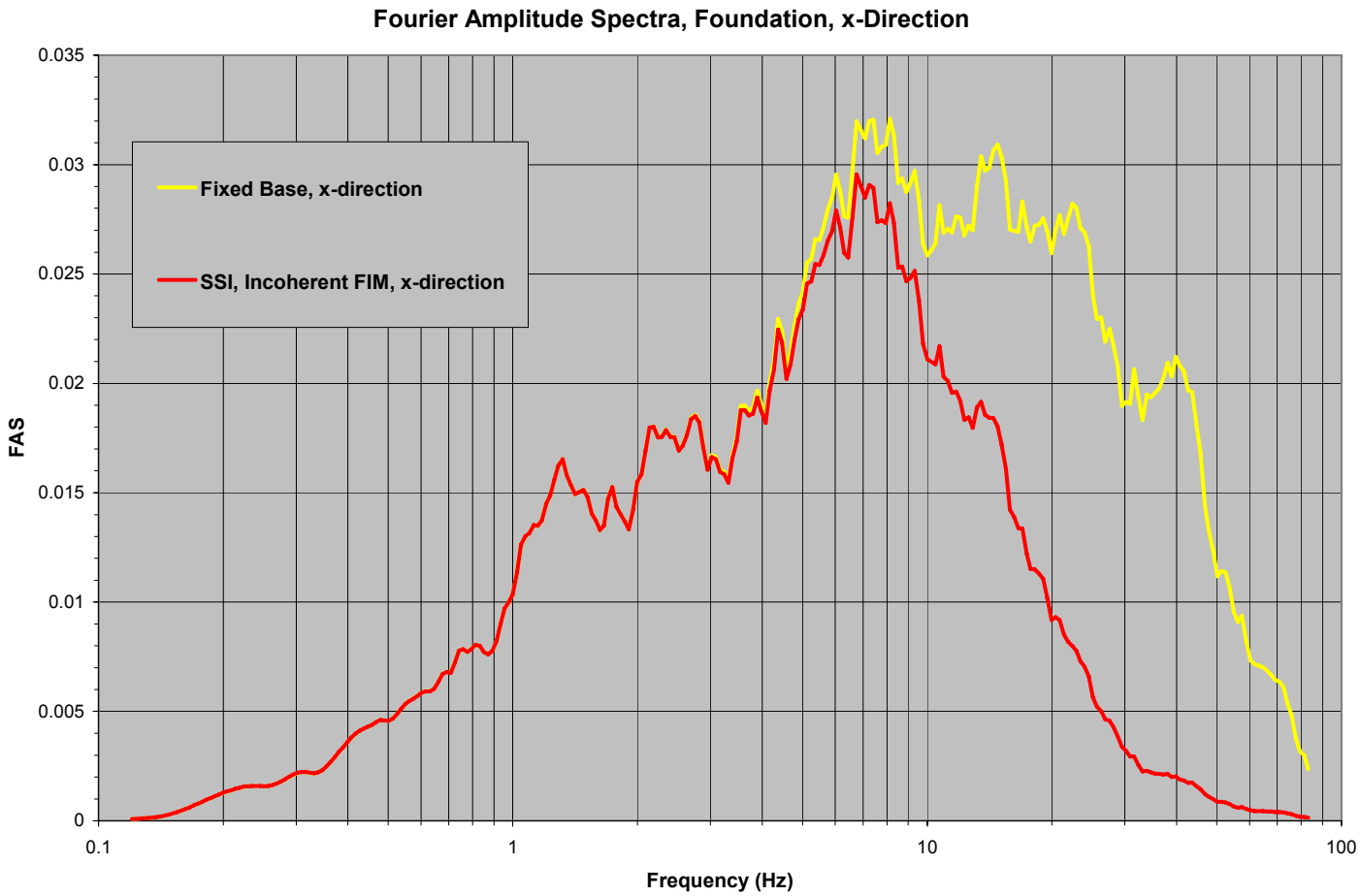
Fourier Amplitude Spectra: Free-Field vs. Foundation Input Motion (Incoherent wave assumption) – Horizontal



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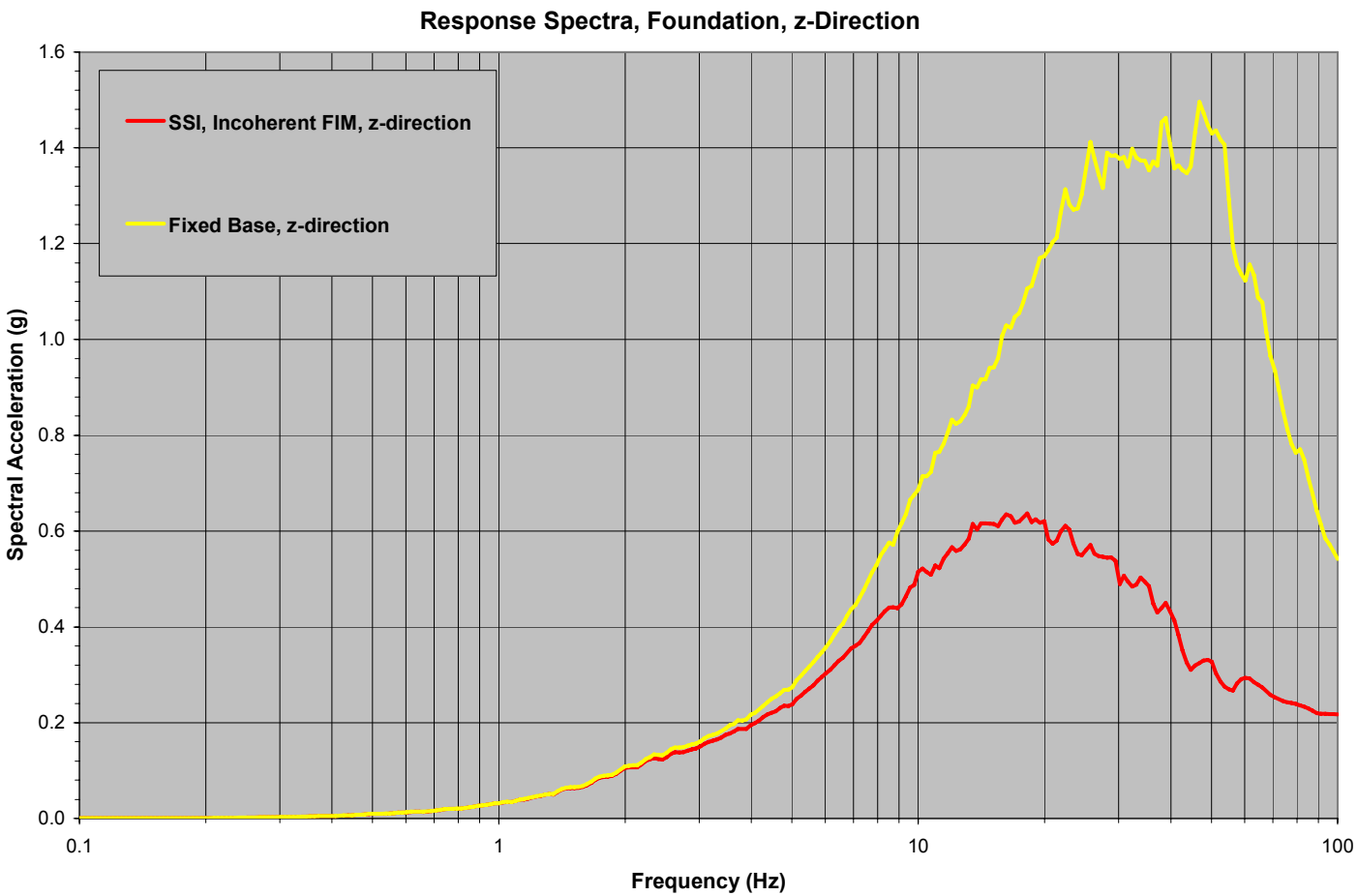
Response Spectra: Free-Field vs. Foundation Input Motion (Incoherent wave assumption) - Vertical



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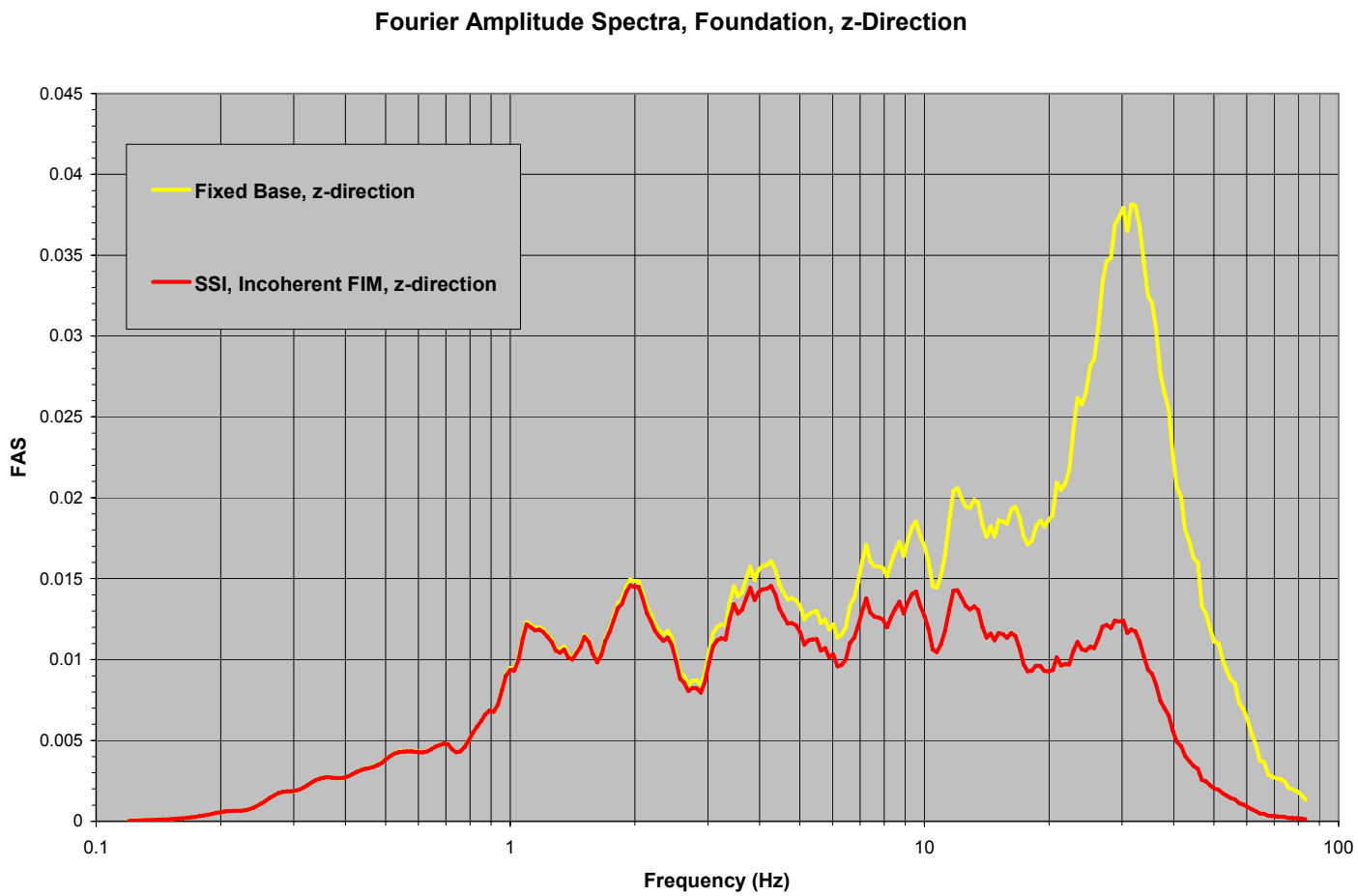
Fourier Amplitude Spectra: Free-Field vs. Foundation Input Motion (Incoherent wave assumption) – Vertical



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Free-Field vs. FIM vs. Foundation Response (SSI for coherent and incoherent wave assumptions)

- Free-field ground motion defined by acceleration time histories (horizontal and vertical)
- Rock site profile
- Foundation is square - 150 ft on a side – 15 ft thick with mass properties
- Advanced reactor structure stick model with eccentricities (160 modes)
- Coherent wave assumption – Inertial interaction (Kinematic interaction = unity)
- Incoherent wave assumption – Kinematic and inertial interaction
- Response spectra (5% damped) and Fourier Amplitude Spectra calculated

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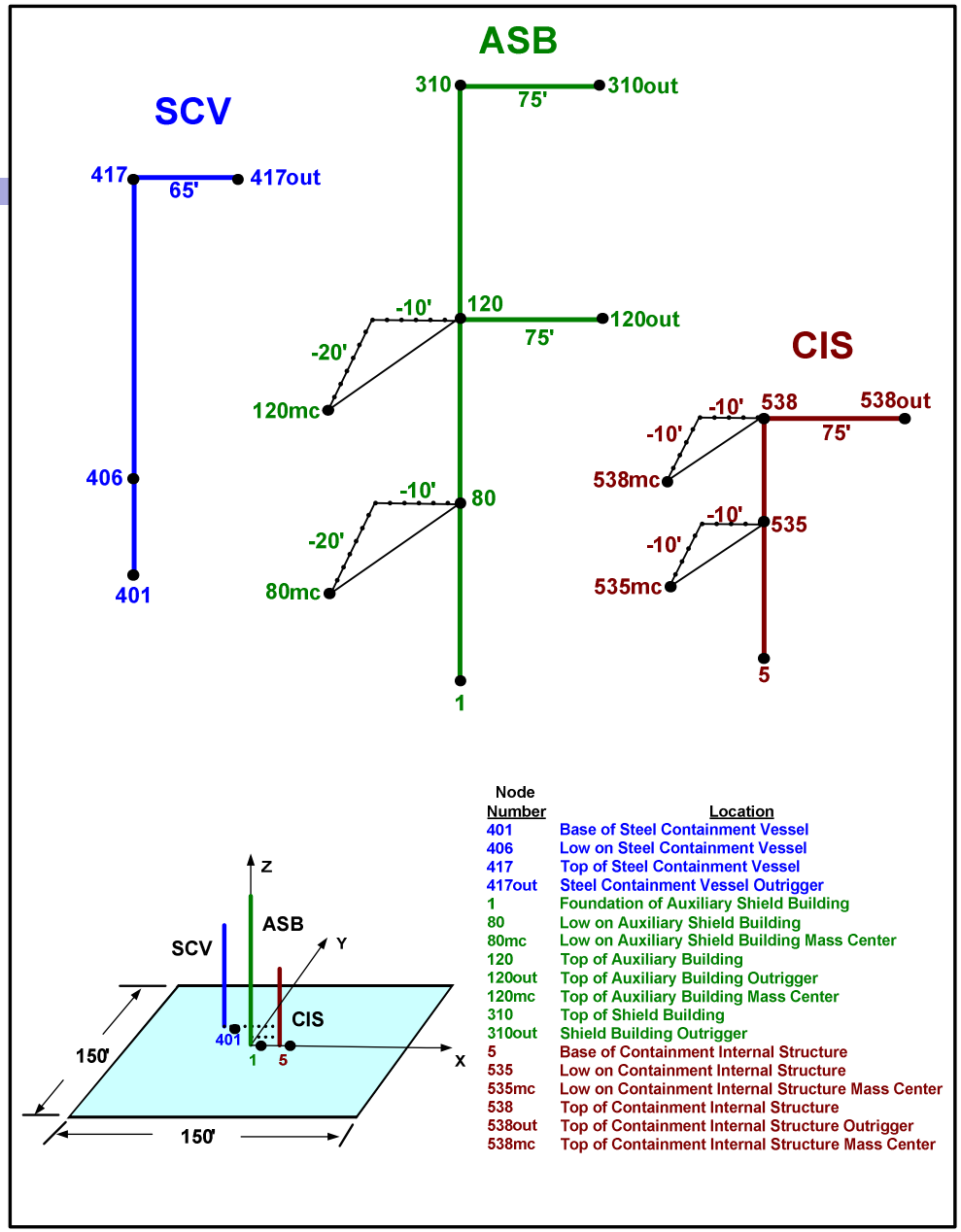
Advanced Reactor Structure Stick Model with Outriggers and Offset Mass Centers



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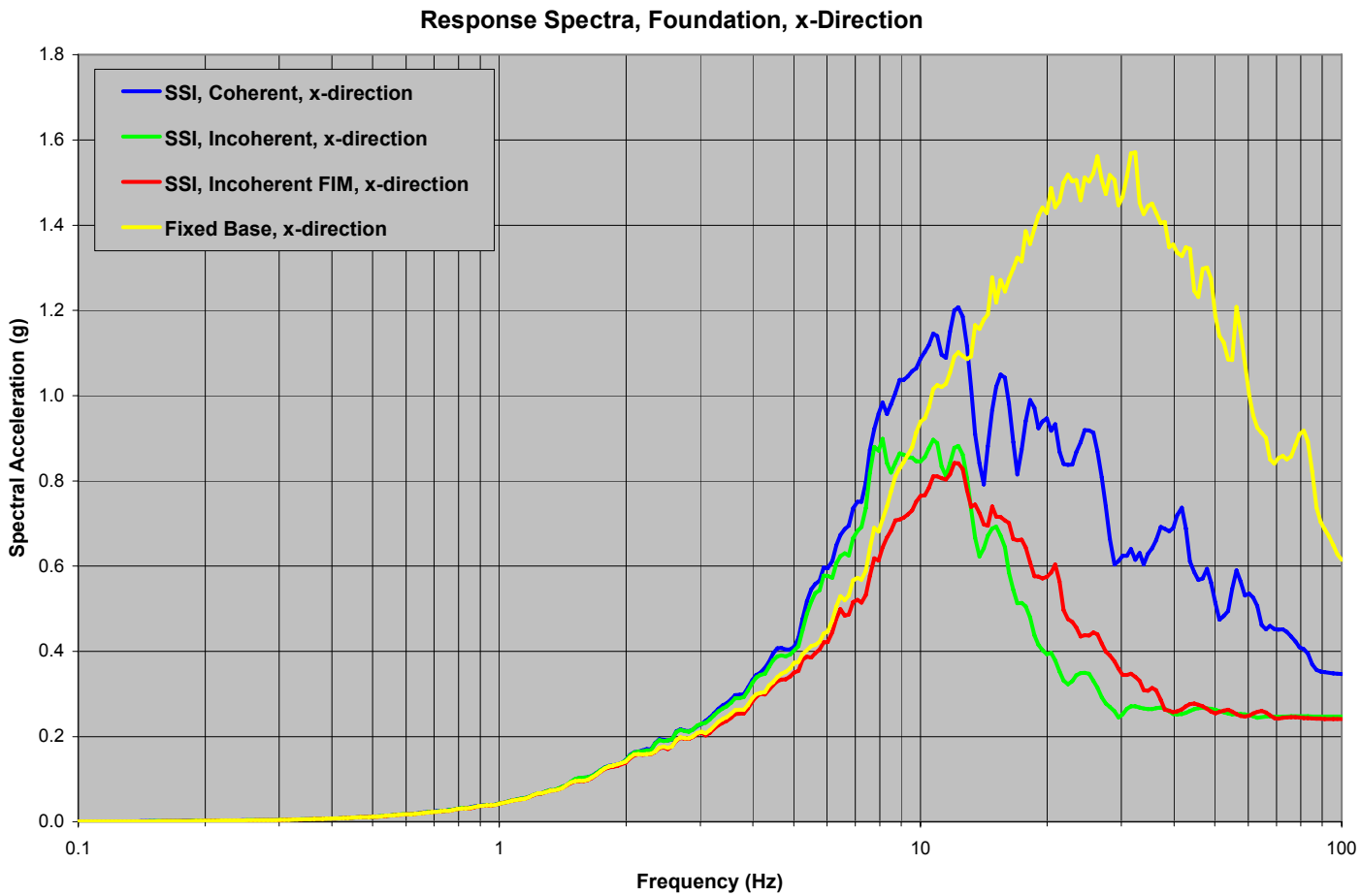
Response Spectra: Free-Field vs. FIM vs. Foundation Response (SSI for coherent and incoherent wave assumptions) - Horizontal



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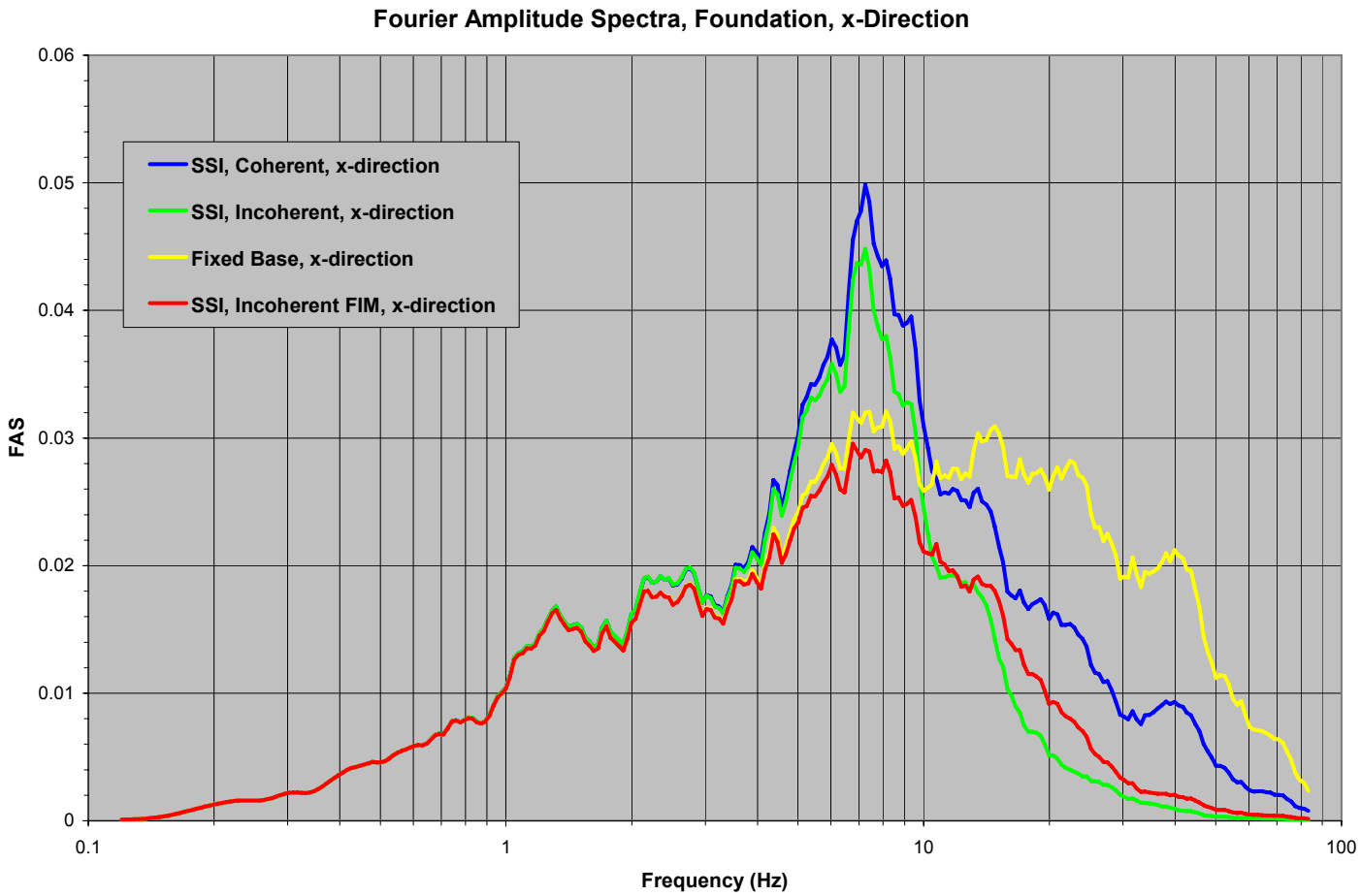
Fourier Amplitude Spectra: Free-Field vs. FIM vs. Foundation Response (SSI for coherent and incoherent wave assumptions) - Horizontal



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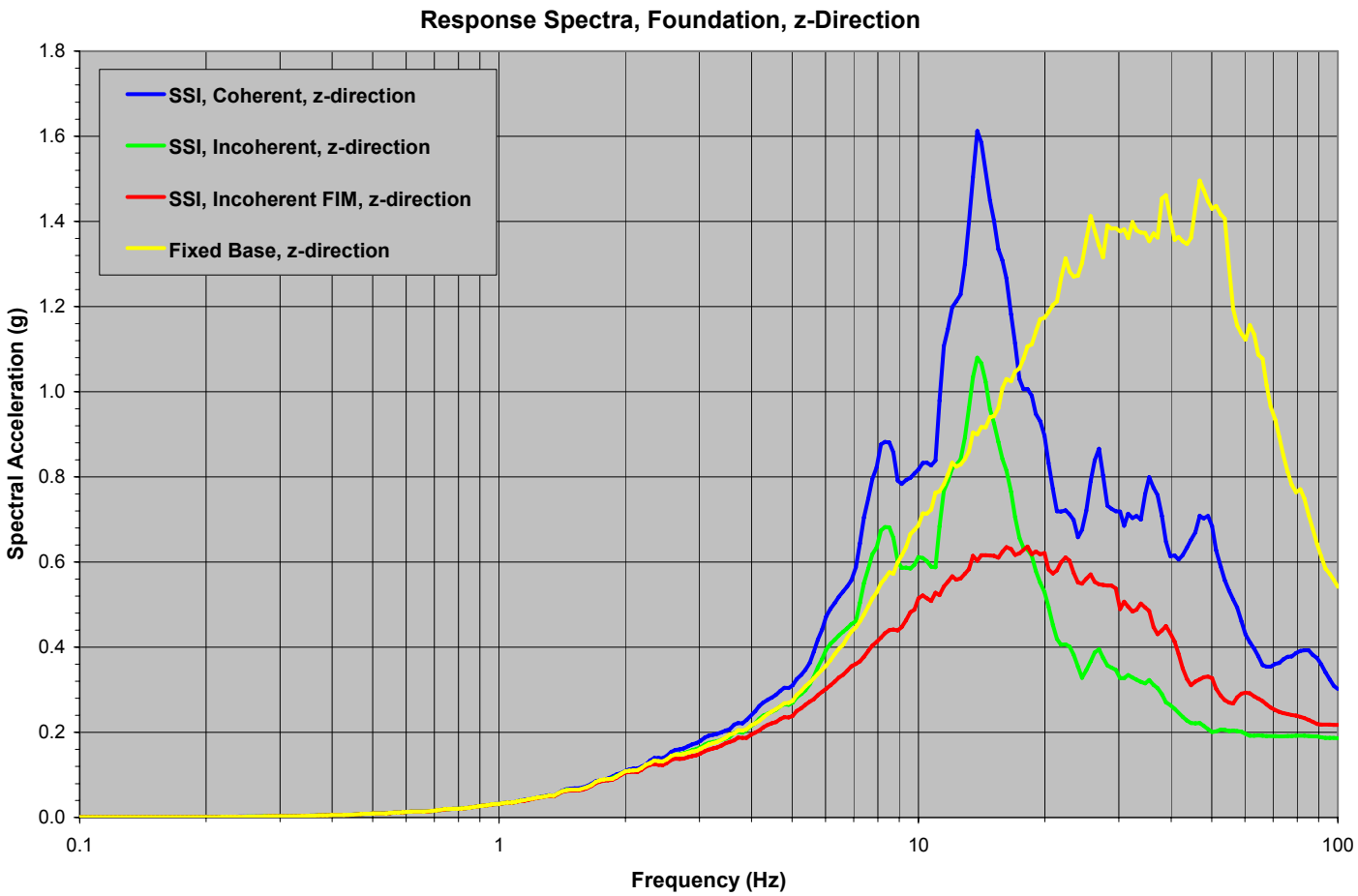
Response Spectra: Free-Field vs. FIM vs. Foundation Response (SSI for coherent and incoherent wave assumptions) – Vertical



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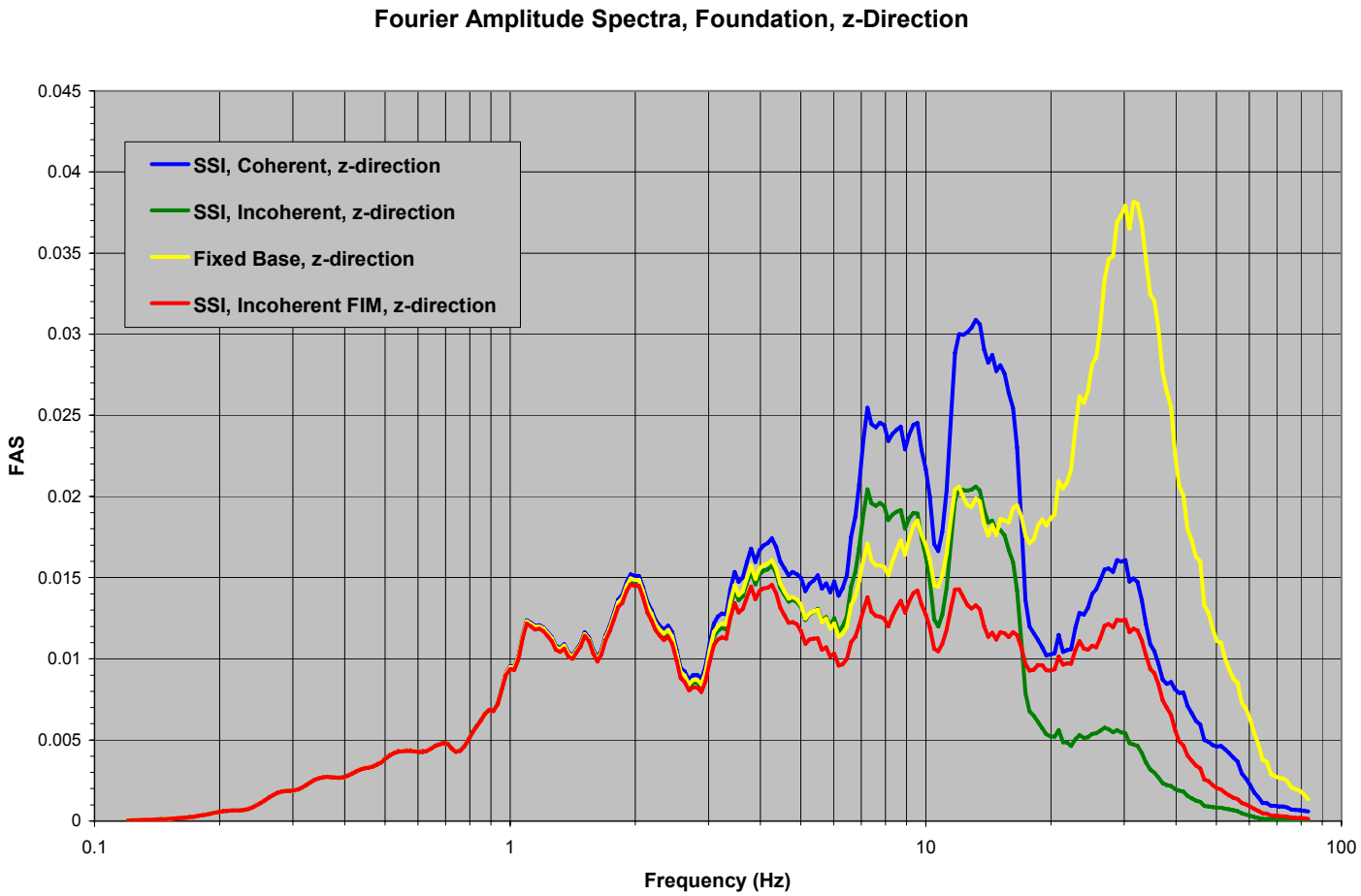
Fourier Amplitude Spectra: Free-Field vs. FIM vs. Foundation Response (SSI for coherent and incoherent wave assumptions) – Vertical



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Foundation Response: Review of Free-Field, Coherent, and Incoherent Response

- Response spectra and Fourier amplitude spectra demonstrate and quantify the effect on the foundation of:
  - Kinematic interaction due to incoherency of ground motion on a rigid, massless foundation
  - Soil-structure interaction effects on foundation response
    - Kinematic and inertial interaction for incoherent ground motion
    - Inertial interaction for coherent ground motion (Kinematic interaction = unity)
  - EPRI Report No. 1013504, Appendix C Figs. C-16 vs. C-4, C-17 vs. C-5, C-18 vs. C-6, further validate the effect of SSI on response of the foundation - coherent motion

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Identification of Important Modes for Simplified Modeling and Behavior Insight

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Identification of Important Modes for Simplified Modeling and Behavior Insight

- Advanced reactor structure stick model with eccentricities
  - 160 fixed-base modes model the dynamic characteristics of the structure
  - Frequencies 3.0 Hz – 141 Hz
  - Total mass (x = 92.7%, y = 92.5%, z = 93.1%)
- Three sticks are coupled at various locations – modes are coupled
- Relative mass distribution
  - ASB – 86%
  - CIS – 11%
  - SCV – less than 5%

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Identification of Important Modes for Simplified Modeling and Behavior Insight

- Measure of importance = Phi * Gamma
  - Phi – eigenvector value for DOF of interest
  - Gamma – modal participation factor for base excitation direction of interest
  - Base translations and rotations are important – identification based on translations – generally same modes are important for rotations
  - Phi * Gamma
    - Signed, but absolute value plotted for clarity
    - Sum of Phi * Gamma = 1.0 or 0.0 for nodes and DOFs considered

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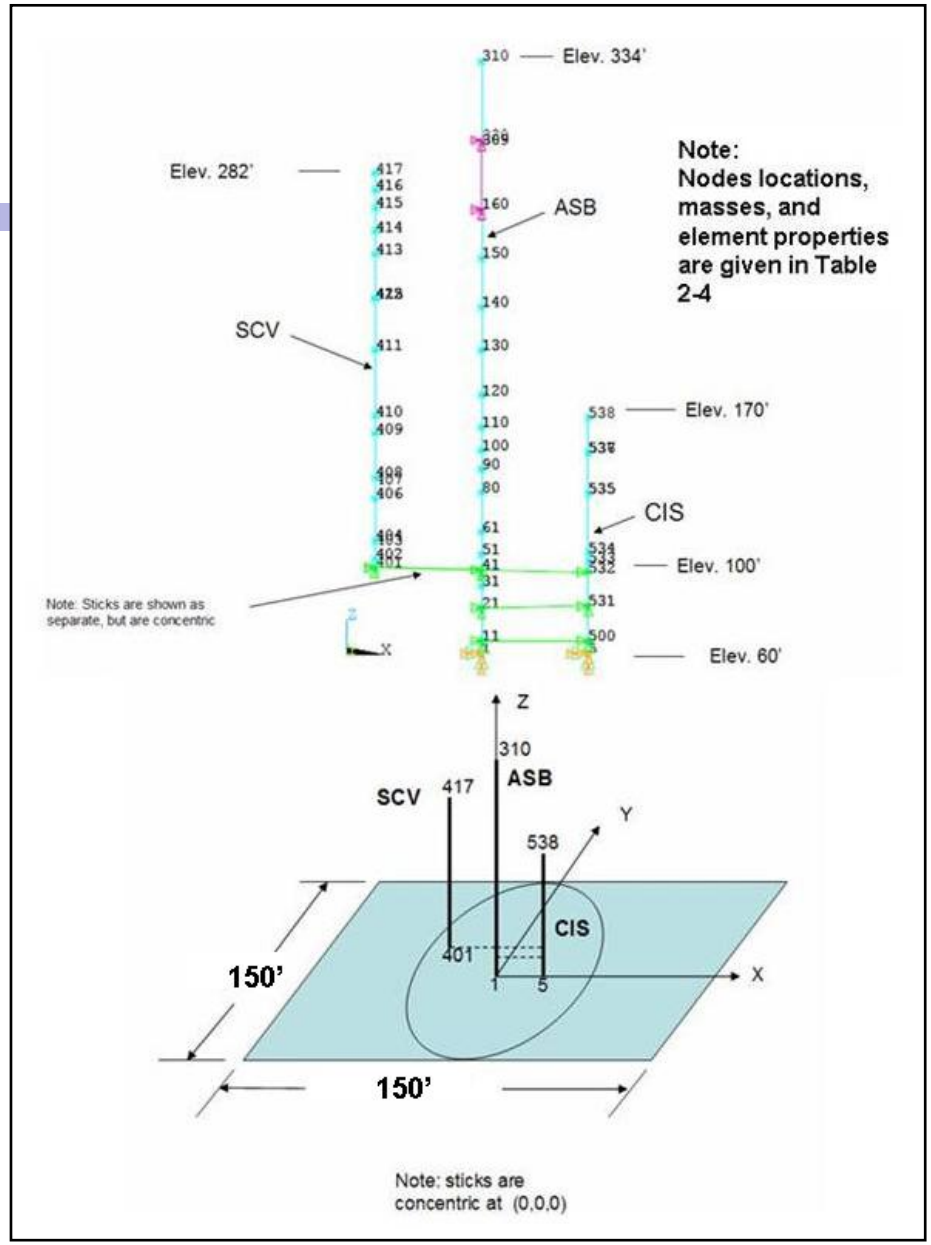
Advanced Reactor Structure Stick Model



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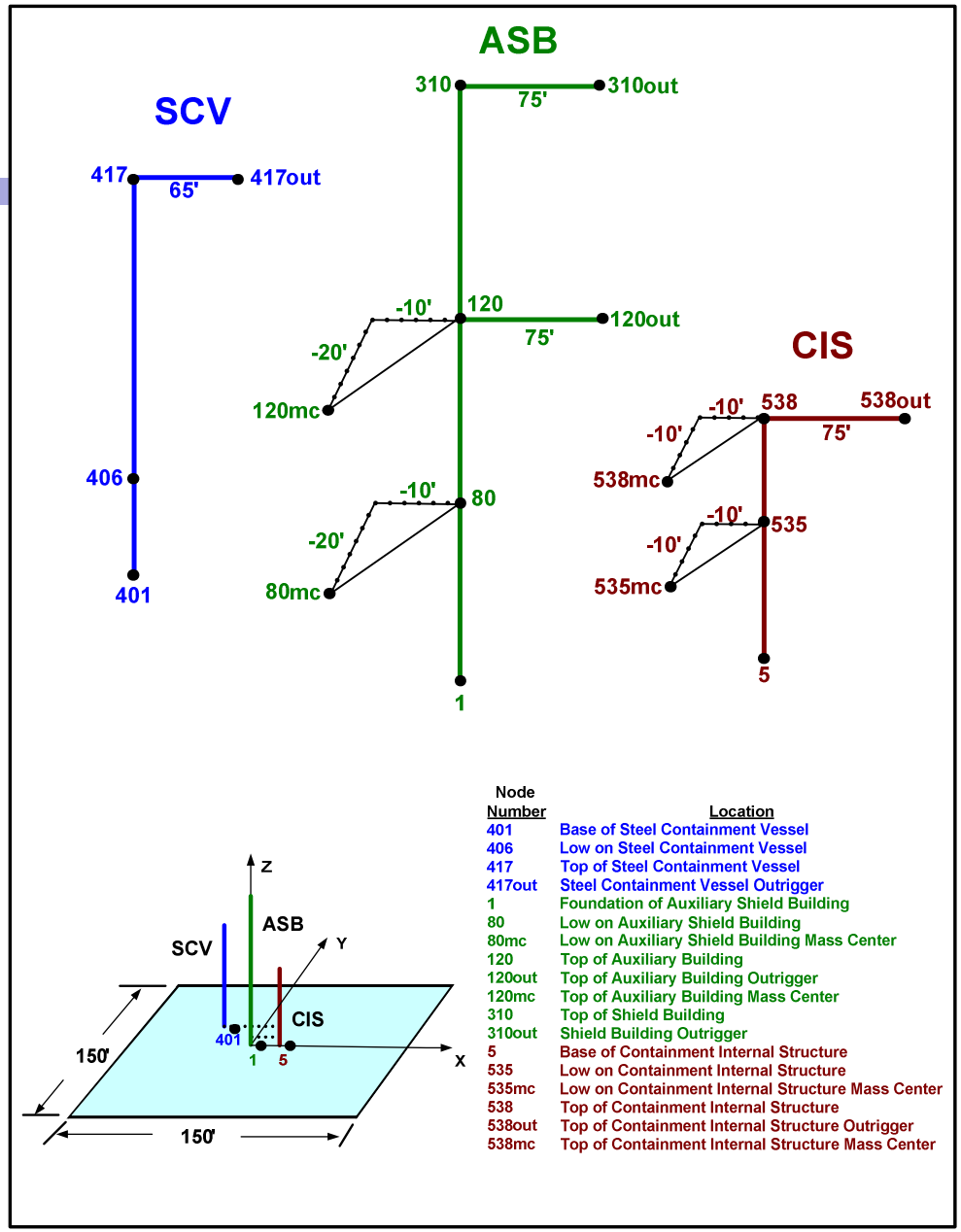
Advanced Reactor Structure Stick Model with Outriggers and Offset Mass Centers



Node Number	Location
401	Base of Steel Containment Vessel
406	Low on Steel Containment Vessel
417	Top of Steel Containment Vessel
417out	Steel Containment Vessel Outrigger
1	Foundation of Auxiliary Shield Building
80	Low on Auxiliary Shield Building
80mc	Low on Auxiliary Shield Building Mass Center
120	Top of Auxiliary Building
120out	Top of Auxiliary Building Outrigger
120mc	Top of Auxiliary Building Mass Center
310	Top of Shield Building
310out	Shield Building Outrigger
5	Base of Containment Internal Structure
535	Low on Containment Internal Structure
535mc	Low on Containment Internal Structure Mass Center
538	Top of Containment Internal Structure
538out	Top of Containment Internal Structure Outrigger
538mc	Top of Containment Internal Structure Mass Center

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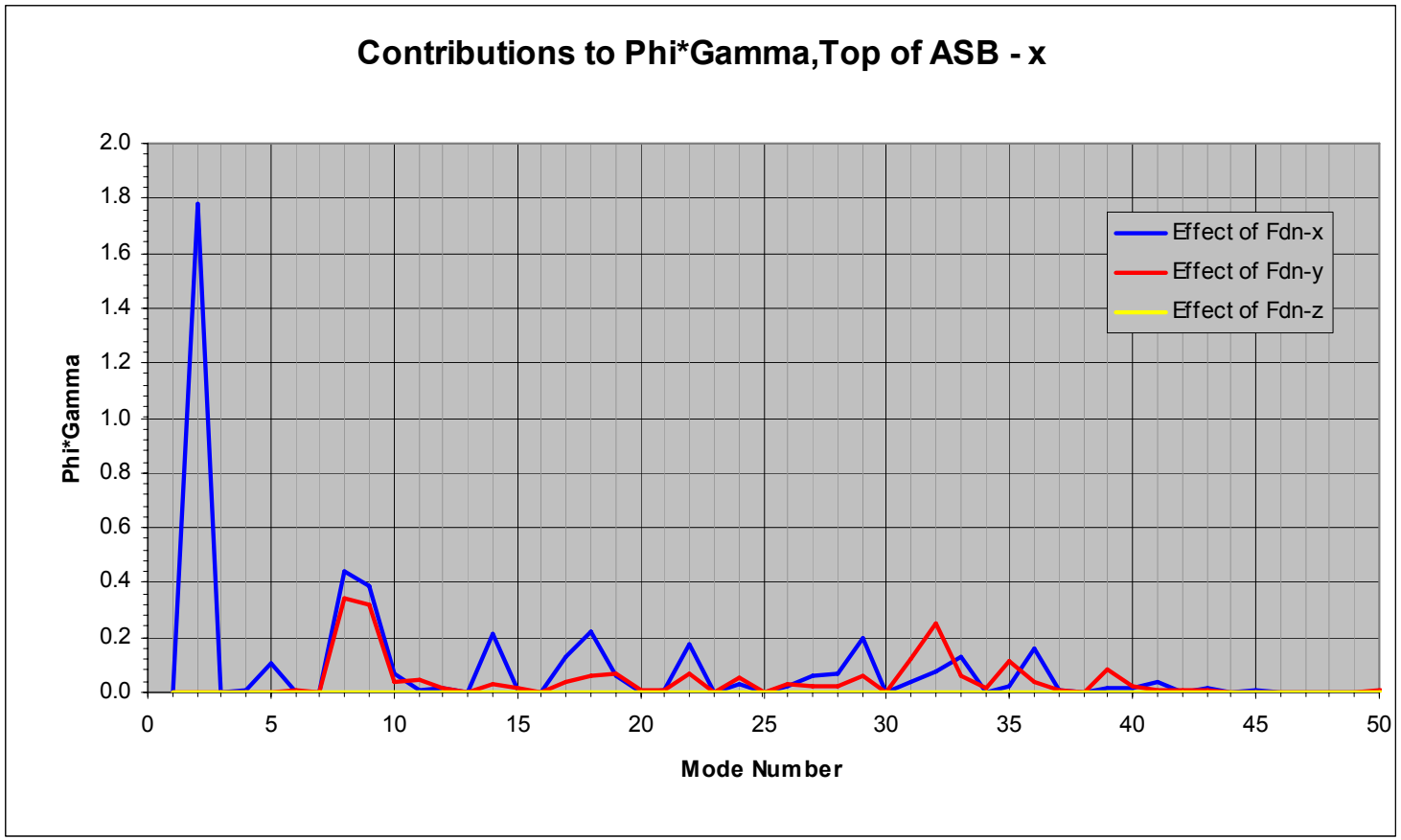
Important Modes – Top of ASB



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Important Modes – Top of ASB

Top of ASB-x

Mode No	Frequency (Hz)	Damping	Modal Mass as Percent of Total			Fnd Direction
			x	y	z	
2	3.21	0.04	20.1	0.0	0.0	x
8	6.54	0.04	3.3	2.0	0.0	x & y
9	6.57	0.04	2.6	1.8	0.0	x & y
14	10.05	0.04	15.5	0.4	0.0	x
18	13.83	0.04	3.6	0.3	0.0	x
22	15.81	0.04	2.5	0.3	0.0	x
29	20.55	0.04	3.2	0.3	0.0	x
32	21.74	0.04	0.2	2.5	0.0	y

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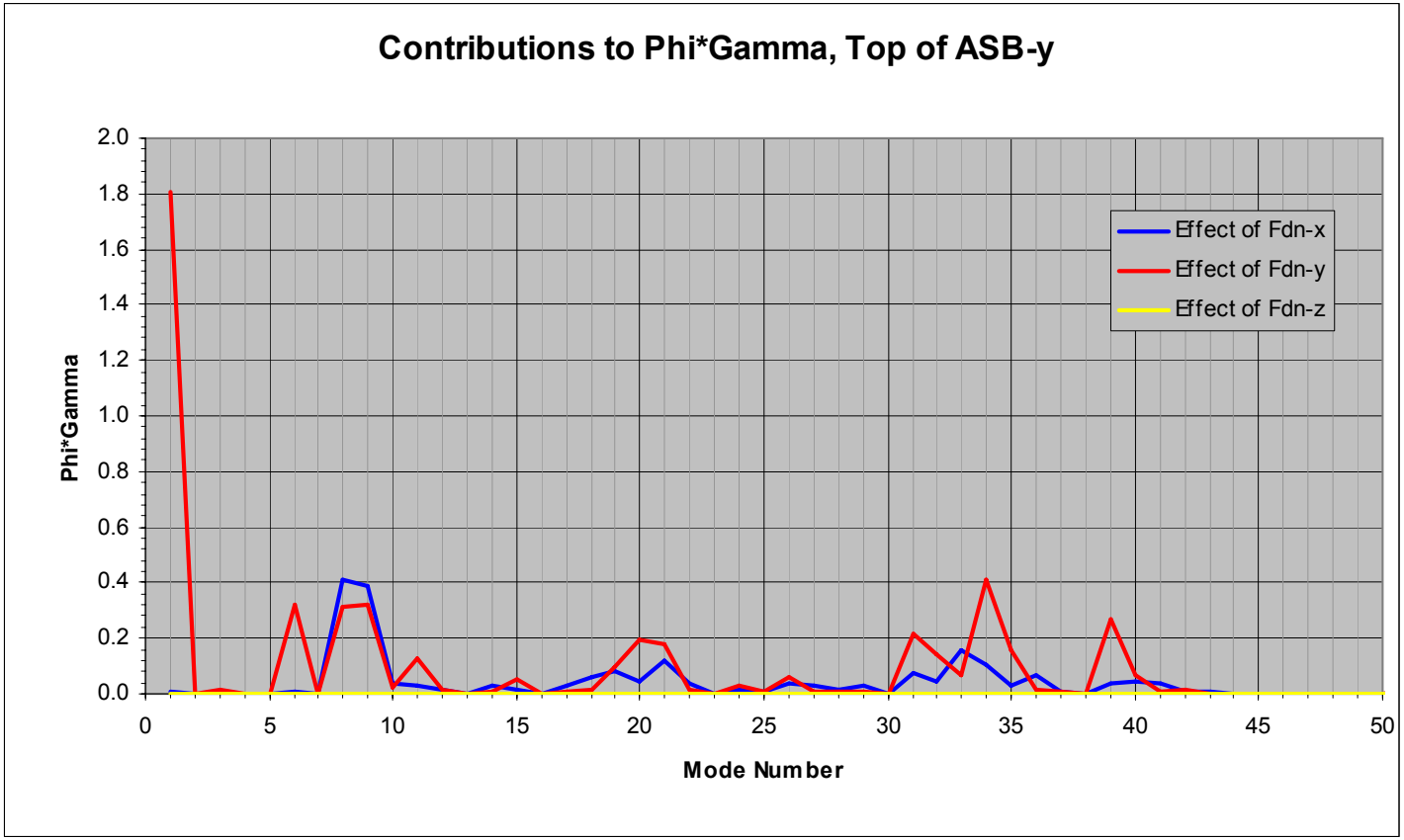
Important Modes – Top of ASB



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Important Modes – Top of ASB

Top of ASB-y

Mode No	Frequency (Hz)	Damping	Modal Mass as Percent of Total			Fnd Direction
			x	y	z	
1	3.00	0.04	0.0	21.6	0.0	y
6	6.14	0.04	0.0	5.3	0.0	y
8	6.54	0.04	3.3	2.0	0.0	x & y
9	6.57	0.04	2.6	1.8	0.0	x & y
31	21.33	0.04	0.6	5.3	0.0	y
34	25.23	0.04	0.1	2.4	0.0	y
39	27.30	0.04	0.1	2.9	0.0	y

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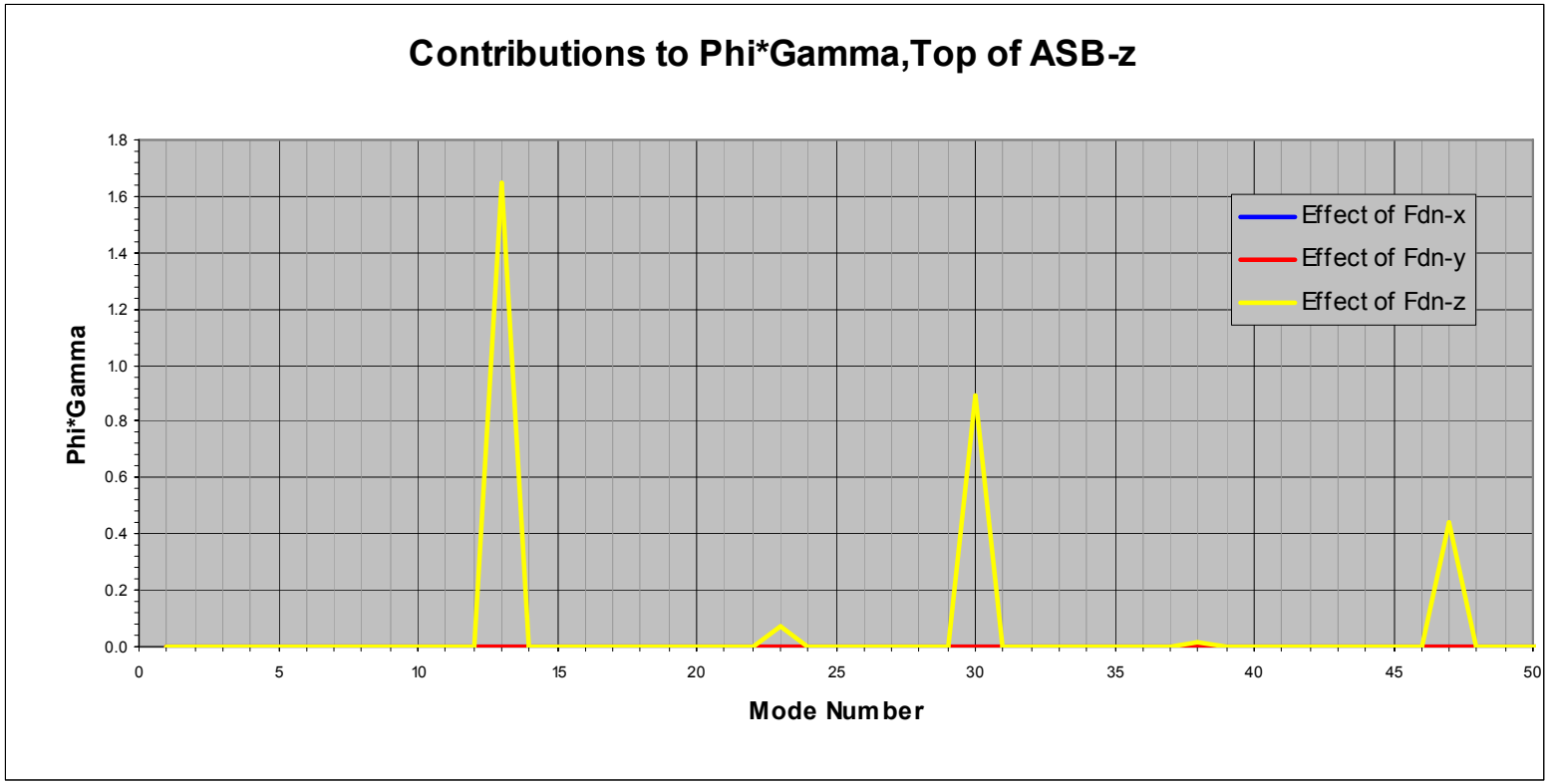
Important Modes – Top of ASB



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Important Modes – Top of ASB

Top of ASB-z

Mode No	Frequency (Hz)	Damping	Modal Mass as Percent of Total			Fnd Direction
			x	y	z	
13	9.85	0.04	0.0	0.0	25.3	z
30	21.07	0.04	0.0	0.0	18.9	z
47	33.02	0.04	0.0	0.0	9.6	z
78	54.49	0.04	0.0	0.0	4.1	z
83	57.60	0.04	0.0	0.0	0.3	z

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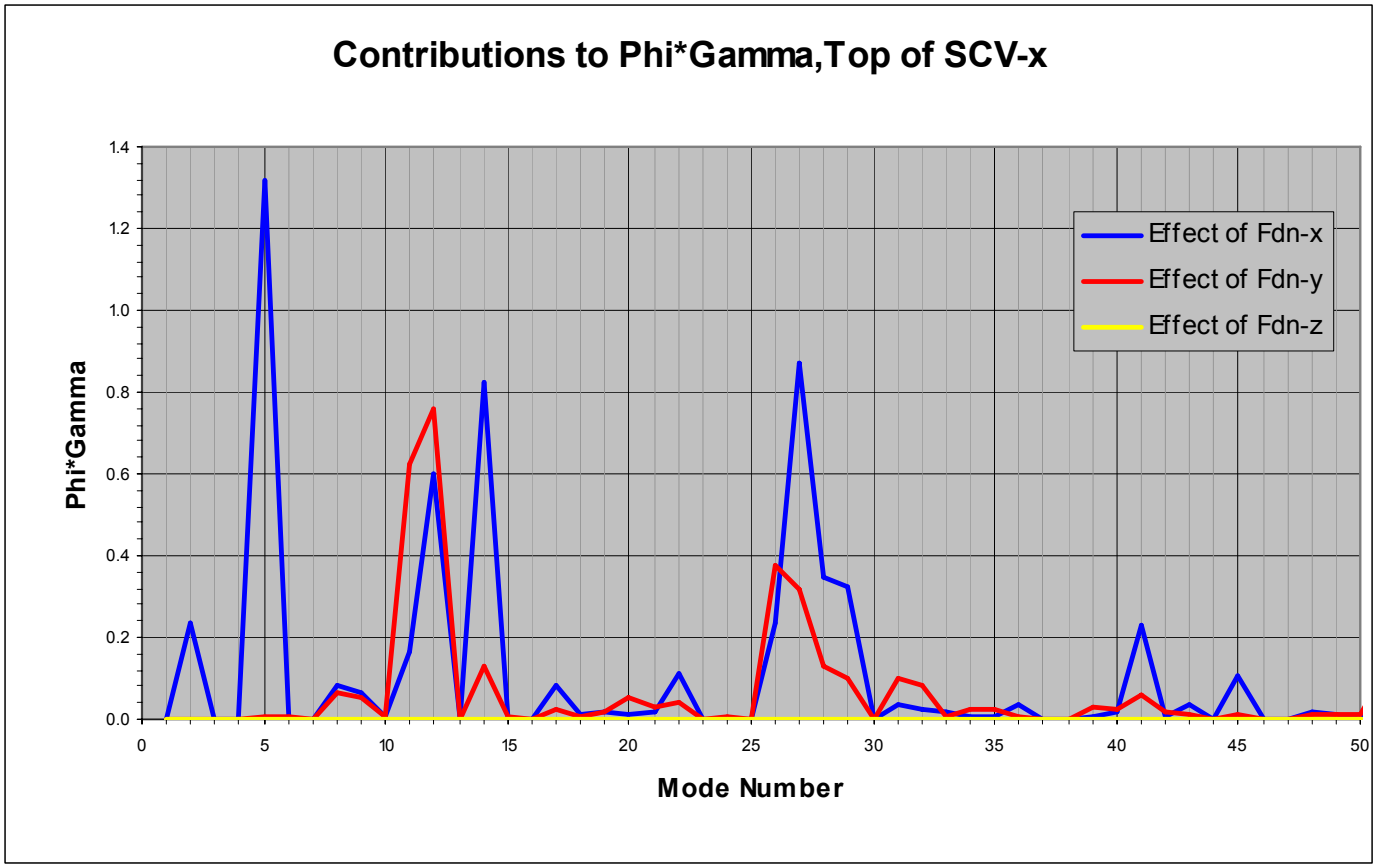
Important Modes – Top of SCV



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Important Modes – Top of SCV

Top of SCV-x

Mode No	Frequency (Hz)	Damping	Modal Mass as Percent of Total x	y	z	Fnd Direction
2	3.21	0.04	20.1	0.0	0.0	x
5	5.46	0.04	3.1	0.0	0.0	x
11	9.49	0.04	1.3	18.8	0.0	x
12	9.57	0.04	1.2	1.9	0.0	x & y
14	10.05	0.04	15.5	0.4	0.0	x
26	18.65	0.04	0.6	1.6	0.0	x & y
27	18.72	0.04	1.8	0.2	0.0	x & y
28	19.77	0.04	2.2	0.3	0.0	x
29	20.55	0.04	3.2	0.3	0.0	x
41	29.33	0.04	6.9	0.4	0.0	x
56	36.41	0.04	0.4	0.1	0.0	x
58	36.94	0.04	1.3	0.1	0.0	x & y

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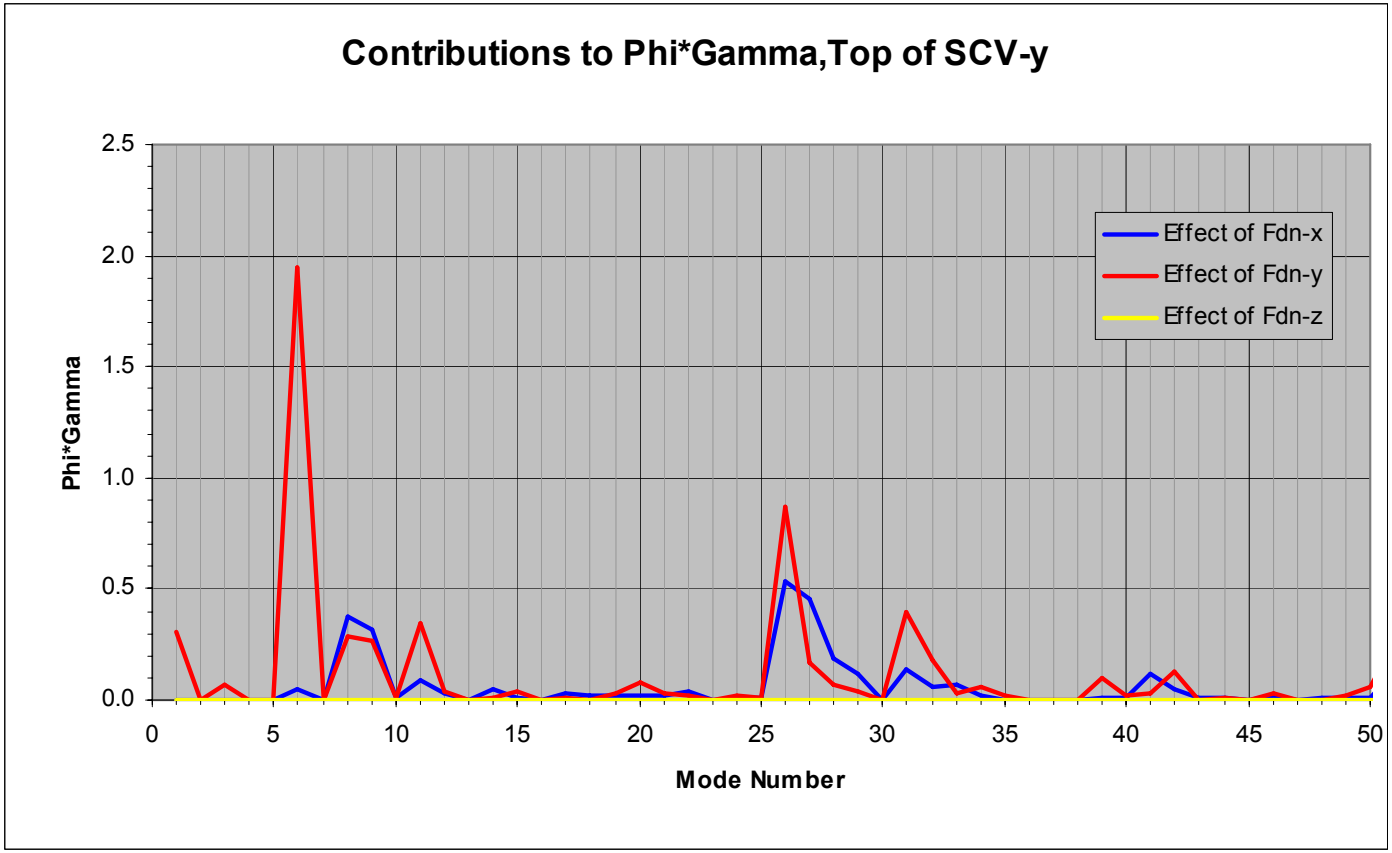
Important Modes – Top of SCV



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Important Modes – Top of SCV

Top of SCV-y

Mode No	Frequency (Hz)	Damping	Modal Mass as Percent of Total			Fnd Direction
			x	y	z	
1	3.00	0.04	0.0	21.6	0.0	y
4	4.96	0.04	0.1	0.0	0.0	y
8	6.54	0.04	3.3	2.0	0.0	x & y
9	6.57	0.04	2.6	1.8	0.0	x & y
11	9.49	0.04	1.3	18.8	0.0	y
26	18.65	0.04	0.6	1.6	0.0	x & y
27	18.72	0.04	1.8	0.2	0.0	x
31	21.33	0.04	0.6	5.3	0.0	y
51	34.15	0.04	0.4	1.5	0.0	y
54	35.84	0.04	0.3	0.0	0.0	x
55	35.95	0.04	0.1	0.2	0.0	y

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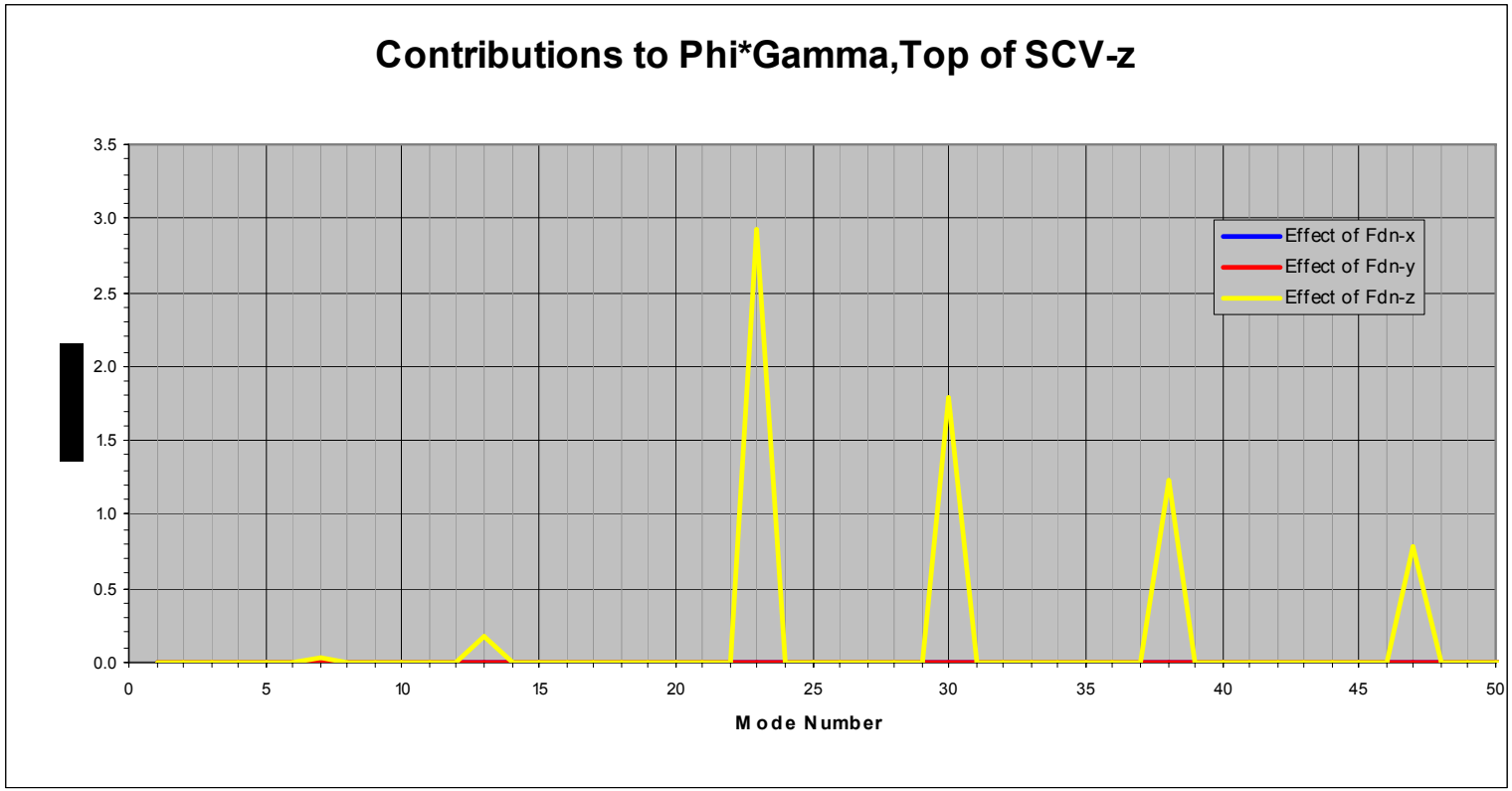
Important Modes – Top of SCV



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Important Modes – Top of SCV

Top of SCV-z

Mode No	Frequency (Hz)	Damping	Modal Mass as Percent of Total			Fnd Direction
			x	y	z	
23	16.00	0.04	0.0	0.0	4.4	z
30	21.07	0.04	0.0	0.0	18.9	z
38	26.55	0.04	0.0	0.0	0.3	z
47	33.02	0.04	0.0	0.0	9.6	z
78	54.49	0.04	0.0	0.0	4.1	z

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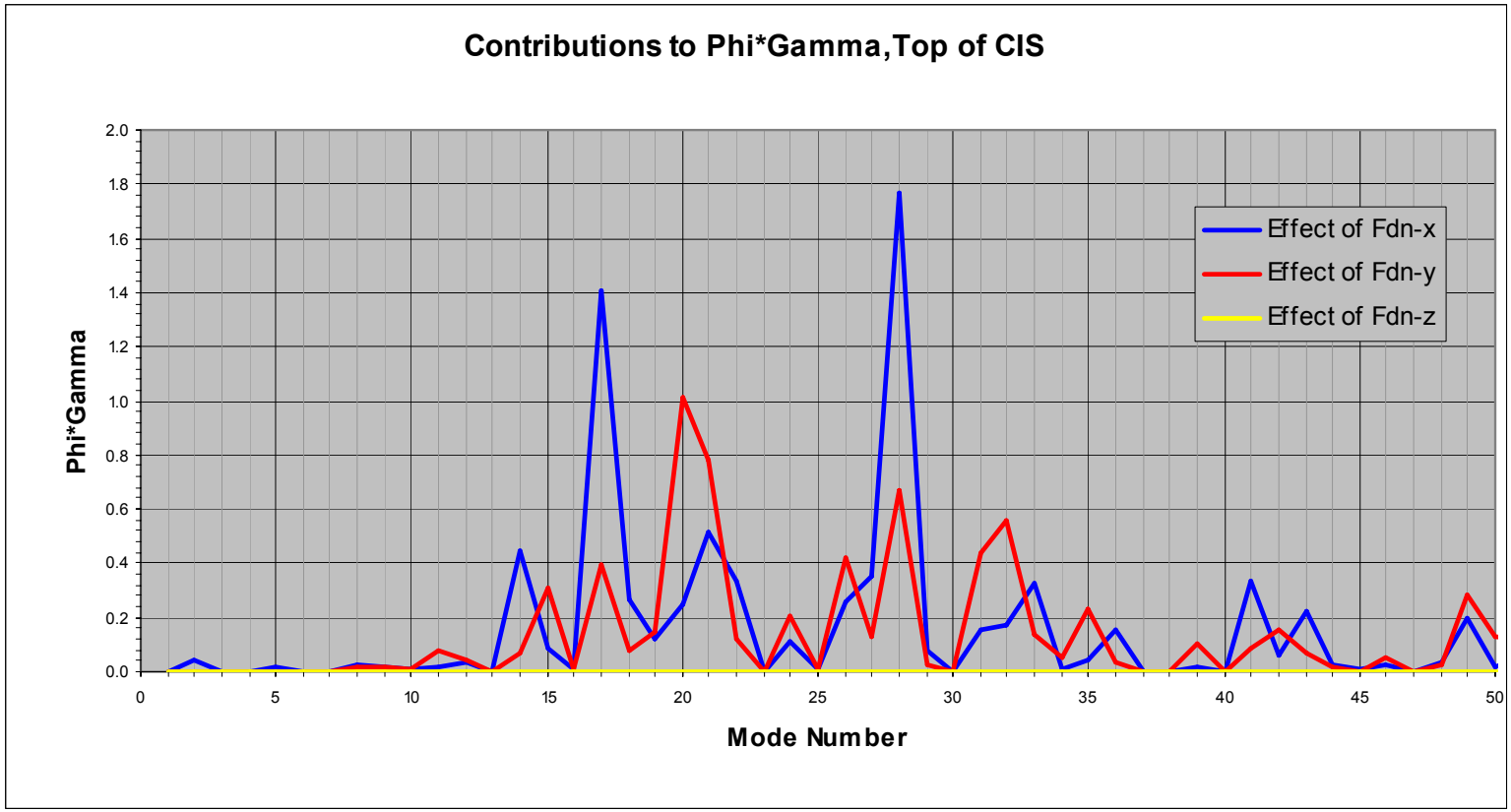
Important Modes – Top of CIS



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Important Modes – Top of CIS

Top of CIS-x

Mode No	Frequency (Hz)	Damping	Modal Mass as Percent of Total x	y	z	Fnd Direction
14	10.05	0.04	15.5	0.4	0.0	x
15	11.56	0.04	0.2	2.4	0.0	y
17	12.96	0.04	5.3	0.4	0.0	x & y
18	13.83	0.04	3.6	0.3	0.0	x
20	14.71	0.04	0.2	3.3	0.0	x & y
21	15.21	0.04	0.6	1.4	0.0	x & y
22	15.81	0.04	2.5	0.3	0.0	x
26	18.65	0.04	0.6	1.6	0.0	y
27	18.72	0.04	1.8	0.2	0.0	x
28	19.77	0.04	2.2	0.3	0.0	x & y
31	21.33	0.04	0.6	5.3	0.0	y
32	21.74	0.04	0.2	2.5	0.0	y
33	23.11	0.04	1.7	0.3	0.0	x
41	29.33	0.04	6.9	0.4	0.0	x
52	35.40	0.04	0.2	0.1	0.0	x
54	35.84	0.04	0.3	0.0	0.0	x
58	36.94	0.04	1.3	0.1	0.0	x
93	65.51	0.04	1.0	0.0	0.0	x

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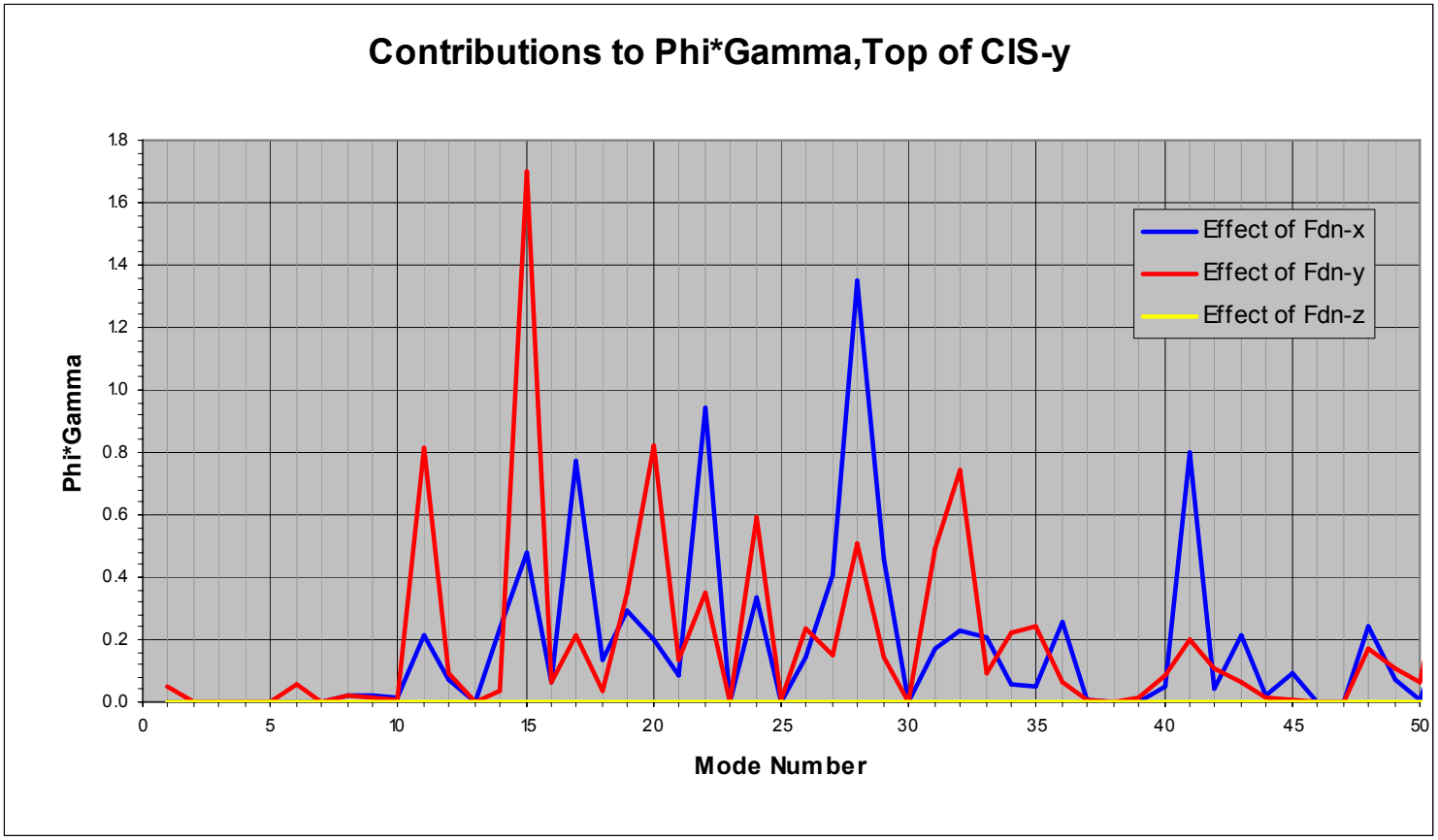
Important Modes – Top of CIS



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Important Modes – Top of CIS

Top of CIS-y

Mode No	Frequency (Hz)	Damping	Modal Mass as Percent of Total			Fnd Direction
			x	y	z	
11	9.49	0.04	1.3	18.8	0.0	y
15	11.56	0.04	0.2	2.4	0.0	x & y
17	12.96	0.04	5.3	0.4	0.0	x
19	14.37	0.04	1.0	1.4	0.0	y
20	14.71	0.04	0.2	3.3	0.0	y
22	15.81	0.04	2.5	0.3	0.0	x & y
24	16.33	0.04	0.1	0.3	0.0	y
27	18.72	0.04	1.8	0.2	0.0	x
28	19.77	0.04	2.2	0.3	0.0	x & y
29	20.55	0.04	3.2	0.3	0.0	x
31	21.33	0.04	0.6	5.3	0.0	y
32	21.74	0.04	0.2	2.5	0.0	y
41	29.33	0.04	6.9	0.4	0.0	x
51	34.15	0.04	0.4	1.5	0.0	y
54	35.84	0.04	0.3	0.0	0.0	x
55	35.95	0.04	0.1	0.2	0.0	y
58	36.94	0.04	1.3	0.1	0.0	x

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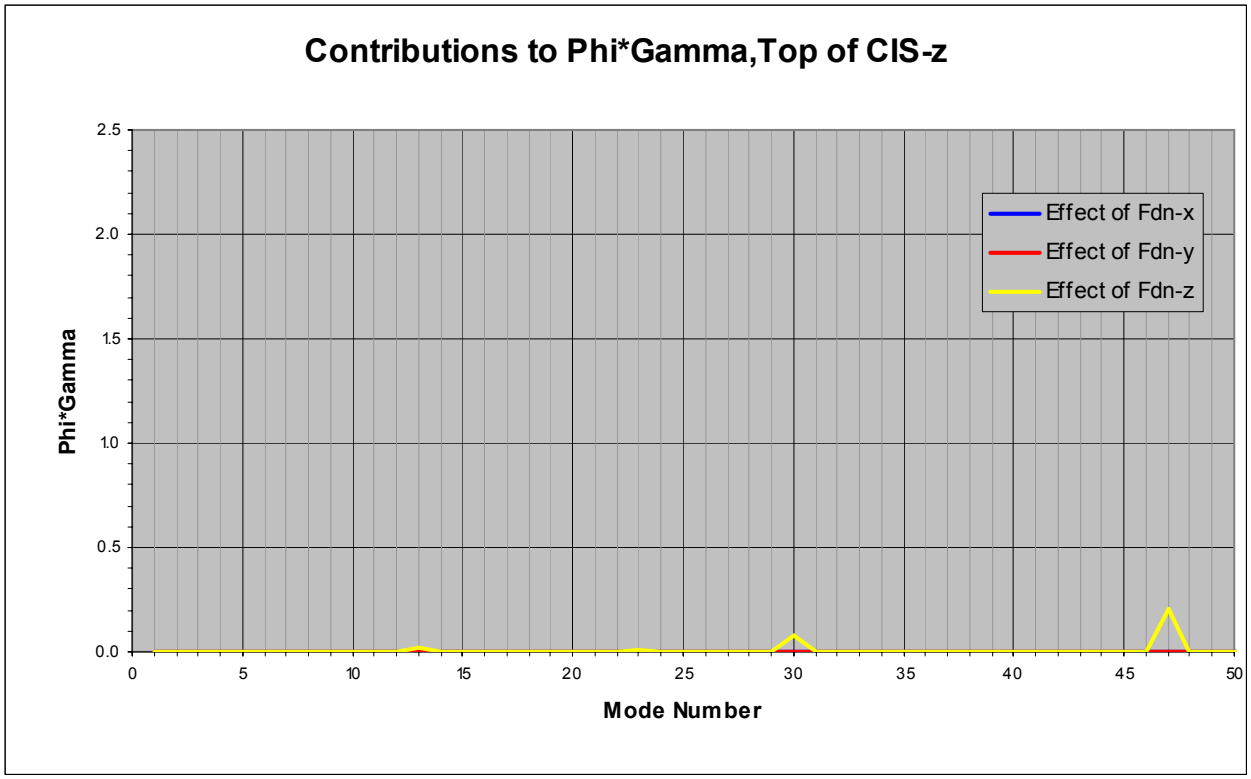
Important Modes – Top of CIS

- Maximum contribution from Mode 61 – f=41.4 Hz



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Important Modes – Top of CIS

Top of CIS-z

Mode No	Frequency (Hz)	Damping	Modal Mass as Percent of Total			Fnd Direction
			x	y	z	
62	41.41	0.04	0.0	0.0	14.5	z
78	54.49	0.04	0.0	0.0	4.1	z
98	67.16	0.04	0.0	0.0	8.6	z
119	90.48	0.04	0.0	0.0	0.6	z

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Identification of Important Modes for Simplified Modeling and Behavior Insight

- Structure model is very complex
  - Coupling of the three sticks through their interconnections
  - Natural torsion due to offsets horizontally of masses from shear centers for ASB and CIS introduces additional coupling
- Simplified analysis could use Phase 1 model with no natural torsion offsets and the three sticks colocated on z-axis

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Validation of CLASSlinco

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Validation of CLASSIinco

- Objective: Benchmark the approach and implementation of CLASSIinco with published literature
- Rigid, massless foundations on a visco-elastic half-space
  - Kinematic interaction
  - Incoherency transfer functions (CLASSI scattering functions)
- Circular disk of radius 84.63 ft (Area = 22,500 ft*ft)
  - Luco and Mita (1987)
  - Veletsos and Prasad (1989)
- Square foundation 150 ft on a side
  - Luco and Wong (1986)

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Validation of CLASSlinco: Key Parameters

- Visco-elastic half-space
  - Shear Wave Velocity, Vs = 6300 ft/sec = 1920.24 m/sec
  - Mass Density, ρ = .004969 k-sec2/ft4
  - Poisson's Ratio, v = 0.33
  - Damping, ξ = 0.01

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Coherency Ground Motion Function

- Coherency ground motion function (vertically incident waves)

$$\Gamma(|r1 - r2|,\omega) = \exp[-(\gamma\omega|r1 - r2|/Vs)^{**}2]$$

where

|r1 - r2| is the distance between points on the foundation (subregion centroids)

γ is a dimensionless incoherence parameter,

ω is the angular frequency (radians/sec),

Vs is the representative shear wave velocity of the soil profile

- CLASSIinco was modified to include the Luco and Wong representation of the coherency ground motion
- Values of γ = 0.1, 0.2, 0.3, 0.4, and 0.5 were benchmarked
- Luco and Wong provide the following guidance

Vs * 2 x 10-4 sec/m $\leq \gamma \leq$ Vs * 3 x 10-4 sec/m

γ = 0.5 approximates this recommendation for Vs = 1920 m/sec

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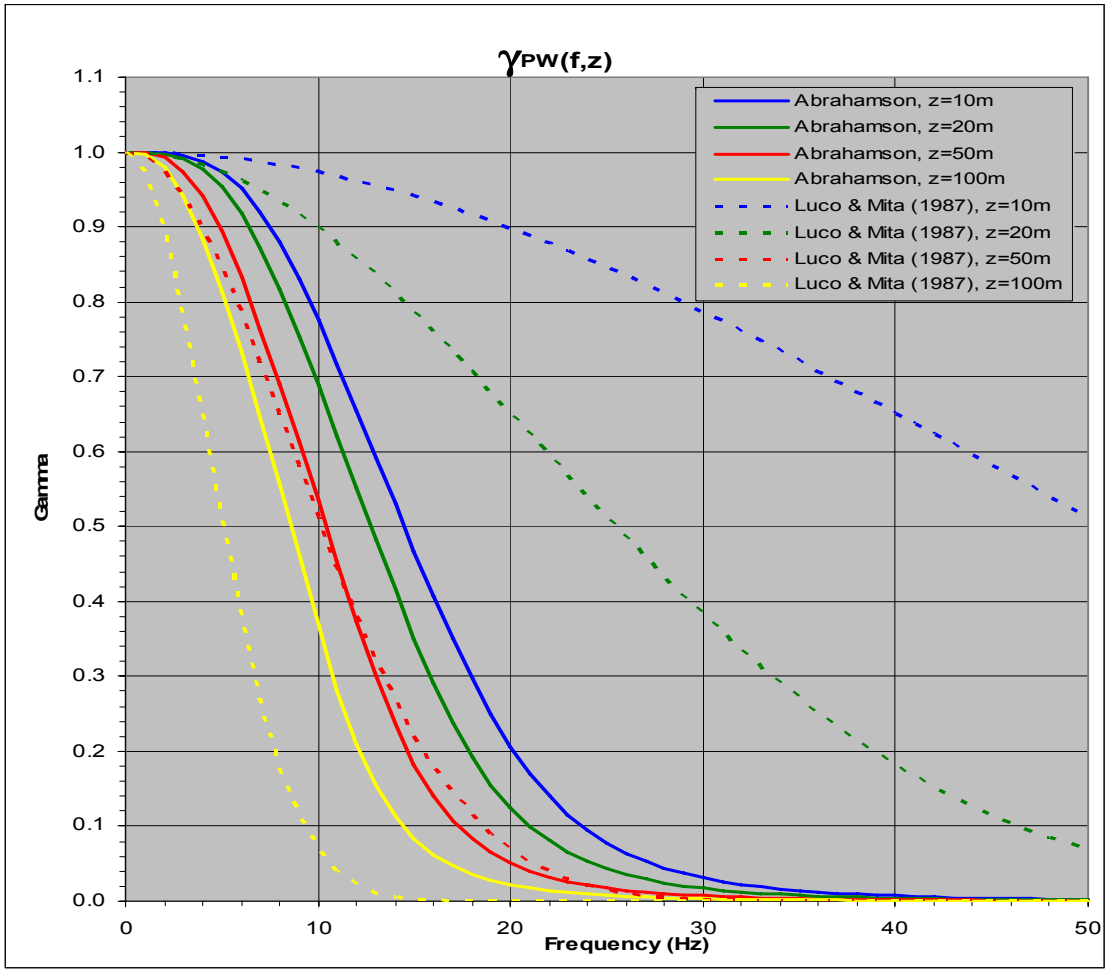
Coherency Ground Motion Function: Abrahamson vs. Luco and Wong (γ = 0.5)



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Circular Disk

- Luco and Mita (1987)
  - Solution in terms of Bessel functions
  - Horizontal and induced torsion
  - Vertical and induced rocking
  - Results plotted vs. dimensionless frequency a0

Frequency (Hz)	a0
10	0.84404123
20	1.68808245
25	2.11010307
30	2.53212368
50	4.22020613

- Veletsos and Prasad (1989)
  - Reduced the number of independent variables
  - Horizontal and induced torsion plotted vs. γ * a0

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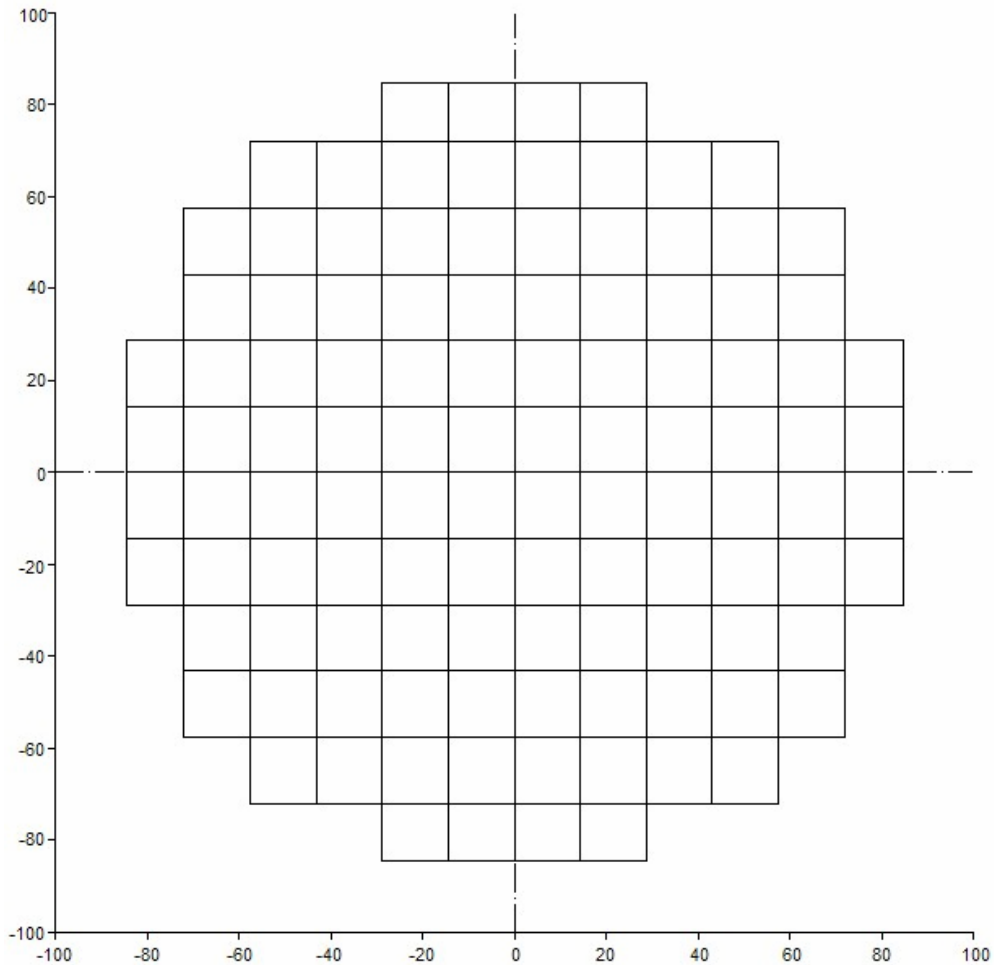
Circular Disk: CLASSlinco Discretization



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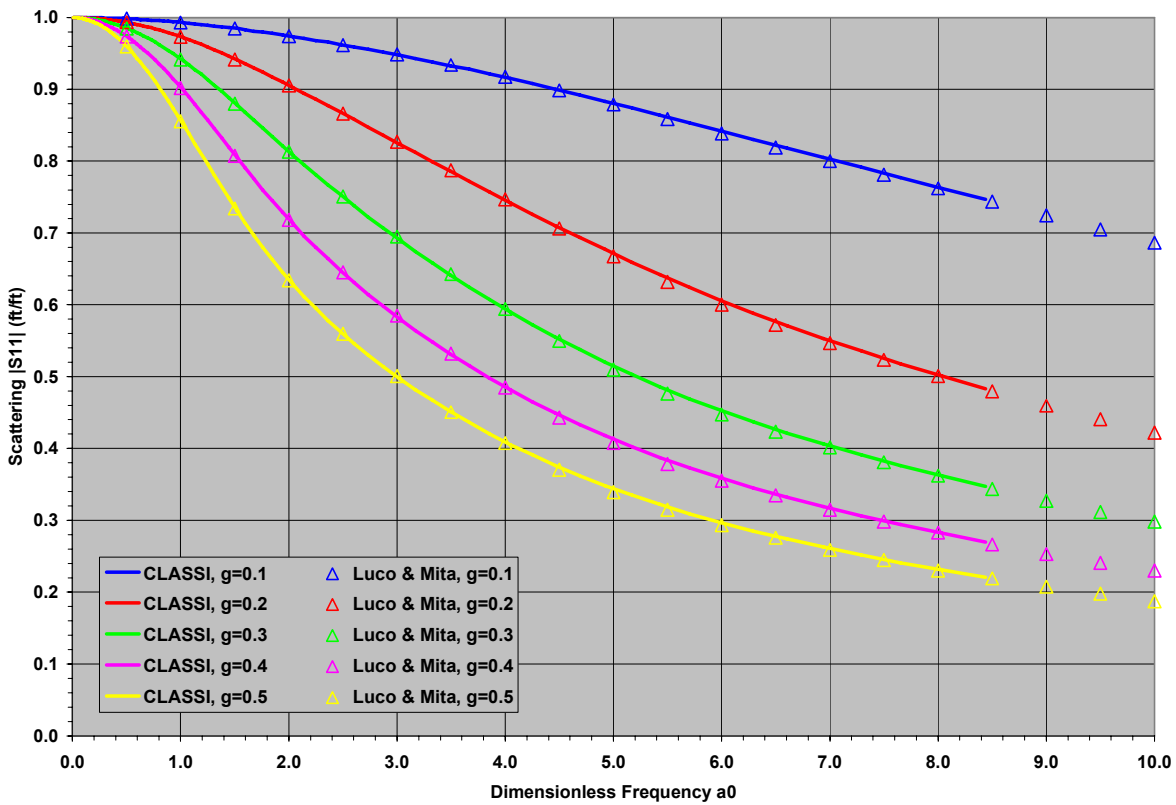
CLASSlinco vs. Luco and Mita (1987): Horizontal ITF



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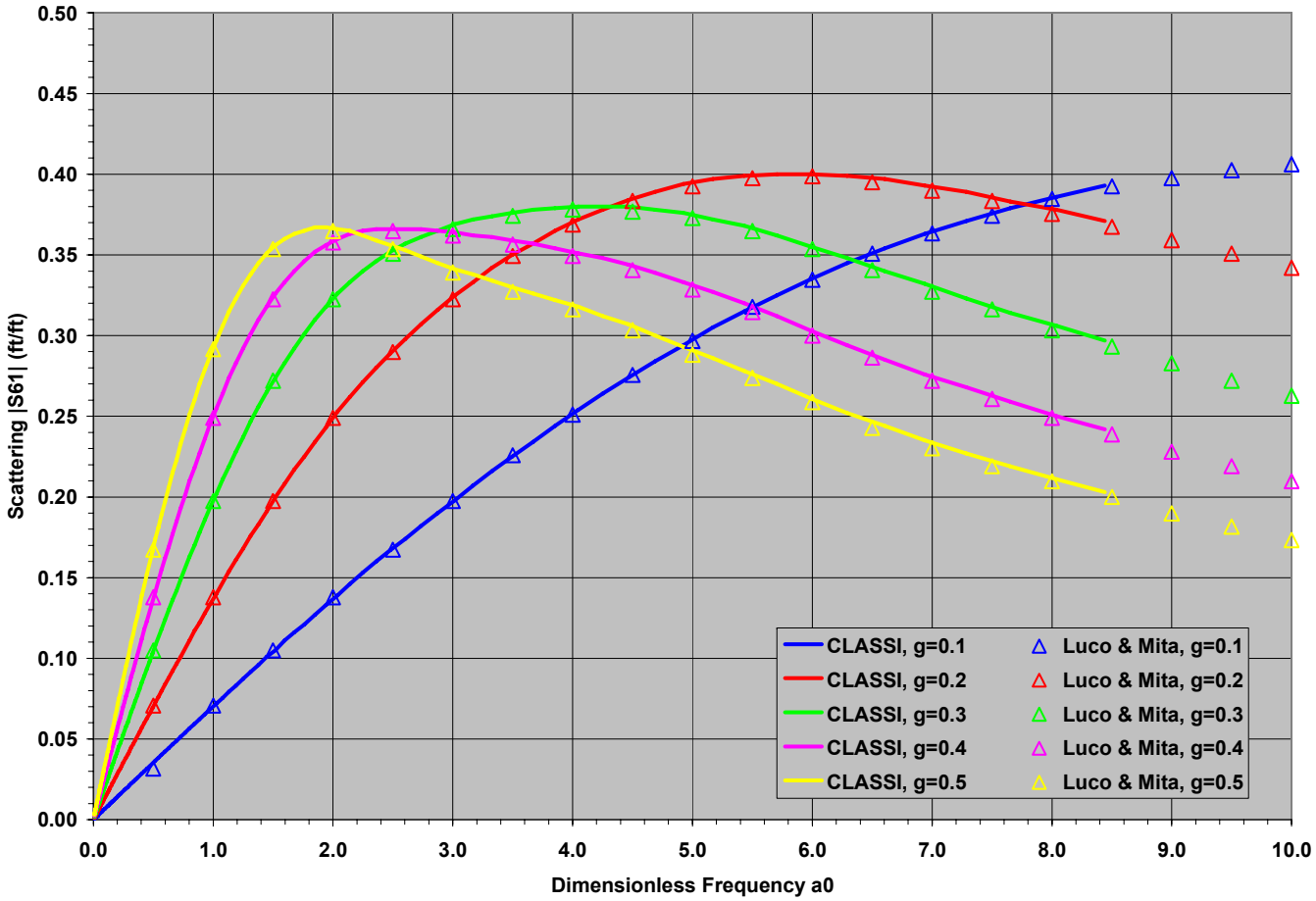
CLASSlinco vs. Luco and Mita (1987): Induced Torsion ITF



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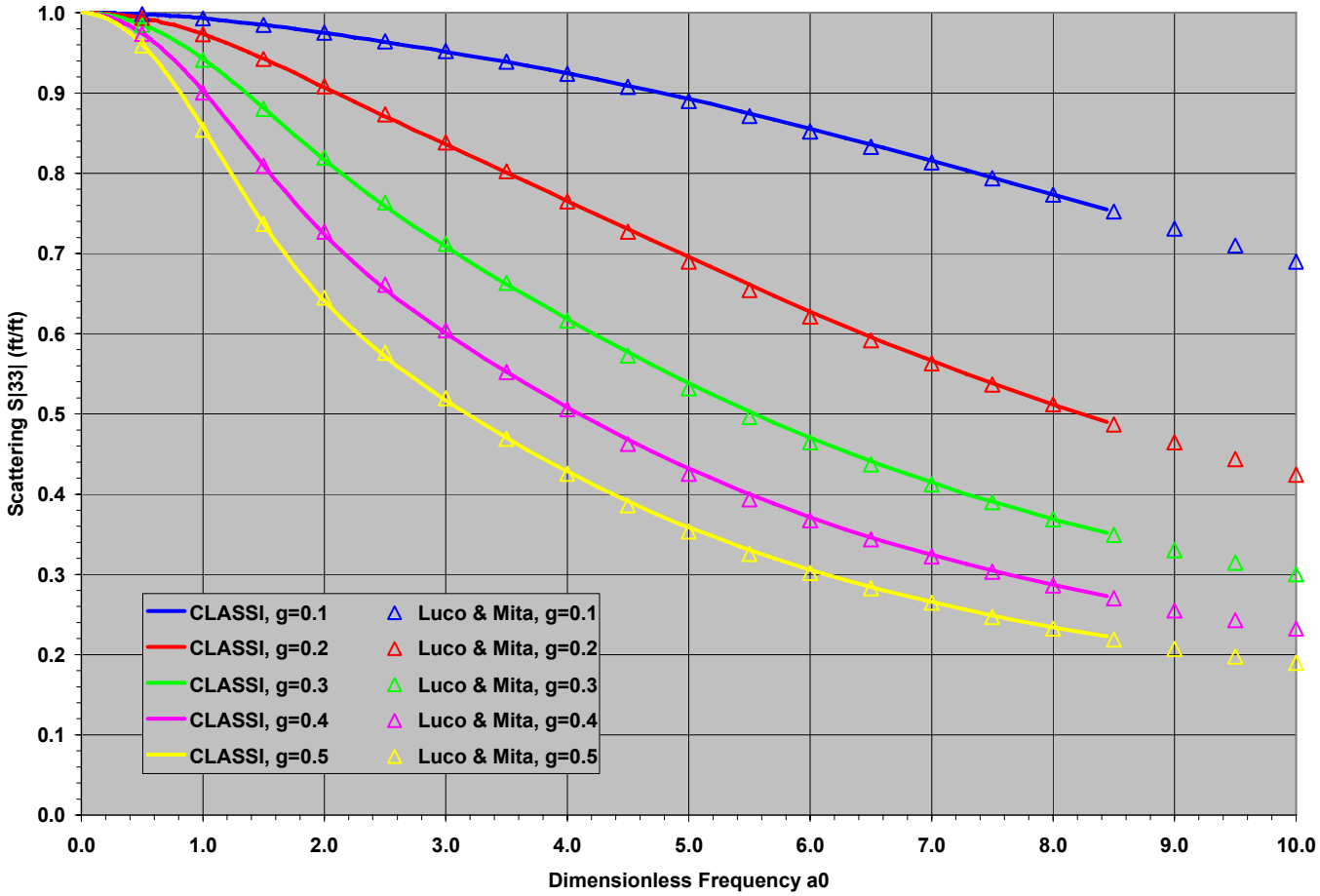
CLASSlinco vs. Luco and Mita (1987): Vertical ITF



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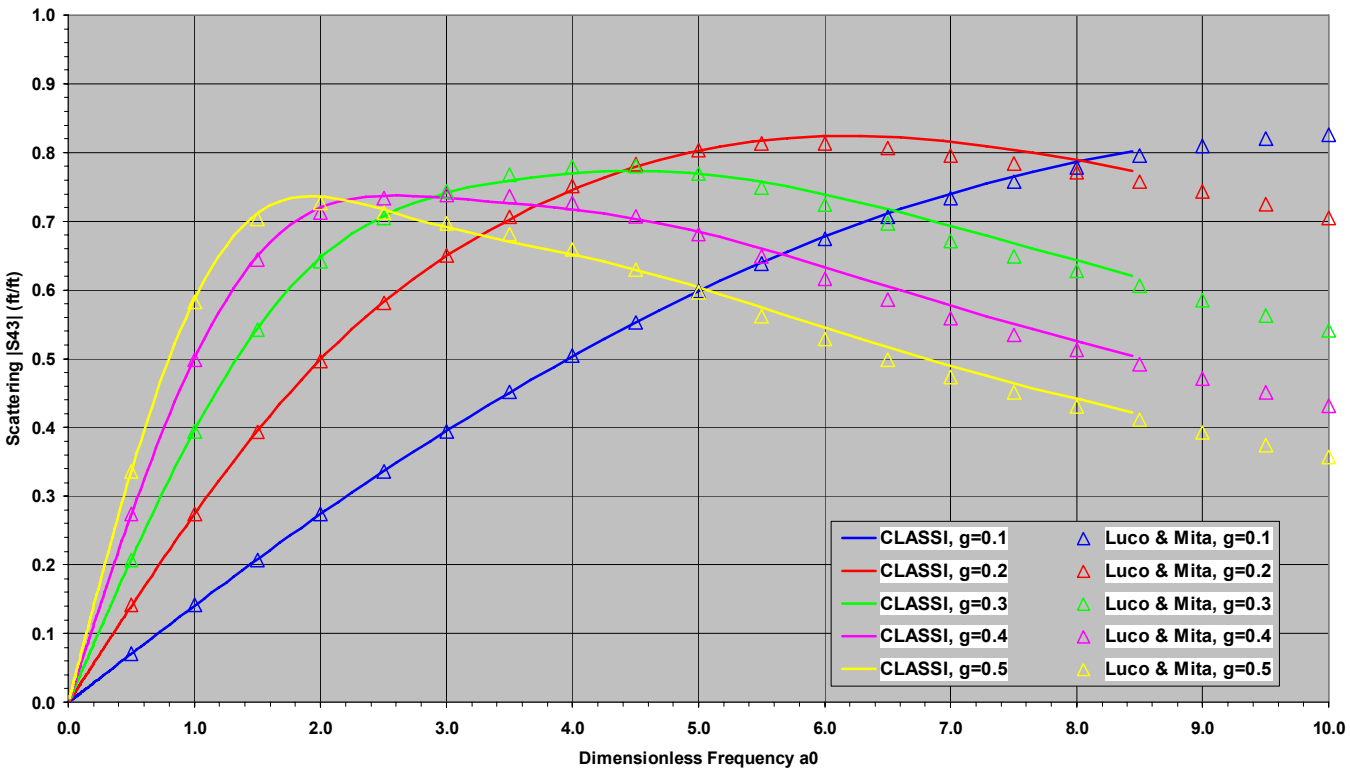
CLASSlinco vs. Luco and Mita (1987): Induced Rocking ITF



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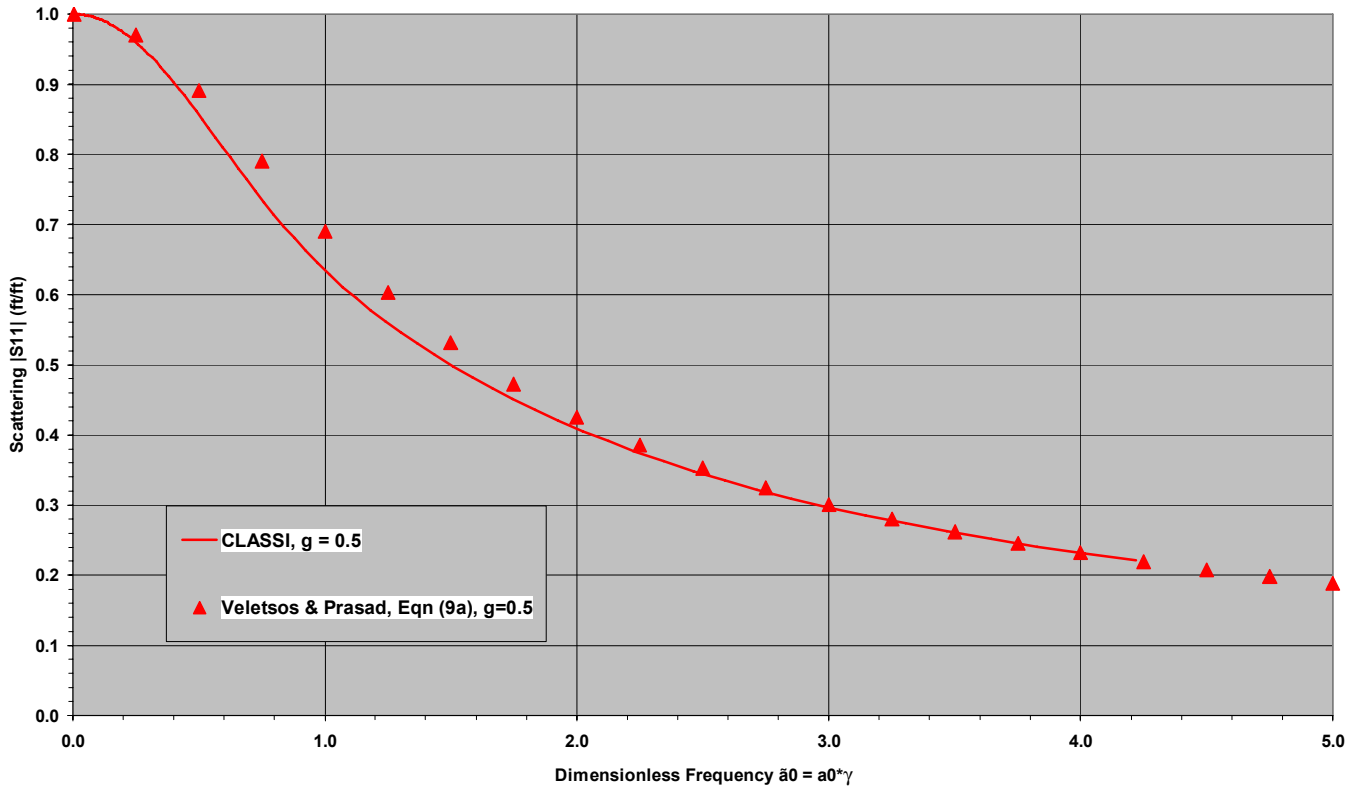
CLASSlinco vs. Veletsos and Prasad (1989) (γ = 0.5): Horizontal ITF



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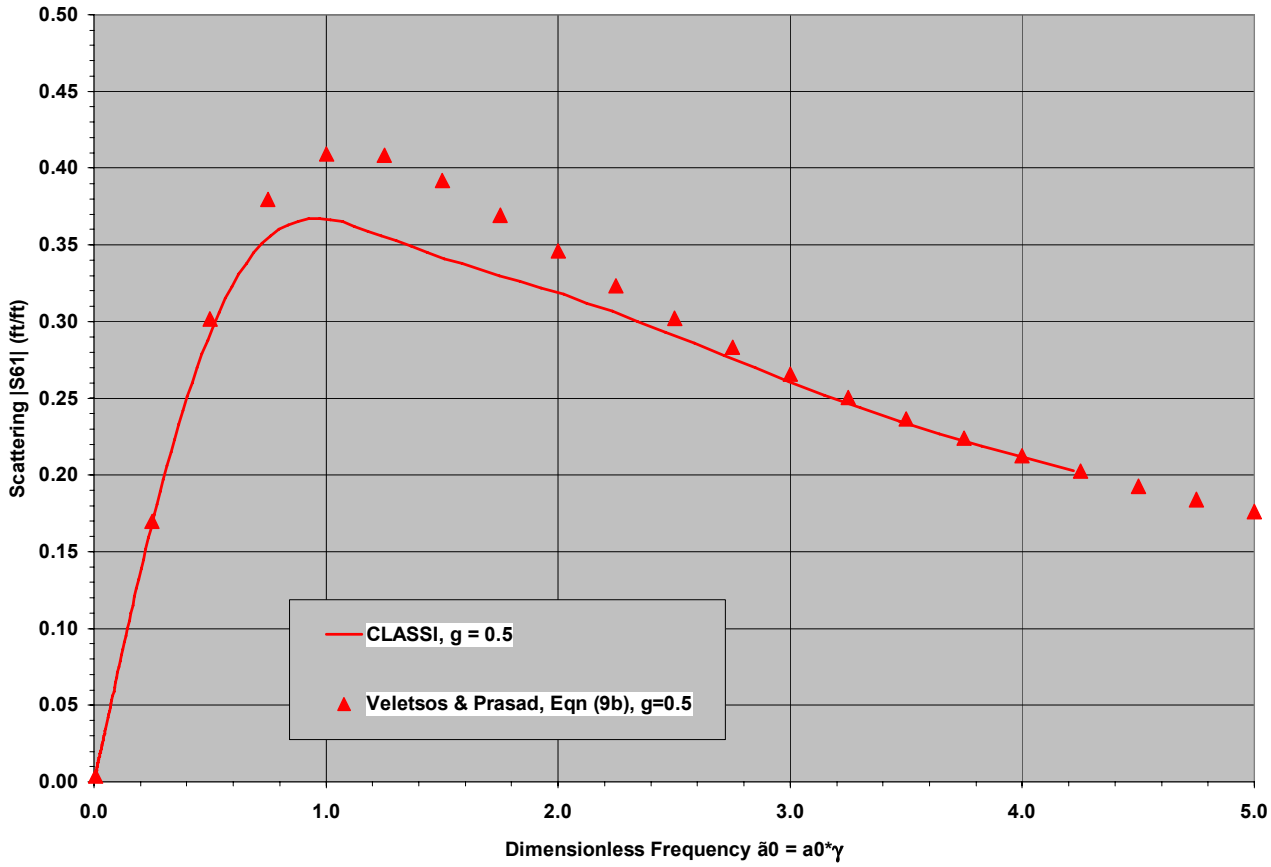
CLASSlinco vs. Veletsos and Prasad (1989) (γ = 0.5): Induced Torsion ITF



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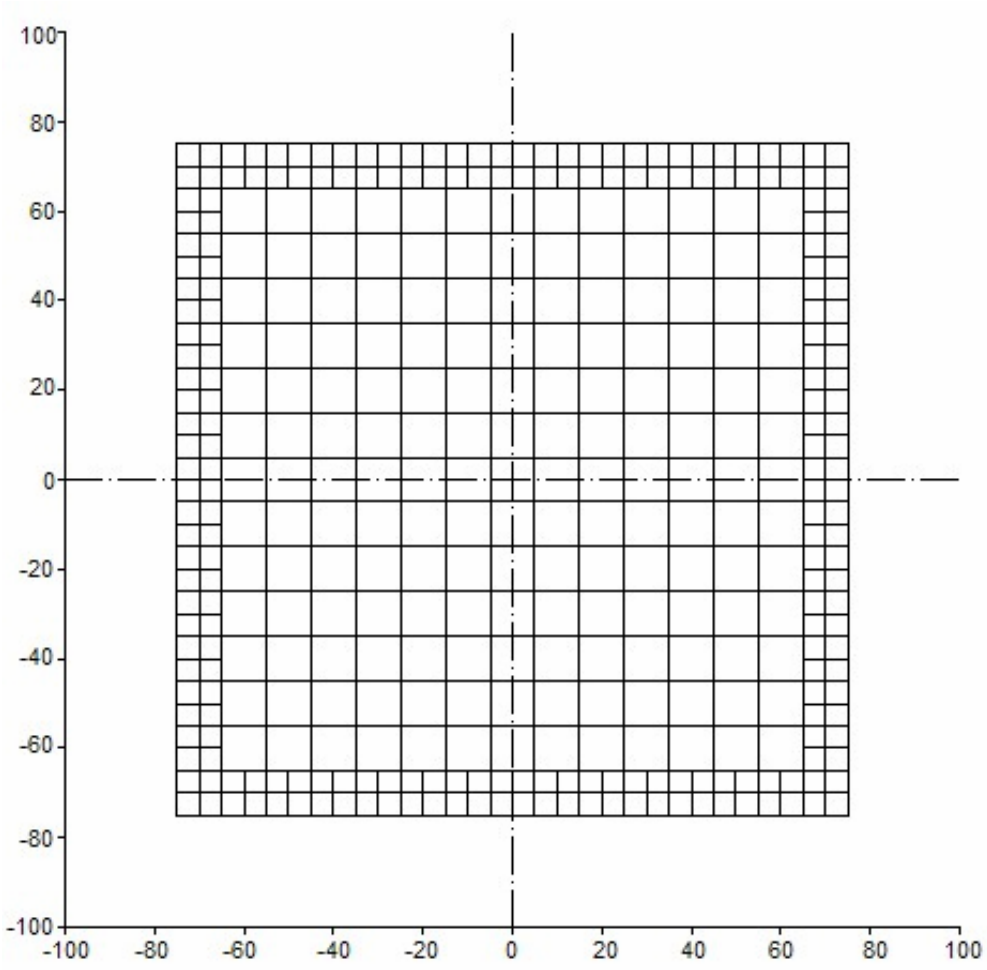
Square Foundation: CLASSlinco Discretization



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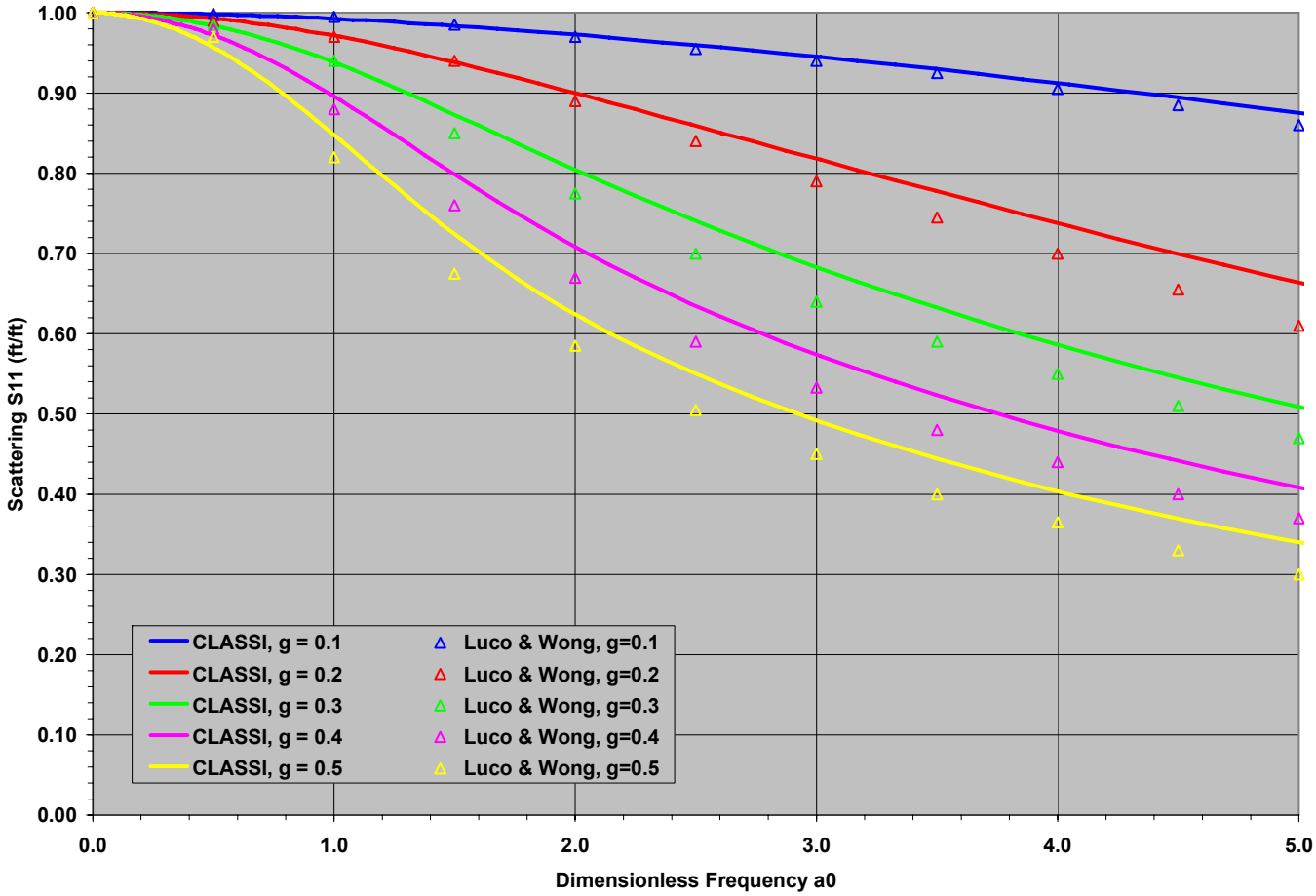
CLASSlinco vs. Luco and Wong (1986): Horizontal ITF



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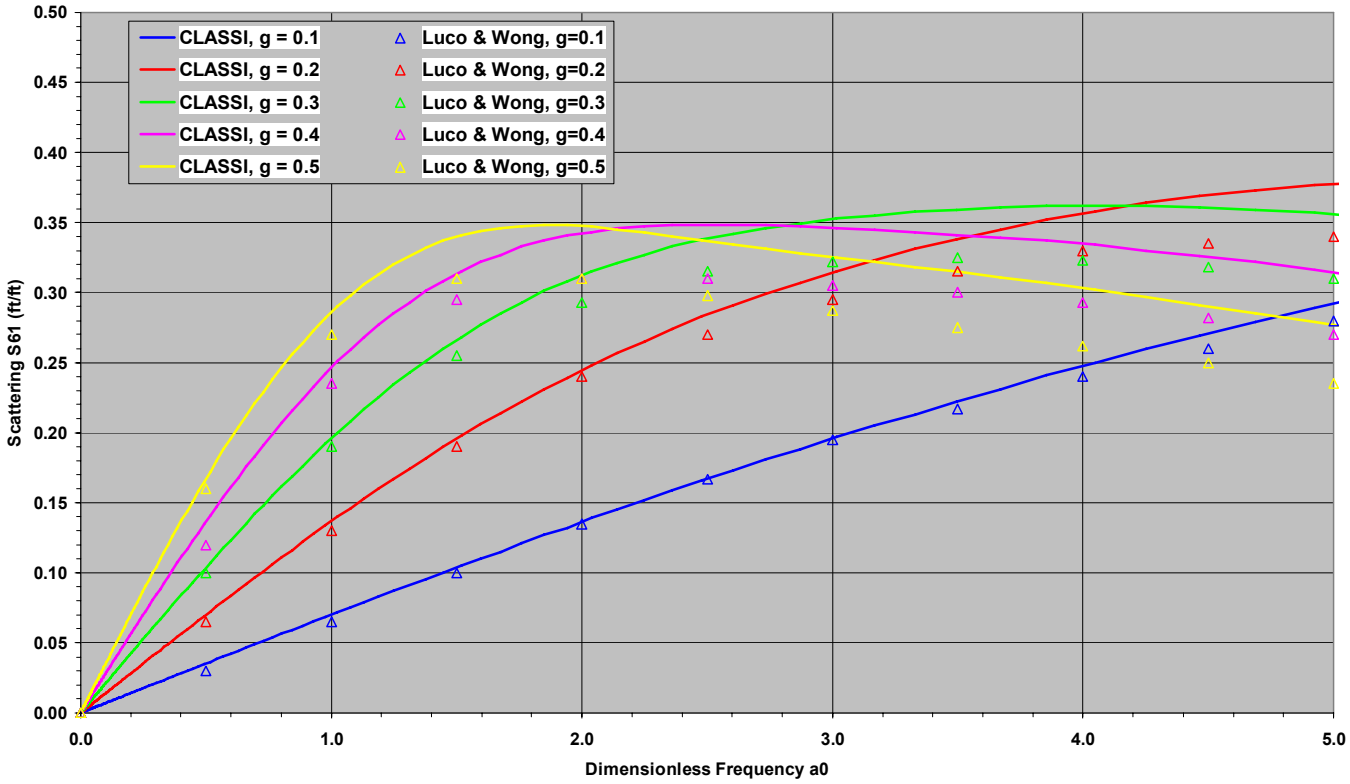
CLASSlinco vs. Luco and Wong (1986): Induced Torsion ITF



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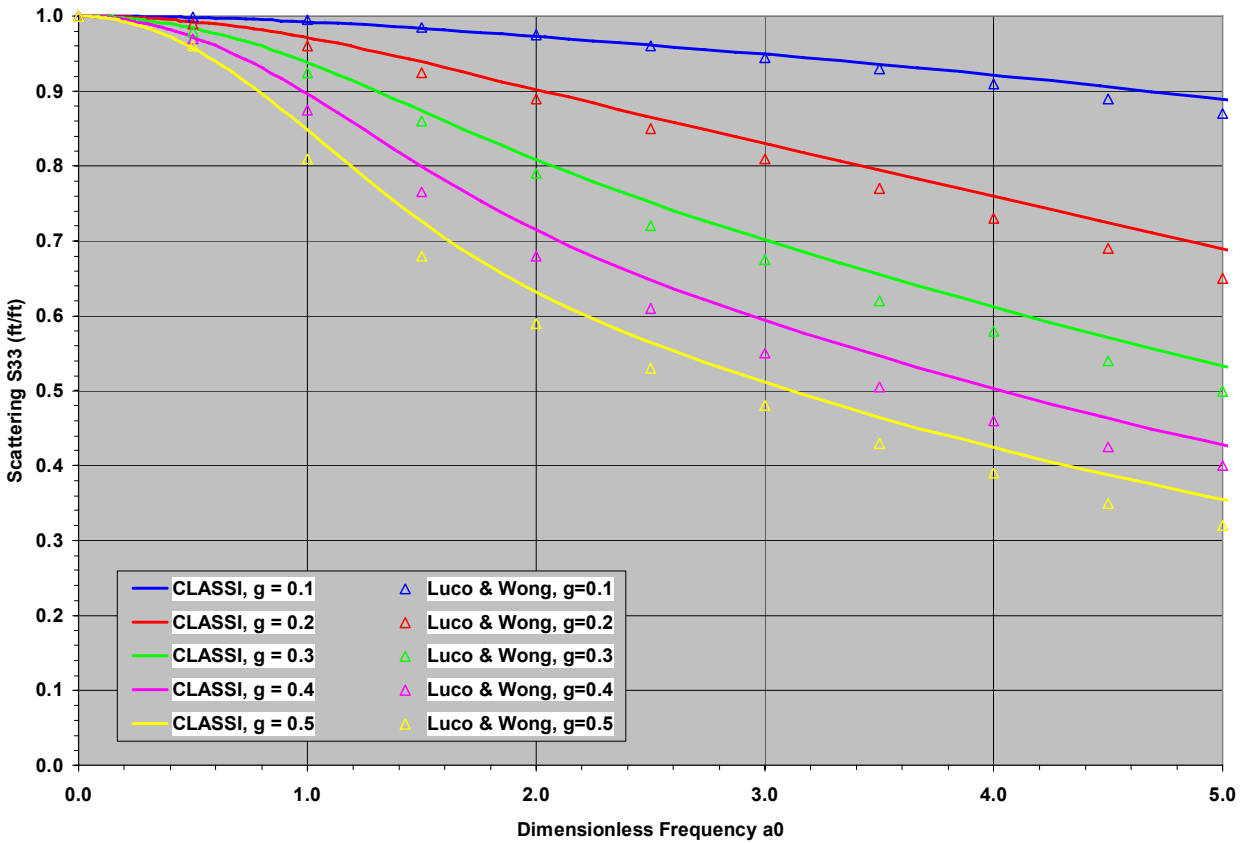
CLASSlinco vs. Luco and Wong (1986): Vertical ITF



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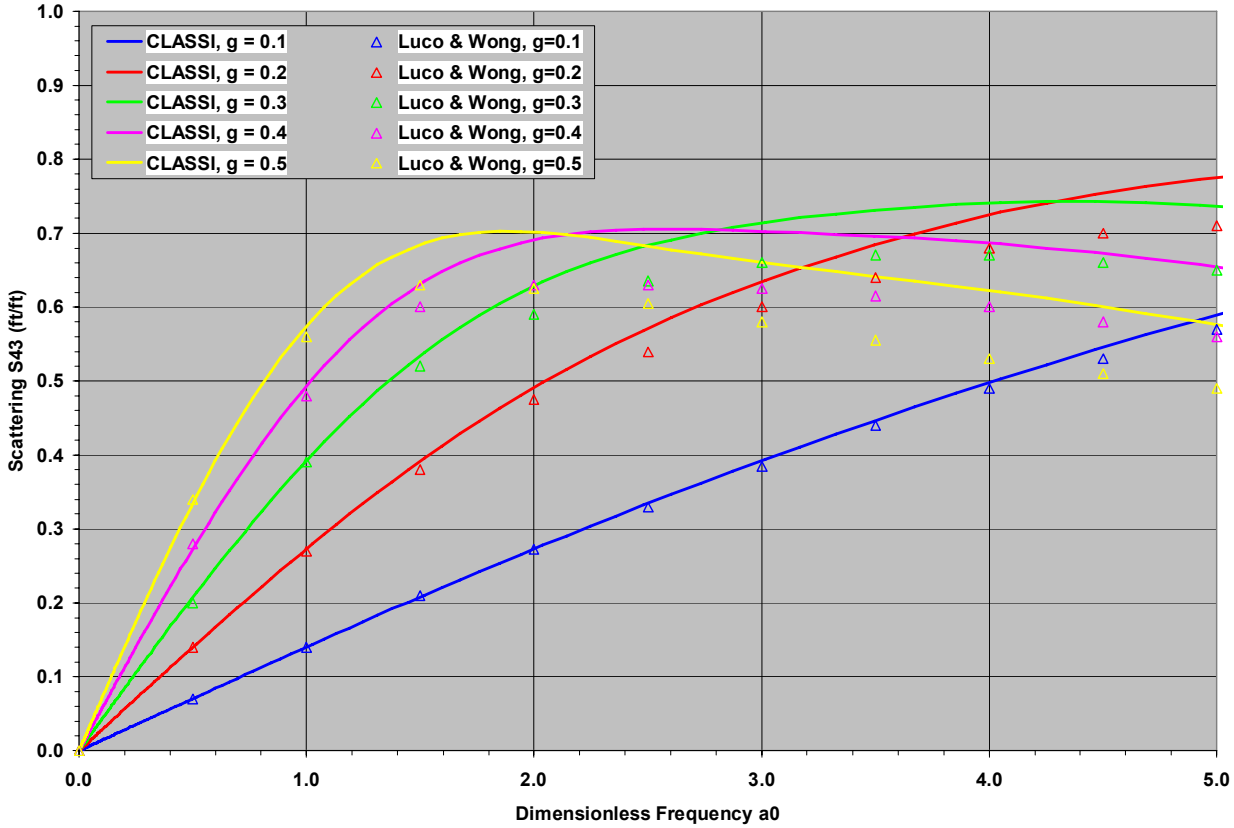
CLASSlinco vs. Luco and Wong (1986): Induced Rocking ITF



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Validation of CLASSIinco

- Benchmark with published literature validates CLASSIinco approach and implementation

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Validation of SASSI with Incoherence

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Validation of SASSI with Incoherence

- Close agreement between CLASSI & SASSI is demonstrated in Appendix C of EPRI No. 1013504
  - Rigid massless foundation transfer functions and response spectra
  - AP1000 stick model on a rigid foundation
- SASSI evaluation of incoherency-induced rotations on rigid massless foundations (Chapter 4)
- SASSI evaluation of incoherency-induced rotations on the AP1000 stick model with offsets & outriggers (Ch. 5)

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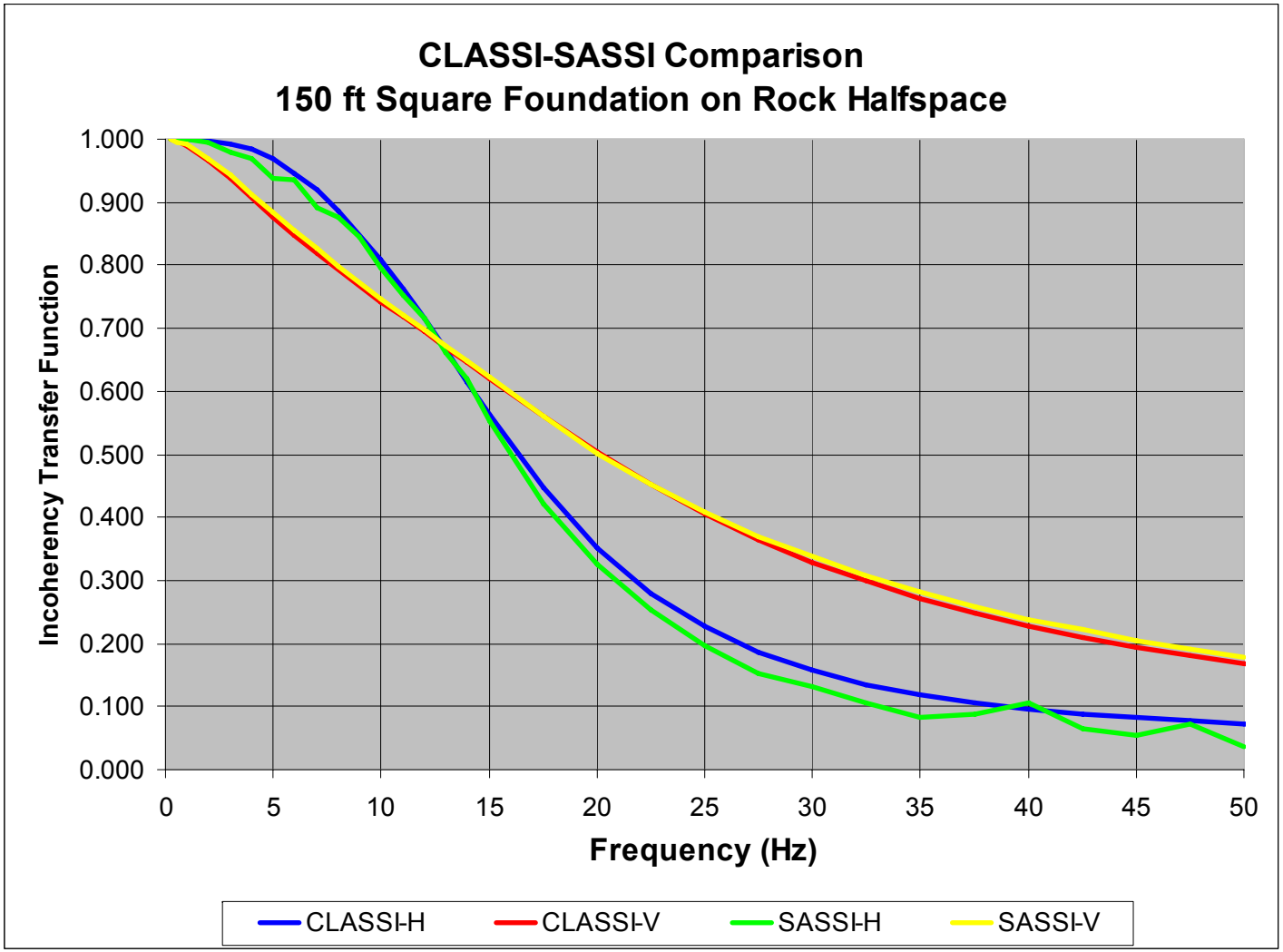
CLASSI-SASSI Comparison from App. C



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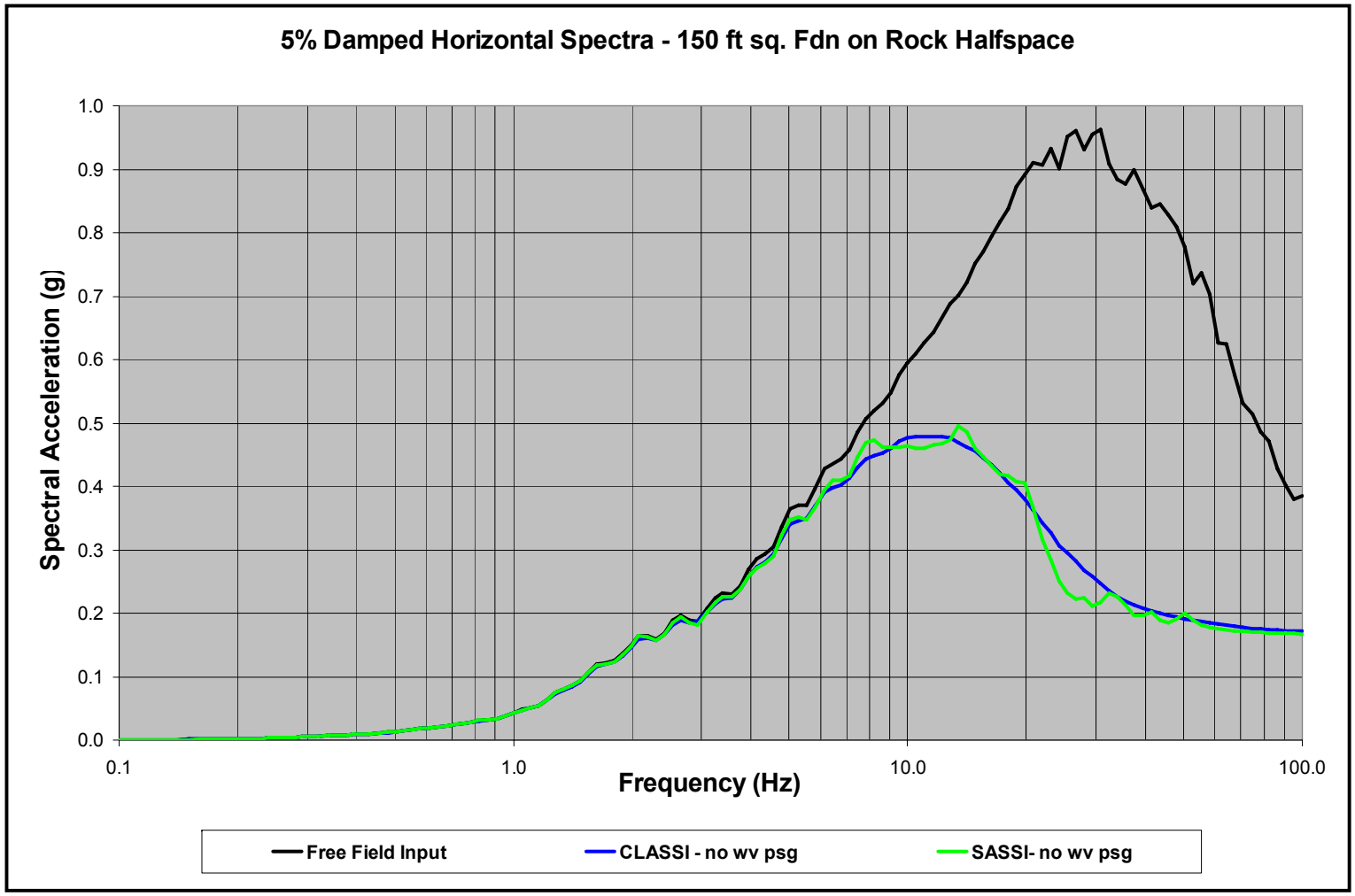

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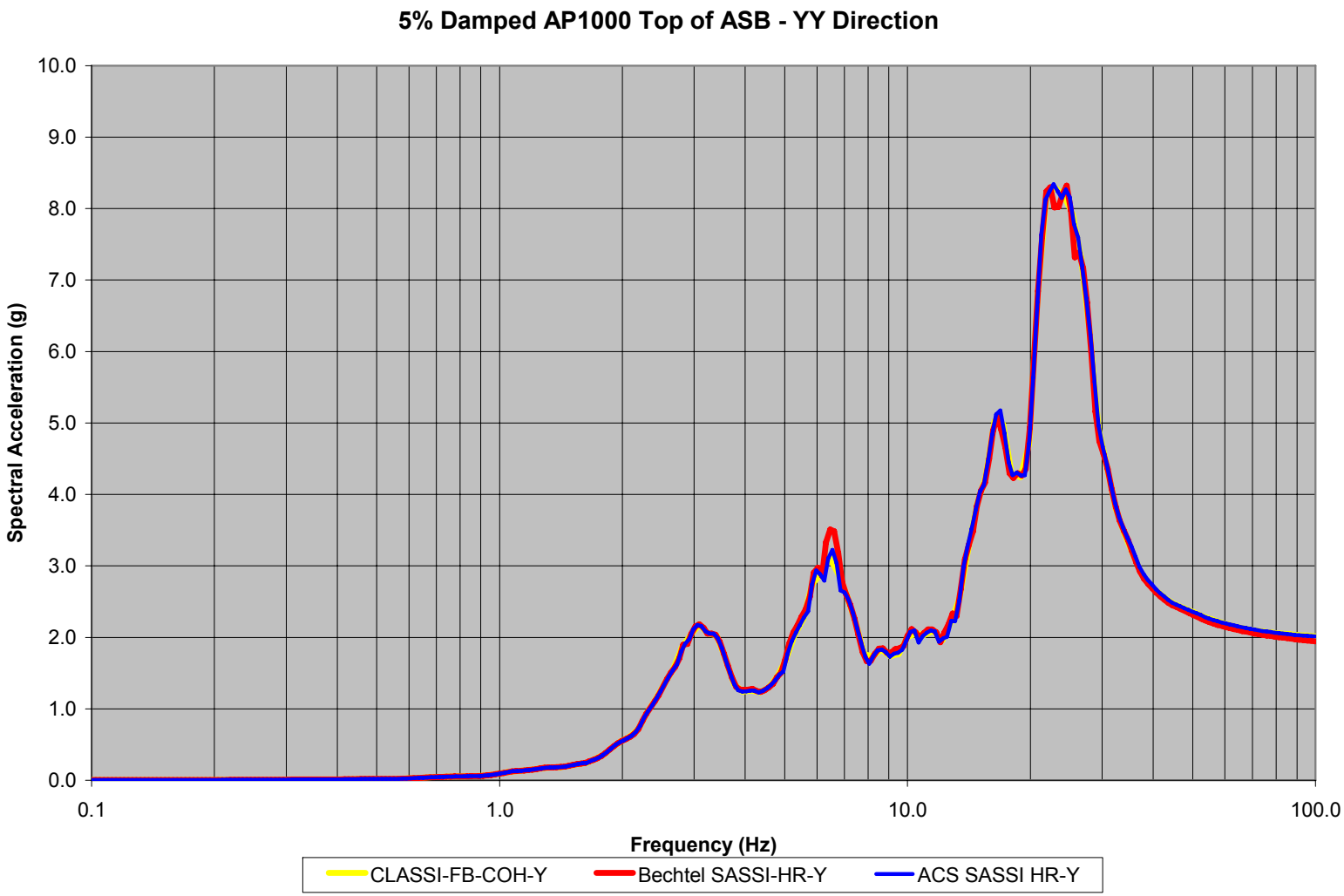
CLASSI-SASSI Comparison from App. C



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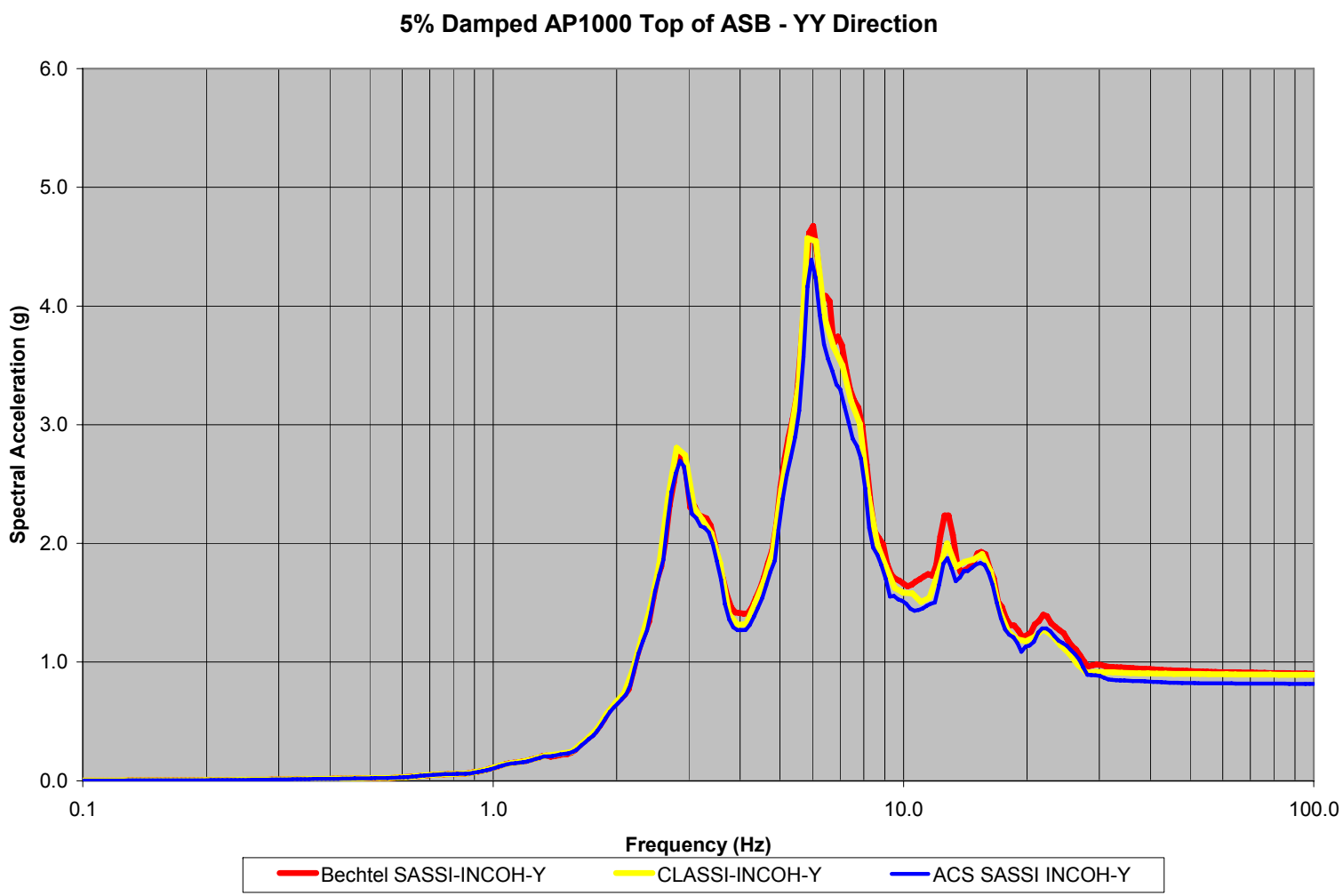
CLASSI-SASSI Comparison from App. C



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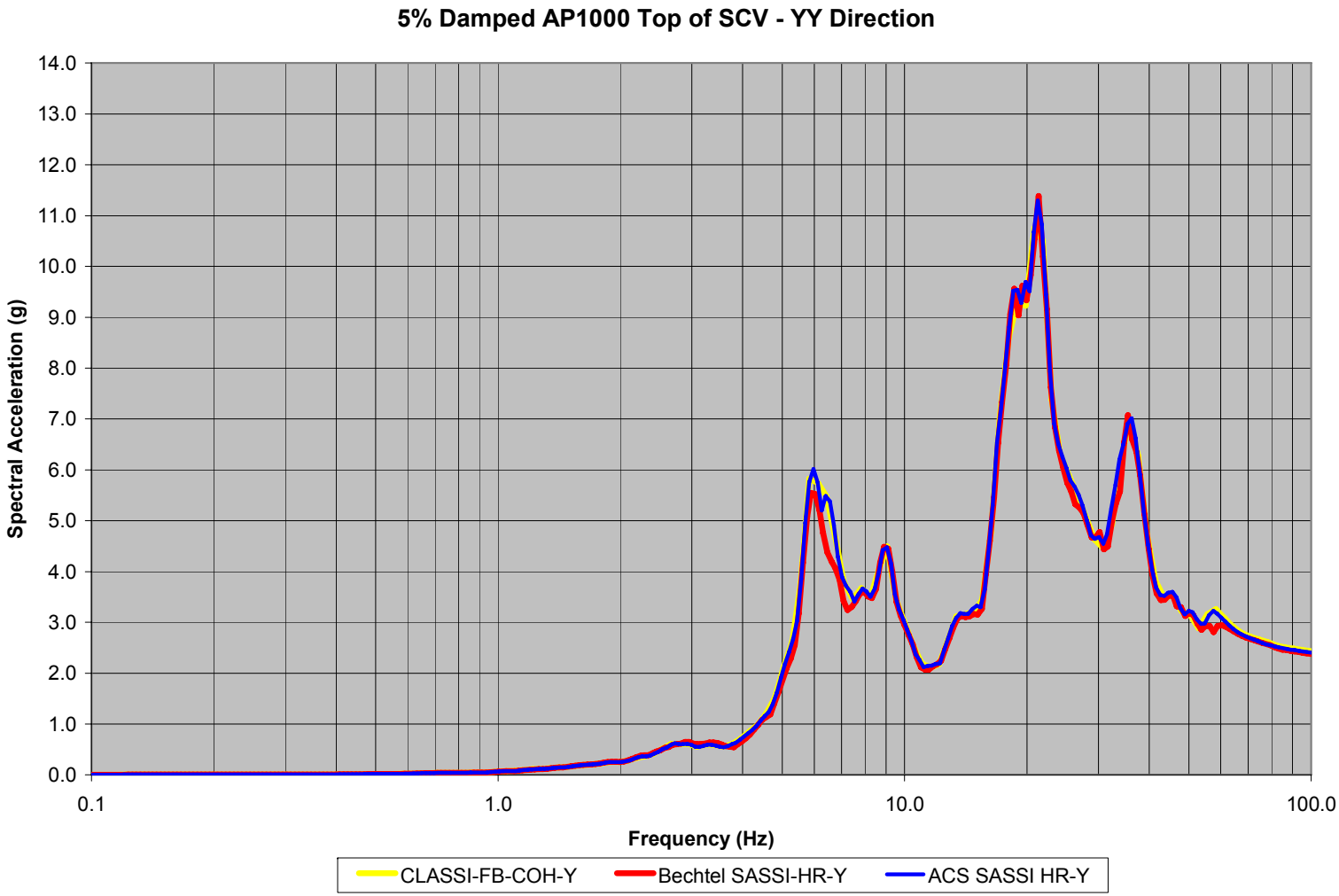
CLASSI-SASSI Comparison from App. C



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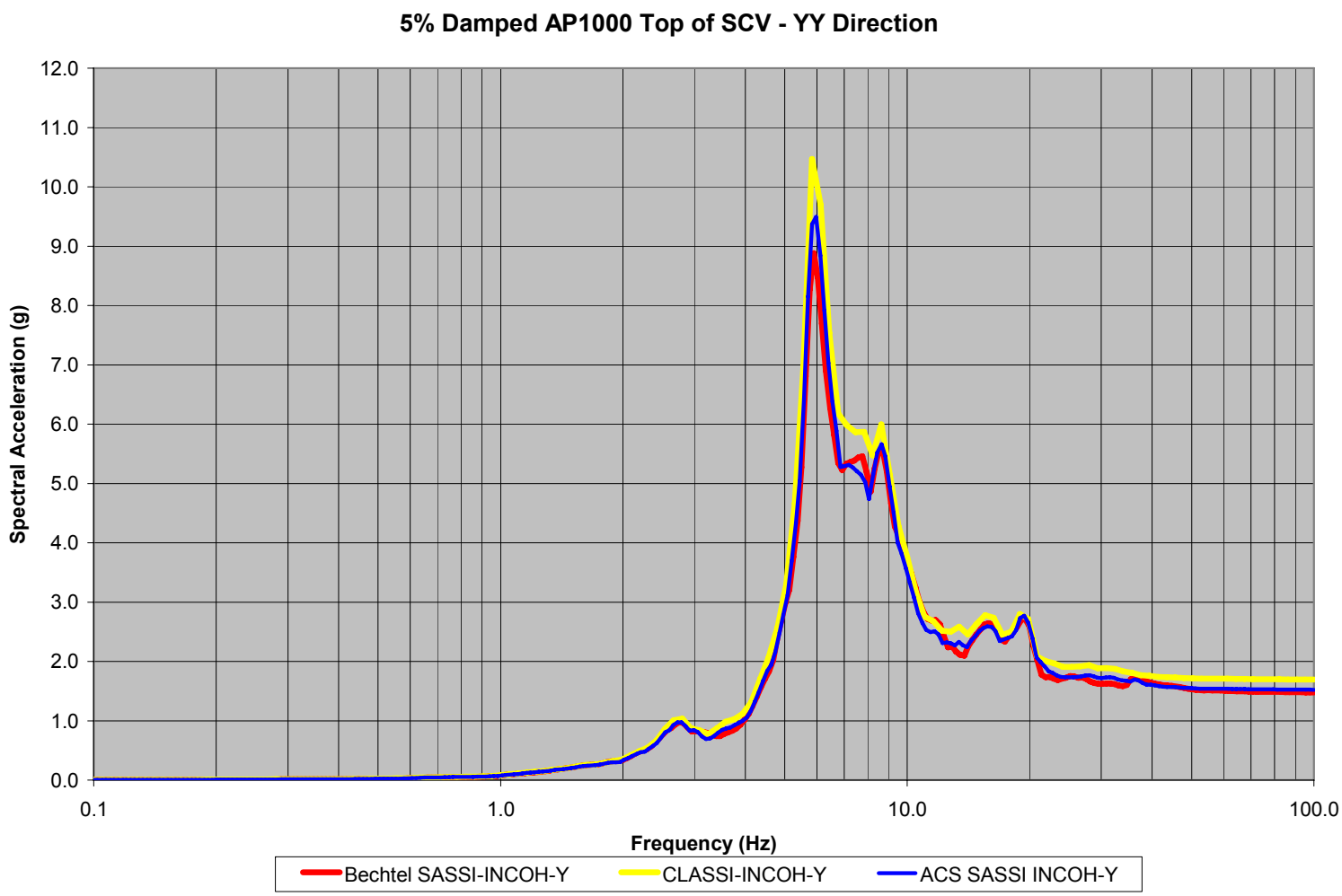
CLASSI-SASSI Comparison from App. C



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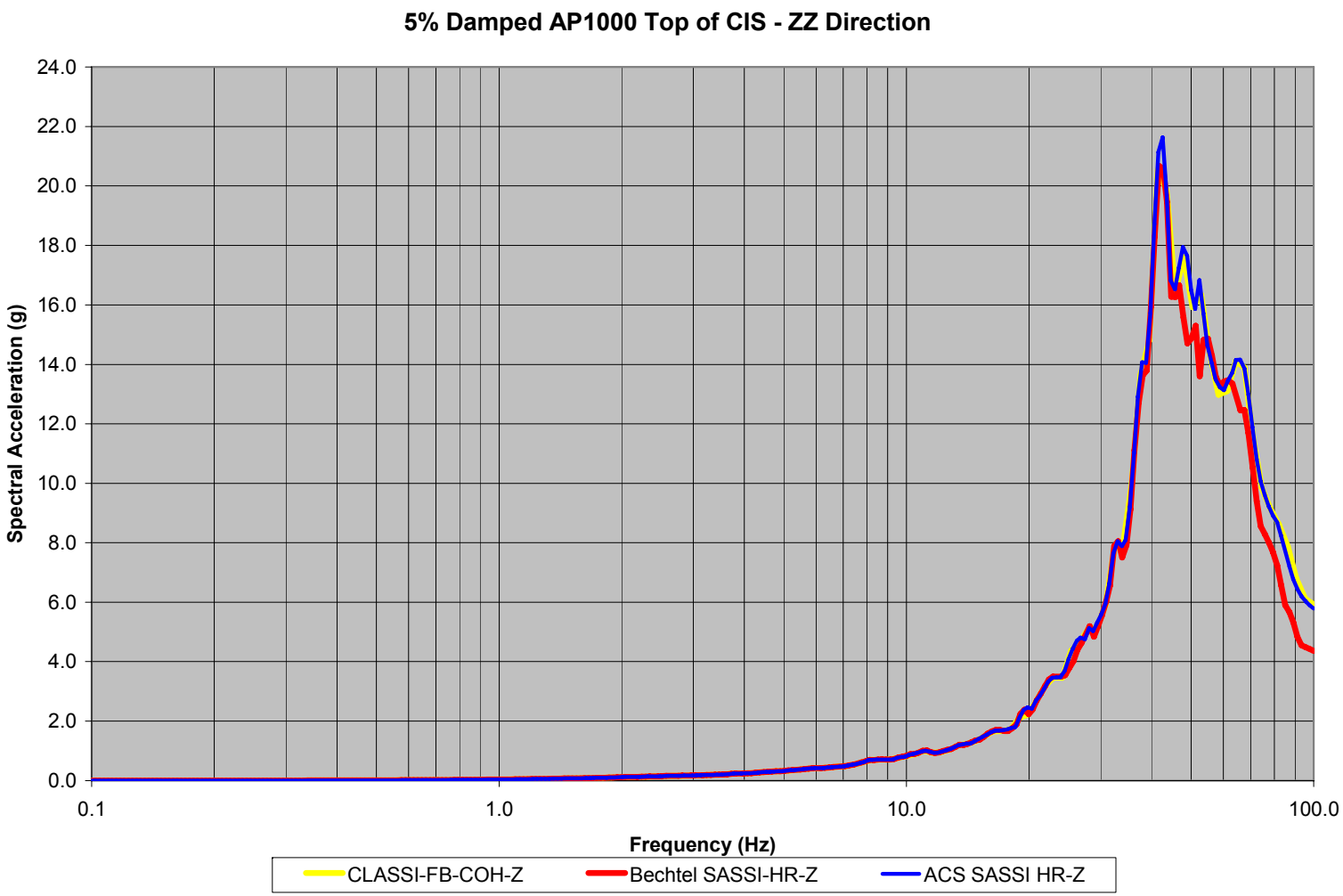
CLASSI-SASSI Comparison from App. C



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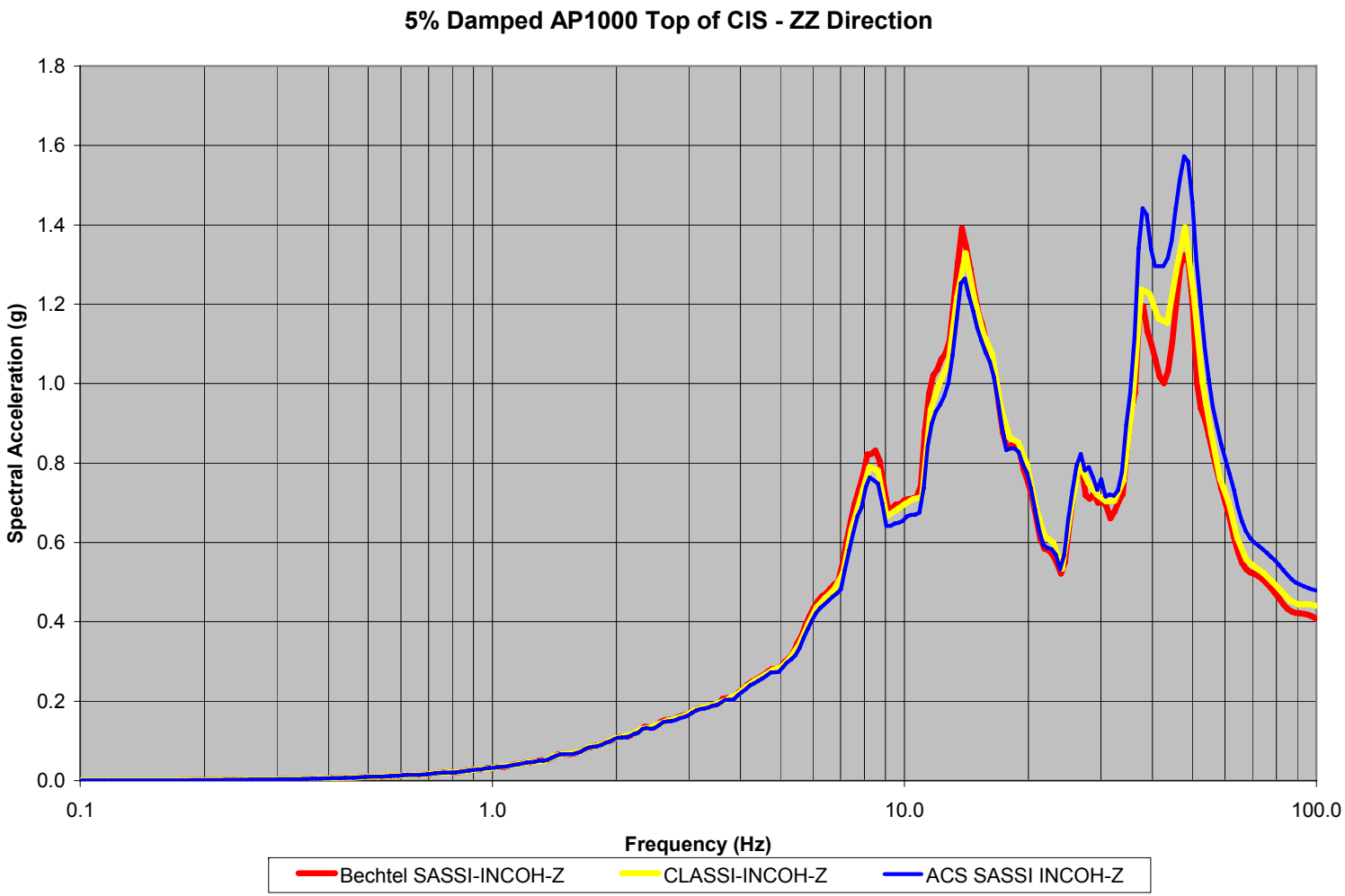
CLASSI-SASSI Comparison from App. C



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SASSI-CLASSI Comparison of Translations, Torsion, and Rocking

- Rigid massless foundation cases from Chapter 4
  - Preliminary results presented here
  - Good agreement for translation (horizontal & vertical)
  - Need improvement for torsion & rocking
- Rigid massless foundation cases from CLASSIincoh validation study
  - Work is underway; no results available
- SSI Cases of AP1000 Model with offsets and outriggers from Chapter 5
  - Work is underway; no results available

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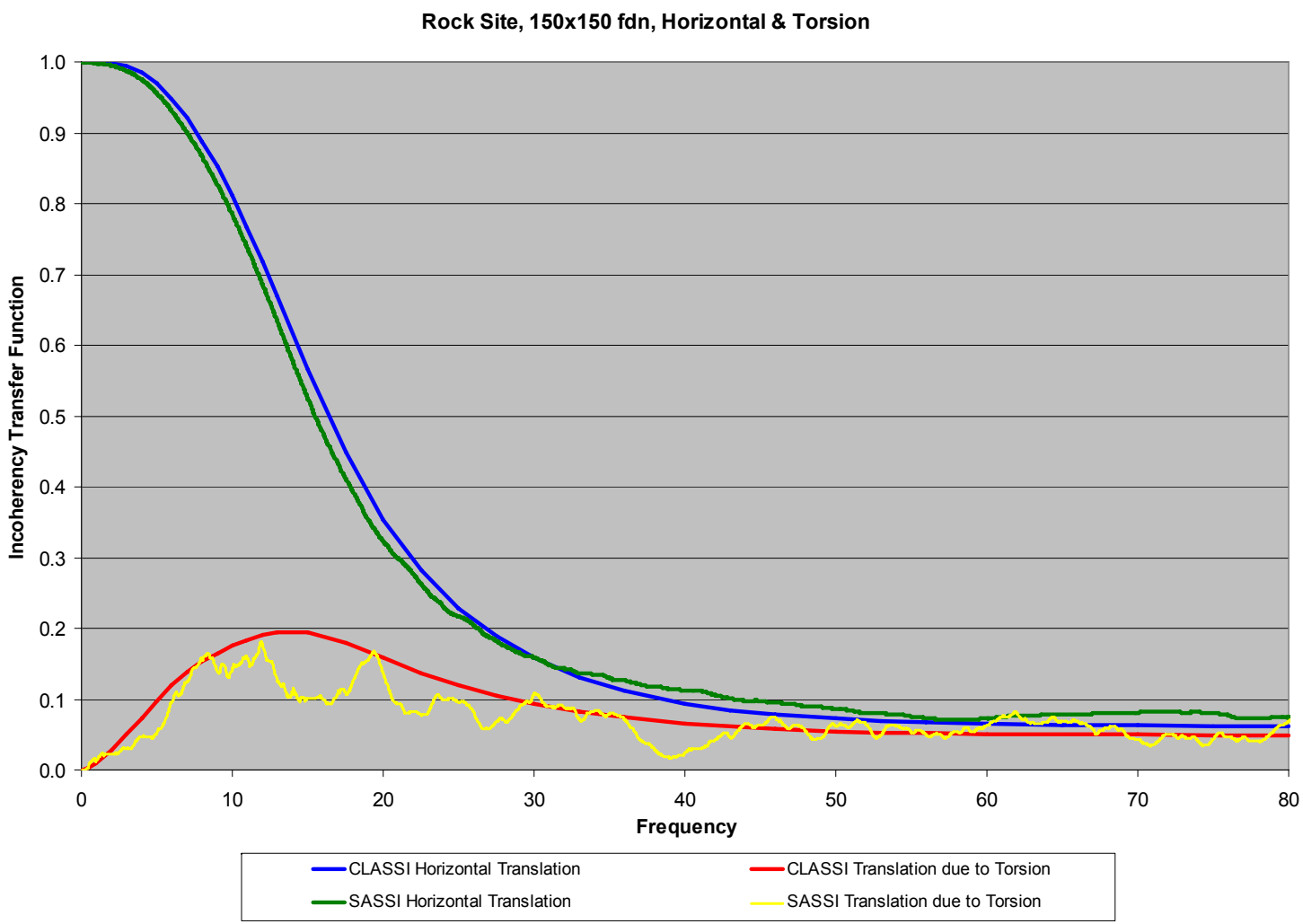
Horizontal Translation & Torsion Transfer Functions



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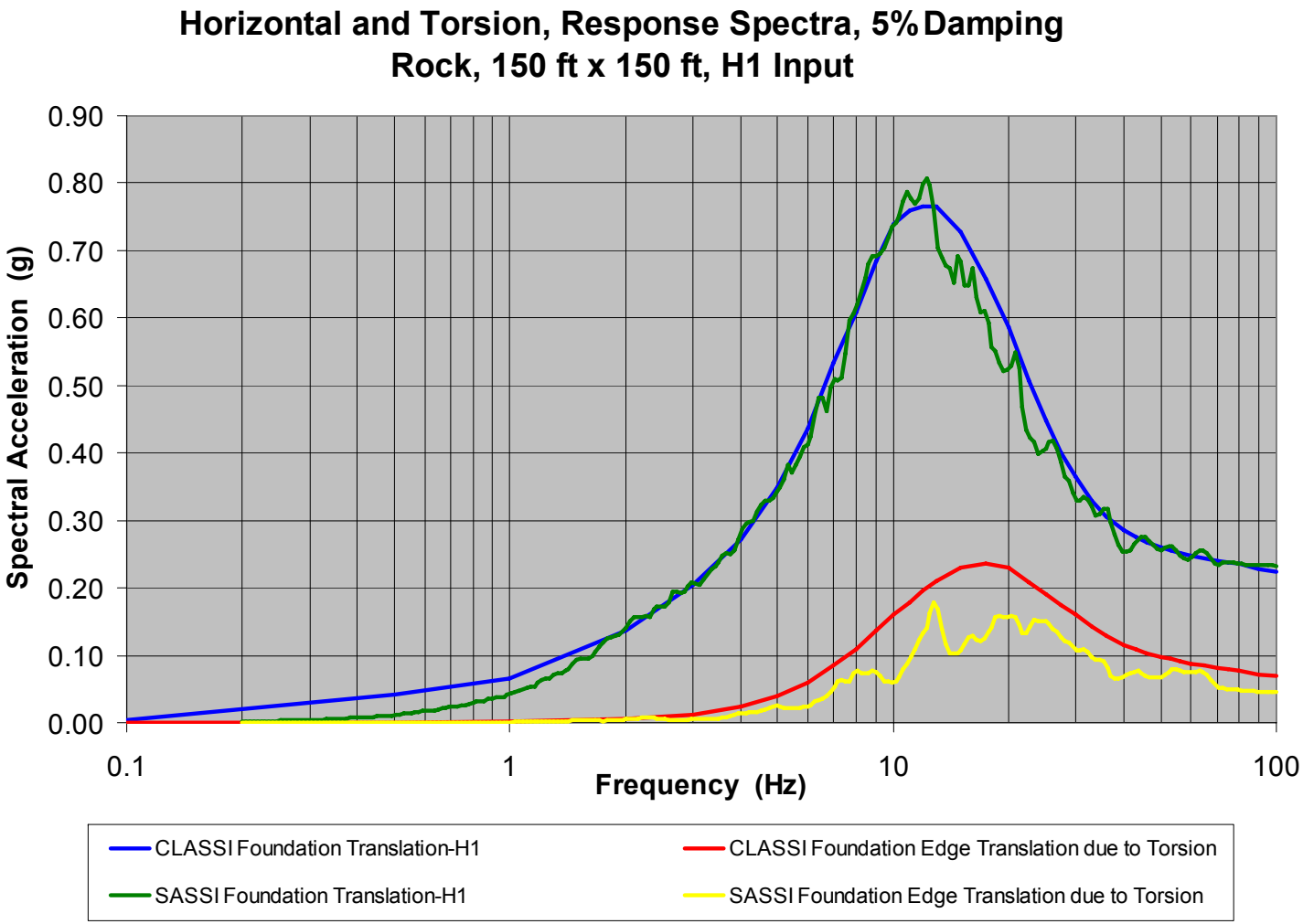
Horizontal Translation & Torsion Response Spectra



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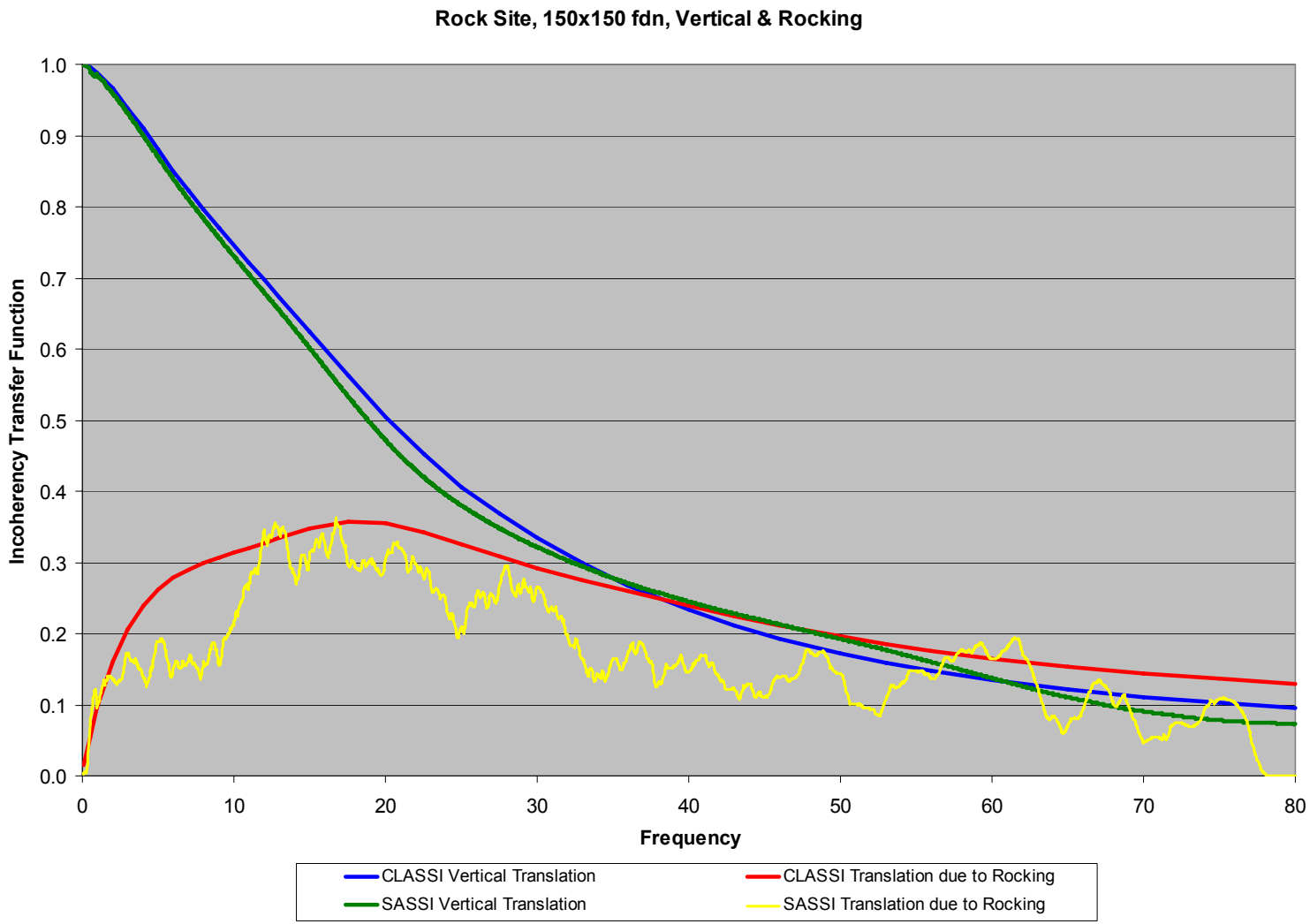
Vertical Translation & Rocking Transfer Functions



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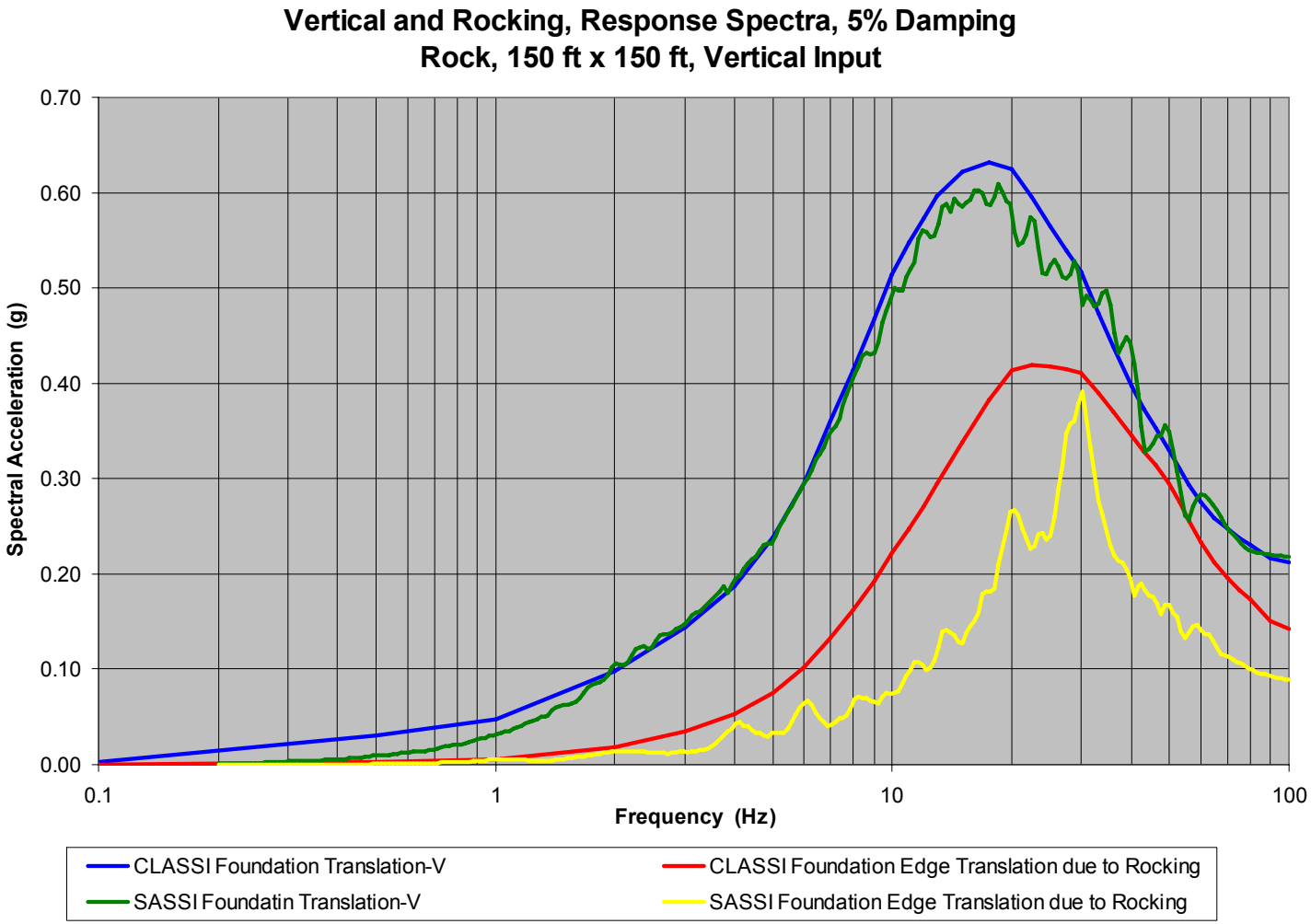
Vertical Translation & Rocking Response Spectra



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SASSI-CLASSI Comparison of Translations, Torsion, and Rocking

- Validation package will include cases from Chs. 4 & 5 and CLASSIincoh validation study with comparisons to published result
- Examining mesh refinement and foundation stiffness to improve comparison for rotations before completing the validation

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