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A NEW GROUND MOTION SELECTION AND SCALING PROCEDURE FOR NONLINEAR SEISMIC RESPONSE PREDICTION

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Abstract: This study presents a methodology for selecting and scaling real earthquake ground motions to be used in the estimation of nonlinear structural response. The proposed procedure explicitly considers the uncertainty in the target intensity measure with the level of spectral variability preserved in the ground motion suite. The candidate ground motion sets are constructed based on dispersion statistics about the target spectral demand. The optimum ground-motion set is linearly scaled by using an optimization algorithm that minimizes the error between scaled median and target spectra. The scaling stage ensures that the median record spectrum provides a reasonable match to target median in a previously defined period interval. The effect of the spectral variability on seismic demand estimations is investigated using various inelastic single degree of freedom structural systems. In order to investigate the impact of different selection and scaling methodologies on nonlinear structural response, the results are compared with those obtained by the Conditional Spectrum (CS) based scaling methodology. The variability in the nonlinear structural response due to the use of different numbers of scaled recordings are also examined with the aim of finding optimum number of ground motions for reliable and stable estimation of nonlinear structural behavior.

Introduction

Reliable and accurate prediction of nonlinear structural response requires specification of appropriate earthquake ground motions to be used in nonlinear time history analysis. The current ground motion selection and modification (GMSM) procedures have mainly focused on assembling the real earthquake records which produce unbiased and accurate estimation of the seismic demand. These GMSM procedures should be evaluated depending on the purpose of the analysis and the project under investigation. In code-based procedure, the main goal is to predict the average response of the structure for a specified intensity of ground shaking (ASCE, 2005). The aim of code-based scaling is to obtain ground motions that are compatible with the target spectrum over a period range of interest such that $0.2T_1$ (to consider higher mode effects) to $2.0T_1$ (to account for period elongation due to nonlinearity), where T_1 is the fundamental period of the structure. In this procedure, the ground motions are mainly selected to match a target spectrum such as UHS or design spectrum (derived from probabilistic seismic hazard analysis, PSHA). On the other hand, when the seismic hazard at a particular site is represented by scenario earthquake parameters (magnitude, distance, site information, etc.), target spectrum can be derived by the median and standard deviation estimation of the ground motion prediction model. In such cases, the ground motions should capture the distribution of the target ground motion intensity for a deterministic scenario event. ATC-58-1 identifies this type of assessment as scenario-based assessment in which the typical outcome will be the average structural response and its variability (NIST, 2011). Apart from the aforementioned approaches, the current probabilistic seismic assessment procedures mainly utilize the ground motion hazard in a probabilistic manner and use the ground motion intensity measure (IM) as a proxy to characterize the earthquake damage potential with respect to structural performance. The

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elastic spectral acceleration at the fundamental period of the structure, Sa (T_1) is commonly adopted intensity measure for seismic structural assessment because of its characteristics of sufficiency and efficiency (Shome and Cornell, 1999; Luco, 2002). It has been shown that scaling records to Sa (T_1) may introduce bias in structural response if ground motions have inappropriate spectral shape or the parameter ε, which is a proxy of spectral shape (Baker and Cornell, 2005). In order to take into account the relationship between ε and the spectral shape, Conditional Mean Spectrum (CMS) has been proposed as the target spectrum for ground-motion selection and scaling (Baker, 2011). It basically generates the expected spectral acceleration values (Sa) using their correlation across a period band for a given Sa conditioned at the fundamental period of the structure (Baker and Jayaram, 2008). More recently, Conditional Spectrum (CS) is developed which accounts for both mean and variability in target response spectrum (Jayaram et al, 2011). CMS (and CS) overcomes the limitations of the UHS that stems from the fact that spectral values at all periods are not likely to occur in a single ground motion. When the ground motions are scaled to common intensity level (Sa (T_1)), variability in this target intensity is considered as zero. The main assertion is that there is no need to account for additional variability in target spectral demand as it is already taken into account in the PSHA. However, this single intensity measure may not always fully consider all sources of variability in the ground motion. Some researchers have proposed record selection and scaling procedures that account for the uncertainty related to ground motion intensity. For example, Huang et al. (2009) presented a distribution scaling (D-scaling) method to capture both median and dispersion in spectral demand characterized by a PSHA or an attenuation relationship. In their study, the ground motions are scaled to the target spectral ordinates at the fundamental period of structure in order to explicitly address the epistemic uncertainty in UHS. Hines et al. (2010) discussed the additional uncertainty associated with the logic tree calculations in the PSHA (epistemic uncertainty) and aleatory uncertainty related to disaggregation of hazard into magnitude-distance pairs. They proposed a suite selection methodology that allows variation of spectral values of the ground motions along the UHS in order to address the epistemic uncertainty of the PSHA logic tree and the aleatory uncertainty related to spectral shape. Ay and Akkar (2012) proposed a selection and scaling procedure that preserves the inherent aleatory variability in the selected recordings without manipulating their inherent features excessively.

The main objective of this study is to present a ground motion selection and scaling procedure that addresses the uncertainty in the target intensity measure with the level of spectral variability preserved within the ground motion suite. We provide a suite selection algorithm that constitutes ground motion set based on the dispersion statistics about the target. The scaling stage ensures that the median spectra of the scaled ground motions are compatible with the target spectra over a specified period range. Moreover, each scaled ground motion can be further modified in order to match the target variance of the scenario-based spectrum. The bilinear inelastic SDOF systems of varying periods are used in different case studies to evaluate the performance of the proposed methodology in predicting the nonlinear structural response. In order to investigate the impact of different scaling methodologies on seismic demand estimations, results are compared with those obtained from the Conditional Spectrum (CS) based scaling procedure.

Main steps of the proposed ground motion selection and scaling procedure

The ground motion database utilized in this study includes 4493 accelerograms with two-horizontal components which are compiled from the Next Generation Attenuation (NGA) strong-motion database (Pacific Earthquake Engineering Research Center, PEER) and RESORCE (Akkar et al., 2014). The overlapping events from NGA and RESORCE databases are excluded from the combined metadata.

Step 1: Ground-motion parameters to obtain representative ground-motion subset

The subset of ground motions can be formed for specific earthquake scenario parameters such as magnitude and distance pair. The magnitude-distance pair can be obtained either deterministic seismic hazard analysis (DSHA) or site-specific disaggregation of PSHA. In order to select records with ground motion parameters representative of the site hazard, ground motion database is constrained based on magnitude (M_w, moment magnitude), source-to site distance (R_{jb}, Joyner and Boore distance) and site information (Vs_{30}, average shear wave velocity for the topmost 30m of soil layers). The magnitude bound is selected as ± 0.5 magnitude units about target magnitude. Source-to-site distance interval is extended to ±80km about target distance. Site classes (determined as a function of V_{S30}) of the recordings should be consistent with the local site conditions of the site of interest. These limits serve as an initial filter for identifying a proper suite of records to assemble the ground motion bin to be used for scaling.

Step 2: Candidate records with similar target spectral shape

Final subset of the candidate ground motions are determined by taking into account the spectral shape. The logarithmic difference (δ_i) between the spectral values of records and the target is calculated for logarithmically equally-spaced *n* periods along the target spectra using Equation 1. The mean (μ_δ) and standard deviation (σ_δ) of each record are calculated along the target spectra using Equation 2 and Equation 3, respectively. The response spectrum which has smaller standard deviation (σ_δ) indicating that the ground motion deviates least from the target. After sorting the computed standard deviations in ascending order, the top half of the sorted records would be chosen to form N number of final candidate ground motions.

$$\delta_i = \ln Sa_i^{record} - \ln Sa_i^{target} \tag{1}$$

$$\mu_\delta = \frac{1}{n}\sum_{i=1}^{n}\delta_i = \frac{1}{n}\sum_{i=1}^{n}(\ln Sa_i^{record} - \ln Sa_i^{target}) \tag{2}$$

$$\sigma_\delta = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(\delta_i - \mu_\delta)^2} \tag{3}$$

Step 3: Construction of the ground motion sets using sliding window approach and optimum set determination

After imposing several filters to obtain N number of final candidate records, the ground motion set is constructed using an algorithm that does not deal with combinatorial problem. Given N number of candidate recordings, the ground motion sets of k accelerograms are assembled through the following steps:

The logarithmic differences (Δ_i) between the spectral ordinates of N candidate ground motions and target at the fundamental period of the structure (T_1) are computed as given in Equation 4.

$$\Delta_i = \ln Sa_i(T_1) - \ln Sa(T_1)^{target} \tag{4}$$

Δ_i represents the distance of i^{th} candidate record to the target at the fundamental period of the structure. To develop ground motion sets of k accelerograms, Δ_i values are sorted in ascending order first, and then k ground motions are chosen under a constant window length over the sorted list. This constant window length moves by one element and calculates the standard deviation at each step until reaching the (N-k+1) number of slides. Thus, each sliding window represents a ground motion set associated with a standard deviation (σ). Figure 1 illustrates the schematic representation of the sliding window procedure.

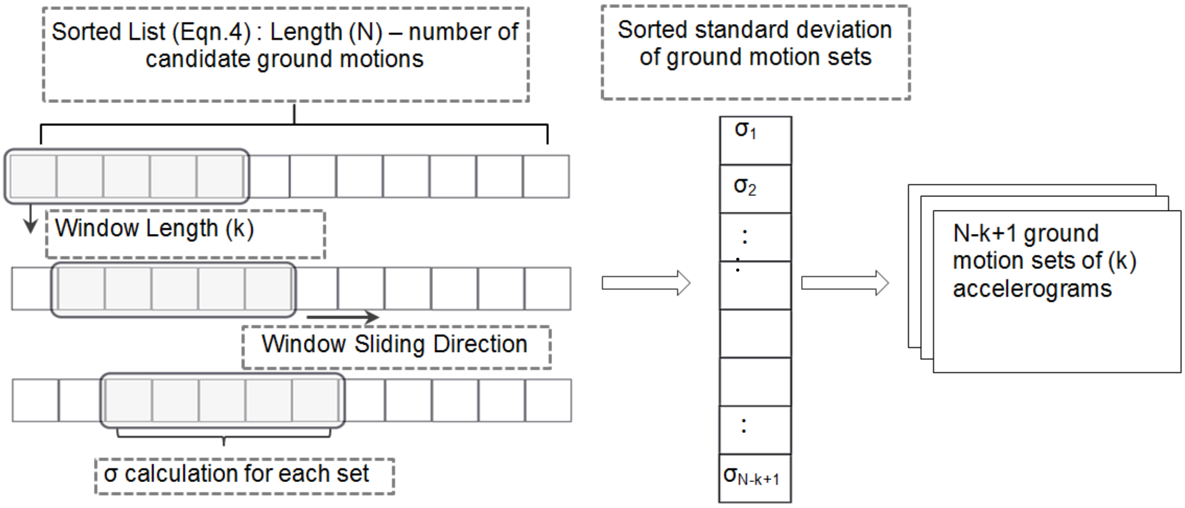

Figure 1. Schematic representation of the sliding window approach to constitute the ground motion sets of (k) accelerograms

The optimum set among the (N-k+1) number of ground motion sets is determined based on the goodness of fit between target and record set median and variances in the period range of interest (i.e., $0.2T_1$ to $2T_1$). The mismatch between record spectrum and target spectrum is estimated using sum of squared error (SSE) formula as given in Equation 5.

$$SSE = \sum_{i=1}^{n} \left[(\mu_{\ln Sa(T_i)} - \mu_{\ln Sa(T_i)}^{target})^2 + w(\sigma_{\ln Sa(T_i)} - \sigma_{\ln Sa(T_i)}^{target})^2 \right] \quad (5)$$

In Equation 5, the parameter w stands for the weighting factor determining the relative significance of the errors in the mean $\ln Sa$ of ground motion set ($\mu_{\ln Sa(T_i)}$) and the target ($\mu_{\ln Sa(T_i)}^{target}$) and their corresponding standard deviation values ($\sigma_{\ln Sa(T_i)}$ and $\sigma_{\ln Sa(T_i)}^{target}$) at the period T_i. The set which has the lowest SSE score would be chosen as the optimum at the end of this stage.

Step 4: Scaling of the optimum ground motion set to match target median and variance

Scaling stage aims to obtain a satisfactory match between the median spectrum of the ground-motion set and the target spectrum for the period range of interest (e.g., $0.2T_1$ to $2T_1$). The scale factor (SF_1) is computed using an optimization algorithm which minimizes the difference between the median record spectrum ($Sa^{median}(T_i)$) and the target spectrum $(Sa^{target}(T_i))$ over the periods (T_i) at which the spectral values are defined. The objective function of the minimization problem can be given by

$$\min_{SF_1} \| \ln(SF_1 x Sa^{median}(T_i)) - \ln(Sa^{target}(T_i)) \|_{0.2T_1<T_i<2T_1} \quad (6)$$

where ||.|| represents the Euclidean norm. Herein, we adopt an additional criterion to ensure that the scaled median of the spectral values do not fall below 90% of the target spectrum in the specified period interval. This is a condition required by the most contemporary seismic code provisions. Thus, the normalized differences (s_d) between the spectral values of the scaled median spectrum and the 90% of the target median are calculated in order to obtain the adjusting scale factor (SF_2). Equation 7 presents the computation steps of SF_2.

$$\text{If } \min_{0.2T_1<T_i<2T_1}\left[SF_1 x Sa^{median}(T_i)/Sa^{target}(T_i)\right] < 0.9 : \\ s_d = \frac{\max_{0.2T_1<T_i<2T_1}(0.9 x Sa^{target} - SF_1 x Sa^{median})}{(0.9 x Sa^{target})} \\ SF_2 = (1-s_d)^{-1} \tag{7}$$

The final scale factor of the ground motions to match target median is computed as $SF_{median} = SF_1 x SF_2$. When the ground motions are multiplied by this median scale factor (SF_{median}) the spectral variability within the ground motion suite is preserved along the period range of interest. It is important to highlight that this scaling procedure is adopted while selecting ground motions to match PSHA-based target spectrum such as UHS or CMS.

On the other hand, for the scenario-based target spectrum, the target distribution of the spectral demand is mainly considered as target median ± standard deviation (σ^{target}) estimation of the ground motion prediction model. Therefore, each scaled ground motion needs to be further modified to control the variance of the ground motion suite. In order to capture the target probability distribution at the given period, the new spectral ordinate of each ground motion is defined by epsilon (ε) values, i.e, the number of standard deviations above or below the median. The location of ε corresponds to the center of equally divided portions in cumulative distribution function (CDF) where the corresponding values can be obtained using inverse CDF. For illustration, the computed ε values for a suite of five motions are shown in Figure 2. The distribution of the target spectral ordinates is developed with respect to the natural logarithm of the scaled median spectrum ($\ln \widetilde{Sa}^{median}(T_1)$) at the fundamental period (T_1). Thus, the match between scaled median and target spectra is preserved and the applied scale factors will affect only the standard deviation of the ground motion set. The target spectral ordinates ($\ln Sa_n^{target}(T_1)$) for the n number of ground motions at the target period are computed by using Equation 8.

$$\ln Sa_n^{target}(T_1) = \ln \widetilde{Sa}^{median}(T_1) + \varepsilon_n(\sigma^{target}) \tag{8}$$

Equation 9 presents the computation of the individual scaling factor (SF_n) of each ground motion which is obtained by taking the ratio of the sorted logarithmic spectral values of the target and the ground motions ($\ln Sa_n(T_1)$) at the fundamental period.

$$SF_n = \frac{\ln Sa_n^{target}(T_1)}{\ln Sa_n(T_1)} \tag{9}$$

After applying the final scale factor ($SF_{final} = SF_{median} x SF_n$) to each ground motion, the scaled ground motion set provides a reasonable match to target median and variance of the scenario-based spectrum over the specified period interval.

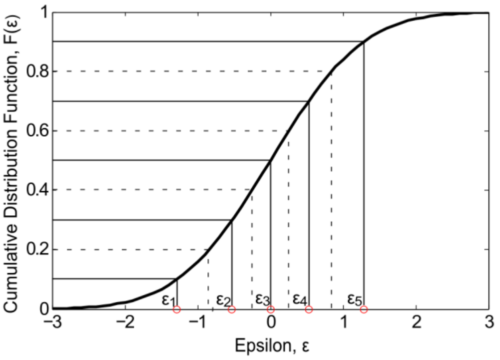

Figure 2. Determination of epsilon (ε) values for suites of five ground motions by dividing cumulative distribution function

Case study based on matching PSHA-based spectrum

This section focuses on the application of the proposed methodology to select ground motions for matching PSHA-based target spectrum. Site-specific PSHA calculations are performed using the EZ-FRISK Program (Risk Engineering, 2005) to estimate the seismic hazard level of the target site (40.99˚N, 29.09˚E) in city of Istanbul. The soil condition at the target site is assumed to be stiff soil with Vs_{30}= 450 m/s. The mean value of the most contributing earthquake scenario parameters such as magnitude (M_w), source to site distance (R_{jb}; Joyner and Boore distance), and epsilon (ε) values are determined by disaggregation of the probabilistic seismic hazard for 2475 years return period (2% probability of exceedance in 50 years). The target Conditional Mean Spectrum (CMS) is developed for the period of interest T_1=2.0s using the disaggregation information with characteristic parameters of the target scenario (M_w =7.23; R_{jb} =25.64 km) and the Campbell and Bozorgnia (2008) ground motion prediction model (GMPM). The target Sa (T_1) level is obtained as 0.30 g. The proposed procedure is used to select a suite of 40 ground motions for matching Conditional Mean Spectrum (CMS). In order to make comparisons across two different scaling approaches, the ground motions are also selected and scaled to match Conditional Spectrum (CS) that takes into account both mean and variability of the response spectrum. Herein, this scaling procedure is referred to as CS-based scaling. Scaled records of both methodologies are plotted along with their median and target spectra in Figure 3. The standard deviations of the lnSa values of the ground motion suites are also provided on each plot. The results of the proposed procedure and the CS-based scaling approach are shown in left and right panels, respectively. It is seen that the median scaled record spectrum provides a reasonable match to target median over a period range for both cases because the records are selected to have an appropriate spectral shape in both methods. In the case of proposed methodology, the earthquake records are modified with a constant scale factor to match the target CMS. Thus, the dispersion within ground motion set and the deviation between seed motions are preserved along the target spectrum. The main assumption of the proposed method is that the additional uncertainty in the target intensity measure may be explicitly addressed by the spectral variability in the ground motion suite. In the case of CS-based scaling, the ground motions are modified with their specific scaling factor to match target intensity. It is assumed that the distribution of the ground motion suite should be consistent with the multivariate normal distribution of logarithmic spectral acceleration (lnSa) of the response spectrum. The uncertainty at the target intensity level is considered as zero, whereas the uncertainty is included at other periods of the response spectrum. As can be seen in Figure 3, the target variance at periods away from the conditioning one increases as a result of decreasing correlations of spectral accelerations. It is shown that the dispersion of the ground motion suit selected by the CS-based scaling method is consistent with the target variance of the CS. On the other hand, the proposed methodology does not consider the variance of the target spectrum while selecting the ground motions to match CMS, and therefore standard deviation of the ground motion suite shows uniform trend along the period range of interest (i.e. $0.2T_1$ to $2T_1$).

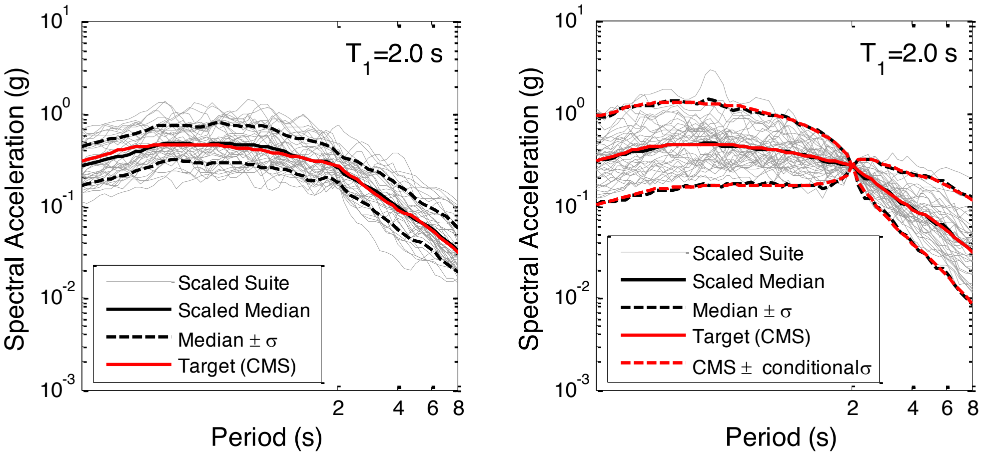

Figure 3. Comparisons of scaled median and target spectra for period of interest T_1=2.0 s. The left panel shows the results of this study and the right panel corresponds to the CS-based scaling case

Estimation of Structural Demand for equivalent SDOF systems

To evaluate the performance of the proposed procedure in predicting the seismic demand, the seismic response analysis results of this study are compared with those obtained by the CS-based scaling method. The non-degrading bilinear SDOF systems (with 3% post-yield stiffness hardening ratio and 5% damping ratio) with fundamental periods of T_1=0.5, 1.0, and 2.0 seconds are used as representative models of the reinforced concrete frame structures with varying stories. The base shear coefficients (i.e. the ratio of yield base shear to total seismic weight) of these equivalent SDOF structural systems (T_1=0.5, 1.0, and 2.0 s) are considered as 0.20, 0.15, and 0.07, respectively. The structural response measure (or engineering demand parameter) is considered as maximum inelastic displacement (Sdi). Nonlinear structural response is investigated through the probability distribution of the demand parameters. Site-specific PSHA calculations are performed for the same target site as discussed above. The most contributing earthquake scenario parameters are determined by disaggregation of the probabilistic seismic hazard for 6 different intensity levels at each period of interest. The intensity levels of target Sa (T_1) for each target period are considered to represent a set of return periods (T_r) ranging from 225 years to 10000 years (i.e., T_r= 225, 475, 975, 2475, 4975, and 10000 years). Target conditional mean spectrum (CMS) is derived from the scenario earthquake parameters of site-specific PSHA and the Campbell and Bozorgnia (2008) ground motion prediction model for all intensity levels and structural period combinations. The proposed methodology is then used to select a suite of 40 ground motions to match the CMS. As discussed before, the ground motions selected by using the CS-based scaling approach are compatible with the distribution of the target CS. Figure 4 illustrates the inelastic displacement estimations of both scaling methodologies which are presented in terms of their median and logarithmic standard deviations at six different return periods (or intensity levels) for each target period. μ_{Sdi} and σ_{lnSdi} correspond to mean and standard deviation estimations of the logarithmic inelastic displacement (i.e. lnSdi), respectively. Note that the distribution of the engineering demand parameter (EDP) for a given level of intensity measure is assumed to have a lognormal distribution in order to evaluate the dispersion values for both scaling approaches in a consistent manner. The results show that both scaling methodologies provide similar trend in median responses. As the target intensity level increases, the structural systems undergo significant inelastic deformations that lead to increase in median demand estimations. Both scaling methods produce fairly similar median response predictions for each fundamental period at different intensity levels. The ground motions selected by CS-based scaling produce approximately 10% larger median responses than the proposed procedure at the period of T_1=2.0 s for high ground motion intensity levels (i.e. return periods higher than 2475 years).The results indicate that the ground motions selected by the proposed methodology do not produce biased estimation of the structural response as the nonlinearity level increases. Moreover, these findings demonstrate the robustness and accuracy of the proposed methodology in predicting the nonlinear median response for different structural periods and intensity levels. The presence of the spectral variability at the target period does not produce biased estimate in the central tendency of the structural response, however it propagates to large variability in the seismic demand. As can be seen in Figure 4, the lower level of dispersion is obtained with the ground motions selected by the CS-based scaling, whereas the proposed procedure overestimate the dispersion relative to CS- based scaling. This result is expected since suppressing the ground motions to Sa (T_1) level reduces the dispersion (or variability) in the structural response. In the CS-based scaling, approximately same level of dispersion is predicted for different structural periods. Dispersion values are changed between 0.2 and 0.35. The estimated dispersion is slightly increased as the nonlinearity level increases. On the other hand, the ground motion suit selected by the proposed method generates values of dispersion between 0.44 and 0.7 in which the largest dispersion is observed for the structural period of T_1=2.0 s.

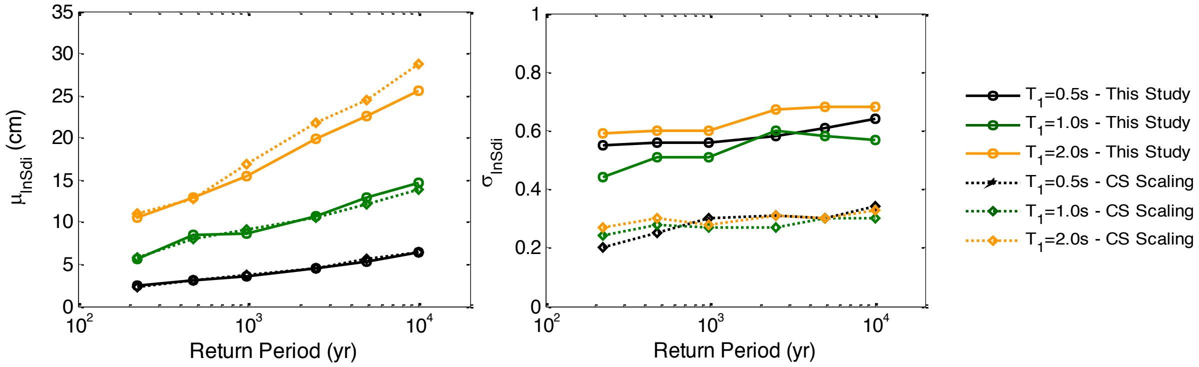

Figure 4. Probability distributions of structural response for different fundamental periods. Left panel: Median of inelastic displacement ($\mu_{\ln Sdi}$) versus return period, Right panel: Logarithmic standard deviation of inelastic displacement ($\sigma_{\ln Sdi}$) versus return period

The seismic response analyses are conducted using sets of 7,10,15,20,30, and 40 records for structural period of T_1=0.5 s with the aim of finding required number of scaled ground motions that yields robust demand estimation. Figure 5 illustrates the median and standard deviation estimations of both scaling methodologies with respect to different number of ground motions for two levels of seismic hazard (i.e. return periods with T_r=475 and 2475 years). The results show that both methods yield similar median estimates for two intensity levels. However, it should be noted that the CS-based scaling method is more effective in minimizing the dispersion in structural response. The proposed method provides lower variability in structural response when the suits of 7-10 records are used because small number of records reduces the elastic dispersion within ground motion suite at the target period as discussed in previous section. The variability in the structural response becomes more stable when more than 15 records are used. The differences between two methods in median estimations are significant if the analyses are conducted using suites of 7-10 ground motions for 2475 years return period. In order to evaluate the confidence level in terms of different number of ground motions, standard error of the inelastic displacements are used as a statistical measure. Standard error ($S.E.$) on the sample mean can be defined as the ratio of variability in the structural response ($\sigma_{\ln EDP}$) to square root of the number of analyses (N_{obs}) carried out (i.e. $\sigma_{\ln EDP} / \sqrt{N_{obs}}$). Figure 6 depicts the comparisons of the standard error estimations of both scaling methodologies with respect to number of ground motions for each intensity level. The error estimation tends to decrease with increasing number of ground motions. In general, using less than 15 records yields unstable error estimation for the CS-based scaling method. On the other hand, the proposed procedure tends to be stable for larger than 20 records. The error estimations of both methodologies tend to converge same value for a large number of ground motions (in the order of 40+). One can infer from these results that at least 15 records are needed to obtain an estimate of inelastic displacement within 10% error (i.e. for a 64% confidence) for the CS-based scaling case, whereas the proposed methodology requires 20-25 records in order to predict the median demand with the same level of precision. On the contrary, many code provisions prescribed using 7 records which may cause significant uncertainty (%15 errors in median estimation) in design and performance evaluation.

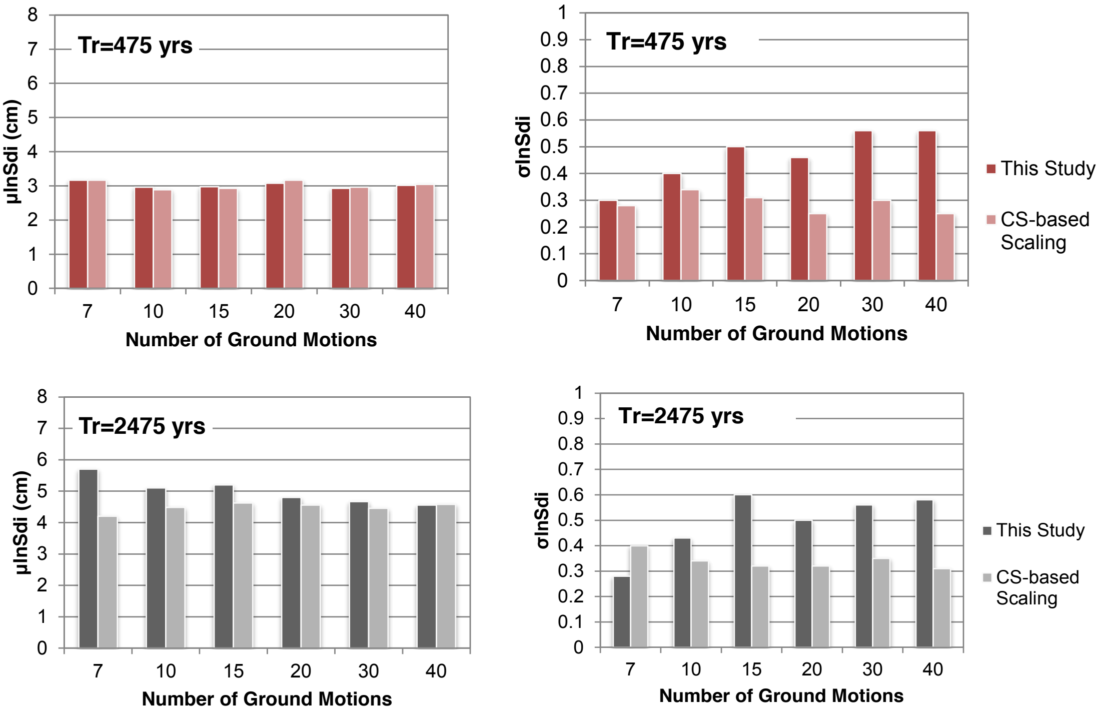

Figure 5. Comparisons of median and standard deviation values predicted by using the two methods. The results are presented as a function of number of ground motions for two intensity levels (with return periods of T_r=475 and 2475 years) for structural period of T_1=0.5 s.

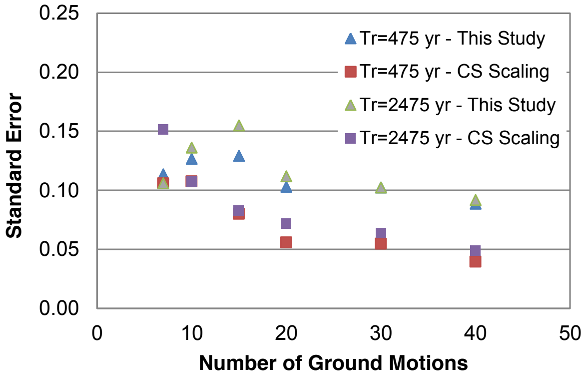

Figure 6. Comparison of standard error estimations of two methods. The results are presented as a function of number of ground motions for two intensity levels (with return periods of T_r=475 and 2475 years) for structural period of T_1=0.5 s.

Conclusion

In this study, we present a new ground motion selection and scaling methodology that addresses the uncertainty in the target intensity measure with the spectral variability preserved within ground motion suite. The proposed ground motion selection and scaling methodology provides appropriate ground motions for both code-based analysis and probabilistic seismic assessment procedures. The performance of the proposed procedure in predicting the nonlinear structural response is tested by comparing the results with those obtained by the Conditional Spectrum (CS) based scaling. The results show that the proposed procedure gives unbiased estimation of the median demand. However, the consideration of the spectral variability at the target period leads to large variability in structural response. For the CS-based scaling case, at least 15 records are needed to obtain an estimate of inelastic displacement within 10% error (i.e. for a 64% confidence), whereas the proposed methodology requires 25 records in order to predict the median demand with the same level of precision.

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