The effect of bounds on magnitude, source-to-site distance and site condition in PSHA-based ground motion selection

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ABSTRACT: In this paper, the effect of using bounds on magnitude, source-to-site distance, and site condition of prospective records for the purpose of ground motion selection based on probabilistic seismic hazard analysis (PSHA) is investigated. Although it is common in ground motion selection to consider bounds on these causal parameters, there is no consistent approach for setting the bounds as a function of the seismic hazard at the site, and no guidance exists on how the bounds should be set considering the distribution of causal scenarios affecting PSHA results. 36 PSHA cases are considered in this paper to empirically illustrate the effects of alternative bounds on the characteristics of selected ground motions, which cover a wide range of deaggregation distributions and site conditions. The obtained results indicate that the use of excessively narrow bounds encompassing only the dominant causal scenario can lead to ground motion ensembles with a biased representation for the target hazard. In contrast, the use of relatively wide bounds results in ensembles with an appropriate representation for the target intensity measure distributions. Quantitative criteria for determining such bounds for general problems are provided, which are expected to be sufficient in the majority of problems encountered in ground motion selection for seismic demand analyses.

1 INTRODUCTION

Selecting ground motion time series for seismic response analysis is one of the intricate tasks in assessing the seismic performance of geotechnical and structural systems. The availability of ground motion time series recorded during past earthquakes from all around the world (e.g. Ancheta et al. 2013) provides engineers with a vast number of prospective ground motions with a broad range of causal parameters (e.g. magnitude, source-to-site distance, site condition). It is common practice in ground motion selection to apply bounds on the causal parameters of prospective ground motions prior to the primary selection process in order to reduce the size of empirical database of records to a reasonable number. The bounded database of as-recorded ground motions are subsequently used in a more rigorous selection process based on explicit intensity measures (e.g. spectral acceleration, peak ground velocity, duration) in order to represent the target seismic hazard at the site (Katsanos et al. 2010).

Despite the prevalent application of causal parameter bounds (Katsanos et al. 2010), specifying the bound limits is a subjective choice. For instance, Stewart et al. (2001) recommended that, because of the considerable effect of magnitude on characteristics of ground motions, ±0.25 magnitude (M_w) units either side of a considered scenario rupture is a desirable bound; while Bommer and Acevedo (2004) recommended $\pm 0.2 M_w$ units. In order to include an adequate number of ground motions when this M_w bound is applied, Bommer and Acevedo (2004) comment that the source-to-site distance (R_{rup}) of records can be bounded over a wider range, without specifically mentioning a limit. The importance of considering records from site conditions compatible with the site of interest is also advocated by others (e.g. Stewart et al. 2001, Bommer and Acevedo 2004, Katsanos et al. 2010). Literature discussing common ground motion selection methods (e.g. Kottke and Rathje 2008, Baker 2010, Jayaram et al. 2011, Wang 2011) has noted the application of causal parameter bounds, however, generally a quantitative approach by which such bounds can be applied is not provided. Importantly, the use of causal parameter bounds is generally cast in the context of a scenario earthquake of interest (as noted above), and thus the specific bounds for use in ground motion selection based on probabilistic seismic hazard analysis (PSHA), which is the summation of the hazard from numerous earthquake sources as quantified via deaggregation, is not obvious.

In this paper, the consideration of bounds on magnitude, source-to-site distance, and site condition of prospective ground motions as a function of probabilistic seismic hazard at the site is rigorously examined. 36 PSHA cases are considered, which encompass a broad range of causal rupture distributions (i.e. deaggregation results) and site conditions. Ground motions are selected based on the generalized conditional intensity measure (GCIM) methodology (Bradley 2010, 2012a). The causal parameter bound range and the number of available ground motions imposed by the application of different bounding criteria, along with the effect of causal parameter bounds on the properties of selected ground motions are examined and pertinent implications are presented.

2 SEISMIC HAZARD AND SITE CONDITIONS CONSIDERED

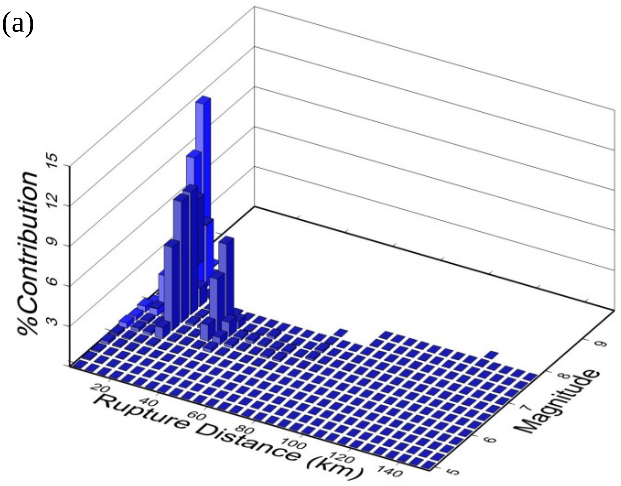
In order to empirically investigate the effect of causal parameter bounds on the characteristics of ground motions selected for PSHA cases with different deaggregation distributions, PSHA was conducted for numerous spectral acceleration (SA) vibration periods and sites in California, US, using the open-source seismic hazard analysis software OpenSHA (Field et al. 2003). The earthquake rupture forecast of Petersen et al. (2007) and empirical ground motion prediction and correlation models presented in section 4.1 were used to conduct PSHA and obtain the GCIM distributions of the considered IMs. 12 PSHA cases are considered for this study which are intentionally chosen to span a wide range of deaggregation conditions in order to examine in detail the subsequently presented proposals for causal parameter bounds (more details on the considered PSHA cases are presented in Tarbali and Bradley (2015)). The considered PSHA cases include: (i) large M_w scenarios and small R_{rup} values in the near-fault region (i.e. cases 1-5); (ii) large variability in M_w and R_{rup} of the contributing scenarios (i.e. cases 6-8); (iii) dominant scenarios with small, moderate, or large R_{rup} values (i.e. cases 9-12). Figure 1 presents deaggregation for PSHA case 2, 6, and 11 with the V_{s30}=200 m/s site condition, which illustrates the typical deaggregation results for these three categories of causal parameter distributions. Three different site conditions, with 30 m time-averaged shear wave velocities (i.e. V_{s30}) of 200, 400, and 800 m/s are considered for each PSHA, making a total of 36 PSHA-based ground motion selection cases. The V_{s30} values considered were chosen to represent typical soft soil, stiff soil, and soft rock conditions, approximately corresponding to NEHRP site classes D, C, and A/B, respectively (NEHRP 2003).

3 ALTERNATIVE CRITERIA FOR CAUSAL PARAMETER BOUNDS

3.1 Definition of the considered bounding criteria

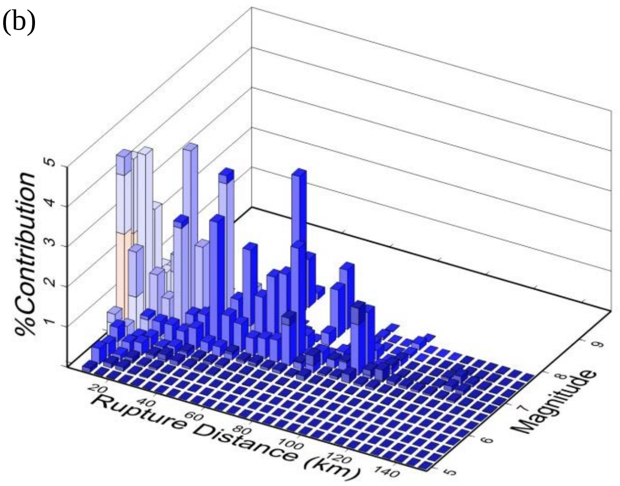
Various bounding criteria for the causal M_w and R_{rup} of prospective ground motions were defined and applied for the considered analysis cases (Tarbali and Bradley 2015). The different bounding criteria were compared in terms of their resulting M_w and R_{rup} ranges in comparison to the deaggregation distributions and the number of available ground motions. Based on the obtained results, two criteria denoted as criterion AC and criterion E are chosen here for comparison as an example for criteria resulting in relatively ‘wide’ and excessively ‘narrow’ bounds, respectively. Criterion AC is defined based on combining two different bound types: criterion A for which the upper and lower bound limits of M_w and R_{rup} are set to values corresponding to 1st and 99th percentiles of their marginal distributions (from deaggregation results); criterion C for which the upper and lower bound limits are first set to values corresponding to 10th and 90th percentiles, and then further extended by $0.5M_w$ and $0.5R_{rup}$ for M_w and R_{rup} , respectively. The reason for extending the bounds is based on the fact that rupture scenarios with a large contribution can exist at the tails of the deaggregation distribution and as-recorded ground motions with causal parameters in the vicinity of these scenarios, but beyond the limits, can still be relevant for ground motion selection for such cases (i.e. consistent with the ranges proposed by prior researchers). For criterion E, M_w and R_{rup} bound limits are set to values corresponding to 20th and 80th percentiles of their marginal distributions. Table 1 outlines the definition of these two criteria (i.e. AC and E).

(a)



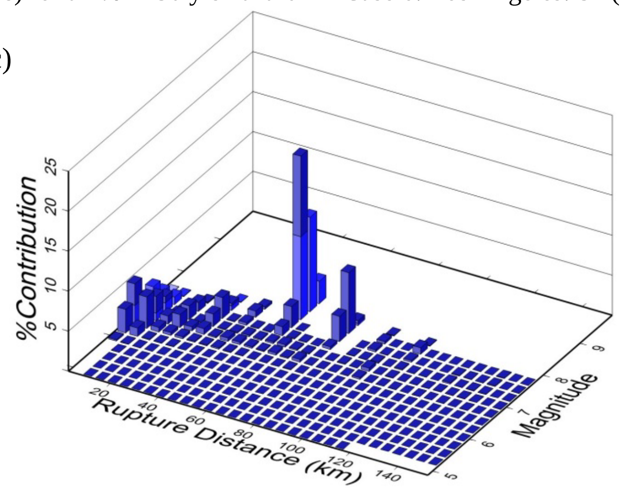
Case 2: San Francisco: SA(0.5s) for a 2% in 50 yrs hazard

(b)



Case 6: Los Angeles: SA(0.5s) for a 50% in 50 yrs hazard

(c)



Case 11: Los Angeles: SA(3.0s) for a 2% in 50 yrs hazard

Figure 1. Deaggregation distribution of three sample PSHA cases with the V_{s30}=200 m/s site condition, representing three categories of deaggregation distributions considered: (a) San Francisco, SA (0.5s) hazard for a 2% in 50 years; (b) Los Angeles, SA(0.5s) hazard for a 50% in 50 years.; (c) Los Angeles, SA(3.0s) hazard for a 2% in 50 years.

Table 1. Bounding criteria AC and E examined on M_w and R_{rup} of prospective ground motions for PSHA-based ground motion selection.

Criterion	Magnitude, M_w		Source-to-site distance, R_{rup}	
	Lower limit	Upper limit	Lower limit	Upper limit
AC	$min(M_w^{1\%}, M_w^{10\%} - 0.5)$	$max(M_w^{99\%}, M_w^{90\%} + 0.5)$	$min(R_{rup}^{1\%}, 0.5R_{rup}^{10\%})$	$max(R_{rup}^{99\%}, 1.5R_{rup}^{90\%})$
E	$M_w^{20\%}$	$M_w^{80\%}$	$R_{rup}^{20\%}$	$R_{rup}^{80\%}$

In addition to the M_w and R_{rup} bounds, the site condition of prospective ground motions are also limited to 0.5 to 1.5 times the V_{s30} of the site as presented in Table 2, ensuring that ground motions within similar soil classes are included for each site condition. The adopted V_{s30} bound is based on numerous sensitivity analyses conducted to investigate the characteristics of selected ground motions with respect to the implemented V_{s30} bound (Tarbali and Bradley 2015).

Table 2. Bounds on site condition of prospective ground motions.

Site condition (i.e. V_{s30} value)	V_{s30}=200 m/s	V_{s30}=400 m/s	V_{s30}=800 m/s
V_{s30} bound: $[0.5V_{s30}, 1.5V_{s30}]$	[100, 300]	[200,600]	[400,1200]

3.2 Application of the defined bounding criteria on sample PSHA cases

Figure 2 illustrates the application of bounds on M_w and R_{rup} for the three sample deaggregation cases with the V_{s30}=200 m/s site condition presented in Figure 1. As shown, criterion AC results in bounds encompassing most of the causal rupture scenarios and extends beyond scenarios with significant contribution at tails of the distribution, whereas, criterion E only encompasses scenarios with the largest contribution to the hazard.

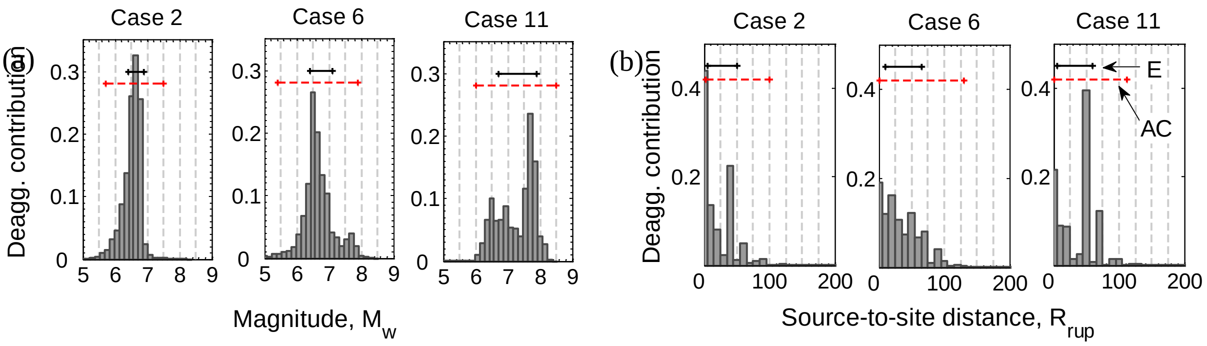


Figure 2. Application of causal parameter bounding criteria AC and E on the three sample deaggregation cases with the V_{s30}=200 m/s site condition: (a) causal magnitude; (b) source-to-site distance.

In addition to the marginal M_w and R_{rup} distributions of considered deaggregation cases, the considered bounding criteria are also compared based on the deaggregation contribution that is 'discounted' (i.e. neglected) by applying bounds on M_w and R_{rup} of contributing scenarios; and the number of available ground motions in the database after applying bounds on the causal parameters. Figure 3 presents the discounted deaggregation contribution for the three sample PSHA cases with the V_{s30}=200 m/s site condition versus the number of ground motions in the NGA-West1 database (Chiou et al. 2008) which satisfy the bounding criteria. As shown, criterion AC results in a lower discounted deaggregation contribution and a larger number of available ground motions across the sample PSHA cases considered, whereas, criterion E results in the opposite trend. This statement holds true for all of the PSHA cases and site conditions considered in this study (Tarbali and Bradley 2015).

In order to investigate the effect of applying bounds on site condition of prospective ground motions (i.e. V_{s30} bounds) in addition to those for M_w and R_{rup}, the number of available ground motions for each PSHA case is calculated twice; first based on M_w and R_{rup} bounds only, and then based on the V_{s30} bound in addition to the M_w and R_{rup} bounds. As shown in Figure 3, the number of the available ground motions after applying the V_{s30} bound decreases significantly for the V_{s30}=200 m/s site condition, which is also the case for the V_{s30}= 800m/s site condition. In contrast, the reduction for the V_{s30}=400m/s site condition is not large (Tarbali and Bradley 2015) due to a relative abundance of stiff soil ground motions in the NGA-West1 database (Chiou et al. 2008) in comparison to those recorded on soft soil or soft rock deposits. In this regard, using a wide bounding criteria such as AC on M_w and R_{rup} ensures that the prospective ground motions databases is not overly restricted to a small number of motions after the application of V_{s30} bounds.

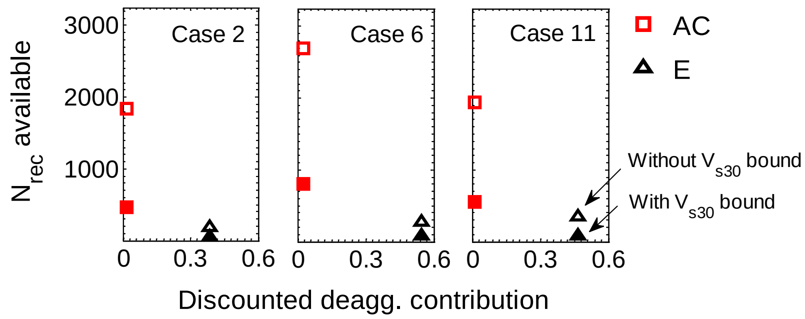


Figure 3. 'Discounted' deaggregation contribution versus the number of available ground motions for the three sample deaggregation cases with the V_{s30}=200 m/s site condition. Open symbols illustrate the results based on only M_w and R_{rup} bounding criteria and the closed symbols illustrate the results based on M_w, R_{rup}, and V_{s30} bounds. The total number of ground motions in the full NGA-West1 database considered is 3222.

It is important to note that a balance should exist between using excessively wide bounds which provide no meaningful benefit (i.e. no different in comparison to having no bounds at all) and using excessively narrow bounds which result in too few prospective ground motions. This balance is particularly important from the perspective that causal parameters are considered of secondary importance relative to explicit intensity measures (IMs) (e.g. spectral acceleration, duration) to characterize the intensity of ground motions for the purpose of ground motion selection. Therefore, using excessively narrow causal parameter bounds seems unnecessary, and as shown in the subsequent section, it can be detrimental from a view point that the remaining ground motions might not be able to appropriately represent the distribution of explicit IMs for the target hazard.

4 EFFECTS OF CAUSAL PARAMETER BOUNDS ON GROUND MOTION SELECTION

4.1 Adopted ground motion selection methodology

The generalized conditional intensity measure (GCIM) methodology of Bradley (2012a) is adopted to select ensembles of ground motions, in which the 'target' for ground motion selection is established based on multiple IMs which accounts for various aspects of ground motion severity (i.e. amplitude, frequency content, duration, and cumulative effects), and incorporates the contribution of all rupture scenarios affecting the probabilistic seismic hazard based on the deaggregation results (Bradley 2010, 2012a). In this study, spectral acceleration for 18 vibration periods (T=0.05, 0.075, 0.1, 0.15, 0.2, 0.25, 0.3, 0.4, 0.5, 0.75, 1.0, 1.5, 2.0, 3.0, 4.0, 5.0, 7.5, and 10.0 s); 5-75% and 5-95% significant durations (D_{s575} and D_{s595}, respectively); and cumulative absolute velocity (CAV) are used as the explicit IMs in the GCIM-based ground motion selection process, with a relative importance emphasised by the presented weight vector in Table 3 (see Tarbali and Bradley (2014) for more details on the implemented weight vector). The marginal distributions of these IMs for the considered PSHAs are obtained based on: Boore and Atkinson (2008) for SA; Bommer et al. (2009) for D_{s575} and D_{s595}; and Campbell and Bozorgnia (2010) for CAV. Correlations between these IMs are considered based on existing empirical models (Baker and Jayaram 2008, Bradley 2011, 2012b).

Table 3. Weight vector considered for GCIM-based ground motion selection.

Amplitude and frequency content	Duration		Cumulative effects
SA ordinates	D_{s575}	D_{s595}	CAV
0.7[1]	0.1	0.1	0.1

[1]Evenly distributed over 18 SA ordinates, e.g. each SA ordinates has a weight of w_i =0.7/18

A total of 20 ground motions are selected (using 10 replicates (Tarbali and Bradley 2014)) from the NGA-West1 (Chiou et al. 2008) database for each of the considered PSHA cases. Three types of causal parameter bounds are considered: no bounds, 'narrow bounds' (i.e. criterion E and the V_{s30} bound), and 'wide bounds' (i.e. criterion AC and the V_{s30} bound). The explicit IM distributions of the selected ground motions in comparison to the target GCIM distribution are used to compare the appropriateness of the ground motion ensembles selected with and without causal parameter bounds.

4.2 Characteristics of the selected ground motions

Figure 4 presents the acceleration spectra of ground motions selected for PSHA case 2 with the V_{s30}=200 m/s site condition and their corresponding median, 16th, and 84th percentiles representing the target GCIM distribution. Figure 4a-c compares the distribution of selected ground motions based on no bounds (Figure 4a), wide bounds (Figure 4b), and narrow bounds (Figure 4c). It can be seen that considering narrow bounds has a detrimental effect on representativeness of the selected ground motions to the target SA distribution, while, considering wide bounds or no bounds does not have such negative effects. Although not presented here for brevity, this holds true for all of the PSHA cases and site conditions considered in this study (Tarbali and Bradley 2015). As mentioned previously, this is caused by an excessive removal of appropriate prospective ground motions using narrow causal parameter bounds.

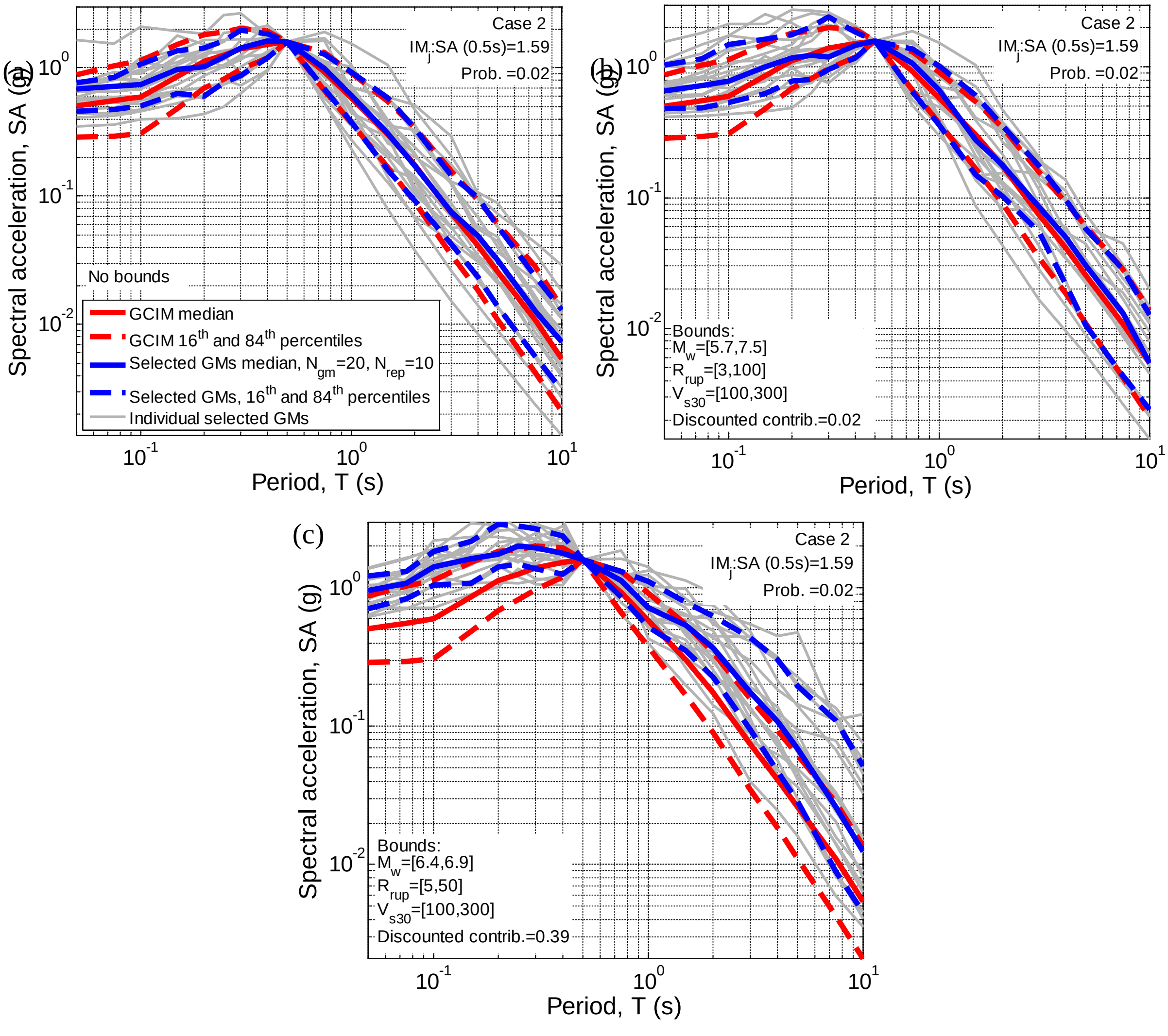


Figure 4. Acceleration spectra of selected ground motions for PSHA case 2 with the V_{s30}=200 m/s site condition and their median, 16th, and 84th percentiles compared with the target GCIM distribution. Ensembles selected: (a) without bounds; (b) with wide bounds (criterion AC); (c) with narrow bounds (criterion E).

In order to examine characteristics of the IMs other than SA ordinates, the CAV and D_{s575} distributions of the ground motions selected for PHSA case 2 are presented in Figure 5, in which the empirical distribution of selected ground motions, target GCIM distribution of the corresponding IM, and the Kolmorogov Smirnov (KS) test confidence bounds at a 5% significance level (i.e. α=0.05) (Ang and Tang 1975) are shown. Statistical rejection that the ground motion ensemble is representative of the target IM distribution occurs if the empirical distribution of the ensemble lies 'outside' the KS test bounds. Figure 5 illustrates that ground motions selected based on wide bounds or no bounds results in ground motion ensembles which are closer to the target distribution than those using narrow bounds for these duration and cumulative-related IMs. Similar results are obtained for ensembles selected for other PSHA cases with V_{s30}=400 and 800 m/s site conditions (Tarbali and Bradley 2015).

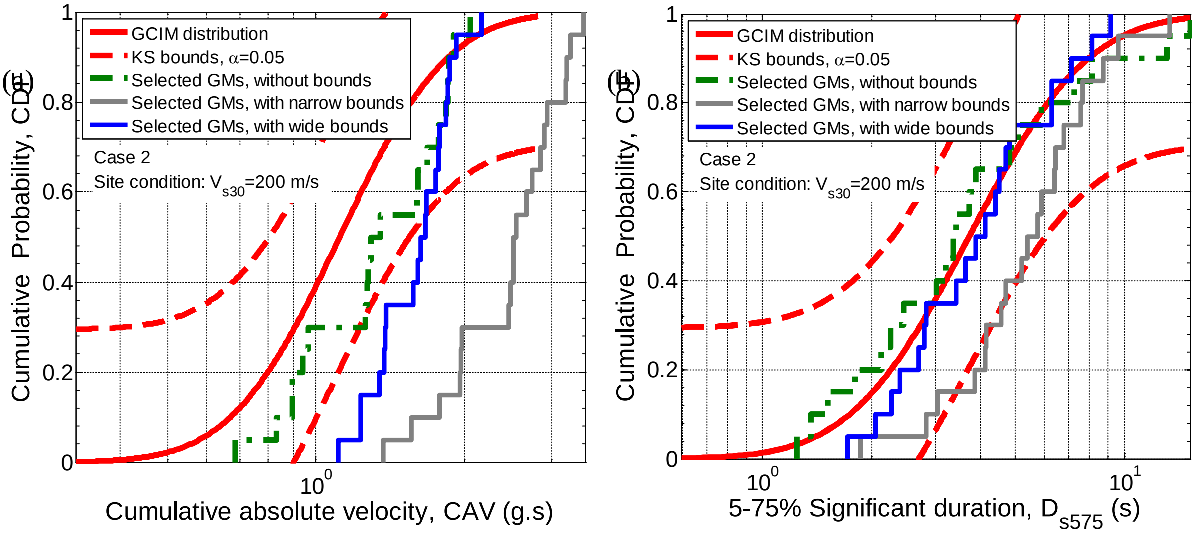


Figure 5. Properties of selected ground motions for PSHA case 2 with the V_{s30}=200 m/s site condition using no bounds, wide bounds (criterion AC), and narrow bounds (criterion E): (a) distribution of CAV; (b) distribution of D_{s575}.

The summary results presented in Figure 4 and Figure 5 illustrate similar ensemble properties for ground motions selected based on (i) no bounds; and (ii) wide bounds. Although not shown due to space limitations, the principal difference between these two cases is evident when the distribution of the causal parameters (i.e. M_w, R_{rup}, V_{s30}) of the selected ensembles are compared, for which obviously the wide bounds case is closer to the deaggregation distribution than that based on no bounds. Further details in this regard are provided in Tarbali and Bradley (2015).

5 CONCLUSION

In this paper, the effect of using bounds on magnitude (M_w), source-to-site distance (R_{rup}), and site condition (V_{s30}) of prospective ground motions for the purpose of ground-motion selection based on probabilistic seismic hazard analysis (PSHA) results was investigated. 36 PSHA cases were considered for ground motion selection, which cover a wide range of causal scenario distributions (i.e. deaggregation results) and site conditions. It was demonstrated that the application of relatively 'wide' bounds on causal parameters can effectively remove ground motions with drastically different characteristics in comparison to the target seismic hazard, resulting in ensembles with an appropriate representation for the target intensity measure distributions as well as a good representation of the underlying causal parameters. In contrast, the use of excessively narrow bounds can lead to ground motion ensembles with a poor representation of the target hazard, as a result of the narrow bounds leading to a small database of prospective ground motions. The specific causal parameter bounding criteria advocated in this study (i.e. criterion AC on M_w and R_{rup}, and the V_{s30} bounds presented in Table 1 and Table 2, respectively) are recommended for general use in ground motion selection from PSHA results as a 'default' bounding criterion. However, if such a criterion results in an excessively small subset of prospective ground motions then variations from this default should be considered.

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