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Conditional Spectrum Record Selection Faithful to Causative Earthquake Parameter Distributions

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SUMMARY

In Performance-Based Earthquake Engineering record selection comes into play at the interface of seismic hazard and structural analysis aiming to repair any loss of essential seismological dependencies caused by the choice of an insufficient intensity measure to be used for structural response prediction. Site-specific selection is best exemplified by the prominent Conditional Spectrum (CS) approach that attempts to ensure a hazard-consistent response prediction by involving site hazard disaggregation. Specifically, CS utilizes a target spectrum (with mean and dispersion) that, in its latest formulation, accounts for all the scenarios (in terms of magnitude, M, and closest to rupture distance, R) contributing to the hazard of the site at a given intensity level. The ground motion records, however, are selected to match this target spectrum based solely on their spectral shape but with no explicit consideration to their underlying M-R characteristics. The main focus of this study is to explore whether the reintroduction of M-R criteria in the selection process preserves hidden dependencies that may otherwise be lost through a spectral-shape-only proxy. The proposed record selection method, termed CS-MR, offers a simple approach to maintain a higher order of hazard consistency able to indirectly account for metrics that depend on M-R (e.g., duration, Arias intensity) but are not captured in the response spectra. Herein the CS-MR response prediction is favorably compared to CS and to the Generalized Conditional Intensity Measure (GCIM) methods that select records according to, respectively, spectral shape only and, for the case at hand, to spectral shape plus duration.

1 Introduction

The objective of Performance-Based Earthquake Engineering (PBEE) [1] is the estimation of the probability of damage and/or losses due to earthquakes that a structure is likely to experience in a given period of time. This information is essential to decide the fitness for purpose of a structure, either existing or new. If usable empirical building damage and loss data for different classes of buildings that experienced past earthquakes were plentiful, this estimation would be carried out in an empirical way. Since these data are scarce for some building classes and non-existent for others, in practice this task is carried out analytically and available data is utilized either for calibration or validation. A key step in the analytical implementation of the PBEE framework prior to damage and loss estimation is the evaluation of the distribution of engineering demand parameters (EDPs) experienced by the structure for multiple levels of ground motion severity. In this framework, the EDP values caused to a structure by a ground motion are traditionally predicted through the knowledge of only a single intensity measure (IM), such as PGA or spectral acceleration, *Sa(T)*, at a given oscillatory period of vibration, *T*.

Due to the significant advances in finite element modeling software, the analytical approach for structural response analysis is often carried out via Nonlinear Dynamic Analysis (NDA). NDA requires as input a suite of ground motion records that encompasses the entire range of IM values likely to occur at the building site. If any two different sets of (a very large number of) randomly selected ground motions sharing the same value of an IM (or the same distribution of that IM) caused two statistically indistinguishable EDP distributions when separately applied to the same structure, then there would be no need for complicated ground motion selection techniques. The two distributions of the EDP given IM would be identical for both sets and, down the line, so would be the two estimates of the probability that that building at the given site would exceed any level of EDP in a given period of time. Unfortunately, this is not the case because, in general, the structural response given an IM, say *Sa(T)*, is still dependent on the other characteristics of the ground motions, such as such as spectral shape at other periods [2] and duration of the motion [3]. Hence, if in the example above these two EDP distributions given IM are different, how shall one proceed in selecting the "right" records for NDA?

This is a key but often neglected question in applications of PBEE. Record selection for site-specific building risk assessment did not always receive the attention it deserves by practitioners. In fact, NDA is often performed using predefined site-independent record sets, such as those suggested by FEMA P695 [4], that are adopted without much of a scrutiny beyond a rather superficial consideration regarding their appropriateness for the scenarios that may pose a threat to the site at hand. The only legitimate, statistically robust answer to this question would be to assemble a set of ground motions whose *joint distribution of all IMs* that influence the EDP is consistent with that of the ground motions that the earthquake scenarios controlling the hazard at the site are likely to generate. Strictly speaking, finding a set of ground motions that empirically fits well the joint distribution of all IMs at a site is, however, an impossible objective to meet because the databases of real ground motions from many combinations of earthquake scenarios, here defined in terms of magnitude, M, and source-to-site distance, R, are not large enough. However, we can approximate the theoretically correct solution, as discussed below.

In the existing literature, different simplified record selection schemes have been proposed in order to approximately enforce the *consistency* of the selected records with the site hazard. Both schemes hinge on considering only a single IM for representing the ground motion severity at any hazard level of interest. These schemes may be classified into two main categories: namely '*scenario-based selection'* and '*target-based selection*' [5].

In the *scenario-based selection* methods, for any IM value associated with the desired hazard level, the selected records fall in bins around central values of seismic parameters such as M, R, site class and epsilon (namely, the number of standard deviations that the ground motion for the given causative scenario is away from the median) [6-9]. If PSHA is available, the causative parameters (e.g. M and R) of the scenario that contribute most to the site hazard are obtained from disaggregation analysis [10] for the IM value associate with the hazard level of interest. In this class of methods, one assumes that the distribution of all other ground motion characteristics that matter for structural response prediction at that site is implicitly obtained by selecting records from past earthquakes that share the same values of the parameters of the scenario earthquakes of interest. Therefore, in these methods the hazard consistency is addressed only in terms of the selection of the causative parameters of the scenario(s) that contribute the most to the hazard gauged by the chosen IM.

The *target based selection* methods, instead, go a step further, namely they chose a set of records to explicitly match a target distribution of ground motion characteristics beyond the conditioning IM employed, such as additional spectral ordinates, duration, or simply other IMs of interest [2, 5, 11-18].

The conditional mean spectrum (CMS), the conditional spectrum (CS) and the generalized conditional intensity measure (GCIM) approaches belong to this second group. CMS [2, 19] accounts for hazard consistency only in terms of the median of the target spectrum, while CS [16] includes, as its target, both the median and variance of the spectral ordinates. However, CS and CMS, in their most recent formulation, implicitly accounts for the contributing scenarios to the seismic hazard only by generating the target spectra. The earthquake scenarios do not enter in any other way the record selection. In fact, for the CMS and CS methods, spectral shape is the only quantity that is presumed to affect the structural response. Therefore, according to this assumption, there is no gain in enforcing record selection to be hazard consistent also in terms of any other earthquake causative parameter. Spectral shape is for sure of paramount importance in estimating building response but, in general, other characteristics do matter as well. For example, many authors have pointed out the differences between pulse-like and non-pulse-like ground motions with regard to selection [20, 21]. Furthermore, some studies have found little effect of duration on building response [22-25], while others argued for a significant effect if appropriate modeling assumptions are adopted [26]. Among others, Chandramohan et al. [27] showed this dependence for a building characterized by cyclic degradation behavior using spectrally-equivalent record sets of differing duration to offer evidence that duration matters, especially when the goal is to predict building global collapse.

GCIM [17] extends the concept of CS to a generalized format to explicitly enforce hazard consistency beyond spectral shape for any parameter that *a priori* is deemed to impact the structural response. Chandramohan et al. [3] employed GCIM to successfully account for the effect of duration, mitigating any bias in the estimated collapse risk at sites whose hazard is affected by both nearby crustal faults (i.e., ground motions with short durations) and subduction zones farther away (i.e., ground motions with long durations). In theory, GCIM could offer a 'perfect' solution for selecting hazard-consistent ground motions on the basis of any characteristic of importance but it has two important caveats that limit the its applications in real case studies. First, the identification of all such characteristics of interest for response prediction is a non-trivial task that requires a time-consuming study to be conducted prior to record selection. Second, its application requires a sufficiently broad and well-populated catalogue of records to select from especially when a few additional IMs are deemed important.

As a simplified but practical alternative for adding more parameters to the ground motion selection, one could instead directly employ the parameters of the causative scenarios contributing to the hazard, in a way merging the aforementioned scenario and target based approaches. So far, causative parameters have been explicitly considered with various degrees of success to constrain the pool of eligible ground motions in the database prior to the selection. For example, Chandramohan et al. [3] employed tight source-specific M-R bounds along with CS, concluding that the reduced number of ground motions left available after the enforcement of the additional limitations resulted in pools of selected ground motions that were poorly consistent with the target site hazard in terms of both spectral shape and duration distribution. On the other hand, placing broader M-R limitations on the ground motions available for selection has been found to have positive effects by removing ground motions with drastically incompatible characteristics with those likely to be observed at the site and in the end resulting in an overall more efficient record selection [28, 29].

Herein, we provide a CS-based approach that explicitly enforces consistency with both the spectral shape and the distribution of the M-R parameters of the causative earthquakes. Termed CS-MR, this approach performs well in matching the target spectrum (mean and variance) while implicitly providing acceptable hazard consistency in terms of ground motion duration distribution and, last but not least, potentially capturing as well, albeit in an approximate sense, the distribution of other magnitude-distance dependent ground motion characteristics that may affect the structural response.

2 Conditional Spectra including causative scenario parameters

2.1 Conditional spectra based record selection

The CS record selection [16, 30, 31] approach comprises two main steps: (i) generation of target spectra including a conditional mean and dispersion of spectral accelerations at multiple vibration periods conditioned on the IM of choice and, (ii) an efficient simulation algorithm integrated with an optimization technique that allows selecting and scaling a suite of records that collectively "match" the simulated target. The conditioning IM could be any spectral ordinate that is relevant to the response of the structure, such as spectral acceleration at the first modal period of the structure, $S_a(T_1)$, or the spectral acceleration averaged in a period range, *AvgSA* [32], for which PSHA and disaggregation analyses are carried out. Estimation of the target CS utilizes available ground motion prediction equations (GMPEs), with the input of (causative) parameters that represent the hazard, together with the correlations between the spectral accelerations at different periods (e.g.[33]). In generating the target spectrum, some studies made use only of the mean value of causative parameters (e.g. mean of magnitude and distance) of the scenarios contributing to the hazard; this approach is usually labeled as the 'approximate' method (henceforth termed *CS-approx*). Lin et al. [30], accounting for the variability in the target spectra due to multiple causative parameters (from disaggregation analysis) and GMPEs (adopted in hazard computations), proposed an improved method (called here *CS-exact*), that modifies the target spectra by inflating the target conditional dispersion and adjusting the target conditional median values.

Once the target spectra are generated, using the multivariate lognormal distribution and based on the lognormality assumption of the spectral accelerations [34], *N* response spectra (with *N* representing the number of required ground motion records in the set) are simulated for each hazard level. Then, the *N* records whose response spectra ensure, one by one, the best match with the simulated response spectra are selected from a reference strong ground motion database. CS benefits also from a 'greedy' optimization technique: the selected records' spectra are substituted one at a time with those previously discarded in order to further improve the match with the target mean and dispersion.

When utilizing the exact method, the CS procedure statistically reproduces the spectral shape of the records consistent with those expected at the site. However, the selected records do not necessarily reproduce the distribution of the causative parameters M and R obtained from disaggregation analysis. This mismatch may become a source of bias in the response prediction and this is the main motivation for a different approach.

2.2 Proposed post processing algorithm to CS accounting for causative parameters

CS-MR is essentially an extension of the *CS-exact* record selection via a post-processing algorithm that accounts for the earthquake ground motion's causative parameter distribution. Disaggregation analysis quantifies the contribution of the contributing earthquake scenarios at any specific hazard level (e.g. 10% in 50 years), typically per discrete M-R bin. Therefore, after the user has chosen the desired bins of magnitude and distance, the proposed algorithm provides a set of records that, in addition to statistically matching the spectral shape of the CS, also respects the contribution of each M-R bin identified by the disaggregation results. In particular, after the CS record selection is completed, the algorithm discards the records that do not belong to any of the desired M-R bins and those that exceed (in number) the contribution of each bin to the specific hazard level; then it adds the desired ground motions from the underrepresented M-R bins creating a set that is consistent with both disaggregation results and spectral acceleration distribution of the target CS.

More formally, let N be the total number of records in the set (say 20) for a given target CS, N_i the number of records in the i^{th} bin and P_i the percentage of the i^{th} bin's contribution to that hazard level (say 22%). The number N_i of desired records from the i^{th} bin in the final ensemble is the nearest integer to $P_i \times N$ (here 4). Therefore, if in the first pass there are too few records from the i^{th} M-R bin (say 3), the missing number of records with these M-R characteristics (in this case only 1) is added to the ensemble and the same number is removed from other bins with too many records. With the overall criterion of matching the target CS in mind, among all possible still unused records in the database that belong to the i^{th} M-R bin, the algorithm adds those with spectral shapes closest to those previously elected but now removed because caused by earthquakes of a different M-R bin. The similarity between a ground-motion response spectrum and a discarded response spectrum is evaluated using the sum of squared errors (*SSE*):

$$SSE = \sum_{n=1}^{H} \left(\ln Sa\left(T_n\right) - \ln Sa^{(t)}\left(T_n\right) \right)^2 \quad (1)$$

Where $\ln Sa(T_n)$ is the logarithmic spectral acceleration of the scaled ground motion at period T_n; $\ln Sa^{(t)}(T_n)$ is the target $\ln Sa(T_n)$ value from one of the response spectra of the discarded ground motions, *H* is the number of periods considered in the CS-matching exercise and *SSE* is the sum of squared errors used as a measure of dissimilarity. This procedure is repeated for all the M-R bins to cover all of the missing records of the set. As described, however, this procedure has an element of arbitrariness since it is sensitive to the order applied for the M-R bins for the record filling-and-removing operation. With the same spirit of the aforementioned "greedy" approach, the procedure is performed *K*! times where *K* is the number of M-R bins considered in the disaggregation. As a factorial number of repetitions may become quite time consuming in any calculations, one should restrict this exhaustive search to only the most influential M-R bins (e.g., 2 to 6 in our experience) as iterating over the remaining ones does not make any appreciable difference in the match of the final CS. Among the *K*! sets produced, the final ensemble of retained ground motions is the one that provides the lowest discrepancy from the original target CS spectrum, according to the following equation [16]:

$$SSE_s = \sum_{n=1}^{H} \left[\left(\hat{m}_{\ln S_a(T_n)} - \mu^{(t)}_{\ln S_a(T_n)} \right)^2 + w \cdot \left(\hat{s}_{\ln S_a(T_n)} - \sigma^{(t)}_{\ln S_a(T_n)} \right)^2 \right] \quad (2)$$

Where SSE_s is the sum of squared errors of the set, which is the parameter to be minimized. For a given period T_n, $\widehat{m}_{\ln S_a(T_n)}$ is the mean $\ln S_a$ value of the set, $\mu^{(t)}_{\ln S_a(T_n)}$ is the target mean $\ln S_a$ of the CS, $\hat{s}_{\ln S_a(T_n)}$ is the standard deviation of $\ln S_a$ of the set, $\sigma^{(t)}_{\ln S_a(T_n)}$ is the target standard deviation of $\ln S_a$ of the CS, and *w* is a weighting factor indicating the relative importance of the errors in matching the standard deviation and the mean. In line with the procedure performed for the *CS-exact* approach [2], *w* has been assumed equal to 2, giving a higher degree of importance in matching the target standard deviation rather than the target mean. The algorithms and MATLAB [35] scripts utilized for the implementation of this method in this study are available at [36].

3 Qualities and challenges of CS-MR record selection

3.1 Which ground motion characteristics are dependent on M and R?

At this stage a question could be raised: What is the advantage of selecting the records consistent with hazard disaggregation of M and R? Intuitively, CS-MR, besides imposing the spectral shape via the CS framework, ensures that other ground motion characteristics that depend on M and R are 'naturally' accounted for. We provide three supporting arguments on the usefulness of the CS-MR record selection along with pertinent implementation challenges.

Firstly, since it makes use of the same target spectrum as the CS method, one may think that adopting the CS-MR approach may not bring any additional advantage in terms of improving the hazard consistency of the spectral shapes of the final ensemble of selected records. However, this is not completely true: the CS approach selects a set of records that collectively reproduce the target conditional distribution of spectral accelerations at a site. However, the CS method does not check whether the spectral shape of each selected record is "appropriate" for the site and intensity level of interest. The CS method could potentially lead to selecting records that were not caused by earthquake scenarios that are likely to cause the exceedance of the corresponding ground motion IM level at the site. In other words, given the high dependency of the spectral acceleration on M and R, the selected records may only have collectively the desired spectral shape but not singularly. As an illustrative example, the ensemble of a CS associated to a high IM level mainly controlled by large magnitude events at moderate distances may end up including many records (perhaps scaled) associated with low magnitude events at short distances because of their large S_a values at short periods and low S_a values at longer periods. CS-MR, by considering M and R in an explicit way, provides an internal control on the selected records avoiding the choice of ground motions with spectral shapes that are unlikely to be observed at the site. Of course, there are challenges in its implementation. Due to the limitations of the available ground motion databases, finding records that simultaneously have both the required M and R and the required spectral shape is not an easy task. Therefore, when applying the CS-MR approach, one has to accept a slightly lower adherence to the target CS than what is provided by the CS-exact method.

Secondly, since ground motion duration is in many cases a parameter that can significantly affect the structural response, a proper record selection procedure should account for its hazard consistency. Several metrics that explicitly or implicitly consider duration exist in literature, e.g. significant duration (D_{S5-75} or D_{S5-95}, collectively termed D_S henceforth) [37], Arias Intensity [38], cumulative absolute velocity (CAV) [39, 40], and bracketed duration [41]. Chandramohan et al. [27] performed a comprehensive study showing that D_S is superior to other duration metrics mainly because: i) it is not correlated to other common IMs (e.g. $S_a(T, 5\%)$ and PGA), ii) it is not dependent on record scaling, iii) it is not a hybrid metric of duration and intensity and, iv) together with amplitude-based IMs (such as S_a) it can improve the prediction of collapse. Herein, in line with the mentioned study, D_S is considered as the reference measure for validating the CS-MR method in terms of duration hazard-consistency. Since D_S is strongly dependent on M and R and it is not affected by scaling, the selected CS-MR record sets (especially if the number of selected records is large) are expected to naturally reproduce the duration distribution at the site. Because of database limitations, however, CS-MR needs the records to be scaled (within reasonable bounds) in order to fulfill the requirements in terms of, amplitude, spectral shape and causative parameters distribution. For this reason, unless the scaling factors are close to one, CS-MR may not be able to select records that match the distribution of other scalable IMs such as peak ground velocity or CAV. Even though such IMs depend on causative parameters, they are not dimensionless and, therefore, they are sensitive to scaling.

Thirdly, CS-MR is admittedly less rigorous but certainly intuitively simpler than GCIM, which allows the user to select records that match the distribution of any pre-specified IM of interest. Obviously, ground motion databases' limitations imply that imposing more constrains always comes at the cost of lower fidelity in meeting them. Thus, CS-MR offers a less user-tunable but considerably more user-friendly compromise in achieving hazard consistency, freeing the user from deciding a priori which ground motion characteristics are important for the structure and site at hand.

3.2 Bin selection, criteria and assumptions

Several popular approaches have appeared in the literature, e.g. [2, 7, 29], that call for constraining the ground motion database on the basis of the parameters of the causative earthquake. These proposals, however, either deal with a single scenario ground motion, with specific M and R values, or, if they are conducted for a PSHA-based record selection, they do not specifically introduce causative parameter bins to reproduce the distribution obtained from disaggregation. Tarbali and Bradley [28], on the basis of a comprehensive test for thirty-six PSHA cases, investigated the impact of causative parameter bins prior to a GCIM based record selection. In order to be able to match the desired target, they suggested the application of wide intervals, especially on M and R, in accordance with those customarily used in hazard disaggregation. That approach has the main advantages of i) reducing the computational effort because of the use of a trimmed ground motion database and, ii) avoiding the selection of record characteristics that are very different than those of the scenarios controlling the target seismic hazard. However, none of these approaches is capable of preserving the causative parameters' distribution provided by the hazard disaggregation.

CS-MR, on the other hand, aims to overcome the shortcomings of the aforementioned approaches by maintaining a higher order of hazard consistency. In particular, as mentioned, once appropriate intervals for M and R are defined, the procedure selects a set of ground motions that collectively match the required distribution of spectral ordinates but also preserve the M-R characteristics of relevance for the site. More specifically, an *a posteriori* M-R disaggregation of the record set will reflect exactly the same scenarios that contribute to the exceedance rate of the IM level for which the CS is constructed. Table 1 shows the four M and three R discretization intervals making for 4×3=12 bins that were chosen for a case study site in Seattle (122.3° W longitude and 47.6° N latitude). Figure 1a shows the changes in the median spectral shapes for ground motion records belonging to the selected bins computed using the GMPE of Boore and Atkinson (BA08) [42] for rock site conditions (Vs_{30}=800m/s). Therein, all the spectra are normalized to S_a(1s)=0.4g in order to make the differences in the expected spectral shapes more obvious. The ground motions belonging to each bin, on average, have markedly different spectral shapes and $D_{S5\text{–}75}$ values in line with the different tectonic regimes influencing the hazard, with large interface subduction events dominating the M>8 bin relative to crustal and in-slab earthquakes. For different sites, the bins should be selected according to disaggregation results to similarly distinguish the seismic sources that influence the hazard. Finer discretization would make the record selection too computationally heavy (or even impossible, due to database limitations), while a coarser one may not be effective in preserving the M-R and duration distributions. Figure 1b shows the median $Ds_{5\text{–}75}$ for the selected bins based on the GMPE of Abrahamson and Silva (AS96) [43]. Even though this GMPE is applicable to magnitudes up to M7.5, for illustration purposes only the median values have been extrapolated here to estimate durations up to M9.0.

Table 1 - Magnitude and distance intervals considered as reference for CS-MR record selection

Interval	**1**	**2**	**3**	**4**
Magnitude (M)	4.5≤ M <6.0	6.0≤ M <7.0	7.0≤ M <8.0	M ≥8.0
Distance (R) [km]	0≤ R <30	30≤ R <80	R ≥80	

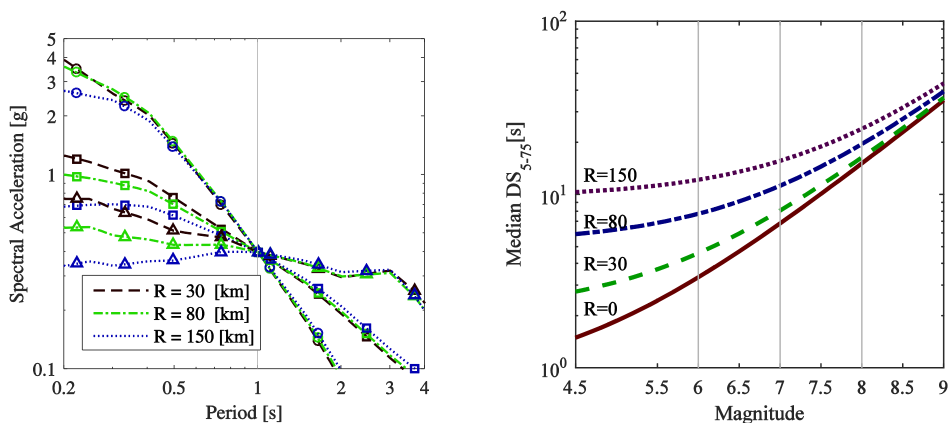

Figure 1 (a) Illustration of the expected spectral shape of ground motions of different M-R scenarios (Legend: circle, M=4.5; square, M=7.0; triangle, M=9.0) based on BA08; (b) median $Ds_{5\text{–}75}$ of earthquake scenarios versus M-R based on AS96.

Figure 2 presents an illustrative example of the CS-MR procedure. In particular, Figure 2a shows the disaggregation results based on the bins of Table 1 for a site in Seattle for the 5% in 50 year value of S_a(1.6s) = 0.37g. The set of 100 records selected by the *CS-exact* approach has a M-R distribution (Figure 2b) that is clearly inconsistent with the target M-R distribution of Figure 2a. In particular, while most of the hazard contributions for this IM at this hazard level should come from bins ‘M=6.0–7.0, R=0–30km’, ‘M=7.0–8.0, R=30–80km’ and ‘M>8, R=80–300km’, the records blindly selected by the *CS-exact* method for this case are rather uniformly distributed among all bins. The *CS-exact* set was used as seed for the CS-MR procedure, which altered the selection to perfectly match the M-R distribution of Figure 2a. Figure 2c and Figure 2d compare the two competing 100 record sets in terms of conditional median and dispersion spectra, respectively. The price paid to keep track of the M-R causative scenarios appears as a slightly inferior consistency with the target CS, particularly in terms of conditional dispersion. This discrepancy is only due to the ground motion database limitations and it typically increases with IM level due to the scarcity of ground motions from large magnitude events that usually cause large IM levels. However, since these high levels of ground motion are very rare, the observed differences do not influence significantly the loss estimates of most structures and only mildly impact the estimates of collapse rates.

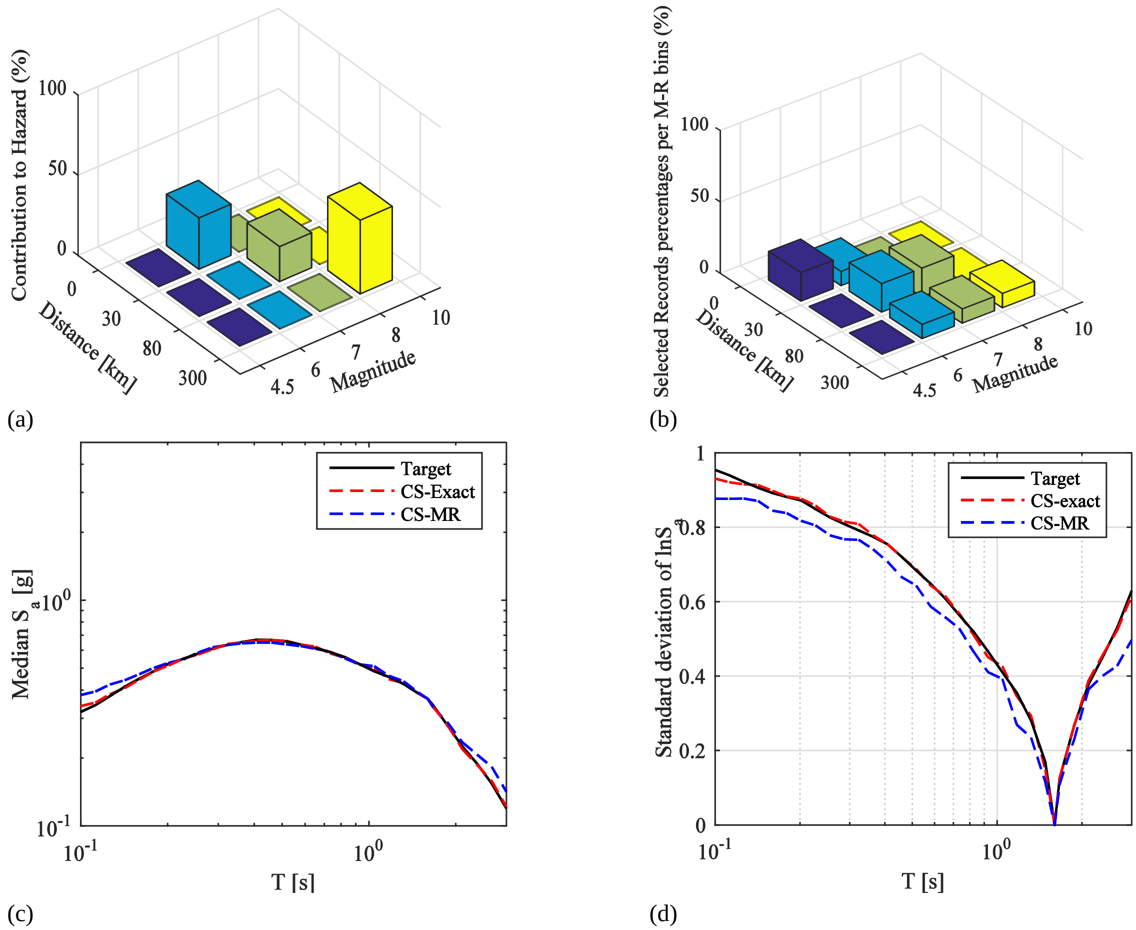

Figure 2 – Comparison of record selection based on CS-exact and CS-MR methods for a site in Seattle corresponding to a conditioning period of *T*=1.6s for the 5% in 50 years value of S_a(1.6s)=0.37g. (a) M and R disaggregation, perfectly matched by CS-MR; (b) Hazard inconsistent M and R distribution of the records selected by the CS-exact method, (c) conditional median of the target and selected record spectra, (d) conditional dispersion of the target and selected record spectra.

4 Case Study: RC modern frame located in Seattle

4.1 Selected site and test building

The aforementioned site in Seattle was chosen as a reference site to illustrate the impact of different types of seismic sources on seismic hazard and, consequently, on risk. Seattle is located in a tectonic region that is exposed to both crustal and subduction events due, respectively, to faults located under the city and to the nearby Cascadia subduction zone, which runs offshore parallel to the coast. Figure 3b shows the disaggregation results extracted from the USGS web tool ([44] and [45], currently merged in the so-called Unified Hazard tool [46]) using the GMPEs logic tree of [47] (at 2% in 50 years exceedance probability for spectral acceleration at T=1s). The multimodal nature of the scenarios contributing to the hazard can easily be observed. In particular, the far and large magnitude earthquakes are caused by the Cascadia subduction zone while the closer events are due to the crustal faults underneath the city.

The test building is a 7-story plan-symmetric reinforced-concrete (RC) perimeter moment-resisting frame designed according to post–2000 provisions for high seismicity regions (site class D according to NEHRP classification [48]) with a first mode period of T_1=1.6s [49]. A 2D multi-degree-of-freedom model is developed in Opensees [50] using lumped-plasticity beam-column elements for both beams and columns. The point-hinge moment-curvature backbone is based on the work of Panagiotakos and Fardis [51]. It has a moderately pinching hysteresis and captures both in-cycle and cyclic strength and stiffness deterioration. P-Delta effects are incorporated while a pinned leaning column is included to account for the gravity-system mass. Maximum inter-story drift ratio (MIDR) larger than 10% and maximum residual drift ratios (RDR) larger than 4% are employed as deterministic collapse thresholds [52].

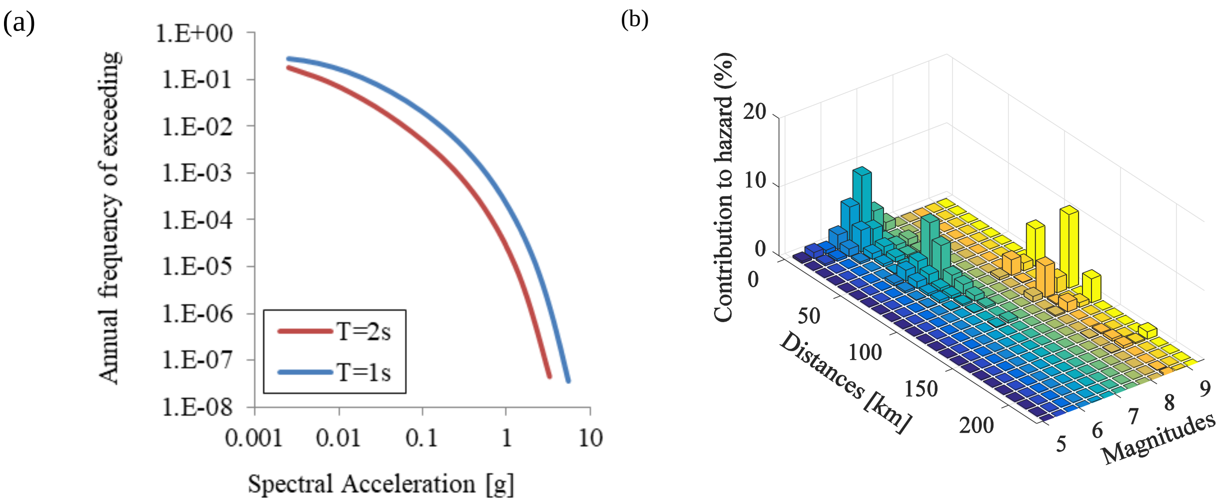

Figure 3 Hazard analysis results for a Soil Type D in Seattle based on the USGS web tool: a) hazard curves for spectral accelerations at *T*=1s and 2s; (b) M-R disaggregation results for 2% in 50 year spectral acceleration at *T*=1s.

The sensitivity of the building model response to duration has been verified by performing a series of Incremental Dynamic Analyses (IDA) [53] based on two sets of 146 pairwise *spectrally equivalent* long- and short-duration records [27]. Essentially, these are record pairs, one of long and one of short duration that, after scaling, have approximately the same S_a spectrum in the [0.05,6sec] oscillator period range (Appendix of [54]). Figure 4 shows IDA and the subsequent fragility collapse curves illustrating the building's sensitivity to record duration. The median collapse capacity in terms of $S_a(T_1$=1.6s) is equal to 0.67g and 0.46g when using short- and long-duration sets, respectively. This difference, given the equivalence in the spectral shape of the two sets, stems mainly from the cumulative damage due to the increased number of cycles of the ground motions in the long-duration record set. It is worthwhile noting that, by design, the impact of duration is amplified in this test with respect to what it would occur in a more realistic case study for Seattle, where any hazard-consistent record set would contain a mix of long- and short-duration ground motions from subduction and crustal earthquakes.

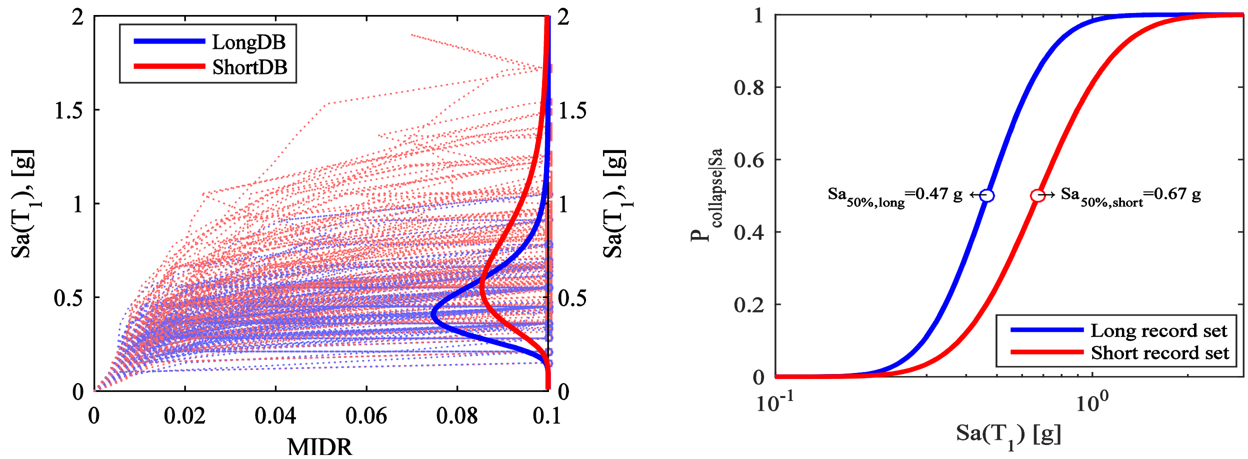

Figure 4 Verification of the building model's sensitivity to ground motion duration; comparison of: a) IDA curves for MIDR; and b) collapse fragility curves for two sets of 146 spectrally-equivalent short- and long-duration records.

5 Ground motion selection

Adopting a multiple stripe analysis approach [55], ten different intensity levels were considered at $S_a(T_1$=1.6s) values equal to 0.06, 0.12, 0.17, 0.25, 0.37, 0.5, 0.63, 0.74, 0.83, 0.97g, with return periods between 30 and $2{\cdot}10^4$ years. At each level, sets of 100 records were selected to be hazard-consistent with the case study site via four target-based methods: CS-approx [2], CS-exact [30], GCIM [17], and CS-MR. CS-approx and CS-exact compose the CS-only group, which as originally cast accounts only for the spectral ordinate distribution.

As mentioned earlier, CS-approx employs a target conditional spectrum conforming to the top-contributing M-R scenario obtained via hazard disaggregation at each intensity level. In its original format, a single target distribution is determined for CS-exact pooling together all sources (and PSHA logic tree branches, if the case). Instead, CS-exact considers "all" M-R bins to determine the spectral target. This makes it amenable to further refinement, e.g., by separately considering different target distributions for different source types (e.g., subduction in-slab, subduction interface and crustal) and preserving the relative contribution of each source in the selected record set [3] [56]. In our application of CS-exact, at each intensity level the target distributions were estimated separately for each of the 3×4 M-R bins having at least a 10% contribution to the hazard. Then the number of ground motion records selected to match each distribution was proportional to the contribution to the total hazard due to its M-R bin. Thus, if for a given intensity level three bins contributed 25%, 60% and 15% (reweighted from original values to sum to 100%) of the hazard and, say, 100 ground motions were budgeted for this hazard level, then target conditional spectrum was matched using 25 records, the second with 60 records and the third with 15 records. Note that no M-R restrictions were posed when selecting records to match the CS for a given M-R bin. Thus, even if the target distribution for the third bin was essentially due to M>8 earthquakes, records caused by M<8 events were allowed to be selected as long as they collectively provided a good match of the target CS.

To provide a comparable proposal, GCIM is herein structured to account explicitly in the record selection for both spectral shape and duration, here measured by $D_{S5\text{–}75}$ (results being similar for $D_{S5\text{–}95}$), but without consideration to the M-R characteristics of the causative event. In particular, the algorithm of [30] was modified by adding $D_{S5\text{–}75}$ as an extra intensity measure to a vector of response spectral ordinates at different periods. In line with what assumed in [3], the quality of fit for the considered S_a and $D_{S5\text{–}75}$ vector is assessed by means of the Kolmogorov-Smirnov test (K-S test). The same approach described above for the improved variant of the CS-exact was adopted for the definition of the target distributions for both duration and spectral shape specific to each M-R bin.

The proposed CS-MR approach is the only one that explicitly accounts for hazard compatibility in terms of both spectral shape and M-R distributions, the latter described by the M-R binning of Table 1. This method employs only a single spectral distribution incorporating all causative scenarios (rather than one spectral distribution per M-R bin) but it accounts for different seismic sources by selecting the records with hazard-consistent M and R characteristics.

In all four cases, we utilized the same NGA-West2 database [57] of ground motions from crustal events along with additional 4106 ground motions caused by subduction zone earthquakes. The latter were included to better populate the database with large magnitude and long duration records such as those that may hit Seattle from events on the Cascadia subduction zone. These additional ground motions were generated by the 2003 Tokachi (Japan), 2007 Kuril Island (Russia), 2011 Tohoku (Japan), 2011 Iquique (Chile), 2013 Okhotsk Sea (Russia), 2015 Chichi-Shima (Japan) and the 2015 Illapel (Chile) earthquakes [58], which have magnitudes between 7.5 and 9.0. Figure 5a shows the scatter plot of M and R of the ground motion database along with the M-R upper and lower bounds of the 3×4=12 bins, as defined in Table 1. Figure 5b shows the scatter plot of magnitude versus $D_{S5\text{–}75}$, highlighting the diverse ground motion durations that characterize the two datasets, as well as the well-known correlation of duration and magnitude.

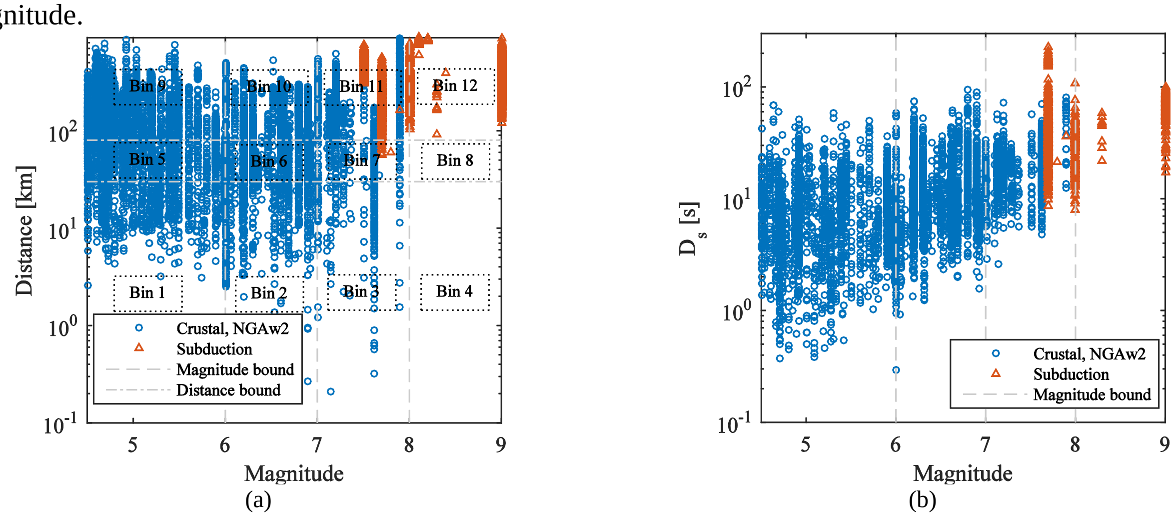

Figure 5. (a) Scatter plot of magnitude and distance of the causative events; and (b) Scatter plot of magnitude and duration for the ground motions in the database used in this study.

The main assumptions and working hypotheses adopted in the four record selection approaches are summarized below:

- The full set of GMPEs used in the PSHA calculations were included in the target spectra generation for the CS-MR, GCIM and CS-exact methods (along with their corresponding weights defined in the logic tree), while the CS-approx method considered only the GMPE with the highest branch weight. The GMPE parameters were estimated using the suggestions in [59].
- Since GCIM explicitly models duration, a prediction equation for duration was needed to define the proper target distribution. In line with [3] and lacking at the time of this writing a GMPE specific to ground motions from large magnitude subduction zone events, the AS96 [43] model was adopted despite its limitations.
- The target conditional distributions of S_a and $D_{S5\text{–}75}$ were defined using the correlation coefficient models of [33, 60], respectively.

- The ground motion records were selected on the basis of the geometric mean of the S_a of the two horizontal components.
- Until the 8th IM level, scale factors were limited to 7; for higher levels values up to 10 were allowed.
- The target spectral accelerations are defined for 40 period values in the range 0.1–3.0s. This range includes the most significant spectral ordinates for predicting the the response of the selected structure.
- Soil type D (NEHRP classification[48]) is assumed. Consequently, the selection was limited to accelerograms recorded at stations characterized by average shear wave velocity, $V_{s,30}$, of the top 30m of the soil profile between 100 and 400 m/s.

Figure 6 compares the empirical distributions of both D_{S5-75} and spectral acceleration for the 5% probability of exceedance in 50 years IM level (i.e., the 5th level considered, designated IML 5) extracted from the selected records. The results of CS-approx are not shown as it considers M-R characteristics neither for the target spectrum, nor for the record selection phase and, therefore, such a comparison would be meaningless. Figure 6 presents the results for bins 2, 7 and 12, which are characterized by 32%, 22% and 46% (reweighted) contributions to the hazard, respectively. The Bins 2 and 7, which represent the scenarios with 'M=6–7, R=0–30km' and 'M=7–8, R=30–80km', are mainly related to crustal and subduction-inslab events, while bin 12 refers to scenarios with 'M>8, R=80–300km' related to subduction-interface earthquakes. The charts in the left panel of Figure 6 include the target D_{S5-75} distribution of each bin obtained from the GCIM method with median values of about 5, 12 and 43s for crustal, in-slab and interface events, respectively. The duration of ground motions is positively correlated with M and the ground motions with longer durations are generated by large subduction events.

As expected, GCIM provides a very good match with the target in terms of D_{S5-75}. However, it is interesting that the CS-MR method, also produces a satisfactory match although this was not explicitly imposed. The CS-exact method, instead, fails in matching the D_{S5-75} distribution despite the bin-specific definition of target spectra. As anticipated, the discrepancies between the "desired" and the empirical D_{S5-75} distributions from the CS-MR approach are larger for the higher magnitude bins, which, on average, are characterized by longer duration ground motions. These differences are likely due to the limitation of the adopted GMPE for duration that, strictly speaking, is not applicable to magnitudes larger than 7.5.

The right panels of Figure 6 show the individual ground motion spectra against the 2.5/50/97.5th percentiles of the selected records for bins 2, 7 and 12. The latter are calculated indirectly, on the basis of lognormality of the conditional S_a assumed by all four selection methods, i.e. via the sample moments of the selected record sets. However, this assumption does not always hold since some positive skewness (i.e., longer upper tail) can be seen especially for S_a's at short periods. Although the spectra of individual records are only shown for CS-MR, similar issues of skewness is present for the records selected by all four methods. Recall that the *CS-exact* and the *GCIM* methods make use of the same bin-specific target spectra consistent with the M-R values of the three bins identified by the hazard disaggregation carried out for this IM level. On the other hand, the *CS-MR* method matches a single target spectrum for the entire IM level and relies on its M-R dependent record selection (Section 2) to populate the final set with ground motions in the proportions consistent with the M-R hazard disaggregation. This consideration explains why the S_a distributions of the records selected by the GCIM and CS-exact approaches are very similar to each other, while the S_a distributions based on CS-MR are, by design, quite different, especially for bins 7 and 12.

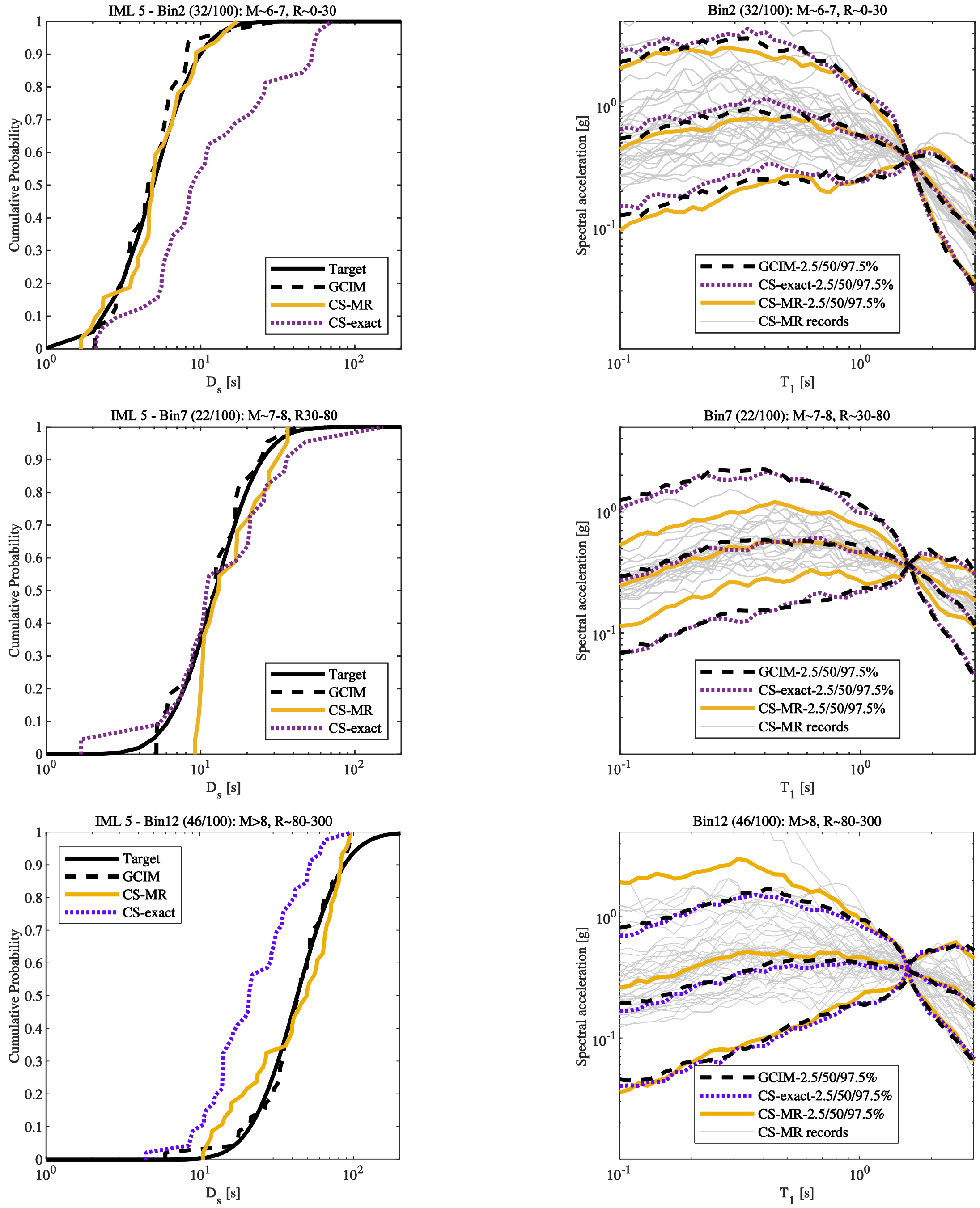

Figure 6. Comparison of the bin-specific *D_S* and *S_a* conditional distributions for the records selected by the GCIM, CS only and CS-MR approaches for the three bins 2, 7 and 12 identified by the disaggregation of the 5% in 50 years IM level for a site in Seattle. Left panels: empirical *$D_{S5\text{–}75}$* distributions of the selected records and the target distribution from the GCIM method. Right panels: empirical 2.5/50/97.5th percentiles of the conditional distribution of *S_a* for the selected records. Note: the numbers in the parentheses in the title above each panel refers to the number of selected records associated to each bin (e.g., 46 out of 100 for Bin 12)

More important than the aforementioned bin-specific comparison, is the comparison of the empirical *Ds* and S_a distributions (Figure 7a and Figure 7b) based on all the records selected for the considered IM level by the four different methods. In addition, Figure 7c illustrates a scatter plot of the M and R pairs of the selected records based on the four approaches for the 5% probability of exceedance in 50 years IM level. Despite the differences between CS-MR, CS-exact and GCIM in terms of S_a and $D_{S5\text{–}75}$ distributions observed previously at the bin level (Figure 6), the whole set of 100 records shows a higher degree of coherence, likely because different bins complement each other. For instance, at the 5% in 50 years level, even though CS-exact overestimates the $D_{S5\text{–}75}$ distribution in bin 2 and underestimates it in bin 12, the combination of the records from these two bins with those coming from bin 7 results, perhaps coincidentally, in a moderately good $D_{S5\text{–}75}$ total distribution (Figure 7a). Also, as shown in the selected records of bin 12 in Figure 6, CS-exact selects crustal records instead of the preferred subduction ground motion simply on the base of their spectral shape, introducing short durations and irrelevant M and R characteristics (see the markers for the records selected for bin 12 by CS-exact in Figure 7c). This analysis provides evidence that CS-exact would not select ground motions with the characteristics proper of different M-R bins or different source types, even if the CS targets are bin- or source-specific.

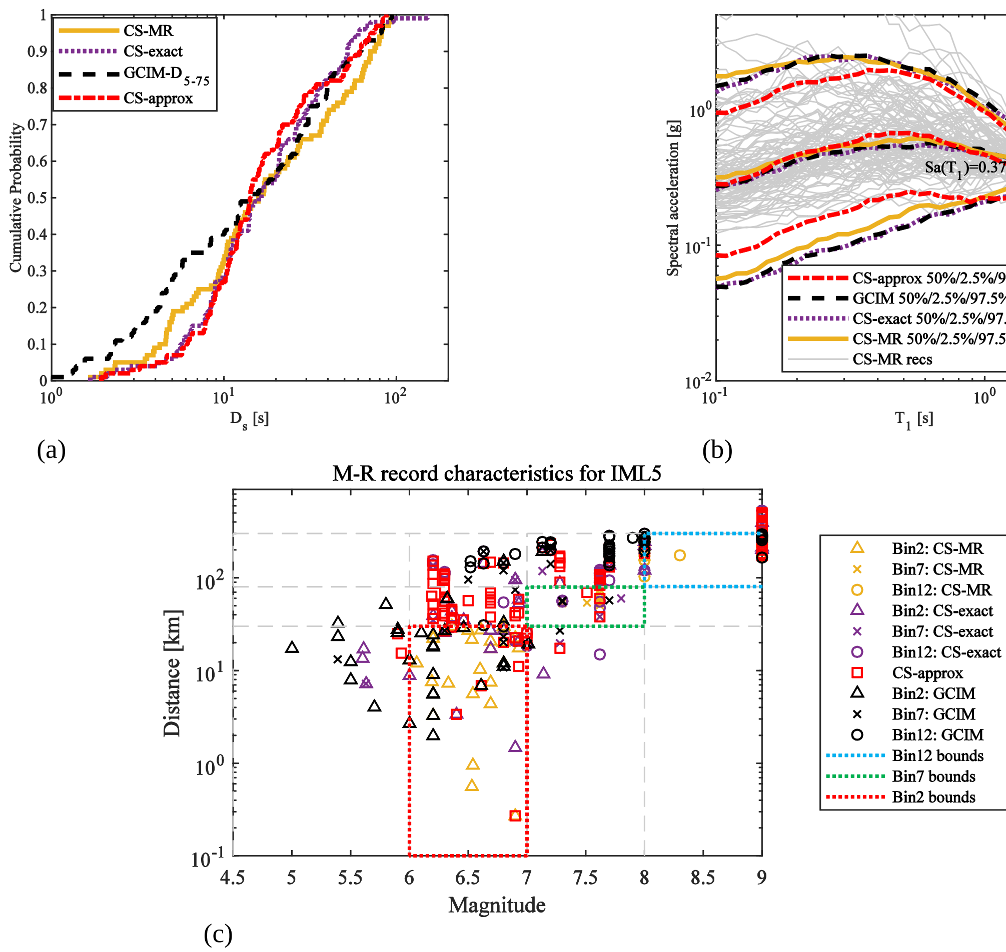

Figure 7. Comparison of the empirical $D_{s5\text{–}75}$ and S_a conditional distributions based on the four sets of 100 records selected by the GCIM, CS-exact, CS-approx, and CS-MR approaches for the 5% in 50 years IM level for a site in Seattle. (a) $D_{s5\text{–}75}$ distribution of the selected records and the target obtained from GCIM; (b) 2.5/50/97.5-th percentiles of the empirically-derived conditional distribution of spectral acceleration of the records selected by the four approaches; (c) Scatter plot of the magnitude and distance pairs of the records selected by the four approaches.

Finally, CS-approx was also included in Figure 7 to test the effectiveness of a more naïve selection approach. A clear difference that can be observed concerns the dispersion of the ordinates of CS-approx that is considerably lower than that of the other three sets for practically all periods, with some lesser discrepancies for the median between 0.4s and 0.7s. The duration distribution also shows a significant difference from the target one of GCIM especially for durations less than 10s and, more importantly for durations above 10s, where in both tails CS-approx is selecting fewer records than GCIM.

6 Results and Discussion

We shall focus on structural collapse, where the impact of duration is generally higher due to damage accumulation. In line with Shome and Cornell [61], the annual rate of the EDP demand exceeding different threshold (or capacity) values of EDP_C, $\lambda\left(EDP > EDP_C\right)$, can be computed using the conditional complementary cumulative distribution function of $EDP|IM$ for the no-collapse (NC) data, $\mathrm{P}\left(EDP > EDP_C \mid NC, IM\right)$, and the probability of collapse given IM, $P_{col|IM}$, along with the annual rate of occurrence of the IM of interest, λIM. Formally:

$$\lambda(EDP > EDP_C) = \int_{IM} \left[\mathrm{P}\left(EDP > EDP_C \mid \mathrm{NC}, IM\right) \cdot \left(1 - \mathrm{P}_{col|IM}\right) + \mathrm{P}_{\mathrm{col}|IM} \right] \cdot \left| d\lambda IM \right| \tag{3}$$

Logistic regression [62] was used to compute the probability of collapse for each IM level while $\mathrm{P}\left(EDP > EDP_C \mid NC, IM\right)$ was evaluated by means of the empirical cumulative distribution function extracted from the multiple stripe analysis results. Figure 8 shows the collapse fragility curve and MIDR response hazard curve computed using the records selected by the four approaches. Since the record selection methods, in line with the PSHA, are based on the geometric mean of the two horizontal components and the analyzed structure is 2D, we chose to run NDA for both components of the selected records, resulting to 200 NDA runs for each of the 10 stripes for each record set. Following the approach of Baker and Cornell [63] we created 100 different sets of 100 responses, picking randomly one horizontal component or the other, resulting to 100 different estimates of the structural response. All generated outputs, both in terms of fragility and drift hazard curves, along with the corresponding mean curves from the set of 100 realizations are shown in Figure 8. CS-MR, GCIM, CS-exact and CS-approx, all provide fairly similar annual collapse rates, of 4.66×10^{-4}, 4.13×10^{-4}, 3.47×10^{-4}, 3.06×10^{-4}, respectively. Overall, the differences are not high enough to be statistically significant. Still, some general trends related to duration/magnitude effects can be observed by correlating the distribution of longer values of D_S in Figure 7a with the estimated collapse rates. Specifically, the CS-approx method provides the lowest rate and at the same time it incorporates fewer records in both tails of the duration distribution, crucially lacking enough long duration records. On the other hand, CS-MR estimates the largest annual collapse rate hand-in-hand with selecting more long-duration records.

It is hard to pick one approach as the reference one. The preference could go to GCIM but only if two conditions hold:

a) If it can count on a GMPE able to predict a hazard-consistent duration distribution for the entire magnitude range of interest. As pointed out previously, this is not the case for Abrahamson and Silva (1996) [43], which is tailored for smaller magnitude crustal events and extrapolated here (out of its field of applicability) to predict durations of high magnitude events.
b) One knows a priori that duration is the only additional IM that matters for the response prediction in addition to the spectral shape.

Nonetheless, the differences between the CS-MR and GCIM estimates of the collapse rate remain practically insignificant (a ~10% difference). Disregarding duration and employing a worse spectral target by considering only the dominant M-R bin, CS-approx is certainly disadvantaged at a higher ~25% difference from GCIM. Curiously, though, it seems that CS-exact, while still disregarding duration, performs, perhaps coincidentally, better than expected with a ~15% difference only.

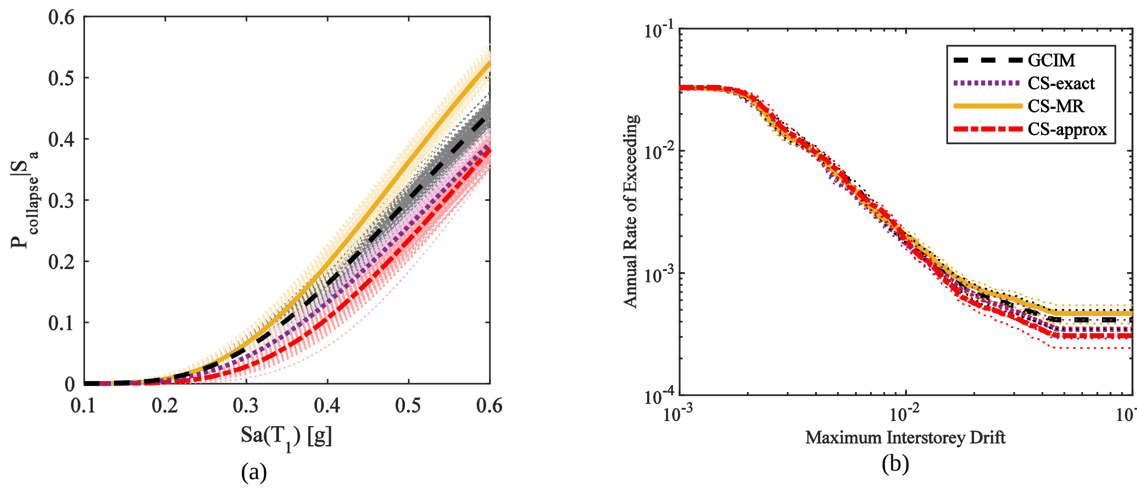

Figure 8. (a) Fragility curves and (b) Drift hazard curves, estimated from the multistripe analyses of the structure subjected to the record sets defined according to the four selection methods. The dotted/lighter lines (for each method) represent the range of variability of 100 different combinations of response estimates

6.1 Is a CS-only approach robust enough to be viable?

The apparent capability of CS-exact and CS-approx to somehow escape the worst effects of not selecting for duration or magnitude is rather puzzling and, we believe, coincidental. A further investigation showed that the methods selected by chance some long-duration subduction zone records simply because it provided a better spectral consistency especially for the long period spectral ordinates) than the available crustal event records. As spectral shape consistency can be ensured to a nearly equally high degree even if records are chosen solely from the crustal database, CS-exact is performed again by limiting the database to NGA-West2, an approach also embraced by Chandramohan et al. [3]. The duration distribution of the set (Figure 9) is now obviously less consistent with the desired target, while the spectral shape remains in perfect agreement (Figure 9). The result of this change is that now the corresponding estimate of the annual collapse rate computes using the set with crustal events becomes $2.86{\times}10^{-4}$, a value that 30% lower than the reference value of GCIM.

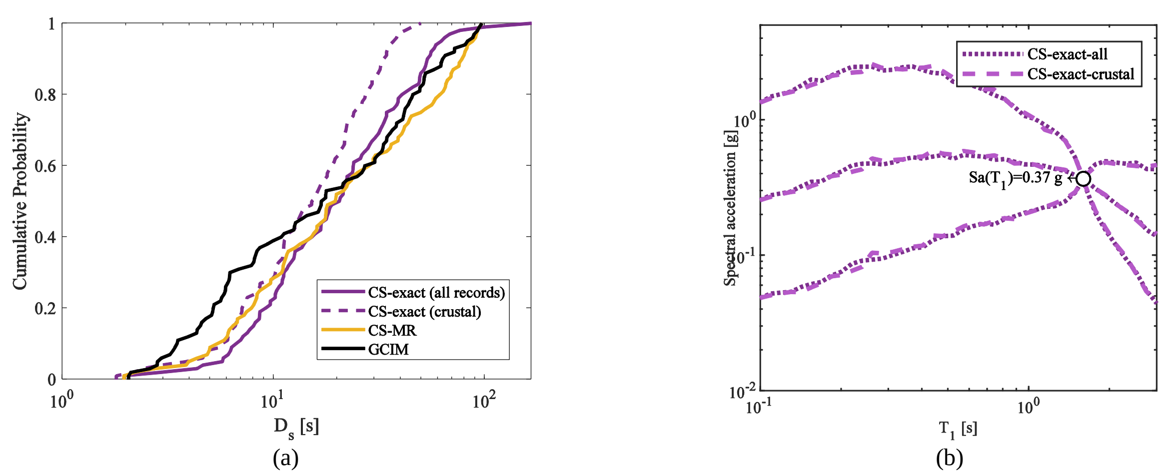

Figure 9. Comparison of the empirical $D_{s5\text{–}75}$ and S_a conditional distributions based on the records selected by the CS-exact approach using first the full (NGA-West2 + subduction) and then the limited (only NGA-West2) databases. (a) Duration distribution; (b) spectral acceleration 2.5/50/97.5th percentiles for the selected site in Seattle corresponding to IM level 5 with S_a(1.6s)=0.37g

In order to demonstrate the need for adopting record selection approaches more sophisticated than CS-exact, the CS-exact and CS-MR record selection procedures were run again multiple times, each time with a slightly modified ground motion database. The scope of this exercise is to test their robustness with respect to the records available in the database. Thus, the subduction records initially selected by each method from the 'complete' database (which, again, includes both crustal and subduction ground motions) are removed and the selection is performed again. Other unselected subduction records, however, are left in the database. At the 5th IM level of S_a(1.6s)=0.37g (5% probability of exceedance in 50 years), this operation led to the removal of 20 subduction records for CS-exact and 46 for CS-MR, a minor portion of the catalogue. This removal process is repeated again for CS-exact until a total of about 46 records is removed, as for CS-MR. As shown in Figure 10, the removal of these subduction zone records severely degraded the accuracy of the empirical duration distribution from the CS-exact set, pushing it further away from the desired duration distribution represented by GCIM. In contrast, the CS-MR duration distribution remains almost unchanged. Moreover, after removing the same number of records as for CS-MR, the CS-exact distribution becomes practically coincident with the one obtained by selecting the records only from NGA-West2 (crustal database). The results of this sensitivity exercise show that, by virtue of considering the causative M-R during selection, the CS-MR method is considerably more robust to small changes in the ground motions available in the database compared to CS-exact. At the same time, one may argue that given a large enough catalogue, CS-exact might just be able to represent duration simply by properly matching the spectral shape. We cannot disprove this, yet we would rather place our trust on a verifiably robust procedure that does not depend on such externalities.

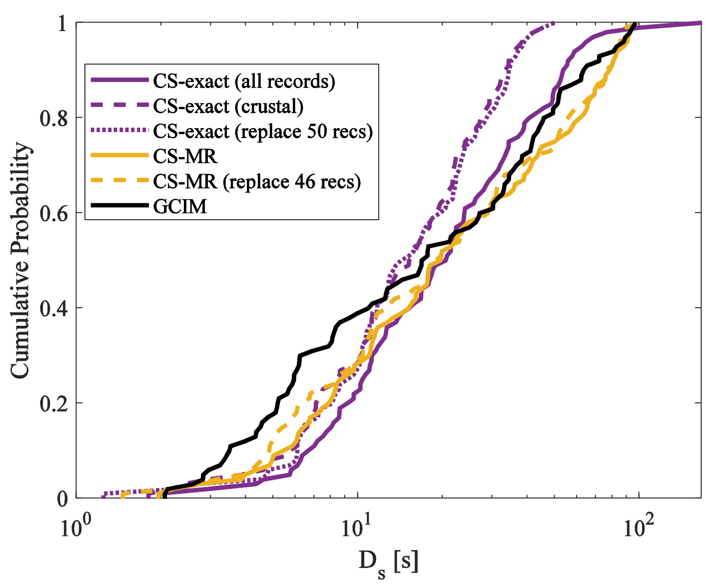

Figure 10. Robustness test: Changes in the empirical duration distribution obtained by removing selected subduction records from the database before selection took place.

7 Conclusions

A post-processing technique is proposed to guide the CS algorithm in selecting ground motion records with Magnitude (M) and Distance (R) characteristics that are consistent with the earthquake scenarios that contribute mostly to the site hazard for each IM level. M and R can be seen as proxies to include ground motion parameters, other than the spectral shape, that could potentially matter in structural response prediction.

The response of an archetype 2D modern ductile RC frame was analytically computed using four ground motion record selection procedures, namely CS-MR (our proposal), GCIM (seen as the reference, although with the caveat that the duration distribution was derived using a currently available GMPE not appropriate for large M subduction events), CS-exact and CS-approx (collectively CS-only). The effective duration has been chosen as the measure, beyond the spectral shape, that significantly influences collapse performance. The building is located in Seattle, a site whose hazard is affected by both crustal and subduction events (typically associated with longer durations). Letting these four procedures select records from the NGA-West2 database enhanced with a set of ground motions from subduction events, produced response statistics that are practically identical for CS-MR, GCIM and CS-exact, and only differ in the case of CS-approx. Interestingly and very likely by coincidence, this holds despite the fact that the CS-exact method does not explicitly account for duration. It seems, at least in this case, that molding the target spectrum on the basis of disaggregation data, implicitly directs the procedure to select records with satisfactory duration characteristics. However, forcing the selection to pick records with proper M-R characteristics (CS-MR method) further improves the final results. Moreover, the CS-MR method was shown to be more robust than CS-exact because it maintains a satisfactory duration distribution and spectral acceleration conditional distribution even if the subduction records 'preferred' at the first pass by the selection procedure were on purpose screened out from the database.

Moreover, we contend that the CS-MR method is intuitively more appealing and certainly less complicated than GCIM. Indeed, it relies on M and R to identify records that are appropriate for the site and have the "right" distribution of IMs (e.g., duration) in addition to the desired hazard-consistent spectral acceleration distribution. The consistency of the distribution of these other IMs, however, is not enforced explicitly as the GCIM method does. Because of this capability of explicitly accounting for any parameter that could possibly influence the structural response, the GCIM method is, in theory, more precise than CS-MR but:

1. It requires selecting a priori the IMs that matter for the prediction of the structural response. This requires engineering judgment and introduces some user-dependent arbitrariness. The CS-MR method does not.
2. It may happen that the IM selected, such as duration for the case study considered here, does not have a proper GMPE necessary for computing a hazard consistent distribution. This renders the practical application of GCIM, as originally intended, intrinsically inaccurate. This problem is bypassed by the CS-MR method.
3. The CS-only methods and the GCIM method enforce the overall distribution of the spectral shape of records conditioned on a single IM at a given level. It is possible that some of the records selected may come from causative M and R scenarios that do not contribute at all to the hazard of the site at hand. These records may not be like any ground motion records that the structure will ever experience in its life. The CS-MR does not have this problem. The spectral shape of each record selected is relevant to the site hazard and not only relevant in the overall spectral shape distribution.
4. The GCIM method allows the consideration of different IMs in addition to the spectral accelerations. However, since the record database is limited, one could simply not be able to accurately match the target distributions of all the IMs. The CS-MR is similarly impeded but to a lesser degree by virtue of imposing fewer constraints.
5. The GCIM method assigns weights to the preferred IMs. This is philosophically equivalent to deciding which IMs are the most important ones. In contrast, the CS-MR method, using Magnitude and Distance as proxies, is able to bring additional information naturally.

However, it should be underlined that, because it imposes in the record selection more constraints than the CS-exact method, the CS-MR method may not always be able to achieve the same consistency with the target CS that the CS-exact method does. Nonetheless, what may be lost in the spectral shape hazard consistency is surely gained in the selection of records that, via M and R, have characteristics similar to those that may be experienced by the structure at the site.

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