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EVALUATION OF GROUND-MOTION RECORD SCALING AND SELECTION METHODS FOR SEISMIC DESIGN AND ASSESSMENT OF STRUCTURES

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ABSTRACT:

Amplitude scaling and selection of ground-motion records are frequently used tools to obtain a group of accelerograms suitable for structural performance assessment for a given hazard level. To provide a suitable set of records to be used in nonlinear dynamic analysis either to estimate median structural response or to predict its full probability distribution, "n" scaled ground motions that best match with target spectrum are selected. Common concerns related with this approach are the use of appropriate definition of target spectrum according to the objective of nonlinear dynamic analysis and the number of required recordings, "n", that yield unbiased structural response. This study uses scenario event spectrum, conditional mean spectrum, and conditional spectrum as alternative targets with 7, 11 and 15 records. Additionally, the adequate level of spectral match between ground-motion records and the target is also a critical issue as it could lead to biased results. This study uses a modified goodness-of-fit measure and investigates corresponding threshold levels to classify records that yield unbiased structural response.

KEYWORDS: nonlinear dynamic analysis, target spectrum, threshold levels of goodness-of-fit

1. INTRODUCTION

Selecting ground-motion records to be used in nonlinear dynamic analyses (NDAs) is an important issue as it directly influences the structural response estimations for a given seismic action. Among various ways, engineers usually scale the amplitude of the records (to provide better match with the target using lesser records) and assemble the optimum set (which has the best match with the target) for obtaining the records to be used for accurate estimation of structural dynamic response. Despite significant progress in record selection theory and emerging software tools, there are still practical challenges confronted by the analyst. Among these, the use of appropriate target spectrum with respect to available disaggregation information and the achieved level of match with target spectrum for a given number of records are studied here.

2. METHODOLOGY

2.1. Structural Model

A reinforced concrete (RC) structure is assumed to be located near Erzurum (seismic zone 1 according to Turkish Earthquake Code (TEC), 2007) on a soft soil site (classified as Z3 in TEC, 2007). The characteristic compressive strength of concrete and steel yield strength are taken as 20 MPa and 420 MPa, respectively. From this moment-resisting frame structure, which is complying with TEC (2007), a representative two-dimensional frame is selected and used in structural analyses. Figure 1 shows the three dimensional model and the geometry of members of the frame (the frame on the plane of C axis, MRFC) used in NDAs.

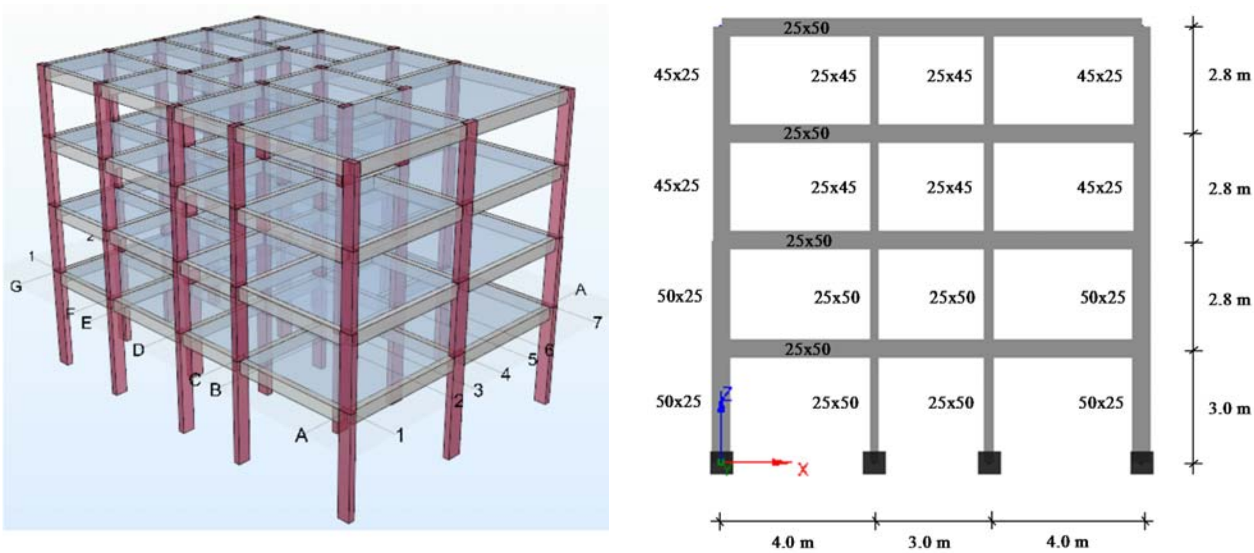

Figure 1. 3 dimensional model of example building, MRFC model and corresponding member dimensions

The modal and dynamic analyses were conducted by using SeismoStruct (Seismosoft, 2013) platform (version 6.5). The first and second mode periods of the MRFC are found as 0.61s and 0.2s, respectively. The translational effective modal mass participation of the first mode is found as 0.84. According to the eigenvalue analysis results, the structure predominantly behaves in the first mode. The base shear coefficient, $\eta=V_y/W$, is found as 0.30. SeismoStruct (Seismosoft, 2013) employs Hilber-Hughes-Taylor integration method (Hilber et al., 1977) while performing NDA. The NDAs of the MRFC are done by using the records selected and scaled according to target spectrum definitions used here. In this study, maximum inter-story drift ratio (MIDR, which is calculated by normalizing the maximum inter-story displacement with the story height) is used as the engineering demand (EDP) parameter.

2.2. Target Response Spectrum

In general, the target spectrum is described as the code spectrum, uniform hazard spectrum (UHS) or scenario event spectrum (SES) associated with the hazard of the site. Alternatively, Baker (2011) suggested using the conditional mean spectrum (CMS) because of the unrealistic representation of earthquake demands by UHS or code spectrum for the particular structural system being assessed for a given future event. In addition to these, conditional spectrum (CS) that includes target mean (equals to CMS) and corresponding variance could be used if the aim of the analyst is to predict full probability distribution of structural response. Different than CMS, CS allows the analyst to consider a reasonable dispersion about target intensity as a proxy of structural response distribution.

Selection of the proper target spectrum mainly depends on the aim of the analysis as well as the available information about the hazard because the latter could be rather limited which makes the analyst use another target definition that may not be the most appropriate one. This study uses CS, CMS and SES in comparisons. Regarding the outline given in Lin et al. (2013), the most approximate CS (single earthquake scenario with single GMPE) has been used in this study. Nevertheless, this CS is assumed to be close enough to the exact CS since the site is dominated by a single seismic source and the site specific PSHA used in this study is exceptionally performed with single GMPE proposed by Akkar and Bommer (2010). Figure 2 shows target SES, CMS (mean of CS) and corresponding variance for a given period (T*) of 0.61s.

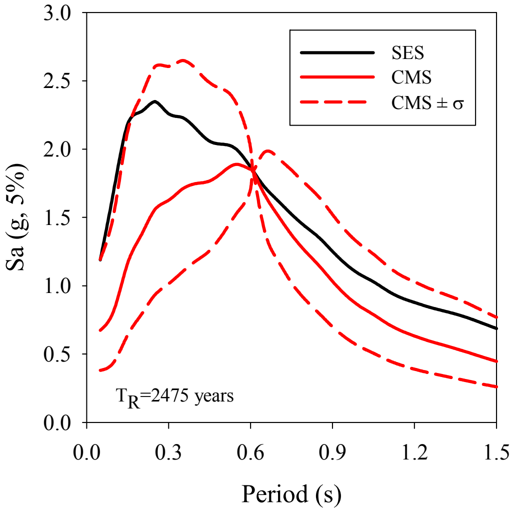

Figure 2. Comparison of alternative target spectrum associated with the expected seismic hazard

2.3. *Scaling and Selection of ground-motion records*

In this study, optimum records that match with the target spectrum have been selected among scaled candidate records. Stripe scaling is preferred to obtain a set of records that all satisfy the expected target intensity level (Sa_{target}) for the given fundamental period (T*=0.61s). The stripe scaling formulation is given in Equation 1 where SF shows the scaling factor for a given record.

$$SF_{record,i} = \frac{Sa_{target}(T^*)}{Sa_{record,i}(T^*)} \tag{1}$$

When selecting records from the candidate bin, the goodness-of-fit (GoF) between candidate spectrum and the target have been measured for a given spectral period band of interest. The candidate data can be either the spectrum of an individual record or the median spectrum (and corresponding variance) of a ground motion set. Equation 2 gives the quantity of dispersion (mismatch) between an individual candidate spectrum and the target spectrum whereas Equation 3 calculates the mismatch of a median response spectrum and corresponding variance of a candidate set with respect to the target. In these formulas "t" is the number of intermediate period values where the GoF is measured. Baker (2011) suggested using 50 as "t". In Equation 3, μ and σ represents the median spectrum and logarithmic standard deviation of candidate record set.

$$ASSE_{record} = \frac{1}{t}\sum_{i=1}^{t}\left[\ln\left(Sa_{record}(T_i)\right) - \ln\left(Sa_{target}(T_i)\right)\right]^2 \tag{2}$$

$$ASSE_{\mu\&\sigma,set} = \frac{1}{t}\sum_{i=1}^{t}\left[\left(\mu_{\ln Sa(T_i)} - \mu_{target(T_i)}\right)^2 + \left(\sigma_{\ln Sa(T_i)} - \sigma_{target(T_i)}\right)^2\right] \tag{3}$$

Note that, the averaged-sum-of-squares (ASSE) suggested by this study is a modified version of sum-of-squares (SSE) to eliminate the influence of "t" on dispersion measure in a cumulative manner. In this study, each record or ground motion set that yields the minimum ASSE score is selected to obtain the optimum recording bin. Selecting "n" records by using Equation 2 (selecting records having minimum mismatch from the target) primarily minimizes (theoretically eliminates) the record-to-record variability. In other words, this method mainly aims to reduce dispersion whereby it presumes that the median spectrum of the final set will theoretically fit to the target. Note that this assumption is strictly valid to the achieved GoF of the selected records. Thus, the records that has the minimum record-to-record variability does not necessarily be the set of which median spectrum has the best match with the target. For instance, Figure 3 shows the difference of selecting 7 records with smallest $ASSE_{record}$ scores (minimum record-to-record variability) and selecting 7 records for the best match with target. Note that the record-to-record variability is relatively less as shown in left panel of Figure 3 whereas the match is much better albeit larger record-to-record variability (especially periods less than 0.61 s) shown in right panel. This figure highlights the difference between reducing of dispersion by selecting "n" records with smallest ASSE scores (suitable for targets that already include the variance, e.g., SES) and selecting group of records whose median (and variance) best matches with the target (e.g., CS). Considering previous studies (Baker, 2011; Jayaram et al., 2011; etc.), this study has used Equation 2 for selecting records compatible with CMS and SES whereas Equation 3 has been used for selecting CS compatible sets.

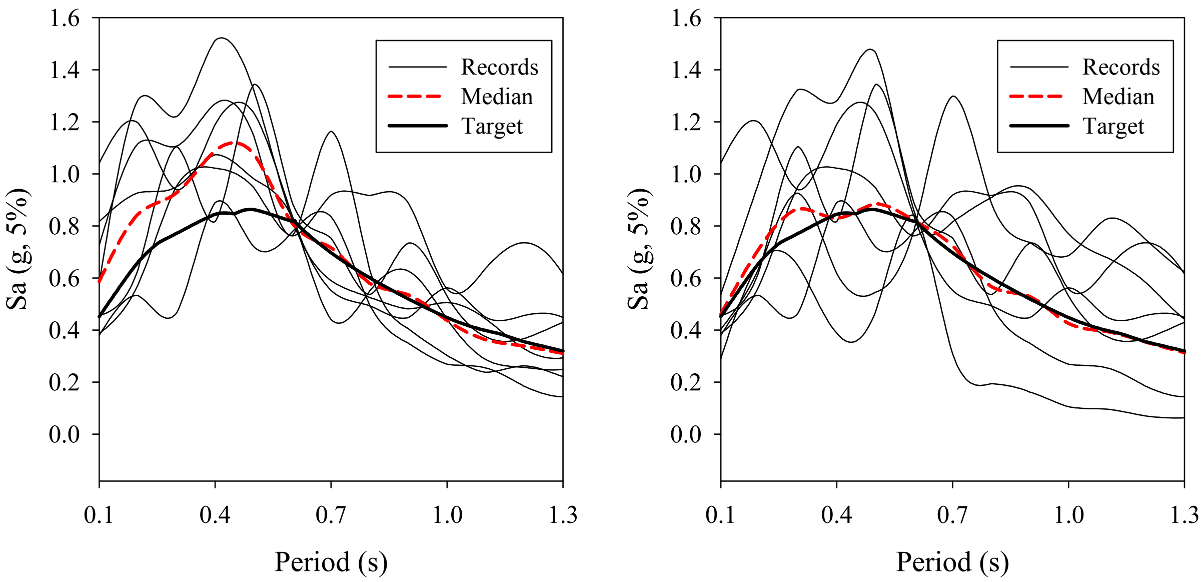

Figure 3. 7 records with minimum ASSE scores (left panel), 7 records with the best-fit-median (right panel)

In this study, SES, CMS and CS associated with different hazard levels have been derived and corresponding record sets have been assembled. Then, these records are used for nonlinear dynamic analysis of the structure described above. Figure 4 displays the 15 hazard levels and corresponding Sa_{target} for the given fundamental period of 0.61s. In this study, 42, 72, 98, 140, 224, 308, 475, 689, 975, 1225, 1403, 1642, 1975, 2475 and 3308years have been used as target hazard levels to obtain structural response estimations. Corresponding target Sa levels (Sa_{target} (0.61s)) are 0.20, 0.28, 0.34, 0.41, 0.53, 0.64, 0.81, 0.99, 1.18, 1.31, 1.40, 1.51, 1.65, 1.84 and 2.09 g. 15 hazard levels from very short to long return periods have been used to make comparisons for different levels of nonlinear response. For return periods longer than 3308 years, the number of converged NDAs is not sufficient for accurate prediction of EDP.

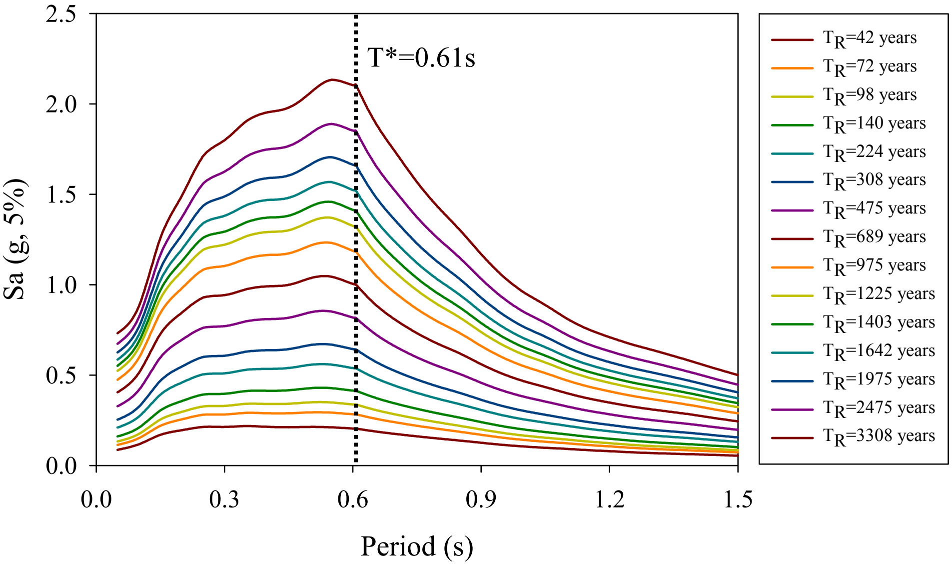

Figure 4. Target CMS conditioned on 0.61s for the given 15 hazard levels

The number of records to be used in the structural response estimation is always an important concern. Hancock et al. (2008) suggest that 3 records that are scaled to the elastic spectral acceleration at the fundamental period of the structure are required to predict the peak roof drift of an 8-story regular wall-frame RC building within ±10% accuracy. Notwithstanding, the common code approach (e.g., Eurocode-8, 2004 and TEC, 2007) requires a minimum number of 7 accelerograms for the median estimation of structural response with limited error. More recently, ATC-58 (2009) suggests using at least 11 accelerograms for estimating the full probability distribution of building response under a specific scenario event. On the other hand, Cimellaro et al. (2011) suggest using at least 20 accelerograms to have an accurate estimation on the fragility functions of a first-mode dominant non-degrading building if the ground-motion intensity is chosen as spectral acceleration in the analysis. They also indicate that the minimum number of scaled recordings is 10 for estimating the first-story drift response with an error less than 10%. With increasing power of computers and way of reducing the standard error, using larger number of records may not seem to be a concern anymore. Nevertheless, the current resolution of ground motion databases and usual constraints imposed by the analyst (maximum scaling factor, maximum usable period, etc.) still introduce limits on optimum number of records that yield unbiased structural response. Figure 5 shows the comparison of achieved mean and standard deviation with respect to corresponding target using 15 and 20 records. The level of match between the target and 15 record set is much better than 20 record set (especially for periods larger than 0.61s) although this difference is less prominent for comparisons of standard deviation. Considering previous studies, codes and discussions given above, comparisons were derived by using 7, 11 and 15 records in this study. The results obtained by using 15 records are assumed fairly accurate and compared with the curves of 7 and 11 records with respect to the GoF measure.

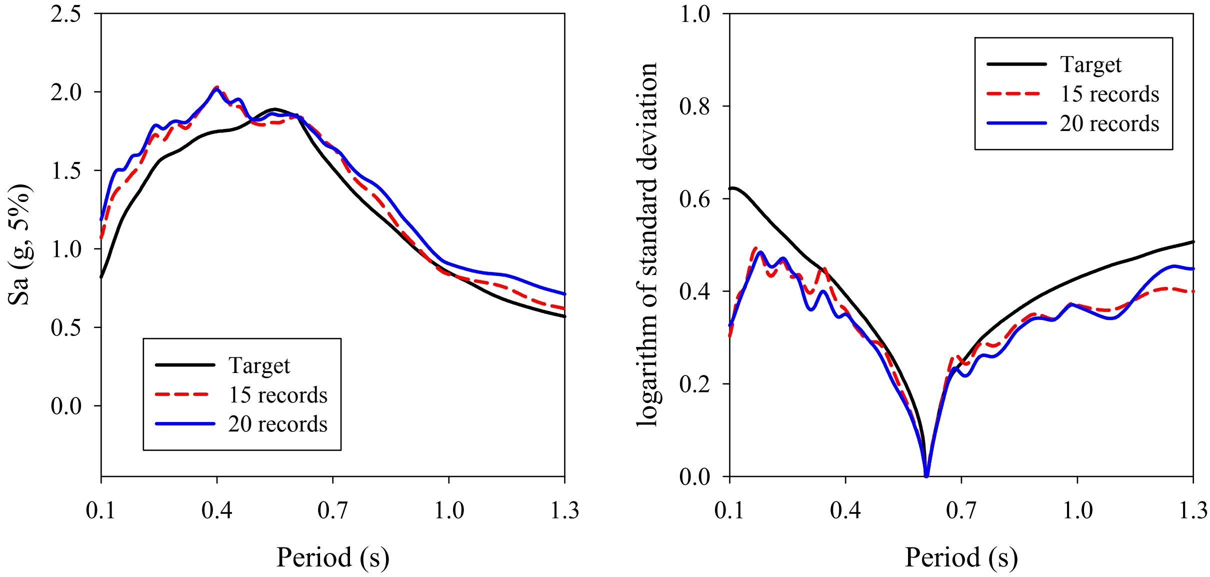

Figure 5. Comparison of target mean and standard deviation (black line) with achieved values for optimum sets having 15 records (red dotted line) and 20 records (blue line)

3. RESULTS AND DISCUSSION

By making use of presented structural model, alternative definitions of target spectrum and sets with 7, 11 and 15 records; this study derived structural response statistics. This information is then used for comparisons in order to investigate record selection criteria for non-degrading, first-mode dominant RC structures.

Figures 6 displays median MIDR (left panel) results and corresponding standard deviation (right panel). This figure shows that, CMS or SES as the target spectrum definition results in similar median structural response estimations (Figure 6 left panel) whereas in terms of variance about median structural response, SES yield slightly smaller values (Figure 6 right panel). Consequently, for cases where the available information doesn't allow the analyst derive CMS, SES could be better than UHS as an alternative. Considering the CS results, median estimations obtained by using CMS or SES and number of records yield similar median values up to median nonlinearity levels. Starting from 975 years (for relatively higher nonlinearity demands), the record sets matching with CS yield smaller median response values whereas the corresponding dispersion statistics is higher than those of CMS and SES as expected. Lower dispersion by targets CMS and SES stems from the suppressed record-to-record variability shown in Figure 3. Considering the recommendations of other studies (e.g., Ay and Akkar, 2014 and Jayaram et al., 2011) and the results shown in Figure 6, target spectrum without variance (i.e., CMS and SES) is not suitable for fragility analysis of structures. Nevertheless, Figure 7 uses fragility curves as a graphical tool to compare the structural response statistics because fragility curves implicitly contain the information of dispersion in EDP as well as the collapse statistics.

In order to compare the influence of alternative target spectrum to the damage probability assessment, three limit state definitions are used for structural system. These limit states are defined as immediate occupancy (IO), life safety (LS), and collapse prevention (CP). It is assumed that structures having no or slight damage perform at IO limit state whereas structures at LS and CP limit states are assumed to sustain significant and severe damage, respectively.

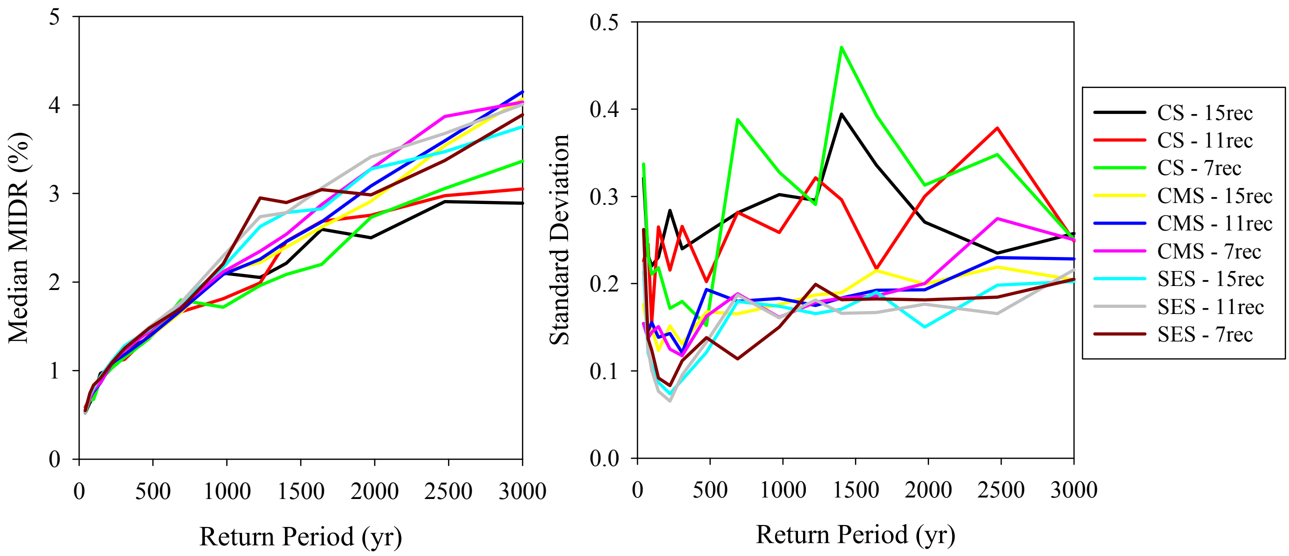

Figure 6. Comparison of alternative target definitions and number of records in terms of median structural response estimations (left panel) and corresponding variance (right panel)

Figures 7 display the fragility curves obtained by selecting 15 records complying with alternative target spectrum definitions (CMS, SES, and CS). Figure 7 shows that, CMS and SES yield steeper (the slope is higher) fragility curves with respect to CS. Thus CS yields larger probability of exceedance at lower intensity whereas smaller probability of exceedance values at higher intensities. The results are similar for increased number of recordings (n=7 and n=11). So, the fragility curves are relatively insensitive to the number of recordings especially in immediate occupancy limit state. As the nonlinearity level increases, using more recordings yield slightly smaller probability of exceedance values. Nevertheless, the difference is less than 15% for each limit state and alternative target definitions.

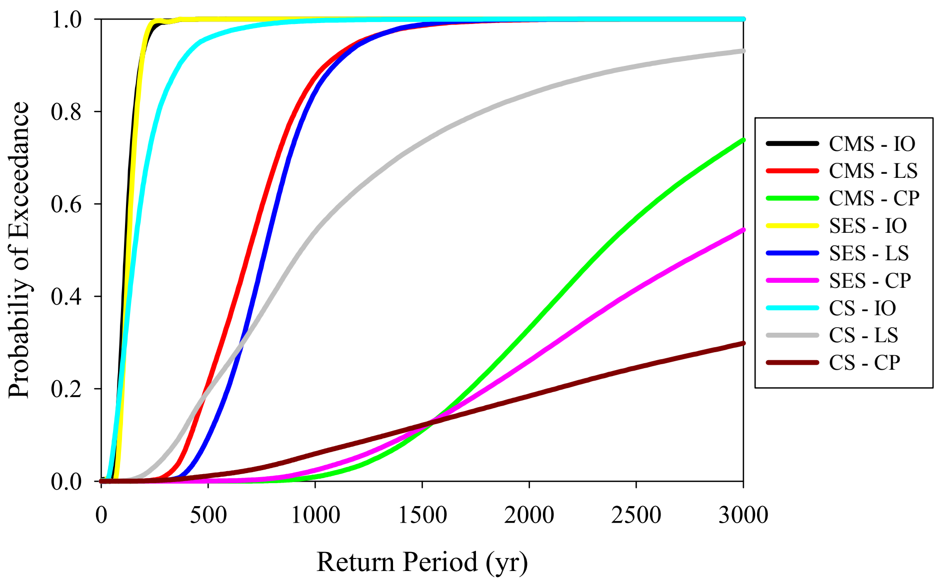

Figure 7. Comparison of CMS, SES and CS by using 15 records

Record selection approaches relies on the assumption that there are adequate candidates yielding unbiased structural response which is not always the case. Thus, we need tools that quantify the adequacy of the final recording set. However, this issue was not adequately addressed neither in codes or specifications nor in research papers. Among available guidance for limitation of mismatch, maximum allowed difference between target spectrum and median spectrum of optimum set is specified as 10% by most of the current codes. Alternatively, the ASSE score, which measures GoF of either individual records ($ASSE_{record}$) or the recording set ($ASSE_{\mu\&\sigma,set}$), can provide guidance to the analyst on the adequacy of final recording set for unbiased structural response estimations.

To investigate the relationship between $ASSE_{record}$ score and unbiased structural response, median estimations obtained by different sets of 7 records that are compatible with CMS (left panel) and SES (right panel) have been compared. In this study, similar median estimations have been observed with records having $ASSE_{record}$ scores less than 0.03 (the smallest score achieved with the candidate set used in this study) and 0.1. The results are similar for n=11 and n=15 record sets. Figure 9 presents the median structural response estimations with respect to increasing $ASSE_{record}$ scores. Note that, structural response with large variations have been observed for cases where $ASSE_{record}$ gets larger thus further analyses are needed to have stable threshold levels.

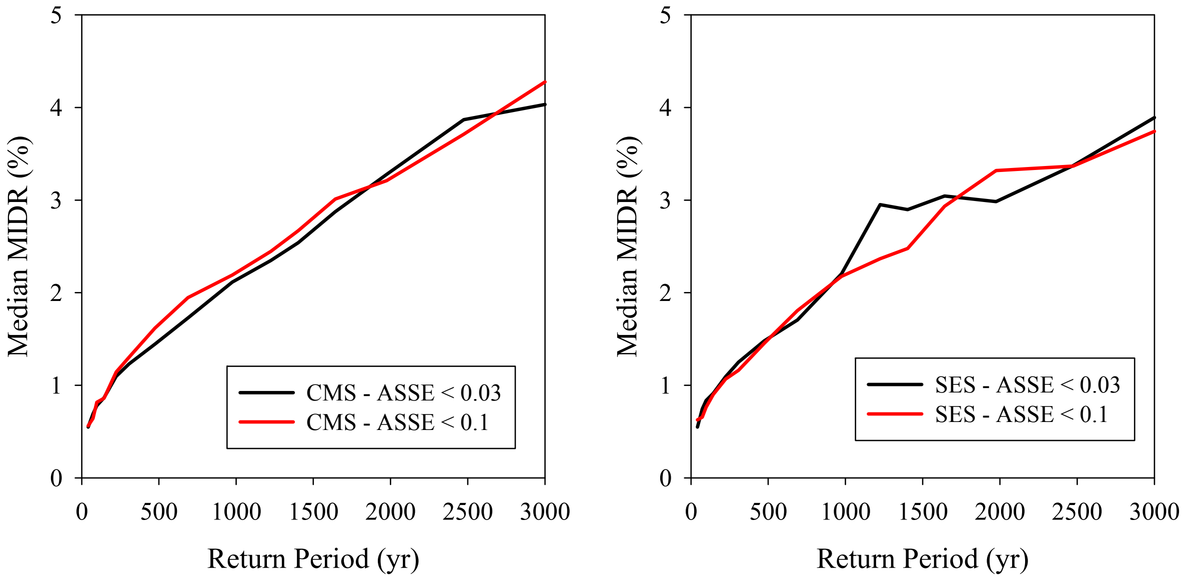

Figure 9. The change in ASSErecord scores with respect to median respose estimations

Similar to $ASSE_{record}$, $ASSE_{\mu\&\sigma,set}$ scores have been compared by using fragility curves obtained by records compatible with CS. Figure 10 shows the comparison between two sets having $ASSE_{\mu\&\sigma,set}$ scores less than 0.001 and 0.01, respectively. Considering fairly similar fragility curves shown in Figure 10, one could claim that using $ASSE_{\mu\&\sigma,set}$ scores less than 0.01 yield still unbiased fragility curves. Nevertheless, further analyses are required to have sound conclusions with respect to $ASSE_{\mu\&\sigma,set}$ scores beyond 0.01.

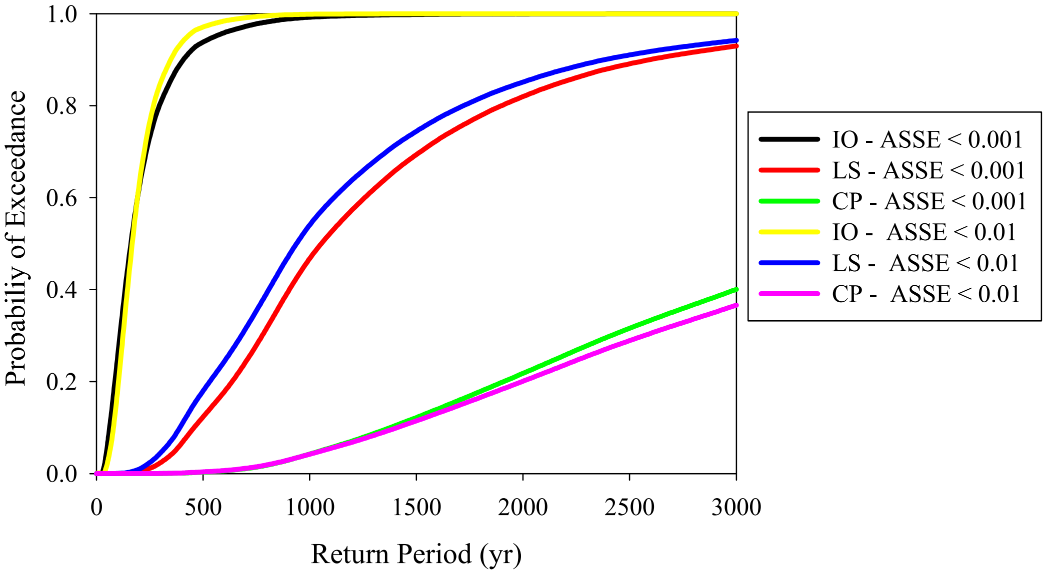

Figure 10. The change in $ASSE_{\mu\&\sigma,set}$ scores with respect to fragility curves

4. CONCLUSION

This study investigated alternative target spectrum definitions for record selection and scaling methodologies. The effects of using larger ground-motion sets (increasing the number of records to be used) have been investigated. For selecting of records compatible with a target spectrum, a modified GoF measure is proposed and its use on accurate structural response estimations were examined.

According to the results presented in this study, CMS and SES generally result in fairly similar median structural response estimations. Observed dispersion about median values of EDP are also fairly similar. However, for cases where the objective of NDA is to analyze probabilistic seismic risk, CMS and SES yield biased results compared to CS. This shows the importance of using proper target spectrum definition for unbiased performance assessment of structures. On the other hand, CMS and SES are advantageous for accurate median structural response estimations because of relatively lower variance in structural response measures.

For a given ground-motion record set, the accuracy of structural response estimations depends on the GoF between available candidates and the target. It is shown that increasing the number of records to be used in NDA does not necessarily yield more accurate performance estimations. To predict the accuracy of estimations for a given final record set, engineers need alternative tools. With this regard, this study used an alternative GoF measure that is a modified version of frequently used SSE (Baker, 2011) score. The modified GoF measure, averaged-sum-of-squares (ASSE), eliminates the influence of number of intermediate periods on SSE quantity. Relative to SSE, ASSE is fairly independent from the user-defined calculation parameters.

This study examined the relative difference between fragility curves and median estimations with respect to the ASSE scores of the records. This way, the level of ASSE scores that yield unbiased results is examined which are valid for the subject structural model and ground motion library. The results are promising to extend the scope of this research for other types of structures, alternative ground-motion libraries and selection methodologies.

The evaluations presented in this report are based on maximum inter-story drift ratio as the engineering demand measure. Although this parameter is proven to be a good indicator of seismic demand on first-mode dominant structures, other damage measures (e.g., maximum roof drift ratio, peak floor accelerations, etc.) can be investigated in future studies for the verification of structures dominated by higher mode contributions. Additionally, future research can be carried out to identify precise threshold levels of ASSE scores that yield unbiased structural response estimations for an extended scope of structural systems and selection methodologies.

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