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GENERIC INPUT FOR STANDARD SEISMIC DESIGN OF NUCLEAR POWER PLANTS

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ABSTRACT

This paper presents the development of a set of Certified Design Response Spectra (CSDRS) for seismic loading and generic profiles for standard design of Nuclear Power Plants (NPP) that provide a realistic representation of seismological and geotechnical conditions existing at a wide range of NPP sites within the contiguous US. The results of soil-structure interaction (SSI) analyses of a typical NPP building for these generic site conditions presented herein illustrate how the different types of conditions existing at candidate sites within contiguous US can impact the NPP standard designs. Another set of SSI analyses of the NPP building is performed for baseline comparisons of the same generic profiles using instead a single RG 1.60 CSDRS as seismic loading. The comparison of results obtained from the two sets of SSI analyses serves to illustrate the benefit of performing standard design with multiple CSDRS. The use of multiple CSDRS ensures NPP standard designs are applicable for a wide range of candidate sites and helps eliminate excessive conservatism in the standard design of structures and stability evaluations that alternatively would be introduced by the use of a single broadband CSDRS.

INTRODUCTION

The objective of this study is to research approaches for standard design of NPP structures, equipment and components that are safe, economical and applicable for a wide range of potential candidate sites. The standard seismic design is based on seismic response SSI analyses for a set of generic dynamic subgrade properties using input control motions compatible to CSDRS defining the horizontal and vertical components of the standard design ground motion. The objective of these SSI analyses is to provide responses that envelope the seismic responses of NPP structures at a majority of candidate sites.

CSDRS envelope the Ground Motion Response Spectra (GMRS) at the majority of NPP sites to ensure a wide applicability of the standard design. The generic profiles provide a realistic representation of the geotechnical conditions existing at candidate sites for construction of NPPs.

GMRS that define the design amplitude and frequency content of the ground motion at a specific site are obtained from a probabilistic seismic hazard analysis using appropriate ground motion prediction equations and site amplification functions. Site response analyses of soil profiles comprised of layers of soil and rock over the geological basement rock provide the site amplification function and the dynamic properties of the site materials that are strain compatible to the ground motion. The effects of non-linearity of the site materials are addressed by using strain compatible rock/soil dynamic properties.

CSDRS AND GENERIC SITE PROFILES

Three sets of CSDRS together with matching seven generic profiles of dynamic soil/rock properties serve as input for the nine SSI analyses listed in Table 1 that provide the basis for the standard seismic design of NPPs. Figure 1 compares the three sets of horizontal and vertical CSDRS for firm, median and hard site conditions with the RG 1.60 ground motion spectra anchored to a Peak Ground

Acceleration (PGA) of 0.3g. Figure 2 presents the S-wave velocity (V_S), P-wave velocity (V_S) and damping of the seven generic profiles. These dynamic soil/rock properties are compatible to the strains generated by the seismic ground motions which spectra are enveloped by corresponding CSDRS.

The three sets of CSDRS accommodate a wide range of sites with low-frequency amplification (deep soft profiles) and high-frequency amplification (shallow soft and stiff profiles) as well as small and large magnitude contributing sources. The multiple CSDRS also accommodate the differences in spectral shape between Western United States (WUS) and Central and Eastern United States (CEUS) reference rock motions. The SSI responses obtained from the nine sets of SSI analyses listed in Table 1 envelope the responses of NPP structures at the majority of sites within the contiguous US.

A value of 0.3g is used for the CSDRS PGA based on a review of publicly available GMRS for NPPs and other nuclear facilities sites. This PGA value appropriately reflects the upper range in GMRS for CEUS sites and is representative of the overall average hazard for WUS sites. CSDRS anchored at 0.3 g PGA will cover the vast majority of CEUS sites but it can be more restrictive for WUS potential site locations, particularly in California or near active large earthquake sources.

The CSDRS are developed as multiple envelopes of median spectra computed using site amplification functions from equivalent-linear site response analyses of a suite of profiles listed in Table 2 that range in stiffness from soft soil to hard rock and profile depths to basement material from 25 ft to 2,000 ft. These profiles of small strain dynamic properties are developed from a database of measured dynamic properties of subsurface materials at CEUS and WUS sites by grouping and averaging the properties of sites with similar velocities or surficial geology. EPRI shear modulus reduction and hysteretic damping curves are used to address the non-linearity of the soft rock and soil. The same suite of profiles and nonlinear dynamic soil properties are used to reflect conditions of CEUS and WUS sites because the geologic processes for these regions are generally equivalent. The differences in ground motions between WUS and CEUS are assumed to be due to differences in basement material, crustal wave propagation, and seismic source processes. Each profile is truncated with hard basement rock with a V_S=2.83 km/sec for CUES and V_S=1 km/sec for WUS.

Control motions for the site response analyses consist of soft rock spectra for WUS and hard rock spectra for CEUS as illustrated in NUREG/CR-6728 with **M** 6.5 spectral shape reflective of a single-corner source model and average soil loading levels at both CEUS and WUS sites. Eleven loading levels with a range of geological rock basement peak acceleration from 0.01g to 1.50g are considered for each profile in Table 2 to cover a wide range of loading levels and accommodate nonlinear soil response. To address variations in dynamic soil properties across potential sites, 30 random profiles and soil degradation curves are generated for each profile and depth bin in Table 1. Site response analyses of these 30 realizations provide median spectra and corresponding strain compatible properties.

Based on a visual examination of the suites of median spectra developed for each profile in Table 2 for WUS and CEUS conditions, three sets of CSDRS in Figure 1 are selected for standard design that cover a reasonable range in site properties while accommodating both WUS and CEUS conditions. Seven site profiles are selected for the standard design SSI analysis from the median strain compatible profiles. Three profiles are matched to each set of CSDRS based on the threefold judgment criteria: (1) median spectrum should approach but not exceed the respective CSDRS (firm, medium, or hard) over as wide a structural frequency range as practical for a single earthquake; (2) the median spectra for each of the three site conditions should cover as much of the respective CSDRS as practical; (3) there should be as wide a range in profile stiffness and depths as practical.

STANDARD DESIGN SSI ANALYSIS

Nine frequency domain SSI analyses are performed on a model of a typical NPP building for the combinations of generic soil profiles and CSDRS listed in Table 1. A set of SSI analyses are also performed for the seven generic profiles using input ground motion compatible to the RG 1.60 spectra. Figure 1 presents with dashed lines the 5% damped acceleration response spectra (ARS) of the input control motion acceleration time histories compatible to the CSDRS and RG 1.60 spectra. The responses due to each of the three components of the earthquake are calculated separately and then combined using the Square Root of Sum of Squares (SRSS) method.

The SSI analyses are performed on a structural model of the NPP building (Short et al. 2007) that consists of three lumped mass stick models (LMSMs) representing the dynamic properties of the Coupled Auxiliary and Shield Building (ASB), the Steel Containment Vessel (SCV), and the Containment Internal Structure (CIS). These three LMSMs are rigidly connected to a 15 ft thick square shaped basemat with 150 ft footprint dimension. Table 3 provides the weight, height and the natural frequencies of vibrations of the structures. The frequency domain SSI analyses are performed using the ACS SASSI computer program. The cut-off frequency for the SSI analyses for RG 1.60, CSDRS Firm, CSDRS Medium compatible input ground motions is 50 Hz. The CSDRS Hard SSI analyses use a cut-off frequency of 70 Hz to better capture the high frequency content of the input control motion.

Tables 4 and 5 provide the results from the two sets of SSI analyses for equivalent quasi-static accelerations representing the maximum seismic reactions from the structures, the basemat and the whole building normalized with respect to the weight. The reactions that are transferred from the structures to the basemat are calculated directly from maximum beam force results. To normalize, these reactions are then divided by the total weight of the building minus the weight of the basemat to obtain the presented structural equivalent acceleration values that are indicators of the global seismic response of the NPP structures for different generic conditions considered. The presented values of basemat quasi-static accelerations are obtained from SSI analyses results for maximum acceleration at the center of the basemat. The maximum basemat inertia forces are obtained by multiplying these basemat accelerations by the weight of the foundation. The sum of the basemat inertia force and the structural reactions provides the total seismic reactions at the base of the building. The products between these base reactions and the weight of the whole building provide the values for total equivalent quasi-static accelerations presented in the last three rows of Tables 4 and 5. The total equivalent accelerations provide a basis for assessing how the different generic conditions affect the stability of the building.

Shear and axial force diagrams are computed for each of the NPP structures using the SSI analyses results for stick elements internal forces. Figure 3 presents the shear force and axial force diagrams obtained from each of the nine SSI analyses listed in Table 1. These shear and axial force diagrams are compared with the envelope of the results obtained from the SSI analyses of generic profiles with RG 1.60 CSDRS to illustrate how the use of multiple CSDRS affects the NPP structural design.

In order to evaluate the importance of the different generic conditions on the generic seismic design of equipment and components, 5% damped ARS are calculated for the response at the top of the common basemat and the top of ASB, SCV and CIS structures. The ARS results presented in Figure 4 show how the different generic conditions listed in Table 1 affect the ISRS for the response at the top of the SCV structure. Figure 4 presents the ARS at these four locations representing the envelope of responses obtained from the two sets of SSI analyses. These ARS comparisons illustrate how the standard design of equipment and components is affected by the use of multiple versus a single RG 1.60 CSDRS.

CONCLUSIONS

The results obtained form the SSI analyses of generic sites with multiple CSDRS listed in Table 1 indicate that SSI resonance and the reduction of geometric damping due to seismic wave reflections at shallow sites can significantly amplify the overall seismic response. In Table 4, these amplifications are observed for sites with design ground motions with medium and lower frequency content (CSDRS Medium and CSDRS Firm) that possess significant energy content in the frequencies corresponding to the first natural frequencies of the heavy ASB structure. These generic site conditions are critical for the stability of the building and govern the design of the flexible ASB and SCV structures as shown in Figure 3. The ARS results presented in Figure 4 show that the peak spectral responses are obtained from the SSI analyses of shallow sites. The softer sites with lower frequency content CSDRS Firm define the envelope standard design ARS at low frequencies and can govern the standard design of flexible subsystems and components. The standard design of equipment and components at the mid frequency range is governed by soil and rock sites with the CSDRS Medium type of design ground motion.

Table 4 shows that overall response of NPP building at CEUS sites characterized with high frequency content ground motion (CSDRS Hard) is small due to the low energy content of the input motion at frequencies corresponding to the first natural frequency of the flexible and heavy ASB structure. Figures 3 and 4 indicate that CEUS sites with high frequency design ground motion can govern the design of the stiffer structures such as the CIS and/or high frequency sensitive equipment.

The comparison of the SSI analyses results in Tables 4 and 5 show that the use of multiple CSDRS does not penalize the standard design as does a single broad-band CSDRS by considering seismic loading for deep and shallow sites or large and small magnitude earthquakes simultaneously. By reducing the excessive conservatism in the calculations of the seismic base reactions, the use of multiple CSDRS appropriately demonstrates foundation stability and reduces foundation bearing pressure demands in addition to reducing demands for structural design. The SSI analyses with multiple CSDRS provide more realistic representation of the seismic response at different sites that as shown in Figure 3, can yield more economical design of flexible structures such as ASB. Figure 3 also indicates that standard design of the stiffer structures, SCV and CIS based on the single RG 1.60 CSDRS may not envelope responses at some WUS sites or CEUS rock sites with high frequency design ground motion (CSDRS Hard). As shown in Figure 5, the use of a single RG 1.60 CSDRS can result in standard design that may not envelope responses of equipment and components at frequencies higher than 10 Hz.

REFERENCES

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Short, S.A., G.S. Hardy, K.L. Merz, and J.J. Johnson (2007). Validation of CLASSI and SASSI to Treat Seismic Wave Incoherence in SSI Analysis of Nuclear Power Plant Structures, Electric Power Research Institute, Palo Alto, CA and US Department of Energy, Germantown, MD, Report No. TR-1015111

Table 1: Matrix of Standard Design SSI analyses

Profile	$V_S(30)$* (m/sec)	Depth to Basement (ft)	Tectonic Region	Controlling CSDRS
180-2000	180	2,000	WUS	Firm
270-200	270	200	WUS	Firm
760-50	760	50	WUS	Firm
400-1000	400	1,000	CEUS	Median
760-50	760	50	WUS	Median
900-25	900	25	WUS	Median
760-200	760	200	CEUS	Hard
900-25	900	25	WUS	Hard
2032-100	2032	100	CEUS	Hard

- represents average V_S in ft/s of top 30 m of soil

Table 2 Profiles for Site Response Analyses

V_S(30') Categories*	Depth Categories		Depth Category	Depth to Hard Rock (ft)
180	1 – 7		1	25 ± 10
270	1 – 7		2	50 ± 20
400	1 – 7		3	100 ± 40
560	1 – 6		4	200 ± 80
740	1 – 4		5	500 ± 200
900	1 – 3		6	1,000 ± 400
1,364	3		7	2,000 ± 800
2,032	3			

- represents average V_S in ft/s of top 30 m of soil

Table 3 Dynamic Properties of Structural Model

Structure	Height (ft)	Weight (kip)	Natural Frequencies of Vibration (Hz)		
			"H1" Horizontal	"H2" Horizontal	"V" Vertical
ASB	272	144,675	3.2	3.0	9.9
SCV	182	8,243	5.5; 9.5; 9.9	6.1	16.0
CIS	71	90,482	13.3; 20.1; 28.9	12.0; 14.9; 17.5	41.4
Basemat	15	50,618	Rigid		
Total	272	294,018	Equivalent Uniform Base Pressure 13 ksf		

Table 4 Normalized Seismic Reactions Results from Multiple CSDRS Analyses

	Direction	CSDRS Firm			CSDRS Medium			CSDRS Hard		
		180-2000	270-200	760-50	400-1000	760-50	900-25	760-200	900-25	2032-100
Structures	H1	0.32	0.34	0.40	0.34	**0.44**	0.39	0.30	0.27	0.27
	H2	0.36	0.37	**0.47**	0.35	0.44	0.41	0.30	0.27	0.28
	V	0.24	0.26	0.39	0.31	**0.40**	0.35	0.32	0.27	0.28
Basemat	H1	0.30	0.31	0.32	0.28	0.32	**0.33**	0.25	0.23	0.30
	H2	0.34	0.35	**0.39**	0.27	0.34	0.35	0.24	0.25	0.32
	V	0.23	0.25	0.31	0.31	0.34	0.31	0.28	0.25	**0.36**
Total	H1	0.32	0.33	0.39	0.33	**0.42**	0.38	0.29	0.27	0.28
	H2	0.35	0.36	**0.45**	0.33	0.42	0.40	0.29	0.27	0.29
	V	0.24	0.26	0.37	0.31	**0.39**	0.35	0.32	0.27	0.29

Table 5 Normalized Seismic Reactions Results from RG 1.60 Analyses

	Direction	RG 1.60 Spectra						
		180-2000	270-200	400-1000	760-50	760-200	900-25	2032-100
Structures	H1	0.33	0.39	0.45	0.45	0.45	**0.47**	0.42
	H2	0.36	0.38	0.48	0.56	**0.61**	0.50	0.42
	V	0.30	0.35	0.37	0.52	**0.55**	0.46	0.44
Basemat	H1	0.30	0.32	0.36	0.33	**0.37**	0.32	0.32
	H2	0.32	0.33	0.34	0.42	**0.44**	0.39	0.33
	V	0.26	0.31	0.35	0.44	**0.48**	0.39	0.33
Total	H1	0.30	0.37	0.44	0.43	0.43	**0.45**	0.41
	H2	0.32	0.37	0.46	0.54	**0.58**	0.48	0.40
	V	0.26	0.34	0.36	0.51	**0.54**	0.45	0.42

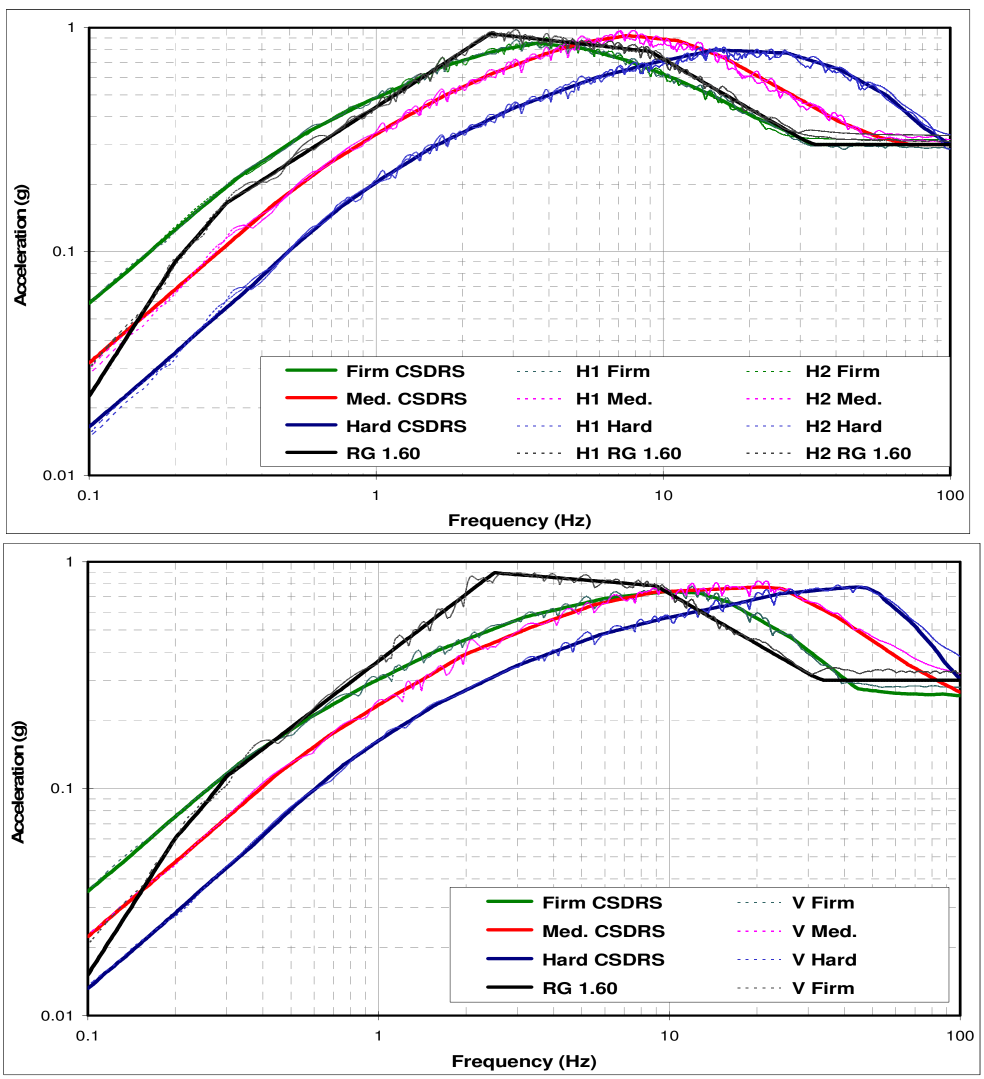


Figure 1. Standard Design Ground Motion 5% Damped ARS

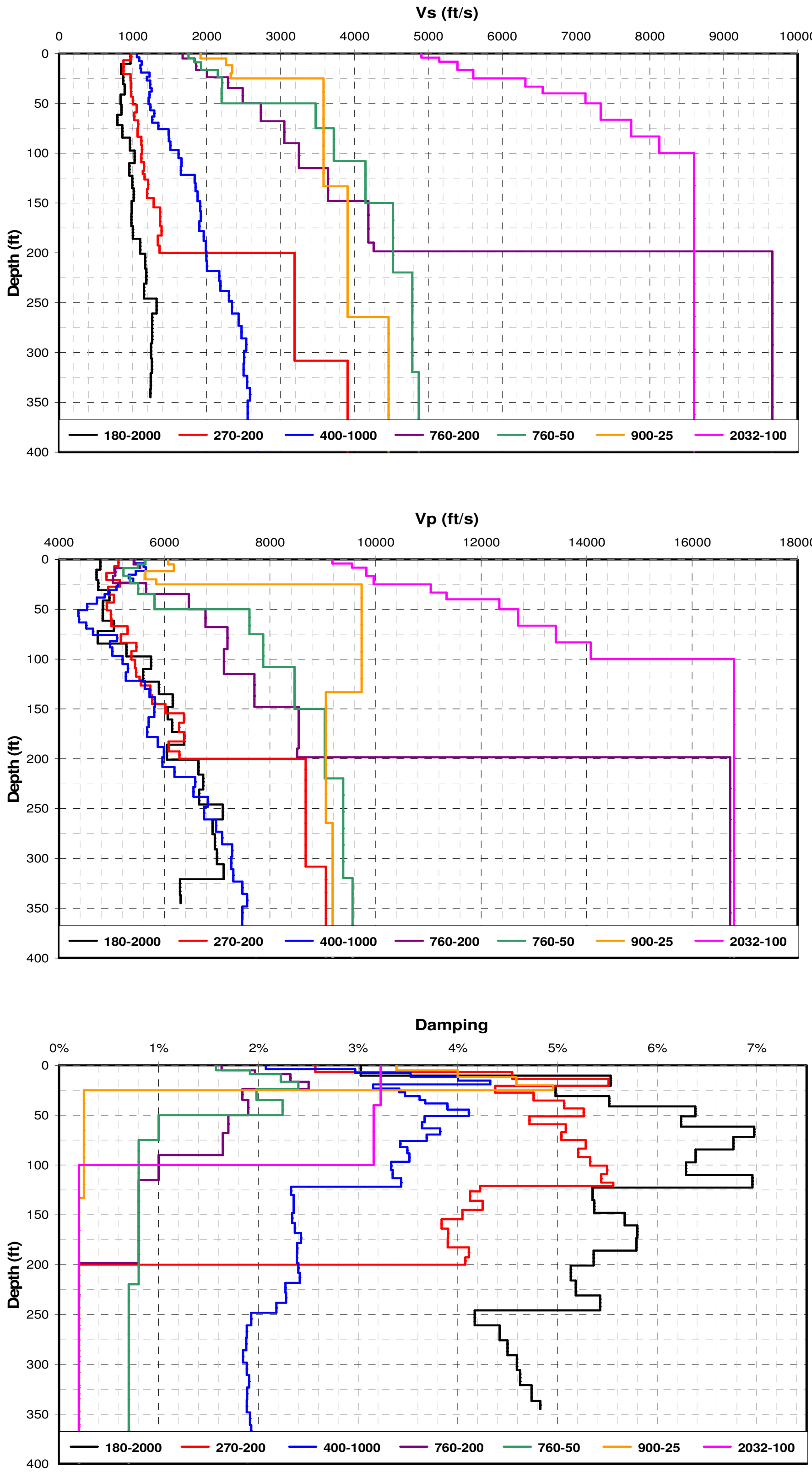


Figure 2. Generic Profiles of Strain Compatible Soil/Rock Properties

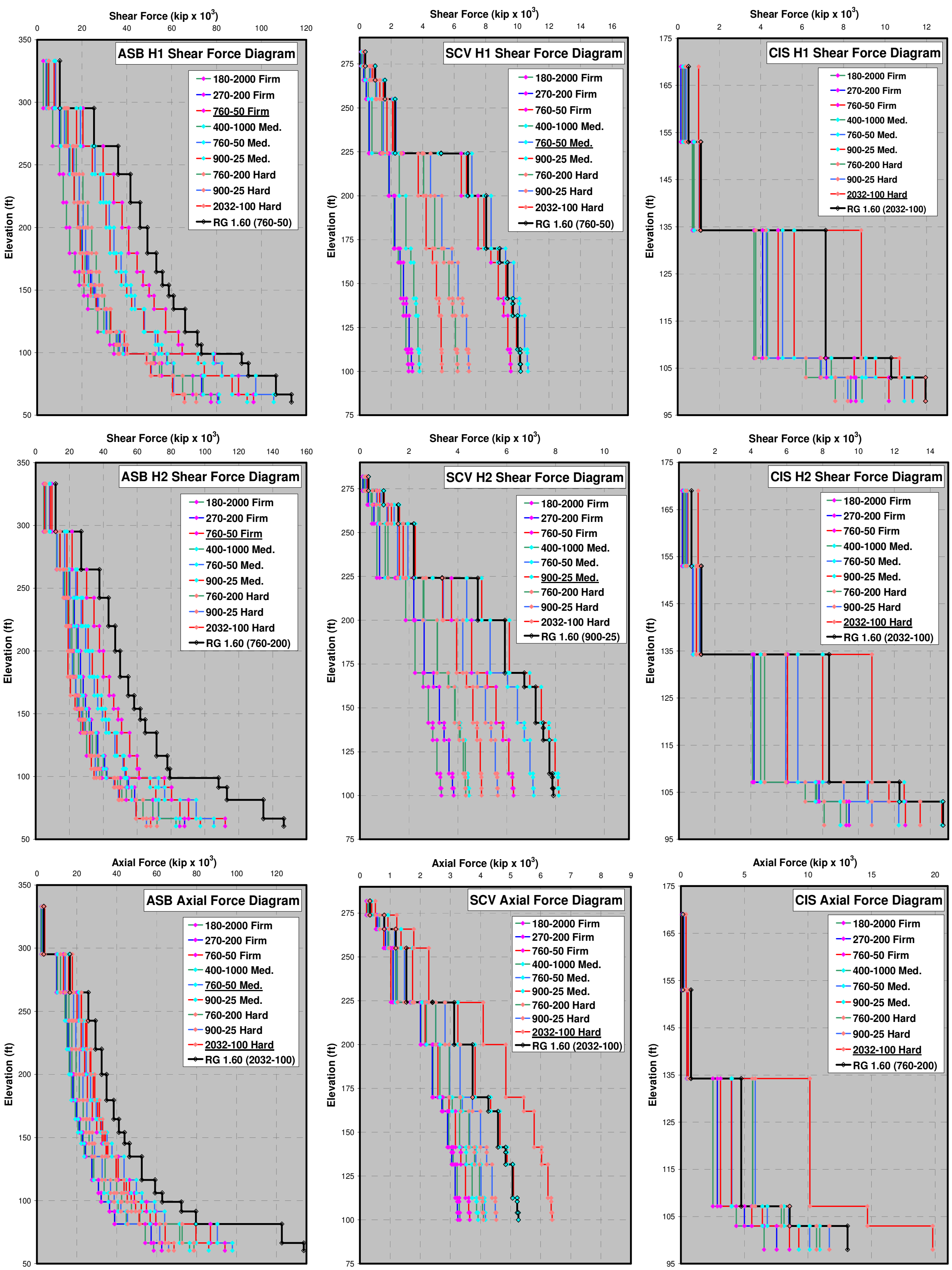
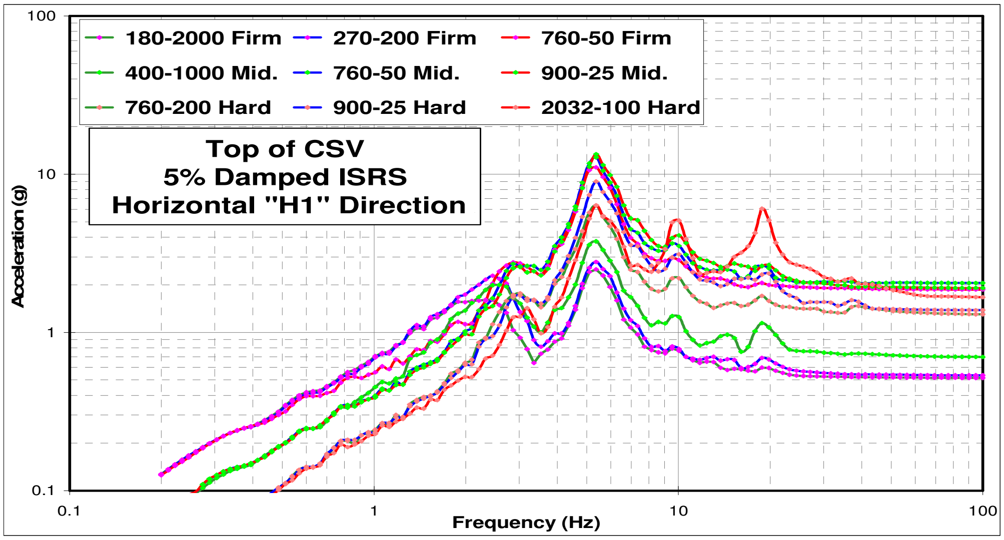
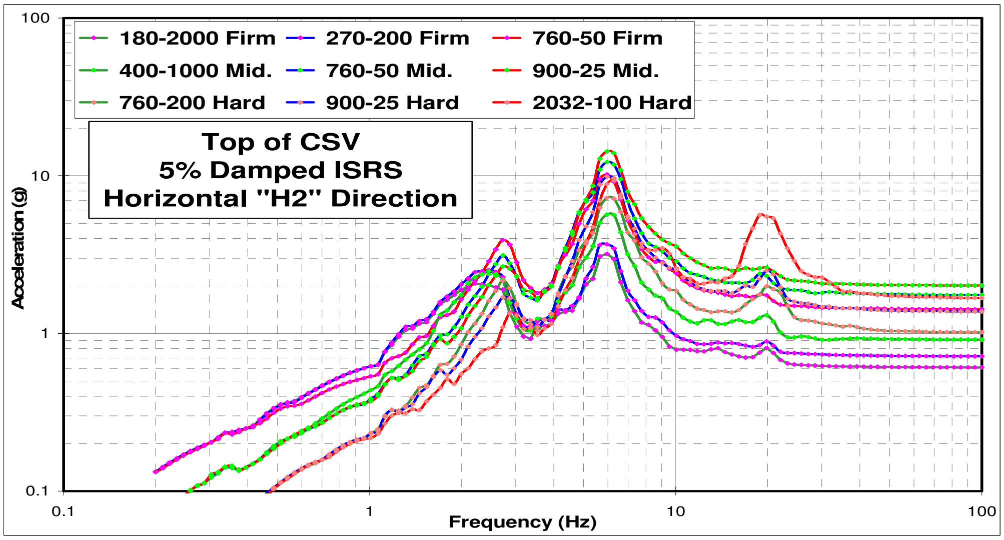


Figure 3. Comparison of Shear and Axial Force Diagrams





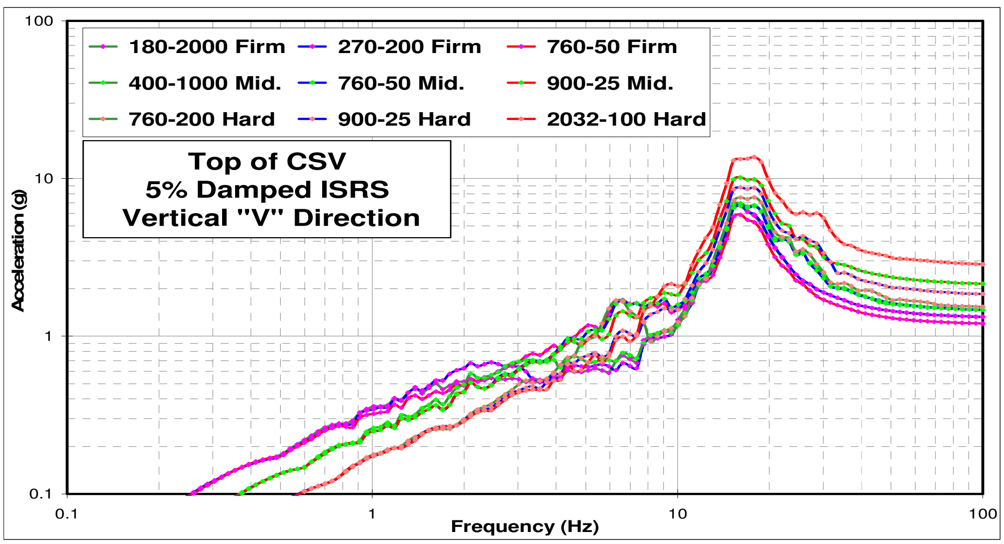


Figure 4. Top of CSV ISRS Results for Different Generic Sites and CSDRS

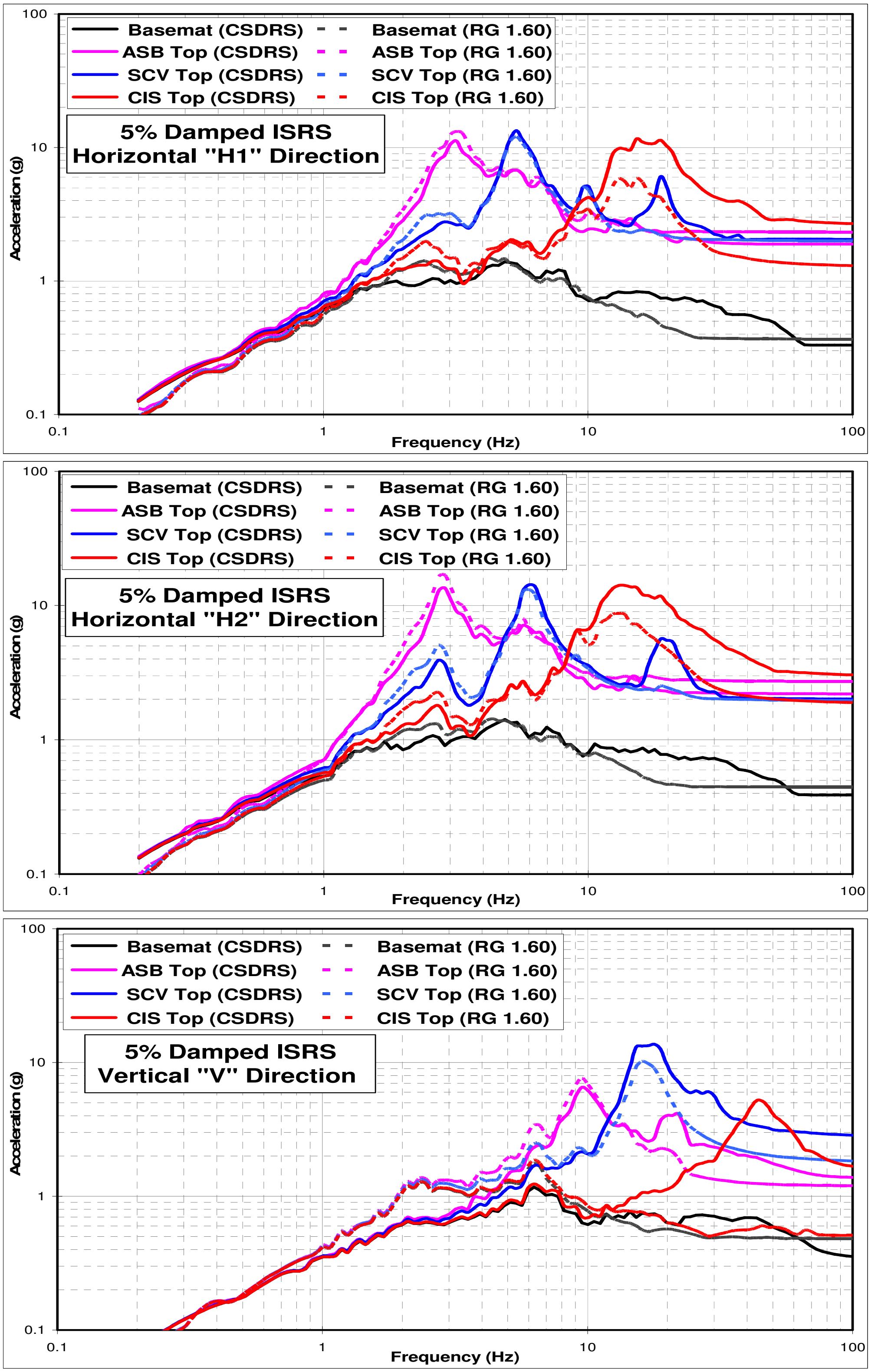


Figure 5. Comparison of ISRS Obtained from Multiple CSDRS and RG 1.60 Spectra