Effect of Abrahamson Ground Motion Coherency Functions for Hard Rock on Response of Simplified Representation of Nuclear Power Plant Structure: Summary

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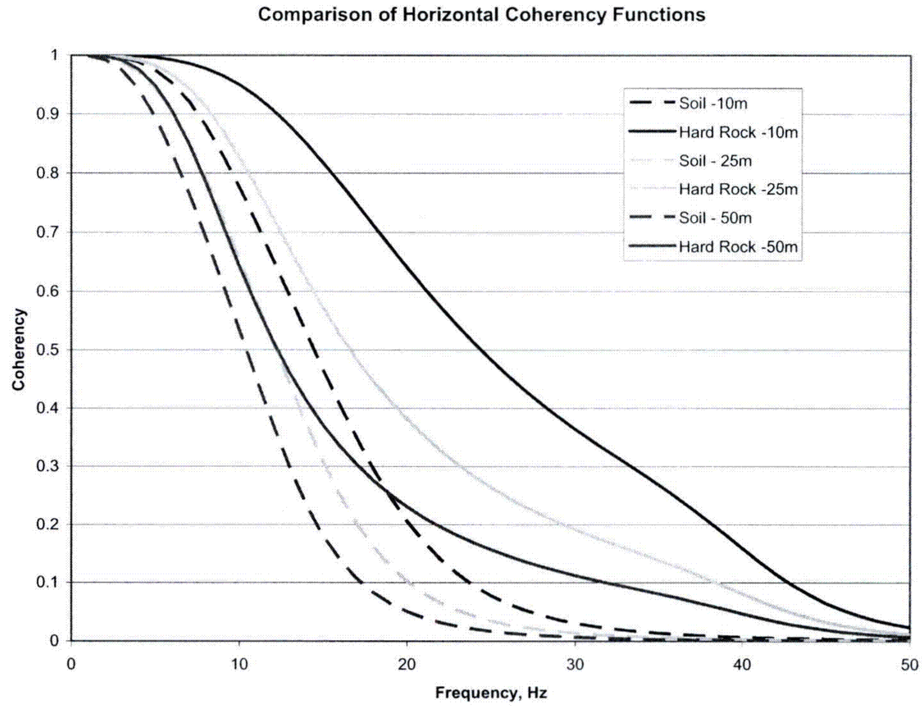
General

An extensive study was performed on the effect of seismic wave incoherence on foundation and structure response (EPRI, 2006). The study evaluated the effects of incoherence on the response of rigid, massless foundations and for example structural models. The starting points for the study were the ground motion coherency functions developed by Dr. Abrahamson (Abrahamson, 2005, 2006). These coherency functions remain applicable to soil sites for surface foundations. Recently, these ground motion coherency functions were revised considering only ground motion data recorded at rock sites. The resulting revisions are applicable to rock sites (Abrahamson, 2007) for surface and embedded foundations. These "Hard Rock" coherency functions were implemented in CLASSIinco, the version of CLASSI used to calculate incoherency transfer functions (ITFs) of the rigid, massless foundation and in-structure response. The soil and hard rock coherency functions are compared in Figure 1. The effects of changes to the coherency functions have been assessed and representative results are presented herein.

SSI and Structure Response

The subject of these analyses is the response of the representative nuclear power plant structure studied previously (EPRI, 2006). The relevant parameters of the analyses are described in detail in Chapter 2, EPRI (2006): the rock site profile; the 15-ft thick, 150-ft square foundation; and the simplified structure model based on some of the AP1000 properties. The structure model is comprised of three sticks with limited inter-connectivity at upper elevations. The free-field ground motion of interest is that motion compatible with the rock site profile, i.e., exhibiting significant high-frequency motion. For all analyses, spectrum compatible time histories defined the free-field ground motion. All analyses considered three directions of simultaneous earthquake input motion. Figure 2 shows a schematic of the structure model with response locations identified.



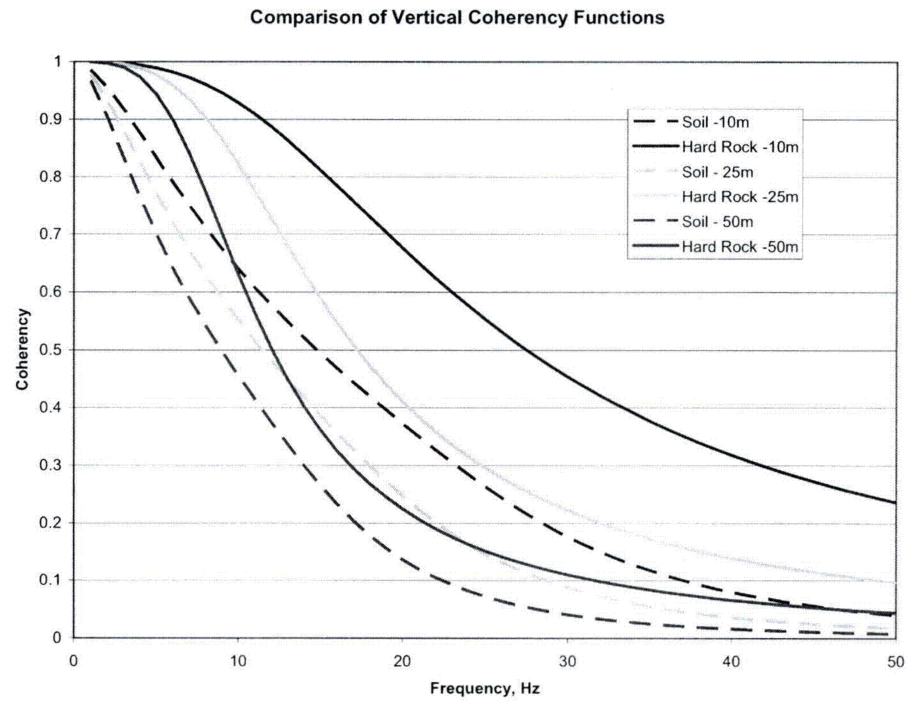
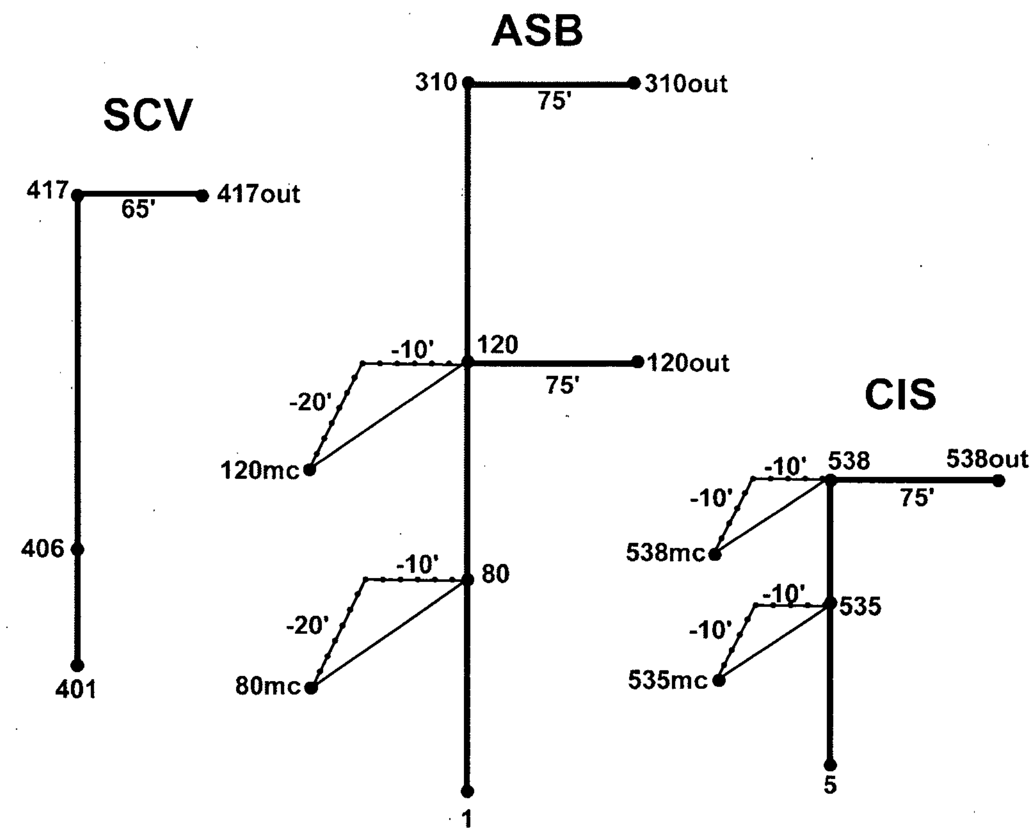
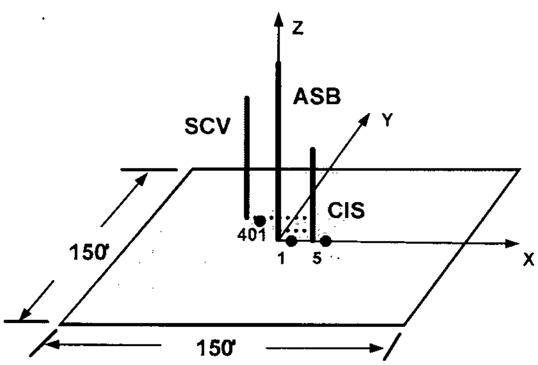


Figure 1
Comparison of Hard Rock (Abrahamson, 2007) and Soil (Abrahamson, 2005, 2006) Coherency Functions





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

Figure 2
Locations on the AP1000-Based Stick Model where In-Structure Response Spectra are Computed

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

1. SSI analysis with coherent input motion (dark blue curves in response spectra figures); identical results to those reported in Chapter 5, EPRI (2006).
2. SSI analysis with incoherent input motion; ground motion coherency functions – soil, surface foundations (Abrahamson, 2005, 2006) (green curves in response spectra figures – denoted NAA 2005-2006); identical results to those reported in Chapter 5, EPRI (2006).
3. SSI analysis with incoherent input motion; ground motion coherency functions – hard rock, surface and embedded foundations (Abrahamson, 2007) (red curves in response spectra figures – denoted NAA 2007).

To evaluate the effects of hard rock ground motion coherency functions on in-structure response, response spectra were calculated and compared for the various analyses at the tops of the structure sticks, at lower elevations on the structure sticks, and on outriggers extending 65 or 75-ft. from the top of each stick in the X direction (these dimensions were selected to approximately correspond to the AP1000 design dimensions).

SSI and Incoherence

As background, the fixed-base modes of the three structure sticks provide some insight into the dynamic behavior. The ASB has predominate modes with frequencies less than 10 Hz with fundamental modes in the horizontal directions of 3.2 Hz (X-direction) and 3.0 Hz (Y-direction); the fundamental mode in the vertical direction of frequency 9.9 Hz (Z-direction). Many modes participate in the response of the ASB. The predominate modes of the SCV in the horizontal directions also have frequencies less than 10 Hz – the lowest frequency of an important X-direction mode being 5.5 Hz; Y-direction mode being 6.14 Hz; the lowest frequency of an important vertical mode being 16 Hz. As with the ASB, many modes participate in the response of the SCV. The predominant modes of the CIS have frequencies greater than 10 Hz. Many modes also participate in the response of the CIS.

The total mass of the structures is apportioned approximately ASB – 86%, CIS – 11%, and SCV – 3%, i.e., ignoring the mass of the foundation. The dynamic behavior of the three stick model is coupled through the inter-connectivity of the sticks and natural torsion is induced throughout the three structures due to the eccentricities assumed in the ASB and CIS structures.

Results presented are in-structure response spectra (5% damping) at the foundation and at points on each of the three models (ASB, SCV, CIS) as shown in Figure 2. Responses at the top of each model and at approximately mid-height (referred to as "low on" a particular structure within Figure 2), are calculated and compared. The near mid-height locations were selected to investigate the potential effect of incoherence on points where higher modes more fully participate in the response. Note that the ASB stick represents both the auxiliary building and the shield building. The combined auxiliary and shield building extends up to the top of the auxiliary building at Node 120. Above this node and elevation, the ASB stick only represents the shield building. Hence, in addition to the top of the shield building and low in the combined ASB model, output was calculated and is presented at the top of the auxiliary building at the centerline (Z-direction), at the center of mass for the horizontal directions (X and Y), and at the outrigger (X, Y, Z).

In addition to foundation response, results are presented at Nodes 310, 310out, 120mc, 120out, and 80mc on the ASB, Nodes 417, 417out and 406 on the SCV, and Nodes 538mc, 538out, and 535mc on the CIS where node locations are illustrated in Figure2. The "mc" designation added to the node number indicates that the mass and shear centers are not coincident and response is given at the mass center. The "out" designation added to the node number indicates an outrigger location used to display torsional response at the periphery of the structure. In-structure response spectra at these twelve locations for two horizontal, X and Y, and the vertical direction, Z, of ground motion are presented in Figures 3 through 38. Again, all analyses considered 3 directions of simultaneous earthquake input motion.

General Observations

For the high frequency ground motion, rock site profile, foundation behavior essentially rigid, and sample nuclear power plant structure, in-structure response spectra are generally reduced in frequency ranges greater than about 12 Hz. as evidenced by comparing spectra including the effects of incoherency as represented by the "Hard Rock" ground motion coherency functions (Abrahamson, 2007) with spectra calculated assuming coherent ground motion. As expected, these reductions in response spectra are less than the reductions derived for the soil ground motion coherency functions (Abrahamson, 2005, 2006). In general, reductions in in-structure response spectra are greater in the vertical direction than in the horizontal directions. With limited exceptions, the reductions are significant at frequencies greater than about 12 Hz. where local peaks in the response spectra occur.

Although not shown here, it is extremely important to account for SSI in the calculation of structure response for ground motions dominated by high frequencies. This is the case for coherent and incoherent ground motion assumptions. Comparisons of fixed-base response with response calculate taking into account SSI show the latter cases to be very significantly reduced when compared to the former.

Foundation Response

Foundation response is presented in Figures 3, 4, and 5. Comparing the foundation response spectra including the effects of incoherency (NAA-2007) with those of the coherent case generally shows significant reductions at frequencies greater than 15 Hz. Spectral accelerations are reduced by a factor of 1.1 to 2 over significant frequency ranges. The free-field ground motion response spectra are plotted in Figures 3, 4, and 5. Comparing coherent and incoherent foundation response with the free-field motion demonstrates the importance of SSI and incoherency of ground motion on foundation response.

Auxiliary and Shield Building (ASB)

- **Top of Shield Building.** Responses at the top of the coupled auxiliary and shield building (ASB) are presented in Figures 6, 7, and 8. Comparing the response spectra due to incoherency effects (Analysis 3) with those of Analysis 1, generally, shows reductions due to incoherency for frequencies greater than 12 Hz. For horizontal directions, the reductions are range from no reduction to a factor of about 2. For the vertical direction, reductions are observed in the frequency range above 10 Hz, including at the ZPA frequency.

  At a frequency of peak amplification less than 10 Hz (X-direction 6.5 Hz; Y-direction 6 Hz), slight increases in spectral accelerations of the incoherent case above the coherent case are observed. As for Analysis Case 2, this is attributed to the effect of induced rotations of the foundation.

  The responses of the outrigger, extending 75-ft. in the X-direction, are presented in Figures 15, 16, and 17. The reductions in response spectral accelerations generally follow the trend of the values on the centerline, but the reductions are observed to be less. The effects of incoherence induced torsion are shown in Figure 16 Y-direction response, where the responses calculated due to coherence and incoherence (blue and red curves) are relatively close for frequencies above 12 Hz. At frequencies of peak amplification less than 10 Hz (X- and Y-directions 6.5 Hz.), slight increases in spectral accelerations of the incoherent case above the coherent case are observed. This is attributed to the effect of induced rotations of the foundation.

- **Top of Auxiliary Building.** Responses at the top of the auxiliary building are presented in Figures 9, 10, and 11. In the X-direction, spectral accelerations are reduced by a factor of 1 (no reduction) to about 1.4 due to incoherence for frequencies greater than about 14 Hz. In the Y-direction, reductions in the response are observed for frequencies greater than 10 Hz up to and including the ZPA. There are no observed low-frequency exceedances of the incoherent responses at this location.

  The responses of the outrigger, extending 75-ft. in the X-direction, are presented in Figures 18, 19, and 20. The reductions in response spectral accelerations generally follow the trend of the values of the points at the mass centers, but the reductions are observed to be less. The X-direction response is close to the same as the response at the center of mass. The Y-direction response demonstrates the effects of induced torsion when compared to the response at the center of mass. The Y-direction response has significant reductions incoherent to coherent in the frequency range of 20 – 60 Hz. Vertical response spectra are significantly reduced for frequencies greater than about 12 Hz.

- **Low in ASB.** Responses at a lower elevation of the coupled auxiliary and shield building (ASB) are presented in Figures 12, 13, and 14. Generally, these spectra in the horizontal directions demonstrate reductions in the spectral accelerations at frequencies greater than 20 Hz. Generally, the response reductions in the vertical direction are significant for frequencies greater than 12 Hz.

Steel Containment Vessel (SCV)

- **Top of SCV.** Response at the top of the steel containment vessel (SCV) at the centerline is presented in Figures 21, 22, and 23. Comparing the response spectra due to incoherency effects (Analysis 3) with those of Analysis 1, generally, show significant reductions in response for frequencies greater than about 15 Hz with less reduction at the ZPA. In the vertical direction, significant reductions are observed for all frequencies greater than 12 Hz.

  The responses of the outrigger extending 65-ft in the X direction from the top of the steel containment vessel (SCV) are presented in Figures 27, 28, and 29. Reductions in response spectral accelerations are observed for frequencies greater than about 15 Hz in the X-direction. The Y-direction response demonstrates the effect of induced torsion coupled with a significant torsional mode at about 12 Hz. – the incoherent response exceeds the coherent response by about a factor of 1.15. At higher frequencies in the Y-direction response, the peak spectral accelerations are reduced when accounting for incoherency. Significant reductions in the vertical direction are observed for frequencies greater than about 12 Hz.

- **Low in the SCV.** Responses at lower elevations of the steel containment vessel (SCV) are presented in Figures 24, 25, and 26. These spectra demonstrate similar behavior to that seen on the centerline at the top of the SCV.

Containment Internal Structure (CIS)

- **Top of CIS.** Responses at the top of the containment internal structure (CIS) at the center of mass are presented in Figures 30, 31, and 32. Comparing the response spectra due to incoherency effects (Analysis 3) with those of Analysis 1, generally, shows significant reductions over those due to coherent SSI effects at frequencies greater than about 12 Hz. These reductions range from factors of 1.0 (no reduction) to 1.5. For vertical response, significant reductions occur for frequencies greater than about 15 Hz.

  Responses of the outrigger extending 75-ft in the X direction from the top of the containment internal structure (CIS) are presented in Figures 36, 37, and 38. Reductions in response spectral accelerations are observed in all three directions at this location at frequencies greater than about 12 Hz. Reductions range from factors of 1.0 (no reduction) to about a factor of 2.

- **Low in the CIS.** Responses at lower elevations of the containment internal structure (CIS) are presented in Figures 33, 34, and 35. Generally, responses in the horizontal directions show minimal reductions compared to the coherent case. For the vertical direction significant reductions occur for frequencies greater than about 11 Hz.

Conclusions

The fundamental conclusion is that there are significant reductions in high-frequency response due to seismic wave incoherence even for the "Hard Rock" ground motion coherency functions.

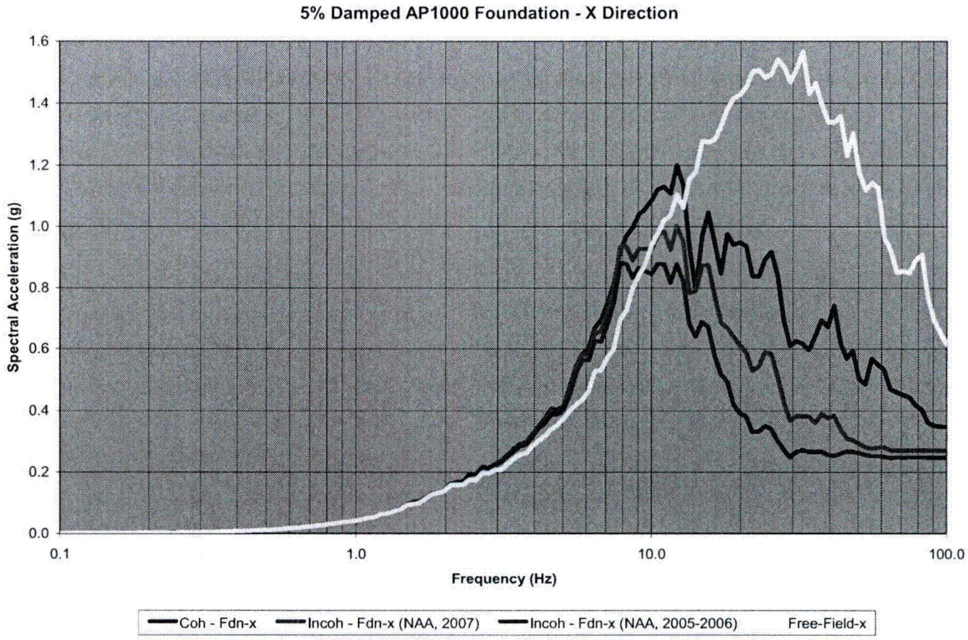


Figure 3
Foundation Response Spectra – X Direction –SSI Coherent, SSI Incoherent NAA2005-2006, SSI Incoherent NAA2007, (Node 1) and Free-Field

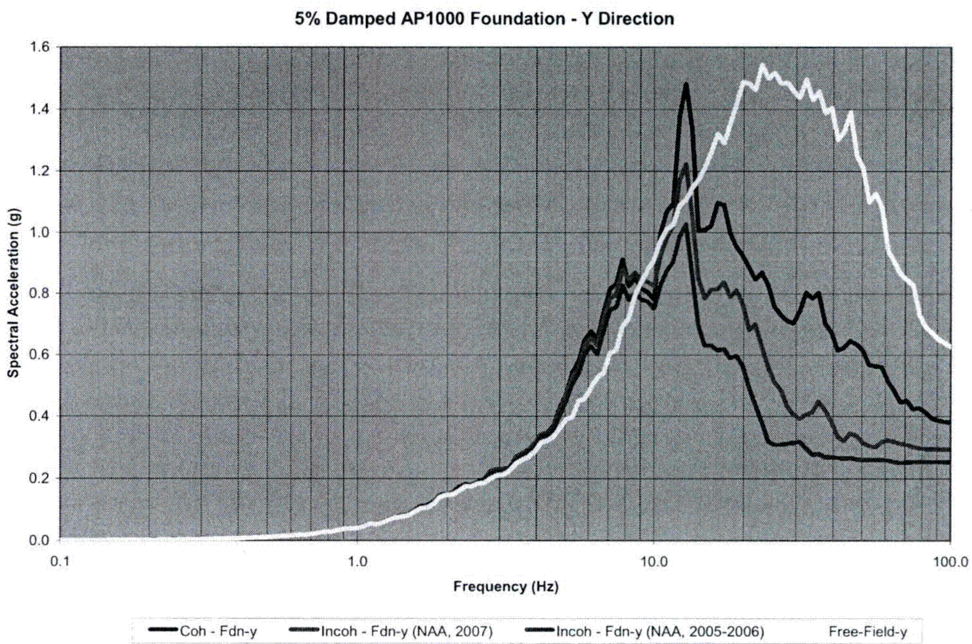


Figure 4
Foundation Response Spectra – Y Direction –SSI Coherent, SSI Incoherent NAA2005-2006, SSI Incoherent NAA2007, (Node 1) and Free-Field

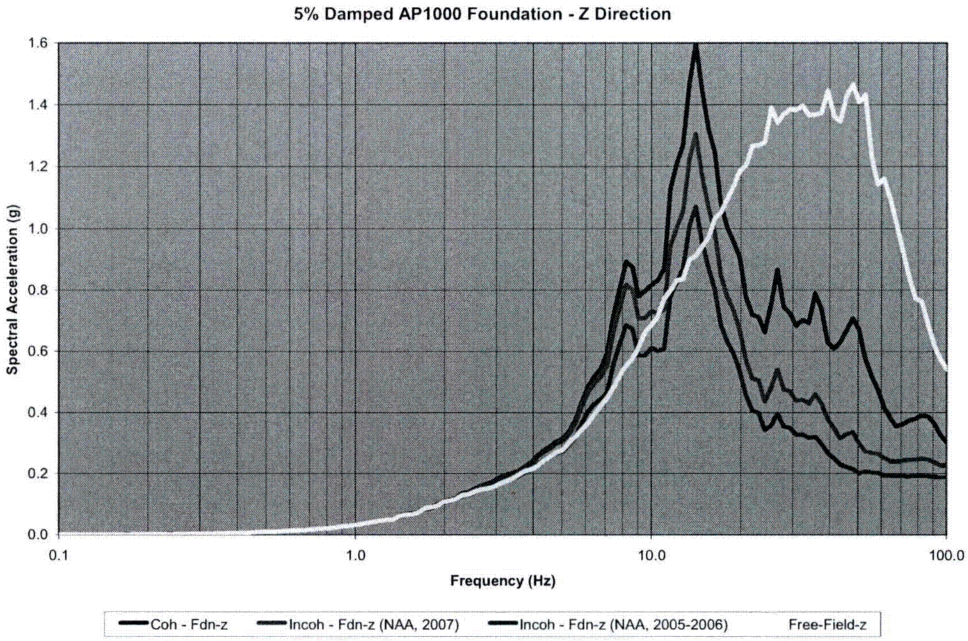


Figure 5
Foundation Response Spectra – Z Direction –SSI Coherent, SSI Incoherent NAA2005-2006, SSI Incoherent NAA2007, (Node 1) and Free-Field

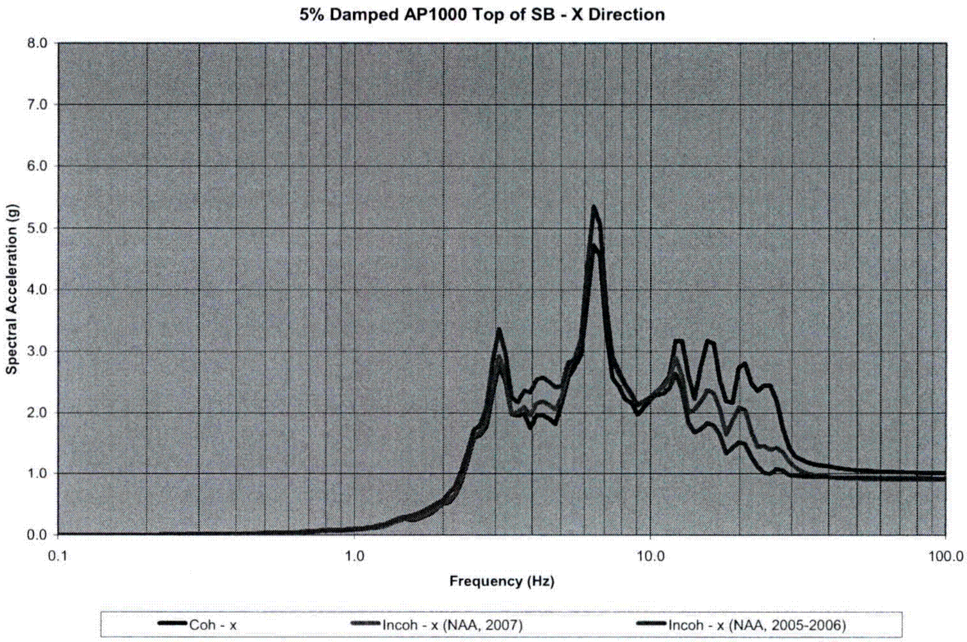


Figure 6
Top of Shield Building Response Spectra – X Direction –SSI Coherent, SSI Incoherent NAA2005-2006, SSI Incoherent NAA2007 (Node 310)

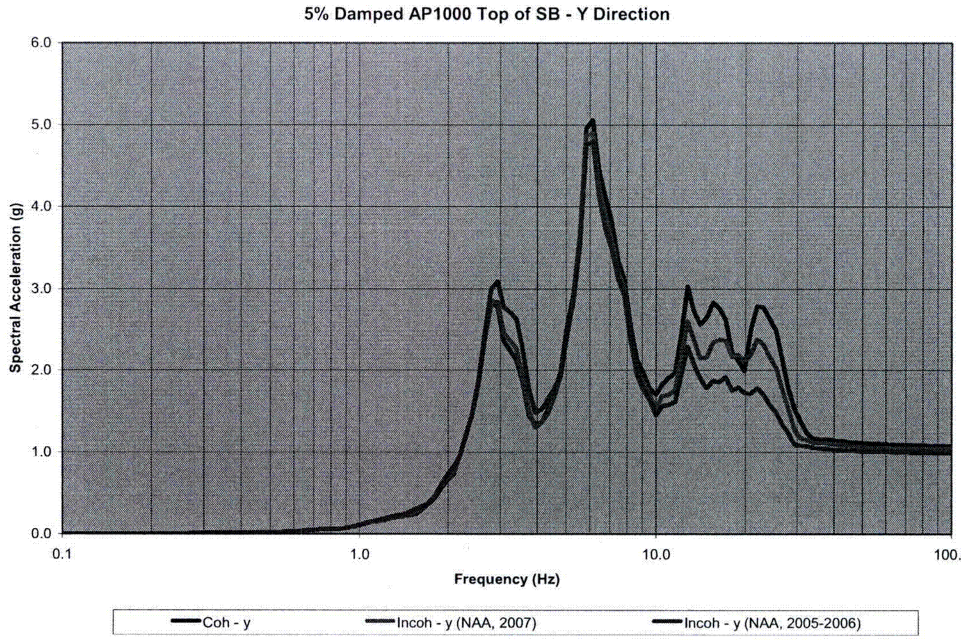


Figure 7
Top of Shield Building Response Spectra – Y Direction –SSI Coherent, SSI Incoherent NAA2005-2006, SSI Incoherent NAA2007 (Node 310)

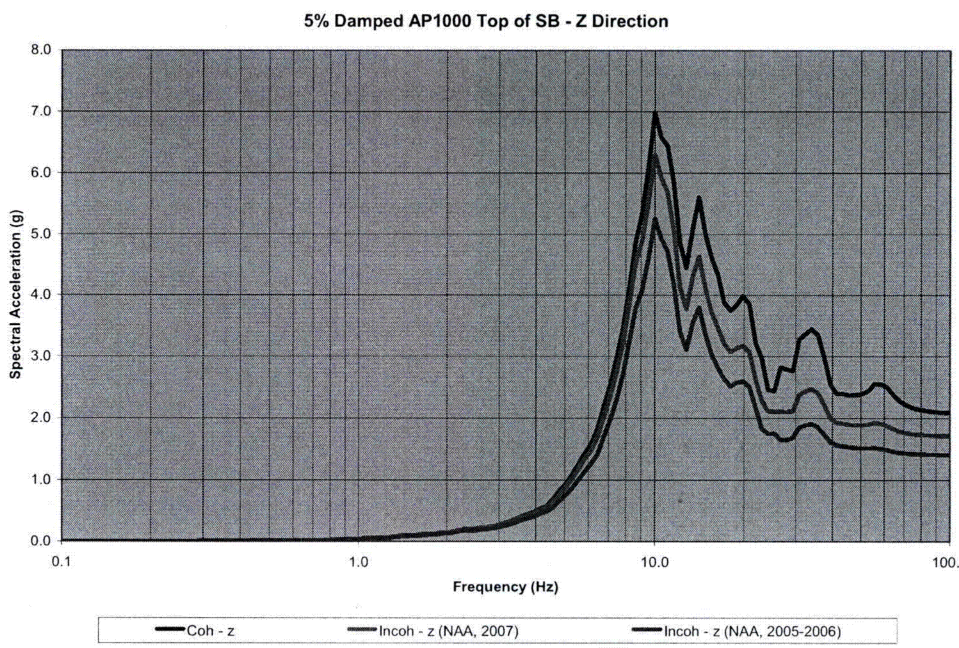


Figure 8
Top of Shield Building Response Spectra – Z Direction –SSI Coherent, SSI Incoherent NAA2005-2006, SSI Incoherent NAA2007 (Node 310)

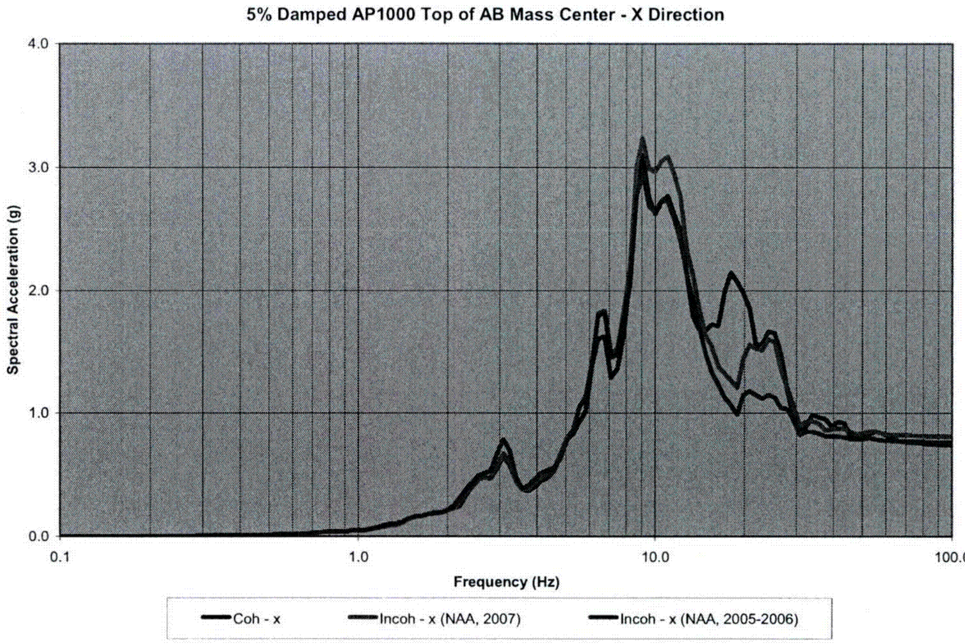


Figure 9
Top of Auxiliary Building Response Spectra – X Direction –SSI Coherent, SSI Incoherent NAA2005-2006, SSI Incoherent NAA2007 (Node 120mc)

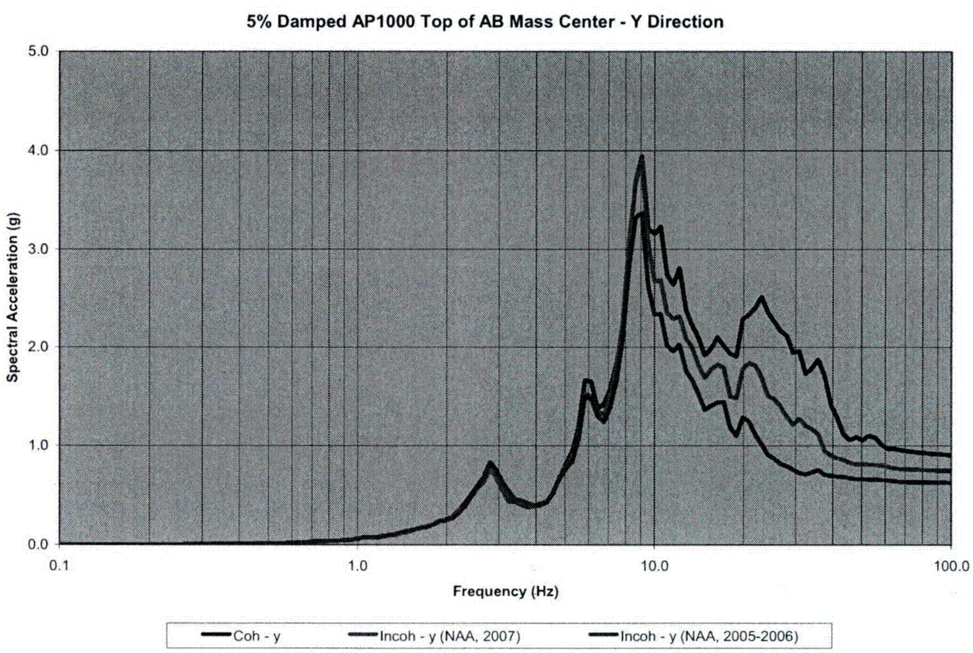


Figure 10
Top of Auxiliary Building Response Spectra – Y Direction –SSI Coherent, SSI Incoherent NAA2005-2006, SSI Incoherent NAA2007 (Node 120mc)

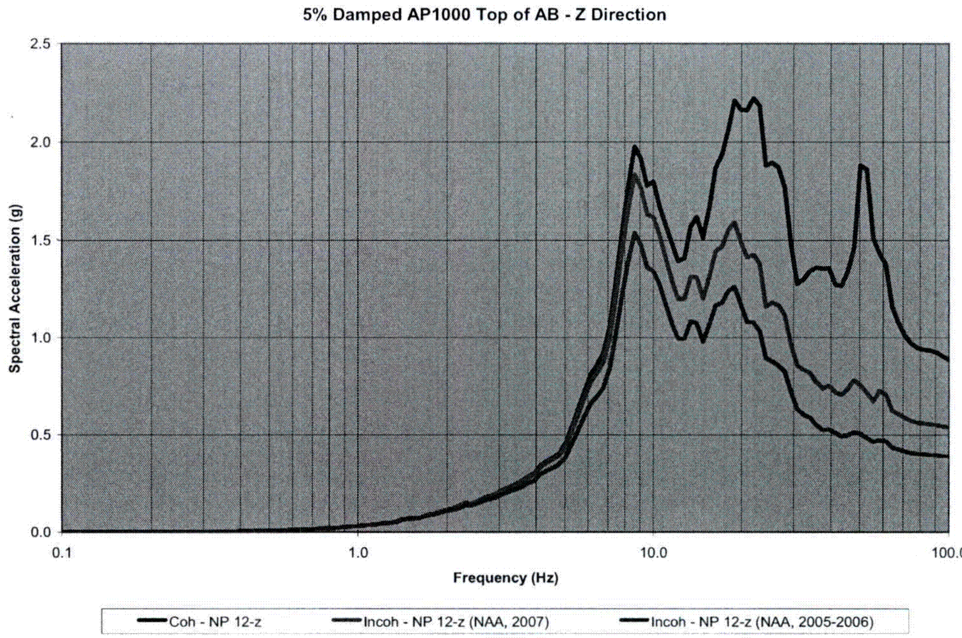


Figure 11
Top of Auxiliary Building Response Spectra – Z Direction –SSI Coherent, SSI Incoherent NAA2005-2006, SSI Incoherent NAA2007 (Node 120)

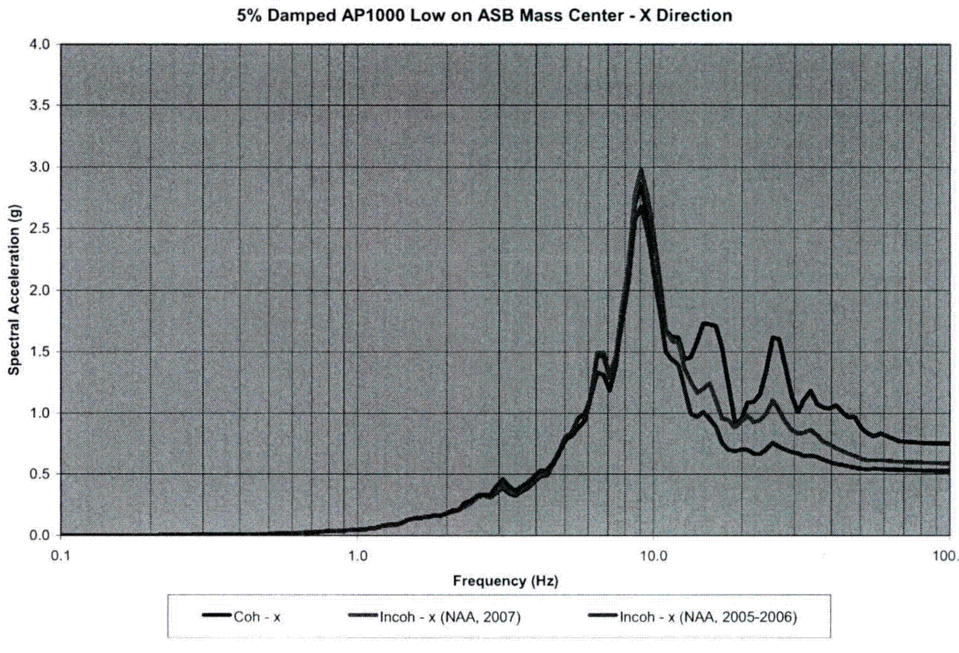


Figure 12
Low on ASB Response Spectra – X Direction – SSI Coherent, SSI Incoherent NAA2005-2006, SSI Incoherent NAA2007 (Node 80mc)

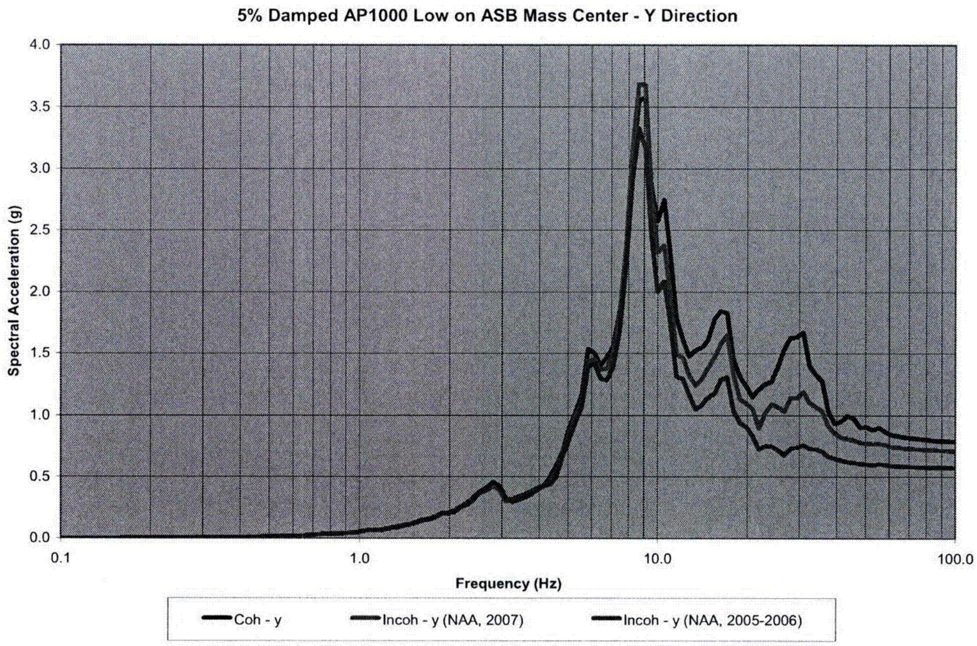


Figure 13
Low on ASB Response Spectra – Y Direction – SSI Coherent, SSI Incoherent NAA2005-2006, SSI Incoherent NAA2007 (Node 80mc)

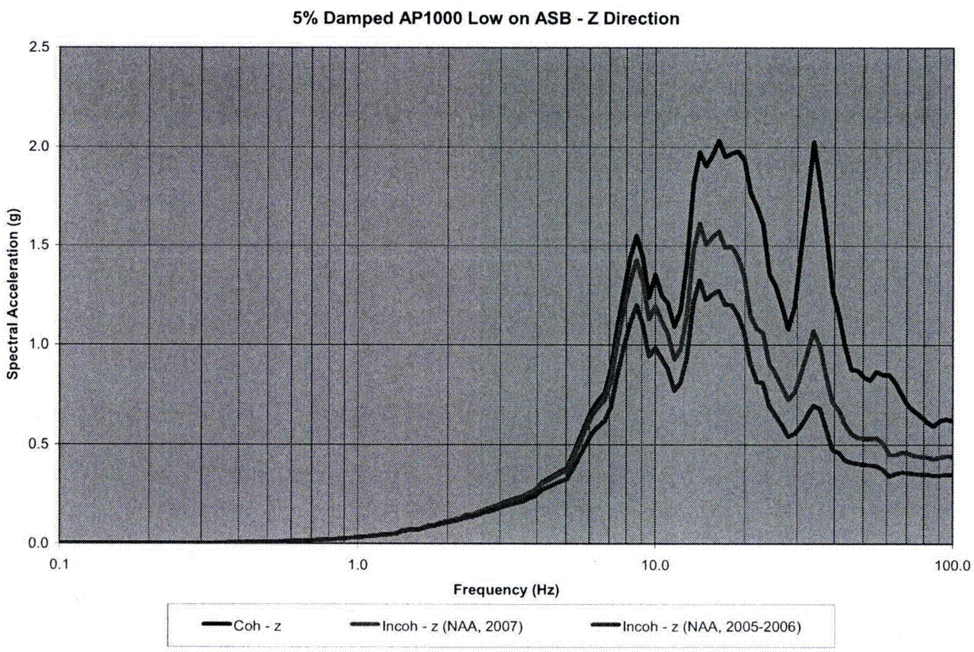


Figure 14
Low on ASB Response Spectra – Z Direction – SSI Coherent, SSI Incoherent NAA2005-2006, SSI Incoherent NAA2007 (Node 80)

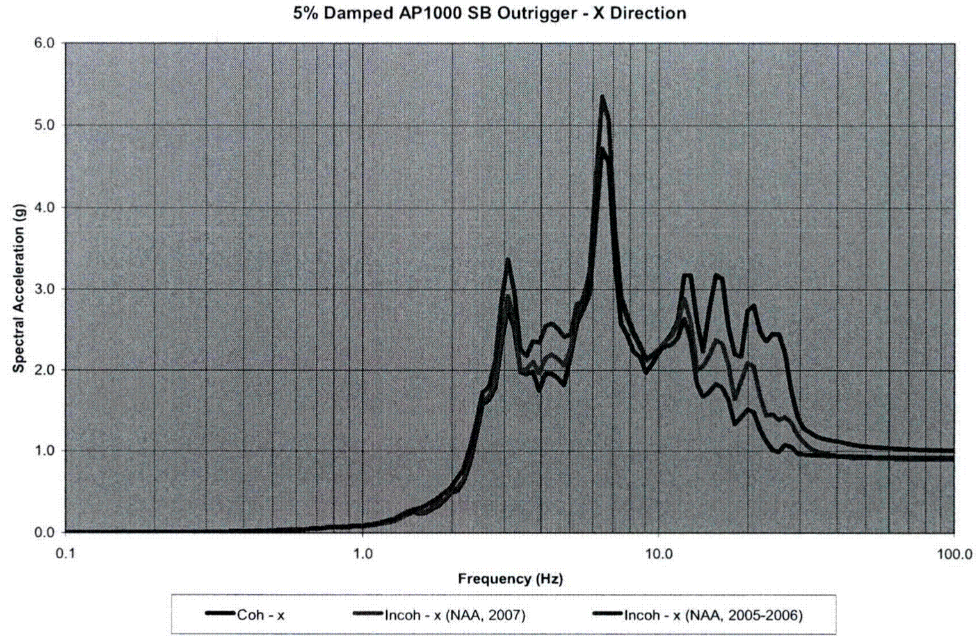


Figure 15
Shield Building Outrigger Response Spectra – X Direction – SSI Coherent, SSI Incoherent NAA2005-2006, SSI Incoherent NAA2007 (Node 310out)

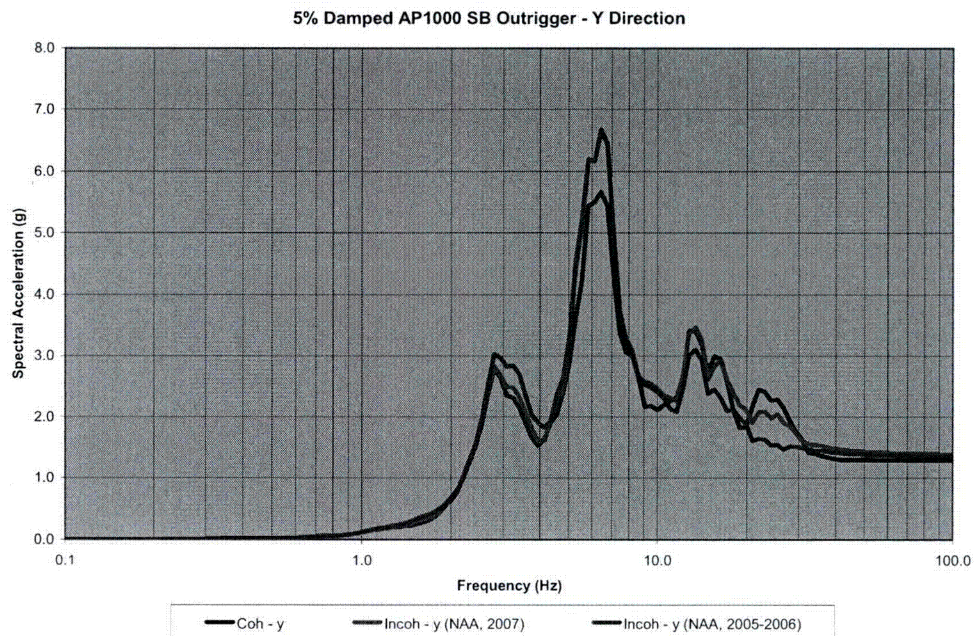


Figure 16
Shield Building Outrigger Response Spectra – Y Direction – SSI Coherent, SSI Incoherent NAA2005-2006, SSI Incoherent NAA2007 (Node 310out)

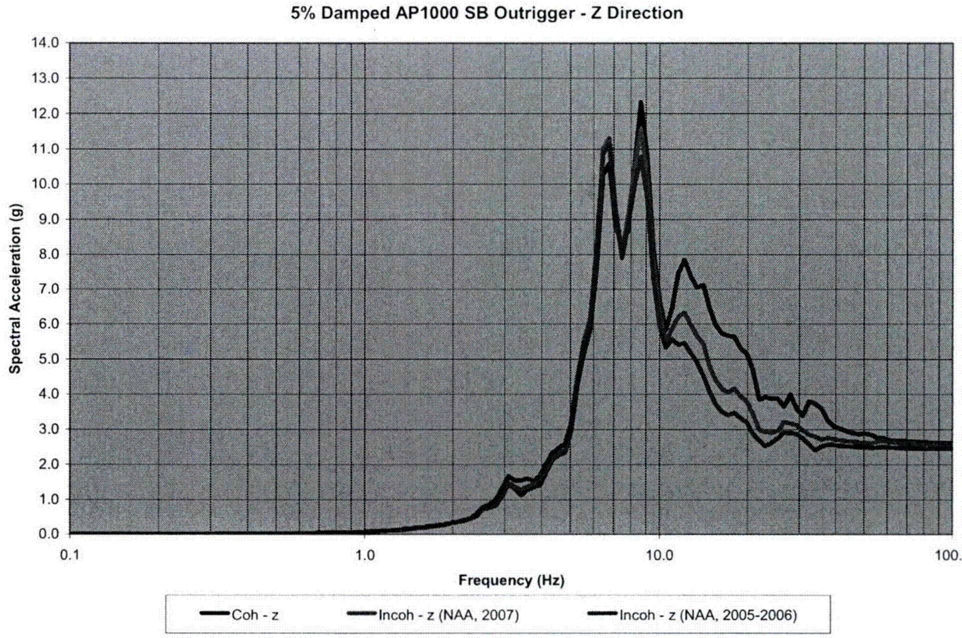


Figure 17
Shield Building Outrigger Response Spectra – Z Direction – SSI Coherent, SSI Incoherent NAA2005-2006, SSI Incoherent NAA2007 (Node 310out)

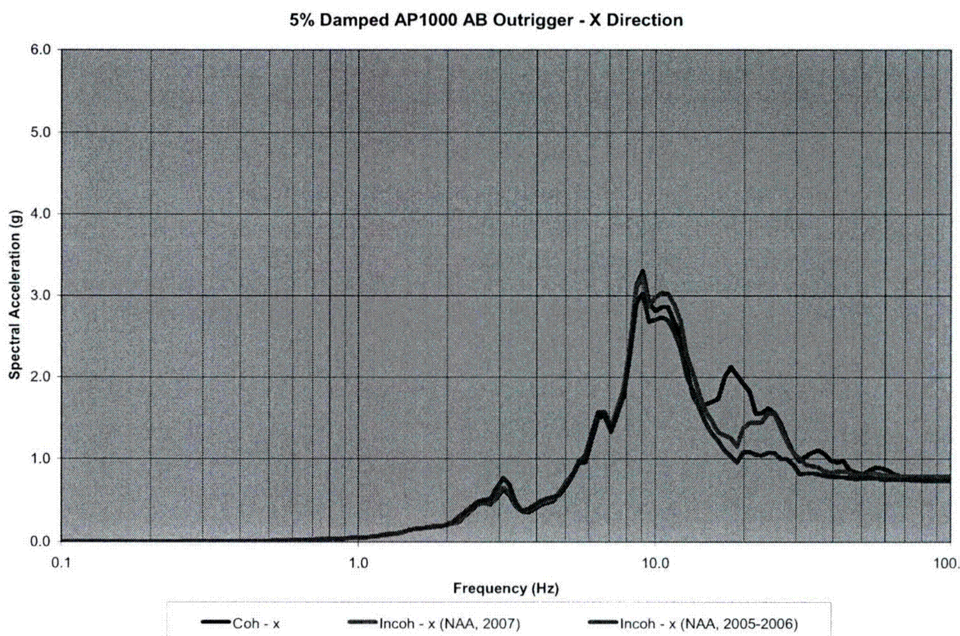


Figure 18
Auxiliary Building Outrigger Response Spectra – X Direction – SSI Coherent, SSI Incoherent NAA2005-2006, SSI Incoherent NAA2007 (Node 120out)

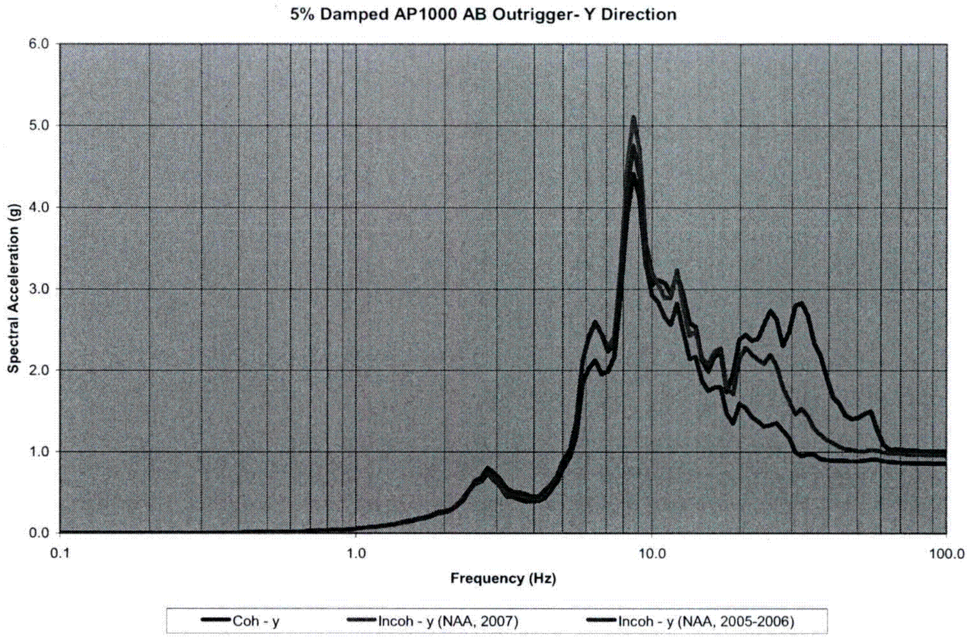


Figure 19
Auxiliary Building Outrigger Response Spectra – Y Direction – SSI Coherent, SSI Incoherent NAA2005-2006, SSI Incoherent NAA2007 (Node 120out)

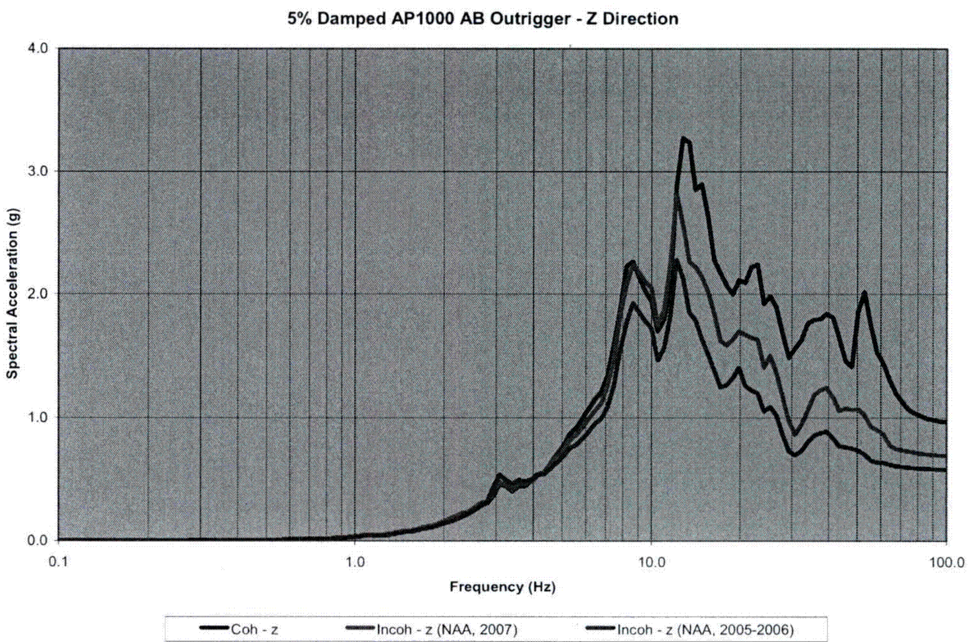


Figure 20
Auxiliary Building Outrigger Response Spectra – Z Direction – SSI Coherent, SSI Incoherent NAA2005-2006, SSI Incoherent NAA2007 (Node 120out)

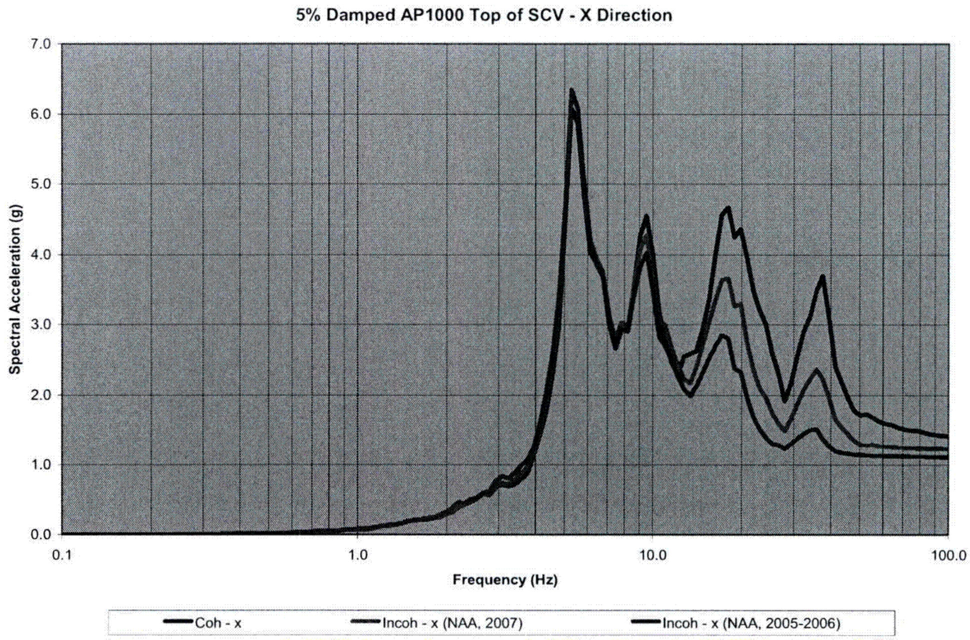


Figure 21
Top of SCV Response Spectra – X Direction –SSI Coherent, SSI Incoherent NAA2005-2006, SSI Incoherent NAA2007 (Node 417)

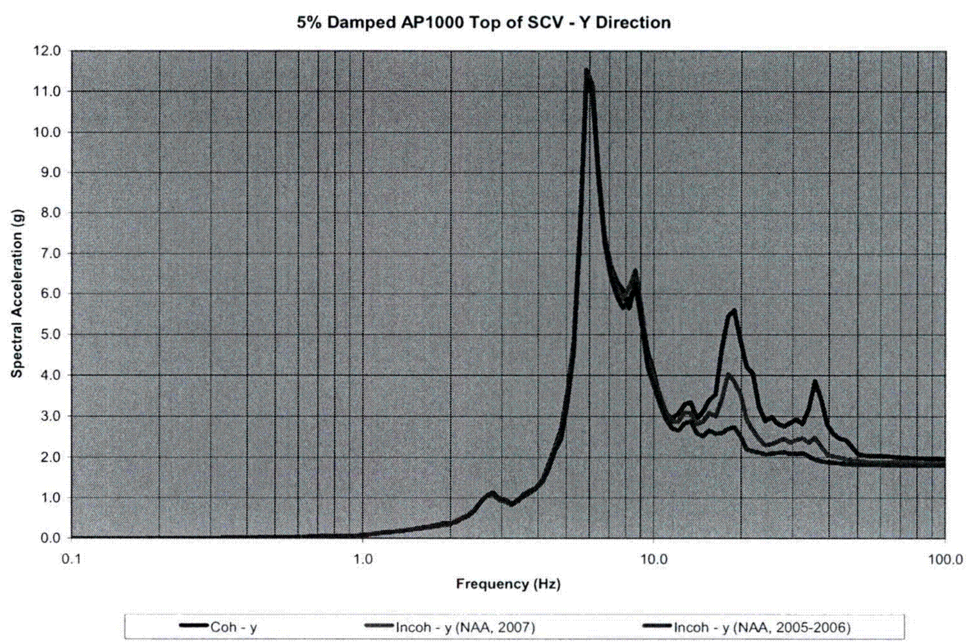


Figure 22
Top of SCV Response Spectra – Y Direction –SSI Coherent, SSI Incoherent NAA2005-2006, SSI Incoherent NAA2007 (Node 417)

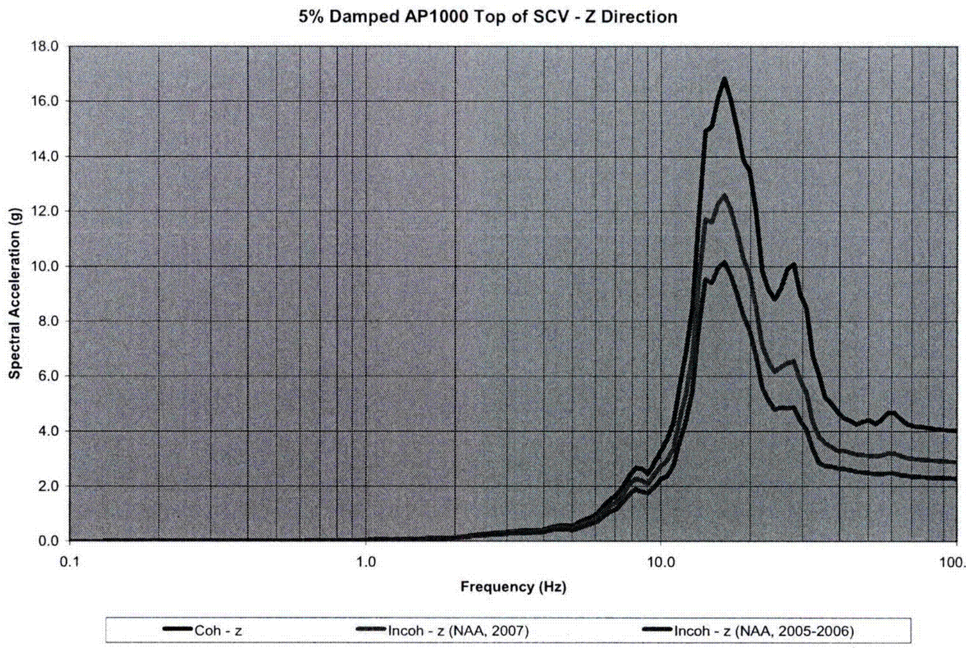


Figure 23
Top of SCV Response Spectra – Z Direction –SSI Coherent, SSI Incoherent NAA2005-2006, SSI Incoherent NAA2007 (Node 417)

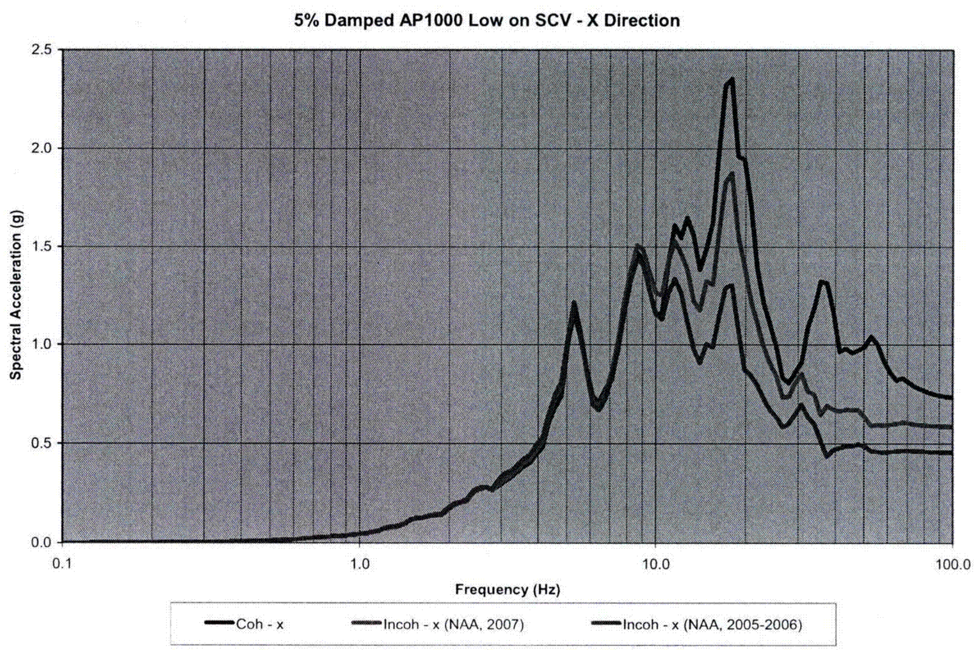


Figure 24
Low on SCV Response Spectra – X Direction – SSI Coherent, SSI Incoherent NAA2005-2006, SSI Incoherent NAA2007 (Node 406)

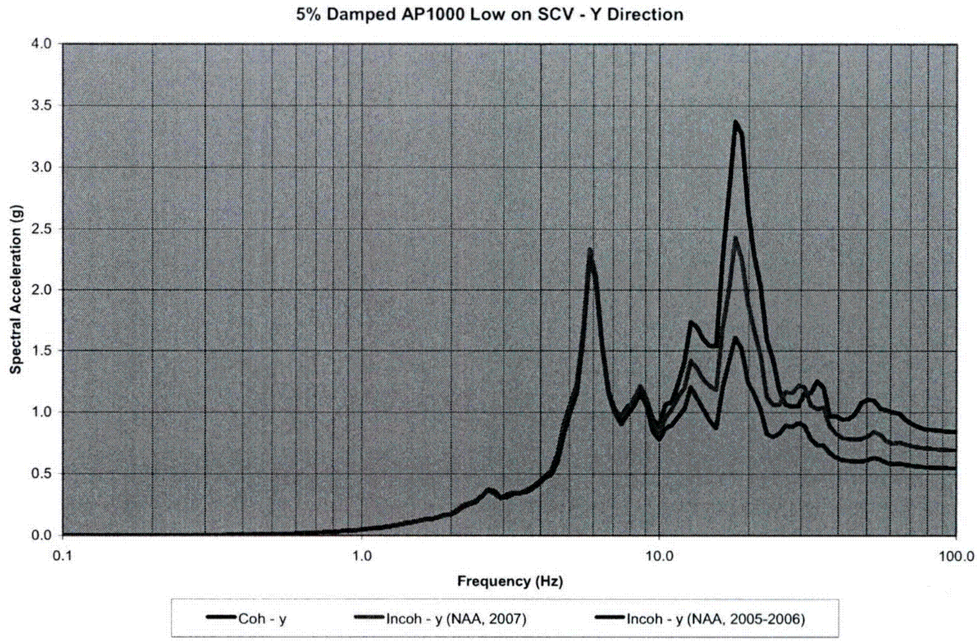


Figure 25
Low on SCV Response Spectra – Y Direction – SSI Coherent, SSI Incoherent NAA2005-2006, SSI Incoherent NAA2007 (Node 406)

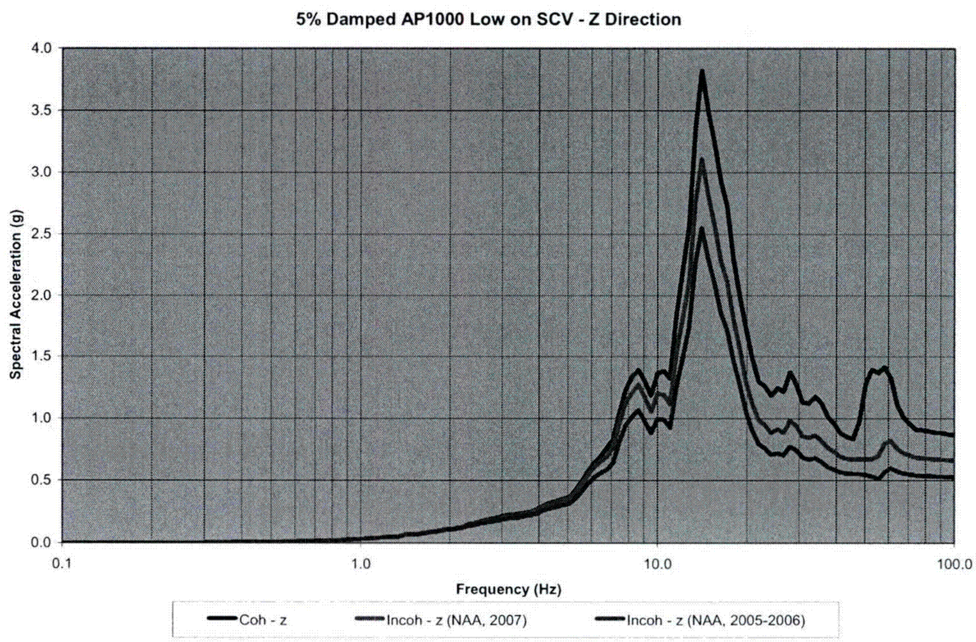


Figure 26
Low on SCV Response Spectra – Z Direction – SSI Coherent, SSI Incoherent NAA2005-2006, SSI Incoherent NAA2007 (Node 406)

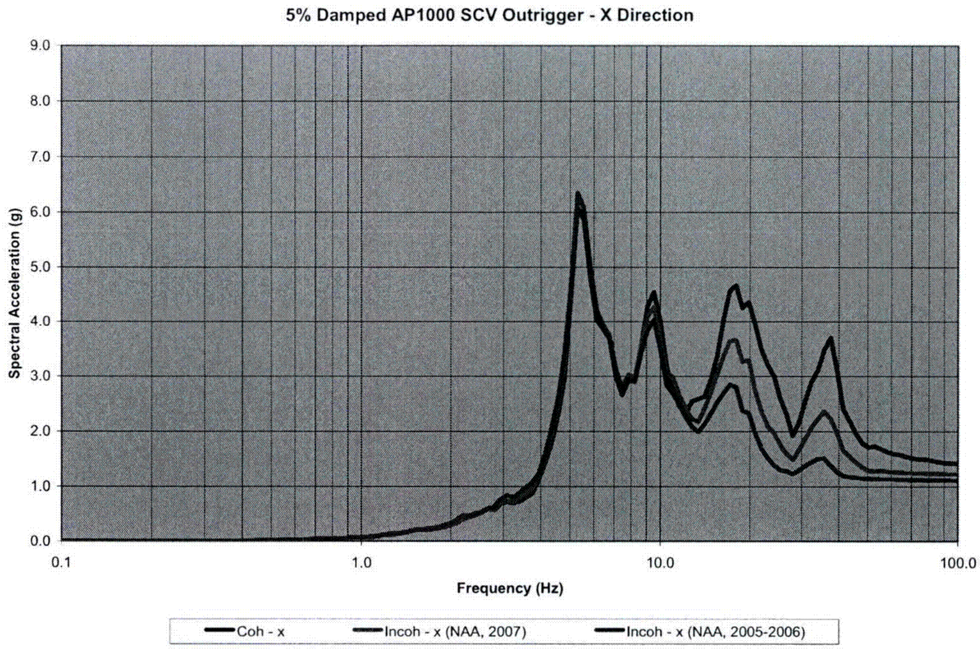


Figure 27
SCV Outrigger Response Spectra – X Direction – SSI Coherent, SSI Incoherent NAA2005-2006, SSI Incoherent NAA2007 (Node 417out)

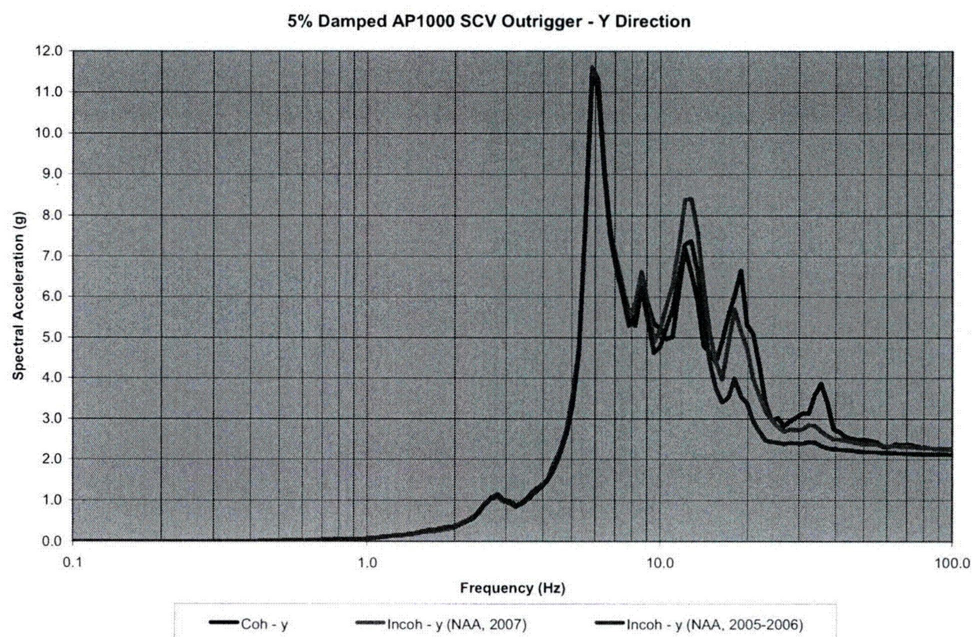


Figure 28
SCV Outrigger Response Spectra – Y Direction – SSI Coherent, SSI Incoherent NAA2005-2006, SSI Incoherent NAA2007 (Node 417out)

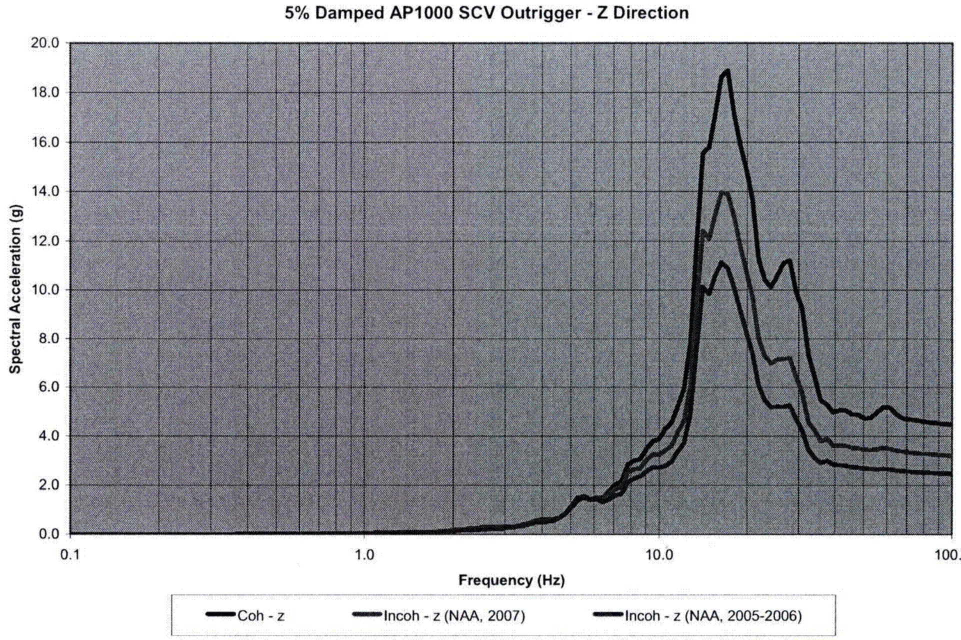


Figure 29
SCV Outrigger Response Spectra – Z Direction – SSI Coherent, SSI Incoherent NAA2005-2006, SSI Incoherent NAA2007 (Node 417out)

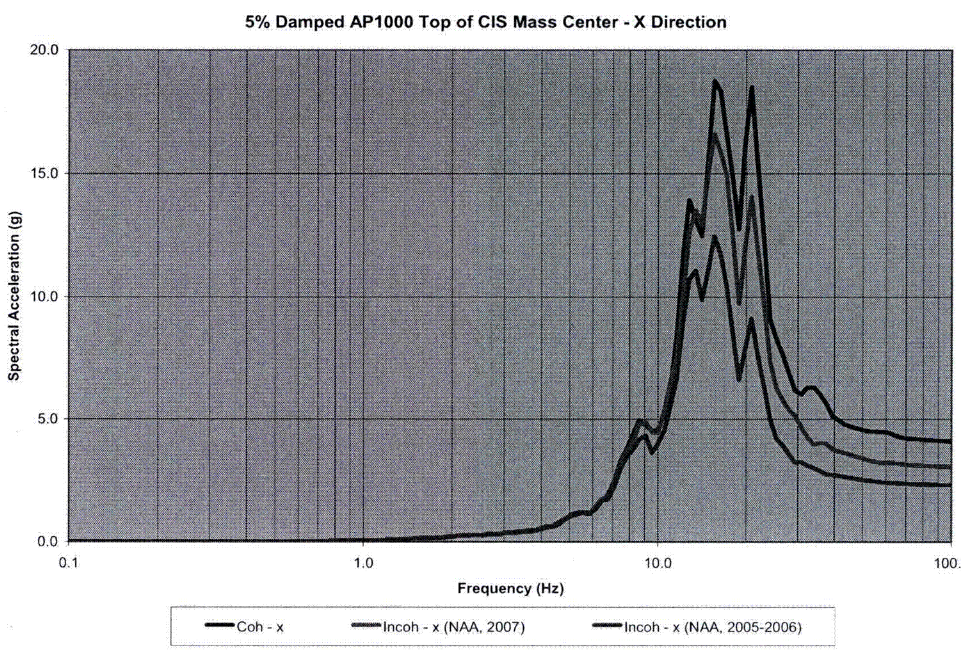


Figure 30
Top of CIS Response Spectra – X Direction –SSI Coherent, SSI Incoherent NAA2005-2006, SSI Incoherent NAA2007 (Node 538mc)

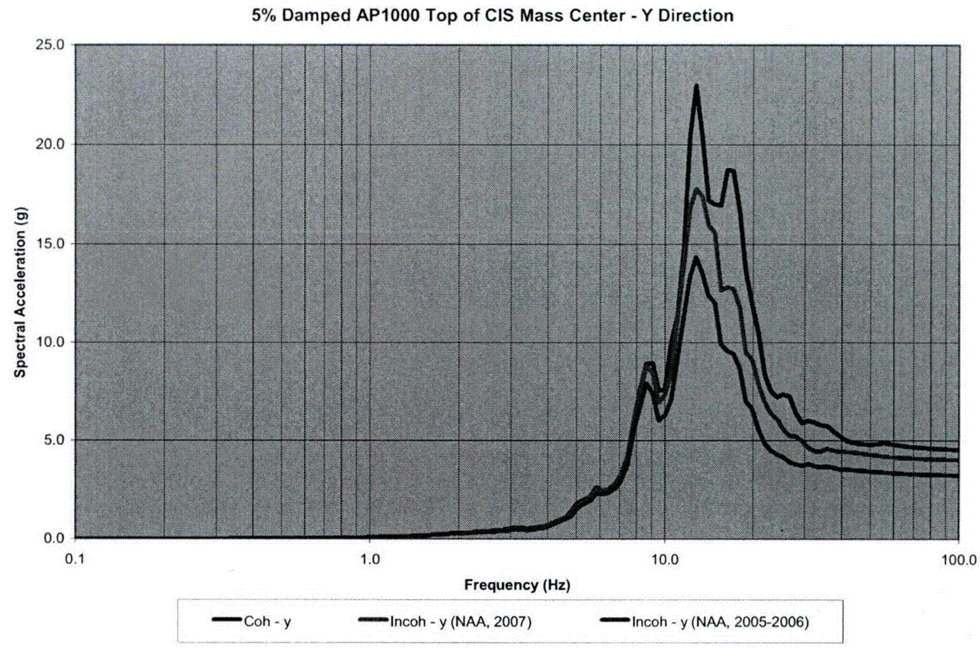


Figure 31
Top of CIS Response Spectra – Y Direction –SSI Coherent, SSI Incoherent NAA2005-2006, SSI Incoherent NAA2007 (Node 538mc)

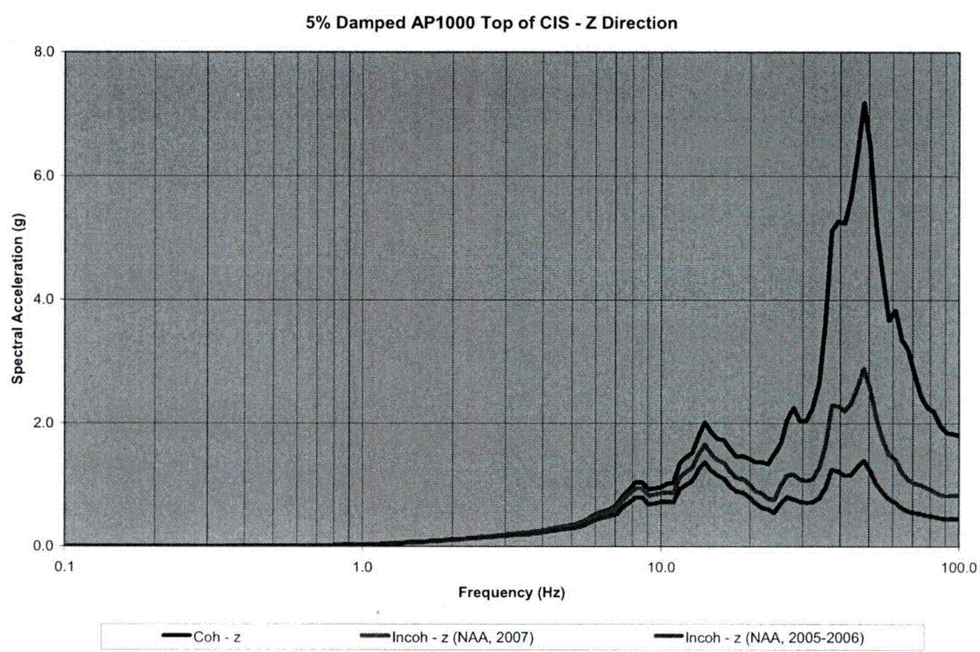


Figure 32
Top of CIS Response Spectra – Z Direction –SSI Coherent, SSI Incoherent NAA2005-2006, SSI Incoherent NAA2007 (Node 538)

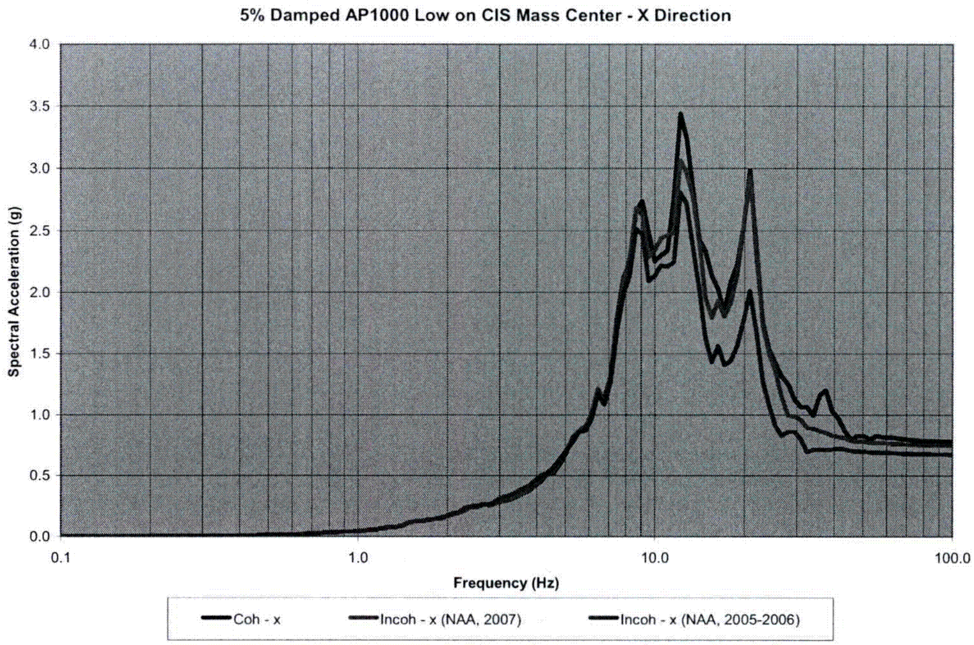


Figure 33
Low on CIS Response Spectra – X Direction –SSI Coherent, SSI Incoherent NAA2005-2006, SSI Incoherent NAA2007 (Node 535mc)

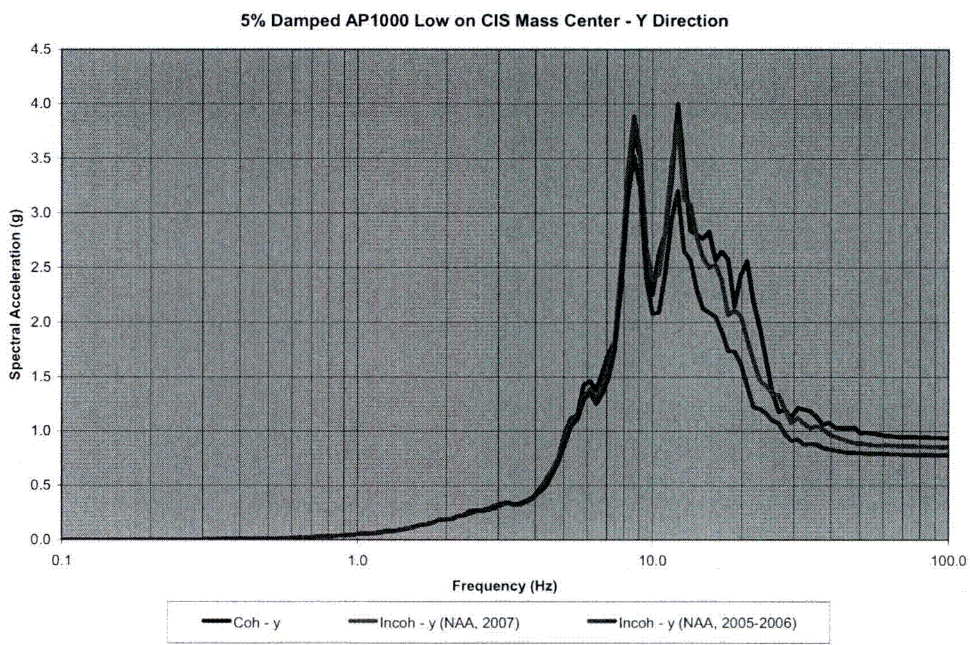


Figure 34
Low on CIS Response Spectra – Y Direction –SSI Coherent, SSI Incoherent NAA2005-2006, SSI Incoherent NAA2007 (Node 535mc)

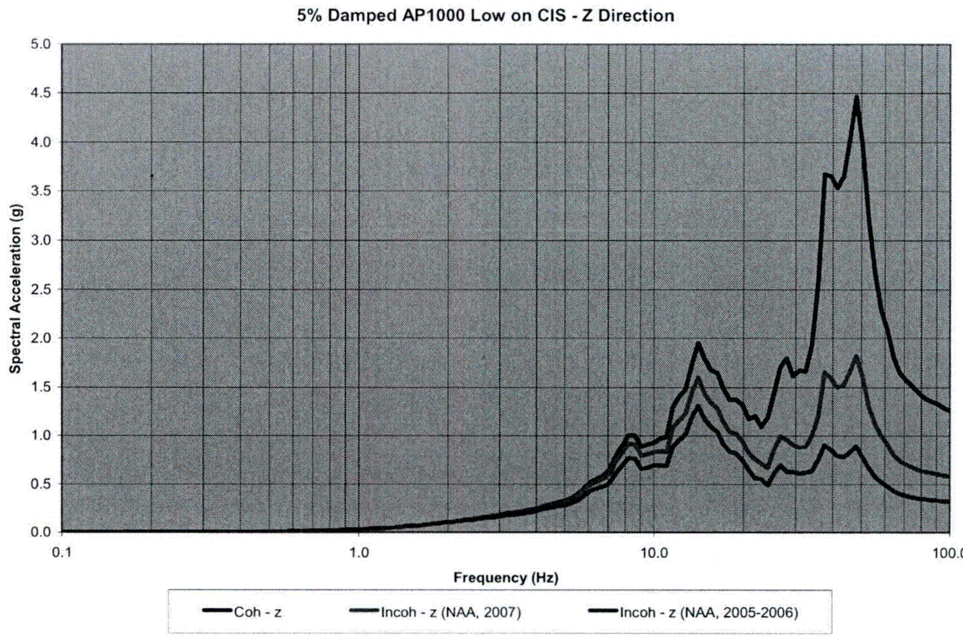


Figure 35
Low on CIS Response Spectra – Z Direction –SSI Coherent, SSI Incoherent NAA2005-2006, SSI Incoherent NAA2007 (Node 535)

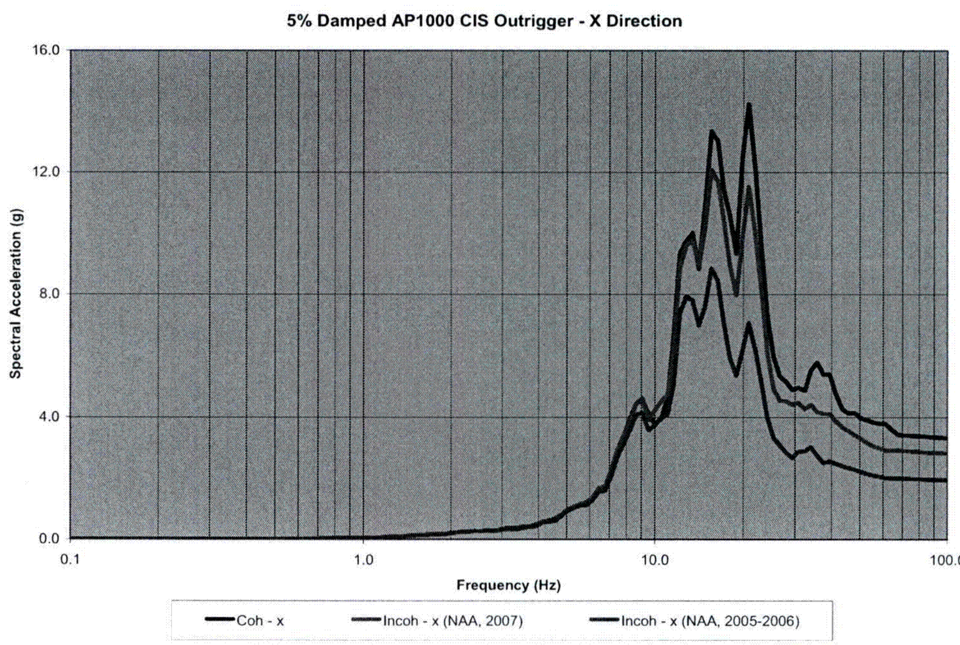


Figure 36
CIS Outrigger Response Spectra – X Direction – SSI Coherent, SSI Incoherent NAA2005-2006, SSI Incoherent NAA2007 (Node 538out)

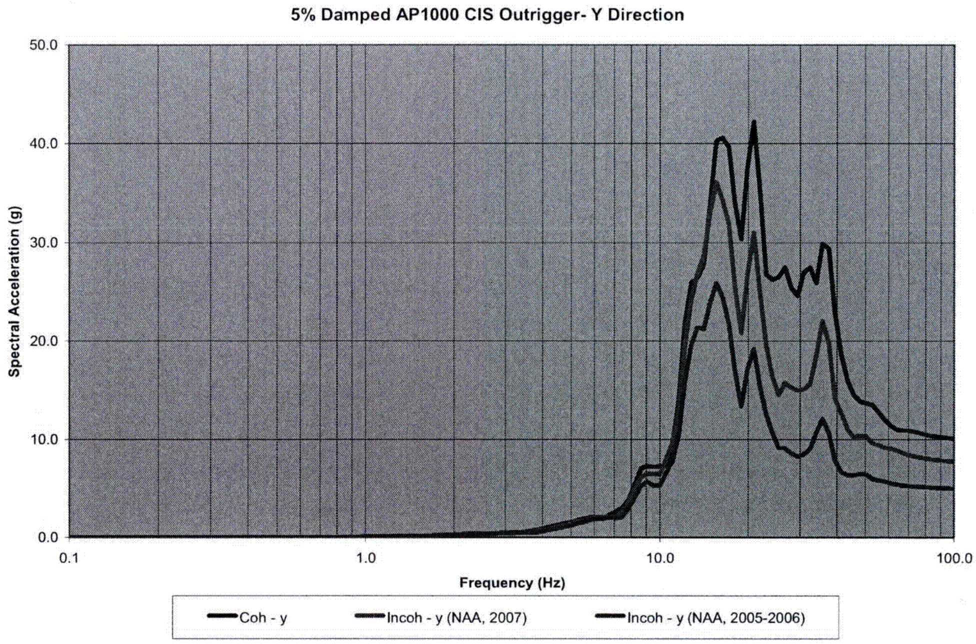


Figure 37
CIS Outrigger Response Spectra – Y Direction – SSI Coherent, SSI Incoherent NAA2005-2006, SSI Incoherent NAA2007 (Node 538out)

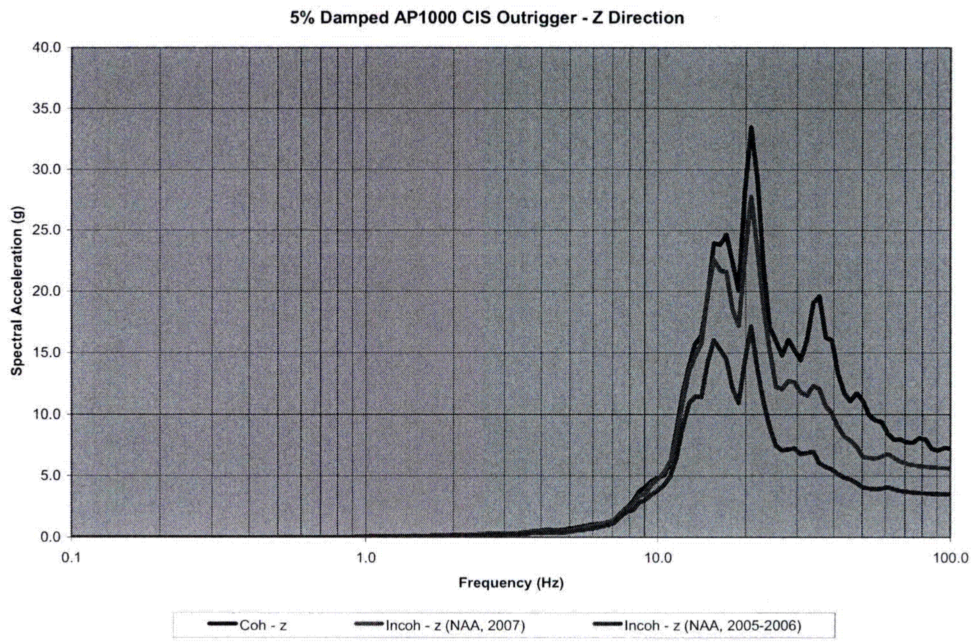


Figure 38
CIS Outrigger Response Spectra – Z Direction – SSI Coherent, SSI Incoherent NAA2005-2006, SSI Incoherent NAA2007 (Node 538out)

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