Ground motion selection using the conditional spectrum: Insights for different tectonic environments

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ABSTRACT: This study investigates the challenges associated with selecting ground motions representative of the site-specific seismic hazards in two major U.S. cities located in different tectonic environments: Seattle and Boston. Seattle is in an active tectonic region, with seismic hazard contributions from crustal and subduction events. Boston is located in a stable continental region with diffuse seismicity. We define multiple target spectra for the selected sites in terms of the conditional spectrum computed for different magnitude-distance combinations. Insights on the selection of ground motions in regions exposed to diverse seismic sources are provided. The influence of the selected ground motion sets on site response analyses is also evaluated. We find that the choice of seismic hazard scenarios for input motion selection must be made in consideration of the tectonic regime, especially in areas with diverse seismic sources, where a mean hazard scenario is not representative of the hazard at the site.

1 INTRODUCTION

The importance of properly characterizing ground motion intensity measures for seismic hazard assessment is unequivocally large. Earthquake ground motions serve as the link between evaluations of seismic hazards and assessments of civil infrastructure performance. However, the selection of hazard-consistent ground motions is a challenging task for both geotechnical and structural engineering analyses. In engineering practice, the design ground motion is based on a target performance. The latter can result from (a) a prescribed design response spectrum from seismic codes, (b) a response spectrum corresponding to a single hazard scenario from either a deterministic seismic hazard analysis or from the governing scenario identified after the deaggregation of hazard, (c) a response spectrum conditioned on a spectral acceleration of interest, or (d) a uniform hazard spectrum (UHS) (Bradley 2012). The UHS is widely used as a target spectrum, and it is computed by probabilistic seismic hazard analyses (PSHA) for a given hazard level, e.g. 2% probability of exceedance in 50 years. The UHS, however, is not representative of the spectrum corresponding to a single recorded ground motion. To bridge the gap between PSHA and deterministic analysis and to be able to select site-specific ground motions, the conditional mean spectrum (CMS) was proposed by Baker and Cornell (2006) and Baker (2011). The CMS can be more representative of the spectrum from a single ground motion which has the same spectral acceleration (Sa) as the UHS at the conditioning period, T^*. The spectral accelerations at all other periods of CMS are conditional on the spectral acceleration at the conditioning period, Sa(T^*).

The computation of a CMS requires the determination of a conditioning period (based on knowledge of the fundamental period of the structure of interest), selection of a single or multiple ground motion prediction equations (GMPEs) deemed representative of the tectonic environment, selection of inter-period correlation coefficients, all of which have been addressed in the literature (Carlton and Abrahamson 2014). However, one critical issue that has not yet been fully explored is the effect of the selection of a magnitude-distance (M-R) scenario that is representative of the hazard at the site. Most studies have focused on selecting the mean values from deaggregation at the conditioning period (Baker 2011, Stewart et al. 2014). In several cases, the dominant earthquake scenario was used (Baker 2015, Haselton et al. 2017) that has the highest contribution to the hazard. Harmsen et al. (1999) had studied the deaggregation plots of 49 cities in the CEUS and investigated the effects of the use of mean and modal M-R values in deterministic engineering design. They found that the mean values may correspond to the earthquakes having little contribution to the hazard and the modal values can be dependent on the binning details of the PSHA.

Moreover, the mean tends to average out the M and R values as it considers the small magnitude earthquakes. Lin et al. (2013) calculated the CMS incorporating multiple causal earthquakes and GMPEs, and compared those to the CMS calculated from mean M-R and single GMPE. They had presented three approximate methods and one exact method for the CMS calculation. The exact method, the most complex, uses all M-R bins and deaggregation weights for each GMPE from the PSHA. However, due to the complexity of this method and often the extensive deaggregation results not being available from a PSHA, researchers are still widely using a single M-R combination to calculate CMS instead of this exact method (e.g. Hashash et al. 2015, Petermann and Rathje 2017). Moreover, the exact CMS can have the tendency to average out the CMS due to consideration of M-R bins with low contribution to the hazard. Using a single M-R combination may not always be representative of the hazard at the site, especially in cases where the site has multiple contributors to the seismic hazard (i.e., multiple seismic sources). Such conditions may arise due to the complex tectonic setting of the site and may result in multiple dominant scenarios (M-R combinations having highest contribution to the hazard).

This paper will investigate whether in such cases the use of a single M-R combination can provide us with a target spectrum that is representative of the hazard at that site. Moreover, the geologic and geotechnical conditions of the site play an important role in finding the representative ground motions for the site. The objective of this study is to highlight the challenges of selecting hazard-consistent ground motion for site response analysis in different tectonic, geologic and geotechnical settings, and propose a reasonable approach to be followed based on the analyses.

2 METHODOLOGY

2.1 *Differences in tectonic, geologic and geotechnical conditions*

In an attempt to investigate the differences in input motion selection for different tectonic, geologic and geotechnical conditions, we have selected Seattle, WA from the western U.S. (WUS) and Boston, MA from the central and eastern U.S. (CEUS) as study sites. Seattle is located in a region of active tectonic activity. The hazard contributions from earthquakes are associated with crustal faults or background seismic sources, and earthquakes associated with the subduction zone located off the coast of Oregon, Washington, and British Columbia. Both shallow large-magnitude interface earthquakes and the deeper intraslab events are characterized in this region for the Cascadia subduction zone. Unlike the Seattle site, the Boston site is in a region of moderate seismicity in which the sources of seismic hazard are much more diffuse.

A geotechnical profile has been developed (Figure 1) for each location to be representative of typical conditions in the center of each city. Large portions of both Boston and Seattle are underlain by layers of artificial fill, and typical profiles are characterized by sharp impedance contrasts at depth (corresponding to the interface between post-glacial and pre-glacial materials). The geotechnical conditions in both locations have been heavily influenced by glaciation. The Seattle site consists of artificial fill over a thick layer of deltaic sand and estuarine silt, overlying a dense layer of reworked glacial deposits to a depth of 56.5 m, which represents dense preglacial deposits that are modeled as soft rock (with shear-wave velocity [V_S] = 760 m/s). The bottom of the soil profile is consistent with the lowest downhole seismometer at the Seattle Liquefaction Array (Shannon and Wilson, 2018); this report is also used as the basis for the assumed V_S profile (which was developed from suspension P-S logging). The Boston site consists of artificial fill, organic silt, glacial outwash (sand), and a thick layer of Boston Blue Clay overlying dense glacial till/bedrock (modeled as crystalline hard rock with V_S = 2830 m/s for engineering purposes) at a depth of 51 m. The 51 m depth is representative of the varying depth to bedrock throughout the city, and it is consistent with the location of the Northeastern University downhole array (Yegian, 2004). The assumed shear-wave velocity profile was developed by Baise et al. (2016) from multiple spectral analysis of surface waves (SASW) measurements throughout the Boston basin (Thompson et al., 2014). The assumed reference rock conditions for Seattle and Boston are prevalent throughout the WUS and CEUS regions, respectively. Recorded ground motions on hard rock conditions are rare to find, and it poses a challenge to find representative motions for CEUS sites.

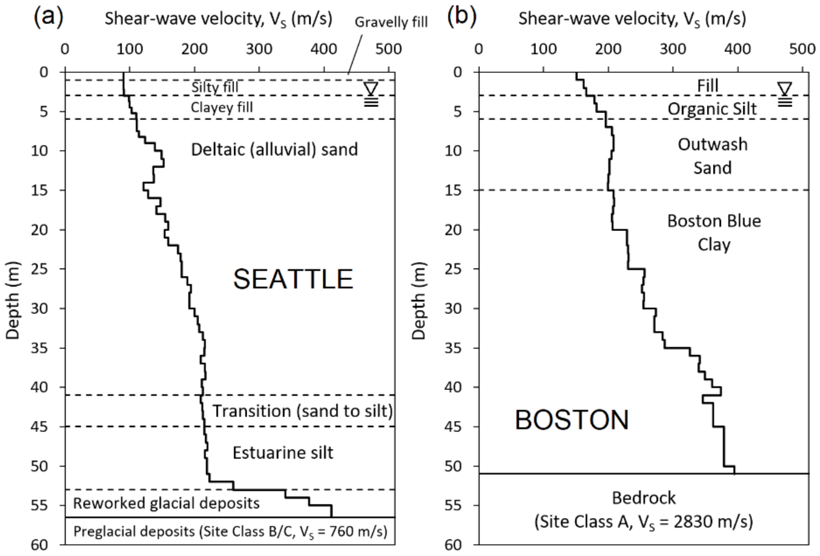

Figure 1. Shear-wave velocity profiles and stratigraphic profiles used in the analyses for (a) Seattle and (b) Boston. The groundwater table was assumed to occur at a depth of 3 m at each site.

2.2 *UHS and CMS calculation*

Probabilistic seismic hazard calculations are carried out using the computer program HAZ46 (Abrahamson and Gregor 2018). The UHS is computed for a hazard level of 2% probability of exceedance in 50 years. For the Seattle site, ground motion prediction equations (GMPEs) are selected for shallow crustal earthquakes as well as for intraslab and interface subduction zone earthquakes. For shallow crustal earthquakes, four equally-weighted Next Generation Attenuation for Western US (NGA-West2) GMPEs (Bozorgnia et al. 2014) are used: Abrahamson, Silva, and Kamai (ASK); Boore, Stewart, Seyhan, and Atkinson (BSSA); Campbell and Bozorgnia (CB); and Chiou and Youngs (CY). For the subduction ground motion model, the recent Abrahamson et al. (2016) model was used. This model was developed as part of the BC Hydro PSHA study and included a GMPE for both interface and intraslab events. For Boston, which is in a stable continental crust region, only significantly contributing areal seismic sources are included in the PSHA computations. The suite of GMPEs used are based on the set of 11 models developed by Silva et al. (2002). These models are based on a point source numerical modeling of ground motions, and the methodology has been validated against previously recorded earthquakes.

Deaggregation on selected periods shows us the magnitude-distance combinations (rupture scenarios) that have the greatest contributions to the hazard. A short period of 0.01 s, which corresponds to peak ground acceleration (PGA), and a long period of 1.0 s are selected, as it is often observed that the hazard at short and long periods are dominated by different seismic sources. The deaggregation plots for Seattle and Boston are presented in Figure 2a, 2b and Figure 2c, 2d for 0.01 s and 1.0 s, respectively. The deaggregation plots for Seattle (Figure 2a,2b) shows the contribution to seismic hazard from three distinct seismic sources: (1) shallow crustal earthquakes on faults within the North American plate (e.g. the Seattle Fault) at less than 30 km distance, (2) deep earthquakes originating along the subducting oceanic plate (intraslab earthquakes) at 50-100 km distance, and (3) large magnitude thrust events along the Cascadia subduction zone (interface earthquakes) at 75-200 km. At the shorter periods in general (0.01-0.5 s), the highest contribution to the hazard comes from shallow crustal earthquakes and intraslab earthquakes. At longer periods (1.0-5.0 s), the contribution from the shallow crustal earthquakes and subduction zone interface earthquakes are dominant. We can observe from Figure 2a and 2b that the mean M-R combination is not the highest contributor to the hazard. Computing the CMS using this mean value may provide us with a target spectrum that is lower than the expected possible hazard in the site. Therefore, for Seattle, we have selected three different dominant M-R scenarios corresponding to the three different seismic sources.

The deaggregation plot of Boston for the 1 s period (Figure 2d) does not show any predominant contribution to the hazard associated with a particular seismic source. However, for the 0.01s period (Figure 2c), we observe higher contributions coming from nearby areal sources at distances of 10-50 km. Therefore, we select causal parameters corresponding to this dominant scenario (i.e. M=5.5, R=30 km) and compare it to results based on mean values from the deaggregation.

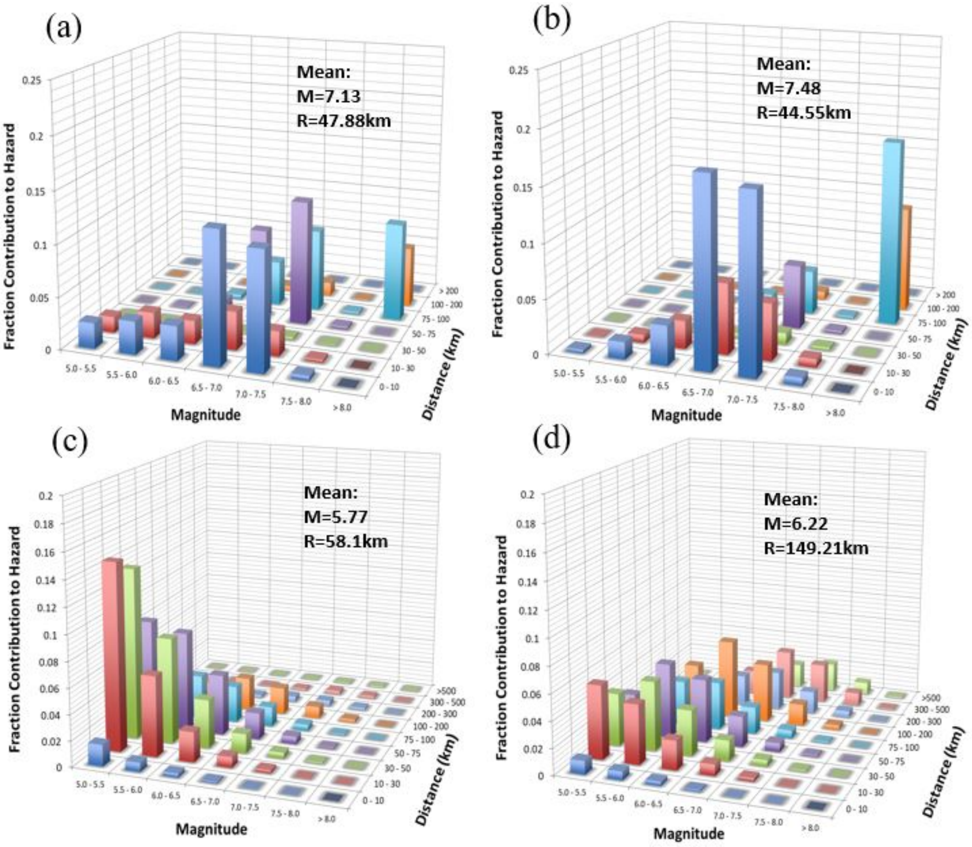

Figure 2. Seismic hazard deaggregation plots for spectral accelerations exceeded with 2% probability in 50 years at (a) Seattle for 0.01s period, (b) Seattle for 1s period, (c) Boston for 0.01s period and (d) Boston for 1s period.

Table 1 shows the mean and selected dominant M-R scenarios for the CMS computations at the study sites in Seattle and Boston. The CMS computed for the mean M-R values from the deaggregation are compared with the CMS computed for the aforementioned dominant scenarios. For the shallow crustal and subduction intraslab and interface dominant scenarios, the corresponding GMPEs used in the PSHA were used in the computation of the CMS. However, when a diverse tectonic setting results in multiple types of GMPEs being used for PSHA (as is the case for Seattle), choosing a single type of GMPE to calculate CMS using the mean M-R values poses a challenge. For comparison purposes, therefore, we compute CMS for mean values using crustal GMPEs and subduction intraslab GMPE separately.

Table 1. Mean magnitude-distance scenario and selected dominant scenarios (DS) from deaggregation

	T = 0.01 s		T = 1.0 s	
	M_w	R_{rup} (km)	M_w	R_{rup} (km)
Seattle:				
Mean from deaggregation	7.13	47.88	7.48	44.55
Shallow crustal DS	7.0	5	7.0	5
Subduction intraslab DS	7.0	50	7.0	50
Subduction interface DS	9.0	100	9.0	100
Boston:				
Mean from deaggregation	5.77	58.1	6.22	149.21
Selected DS	5.5	30	6.0	30

* M_w = moment magnitude, R_{rup} = Rupture distance

2.3 *Input motion selection and scaling*

The input motion selection protocol proposed by Baker and Lee (2017) is used to select ground motions matching the conditional spectra (CS) in this study. The CS quantifies the variability in spectral values at periods other than the conditioning period, while the CMS considers the mean spectral values only. Eleven pairs of ground motions are selected and scaled for each scenario to match the CS. Identifying appropriate databases with representative motions from the seismic sources that contribute to the hazard imposes yet another challenge. The NGA-West2 database (Ancheta et al. 2013) is used to select shallow crustal earthquake motions for Seattle. The subduction database for U.S. is under process and not available yet. Therefore, we have used the Japanese Kiban-Kyoshin network (KiK-net) database (Okada et al. 2004, Dawood et al. 2016) that contains records from both subduction interface and intraslab earthquakes. On the other hand, for Boston, we use the NGA-East database (Goulet et al. 2014). As mentioned earlier in the paper, even for the NGA-East database, it is hard to find ground motions recorded at locations with an average shear-wave velocity in the upper 30 m (V_{S30}) of 2830 m/s. To screen the database for finding the appropriate ground motions for scaling and matching to the target spectra, typically the causal parameters (magnitude, distance, source mechanism, V_{S30}) are kept within a reasonable bound. However, Tarbali and Bradley (2016) showed that keeping this bound wide can help to select ground motions with a better representation of the target intensity measure distribution. Hence, we kept the causal parameter bound wide while selecting ground motions matching CS. For the scaling of ground motions, Haselton et al. (2017) mentions that a factor of 0.25-4.0 is not uncommon. However, for both NGA-East database and KiK-net database, it was difficult to find appropriate number of ground motions maintaining this range and thus we had to widen the range.

3 RESULTS AND DISCUSSION

The first set of analyses investigated the impact of choosing different M-R scenarios on the spectral shape of the target CMS. Figure 3 presents the UHS for 2% probability of exceedance in 50 years for Seattle, and the CMS computed for the scenarios presented in Table 1. This figure reveals remarkable differences in the computed CMS. The disagreements between the multiple CMS (for the different scenarios) tend to be higher at periods that are more distant from the conditioning period. This trend is also observed with respect to the UHS and stems from the way the CMS is computed (i.e. fixing the value from the UHS as the spectral acceleration at the conditioning period and using inter-period correlations to define spectral values at other periods). For instance, given a specific M-R combination, the mean natural logarithmic spectral value $\mu(T)$ and natural logarithmic standard deviation $\sigma(T)$ are calculated at all periods using a GMPE. $\varepsilon(T^*)$ is the number of standard deviation difference between the $\mu(T^*)$ and the natural logarithm of the UHS value at the conditioning period T^*. The CMS in natural logarithmic units at a period T_i conditioned at a period of T^* is then computed as follows:

$$CMS_{T^*}(T_i) = \mu(T_i) + \varepsilon(T^*) \times \sigma(T_i) \times \rho(T_i, T^*) \quad (1)$$

Here, $\rho(T_i, T^*)$ is the correlation between ε at T^* and ε at different periods. In this study, we have used the inter-period correlation proposed by Baker and Jayaram (2008).

It can be observed from Figures 3a and 3b that the mean M-R scenario is not always representative of the possible hazard at the site. The same figures also show that the shallow crustal and intraslab dominant scenarios have higher spectral accelerations at shorter periods. In contrast, the interface events have higher spectral accelerations at longer periods, which are expected for distant large magnitude earthquakes (e.g. M = 9.0, R = 100 km from Table 1). For dynamic structural analyses, if a structure is expected to be more sensitive to spectral acceleration values at certain periods (e.g. long periods for high-rise structures or bridges), care should be taken to select the M-R-ε scenario that better represents the hazard at those periods.

Figure 4 presents the CMS for the mean and dominant scenarios in Table 1 for Boston. The UHS is also shown for comparison purposes. In the case of Boston, the differences in spectral shapes between the CMS for dominant and mean scenarios at a conditioning period of 0.01 s are not as significant (Figure 4a). This is expected because the selected dominant scenario (M = 5.5, R = 30 km) is very similar to the mean values (M = 5.77, R = 58.1 km). Nevertheless, the 1.0 s CMS (Figure 4b) presents a notable disagreement between the spectral shape corresponding to the mean values and dominant scenarios. Interestingly, we observe that the dominant scenario CMS exceeds the UHS in Figure 4b. This can be due to the fact that CMS comes from a combination of deterministic and probabilistic method, and it is not unusual for a deterministic spectrum to exceed the UHS.

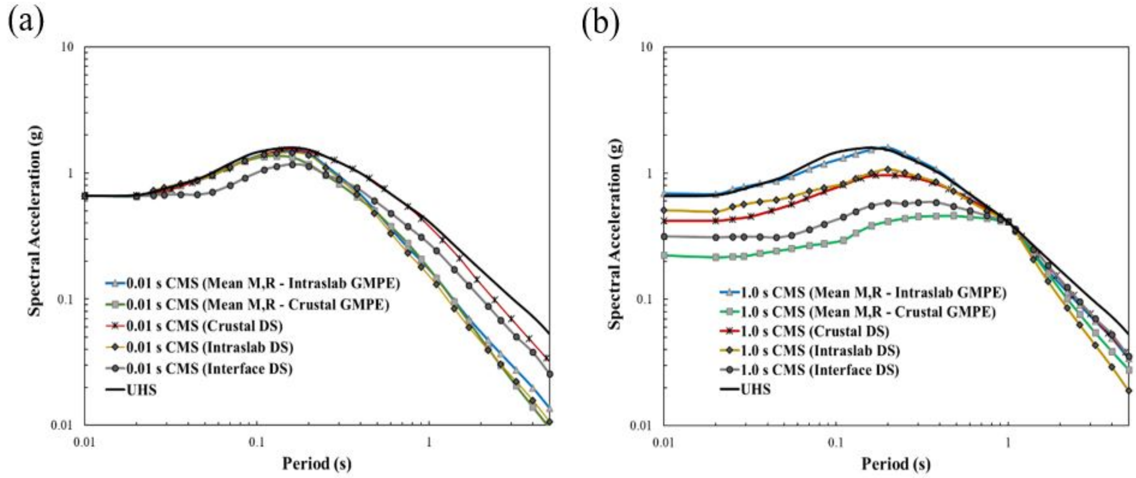

Figure 3. UHS and CMS at Seattle for selected scenarios (M-R combinations) for conditioning periods of (a) 0.01 s and (b) 1 s.

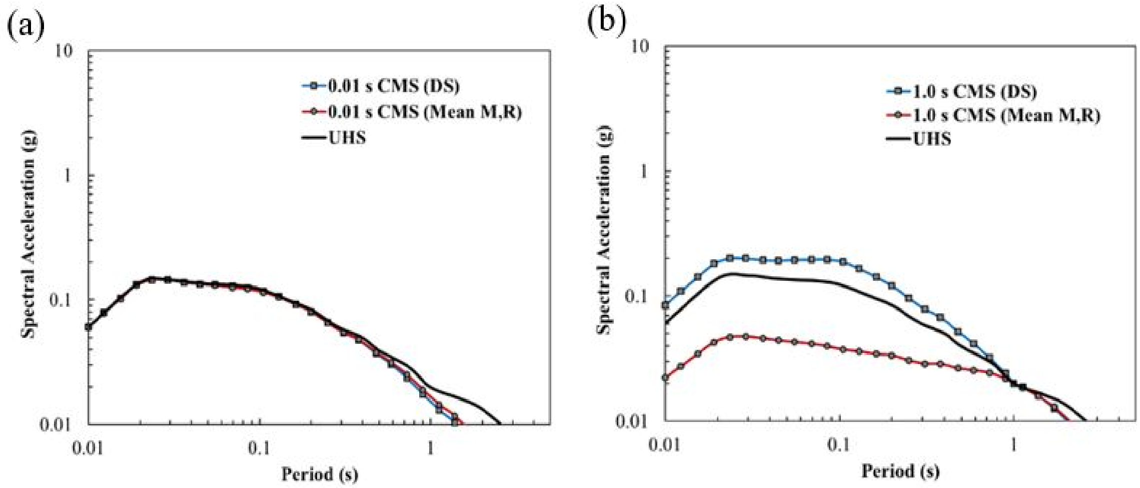

Figure 4. UHS and CMS at Boston for selected scenarios (M-R combinations) for conditioning periods of (a) 0.01s and (b) 1s.

The input ground motions are selected for each case from their corresponding databases. The use of the mean M-R combination for Seattle is not realistic given the complexity of the tectonic environment and implications in the selection of a unique GMPE and corresponding database. Therefore, we do not consider the mean M-R scenario for Seattle for selecting input motions; instead, we consider the three separate dominant scenarios. Figure 5 shows the CS (mean and spectral variability) and selected input motion spectra matching the CS for two example cases in Boston and Seattle. Nonlinear site response analyses are performed using DEEPSOIL (Hashash et al. 2018) to estimate the predicted response spectra at the ground surface. The Darendeli (2001) modulus-reduction and damping curves are used as the target relations for the nonlinear analyses, and the fitting is performed using the MRDF pressure-dependent hyperbolic model procedure (Phillips and Hashash 2009) in DEEPSOIL. The dynamic behavior of the soil layers is represented using the MKZ model (Matasovic and Vucetic 1993), and the bedrock is represented as an elastic halfspace.

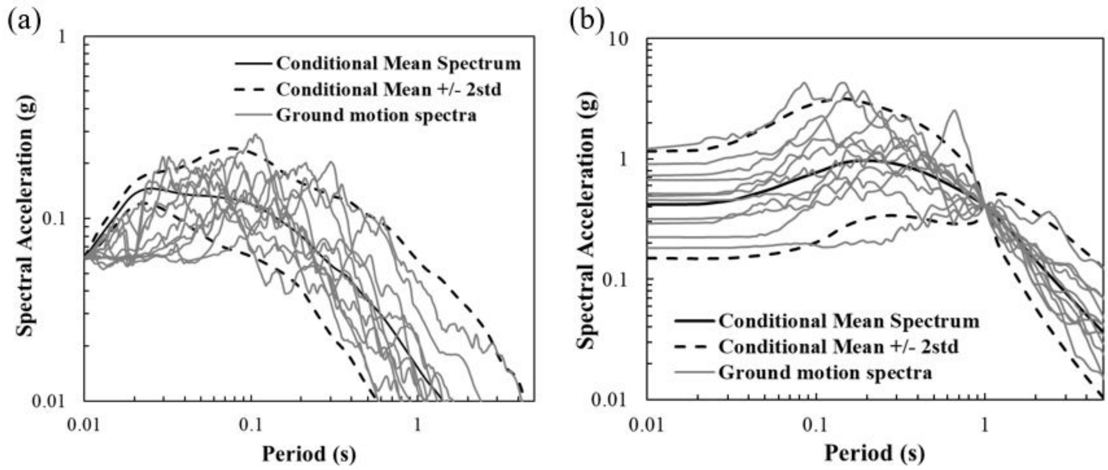

Figure 5. 5% damped response spectra of selected ground motions matching the CS for (a) Boston for T^*=0.01 s (selected dominant scenario) and (b) Seattle for T^*=1.0 s (shallow crustal dominant scenario).

Figure 6 displays the predicted surface response spectra for the median of each suite of 11 ground motions for Boston and Seattle. The surface response spectra at short periods in Boston (Figure 6a) display greater variability than those of Seattle (Figure 6b), particularly for the spectra conditioned at a period of 1 s. The surface response spectra based on the mean values is significantly lower than the surface response spectra based on the dominant scenario. For all suites in Boston, the amplifications are similar in the vicinity of the fundamental period of the site (approximately 0.7 s) and at longer periods. For Seattle, the surface response spectra are much similar at short periods than at long periods. Despite significant variations in the CMS of the input motions conditioned at a period of 1 s (Figure 3b), it is notable that all the surface response spectra appear to converge at 0.1g for short periods (Figure 6b). A high degree of nonlinearity is predicted at this site; relative to the input spectra, there is significant deamplification in the surface ground motions at short periods. It is striking that the predicted surface response spectra at short periods (< 0.3 s) are similar between Boston and Seattle, two cities with extremely different seismic hazards. Nonlinear effects are less significant at longer periods, and therefore the predicted long-period motion is greater for Seattle than Boston, as expected. For Seattle (Figure 6b), the difference in the surface response spectra for three different scenarios considered shows the importance of considering all dominant scenarios.

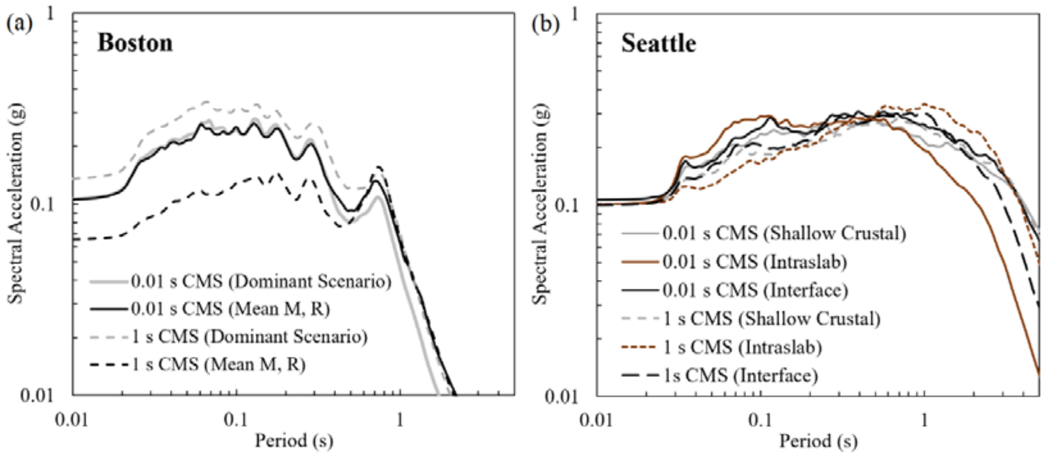

Figure 6. Predicted surface response spectra from nonlinear site response analyses for the medians of various suites of ground motions in (a) Boston and (b) Seattle.

The study presented herein explores the implications of the choice of seismic hazard scenarios for input motion selection in different tectonic conditions. We find that such choice must be made in consideration of the tectonic regime, especially in areas with diverse seismic sources, such as subduction zone environments (e.g., Seattle, WA). In that case, a single M-R scenario such as the mean value is not representative of the real seismic hazard, and all dominant scenarios representative of known seismic sources should be explored instead. Sites in the CEUS, such as Boston, face different challenges imposed by a low-to-moderate seismicity and scarcity of records. In this case, dominant scenarios for the region also need to be explored if the mean value is not representative of the hazard at the site. More research on hazard assessment for sites in CEUS is needed to further explore differences in hazard-consistent input motions at sites with known dominant contributors to the seismic hazard (e.g. Charleston, SC).

4 CONCLUSION

In this study, we provide insights on the selection of ground motions in regions exposed to diverse seismic sources, including recommendations on potential databases to use and the importance of selecting motions representative of each seismic source. This study investigated the effect of the selection of an M-R scenario on the computation of the CMS, and also on the corresponding intensity measures obtained from site response analyses. Two sites with different tectonic, geologic, and geotechnical conditions were chosen for comparison purposes. For a study site in Seattle, where the contributions of three different seismic sources to the hazard are clearly distinguishable, computing the CMS using a single M-R value is not representative of the hazard at the site. In the case of Boston, which has diffuse seismic sources, dominant scenarios need to be considered if the mean M-R scenario is not the highest contributor to the hazard at the site. The predicted response spectra from site response analyses show greater dispersion at short periods in Boston, and greater dispersion at long periods in Seattle (due to excessive nonlinearity at short periods). This study highlights how important it is to select representative M-R-ε scenarios to compute the CMS and select hazard consistent ground motion for geotechnical analysis. The consideration of the tectonic, geologic, and geotechnical settings of the site of interest play a key role in defining hazard-consistent ground motions. We found that these conditions may not always be well represented by choosing a single M-R value from deaggregation results. Therefore, careful attention must be paid when selecting representative M-R combinations to compute the CMS, even if it requires considering multiple scenarios. A comprehensive understanding of the contributions to the hazard at a site is required for more complex environments.

Current practice relies on the spectral acceleration as the primary intensity measure for characterizing the ground motion hazard and selection of scenario events. The authors acknowledge that hazard from other intensity metrics (e.g. Arias intensity) may better characterize the ground motion for a specific evaluation. The effects of different definitions of hazard-consistent ground motions on the uncertainty of other intensity measures, such as Fourier spectra, Arias intensity, and duration, will be investigated in future work.

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