SELECTING AND SCALING OF REAL ACCELEROGRAMS TO REDUCE THE SCATTER IN DYNAMIC RESPONSE

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ABSTRACT

One of the major objectives in ground-motion scaling techniques is to reduce the dispersion (bias) in structural response. The current scaling techniques generally modify the amplitude of each record in a bin to a target peak ground motion value. Although these approaches are proved to be efficient for obtaining suits of scaled records that would yield lower dispersion in spectral demand parameters, they do not warrant any physical basis. This study not only focuses on reducing the scatter in structural response, but also emphasizes the significance of preserving basic seismological features of the records after being scaled. Consequently, the limitations of an alternative scaling methodology are investigated by comparing the results from the conventional procedure described above. The explored methodology uses ground motion prediction equations (GMPEs) and scales each record with known fundamental seismological parameters (i.e. magnitude, distance and site class) by using the estimations obtained from the chosen predictive model. The procedure uses the standard deviation of the chosen GMPE to incorporate the aleatory variability to the entire process. We compiled a ground-motion dataset from Turkish, PEER-NGA and European strong-motion databanks and conducted spectral analyses to compare the efficiency of these two methods in reducing the uncertainty in structural response. The comparative statistics are presented for elastic and constant strength spectral displacements for vibration periods of 0.3s, 0.6s, 0.9s, 1.2s, and 1.5s.

Introduction

The need for scaling accelerograms and corresponding selection techniques is arisen from the purpose of using an ensemble of actual records to estimate the linear and nonlinear structural response accurately. In other words, scaling of accelerograms is mainly used in reducing the dispersion in structural response due to intricate features of strong-motion records. This way, the analyst can reduce the number of ground motions required to obtain reliable information on the seismic performance of structural systems. Besides the aim of reducing the dispersion, scaling

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(up and down) is also used to investigate different structural response states in incremental dynamic analysis. Finally, in probabilistic seismic hazard analysis, records that are selected from a specific magnitude and distance interval have to be scaled to match the predefined seismic hazard level.

Although variability in structural response primarily depends on the nature of input ground motions, guidelines that provide insight regarding the appropriate ways of establishing suitable suites of accelerograms have not come to a mature level yet (Bommer and Acevedo 2004, Haselton 2009). Nau and Hall (1984) compared alternative scaling factors based on ground-motion data and spectrum intensities to reduce dispersion in normalized spectral ordinates and found that scaling with respect to spectrum intensities provides less dispersion. Shome et al. (1998) showed that halving the dispersion in ground-motion intensities decreases the necessary number of nonlinear response history analysis by a factor of 4. Shome et al. (1998) also concluded that scaling of records within a bin to the bin-median spectral acceleration produces relatively lower dispersion in structural response. Martinez-Rueda (1998) proposed using scaling factors based on different spectrum intensities and an ensemble of records compatible with the design spectrum. Similarly, Kappos and Kyriakakis (2000) proposed a scaling methodology that depends on spectrum intensity for reducing the scatter in structural response. Bommer and Acevedo (2004) investigated several record selection criteria and proposed a simple one based on magnitude, distance and site class. They concluded that magnitude is the most dominant and effective seismological parameter in ground-motion selection whereas distance and site class can be considered within more tolerable limits. Bommer and Acevedo (2004) examined the previously proposed scaling procedures and pointed out some potential shortcomings of scaling to the median spectral acceleration at the fundamental period due to the inherent uncertainties in predicting the fundamental period of structures as well as the period elongation of structures with increased nonlinear behavior. Iervolino and Cornell (2005) investigated whether scaling of records with usual principal seismological parameters (magnitude and distance) matters to the nonlinear structural response. Watson-Lamprey and Abrahamson (2006) discovered that the deformation demand is directly correlated with the scale factor used to match the ground-motion parameter (PGV, PGA and Arias Intensity) of a record with the corresponding bin average. The interpretation of this observation is that larger scaling factors would introduce bias to the computed deformation demands. Consequently, Watson-Lamprey and Abrahamson (2006) proposed a new record selection procedure that is based on the analysis results of approximate nonlinear models. In a similar manner, Luco and Bazzurro (2007) also investigated whether scaling introduce a bias in nonlinear drift response and found that scaling the amplitude of a record to the target pseudo-spectral acceleration level at the fundamental period of structure introduce bias that can be reduced by selecting records having similar shapes to the target spectrum. Finally, Beyer and Bommer (2007) investigated the selection and scaling of accelerograms for bi-directional analysis. They showed that selecting the records based on a goodness-of-fit criterion to the target spectrum leads to smaller coefficient of variation (COV).

The objective of this study is to investigate two alternative scaling procedures and their limitations in reducing the bias in structural response. One of these methodologies uses empirical ground-motion prediction equations (GMPEs) whereas the other one establishes the scaling strategy on the median ground motion of a particular suit of records. The comparative statistics between these two methods are given in terms of different magnitude and distance intervals as well as different levels of inelasticity that are described through normalized lateral strength, R.

Ground Motion Selection

The reliability and consistency of data processing and uniformity of records in terms of magnitude and distance metrics are considered as the main parameters while selecting the ground-motion records of this study. The records are gathered primarily from the recently compiled Turkish strong-motion database[3] whereas PEER (http://peer.berkeley.edu/nga) and European strong-motion databank (Ambraseys et al. 2004) are also used for a better magnitude-distance distribution. Initial record search is based on geophysical parameters such as moment magnitude (M_w), source-to-site distance (R_{jb}, closest distance between the station and the horizontal surface projection of fault rupture) and site-class. Records with M_w smaller than 5.0 and R_{jb} larger than 100 km were excluded to focus on earthquake excitations that are of engineering significance. The selected records satisfy NEHRP C and D site classifications (BSSC, 2003). Dominancy of records from one single event is prevented in the dataset in order not to have biased results towards that prominent earthquake (Bommer and Acevedo, 2004). The records are then clustered for specific M_w and R_{jb} intervals. Magnitude-dependent clustering implies a more realistic consideration of frequency content and strong-motion duration of ground motions (Bommer and Acevedo 2004, Stewart et al. 2001). Three magnitude groups are described to account for the above facts: small magnitude (SM), intermediate magnitude (IM) and large magnitude (LM). Although source-to-site distance (R_{jb}) is found to have minor significance with respect to magnitude in ground-motion variability (Iervolino and Cornell 2005, Bommer and Acevedo 2004), records in the dataset are also classified in three R_{jb} bins: short distance (SR, $0\text{km} \leq R_{jb} < 20\text{km}$), intermediate distance (IR, $20\text{km} \leq R_{jb} < 50\text{km}$) and large distance (LR, $50\text{km} \leq R_{jb} < 100\text{km}$). In essence, the entire database is divided into 9 ground-motion bins of different magnitude and distance intervals. In order to finalize the record selection, a statistical analysis is conducted to exclude the outlier accelerograms. Elastic spectral ordinates of ground motions pertaining to a specific M_w-R_{jb} bin are compared with the corresponding bin average for the specific vibration periods considered in this study (T = 0.3s, 0.6s, 0.9s, 1.2s, and 1.5s). Records with spectral ordinates outside the mean ± 2 standard deviation bandwidth are accepted as outliers and they are removed from the database. The outlier analysis ensures the spectral shape compatibility within the strong-motion bin that is defined as one of the important factors in reducing the variability in structural response (Bommer and Acevedo 2004, Baker and Cornell 2005, Luco and Bazzurro 2007). Table 1 lists the size of each M_w - R_{jb} bin in the database after excluding the outlier records.

Table 1. Number of records within each M_w and R_{jb} interval pair.

RECORD NUMBERS		**SR**	**IR**	**LR**
		$0\text{km} \leq R_{jb} < 20\text{km}$	**$20\text{km} \leq R_{jb} < 50\text{km}$**	**$50\text{km} \leq R_{jb} < 100\text{km}$**
SM	**$5.0 \leq M_w < 6.0$**	32	34	37
IM	**$6.0 \leq M_w < 6.5$**	23	21	27
LM	**$6.5 \leq M_w < 7.6$**	30	35	29

[3] The Turkish strong-motion database is compiled under the project entitled "Compilation of Turkish strong-motion network according to the international standards" with an award no. 105G016 granted by The Scientific and Technological Research Council of Turkey.

Scaling Methodologies

Aiming to obtain suits of accelerograms with low variability in terms of engineering demand measures (e.g. peak structural deformations), conventional scaling techniques generally modify the amplitude of records in a ground-motion bin to a target motion value that is either the average spectral quantity at the fundamental period or the average of a peak ground motion value. They simply aim to obtain suitable sets of records that represent a pre-defined seismic level with low dispersion about the mean linear or nonlinear structural response to reduce the number of structural analysis. These methods usually overlook the seismological constraints that are related to earthquake kinematics and they may result in unrealistic variations in the scaled ground motions. On the other hand, scaling methodologies should warrant a strong geophysical basis in order to avoid having physically irrational time series.

In the light of these concerns, this study focuses not only on reducing the scatter in structural response, but also on preserving basic seismological features of the records after being scaled. Consequently, we investigated the limitations of an alternative scaling methodology that uses the estimations of GMPEs and compared the corresponding results with those of the conventional procedure that is outlined in the above paragraph. Detailed description of scaling methodologies explored in this study is presented below.

Scaling with respect to a Predefined GMPE

This methodology (Method 1 hereafter) constrains the scaling to the estimations of GMPEs. Ground-motion records with known geophysical parameters (i.e. magnitude, distance and site class) are scaled with respect to epsilon (ε, logarithmic difference between the actual ground-motion parameter and the corresponding GMPE estimation normalized by the standard deviation, σ, of the GMPE). In this study, GMPE presented by Akkar and Bommer (2007) (abbreviated as AB07 in the text) is selected and analysis results are derived in terms of spectral displacement (SD) values because this model estimates SD. [Note: Any prediction equation derived for estimating spectral ordinates (pseudo-spectral acceleration, pseudo-spectral velocity and spectral displacement) or peak-ground motion values (PGA, PGV and PGD) can be implemented in Method 1]. The Akkar and Bommer (2007) model predicts for the geometric mean of SD ordinates, hence a single scaling factor for each accelerogram is found using the two horizontal components. The same scaling factor is then applied to both horizontal components simultaneously to preserve the original difference between these components. The mathematical expressions that describe the computation of scaling factor are given in Eqs. 1 to 3. Given the magnitude, site and distance properties of a particular accelerogram, Eq. 1 describes the calculation of ε where $\log10(SD(T_i,\xi)_{rec})$ and $\log10(SD(T_i,\xi)_{AB07,median})$ are the logarithms of the geometric means of spectral displacements from the real accelerogram and Akkar and Bommer (2007) at period (T_i) and damping (ξ), respectively. The parameter $\sigma(T_i,\xi)$ is the standard deviation of the considered GMPE at T_i and ξ. The target SD for a scenario earthquake, $SD(T_i,\xi)_{target}$, is obtained in Eq. 2 by modifying the median SD estimation of the scenario event (i.e. $SD(T_i,\xi)_{AB07,target}$) with the epsilon computed in Eq. 1. This way, the inherent aleatory variability of ground motions is taken into consideration. The major assumption in Eq. 2 is the independency of σ with the variations between the actual M_w - R_{jb} pair of the record and the target M_w - R_{jb} pair of the scenario earthquake. In this study, the average magnitude value of the records in each bin represents the pertaining M_w of the scenario event. The R_{jb} distances for scenario earthquakes are selected as 10 km, 35 km, and 75 km for SR, IR and LR distance intervals, respectively. Other seismological parameters (site class and fault mechanism) used for computing the target SD are taken as those pertaining to the actual record. The scaling factor of each accelerogram is found by computing the ratio between the target and actual SD that is presented in Eq. 3. This factor is applied to the horizontal components of the accelerogram simultaneously to preserve the original difference between each other.

$$\varepsilon(T_i,\xi)=\frac{\log10(SD(T_i,\xi)_{rec})-\log10(SD(T_i,\xi)_{AB07,median})}{\sigma(T_i,\xi)} \quad (1)$$

$$SD(T_i,\xi)_{target}=SD(T_i,\xi)_{AB07,target}\times10^{\varepsilon\sigma} \quad (2)$$

$$\text{Scaling Factor}=\frac{SD(T_i,\xi)_{target}}{SD(T_i,\xi)_{rec}} \quad (3)$$

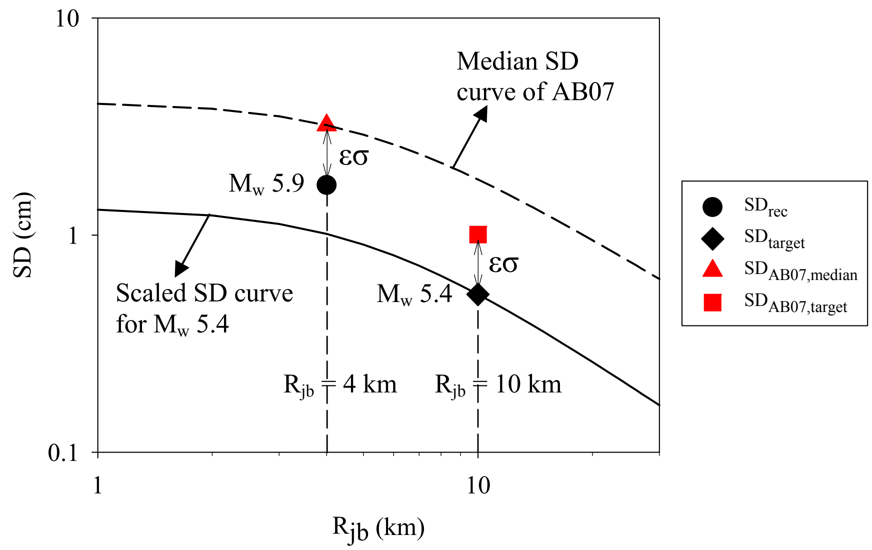

Figure 1. A scaling example to describe Method 1.

Fig. 1 presents an illustrative example for scaling an accelerogram of M_w 5.9 and R_{jb} = 4 km (SM-SR bin) to the scenario (target) event of M_w 5.4 and R_{jb} = 10 km. (Note that M_w 5.4 is the average magnitude of SM cluster). The scaling is performed for a 5%-damped spectral displacement at T_i = 0.6s. Initially, the geometric mean SD of the real accelerogram (SD_{rec}) is found and the corresponding estimation from the considered GMPE ($SD_{AB07,median}$) is obtained using the pertaining geophysical parameters of the recording. Afterwards, epsilon is calculated as described in Eq. 1. The estimation of GMPE for scenario (target) event ($SD_{AB07,target}$) is modified by using the epsilon to obtain the target spectral displacement (SD_{target}) for this record. Finally, the ratio of SD_{target} to SD_{rec} is used to scale each horizontal component of real accelerogram.

Scaling to a Target Average Value of a Ground-Motion Bin

This procedure (Method 2 hereafter) is proposed by Shome et al. (1998) and is widely accepted by the engineering community as it focuses on the concepts that are familiar to the structural engineers. The method addresses some basic concerns on ground motion selection and scaling through robust statistical measures. Basically, Shome et al. (1998) point out that the number of records required to obtain an estimate of the median response depends on the standard deviation of the analysis results and propose to scale each record in a bin to the median spectral ordinate of the bin (at a given period) to reduce dispersion in dynamic response. Shome et al. (1998) conclude that such a scaling procedure produces unbiased nonlinear response results. In this study Method 2 is implemented such that each record within a ground motion bin (LM-SR, SM-LR, etc.) is scaled individually to the bin-median spectral acceleration at the predetermined vibration periods. Fig. 2 shows acceleration spectrum of each horizontal component of accelerograms in IM-SR bin before (left) and after (right) scaling by using Method 2 for a vibration period of 1.2 seconds. It is worth to mention that, Method 1 consider the total standard deviation of GMPEs to address the aleatory variability in ground motions whereas the ground-motion variability in Method 2 is limited to the variations of the records in the considered ground-motion bin. Since GMPEs are based on much larger datasets, the aleatory variability described by their standard deviation is more definite with respect to the one described through Method 2.

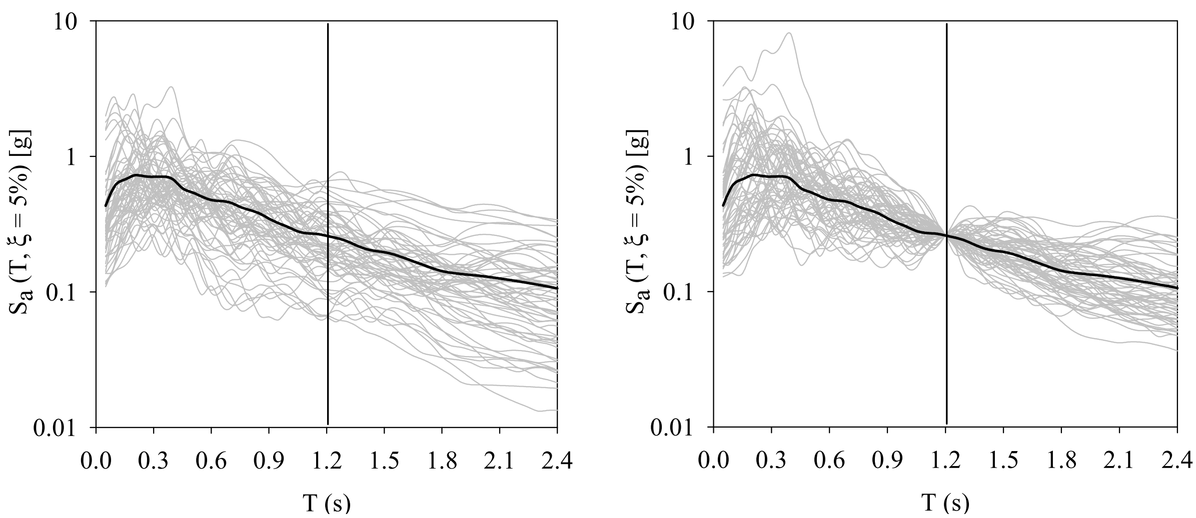

Figure 2. Scaling to the bin-median spectral acceleration according to Method 2. Black line presents the average acceleration spectrum of IM-SR bin.

Effect of Scaling on Structural Response

Analysis

Spectral analyses of single-degree-of-freedom (SDOF) systems are conducted to compare the efficiency of the presented scaling methods in reducing the scatter for structural response. SDOF are used in this study, in order to compare the results of considered scaling methodologies by excluding variability that can originate from structural modeling uncertainties. Although scaling procedure of Method 1 is based on the geometric mean of two horizontal components, for consistency with Method 2, each scaled component of an accelerogram in a ground motion bin is included in the comparative statistics. The comparisons between Methods 1 and 2 are based on the COV statistics and the scaling factors implemented by each methodology. The COV statistics is a measure of dispersion and displays the standard deviation (scatter) normalized by sample mean. Scaling factors of each method are presented in terms of their maximum and minimum values computed during the entire set of analysis. The comparative statistics are described for elastic and constant strength (R, elastic strength normalized by the yield strength of the SDOF system) spectral displacements for vibration periods of 0.3s, 0.6s, 0.9s, 1.2s, and 1.5s. The nonlinear response of SDOF systems is represented by bilinear hysteretic model with 3% postyield stiffness.

Comparison of Results

Fig. 3 compares the COV statistics of Method 1 (left panel) and 2 (right panel) for the entire set of M_w - R_{jb} bins considered in this study. The figures depict that COV statistics of Method 2 increases with the increasing level of inelasticity (represented by the increase in R values). The COV statistics by Method 1 displays a more stable trend with respect to Method 2 suggesting that the uncertainty in nonlinear structural response is influenced less with the variations in the inelasticity level for this scaling methodology. Inherent to the scaling strategy of Method 2, the COV is 0 for the elastic (R = 1) case.

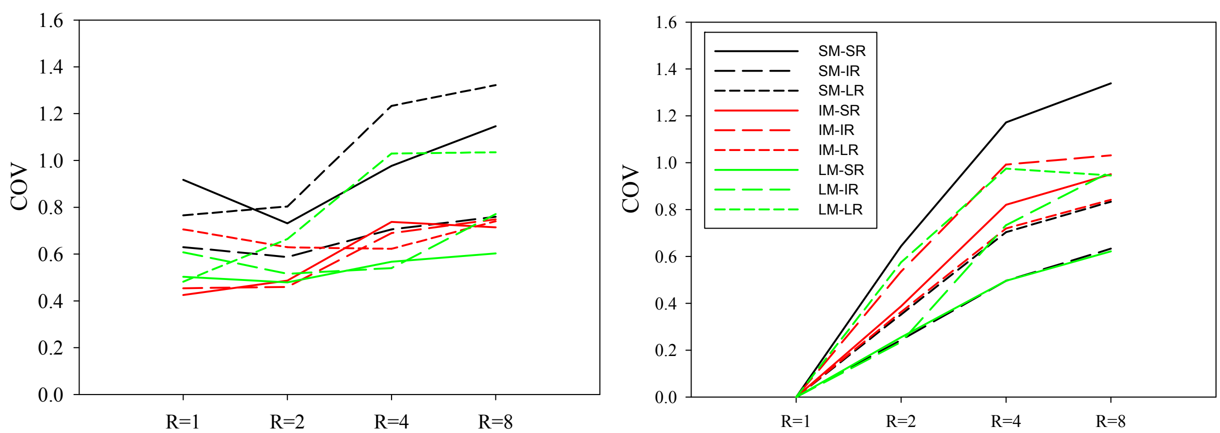

Figure 3. COV statistics computed at T = 0.6s for constant strength values varying between R = 1(elastic behavior) to R = 8 (highly nonlinear behavior).

Fig. 4 explores the discussions in Fig. 3 in a more specific way. It compares the dispersion statistics of Method 1 and 2 for two particular R values as a function of vibration periods considered in this study. The panel on the left compares COV statistics for a moderate level inelasticity (mimicked by R = 4) whereas the right-hand-side panel exhibits the same statistics for R = 8 (high level inelasticity). The comparative plots show that Method 2 results in high dispersion in short period structural response and dispersion increases with increasing inelasticity level. As a matter of fact, the dispersion in Method 1 is almost insensitive to the changes in the level of inelasticity whereas scatter (COV) increases considerably in Method 2 when normalized lateral strength changes from R = 4 to R = 8. Scaling of records to bin-median ground motion at a particular elastic period and inherent period shift with increasing level of inelasticity is the most reasonable explanation of amplified dispersion in Method 2 as R attains larger values. Since the period elongation is much more pronounced at short-period structural systems, the uncertainty in structural response is much higher in Method 2 when compared to Method 1.

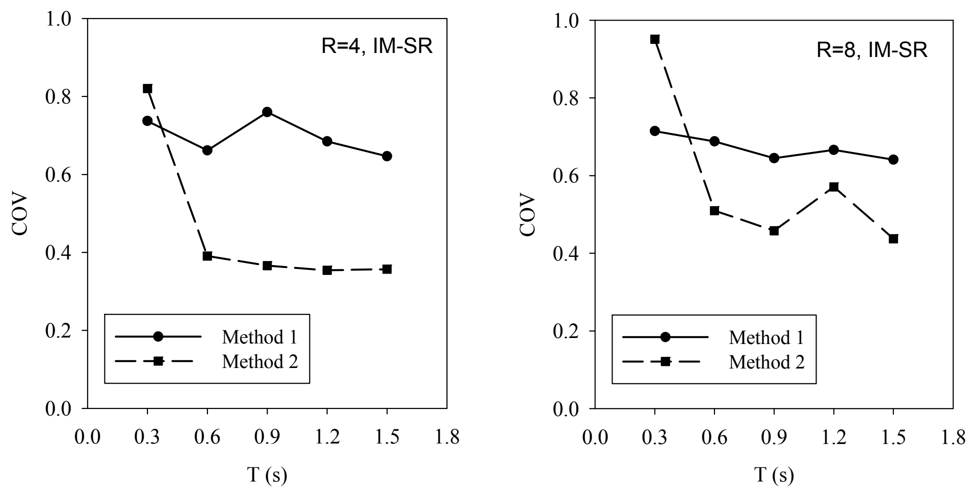

Figure 4. COV statistics of SDOF systems as a function of vibration period with different level of inelasticity.

The level of scaling of accelerograms has been the subject of discussion by many researchers. In their study Luco and Bazzurro (2007) concluded that large scaling factors can introduce a systematic bias to the median nonlinear structural response that tends to increase with decreasing strength and structural period. Iervolino and Cornell (2005) stated that scaling factors up to 4 do not introduce significant bias to the nonlinear peak displacements of moderate to short period SDOF systems. Krinitzsky and Chang (1977) and Malhotra (2003) also discussed the drawbacks of using high scaling factors in structural response. Based on these discussions one would immediately infer that records that are scaled with factors close to 1 are not manipulated significantly (i.e. they still preserve their fundamental seismological features after being scaled) and would yield relatively more reliable results in terms of structural response. Bearing on these discussions Fig. 5 presents the maximum and minimum scaling factors used by Method 1 and 2 for the entire set of response history analysis and for all periods considered in this study. The plots clearly show that scaling factors of Method 2 are significantly larger than those of Method 1. While the maximum amplification factors of Method 1 vary between 2 and 4, the maximum scaling values of Method 2 are generally above 10 and reach to values of 20 that would suggest a significant manipulation in the genuine features of the ground motions.

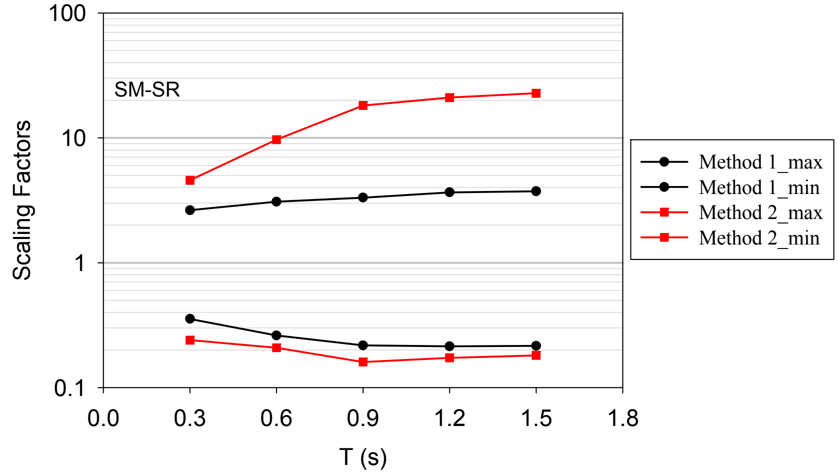

Figure 5. Maximum and minimum scaling factors computed by Methods 1 and Method 2.

Conclusion

A conventional procedure that scales the amplitude of each record in a ground-motion bin to the bin-median spectral acceleration at fundamental vibration period of the system is compared with another methodology that uses estimation of GMPEs. Records having reliable magnitude, site class, faulting style and source-to-site distance information are used, and an outlier analysis based on spectral acceleration values is performed. Consequently, 268 records classified into 9 ground motion bins were obtained. Using these records, spectral displacement analyses are completed for elastic and constant strength cases for vibration periods of 0.3s, 0.6s, 0.9s, 1.2s, and 1.5s. For each of the 9 ground motion bins, comparative statistics in terms of COV that quantifies the dispersion in dynamic response and scaling factors are presented.

According to the results given above, Method 1 yields lower dispersion in response of SDOF systems having short vibration periods at moderate or high inelastic levels. On the other hand, as vibration period increases or level of inelasticity decreases, lower variability in dynamic analysis results is achieved by Method 2. Consequently, it is seen that, the amount of variability reduction depends on the period and inelasticity level of the system. Nevertheless, for each case, amplifying factors used by Method 2 are always larger than those used by Method 1. Since Method 1 uses scaling (up or down) factors close to unity, it is concluded that, the manipulation of the records is relatively small. From this point of view, Method 1 as a procedure beyond being just a mathematical manipulation captures some amount of inherent uncertainty by following seismological constraints due to earthquake kinematics.

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