ELECTRIC POWER RESEARCH INSTITUTE

New Plant Seismic Issues Resolution Program – Discussion on S2.1 Incoherence Project

October 24-25, 2006

Stephen Short
Jim Johnson
Greg Hardy

Agenda – Tuesday, October 24, 2006

8:30 a.m.	Introductions and Opening Remarks	NRC and EPRI
9:00 a.m.	Discussions of Report S2.1(a) - "Effect of Seismic Wave Incoherence on Foundation and Building Response"	NRC and EPRI
10:30 a.m.	Break	
10:45 a.m.	Discussions of Report S2.1(b) - "Spatial Coherency Models for Soil-Structure Interaction" and RAI Responses	EPRI
12:00 p.m.	Lunch	
1:00 p.m.	NRC Staff Comments/Identification of Issues	NRC
2:00 p.m.	Break	
2:15 p.m.	Open Discussion and NEI/Industry Responses and Plans to Address NRC Comments	
5:00 p.m.	Adjourn	

Agenda – Wednesday, October 25, 2006

8:30 a.m.	Summary of Tuesday Meeting	NRC and EPRI
9:00 a.m.	Continued Discussions of Report S2.1(a) and RAI Responses	EPRI
10:30 a.m.	Break	
10:45 a.m.	NRC Staff Comments/Identification of Issues	NRC
12:00 p.m.	Lunch	
1:00 p.m.	Continuation of NRC Comments, Open Discussion and NEI/Industry Responses and Plans to Address NRC Comments	NRC and EPRI
2:30 p.m.	Break	
2:45 p.m.	Summary of Meeting Action Items	NRC and NEI
4:00 p.m.	Adjourn	

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New Plant Seismic Program Task S2.1(a)

- Report – "Effect of Seismic Wave Incoherence on Foundation and Building Response"
  - October 2006
- Meeting Topics
  - Report Discussion
    - Study Input Parameters
    - Technical Approach
    - Rigid, Massless Foundation Response
    - SSI and Structure Response
    - Conclusions and Recommendations
  - NRC Responses to New Material

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Report Table of Contents

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S2.1(a) Project Sub-Tasks

- Define cases to be analyzed including site conditions, foundation characteristics, and structural characteristics.
- Develop the ground motion input to be considered including response spectra and time histories.
- Derive the approach to incorporating the coherency functions into the CLASSI family of programs.
- Conduct parametric studies of the rigid, massless foundation to determine incoherency transfer functions and foundation response spectra. Comparison of foundation and free-field response spectra demonstrate the effect of SSI and incoherence on foundation response.

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S2.1(a) Project Sub-Tasks

- Benchmark the computed incoherency transfer functions and modified spectra for a specific case by comparing CLASSI results to those obtained using SASSI.
  - Two different SSI computer programs; CLASSI and SASSI (two different versions of SASSI were used – Bechtel and ACS).
  - Two different algorithms; CLASSI-stochastic method and SASSI-eigen decomposition method.
  - Two different analytical approaches; random vibration theory (RVT) by CLASSI, and time history dynamic analyses by SASSI.
  - Two different organizations conducting the analyses; CLASSI by the ARES team, and SASSI by the ARES team and the Bechtel Corporation.

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S2.1(a) Project Sub-Tasks

- Conduct SSI analyses of an example structure incorporating seismic wave incoherence by the direct approach of the CLASSI family of programs. Quantify the effect on in-structure response spectra of SSI vs. fixed-base conditions and the additional effect of incoherence of ground motions.
- Investigate the feasibility of a *simplified* (alternate) *method* to modeling the effects of seismic wave incoherence. The *simplified method* is based on developing a function derived from the incoherency transfer function that is applied to the amplitude of the Fourier Transform of the free-field ground motion. The end result being a modified free-field ground motion that incorporates the effects of incoherency and can be used in standard SSI analysis programs assuming coherent input motion.
- Document all work in a final report.

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Chapter 2:
Study Input Parameters

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Dr. Abrahamson Coherency Function (Abrahamson 2005, 2006)

$$\gamma_{PW} = \left[1+\left(\frac{f\,Tanh(a_3\xi)}{a_1 f_c}\right)^{n1}\right]^{-1/2}\left[1+\left(\frac{f\,Tanh(a_3\xi)}{a_2 f_c}\right)^{n2}\right]^{-1/2}$$ **Equation 2-1**

$$\gamma = |\gamma_{PW}|[\cos(2\pi f\xi_R s) + i\sin(2\pi f\xi_R s)] = |\gamma_{PW}|e^{i2\pi f\xi_R s}$$ **Equation 2-2**

Where γ_{PW} is the plane wave coherency representing random horizontal spatial variation of ground motion and γ is coherency including both local wave scattering and wave passage effects.

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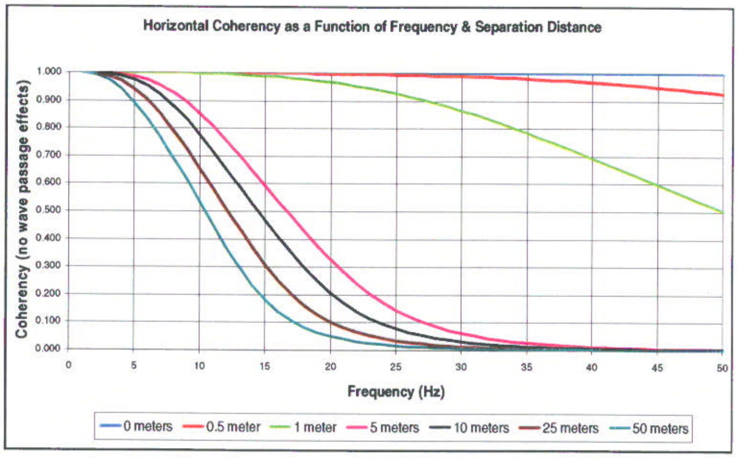
Coherency Function for Horizontal Ground Motion



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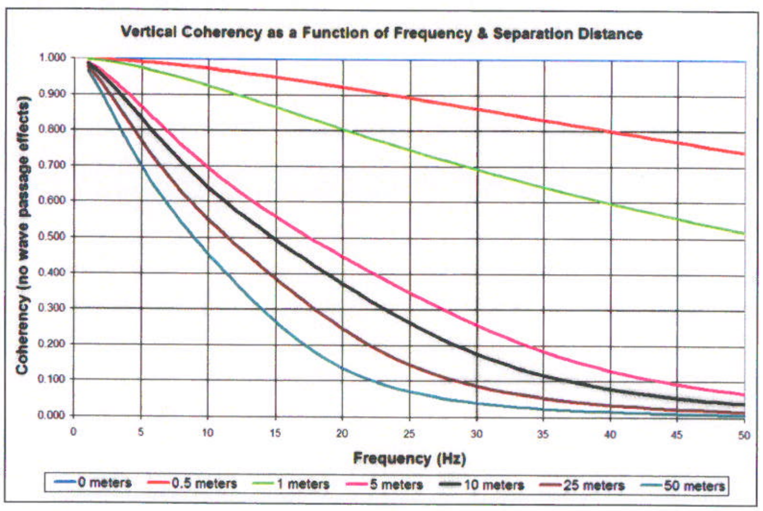
Coherency Function for Vertical Ground Motion



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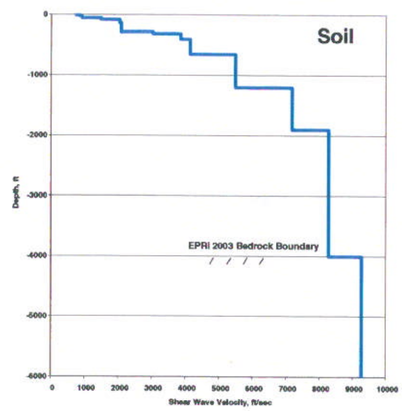
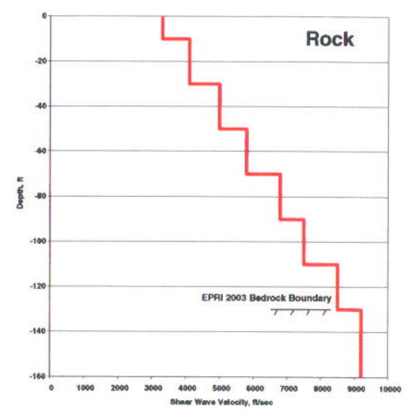
Rock and Soil Site Profile Shear Wave Velocities vs. Depth





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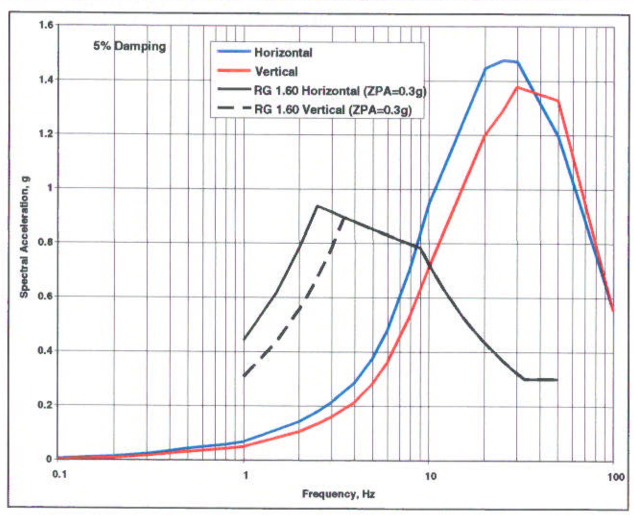
Site-Specific Response Spectra for Rock Site at Ground Surface (Depth 0-ft)



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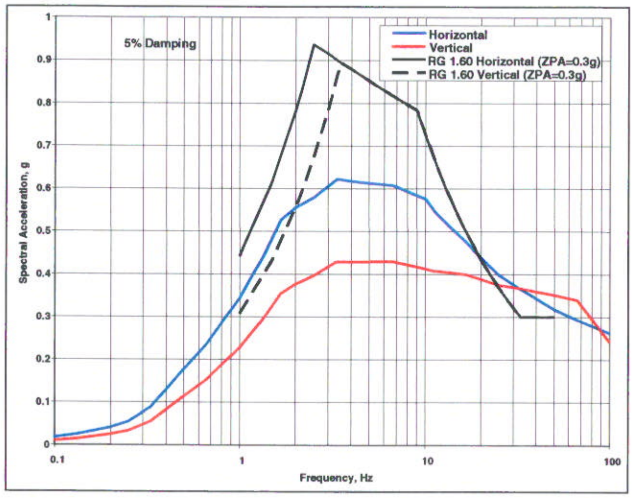
Site-Specific Response Spectra for Soil Site at Ground Surface (Depth 0-ft)



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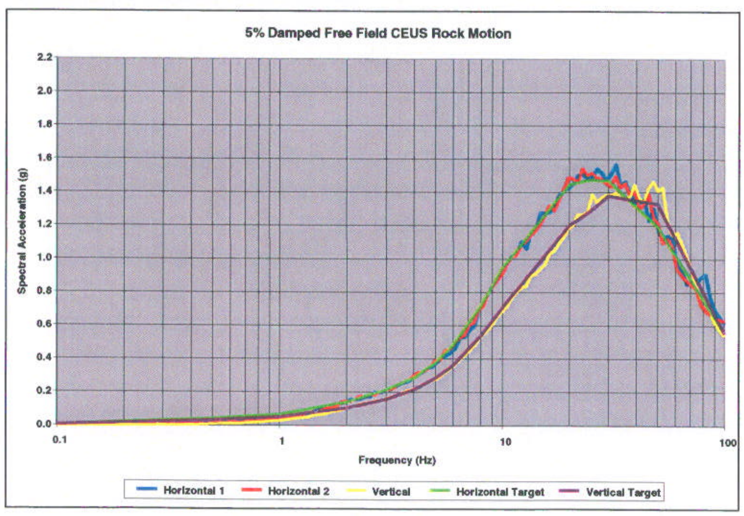
Computed and Target Response Spectra for Rock Site



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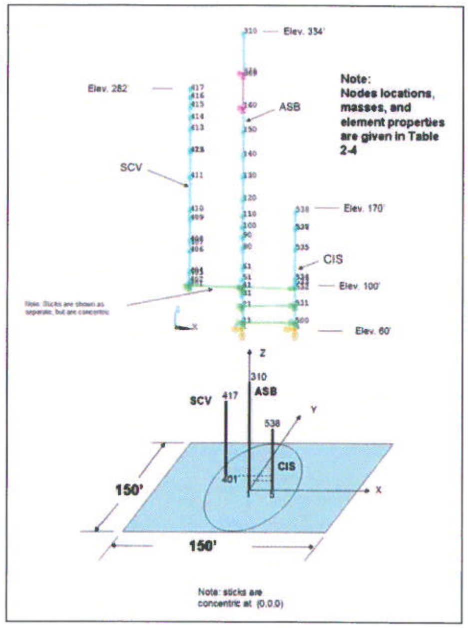
Advanced Reactor Structure Stick Model



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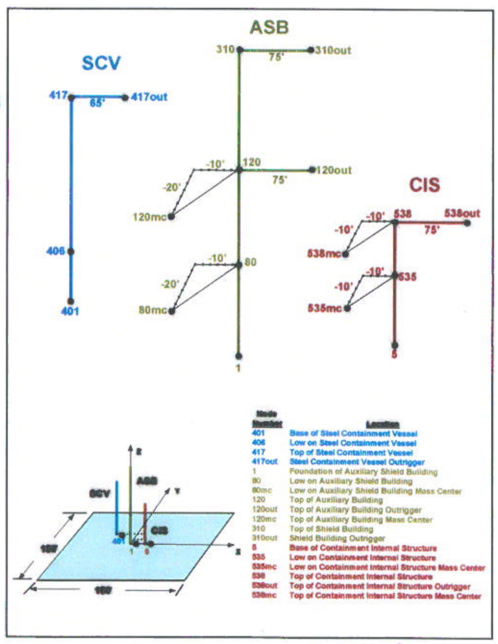
Advanced Reactor Structure Stick Model with Outriggers and Offset Mass Centers



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Chapter 3:
Technical Approach

S2.1 Technical Approach Discussion Points

- Incoherency Transfer Function
- Rigid, Massless Foundation Response including Seismic Wave Incoherence
- Seismic Wave Incoherence in SSI Analysis
  - Direct Approach
    - CLASSI
    - SASSI
  - Simplified Approach

Technical Approach

- Determine the Incoherency Transfer Function by Stochastic Approach with CLASSI
- Evaluate Rigid, Massless Foundation Response Spectra from the ITF and Random Vibration Theory
- Evaluate SSI and Incoherency by Inserting the ITF as the CLASSI Scattering Matrix and Performing Normal Seismic Analysis
- Benchmark Against Eigen Decomposition Method Using SASSI
- Develop Simplified Method for Rock Sites, High Frequency Input, & Example Structure with Multiple Significant Frequencies

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Chapter 4:
Rigid, Massless Foundation Response

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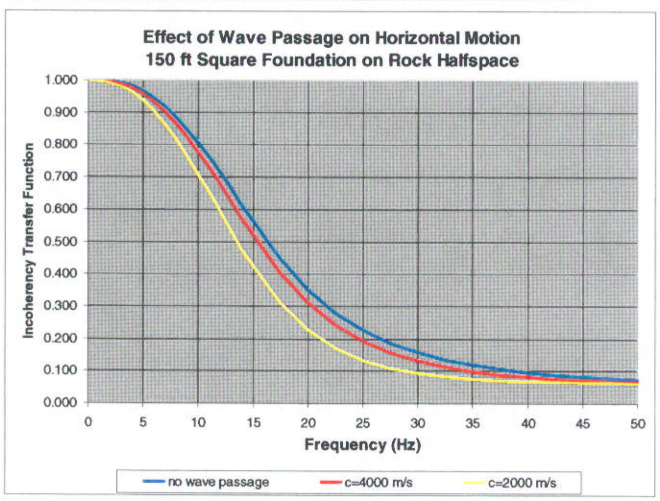
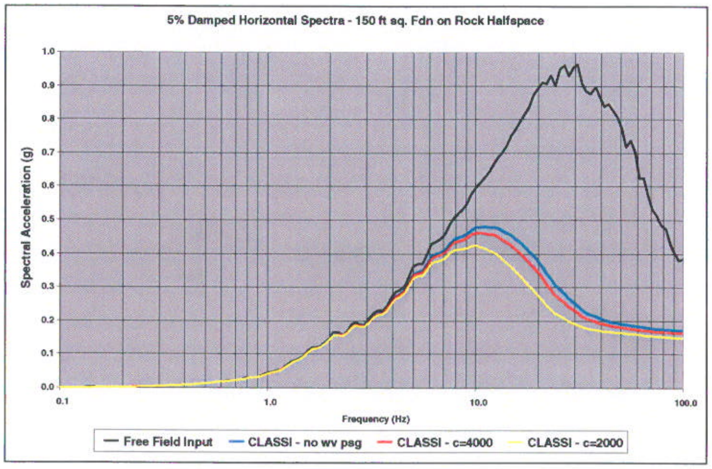
Chapter 4 Sections

- Wave Passage Effects
- Incoherency Transfer Function
- Spectral Corrections
- Rotations Induced by Incoherence

Effect of Wave Passage on Incoherency Transfer Function for Horizontal Motion



Effect of Wave Passage on Foundation Horizontal Response Spectra



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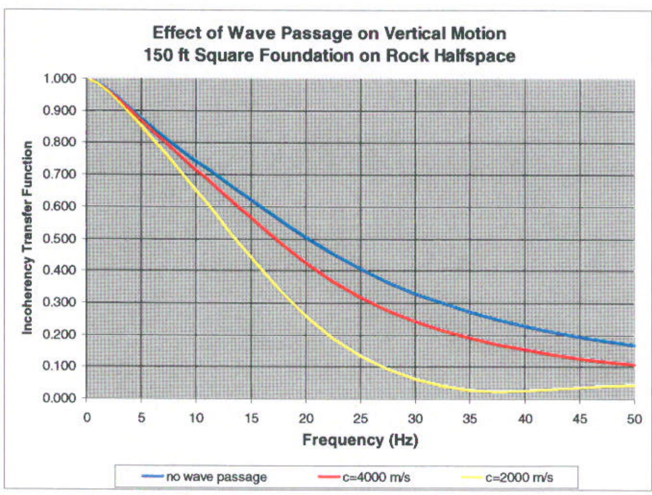
Effect of Wave Passage on Incoherency Transfer Function for Vertical Motion



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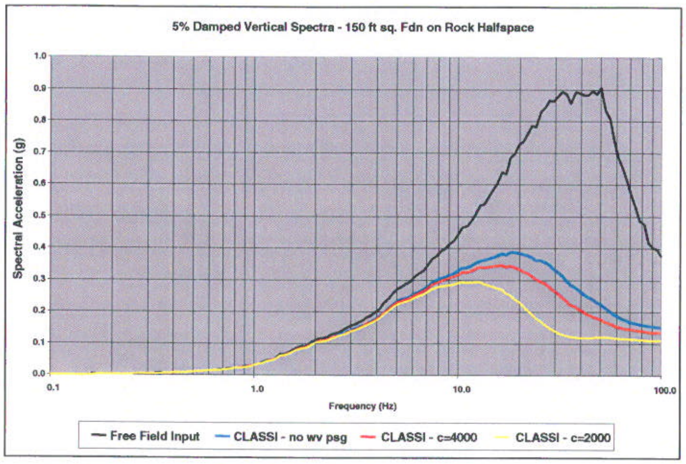
Effect of Wave Passage on Foundation Vertical Response Spectra



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Parametric Studies on Rigid, Massless Foundations

- Foundation Shape (Constant Area)
  - 150-ft square footprint
  - 100 by 225-ft rectangle footprint
  - 84.63-ft radius circle footprint
- Foundation Area (Constant Shape)
  - 75-ft square footprint
  - 150-ft square footprint
  - 300-ft square footprint
- Calculations have been performed for local wave scattering effects only; wave passage effects have not been considered

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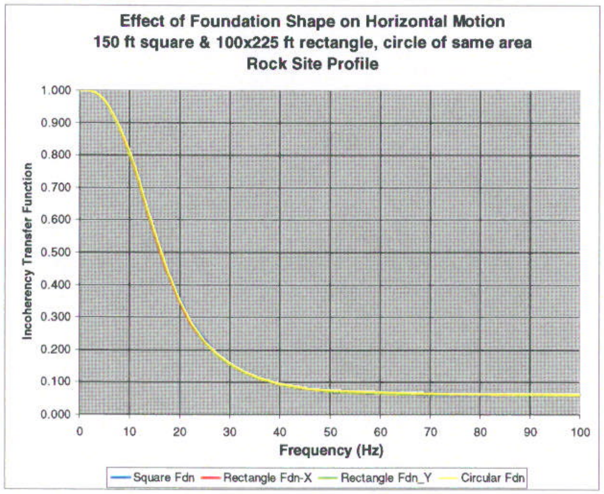
Horizontal Motion Incoherency Transfer Function – Effect of Foundation Shape



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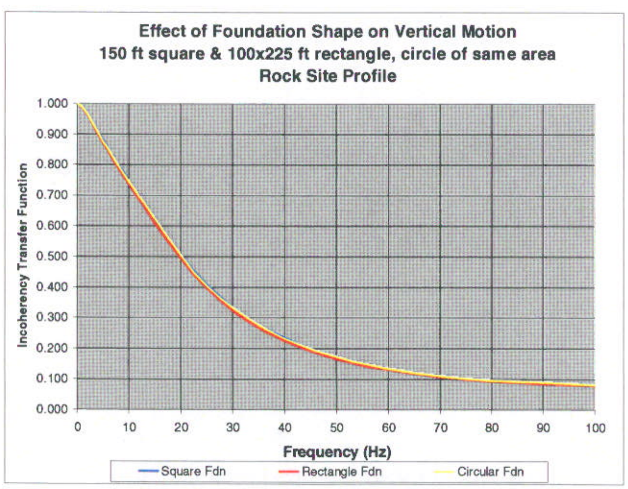
Vertical Motion Incoherency Transfer Function – Effect of Foundation Shape



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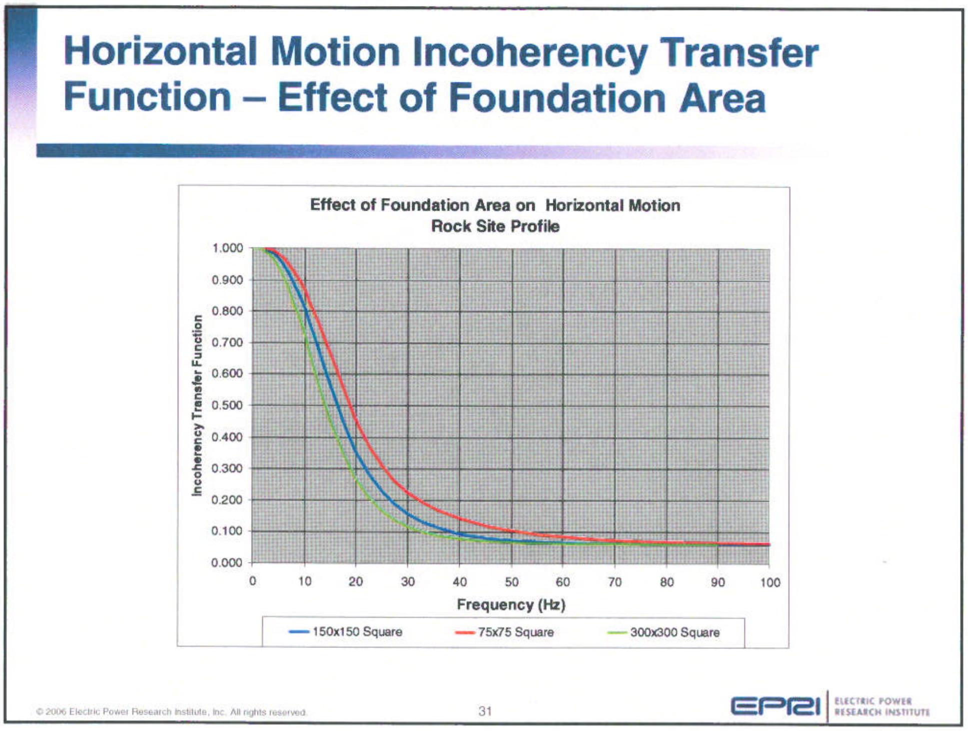
Horizontal Motion Incoherency Transfer Function – Effect of Foundation Area
Effect of Foundation Area on Horizontal Motion
Rock Site Profile
Incoherency Transfer Function
1.000
0.900
0.800
0.700
0.600
0.500
0.400
0.300
0.200
0.100
0.000
0
10
20
30
40
50
60
70
80
90
100
Frequency (Hz)
150x150 Square
75x75 Square
300x300 Square
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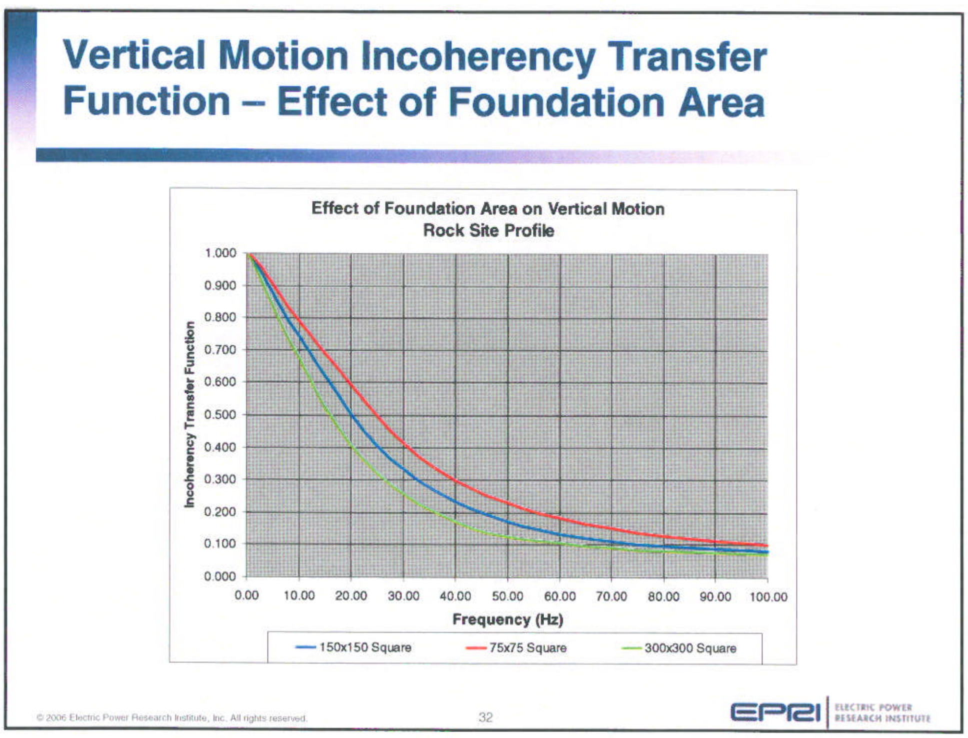
Vertical Motion Incoherency Transfer Function – Effect of Foundation Area
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1.000
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0.600
0.500
0.400
0.300
0.200
0.100
0.000
0.00
10.00
20.00
30.00
40.00
50.00
60.00
70.00
80.00
90.00
100.00
Frequency (Hz)
150x150 Square
75x75 Square
300x300 Square
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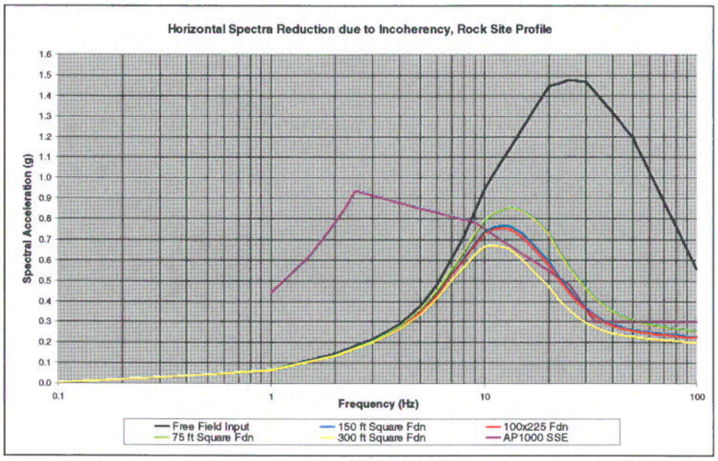
Horizontal Motion Foundation Response Spectra, Rock Site



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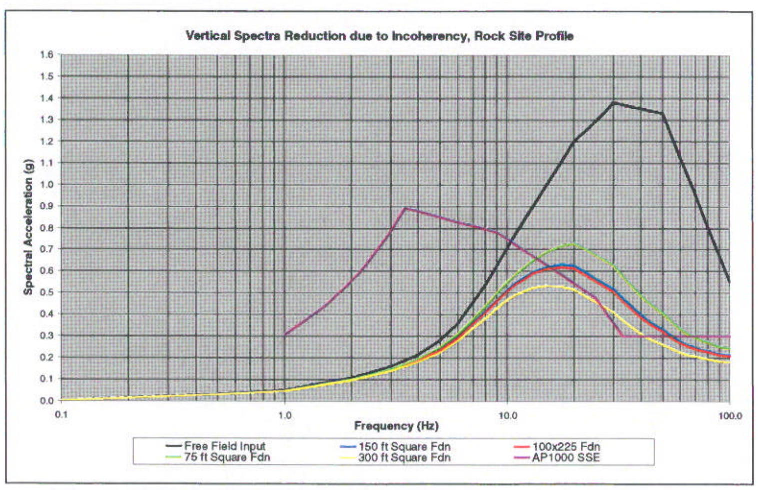
Vertical Motion Foundation Response Spectra, Rock Site



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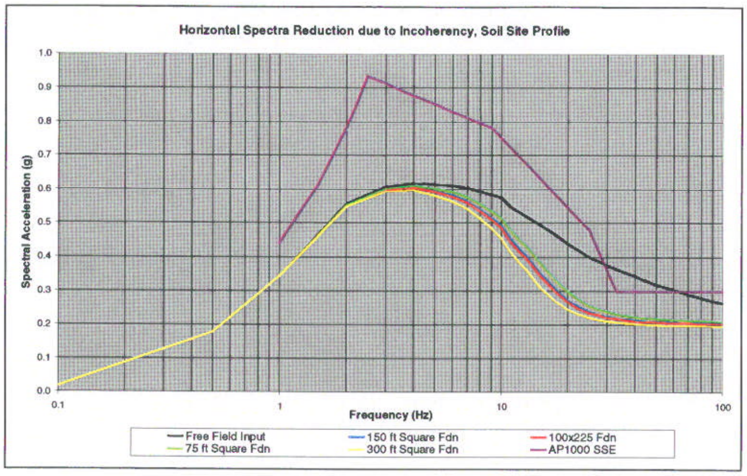
Horizontal Motion Foundation Response Spectra, Soil Site



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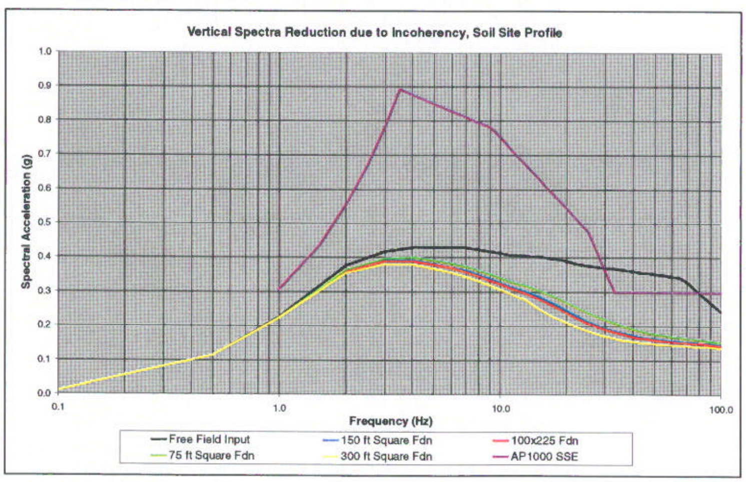
Vertical Motion Foundation Response Spectra, Soil Site



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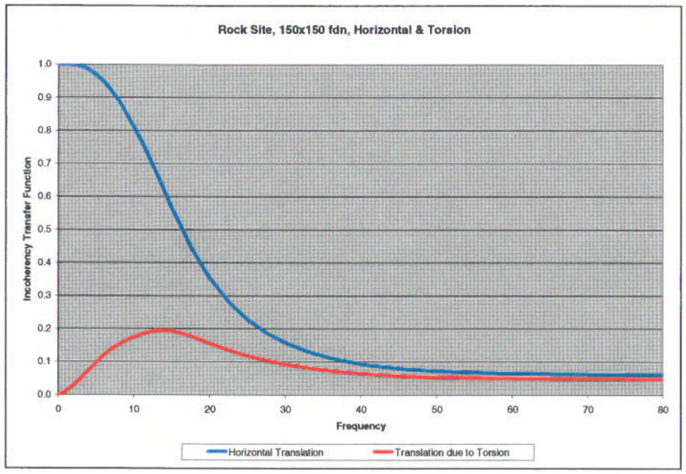
Torsion Induced by Incoherent Horizontal Input, Square Foundation



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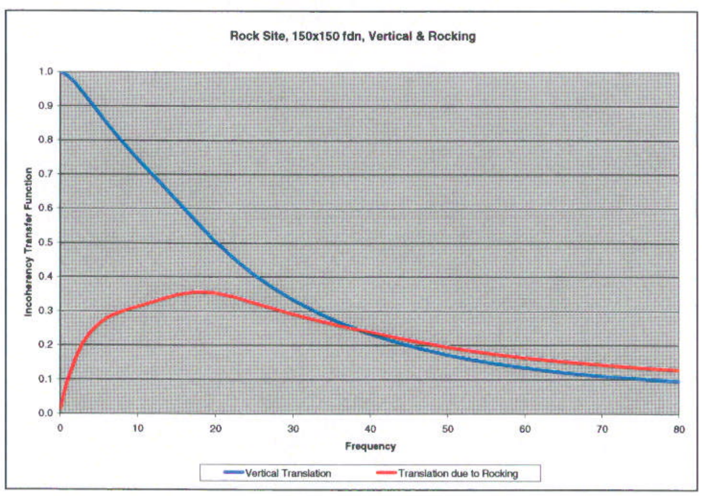
Rocking Induced by Incoherent Vertical Input, Square Foundation



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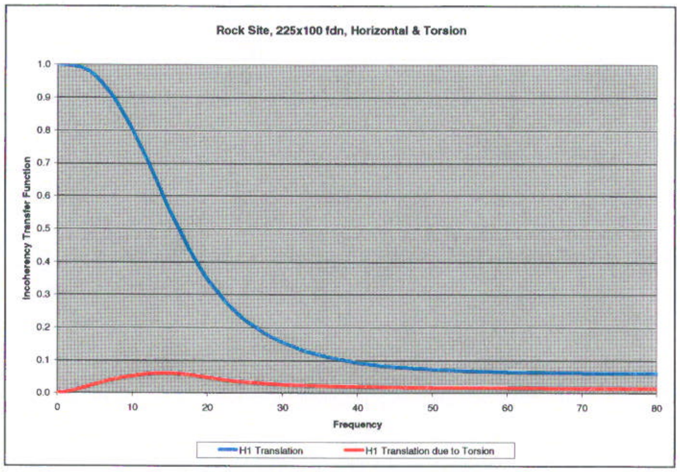
H1 Torsion Induced by Incoherent Horizontal Input, Rectangle Foundation



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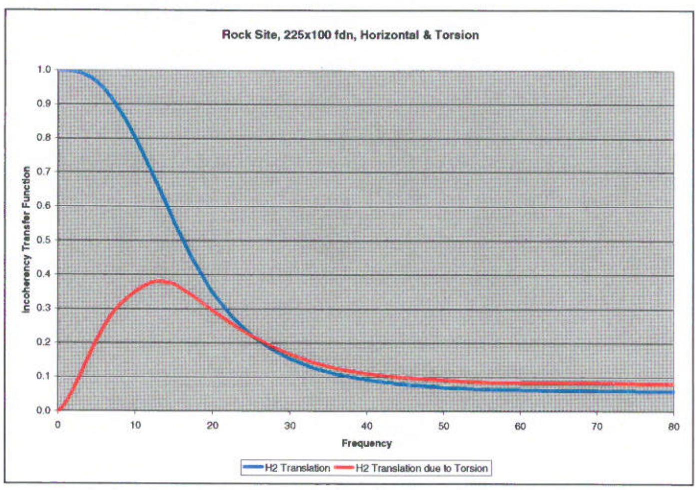
H2 Torsion Induced by Incoherent Horizontal Input, Rectangle Foundation



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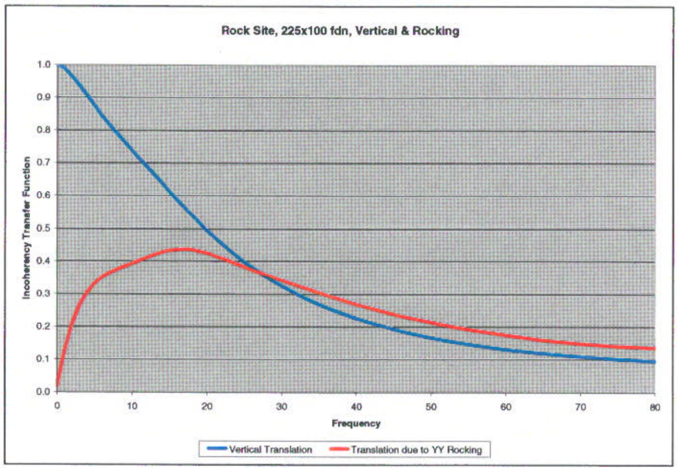
Rocking Induced by Incoherent Vertical Input, Rectangle Foundation



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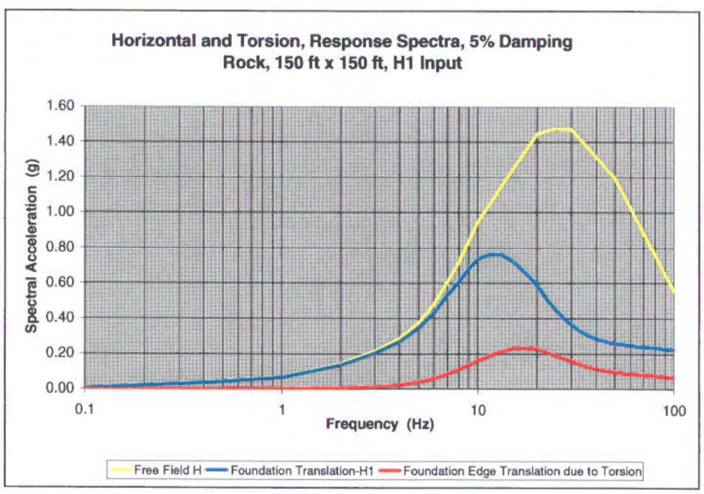
Response Spectra Including Torsion, Square Foundation, Rock Site



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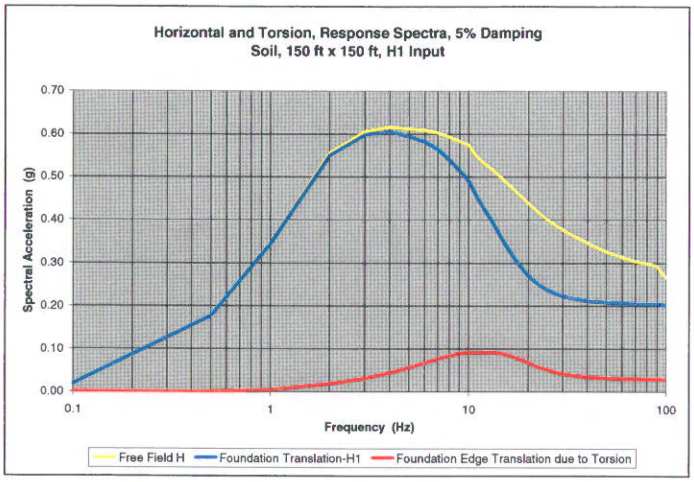
Response Spectra Including Torsion, Square Foundation, Soil Site



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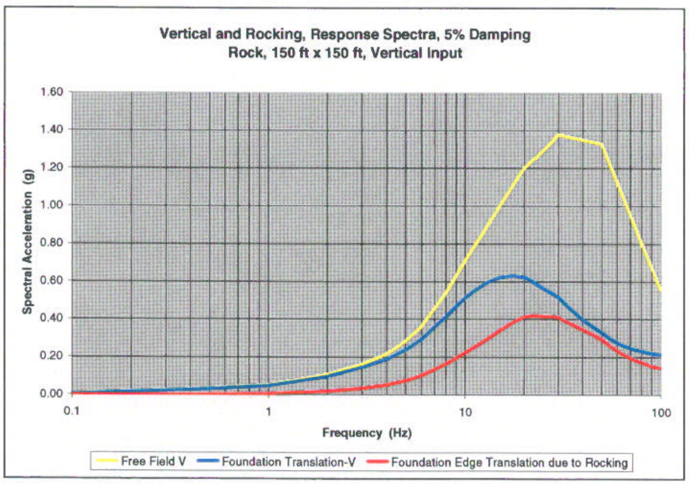
Response Spectra Including Rocking, Square Foundation, Rock Site



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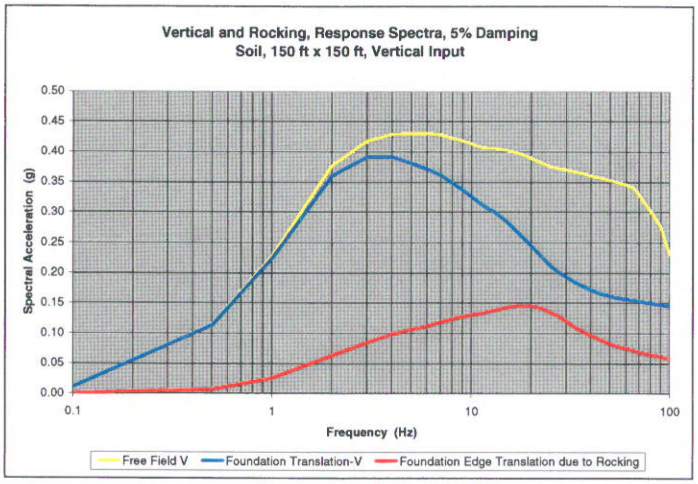
Response Spectra Including Rocking, Square Foundation, Soil Site



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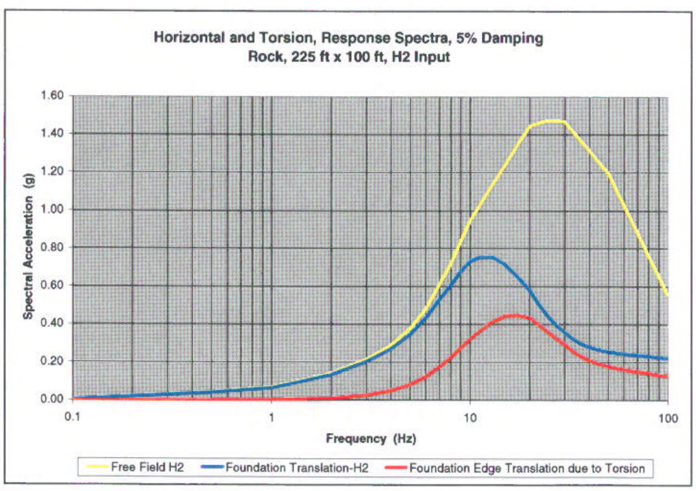
Response Spectra Including Torsion, Rectangle Foundation, Rock Site



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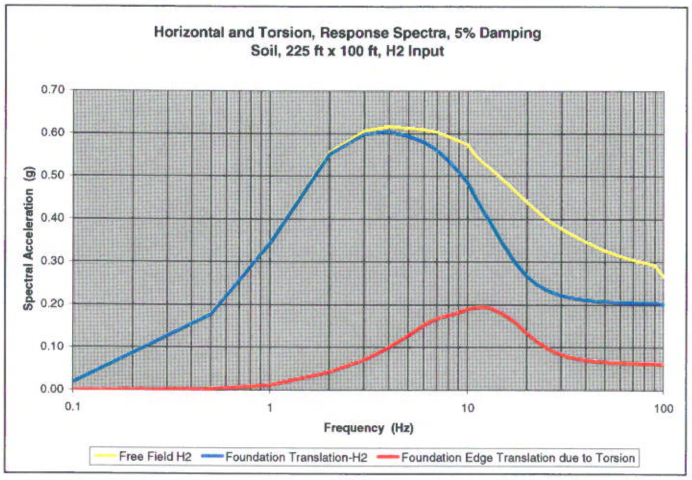
Response Spectra Including Torsion, Rectangle Foundation, Soil Site



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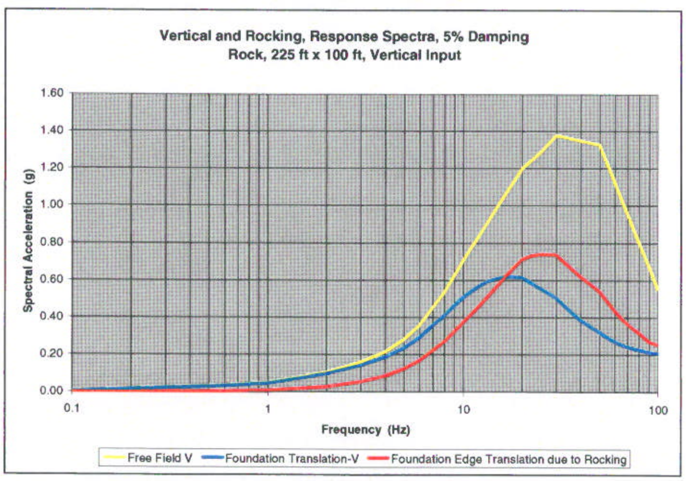
Response Spectra Including Rocking, Rectangle Foundation, Rock Site



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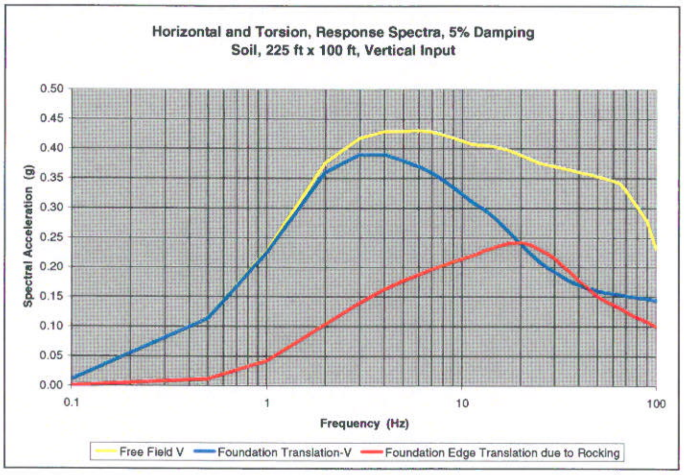
Response Spectra Including Rocking, Rectangle Foundation, Soil Site



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Chapter 5:
SSI and Structure Response

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Example Evaluations of SSI and Structural Response

Four sets of analyses have been performed for the example structural model:

1. SSI analysis with coherent input motion
   (dark blue curves in all Chapter 5 response spectra figures)
2. SSI analysis with incoherent input motion
   a) Rigorous (direct) approach including all components of foundation input motion (three translations and three rotations)
      (green curves in all Chapter 5 response spectra curves)
   b) Rigorous (direct) approach excluding rotational foundation input motion
      (red curves in all Chapter 5 response spectra figures)
3. SSI analysis with input motion modified by Incoherency Transfer Function (simplified approach)
   (light blue and yellow curves in all Chapter response spectra curves)

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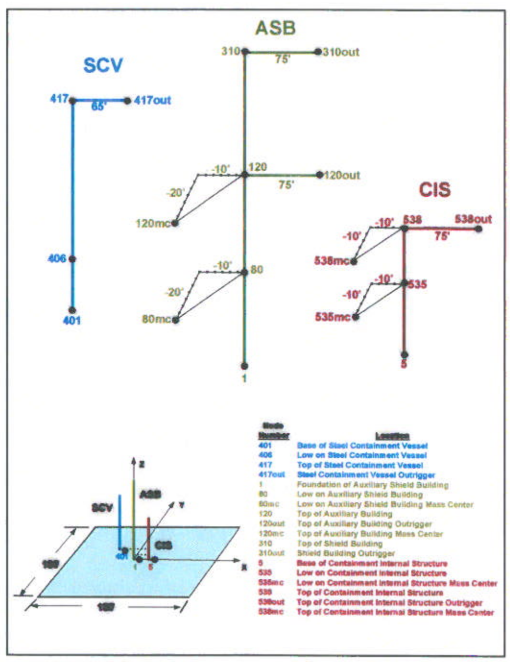
Three Stick Example Model Key Locations



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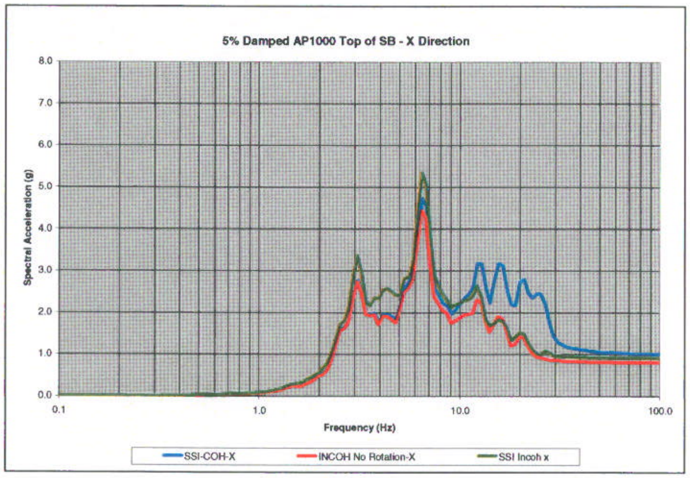
Top of Shield Building Response Spectra – X Direction – SSI Coherent, SSI Incoherent, SSI Incoherent with No Rotations (Node 310)



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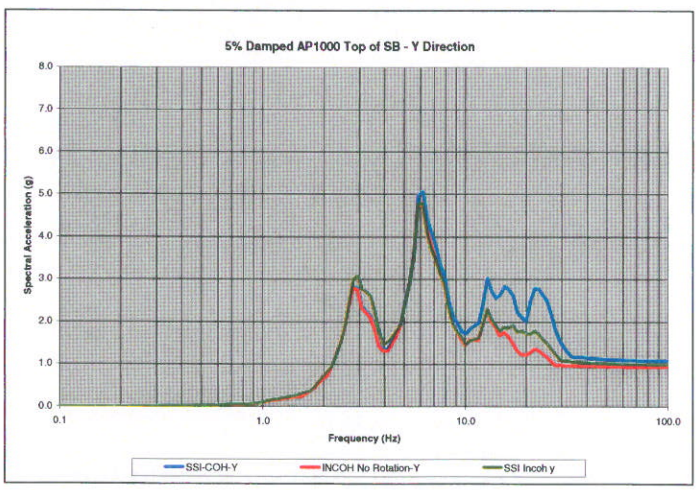
Top of Shield Building Response Spectra – Y Direction – SSI Coherent, SSI Incoherent, SSI Incoherent with No Rotations (Node 310)



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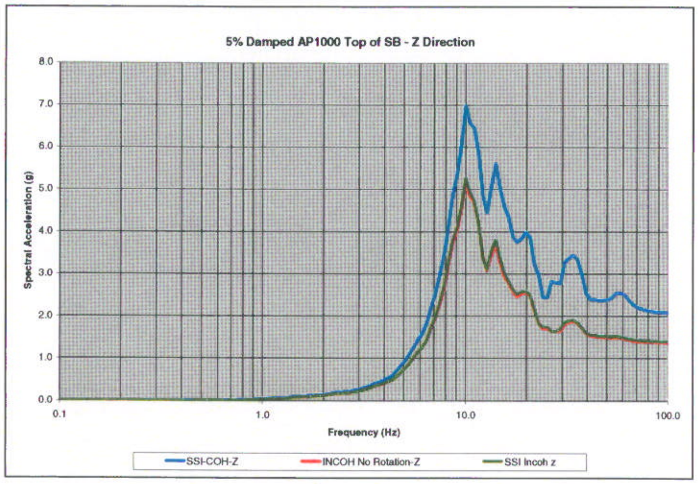
Top of Shield Building Response Spectra – Z Direction – SSI Coherent, SSI Incoherent, SSI Incoherent with No Rotations (Node 310)



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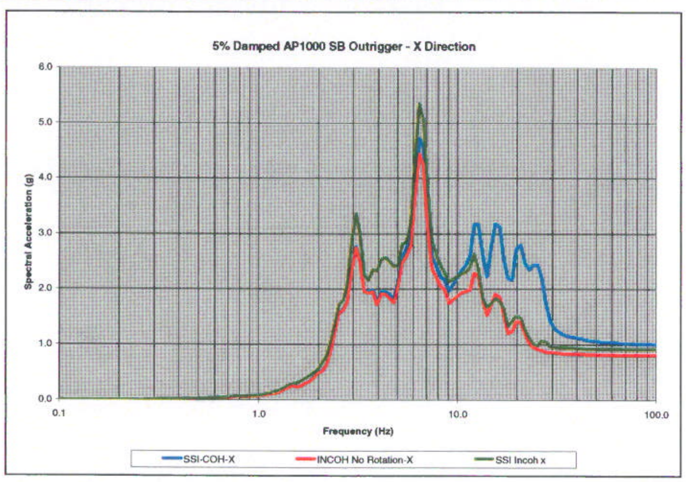
Shield Building Outrigger Response Spectra – X Direction – SSI Coherent, SSI Incoherent, SSI Incoherent with No Rotations (Node 310out)



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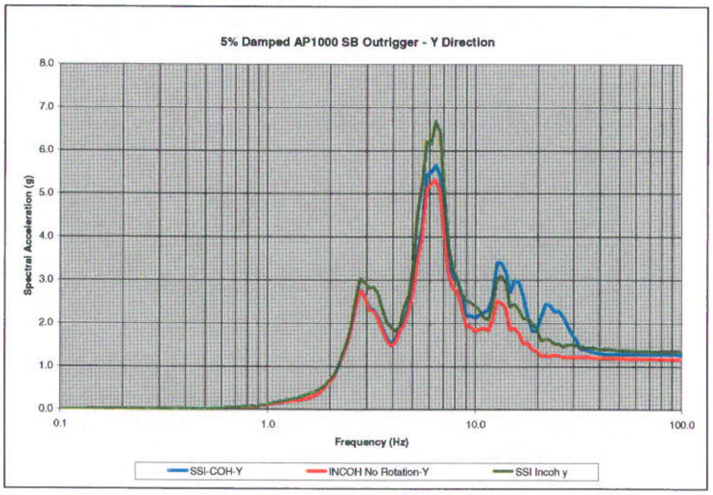
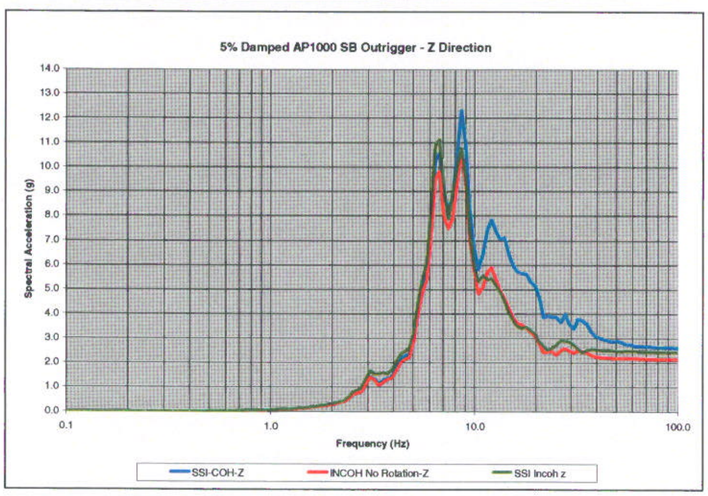
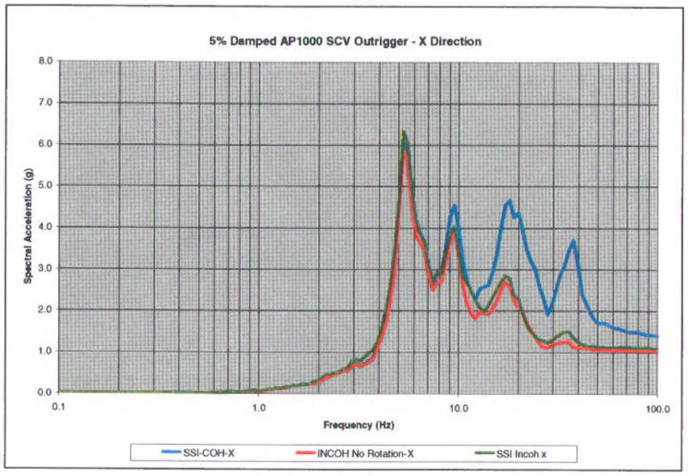
Shield Building Outrigger Response Spectra – Y Direction – SSI Coherent, SSI Incoherent, SSI Incoherent with No Rotations (Node 310out)



Shield Building Outrigger Response Spectra – Z Direction – SSI Coherent, SSI Incoherent, SSI Incoherent with No Rotations (Node 310out)



SCV Outrigger Response Spectra – X Direction – SSI Coherent, SSI Incoherent, SSI Incoherent with No Rotations (Node 417out)



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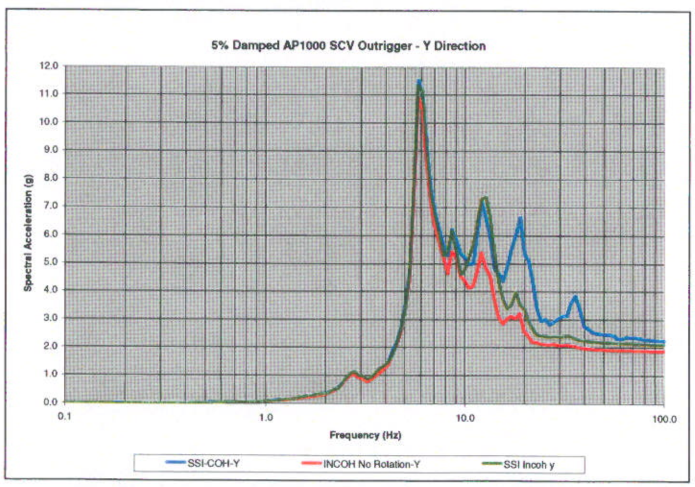
SCV Outrigger Response Spectra – Y Direction – SSI Coherent, SSI Incoherent, SSI Incoherent with No Rotations (Node 417out)



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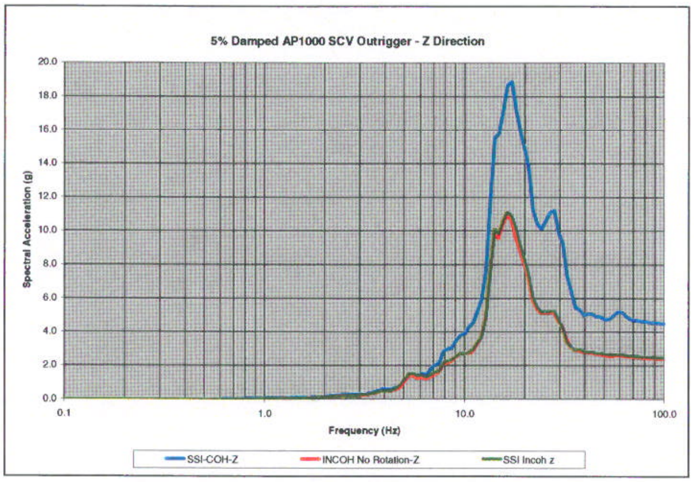
SCV Outrigger Response Spectra – Z Direction – SSI Coherent, SSI Incoherent, SSI Incoherent with No Rotations (Node 417out)



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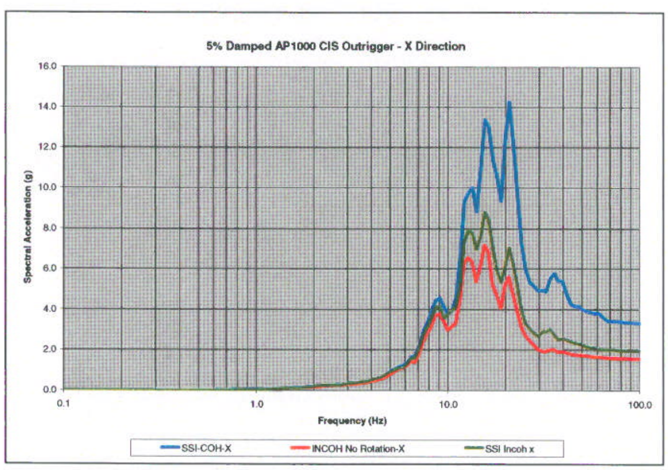
CIS Outrigger Response Spectra - X Direction – SSI Coherent, SSI Incoherent, SSI Incoherent with No Rotations (Node 538out)



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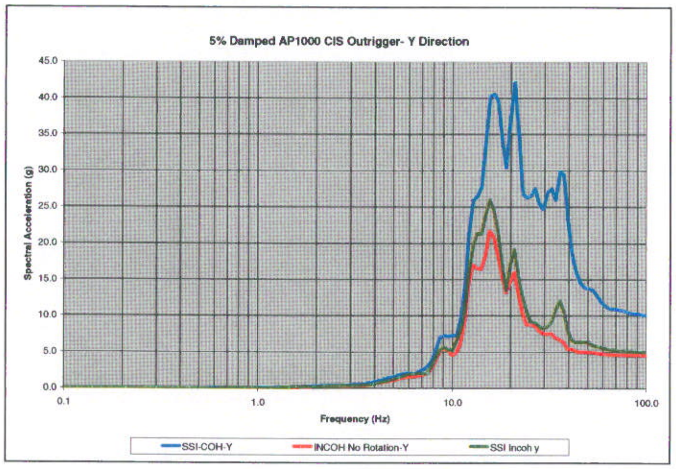
CIS Outrigger Response Spectra - Y Direction – SSI Coherent, SSI Incoherent, SSI Incoherent with No Rotations (Node 538out)



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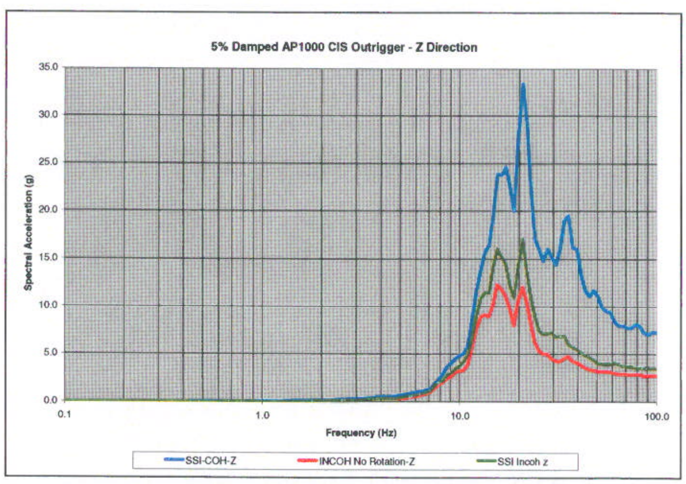
CIS Outrigger Response Spectra - Z Direction – SSI Coherent, SSI Incoherent, SSI Incoherent with No Rotations (Node 538out)



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Simplified Method

65

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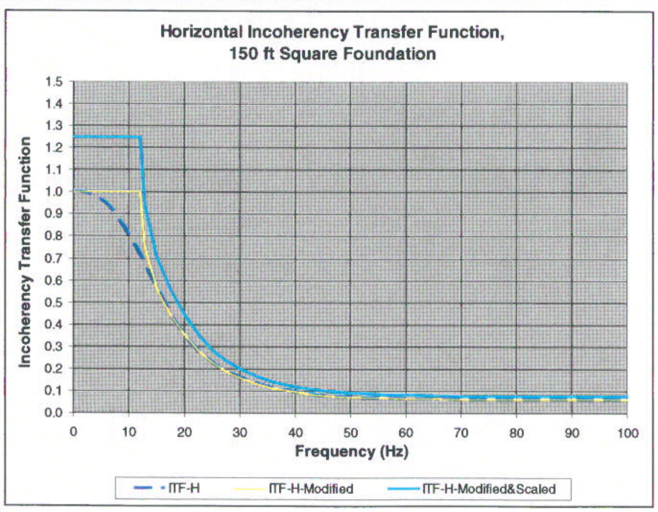
Horizontal Incoherency Transfer Function Used for Simplified Approach



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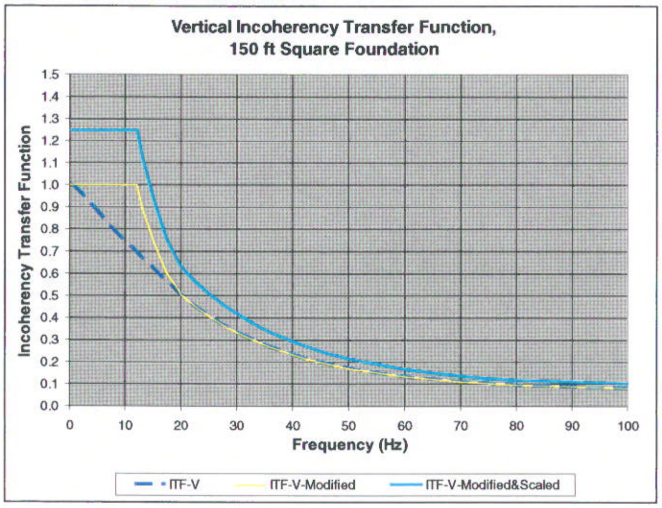
Vertical Incoherency Transfer Function Used for Simplified Approach



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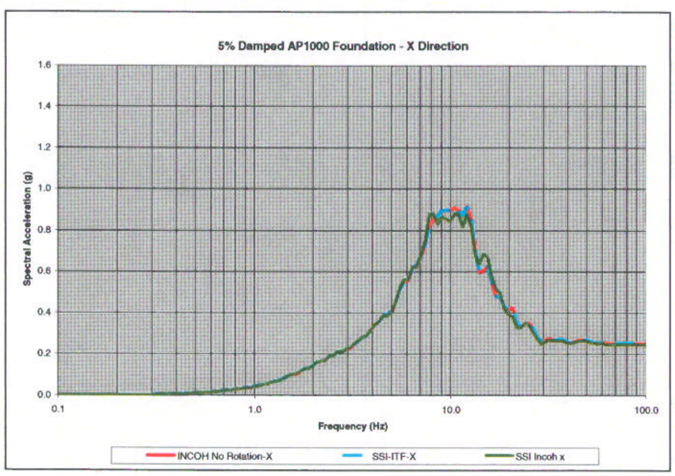
Foundation Response Spectra – X Direction– SSI Incoherent, SSI Incoherent with No Rotations, SSI Incoherent by ITF Scaling (Node 1)



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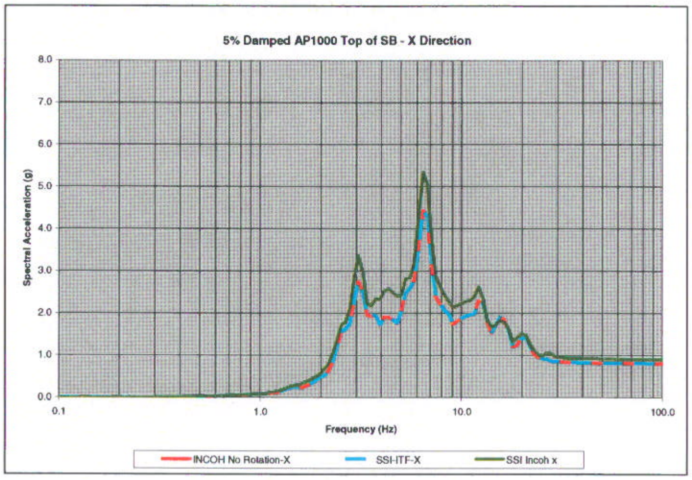
Top of Shield Building Response Spectra – X Direction – SSI Incoherent, SSI Incoherent with No Rotations, SSI Incoherent by ITF Scaling (Node 310)



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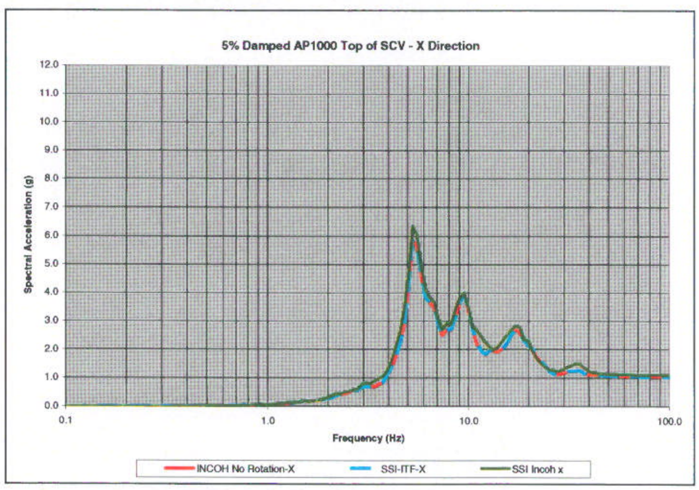
Top of SCV Response Spectra – X Direction – SSI Incoherent, SSI Incoherent with No Rotations, SSI Incoherent by ITF Scaling (Node 417)



70
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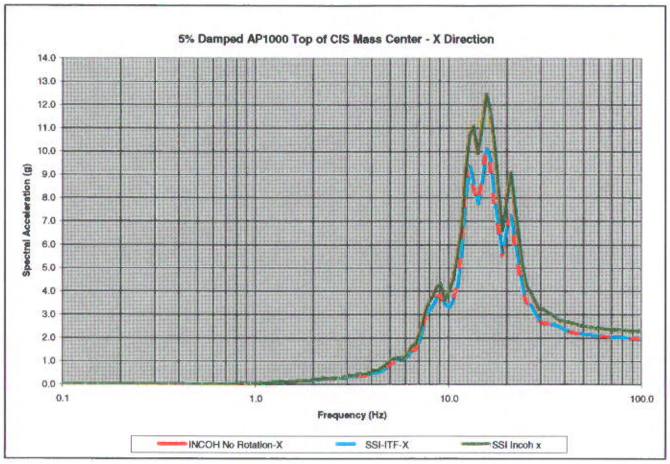
Top of CIS Response Spectra – X Direction – SSI Incoherent, SSI Incoherent with No Rotations, SSI Incoherent by ITF Scaling (Node 538mc)



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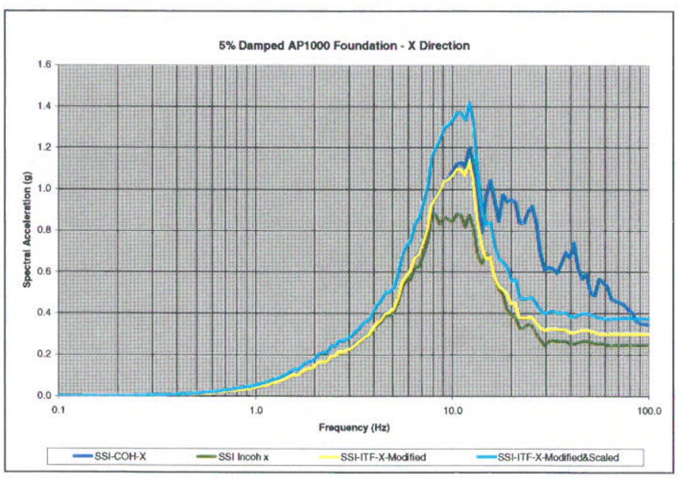
Foundation Response Spectra – X Direction – SSI Coherent, SSI Incoherent, SSI Incoherent by Modified ITF, SSI Incoherent by Modified and Scaled ITF (Node 1)



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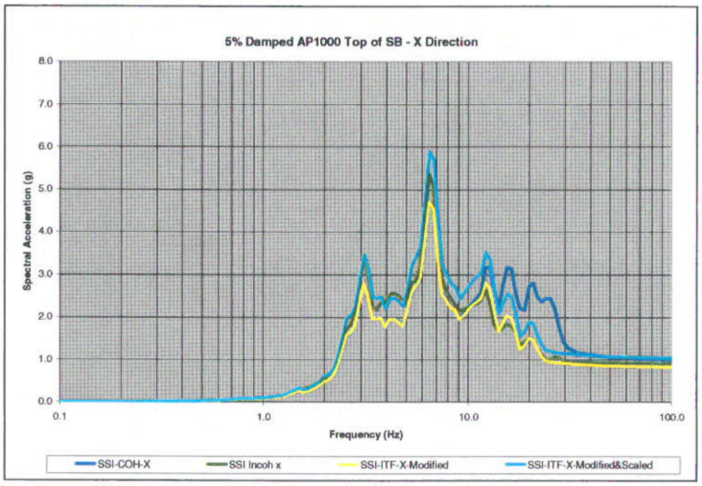
Top of Shield Building Response Spectra – X Direction – SSI Coherent, SSI Incoherent, SSI Incoherent by Modified ITF, SSI Incoherent by Modified and Scaled ITF (Node 310)



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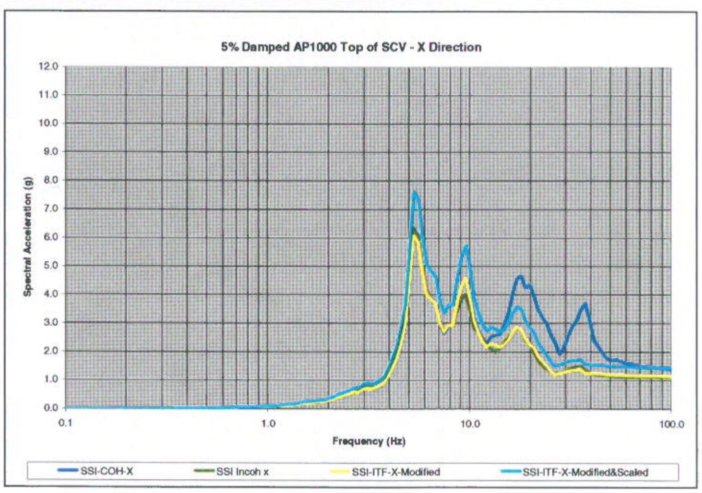
Top of SCV Response Spectra – X Direction – SSI Coherent, SSI Incoherent, SSI Incoherent by Modified ITF, SSI Incoherent by Modified and Scaled ITF (Node 417)



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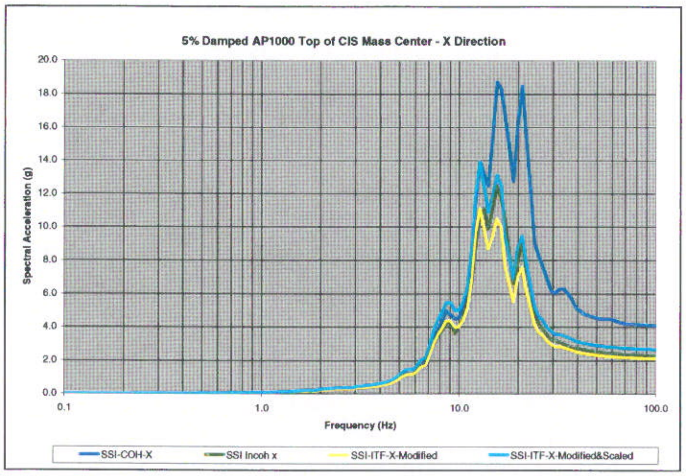
Top of CIS Response Spectra – X Direction – SSI Coherent, SSI Incoherent, SSI Incoherent by Modified ITF, SSI Incoherent by Modified and Scaled ITF (Node 538mc)



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Comparison of Incoherent Direct and Incoherent Simplified Spectra

NODE	Location	Scaled (1.25) & Modified ITF Simplified vs. Incoherent
Fdn	Foundation - X Direction	Envelopes incoherent at all frequencies
Fdn	Foundation - Y Direction	Envelopes incoherent at all frequencies
Fdn	Foundation - Z Direction	Envelopes incoherent at all frequencies
45	Top of SCV - X Direction	Envelopes incoherent at all frequencies
45	Top of SCV - Y Direction	Envelopes incoherent at all frequencies
45	Top of SCV - Z Direction	Envelopes incoherent at all frequencies
18	Top of SB - X Direction	Incoherent exceeds from 4 to 5 Hz by 7%
18	Top of SB - Y Direction	Incoherent exceeds @ 20 Hz by 7%
18	Top of SB - Z Direction	Envelopes incoherent at all frequencies
12	Top of AB Shear Center - X Direction	Envelopes incoherent at all frequencies
12	Top of AB Shear Center - Y Direction	Envelopes incoherent at all frequencies
12	Top of AB Shear Center - Z Direction	Envelopes incoherent at all frequencies
112	Top of AB Mass Center - X Direction	Envelopes incoherent at all frequencies
112	Top of AB Mass Center - Y Direction	Envelopes incoherent at all frequencies
112	Top of AB Mass Center - Y Direction	Envelopes incoherent at all frequencies
29	Top of CIS Shear Center - X Direction	Incoherent exceeds from 32 to 34 Hz by 10%
29	Top of CIS Shear Center - Y Direction	Envelopes incoherent at all frequencies
29	Top of CIS Shear Center - Z Direction	Envelopes incoherent at all frequencies
129	Top of CIS Mass Center - X Direction	Envelopes incoherent at all frequencies
129	Top of CIS Mass Center - Y Direction	Envelopes incoherent at all frequencies
129	Top of CIS Mass Center - Z Direction	Envelopes incoherent at all frequencies

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Comparison of Incoherent Direct and Incoherent Simplified Spectra

NODE	Location	Scaled (1.25) & Modified ITF Simplified vs. Incoherent
145	SCV Outrigger - X Direction	Envelopes incoherent at all frequencies
145	SCV Outrigger - Y Direction	Envelopes incoherent at all frequencies
145	SCV Outrigger - Z Direction	Envelopes incoherent at all frequencies
118	SB Outrigger - X Direction	Incoherent exceeds from 4 to 5 Hz by 7%
118	SB Outrigger - Y Direction	Envelopes incoherent at all frequencies
118	SB Outrigger - Z Direction	Envelopes incoherent at all frequencies
229	CIS Outrigger - X Direction	Incoherent exceeds @ 34 Hz by 11%
229	CIS Outrigger - Y Direction	Incoherent exceeds 32 to 40 Hz by as much as 34%
229	CIS Outrigger - Z Direction	Incoherent exceeds @ 21 Hz by 11% and from 27 to 33 Hz by as much as 26%
212	AB Outrigger - X Direction	Envelopes incoherent at all frequencies
212	AB Outrigger - Y Direction	Envelopes incoherent at all frequencies
212	AB Outrigger - Z Direction	Envelopes incoherent at all frequencies
34	Low on SCV - X Direction	Incoherent exceeds @ 31 Hz by 21%
34	Low on SCV - Y Direction	Incoherent exceeds @ 30 Hz by 7%
34	Low on SCV - Z Direction	Envelopes incoherent at all frequencies
8	Low on ASB Shear Center - X Direction	Envelopes incoherent at all frequencies
8	Low on ASB Shear Center - Y Direction	Envelopes incoherent at all frequencies
8	Low on ASB Shear Center - Z Direction	Envelopes incoherent at all frequencies
26	Low on CIS Shear Center - X Direction	Envelopes incoherent at all frequencies
26	Low on CIS Shear Center - Y Direction	Envelopes incoherent at all frequencies
26	Low on CIS Shear Center - Z Direction	Envelopes incoherent at all frequencies

Comparison of Incoherent Direct and Incoherent Simplified Spectra

NODE	Location	Scaled (1.25) & Modified ITF Simplified vs. Incoherent
108	Low on ASB Mass Center - X Direction	Envelopes incoherent at all frequencies
108	Low on ASB Mass Center - Y Direction	Envelopes incoherent at all frequencies
108	Low on ASB Mass Center - X Direction	Envelopes incoherent at all frequencies
126	Low on CIS Mass Center - X Direction	Incoherent exceeds from 19 to 24 Hz by 15%
126	Low on CIS Mass Center - Y Direction	Envelopes incoherent at all frequencies
126	Low on CIS Mass Center - Z Direction	Envelopes incoherent at all frequencies

Summary of Simplified Method Results

- An alternate means of incorporating seismic wave incoherence into seismic analyses has been developed and implemented. This alternative approach is to scale the Fourier amplitude spectrum of the free-field input motion by a function related to the Incoherency Transfer Function (ITF). The Fourier phase spectrum is unaffected. The result is a re-defined ground motion for SSI and dynamic structure analysis.
- The results of this simplified method are compared with the results generated by the direct or "exact" implementation and are judged to adequately and conservatively represent those results.
- This simplified approach has been developed considering ground motion on a rock site in the central and eastern United States where the peak of the free-field ground motion is in the range of 20 to 30 Hz. It is judged that this simplified approach is applicable for other similar rock sites with high-frequency ground motion. It is further judged that this simplified approach would not necessarily (without additional studies) be applicable for soil sites with low-frequency ground motion. In fact, the low-frequency increase to 1.25 for frequencies less than 12 Hz would likely not be required.

Summary of Simplified Method Results

- This simplified approach has been developed considering one representative structure model. The model considered has three major structure elements representing the Steel Containment Vessel, the Auxiliary Shield Building, and the Containment Internal Structure, and demonstrates the structural response behavior at a broad range of structural frequencies. The model is tall and has significant outriggers out to the periphery of the foundation in order to understand the full effects of incoherence induced rotations (rocking and torsion). However, this simplified method would require validation with other structural models that differ significantly from the range of parameters (structural frequencies, foundation stiffness, site profile, etc.) utilized within this demonstration study.
- The simplified approach relies on conservative assumptions in order to envelope the exact responses at all the representative locations within the demonstration model. If new plants find this approach to be beneficial, i.e., this conservatism does not preclude its implementation, then further sensitivity studies could be warranted in the future. Examples are different foundation sizes and shapes, different structural models with frequency characteristics of interest, and different site conditions.

Effect of Embedment and Incoherence

- Two aspects of spatial variation of ground motion are to be considered:
  - The variation of free-field ground motion with depth in the soil or rock over the embedded portions of the foundation/partially embedded structure
  - The incoherency effects
- A sensitivity study considering the effect of ground motion incoherence and embedded foundations has been performed and is presented in Appendix E
- There were two objectives to the study:
  1. Demonstrate the effects of combined incoherency and embedment on seismic response
  2. Assess whether it is possible to consider incoherency and embedment effects separately in which incoherency is treated by modified free-field motion per the simplified approach and embedment is treated by conventional SSI analysis

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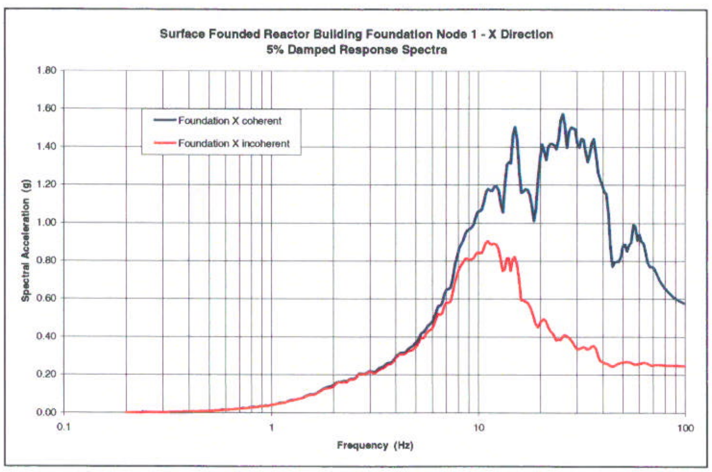
Comparison of SRS at the Center of the Foundation of the Surface Founded Building to the Coherent and Incoherent Ground Motion



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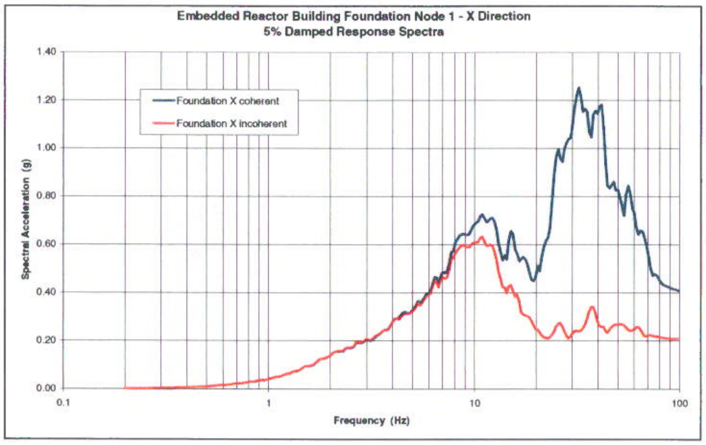
Comparison of ISRS at the Center of the Foundation of the Embedded Building for the Coherent and Incoherent Ground Motion



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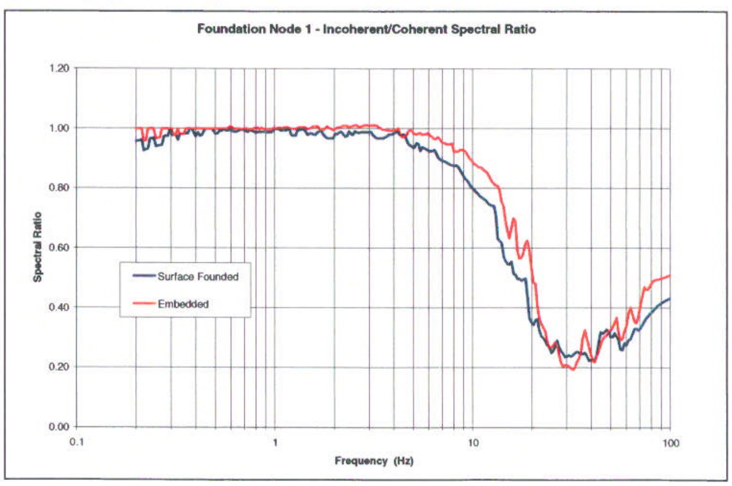
Comparison of the Spectral Ratios at the Center of the Foundation for the Surface Founded and Embedded Cases



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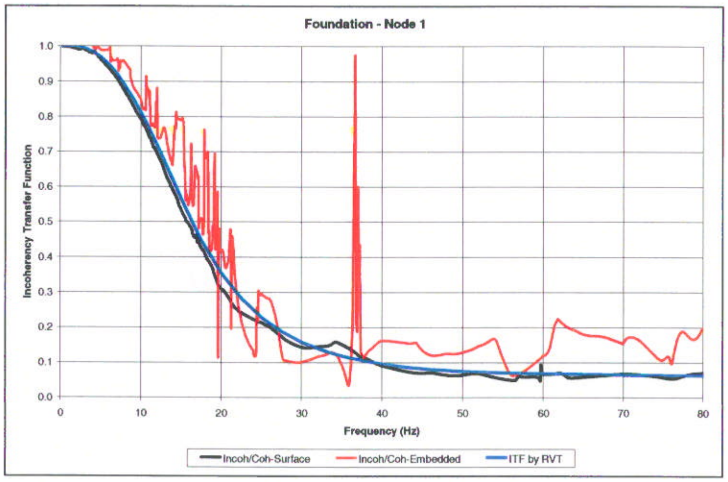
Incoherency Transfer Function at the Center of the Foundation for the Surface Founded and Embedded Cases



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Effect of SSI on High-Frequency Seismic Response

- On rock sites, soil-structure interaction (SSI) is not generally considered. However, for the high-frequency content input motion considered herein, the effects of SSI are shown to be very significant.
  - The following charts show SSI effects
    - Fixed-Base – no SSI
    - SSI Coherent indicates inertial interaction effects
    - SSI Incoherent indicates both kinematic and inertial interaction
  - Conclusions
    - SSI effects can be very significant on a rock site where there is high-frequency input motion
    - Reductions due to inertial interaction of high-frequency seismic response are, in many cases, equal to or greater than the reductions due to seismic wave incoherence

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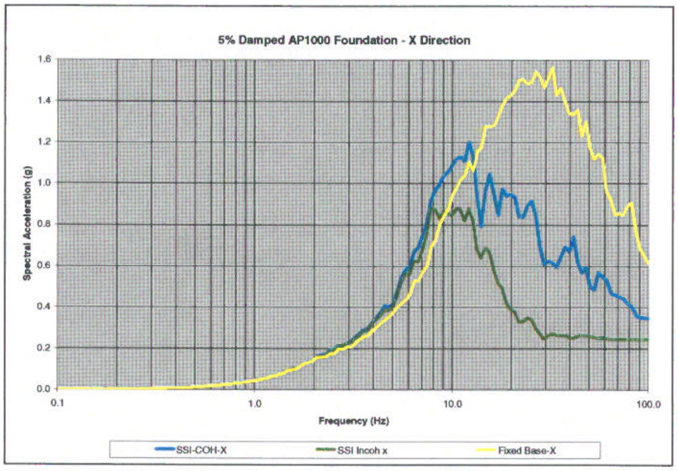
Foundation Response Spectra – X Direction– SSI Coherent, SSI Incoherent, Fixed-Based (Node 1)



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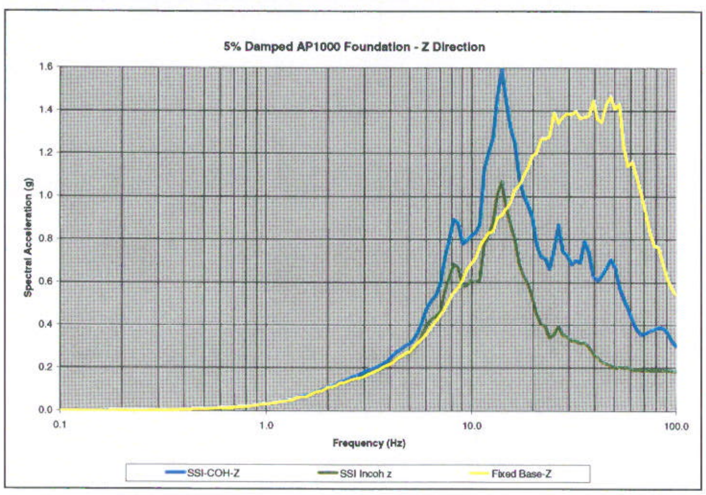
Foundation Response Spectra – Z Direction– SSI Coherent, SSI Incoherent, Fixed-Based (Node 1)



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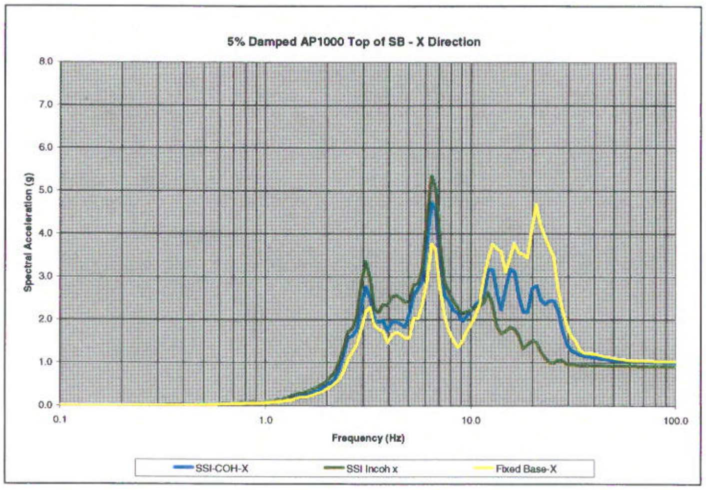
Top of Shield Building Response Spectra – X Direction– SSI Coherent, SSI Incoherent, Fixed-Based (Node 310)



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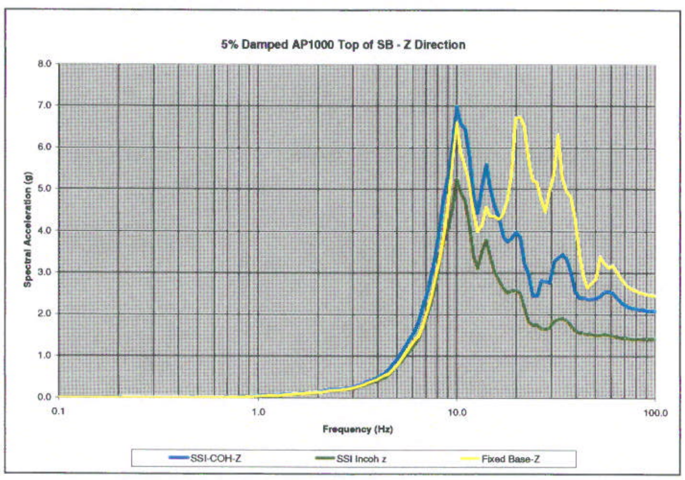
Top of Shield Building Response Spectra – Z Direction– SSI Coherent, SSI Incoherent, Fixed-Based (Node 310)



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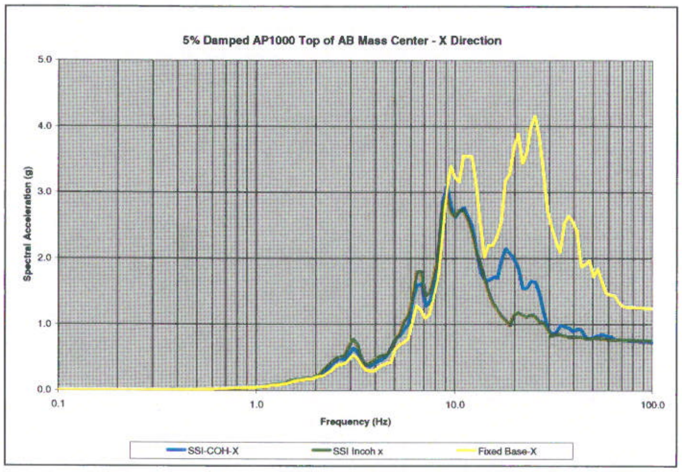
Top of Auxiliary Building Response Spectra – X Direction– SSI Coherent, SSI Incoherent, Fixed-Based (Node 120mc)



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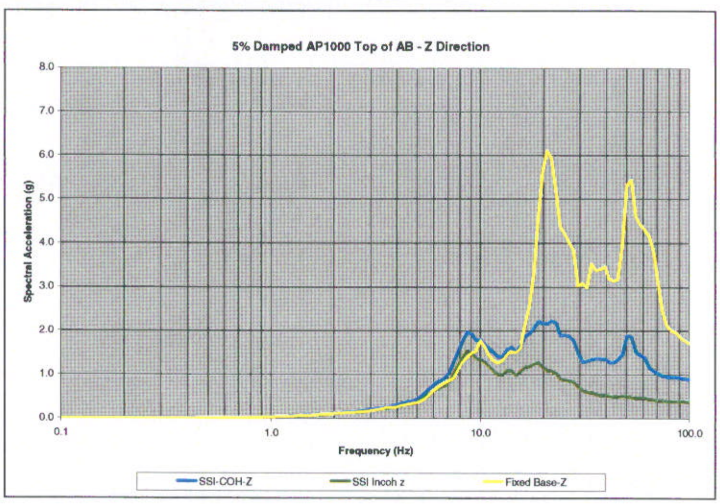
Top of Auxiliary Building Response Spectra – Z Direction– SSI Coherent, SSI Incoherent, Fixed-Based (Node 120)



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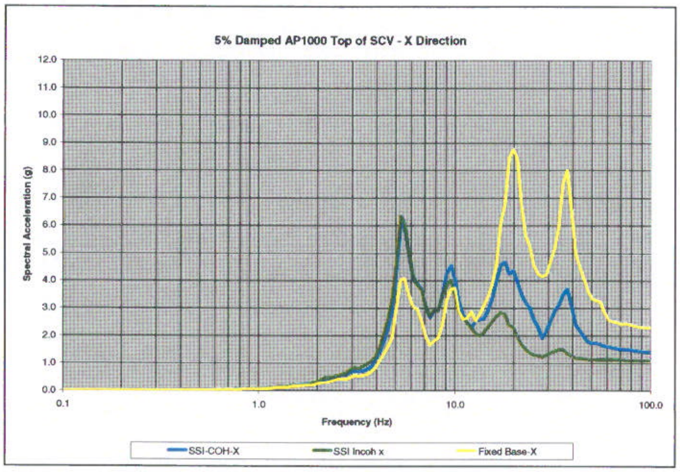
Top of SCV Response Spectra - X Direction– SSI Coherent, SSI Incoherent, Fixed-Based (Node 417)



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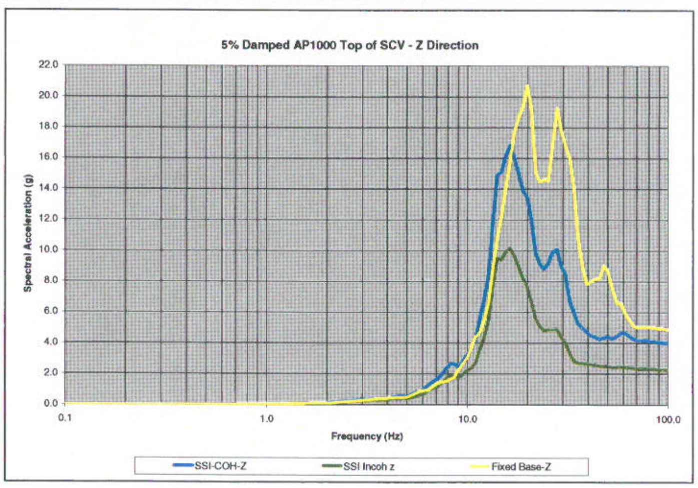
Top of SCV Response Spectra - Z Direction– SSI Coherent, SSI Incoherent, Fixed-Based (Node 417)



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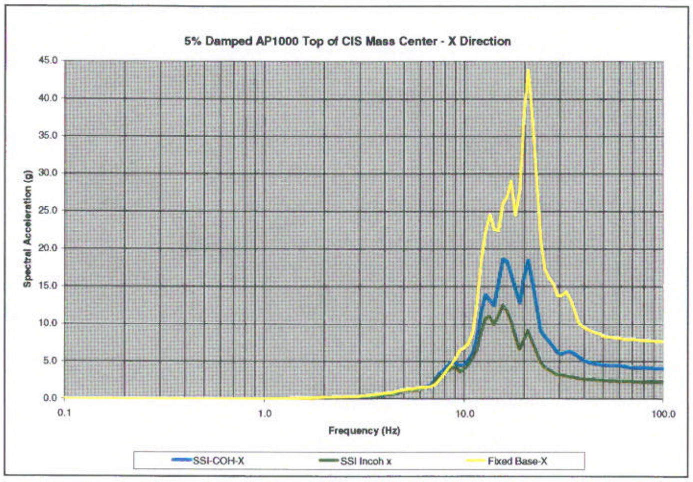
Top of CIS Response Spectra - X Direction – SSI Coherent, SSI Incoherent, Fixed-Based (Node 538mc)



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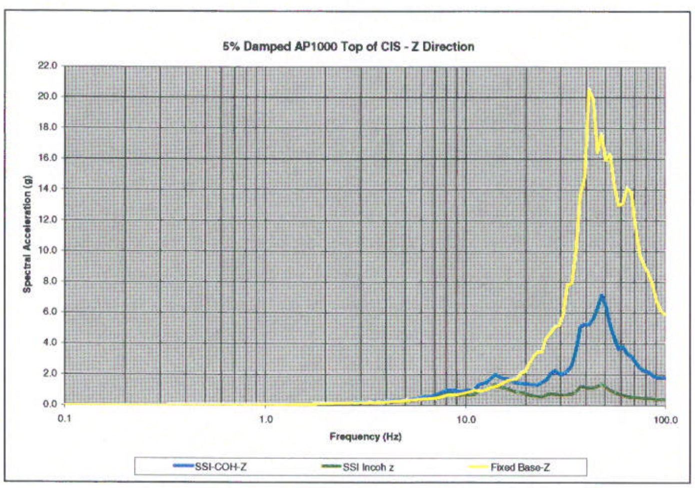
Top of CIS Response Spectra - Z Direction – SSI Coherent, SSI Incoherent, Fixed-Based (Node 538)



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Conclusions and Recommendations

Conclusions

- The phenomena of incoherence are important for high-frequency ground motions (primarily greater than 10 Hz) and high-frequency response of structures. Realistically accounting for ground motion incoherence on the seismic response of nuclear power plant structures is significant and should be properly incorporated into seismic design analyses.
- Generally, for the rock site and corresponding high-frequency free-field ground motion considered in this study, incoherent earthquake ground motion results in calculated in-structure response spectra at the tops of the structures and at mid-heights showed minimal effects below 10 Hz. For the case of the top of the Shield Building, the incoherent responses showed amplification in spectral accelerations above those for the coherent case at frequencies of peak amplification less than 10 Hz. In frequency ranges above 10 Hz, the ratio of coherent response spectra to incoherent response spectra varied from about 1 to greater than 2.

Conclusions

- Induced rotations may be important to in-structure response depending on the structure and its dynamic characteristics.
  - The effect of induced torsional response was quantified for the three structure models of interest by evaluating response at outriggers placed at structure peripheries. Induced torsion is important, but does not invalidate the significant reductions observed in in-structure response spectra for frequencies greater than approximately 12 Hz.
  - The effect of induced rocking on horizontal structure response was evaluated. For those portions of the structure model with frequencies of important fixed-base horizontal modes below 10 Hz, i.e., the ASB and SCV, induced rotations had minimal impact on in-structure response. For the CIS with frequencies of important fixed-base horizontal modes greater than 10 Hz, the impact of induced rocking on in-structure response was significant.
- The phenomena of incoherence are three-dimensional. Induced torsion couples horizontal response in the two horizontal directions. Induced rocking couples horizontal and vertical response, i.e., incoherent vertical ground motion induces horizontal response in the structure.

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Conclusions

- Two valid direct approaches for accurately addressing incoherency effects have been studied and recommendations for their implementation have been provided within this report:
  - The primary direct approach utilized within these studies incorporates the Abrahamson coherency functions directly into the CLASSI soil-structure interaction program.
  - As a result of the effort to benchmark the CLASSI direct incoherency approach, the SASSI method by Bechtel and the ACS SASSI method by ARES are also available to treat the effects of incoherence on structures.
- Another valid, but conservative approach for addressing incoherency effects has been studied, and recommendations for its implementation have been provided within this report. The simplified approach applies a modified form of the Incoherency Transfer Function (ITFs) to the free-field ground motion and allows for the performance of the SSI analysis for the resulting modified ground motion assuming coherent input motions.

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Conclusions

- Regarding the simplified approach, a recommendation has been provided for a simplified approach which will provide insight into the effects of incoherence on foundation and structure response. The simplified approach is applicable to rock sites and the corresponding free-field ground motion with significant high-frequency content. The concept of the simplified approach has been validated herein. However, its generalization to foundation/structure systems of all types will require additional sensitivity studies to be performed.
- The CLASSI analyses performed in this study rely on the assumption that the foundation of the structure behaves rigidly when subjected to earthquake ground motion. The behavior of a foundation is dependent on the effective stiffness, which is a function of the foundation itself and the stiffening due to the interconnecting structural elements anchored to the foundation. The results of this study are applicable to typical nuclear power plant structures whose foundations are significantly stiffened by inter-connecting structural systems. Examples of such structures are reactor containments with internal structures and heavy shear wall structures. It is important to note that SSI analysis programs utilizing finite element modeling of the foundation, such as SASSI, are not restricted to the assumption of foundations behaving rigidly. An additional observation is that any effective flexibility of the foundation will likely reduce the effect of induced rocking on structure response.

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Conclusions

- The combined effects of spatial variation of ground motion with depth in the rock/soil and the effect of incoherence of ground motion for structures with embedded foundations and partially embedded walls is judged to be analyzable by considering the effects simultaneously or by separation of the two effects and superimposing the results. Appendix E documents a sensitivity study performed to evaluate the effects of incoherence on surface/embedded foundation/structure systems. In general terms, the results demonstrate that the effects of incoherence and embedment are separable.
- Computer programs that model flexible foundations and embedment, such as SASSI (when modified to treat the phenomena of incoherency), can effectively analyze soil-structure systems including those effects.
- Appendix B highlights the difficulties of validating the effects of incoherence of ground motion on nuclear power plant structures with currently existing data. The approach taken in the present study to account for incoherence of ground motion is compatible with that taken by Stewart and colleagues to evaluate recorded data and to implement the results into the seismic design process. Recorded data at Diablo Canyon and Perry nuclear power plants, as well as the data used in the Stewart and Kim studies, highlight the difficulties in using recorded data to validate specific elements of SSI. Carefully designed instrumentation schemes will be required in the future to validate these individual elements.

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