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HAZARD-CONSISTENT GROUND MOTION DURATION: CALCULATION PROCEDURE AND IMPACT ON STRUCTURAL COLLAPSE RISK

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ABSTRACT

Calculation of structural collapse risk using non-linear response history analysis requires the selection of ground motions at different intensity levels. These selected ground motions should be consistent with the seismic hazard at the site under consideration. Source-specific, conditional distributions of ground motion duration and response spectra are proposed as targets to select hazard-consistent ground motions. Target distributions of duration are computed using a prediction equation for duration and earthquake source characteristics (e.g. source type, magnitude, and distance) obtained from seismic hazard deaggregation calculations, conditional on the exceedance of a spectral acceleration value corresponding to a specific hazard level. The correlation between the residuals ($\boldsymbol{\varepsilon}$ values) of response spectral ordinates and duration are accounted for in the calculation procedure. Sample calculations are performed for three sites in Western USA: Seattle (Washington), Eugene (Oregon), and San Francisco (California) to illustrate the contribution of interface earthquakes in subduction zones that are known to produce long duration ground motions. Previous studies have found that long duration ground motions, on average, predict lower collapse capacities than short duration ground motions such as the FEMA P695 far field records and moderate to large amplitude records from the PEER NGA West2 database, which are commonly used for collapse capacity estimation. The examples presented in this paper illustrate that the use of only short duration records for sites where interface earthquakes contribute significantly to the seismic hazard can lead to an over-estimation of collapse capacity and un-conservative structural designs.

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Calculation of structural collapse risk using non-linear response history analysis requires the selection of ground motions at different intensity levels. These selected ground motions should be consistent with the seismic hazard at the site under consideration. Source-specific, conditional distributions of ground motion duration and response spectra are proposed as targets to select hazard-consistent ground motions. Target distributions of duration are computed using a prediction equation for duration and earthquake source characteristics (e.g. source type, magnitude, and distance) obtained from seismic hazard deaggregation calculations, conditional on the exceedance of a spectral acceleration value corresponding to a specific hazard level. The correlation between the residuals ($\boldsymbol{\varepsilon}$ values) of response spectral ordinates and duration are accounted for in the calculation procedure. Sample calculations are performed for three sites in Western USA: Seattle (Washington), Eugene (Oregon), and San Francisco (California) to illustrate the contribution of interface earthquakes in subduction zones that are known to produce long duration ground motions. Previous studies have found that long duration ground motions, on average, predict lower collapse capacities than short duration ground motions such as the FEMA P695 far field records and moderate to large amplitude records from the PEER NGA West2 database, which are commonly used for collapse capacity estimation. The examples presented in this paper illustrate that the use of only short duration records for sites where interface earthquakes contribute significantly to the seismic hazard can lead to an over-estimation of collapse capacity and un-conservative structural designs.

Introduction

Recent studies by the authors and others [1, 2] have highlighted the influence of ground motion duration on structural collapse risk. Chandramohan et al. [1] used spectrally equivalent, long and short duration record sets to demonstrate that longer duration records, on average, predict lower collapse capacities (i.e. longer duration records cause structural collapse when scaled to lower intensities). This effect of duration was observed only when realistic structural models that incorporate both the in-cycle and cyclic deterioration of the strength and stiffness of structural elements were employed.

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The ground motions employed in the aforementioned study were, however, not consistent with the hazard at any particular site. Therefore, although the study demonstrated that long duration ground motions are relatively more damaging than short duration ground motions, it did not address the durations of ground motions that can be expected a particular site, and thereby, the relative importance of considering ground motion duration at different geographic locations. This study uses the generalized conditional intensity measure (GCIM) approach proposed by Bradley [3] to compute hazard-consistent, conditional probability distributions of the anticipated ground motion duration at a particular site and hazard level. When used along with conditional spectra [4], they serve as suitable, hazard-consistent targets for ground motion selection. Target distributions of ground motion duration are computed at three sites in Western USA located in different tectonic settings: Seattle (Washington), Eugene (Oregon), and San Francisco (California). The characteristics of the computed target durations are analyzed, and implications for the design and evaluation of structures at these sites are discussed.

Besides their primary application in ground motion selection for structural design and assessment, the computed hazard-consistent target distributions of ground motion duration are expected to have a number of other applications in geotechnical engineering [5] and the design of non-structural components [6].

Sites chosen for sample calculations

Seattle (Washington), Eugene (Oregon), and San Francisco (California) are the three sites chosen for sample calculations of target distributions of duration. All three sites are located in Western USA, and as illustrated in Fig. 1, they are each located in different tectonic settings with different levels of contribution to their seismic hazard from different types of seismic sources. Almost all the contributions to San Francisco's seismic hazard come from the surrounding San Andreas, Hayward, and San Gregorio crustal faults. Eugene, on the other hand, is adjacent to the Cascadia subduction zone with no nearby crustal faults, so the subduction zone is the dominant contributor to its seismic hazard. The seismic hazard at Seattle receives sizeable contributions from both the Cascadia subduction zone and the Seattle fault zone, which is a network of crustal faults underneath the city.

The Cascadia subduction zone is a source of both interface and in-slab earthquakes (also known as intra-plate or slab earthquakes). Interface earthquakes are large magnitude, megathrust earthquakes that occur due to relative motion of the subducting Juan de Fuca plate and the over-riding North American plate. The U.S. National Seismic Hazard Maps [7] consider future interface earthquakes of magnitude as large as 9.2 in the Cascadia subduction zone. The 1700 Cascadia earthquake was an interface earthquake with an approximate magnitude of 9.0. In-slab earthquakes, on the other hand, are deep earthquakes caused by ruptures within the subducting Juan de Fuca plate, at depths of 30 to $70\ km$, as it sinks into the mantle. Although in-slab earthquakes are of smaller magnitude than interface earthquakes, they are much more frequent. The 2001 Nisqually earthquake was an in-slab earthquake of magnitude 6.8.

The seismic hazard deaggregation plots for $S_a(1\ s)$ (5% damped response spectral ordinates are implied throughout this paper) at the 2% in 50 year hazard level, at all three sites, are shown in Fig. 2. Within each plot, contributions from each source can be distinguished

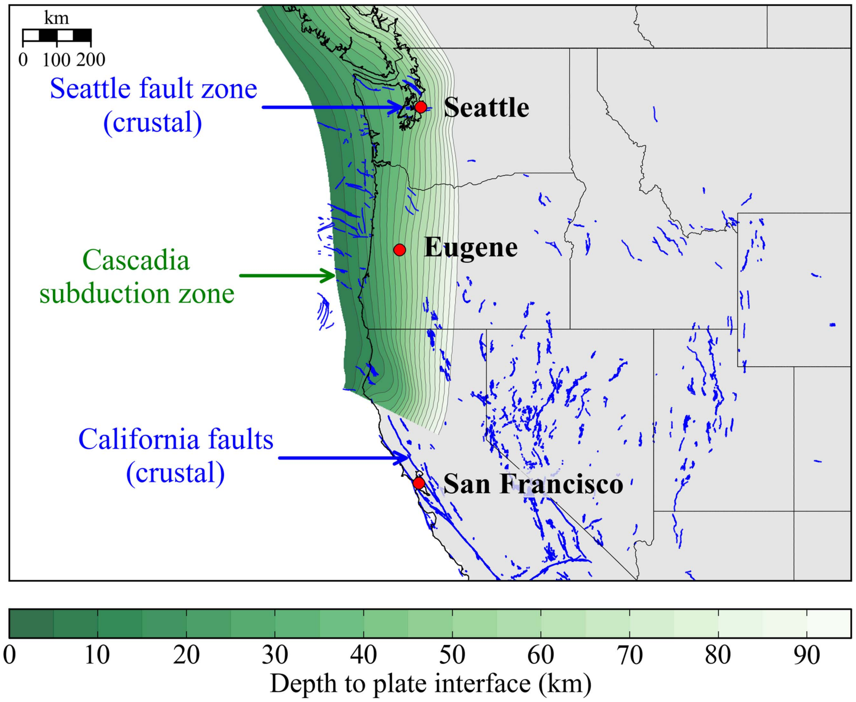
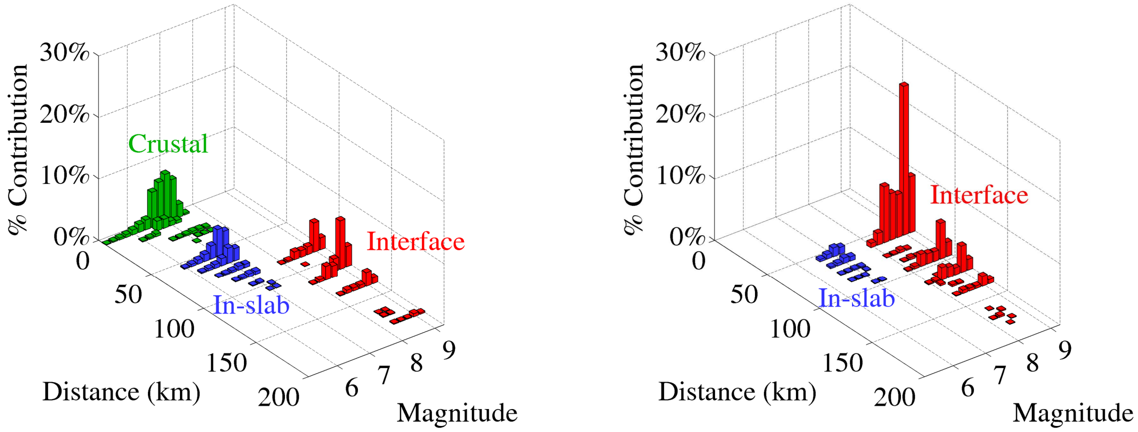


Figure 1. Sites chosen for sample calculations of target distributions of duration and their contributing seismic sources.

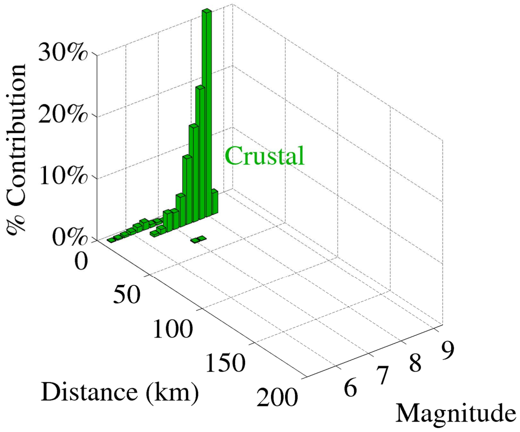
because they have distinct ranges of magnitudes and distances. As expected, crustal, interface, and in-slab earthquakes are observed to contribute to the hazard at Seattle, whereas only interface and in-slab earthquakes contribute to the hazard at Eugene due to the absence of nearby crustal faults, and only crustal earthquakes contribute to the hazard at San Francisco due to its distance from the Cascadia subduction zone.

Calculation procedure for hazard-consistent target probability distributions of duration

The procedure described here to compute the conditional distribution of ground motion duration at a particular site and hazard level follows the generalized conditional intensity measure (GCIM) approach proposed by Bradley [3] and is a generalized version of the procedure to compute a conditional spectrum [4]. The computation procedure first requires the choice of a conditioning intensity measure (e.g. peak ground acceleration, PGA, peak ground velocity, PGV, pseudo spectral acceleration at a certain period, $S_a(T)$) and a metric to represent ground motion duration (e.g. bracketed duration [8], significant duration [9], I_D [10]). This study uses $S_a(T^*)$ as the conditioning intensity measure, where T^*, known as the conditioning period, is a period of vibration that is representative of the dynamic response of the structure under consideration. The fundamental modal period of the structure is often chosen as the conditioning period, but elongated periods corresponding to structural response in the inelastic range, or shorter periods corresponding to higher modes may equivalently be used. Significant duration (Ds) is used to represent ground motion duration, given its effectiveness in collapse capacity prediction as determined in [11] and the number of models to predict it that are readily available in the literature. Ds is described as the time interval over which a specific percentage (e.g. 5-75%,



(a) Seattle (b) Eugene



(c) San Francisco

Figure 2. Seismic hazard deaggregation plots for $S_a(1\ s)$ at the 2% in 50 year hazard level.

5-95%) of the integral $\int_0^{t_{max}} a(t)^2 dt$ is accumulated, where $a(t)$ represents the ground acceleration and t_{max} represents the length of the acceleration record. The computation of 5-75% significant duration (Ds_{5-75}) is illustrated in Fig. 3. Although $S_a(T^*)$ and Ds are used here, the calculation procedure described below is general and can be used with any combination of conditioning intensity measure and duration metric.

The computed target distributions of duration are specific to the chosen hazard level. Conventional probabilistic seismic hazard analysis [12] is used to obtain the spectral acceleration at the conditioning period, $S_a(T^*)$, which is exceeded at the specified annual rate. Seismic hazard deaggregation calculations are then carried out to find the events that are most likely to cause the exceedance of that $S_a(T^*)$ at the site, their corresponding deaggregation weights, p_i, and their characteristics including source type, ST_i ($ST_i =$ "interface", "in-slab", or "crustal"), magnitude, M_i, source-to-site distance, R_i, other source characteristics, $\boldsymbol{\theta}_i$, and epsilon value [13] for $S_a(T^*)$, ε_i (subscript i denotes the i^{th} contributing event). A prediction equation for duration can now be used to compute the mean and standard deviation of the natural logarithm of duration anticipated at the site for each contributing event as a function of its M, R, and $\boldsymbol{\theta}$.

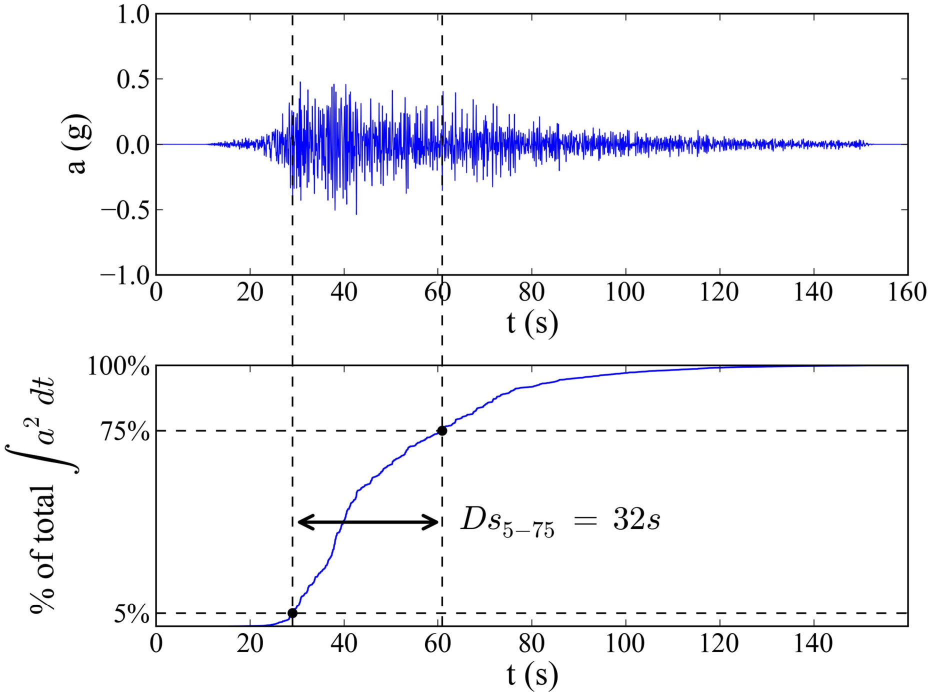


Figure 3. Calculation of 5-75% significant duration.

$$\mu_{\ln Ds_i} = f(M_i, R_i, \boldsymbol{\theta}_i) \tag{1}$$

$$\sigma_{\ln Ds_i} = g(M_i, R_i, \boldsymbol{\theta}_i) \tag{2}$$

The logarithm of duration is used since most prediction equations for Ds (e.g. [14–16]) find it to be lognormally distributed. The conditional distribution of duration for each contributing event can now be computed using a model for the correlation coefficient, $\rho(T^*)$, between the residuals from the predictions of the logarithms of $S_a(T^*)$ and Ds.

$$\mu_{\ln Ds_i | \ln S_a(T^*)} = \mu_{\ln Ds_i} + \rho(T^*)\varepsilon_i \sigma_{\ln Ds_i} \tag{3}$$

$$\sigma_{\ln Ds_i | \ln S_a(T^*)} = \sigma_{\ln Ds_i}\sqrt{1 - \rho(T^*)^2} \tag{4}$$

Currently, no prediction equations for duration or models for correlation coefficients exist for interface and in-slab earthquakes. The need for the development of such models is motivated below. Preliminary studies by the authors have found the duration predictions of the Abrahamson and Silva prediction equation [14], which was developed for crustal earthquakes, to be most consistent with the recordings from the 2010 Maule (Chile) and 2011 Tohoku (Japan) interface earthquakes. Therefore, this study uses this equation along with the model for correlation coefficients proposed by Bradley [17], which was also developed for crustal earthquakes. Prediction equations generally find that duration increases with both magnitude and source-to-site distance, and that it is more sensitive to changes in magnitude than distance. The Bradley [17] model predicts small negative correlation coefficients between the residuals for periods shorter than 2.1 s and small positive correlation coefficients for periods longer than 2.1 s.

Source-specific, conditional distributions of duration can now be computed by averaging the conditional distributions of duration computed from all contributing events from a specific type of source, st, using the following equations:

$$\mu_{\ln Ds|\ln S_a(T^*)}(st) = \sum_{ST_i=st} p_i \mu_{\ln Ds_i|\ln S_a(T^*)} \tag{5}$$

$$\sigma_{\ln Ds|\ln S_a(T^*)}(st) = \sqrt{\sum_{ST_i=st} p_i \left[\sigma^2_{\ln Ds_i|\ln S_a(T^*)} + \left(\mu_{\ln Ds_i|\ln S_a(T^*)} - \mu_{\ln Ds|\ln S_a(T^*)}(st)\right)^2\right]} \tag{6}$$

Therefore, in the case of Seattle, where interface, in-slab, and crustal earthquakes contribute to the seismic hazard, three conditional distributions of duration will be obtained, one corresponding to each type of source. The moments of the conditional distribution of duration computed using Eqs. 5 and 6 are approximated to represent a lognormal distribution. The relative contribution of each type of source to the total seismic hazard can be computed by summing up the deaggregation weights of all the contributing events from that type of source.

$$\bar{p}(st) = \sum_{ST_i=st} p_i \tag{7}$$

Table 1 shows the source-specific, conditional median Ds_{5-75} values for all three sites along with the percentage contributions of each type of source, conditioned on the exceedance of an $S_a(1\ s)$ value with a probability of 2% in 50 years. The source-specific, conditional distributions of Ds_{5-75} are plotted in Fig. 4 along with the corresponding source-specific, conditional mean spectra.

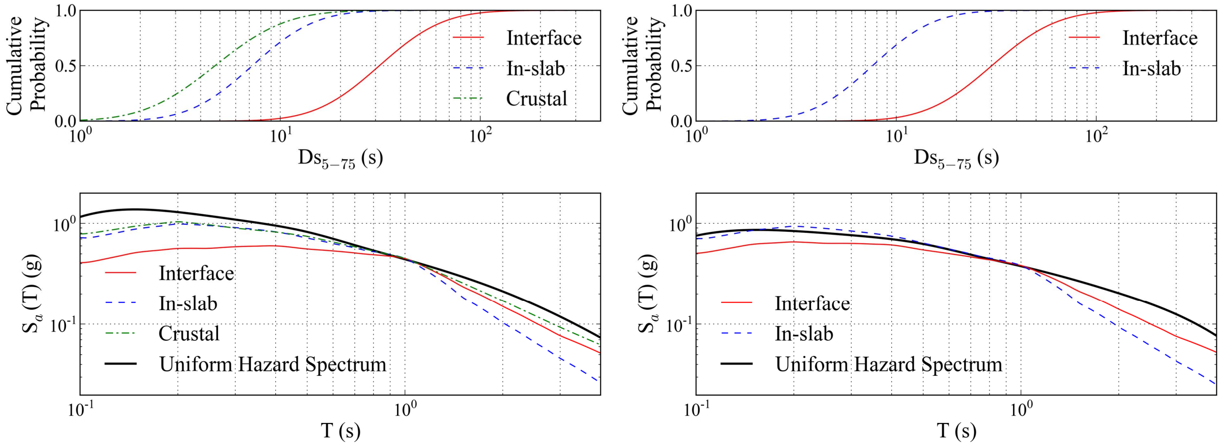
Table 1 shows that, as expected, the duration of shaking from interface earthquakes is much longer than that from in-slab and crustal earthquakes. This is because longer durations of shaking are expected from larger magnitude earthquakes, and as observed in Fig. 2, the mean causal magnitude for interface earthquakes is close to 9, while that for in-slab and crustal earthquakes is around 7.

Selection of hazard-consistent ground motions

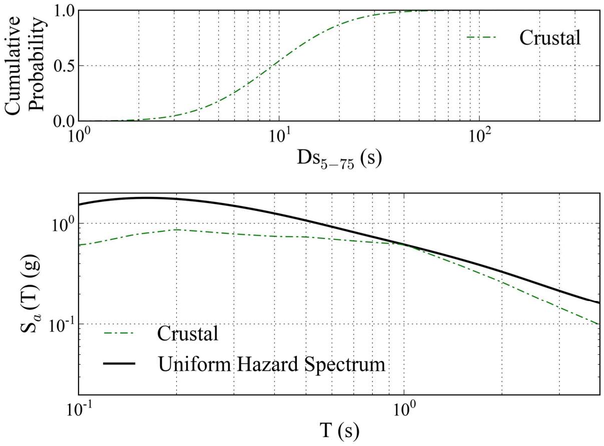
Once source-specific, conditional distributions of duration and response spectra are computed at a hazard level, they serve as suitable, hazard-consistent targets for ground motion selection. The reason for the emphasis on "source-specific" targets is that ground motions from different types of sources usually have different characteristics, notably frequency content and duration. While this would not be a concern for a site like San Francisco, using a single target for selecting all ground motions for a site like Seattle would be difficult to reconcile with the varying ground motion characteristics associated with each type of source. To ensure hazard consistency, the fraction of selected ground motions corresponding to one type of source should equal the $\bar{p}(st)$ value for that type of source. Algorithms to select ground motions that match target joint distributions of intensity measures have been proposed by Jayaram et al. [18] and Bradley [19]. This procedure could be repeated for different hazard levels to obtain the suites of ground motions required to estimate structural collapse capacity using non-linear response history analysis.

Table 1. Source-specific, conditional median Ds_{5-75} values for all considered sites along with the percentage contributions of each type of source (indicated in parentheses), conditioned on the exceedance of an $S_a(1\ s)$ value with a probability of 2% in 50 years

Site	Interface	In-slab	Crustal
Seattle	31 s (35%)	7 s (24%)	5 s (41%)
Eugene	30 s (93%)	8 s (7%)	-
San Francisco	-	-	9 s (100%)



(a) Seattle (b) Eugene



(c) San Francisco

Figure 4. (Top) Source-specific, conditional distributions of duration and (Bottom) source-specific, conditional mean spectra with the uniform hazard spectrum (UHS) conditioned on the exceedance of an $S_a(1\ s)$ value with a probability of 2% in 50 years

The importance of ensuring a match to target distributions of duration, in addition to target response spectra, is demonstrated in Fig. 5, which plots the Ds_{5-75} distributions of the ground motions in record sets commonly used for collapse capacity estimation. These include the FEMA P695 far field set [20], the PEER Transportation Research Program Set #2 [21], and the PEER NGA West 2 database [22] (only intense ground motions with $PGA > 0.1\,g$ and $PGV > 10\,cm/s$ were considered). It can be observed that the durations of ground motions in these commonly used sets are mostly short with $Ds_{5-75} < 20\,s$. The Ds_{5-75} distributions of the spectrally equivalent, long and short duration record sets used in Chandramohan et al. [1] have also been included since as a part of a different study, the long duration set was found to produce a median collapse capacity estimate for a modern 5-story steel special moment frame, 28% lower than the short duration record set, although the two sets were spectrally equivalent. It can be seen in Fig. 5 that the Ds_{5-75} distribution of the short duration set is similar to that of the commonly used record sets, and the Ds_{5-75} distribution of the long duration set closely matches the target distribution for interface earthquakes in Seattle associated with $S_a(1\,s)$ at the 2% in 50 year hazard level. Therefore, using only short duration records (without including the appropriate fraction of long duration records) at a site where interface earthquakes contribute to the seismic hazard could lead to an over-estimation of collapse capacity and un-conservative structural designs.

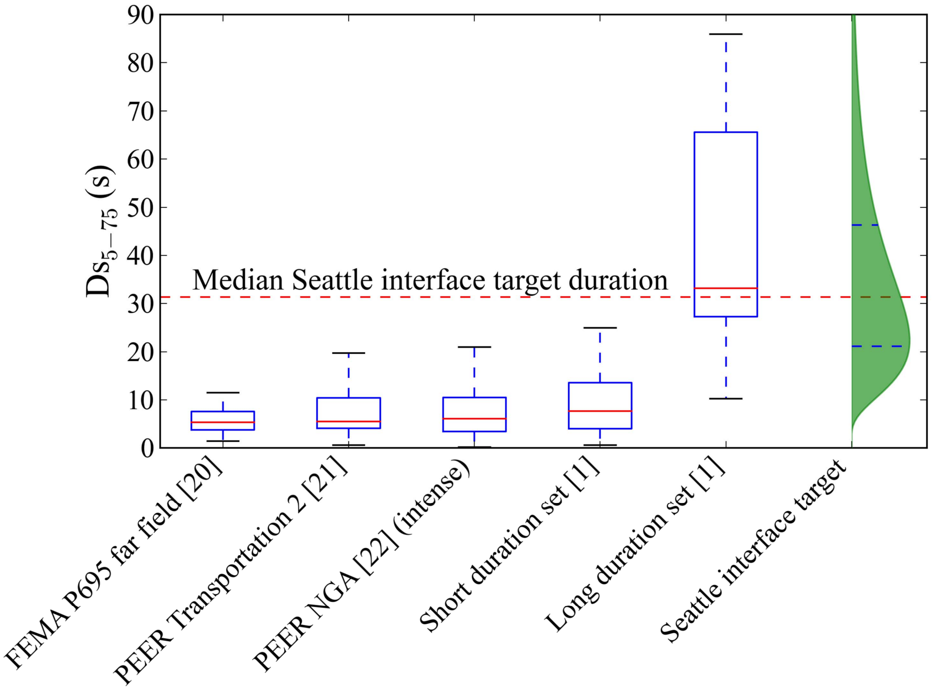


Figure 5. Distributions of the Ds_{5-75} of the ground motions in benchmark record sets and the spectrally equivalent, long and short duration record sets used in Chandramohan et al. [1], compared to the target distribution of Ds_{5-75} for interface earthquakes at Seattle, associated with $S_a(1\,s)$ at the 2% in 50 year hazard level (median in red and first and third quartiles in blue).

Conclusion

A procedure to compute source-specific, conditional probability distributions of duration was described, and sample calculations were carried out for three sites in Western USA located in different tectonic settings: Seattle (Washington), Eugene (Oregon), and San Francisco (California). While interface, in-slab, and crustal earthquakes all contribute to the seismic hazard at Seattle, only interface and in-slab earthquakes contribute to the hazard at Eugene, and only crustal earthquakes contribute to the hazard at San Francisco. As expected, the computed median durations for interface earthquakes were significantly longer than in-slab and crustal earthquakes. These source-specific, conditional distributions of duration, along with conditional spectra, serve as suitable hazard-consistent targets for ground motion selection. Record sets commonly used for collapse capacity estimation, like the FEMA P695 far field set [20], the PEER Transportation Research Program Set #2 [21], and the PEER NGA West2 database [22] (considering those records with $PGA > 0.1\, g$ and $PGV > 10\, cm/s$ only), contain mostly short duration ground motions. A previous study by the authors [1] showed that a short duration ground motion will, on average, produce a higher collapse capacity than a long duration ground motion that has a similar spectral shape. Therefore, choosing records from these record sets without explicitly ensuring a match to the source-specific, target distributions of duration could lead to an over-estimation of collapse capacity, and un-conservative structural designs at sites where interface earthquakes contribute significantly to the seismic hazard. This signals the need to develop prediction equations for duration and models for the correlation coefficient between the residuals of common intensity measures and duration, for subduction zones.

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