Effect of Spectra Scaling on Site Specific Design Earthquake Characteristics Based on 1D Site Response Analysis

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SUMMARY
A parametric study was conducted to evaluate the effects of different strong motion scaling options to be used for preparing input acceleration time histories for 1D site response analyses. The first alternative is to use outcrop PGA from the hazard study to scale strong motion acceleration records that are compatible with the selected outcrop NEHRP hazard spectrum in addition to the hazard compatibility with respect to fault type, earthquake magnitude, source distance and site conditions of the recording station. The second alternative is to scale these selected records by an optimization routine to obtain the best fit mean acceleration spectra with respect to the outcrop NEHRP hazard spectra. The third option is modify the amplitude and frequency content of the selected strong motion records to have better outcrop NEHRP spectrum compatibility. The results of site response analysis using 22 hazard compatible strong motion records with different scaling options are compared for a site specific study based on 25 soil profiles.

Keywords: site response, design spectra, spectra scaling, input motion

1. INTRODUCTION

The purpose of a probabilistic site specific earthquake hazard analysis is to estimate peak ground acceleration and uniform hazard acceleration spectrum for performance levels of Collapse Prevention, Life Safety, and Immediate Occupancy that may correspond to exceedance levels of 50%, 10%, and 2% in 50 years or 72, 475 and 2475 year return periods. In the case of new engineering structures, it is preferable to adopt a probabilistic earthquake hazard assessment, however in evaluating possible response for the existing structures; deterministic approach may also be suitable. Independent of the methodology adopted for the earthquake hazard analyses, strong motion (SM) records are needed to conduct site response analyses and to estimate possible earthquake characteristics on the ground surface. It was demonstrated by Ansal and Tönük (2007) that if limited number of acceleration time histories (e.g. 3 records as specified in some earthquake codes) is used even with scaling to the same PGA amplitude for site response analysis, the results on the ground surface can be different for different sets of input acceleration records. One possible option to overcome this variability is to conduct site response analyses using large number of hazard compatible acceleration time histories and by adopting a probabilistic approach to estimate earthquake characteristics on the ground surface for design and vulnerability assessments.

Assessment of site-specific design earthquake characteristics may be conducted as composed of statistically independent two consecutive stages. The first stage involves the seismic hazard study to assess the design earthquake characteristics on rock outcrop for the selected performance levels. The second stage involves site response analysis to estimate design earthquake characteristics on the ground surface based on geotechnical and geological site conditions. A probabilistic approach may be adopted to estimate the overall exceedance probability for the design earthquake characteristics on the ground surface for the selected performance levels (Ansal et al. 2011).

The uncertainties arising from the source characteristics may be taken into account by using large number of seismic hazard compatible (fault mechanism, earthquake magnitude, and source distance) strong motion acceleration records for site response analyses. In using a selected set of strong motion records for site specific study, even though they may be recorded under similar tectonic conditions and were selected based on hazard compatibility with respect to the probable earthquake magnitude, fault type, source distance and site conditions at the recording station, it would still be necessary to scale them to have a better compatibility with the site specific earthquake hazard study. This scaling can be with respect to different earthquake parameters such as PGA, PGV, Arias Intensity and others without altering the frequency content (Ansal, et al., 2006, Tönük and Ansal, 2010).

The other alternative is to adopt uniform hazard spectra from the earthquake hazard study on rock outcrop for scaling strong motion records for site response analysis. Spectral scaling approaches include methods developed in the time domain (Abrahamson, 1992; Hancock et al., 2006) and in the frequency domain (Gasparini and Vanmarcke, 1976; Silva and Lee, 1987). Both approaches can be used to modify existing time-histories to match the design response spectrum. One important issue is not to modify significantly the basic time domain character of the recorded strong motion records. The scaling process would be more efficient if the overall shape of the acceleration spectrum of the selected strong motion record is not very different from the specified design acceleration spectrum and PGA scaling may be adopted first so that the spectrum is approximate at the same level of the target spectrum before initiating spectrum scaling. It was observed that time domain scaling gives better fits with respect to target spectrum.

One dimensional (1D) site response analysis were conducted using slightly modified version of Shake91 (Idriss and Sun, 1992) site response analysis code (Ansal, et al., 2009) to evaluate design earthquake characteristics with respect to exceedance levels of 10% and 2% in 50 years or return periods of 475 and 2475 years for a specific site where 25 soil borings were conducted.

A parametric study was carried out to evaluate the effects of different scaling options for input strong motion set used in 1D site response analyses. The first option is to use outcrop hazard PGA scaled set of strong motion records that are most compatible with the selected outcrop NEHRP hazard spectrum obtained from regional hazard study in addition to hazard compatibility with respect to fault type, earthquake magnitude, distance and average shear wave velocity of the recording station. The second option is to scale these selected hazard and spectra compatible records by an optimization routine to obtain the best fit for the mean acceleration spectra with respect to the outcrop NEHRP hazard spectrum. The third option is to modify the amplitude and frequency content of the input motion set to have better outcrop NEHRP hazard spectra compatibility using the available spectrum scaling methodologies (Abrahamson, 1992, 1993, Hancock et al., 2006).

2. SITE RESPONSE ANALYSIS

There are different options for the estimation of earthquake characteristics on the ground surface at the selected site to be used for engineering analyses. The simplest option is to use contemporary ground motion prediction relationships formulated in terms of site and source classifications (Abrahamson et. al., 2008) or to use empirical formulations such as amplification factors suggested by Borcherdt (1994) based on equivalent shear wave velocity. The more comprehensive approach is based on site response analyses using detailed site characterization. Taking into consideration possible differences in soil profiles even within relatively short distances and observations in previous earthquakes that indicated site conditions are important, and as demonstrated based on parametric studies (Ansal, et al., 2010), the use of empirical amplification factors may not yield results on the conservative side. Thus, it is preferable to adopt the comprehensive option for the assessment of site-specific ground motion characteristics.

Site characterizations at the selected site are based on 25 soil borings where shear wave velocity profiles for each boring were modelled by averaging the measured or calculated values for each soil layer. The variations of shear wave velocities with depth were determined from SPT blow counts using the empirical relationship proposed by Iyisan (1996) and based cross-hole, down-hole and MASW measurements conducted at the site.

2.1. Input acceleration time histories

As suggested by Bommer and Acevedo (2004) and Bommer et al., (2000), it would be preferable to use strong ground motion records for site response analysis and as observed by Ansal and Tonuk (2007) use of simulated acceleration records may yield overconservative resuls thus may be considered not very suitable in some cases.

Based on regional geological and hazard studies in the region, the investigated site may be affected from earthquakes that may occur in different fault zones basically with two different fault mechanisms; strike-slip and normal faulting. 11 pairs of acceleration time histories were selected using the PEER data base that are compatible with the outcrop NEHRP Hazard spectrum in addition to hazard compatibility with respect to probable magnitude (M=6.0-7.0), epicentre distance (R=5-20km) and fault mechanisms (strike slip, normal, and reverse) recorded on stiff site conditions with average shear wave velocities $V_{s30} \geq 546$m/s as input acceleration time histories. The purpose is to account for the variability arising from the differences in the source characteristics observed in the acceleration time histories. Special effort was spend using PEER database to select as much as possible strong motion records with similar acceleration spectra in comparison to target NEHRP hazard spectrum.

It is assumed that the selected strong motion records (Table 2.1) represent the characteristics of future possible earthquakes that may take place in the near vicinity of the investigated site since the records were obtained under similar tectonic conditions. Thus the effects of differences in the characteristics of probable earthquakes can be taken into account with respect to the required design level.

Table 2.1. Set of strong motion records (SM) with outcrop NEHRP spectra compatibility (PEER)

Earthquake	Station	Fault type	Date YMD	M_w	V_{s30} (m/s)	R_{epc} (km)	Components	PGA (g)
Gazli, USSR	Karakyr		1976-09-15	6.8	660	5.5	GAZ000	0.608
							GAZ090	0.718
Victoria, Mexico	Cerra Prieto	SS	1980-06-09	6.33	660	14.4	CPE045	0.621
							CPE315	0.587
Irpina	Sturno	N	1980-11-23	6.9	1000	10.8	A-STU000	0.251
							A-STU270	0.358
Nahanni, Canada	Site 1	RV	1985-12-23	6.8	660	9.6	S1010	0.978
							S1280	1.096
Nahanni, Canada	Site 2	RV	1985-12-23	6.8	660	4.9	S2240	0.489
							S2330	0.323
Northridge	Beverly Hills Mulhol	RV	1994-01-17	6.7	546	18.4	MU2035	0.617
							MU2125	0.444
Northridge	LA 00l	RV	1994-01-17	6.7	706	19.1	LA0000	0.261
							La0090	0.388
Northridge	Simi Valley Katherine Rd	RV	1994-01-17	6.7	557	13.4	KAT000	0.877
							KAT090	0.640
Loma Prieta	San Jose Santa Teresa Hills	RV-OBL	1989-10-18	6.9	672	14.7	SJTE225	0.275
							SJTE315	0.228
Loma Prieta	Gilroy Gavilan Coll.	RV-OBL	1989-10-18	6.9	730	10	GIL337	0.325
							GIL067	0.357
Morgan Hill	Gilroy Array #6	SS	1987-01-10	6.2	663	9.9	G06000	0.222
							G06090	0.292

3. INPUT MOTION SCALING

A parametric study was conducted to evaluate the effects of different input ground motion scaling options for 1D site response analyses. The first option which happens to be the most widely adopted and simpler is PGA scaling of the selected hazard compatible set of SM acceleration records (Ansal et al., 2006). The acceleration spectra of these PGA scaled strong motion records are shown in Fig.1 in comparison to the uniform outcrop hazard spectra for return periods of 2475 and 475 years. In this case the mean spectral accelerations of all PGA scaled strong motion records in general are less than the outcrop NEHRP spectral accelerations.

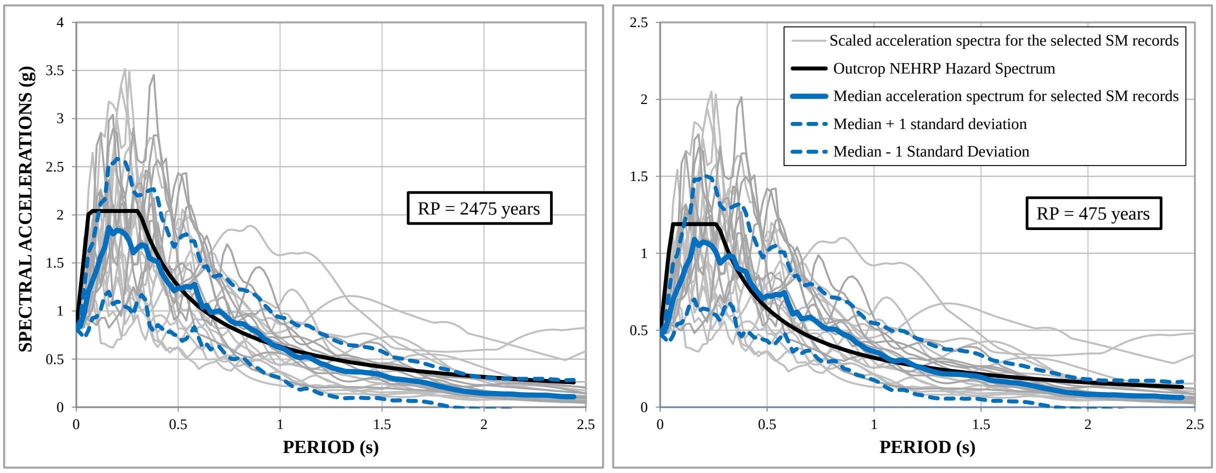

Figure 1. Acceleration spectra of for PGA scaled input acceleration records

The second option is to modify the strong motion acceleration set to have better outcrop NEHRP hazard spectra compatibility by using a simple optimization scheme based on PGA scaling to have the best fit of the mean acceleration spectrum with respect to the target outcrop NEHRP hazard spectra. The spectra of all scaled strong motion records and the mean spectrum with respect to outcrop hazard spectrum are shown in Fig. 2.

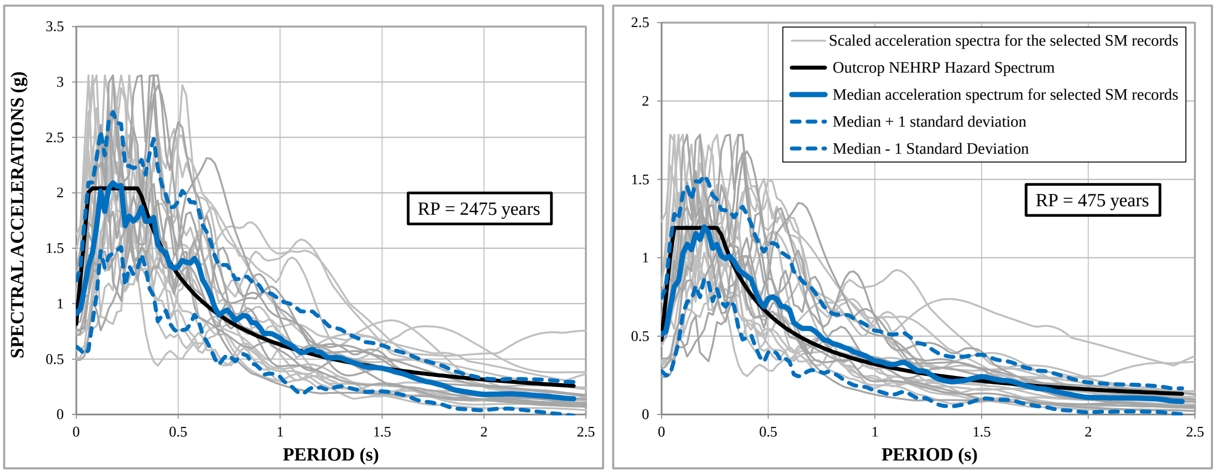

Figure 2. Acceleration spectra of for input acceleration records obtained for best fit mean spectra

The third option is to modify the input motion set by spectra scaling using the available two methodologies that also modifies the frequency content of the input acceleration records to have better fit to the outcrop NEHRP hazard spectra. The spectra of all scaled strong motion records by Method A using SeismoMatch (2011) and the mean spectrum in comparison to the outcrop hazard spectrum are shown in Fig. 3.

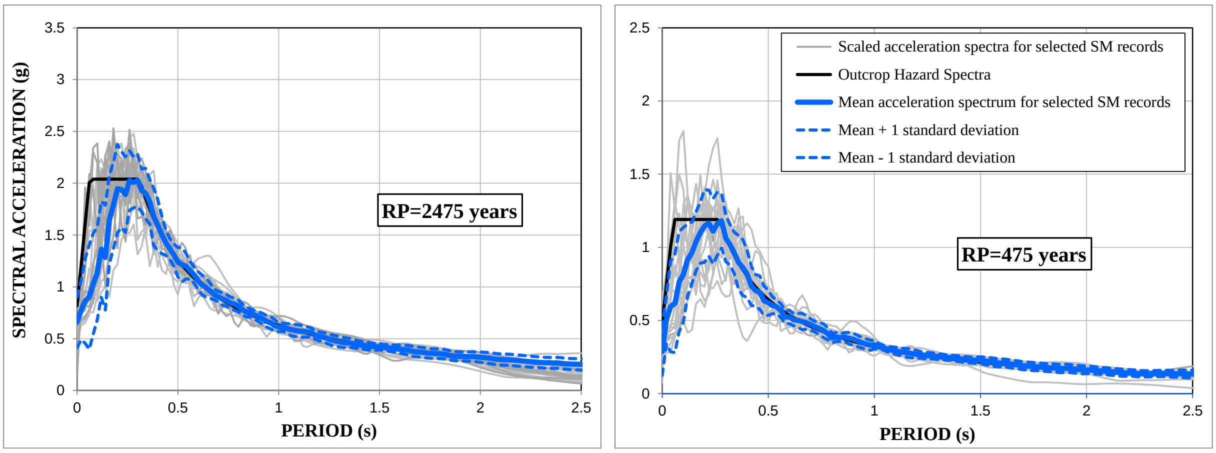

Figure 3. Acceleration spectra of for input acceleration records by one spectra scaling using Method A

The spectra of all spectra scaled earthquake records by Method B based on Abrahamson (1993) methodology and the mean spectrum are shown in Fig. 4 in comparison to outcrop hazard spectrum.

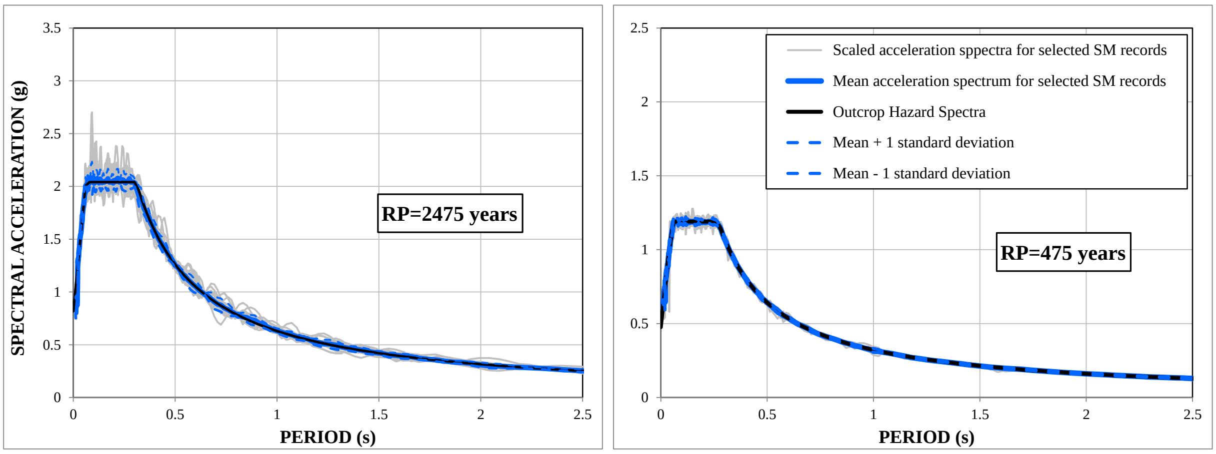

Figure 4. Acceleration spectra of for input acceleration records by one spectra scaling using Method B

The approach based on Abrahamson (1993) gave the best fits with respect to spectra scaling for the outcrop NEHRP hazard spectra with very limited scatter in the individual acceleration spectra of the 22 scaled strong motion records and with very low standard deviation. On the other side, the differences between spectral fitting using Method A and mean spectrum matching by an optimization scheme can be considered negligible with respect to the mean spectral curves. However, the scatter with respect to spectral accelerations of scaled strong motion records are more in the case of mean spectrum matching since this approach only involved amplitude scaling and without altering the frequency contents of input strong motion records as in the case of spectral scaling using Method A.

4. EARTHQUAKE CHARACTERISTICS ON THE GROUND SURFACE

Site specific earthquake design characteristics were investigated for one site in. Site response analyses were carried out for 25 borings conducted as a part of the geotechnical investigation that was supplemented with shear wave velocity profiles determined based on SPT blow counts, seismic surface and in-hole tests. The above summarized four sets of input strong motion acceleration records scaled with respect to four options are used for site response analyses. The results of site response analysis using outcrop hazard PGA scaled strong motion records are shown in Fig. 5 as mean and mean + 1 standard deviation acceleration response spectra. The best fit envelop as NEHRP design spectrum is plotted to reflect the design levels corresponding to return periods of 2475 and 475 years.

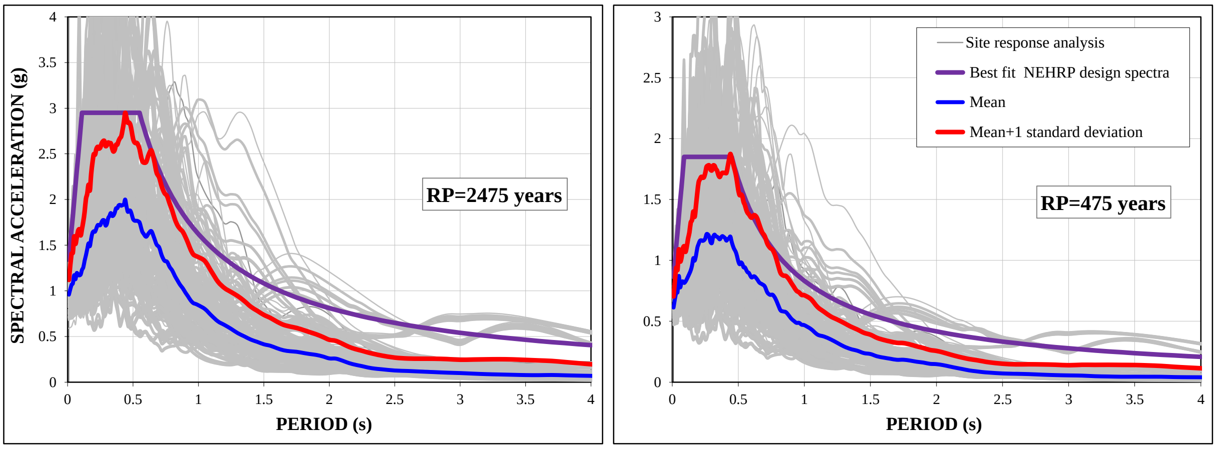

Figure 5. Acceleration spectra on the ground surface calculated using PGA scaled acceleration records

The results of site response analysis using set of strong motion records scaled for mean spectra matching by an optimization based on PGA scaling to have the best fit of the mean acceleration spectra with respect to outcrop hazard spectrum are shown in Fig. 6.

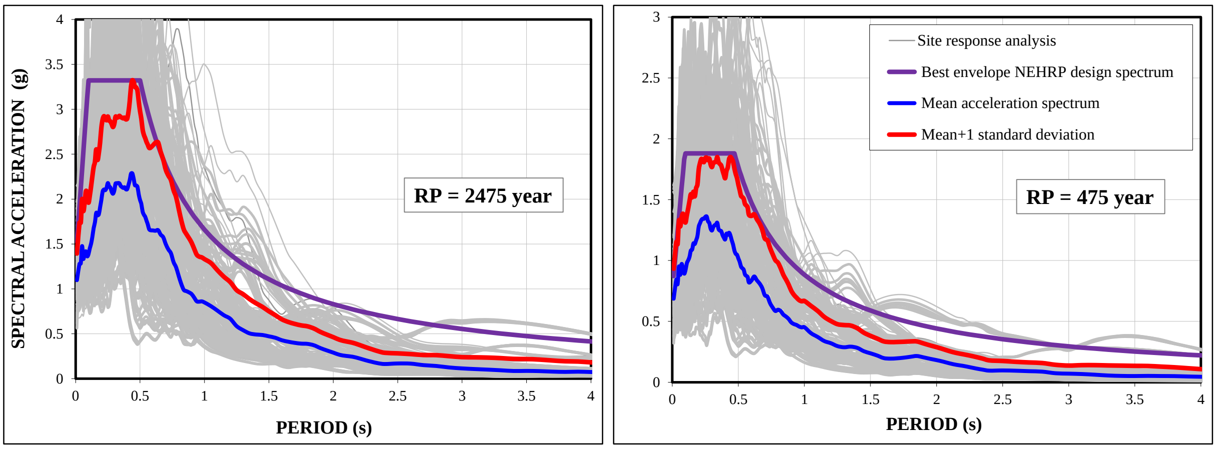

Figure 6. Acceleration spectra on the ground surface calculated using mean spectra scaled SM records

The results of site response analysis using spectra scaled strong motion records using Method A to match the target NEHRP hazard spectrum are shown in Fig.7 in terms acceleration spectra on the ground surface for 2475 and 475 year return periods.

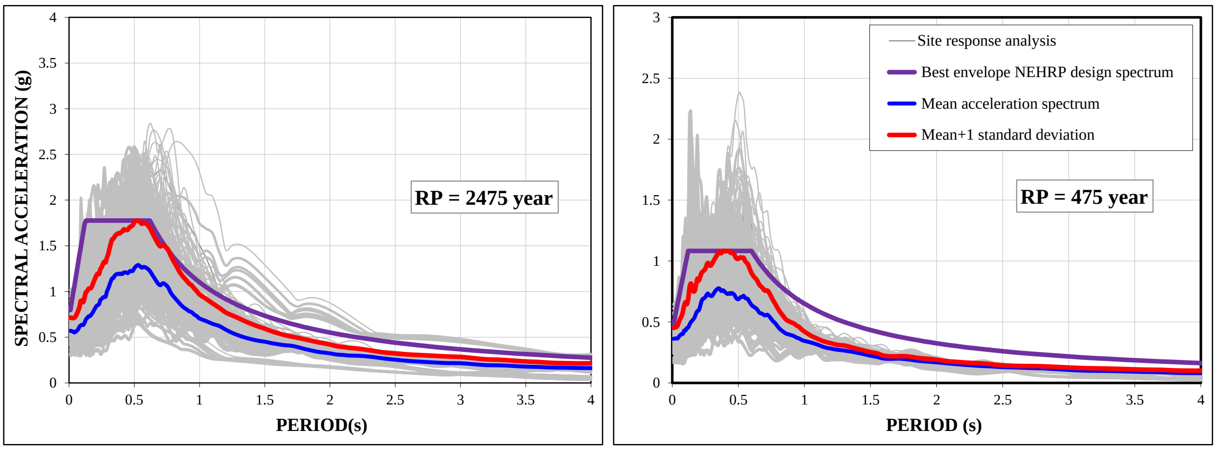

Figure 7. Acceleration spectra on the ground surface calculated using Code A spectra scaled SM records

The results of site response analysis using set of records that are spectra scaled using Method B approach to match the target NEHRP hazard spectrum are shown in Fig.8 with respect to acceleration spectra on the ground surface for 2475 and 475 year return periods.

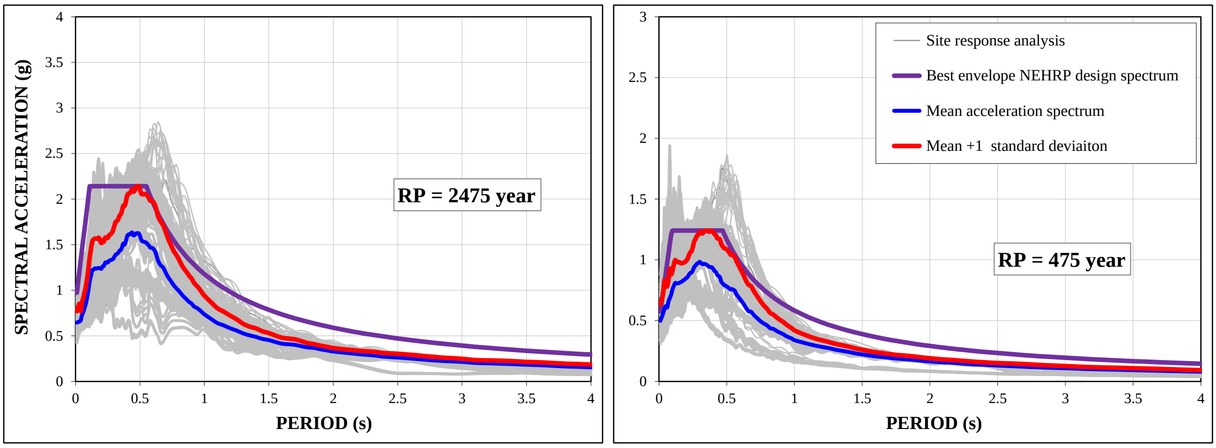

Figure 8. Acceleration spectra on the ground surface calculated using Code B spectra scaled SM records

The results of site response analyses indicate slight to significant deamplification with respect to mean spectral accelerations (Fig.9) on the ground surface with respect to outcrop NEHRP hazard spectrum depending on the approach adopted for input motion scaling. One of the reasons for lower amplification in the case of spectra scaling is most likely due to frequency changes applied to acceleration time histories to match the target acceleration spectrum. On the other hand, the spectra compatibility for the selected SM records that was improved by PGA scaling to have better fit with the outcrop NEHRP hazard spectrum gave slightly higher spectral accelerations with respect to conventional PGA scaling approach.

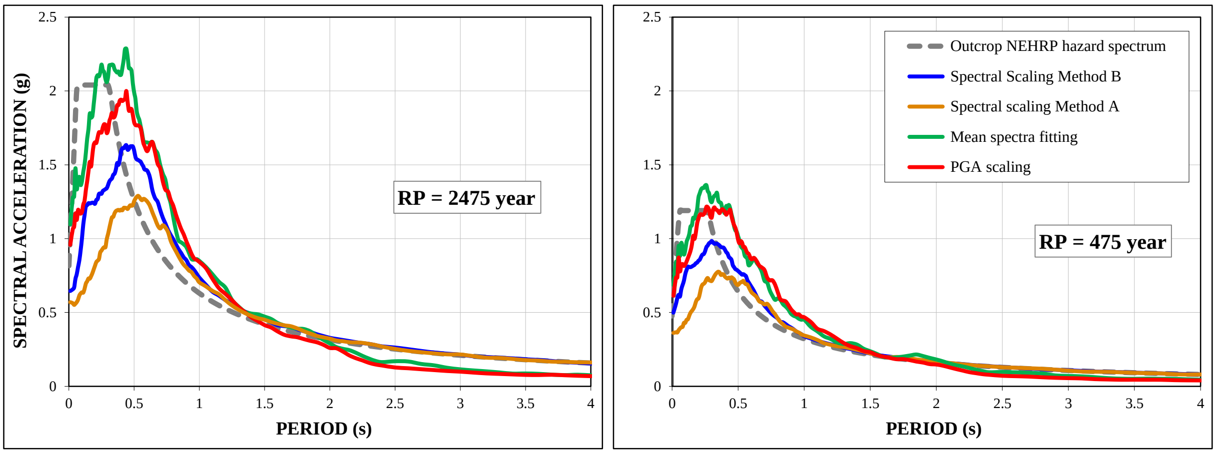

Figure 9. Comparison of mean acceleration spectra calculated on the ground surface using four different approaches for scaling the hazard compatible input SM records

It may not suitable to adopt mean acceleration spectra for design purposes; one option preferred by the authors is to adopt mean + 1 standard deviation as possible design spectrum corresponding to return periods of 475 and 2475 year return periods (Ansal and Tonuk, 2009). In that case as shown in Fig.10 and Fig.11, acceleration spectra obtained for mean +1 standard deviation and corresponding envelope NEHRP design spectra are more suitable for design and vulnerability assessment purposes.

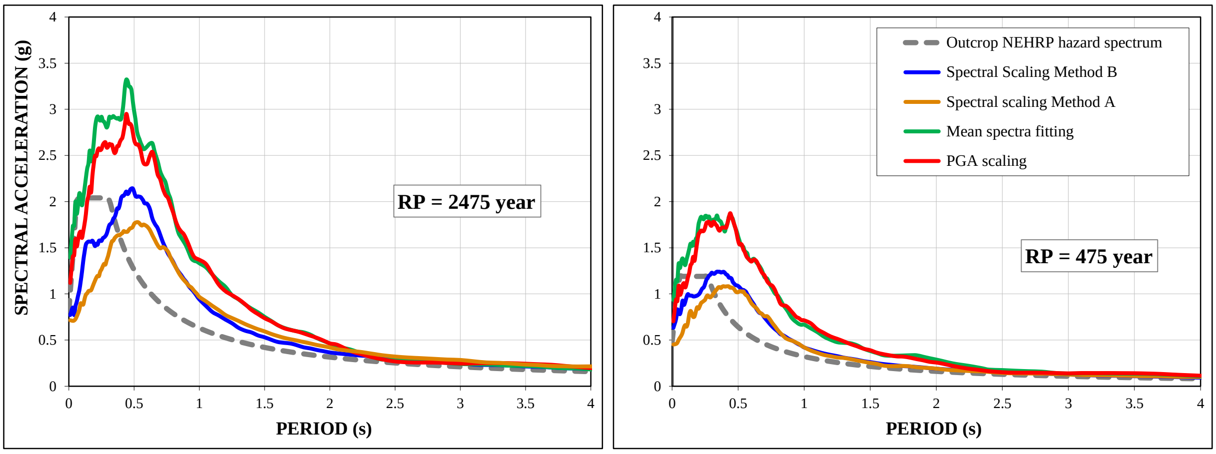

Figure 10. Comparison of mean + 1 standard deviation acceleration spectra on the ground surface using four different approaches for scaling the hazard compatible input SM records

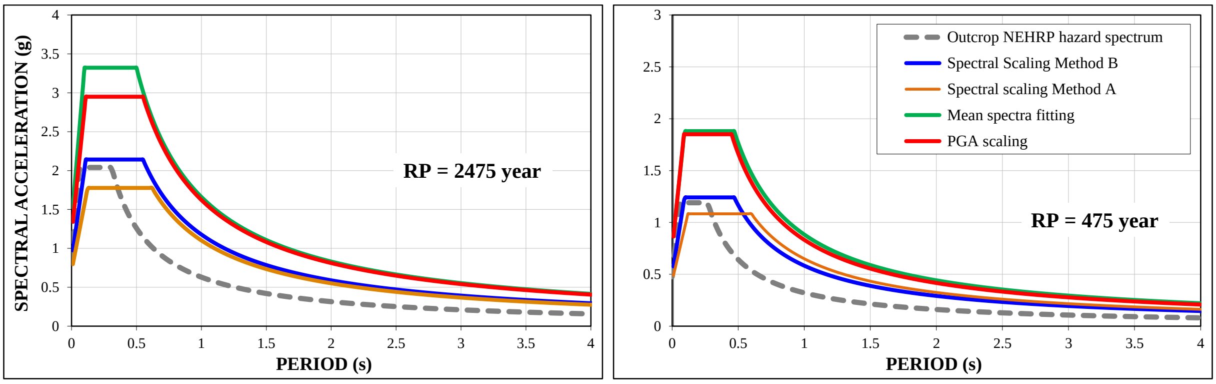

Figure 11. Comparison of NEHRP design spectra on the ground surface using four different approach for scaling the hazard compatible input SM records

4. CONCLUSION AND RECOMMENDATIONS

For the case of site specific assessment of earthquake ground motion characteristics on the ground surface, earthquake hazard determination is based on regional scale to take into account earthquake source zones and characteristics in a more comprehensive manner. In order to account for the variability of the ground motion characteristics due to source mechanism and path effects large number of hazard compatible strong motion acceleration records need to be used as input for site response analysis to determine the possible earthquake characteristics on the ground surface. The first requirement for the selection of strong motion acceleration records is the hazard compatibility with respect to fault type, earthquake magnitude, source distance and average shear wave velocity at the recording station. The second criteria may be defined with respect to similarity to the regional outcrop acceleration hazard spectra and estimated peak ground acceleration. The third and maybe the most important stage in this type of analyses and the methodology adopted to scale the hazard compatible strong motion acceleration records to be used for site response analyses as outcrop motion. A parametric study was conducted using a very widely used 1D site response analysis, Shake91 code, to evaluate the effects of four possible options of scaling.

The geotechnical data comprised of 25 soil profiles also indicating possible variability at one site was adopted to study the site specific design earthquake characteristics for two performance levels corresponding to 475 and 2475 years. The results obtained indicate that the highest level of ground shaking in terms of acceleration spectrum was calculated by using mean spectra matching approach. However, the conventional PGA scaling approach yielded very similar or slightly lower results. In the case of spectra scaling approaches the calculated acceleration spectra on the ground surface were lower in comparison to conventional PGA scaling option, interestingly for the case studied; both spectra matching schemes did not lead to spectral amplifications. Considering the extra effort and time for spectral scaling and in the light of these preliminary results it may not be feasible and sufficiently conservative to adopt spectral scaling schemes for site response analyses.

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