Transactions, SMiRT-25
Charlotte, NC, USA, August 4-9, 2019
Division IV

DESIGN RESPONSE SPECTRA FOR SEISMIC DESIGN OF NUCLEAR POWER PLANT STRUCTURES IN STANDARD DESIGN APPLICATIONS FOR NEW REACTORS

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ABSTRACT

This paper presents the results of an investigation of the response spectra associated with recorded ground motions that have occurred worldwide since the development of the Regulatory Guide (RG) 1.60 response spectra. The paper compares the response spectra for the newer ground motions with the RG 1.60 horizontal response spectrum to evaluate their consistency with the RG 1.60 spectrum shape. To perform the comparisons, statistical studies at each frequency of interest are performed for ensembles of response spectra grouped by earthquake magnitude bins. The ground motion records are obtained from the Pacific Earthquake Engineering Research (PEER) ground motion database. Prior to use with the response spectra for the newer recorded ground motions, the statistical process is verified with the earthquake records that form the basis for the development of the RG 1.60 spectra [Newmark, Blume, and Kapur (1973)]. Based on this investigation, preliminary recommendations for spectral shape updates are provided and potential next steps for the investigation are discussed.

INTRODUCTION

The NRC staff has used the 1973 version of RG 1.60 spectra (Figure 1) for numerous siting and licensing activities since its initial publication and it has also been used effectively by both domestic and international stakeholders. More recently, the certified seismic design response spectra (CSDRS) for several new reactor design certification applications are derived from RG 1.60 spectra by modifying the control points to broaden the spectra in the higher frequency range. Many earthquake records have become available since the development of RG 1.60. This paper describes preliminary statistical studies performed on the response spectra associated with a larger sample of recorded ground motions than that considered in the studies performed for the development of the RG 1.60 response spectra.

SUMMARY OF RG 1.60 RESPONSE SPECTRA DEVELOPMENT

The RG 1.60 response spectra was developed based on studies involving independent calculations of response spectra for a number of earthquakes, and then the processing of those results by statistical methods [Newmark, Blume, and Kapur (1973)]. Specifically, Blume's study used the two horizontal components of ground motion for 16 earthquakes and one horizontal component for an additional earthquake resulting in a total of 33 earthquake records. Newmark's study used the three components of ground motion for 14 earthquakes. Generally, the statistical processing involved calculations, over the entire frequency range, of the mean and standard deviation of response spectrum values scaled or normalized to some predetermined parameter. In Blume's study, all comparisons were based on values normalized to a constant maximum ground acceleration, with primary consideration given to the high and intermediate range of frequencies. In Newmark's study, the normalizations were made to maximum ground acceleration, maximum ground velocity, or maximum ground displacement over the entire range for frequencies, with primary consideration given to the normalization relative to maximum velocity for intermediate frequencies, and relative to maximum acceleration for higher frequencies. These studies found that the distribution function for the normalized spectral values or for the amplification factors relative to the maximum ground motion can be characterized as either a normal or a log-normal probability distribution.

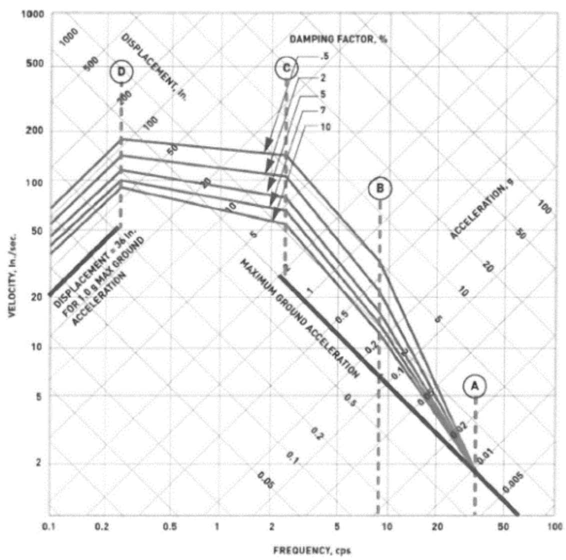

Figure 1. Horizontal Design Response Spectra Scaled to 1g Horizontal Ground Acceleration

VERIFICATION OF STATISTICAL PROCESS

Prior to performing statistical studies on the response spectra for the newer recorded ground motions, the statistical process was verified by implementing the process on the same earthquake records that form the basis for the development of RG 1.60 spectra [Newmark, Blume, and Kapur (1973)]. The verification consisted of normalizing the 5% damped response spectrum for the horizontal components of each earthquake record to its respective PGA and using either a log-normal or normal distribution to develop the 84th percentile spectral shape corresponding to the records used in the Blume and Newmark studies, respectively. Figure 2 shows a comparison between the log-normal and normal 84th percentile spectral shapes resulting from this verification compared to the RG 1.60 horizontal response spectrum. The authors note that the normalization used in this verification is different than the one implemented in by Newmark (see discussion under the Summary of RG 1.60 Response Spectra Development) and is more consistent with that implemented by Blume. Therefore, a log-normal distribution is used, consistent with Blume's study.

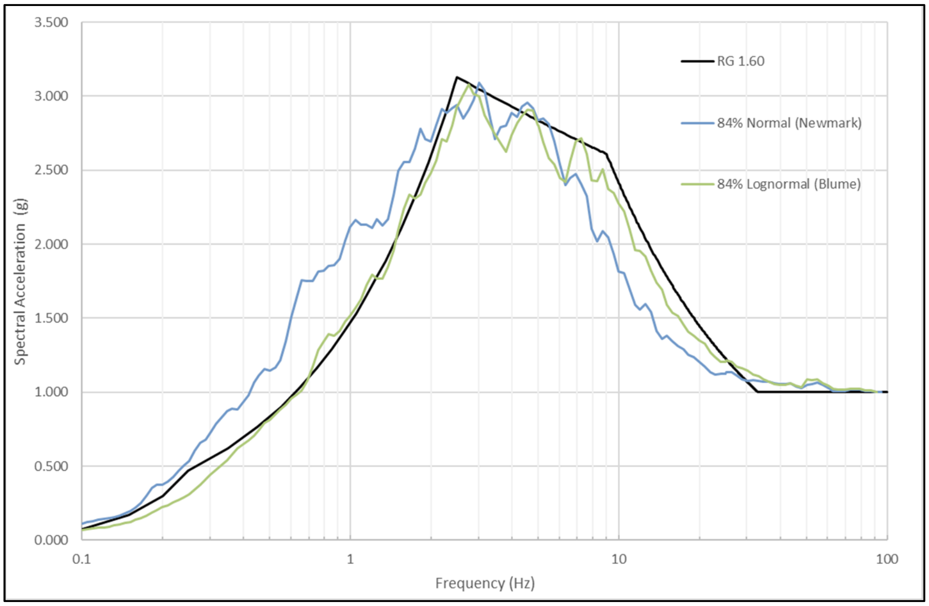

Figure 2. Comparison of 5% damped log-normal and normal spectral shapes with RG 1.60 horizontal response spectrum

DISCUSSION OF PRESENT STUDY

This study reviewed the response spectra associated with a set of recorded ground motions that have occurred in the US and other countries since the development of the RG 1.60 response spectra. Specifically, this study reviewed the 5% damped response spectra for the two horizontal components of ground motion from 150 ground motion records adding up to a total of 300 ground motion records. The response spectra were calculated at 111 frequencies over a frequency range of 0.05 Hz to 100 Hz. The ground motion records were randomly selected from the records available in the PEER ground motion database, NGA West-2 Section for shallow crustal earthquakes in active tectonic regions. The selection was made by using the RANDBETWEEN function in Excel to randomly select 50 earthquake records from each of three magnitude bins considered; namely, Magnitude 5 to Magnitude 6 (M5 to M6), Magnitude 6 to Magnitude 7 (M6 to M7), and greater than Magnitude 7 (> M7). Tables 1 through 3 show the list of the ground motion records for each bin. The PGA for the selected ground motion records ranged from 6.71E-5 g to 1.01 g. Subsequently, each response spectrum was normalized to its PGA. The mean and standard deviation at each of the 111 response spectra frequencies were used with a log-normal distribution to develop the mean + one standard deviation (84^{th} percentile) spectral shape.

Table 1: List of Earthquake Records for Magnitude 5 to Magnitude 6 Bin

M5 to M6				
RSN	**Earthquake Name**	**Year**	**Station Name**	**Magnitude**
204	Imperial Valley-07	1979	El Centro Array #6	5.01
206	Imperial Valley-07	1979	El Centro Array #8	5.01
242	Mammoth Lakes-04	1980	Long Valley Dam (L Abut)	5.7
309	Taiwan SMART1(5)	1981	SMART1 M01	5.9
392	Coalinga-03	1983	Coalinga-14th & Elm (Old CHP)	5.38
489	Taiwan SMART1(33)	1985	SMART1 M01	5.8
543	Chalfant Valley-01	1986	Benton	5.77

545	Chalfant Valley-01	1986	Bishop - Paradise Lodge	5.77
647	Whittier Narrows-01	1987	LB - Recreation Park	5.99
654	Whittier Narrows-01	1987	Lawndale - Osage Ave	5.99
679	Whittier Narrows-01	1987	Pasadena - CIT Keck Lab	5.99
1649	Sierra Madre	1991	Vasquez Rocks Park	5.61
1689	Northridge-05	1994	Pacoima Kagel Canyon	5.13
1720	Northridge-06	1994	Mill Creek, Angeles Nat For	5.28
3779	Northridge-06	1994	Glendale - Las Palmas	5.28
1132	Kozani, Greece-03	1995	Grevena	5.3
1749	Northwest China-01	1997	Xiker	5.9
4357	Umbria Marche (aftershock 3), Italy	1997	Nocera Umbra-Biscontini	5.3
2175	Chi-Chi, Taiwan-02	1999	CHY047	5.9
2294	Chi-Chi, Taiwan-02	1999	ILA061	5.9
2297	Chi-Chi, Taiwan-02	1999	ILA064	5.9
2301	Chi-Chi, Taiwan-02	1999	KAU010	5.9
2307	Chi-Chi, Taiwan-02	1999	KAU085	5.9
2317	Chi-Chi, Taiwan-02	1999	TAP021	5.9
2340	Chi-Chi, Taiwan-02	1999	TAP087	5.9
2346	Chi-Chi, Taiwan-02	1999	TAP098	5.9
2373	Chi-Chi, Taiwan-02	1999	TCU053	5.9
2411	Chi-Chi, Taiwan-02	1999	TCU111	5.9
2417	Chi-Chi, Taiwan-02	1999	TCU118	5.9
4429	Molise-01, Italy	2002	Norcia	5.7
4435	Molise-02, Italy	2002	Chieti	5.7
4438	Molise-02, Italy	2002	Sannicandro	5.7
8988	14151344	2005	Black Rock Canyon Campground 2	5.2
8995	14151344	2005	San Bernardino - FS No. 01	5.2
9031	14151344	2005	Joshua Ridge: China Lake	5.2
9097	14151344	2005	Shoshone	5.2
9099	14151344	2005	Banning, Hwy 243, San Jacinto	5.2
8711	40204628	2007	McLaughlin Mine, CA, USA	5.45
8743	40204628	2007	San Luis Hill Digital	5.45
20134	40204628	2007	Meloland, E Holton Rd.	5.45
8773	14383980	2008	Buzz Northern'S Place, Terwilliger, Ca, USA	5.39
8784	14383980	2008	Domenigoni Reservoir	5.39
8810	14383980	2008	Laurel Mtn Radio Fac	5.39
8854	14383980	2008	Summit Elementary School	5.39
8899	14383980	2008	Hesperia - 4th & Palm	5.39
4543	L'Aquila (aftershock 1), Italy	2009	Castelmauro	5.6
4573	L'Aquila (aftershock 2), Italy	2009	Petrella Tifernina	5.4
18031	14517500	2009	Table Mountain 2	5
18075	14519780	2009	Cottonwood Creek	5.19
18119	14519780	2009	Osito Audit: Castaic Lake Dam	5.19

Table 2: List of Earthquake Records for Magnitude 6 to Magnitude 7 Bin

M6 to M7				
RSN	**Earthquake Name**	**Year**	**Station Name**	**Magnitude**
3598	Taiwan SMART1(25)	1983	SMART1 O04	6.5
522	N. Palm Springs	1986	Indio	6.06
809	Loma Prieta	1989	UCSC	6.93
944	Northridge-01	1994	Anaheim - W Ball Rd	6.69
1652	Northridge-02	1994	Castaic - Old Ridge Route	6.05
2898	Chi-Chi, Taiwan-04	1999	TCU140	6.2
2932	Chi-Chi, Taiwan-04	1999	TTN046	6.2
2946	Chi-Chi, Taiwan-05	1999	CHY029	6.2
3015	Chi-Chi, Taiwan-05	1999	HWA028	6.2
3023	Chi-Chi, Taiwan-05	1999	HWA036	6.2
3117	Chi-Chi, Taiwan-05	1999	TAP021	6.2
3214	Chi-Chi, Taiwan-05	1999	TCU119	6.2
3254	Chi-Chi, Taiwan-05	1999	TTN046	6.2
3355	Chi-Chi, Taiwan-06	1999	HWA046	6.3
3380	Chi-Chi, Taiwan-06	1999	ILA030	6.3
3401	Chi-Chi, Taiwan-06	1999	KAU030	6.3
3480	Chi-Chi, Taiwan-06	1999	TCU086	6.3
3889	Tottori, Japan	2000	HRSH05	6.61
3946	Tottori, Japan	2000	SMN018	6.61
6176	Tottori, Japan	2000	FKIH07	6.61
6184	Tottori, Japan	2000	FKO010	6.61
6252	Tottori, Japan	2000	KOC005	6.61
6332	Tottori, Japan	2000	OIT016	6.61
6406	Tottori, Japan	2000	WKYH07	6.61
2060	Nenana Mountain, Alaska	2002	Anchorage - DOI Off. of Aircraft	6.7
2068	Nenana Mountain, Alaska	2002	Anchorage - K2-08	6.7
4180	Niigata, Japan	2004	GNMH07	6.63
6466	Niigata, Japan	2004	AKTH16	6.63
6480	Niigata, Japan	2004	CHB016	6.63
6489	Niigata, Japan	2004	CHBH04	6.63
6663	Niigata, Japan	2004	MYG008	6.63
6669	Niigata, Japan	2004	MYG016	6.63
6823	Niigata, Japan	2004	TYMH01	6.63
8444	Parkfield-02, CA	2004	Campbell; Westmont High Sch	6
8486	Parkfield-02, CA	2004	Hog Canyon	6
8451	Parkfield-02, CA	2004	Angel Island	6
4857	Chuetsu-oki	2007	Kamo Kouiti Town	6.8
5140	Chuetsu-oki	2007	IWT012	6.8
5194	Chuetsu-oki	2007	NGN002	6.8
5197	Chuetsu-oki	2007	NGN005	6.8

5233	Chuetsu-oki	2007	NGNH23	6.8
5253	Chuetsu-oki	2007	NIG007	6.8
5460	Iwate	2008	AKT005	6.9
5553	Iwate	2008	FKS012	6.9
5586	Iwate	2008	FKSH18	6.9
5666	Iwate	2008	MYG007	6.9
5719	Iwate	2008	NIGH11	6.9
5771	Iwate	2008	YMTH14	6.9
5752	Iwate	2008	YMT009	6.9
8076	Christchurch, New Zealand	2011	DSZ	6.2

Table 3: List of Earthquake Records for Magnitude 7 and Greater Bin

M7 and Greater				
RSN	**Earthquake Name**	**Year**	**Station Name**	**Magnitude**
579	Taiwan SMART1(45)	1986	SMART1 O04	7.3
1633	Manjil, Iran	1990	Abbar	7.37
845	Landers	1992	Calabasas - N Las Virg	7.28
3759	Landers	1992	Whitewater Trout Farm	7.28
1181	Chi-Chi, Taiwan	1999	CHY004	7.62
1195	Chi-Chi, Taiwan	1999	CHY026	7.62
1206	Chi-Chi, Taiwan	1999	CHY042	7.62
1235	Chi-Chi, Taiwan	1999	CHY087	7.62
1267	Chi-Chi, Taiwan	1999	HWA016	7.62
1281	Chi-Chi, Taiwan	1999	HWA032	7.62
1294	Chi-Chi, Taiwan	1999	HWA048	7.62
1321	Chi-Chi, Taiwan	1999	ILA021	7.62
1338	Chi-Chi, Taiwan	1999	ILA050	7.62
1340	Chi-Chi, Taiwan	1999	ILA052	7.62
1383	Chi-Chi, Taiwan	1999	KAU062	7.62
1419	Chi-Chi, Taiwan	1999	TAP017	7.62
1436	Chi-Chi, Taiwan	1999	TAP052	7.62
1469	Chi-Chi, Taiwan	1999	TCU011	7.62
1532	Chi-Chi, Taiwan	1999	TCU105	7.62
1549	Chi-Chi, Taiwan	1999	TCU129	7.62
1577	Chi-Chi, Taiwan	1999	TTN025	7.62
1584	Chi-Chi, Taiwan	1999	TTN036	7.62
1605	Duzce, Turkey	1999	Duzce	7.14
1805	Hector Mine	1999	Lake Hughes #1	7.13
1834	Hector Mine	1999	Sylmar - County Hospital Grounds	7.13
3810	Hector Mine	1999	Newport Beach - Balboa Island	7.13
3815	Hector Mine	1999	Riverside - Hole & La Sierra	7.13
2110	Denali, Alaska	2002	Fairbanks - Geophysic. Obs, CIGO	7.9
5825	El Mayor-Cucapah	2010	CERRO PRIETO GEOTHERMAL	7.2

5831	El Mayor-Cucapah	2010	EJIDO SALTILLO	7.2
5841	El Mayor-Cucapah	2010	Alpine Fire Station	7.2
5855	El Mayor-Cucapah	2010	San Diego - UCSD Hospital Grnds	7.2
5879	El Mayor-Cucapah	2010	San Jacinto - CDF Fire Station	7.2
5988	El Mayor-Cucapah	2010	Meloland, E Holton Rd.	7.2
5999	El Mayor-Cucapah	2010	San Bernardino - Fire Sta. #10	7.2
6006	El Mayor-Cucapah	2010	Idyllwild - Kenworthy Fire Sta.	7.2
6026	El Mayor-Cucapah	2010	Oceanside - Fire Station No. 1	7.2
6027	El Mayor-Cucapah	2010	Ocotillo Wells - Veh. Rec. Area	7.2
6040	El Mayor-Cucapah	2010	Saddleback	7.2
6047	El Mayor-Cucapah	2010	Serrano	7.2
6887	Darfield, New Zealand	2010	Christchurch Botanical Gardens	7
6920	Darfield, New Zealand	2010	KHZ	7
6935	Darfield, New Zealand	2010	MECS	7
6936	Darfield, New Zealand	2010	MISS	7
6951	Darfield, New Zealand	2010	POLS	7
6971	Darfield, New Zealand	2010	SPFS	7
6976	Darfield, New Zealand	2010	TRCS	7
8492	El Mayor-Cucapah	2010	Salton Sea Wildlife Refuge	7.2
8531	El Mayor-Cucapah	2010	Hector	7.2
8585	El Mayor-Cucapah	2010	Santa Barbara	7.2

DISCUSSION OF RESULTS

Figures 3, 4, and 5 compare the 5% damped RG 1.60 horizontal response spectrum with the 5% log-normal spectral shapes obtained for the M5 to M6, M6 to M7, and >M7 bins, respectively. Additionally, Figure 6 compares the 5% damped RG 1.60 horizontal response spectrum with the log-normal spectral shape for the ensemble of ground motion records across all magnitude bins. In general, these comparisons demonstrate a trend of increasing spectral acceleration content with increasing earthquake magnitude bin for frequencies lower than 2.5 Hz. This trend is consistent with the authors' expectations that as the earthquake magnitude increases, the rupture of the subgrade media increases thereby resulting in more a flexible system with dominant frequencies in low frequency ranges. These results suggest that the RG 1.60 response spectrum component could be enhanced in the lower than 2.5 Hz frequency rage. However, the authors recognize that while this study considered about 5 times the number of records considered in the Newmark, Blume, and Kapur studies, this observation is preliminary given the availability of additional thousands of ground motion records that could be considered in the investigation. Further, this investigation could benefit from consideration of ground motion records with dominant spectral acceleration content in the high frequency range, which would better inform recommendations for enhancements in both the very low and high frequency ranges, as necessary.

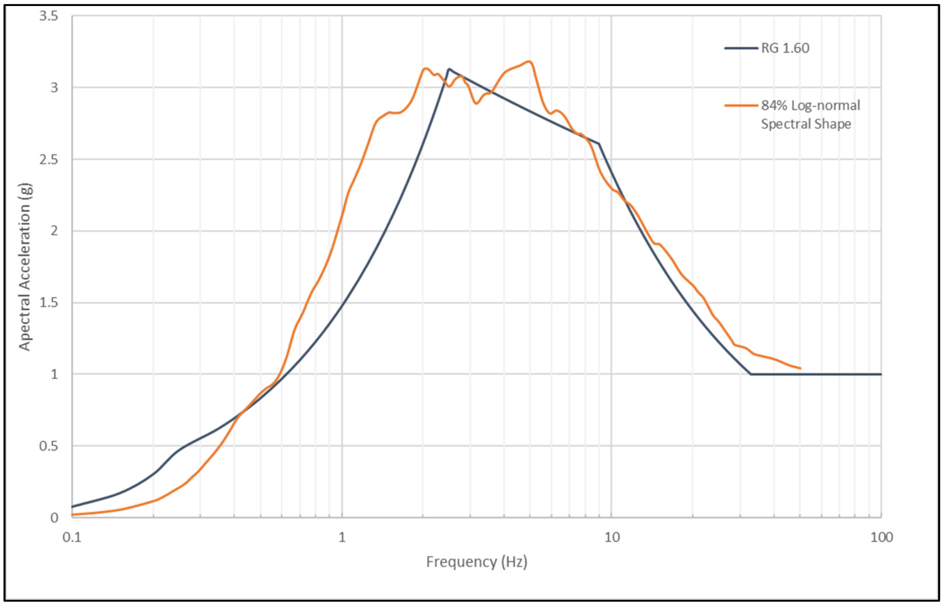

Figure 3. Comparison of 5% damped log-normal spectral shape for M5 to M6 Bin with RG 1.60 horizontal response spectrum

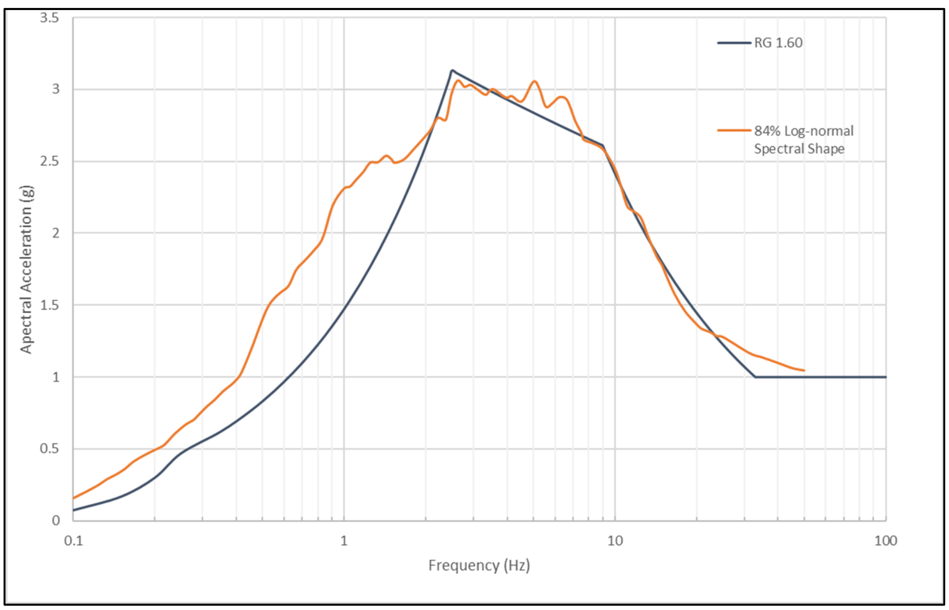

Figure 4. Comparison of 5% damped log-normal spectral shape for M6 to M7 Bin with RG 1.60 horizontal response spectrum

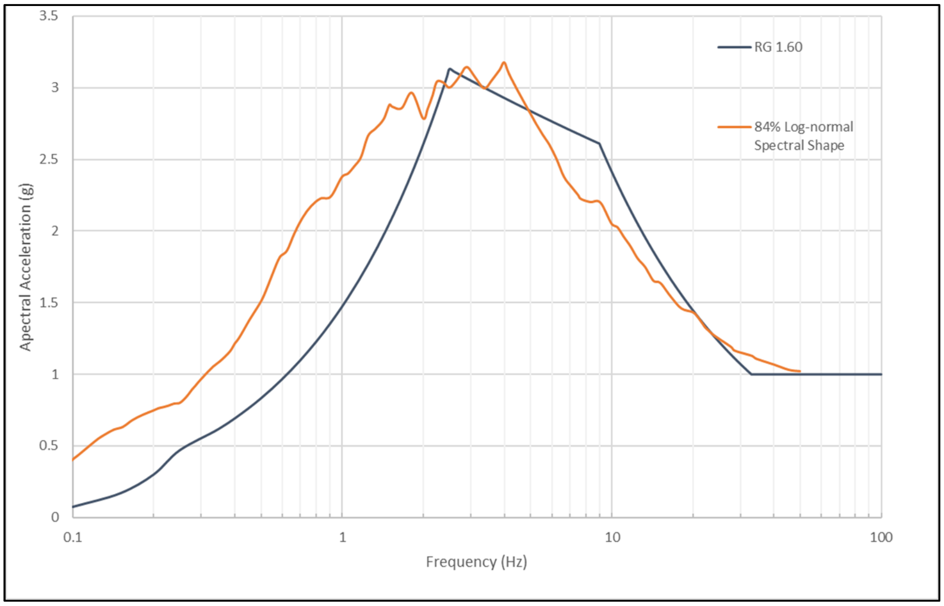

Figure 5. Comparison of 5% damped log-normal spectral shape for M7 and Greater Magnitude Bin with RG 1.60 horizontal response spectrum

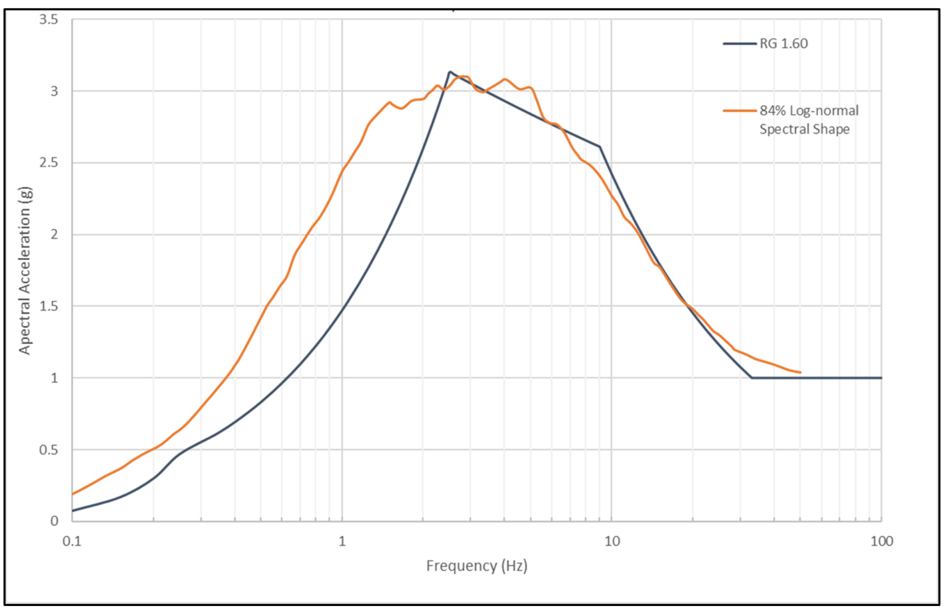

Figure 6. Comparison of 5% damped log-normal spectral shape for Ground Motion Records across all Magnitude Bins with RG 1.60 horizontal response spectrum

CONCLUSIONS

This paper described the investigation of response spectra associated with recorded ground motions that have occurred worldwide since development of the RG 1.60 response spectra. Statistical studies were performed on ensembles of response spectra based on earthquake magnitude bins to develop 84^{th} percentile log-normal spectral shapes. The results of this investigation suggest that the RG 1.60 horizontal response spectrum component could be enhanced in the lower than 2.5 Hz frequency rage. However, while this study considered about 5 times the number of records considered in the Newmark, Blume, and Kapur studies, this observation is preliminary given the availability of additional thousands of ground motion records that could be considered in the investigation.

Additionally, the study described in this paper could benefit from additional variables known to have specific impacts on the response spectra shape. For example, further steps in this investigation could consider ground motion records with dominant spectral acceleration content in the high frequency range. In this regard, further research should address the addition of records that have high frequency content; for example, those records existing in the NGA East Section of the PEER database for Central and Eastern North America. Moreover, this study could be expanded to address the vertical component of recorded ground motions and multiple response spectra damping levels for both the horizontal and vertical components of ground motion. Other variables that should be considered in additional studies are those recommended by Newmark, Blume, and Kapur, and include the consideration of spectral shape data grouped by PGA, by site-soil impedance, and by epicentral distance to the recording station. This additional research has the potential to contribute to the development of regional spectral shapes, which may be more appropriate for specific circumstances and use in the design of nuclear power plant structures in future applications for New Reactors.

DISCLAIMER

The findings and opinions expressed in this paper are those of the authors, and do not necessarily reflect the views of the US Nuclear Regulatory Commission.

REFERENCES

Newmark, N. M., John A. Blume, and Kanwar K. Kapur (November 1973). "*Seismic Design Spectra for Nuclear Power Plants*," Journal of The Power Division, ASCE, 287-303.

Pacific Earthquake Engineering Research Center (PEER) ground motion database, https://ngawest2.berkeley.edu/