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EVALUATION ON COMMONLY USED GROUND MOTION SELECTING AND SCALING METHODS WITH PRACTICAL COMMENTS

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Abstract

This study compares the reliability of six commonly used ground motion selecting and scaling methods for the structural seismic response assessment. Results based on a total of 400 records which are selected from the PEER strong ground motion database and compatible to the earthquake environment are used as the benchmark seismic responses of structures. Using the six methods, records of 7-ground-motion set and 3-ground-motion set for each method are selected from the database and scaled to the design earthquake intensity. An engineering demand parameter, i.e., EDP (the inter-story drift ratio), of a 4-story and a 16-story frame structures are calculated with these sets of records. The accuracy of the six methods are examined by comparing the EDP against the benchmark seismic responses. For the 7-ground-motion set, the results demonstrate that the double frequency control and modal pushover scaling methods could provide more accurate evaluation results comparing with other methods. The maximum seismic responses predicted by the 3-ground-motion set may be conservative to the average seismic response predicted by the 7-ground-motion set. If each story of a structure is considered, almost none of the six methods could predict totally conservative inter-story drift ratio results when considering 1 or 2 standard deviations.

Keywords: ground motion; selecting and scaling method; structural response prediction; average response; high confidence interval.

1. Introduction

Nonlinear dynamic analysis is widely used for verification of the strength-based initial structural seismic designs, which is recognized as the most reliable way to analyze the seismic demand of structures. Several codes for seismic design of buildings [1-3] recommend that dynamic analysis should be conducted as a supplement calculation of seismic design for some specific buildings. Because many studies shown that uncertainty of ground motions affects the dynamic analysis results [4-6], how to select and scale the input ground motions is one of the major issues in the structural seismic response assessments.

The ground motion selecting and scaling procedures involve two main steps. The first step is to generate a database with a large number of ground motions as the candidate records, which is usually according to the earthquake environment of the building site, such as the earthquake magnitude, distance, site condition, and even the fault type. The initially selected candidate records can be used in academic studies which are not sensitive to the number of ground motions because of a small structural example may be used, i.e. the computational cost is still acceptable. Nevertheless, for practical verification on an actual structure, only a few numbers of ground motions can be used in the verification because the issue of computational cost [7]. Thus, the second step selects a few ground motions from the candidate records and scales them to the specific design earthquake intensity (e.g., with an exceedance probability of 2% in 50 years of the intensity of peak ground acceleration at the building site).

An appropriate number of input ground motions will lead to both rational dynamic analysis results and computational cost. The commonly used number of records required to be adopted in the dynamic analysis by seismic design codes was initially based on the 1994 Uniform Building Codes [8], which the maximum response should be used if 3 records are selected, while the average response can be used if 7 or more records are selected. This recommendation is followed by some other seismic design codes, such as Eurocode 8 [1], ASCE 7-10 [2], and CSDB [3]. FEMA P-58 [9] suggests that the number of analyses required for each scenario or intensity level depends on the match to the shape of the target spectrum. When the match is poor, 11 ground motions, or more, are recommended. He et al. [10] concluded that the proper number of ground motions is 2 + 1 (real + synthetic) when the maximum response is used and 8 + 4 (real + synthetic) when the average response is used. On the other hand, a small increase in the number of records may not play obvious roles. The study by Reyes and Kalkan [11] concluded that increasing the number of records from 7 to 10 has only minor effect in the accuracy of the structural seismic response assessments and thus use of 7 records is found to be sufficient. In summary, although more may be better, the maximum response from 3 records and average response from 7 records are most commonly used strategy in verification of structural designs, nevertheless this recommendation is based on the code drafting committee since they considered to be a “reasonable” number of analyses within a design office environment and it has few scientific basis [7].

The aim of ground motion scaling is that the match of certain ground motion parameters to specific earthquake intensities or match the response of a simple structure that similar to the analyzed structure. Many ground motion scaling methods were proposed in recent years (e.g., [12-17]) in order to improve the reliability of structural seismic response analyses. Although various methods for selecting and scaling ground motions in dynamic analysis were proposed, there is still no consensus on the issue about how to determine appropriate input ground motions in practical applications. In addition, although several methods were proposed, the most popular methods widely used in the verification of actual structural design are the code-specific methods (e.g., [2, 3]) and the methods with simple implementation procedures (e.g., [18-21]).

The objective of this study is to present a comparison on commonly used methods for selecting and scaling ground motions. In order to study the reliability of these methods, quantitative evaluation on the inter-story drift ratio is conducted through the numerical analysis of two frame structures under specific intensity of earthquake loadings, and the responses with high confidence intervals are also evaluated for engineering demands.

2. The ground motion database and structural models

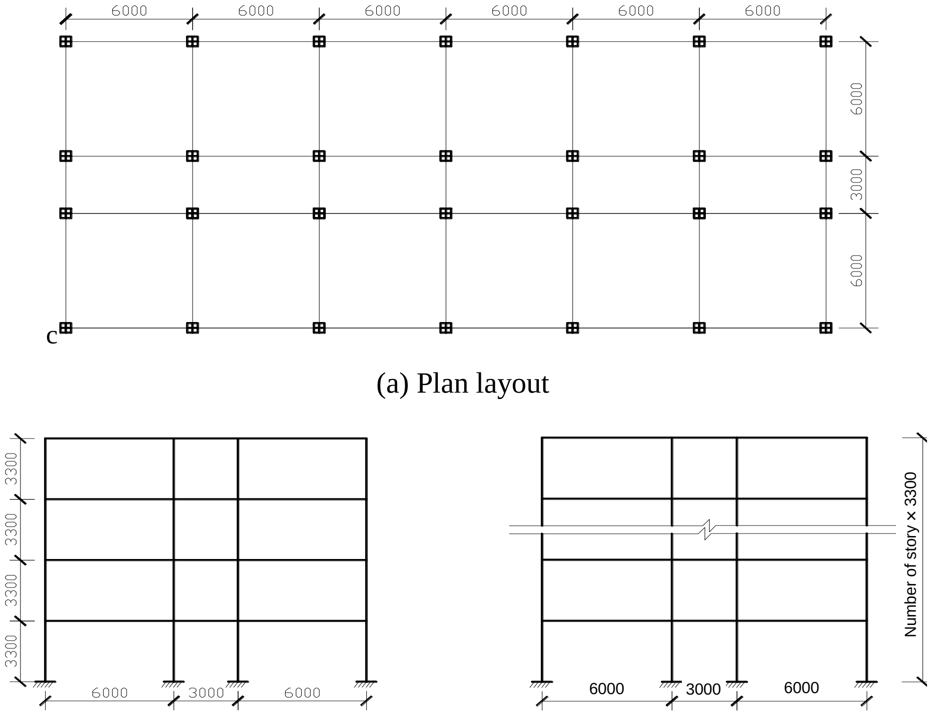
Ground motions are selected from the PEER strong motion database (http://ngawest2.berkeley.edu). The verified structures are assumed located at San Francisco in California, which has the NEHRP site classification of C-type (very stiff soil or soft rock) [22]. Based on the probabilistic seismic hazard analysis tool from USGS (https://earthquake.usgs.gov/hazards), the seismological information of the assumed site is as follows: (1) Control seismic magnitude: Mw is 7.0; (2) Site-to-source distance: D sis 12 km; (3) Site condition: NEHRP C-type with shear wave velocity equals 700 m/s.

Based on the above seismological information and in order to extend the selection range, the criteria used for selecting the ground motions from PEER strong motion database are given below: (1) Moment magnitude: ±0.6 around target magnitude 7.0 is used; (2) Site-to-source distance: ±12 km around the target distance 12 km is used; (3) Site condition: ±200 m/s around the target value is used; and (4) Fault pattern: the strike slip fault and reverse fault are taken into consideration. A total of 400 ground motions satisfying the above criteria from PEER strong motion database are selected (listed in Table 1). They are derived from 25 earthquake events and maximum number from one event is controlled to avoid the potential event-based bias.

In order to evaluate the ground motion selecting and scaling methods, a 4-story and a 16-story reinforced concrete (RC) frame structures are designed with a regular configuration in plan and elevation. The geometry of these frames is shown in Fig. 1. For detailed information of these RC frames, such as cross-section dimensions of beams and columns, and material parameters of concrete and steel rebars, the 4-story and 16-story RC frames are provided in study by Xie [23]. The fundamental and second periods of the structures are 0.91s and 0.27s for the 4-story frame, 2.60s and 0.95s for the 16-story frame, respectively. The seismic response analysis is conducted by IDARC-2D program [24]. The compressive strengths of C30 an C45 concrete (used in 4-story and 16-story structures respectively) are 20.1 MPa and 29.6 MPa, and the yielding strengths of the longitudinal reinforcement and stirrup are 335 MPa.

Table 1 – The basic information of 400 selected ground motions

Earthquake event	Year	Moment magnitude	Number of selected records
Bam, Iran	2003	6.6	6
Cape Mendocino, USA	1992	7.01	14
Chi-Chi, Taiwan, China	1999	7.62	40
Chuetsu-oki, Japan	2007	6.8	42
Darfield, New Zealand	2010	7	26
Duzce, Turkey	1999	7.14	16
EL Mayor-Cucapah, USA	2010	7.2	18
Erzican, Turkey	1992	6.69	4
Friuli, Italy	1976	6.5	4
Gazli, USSR	1976	6.8	4
Imperial Valley, USA	1940	6.95	2
Imperial Valley, USA	1979	6.53	38
Iwate, Japan	2008	6.9	28
Kobe, Japan	1995	6.9	16
Kocaeli, Turkey	1999	7.51	6
Landers, USA	1992	7.28	6
Loma Prieta, USA	1989	6.93	28
Montenegro, Yugo	1979	7.1	8
Niigata, Japan	2004	6.63	16
Northridge, Japan	1994	6.69	42
San Fernando, USA	1971	6.61	4
San Simeon, USA	2003	6.5	6
Superstition Hills, USA	1987	6.54	10
Tabas, Iran	1978	7.35	4
Tottori, Japan	2000	6.61	12



(a) Plan layout

(b) Elevation layout of the 4-story frame (c) Elevation layout of the 16-story frame

Fig. 1 – Geometry of the 4-story and 16-story RC frames (unit: mm)

3. Benchmark structural responses for evaluation

The inter-story drift ratio is usually used for seismic performance evaluation for structures, and it is selected as EDP in this study. Inputting the scaled ground motions as the earthquake loadings, nonlinear dynamic analyses are carried out on the two frames to obtain the EDP. The average value (Δ) of the EDP under all ground motions is taken as the benchmark seismic response of structures. In terms of probability, the average value of seismic response represents both the failure and safe probabilities are with confidence intervals of 50%, which may not satisfy the engineering safety demands for such a low safety guarantee rate. Thus, the average value with 1 standard deviation (Δ+σ) and with 2 standard deviation (Δ+2σ) are also studied, which respectively represents the structural seismic safety with 84% and 96% confidence intervals.

The 400 ground motions are employed as the input excitations to calculate the benchmark structural responses, for comparison with those obtained by using 3- or 7-ground motion set. Referencing to the seismic zonation map from USGS, peak ground acceleration (PGA) of the maximum considered earthquake of the building-specific location is 0.6g. The intensity of design earthquake is 2/3 of MCE (Maximum Considered Earthquake) intensity; as a result, the design earthquake intensity of building-specific location is with PGA=0.4g. Therefore, the seismic responses (Δ, Δ+σ, and Δ+2σ) of the 4-story and 16-story frames under the 400 ground motions scaled to PGA=0.4g are used as the benchmarks.

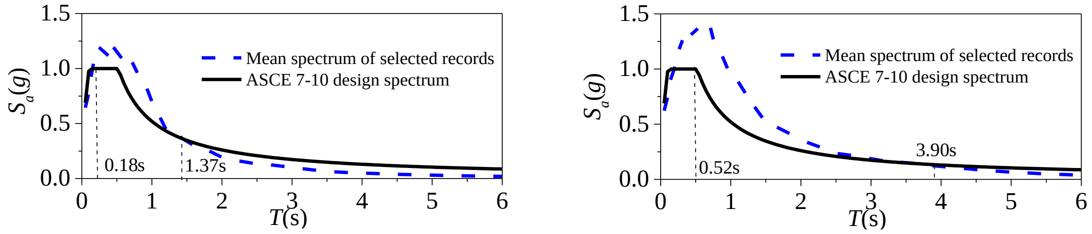
4. Selecting and scaling methods

Six ground motion selecting and scaling methods which are regarded as commonly used methods are considered in the study. Some of these methods use elastic response spectrum matching to select and scale ground motions, either based on the design response spectrum in seismic design codes, such as ASCE 7-10 method [2], CSDB method [3] and double frequency control (BFC) method [25], or computed based on the site seismological characteristics, such as methods based on uniform hazard spectrum (UHS) and condition mean spectrum (CMS) [18, 19]. Other method considers the matching to the inelastic deformation response, such as method based on modal pushover analysis (MPS) [20, 21].

In order to conduct the comparison, a same earthquake environment should be given for the six methods, i.e., the 400 ground motions, PGA, design response spectrum, UHS, CMS, etc., which are used in the selecting and scaling procedures based on a same earthquake environment, i.e., the San Francisco in California. The subsequent sections will give brief introductions on the implementations of these ground motion selecting and scaling methods. Note that the use of multiple sets of ground motion is better than that only use one set, in which each set includes 3 or 7 ground motions. In this way, we can give a comprehensive evaluation based on the results from multiple sets. Nevertheless, this way may not be a preferable choice in practical situations because the analyzers cannot select a unique set and therefore different analyzers may get different prediction results. This causes uncertainties in the evaluation of the structural responses and gives difficulties in the application of these methods. In this study, one unique set of records is used, i.e., analyzers will select a same set of records after the selection rule is defined.

4.1. ASCE 7-10 method

ASCE 7-10 [2] presents the following criteria, i.e., the ground motions should be scaled such that their average acceleration response spectrum for the selected ground motions is not less than the design response spectrum in the period range between $0.2T_1$ and $1.5T_1$, where T_1 is the structural fundamental period. The design response spectrum is equal to 2/3 of the MCE spectrum, which is based on the information of San Francisco [2]. The ASCE 7-10 scaling procedure does not insure a unique scaling factor for each record. Hence, various combinations of scaling factors can be defined to ensure that the average response spectrum of scaled records remains above the design response spectrum over the period range between $0.2T_1$ and $1.5T_1$. The scaling method given by Reyes and Kalkan [11] is used. The group of records (7-ground-motion set and 3-ground-motion set) with scaling factor closer to unity are selected for the 4-story and 16-story frames, and the subsequently five methods follow the similar treatment. Fig. 2 shows the mean spectrum of selected records v.s. the target spectrum (ASCE 7-10 design spectrum for San Francisco). The figure illustrates the mean spectra of selected ground motions are larger than the target spectrum in the period range between $0.2T_1$ and $1.5T_1$ (0.18s~1.37s for 4-story frame and 0.52s~3.90s for 16-story frame).

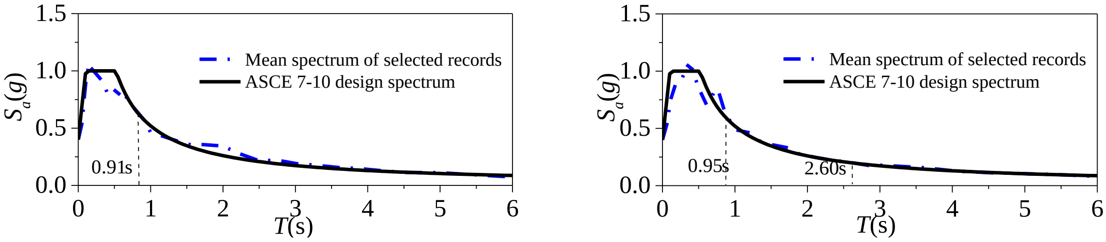


(a) 4-story frame (b) 16-story frame

Fig. 2 – Mean spectrum of selected records v.s. target spectrum (ASCE 7-10 method)

4.2. CSDB method

The method in CSDB [3] uses the following criteria. All the ground motions are scaled to the PGA intensity of the building-specific location. The records should be selected such that the average acceleration response spectrum is consistent to the design response spectrum in a statistical sense, where the differences between the average response spectrum and the design response spectrum at main structural periods are within 20%. For the 4-story and 16-story frames whose modal participation mass for the first mode are 84% and 73% of total structural mass, and for the second mode are 11% and 14%, respectively. The fundamental period for the 4-story frame, the fundamental period and second period for the 16-story frame are considered as the main structural periods, respectively. Note that although this method is based on CSDB [3], in order to use a same earthquake environment, the PGA and the design response spectrum still use the information from the building-specific location, i.e., San Francisco, where the PGA used for design in San Francisco is 0.4g. Meanwhile, the design response spectrum is same as that used in the ASCE 7-10 method. Fig. 3 shows the mean spectrum of selected records v.s. the target spectrum (still is the ASCE 7-10 design spectrum for San Francisco). The figure illustrates the mean spectra of selected ground motions are well matched to the target spectrum at the main structural periods and even in the entire period range.

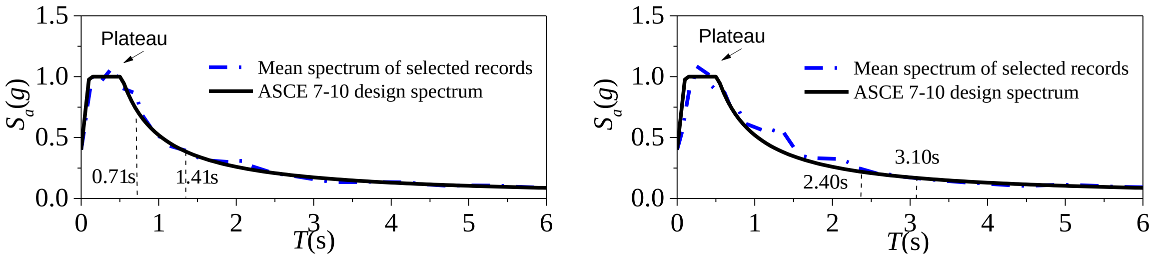


(a) 4-story frame (b) 16-story frame

Fig. 3 – Mean spectrum of selected records v.s. target spectrum (CSDB method)

4.3. BFC method

The double frequency control (BFC) method is proposed by Yang et al. [25]. The method matches the design response spectrum in two frequency domains, one is the plateau range of design response spectrum, another is a range around structural fundamental period T_1 as [T_1-ΔT_1, T_1+ΔT_2], where ΔT_1 and ΔT_2 are constants with recommended values of 0.2 and 0.5, respectively. The former frequency domain intends to consider the influence of high-order modes, while the latter frequency domain includes periods around the fundamental period for considering the possibly error in estimating the period or plastic development of the structure subjected to strong ground motions. Similar as the CSDB method, the records are scaled such that the average response spectrum of these records is consistent to the design response spectrum in a statistical sense. However, the differences between the average response spectrum and the design response spectrum in the two frequency domains are required within 10%, which is more rigorous than that in the CSDB method. The design response spectrum is also same as that used in the ASCE 7-10 method. Fig. 4 shows the mean spectrum of selected records v.s. the target spectrum (ASCE 7-10 design spectrum for San Francisco). The figure illustrates the mean spectra of selected ground motions are well matched to the target spectrum at the plateau range and the range around the fundamental period [T_1-ΔT_1, T_1+ΔT_2] (0.71s~1.41s for 4-story frame and 2.40s~3.10s for 16-story frame).



(a) 4-story frame (b) 16-story frame

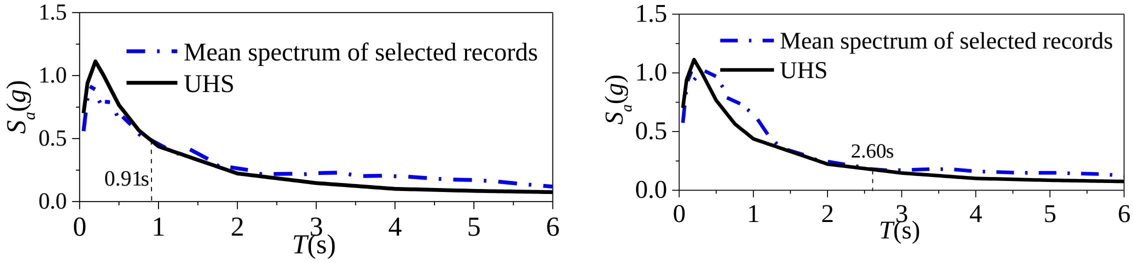
Fig. 4 – Mean spectrum of selected records v.s. target spectrum (BFC method)

4.4. UHS method

The uniform hazard spectrum (UHS) can be generated from a series of probabilistic seismic hazard (PSH) curves. For the PSH curves of spectral acceleration for San Francisco corresponding to different structural periods are calculated using the USGS hazard analysis tool (https://earthquake.usgs.gov/hazards). The UHS is then calculated based on these PSH curves for 10% exceedance probability in 50 years, which is regarded as comparable to the design response spectrum that obtained according to the 2/3 MCE earthquake. The response spectrum of each ground motion is scaled to let its spectral value at the structural fundamental period same as that on the UHS. Then, Eq. (1) is used for each record to calculate the root measure of spectral errors (RMSE) between the response spectrum and the UHS. Fig. 5 shows the mean spectrum of selected records v.s. the target spectrum (UHS spectrum). The figure illustrates the mean spectra of selected ground motions are equal to the target spectrum at the fundamental period T_1 (0.91s for 4-story frame and 2.60s for 16-story frame); meanwhile, the use of Eq. (1) try to let minimum discrepancies in other period ranges.

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{j=1}^{n}\left[\ln S_{a,target}(T_j) - \ln S_{a,i}(T_j)\right]^2} \tag{1}$$

where $S_{a,target}(T_j)$ and $S_{ai}(T_j)$ are the spectral acceleration at j^{th} period point on UHS and acceleration spectrum of i^{th} record, respectively; n is total period points used in the calculation of RMSE, which n=100 is used in this study.

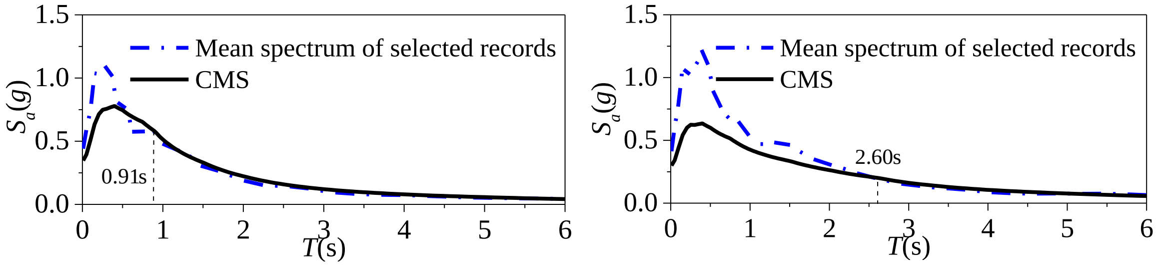


(a) 4-story frame (b) 16-story frame

Fig. 5 – Mean spectrum of selected records v.s. target spectrum (UHS method)

4.5. CMS method

The method was proposed by Baker and Cornell [18], in which the CMS is used as the matching spectrum. In the calculation of the ε value in the method, one of the ground motion prediction equation giving in NGA-WEST2, i.e., the A-S model, proposed by Abrahamson and Silva [26] is used. Similar as that in the UHS method, Eq. (1) is adopted for each ground motion to calculate the RMSE between the CMS and the response spectrum of each ground motion. Fig. 6 shows the mean spectrum of selected records v.s. the target spectrum (CMS spectrum). The figure illustrates the mean spectra of selected ground motions are equal to the target spectrum at the fundamental period T_1 (0.91s for 4-story frame and 2.60s for 16-story frame); meanwhile, the use of Eq. (1) try to let minimum discrepancies in other period ranges.



(a) 4-story frame (b) 16-story frame

Fig. 6 – Mean spectrum of selected records v.s. target spectrum (CMS method)

4.6. MPS method

The method was proposed by Kalkan and Chopra [20, 21]. In the method, the ground motions are scaled to match inelastic response spectra, i.e., a target inelastic deformation of a single degree of freedom (SDOF) system whose properties are determined by first-modal pushover analysis of structures with a specified tolerance, which similar as the match of inelastic spectrum. The target deformations corresponding to the first-mode and second-mode SDOFs are set as the medium values of maximum responses under the 400 ground motions. If the higher modes have non-negligible contributions, this method can also consider the higher modes with the use of elastic deformation of the second-mode SDOF system. For the 4-story and

16-story frames whose modal participation mass for the first mode are 84% and 73% of total structural mass, and for the second mode are 11% and 14%, respectively. In the scaling procedure, the effect of second mode is ignored for the 4-story frame but considered for the 16-story frame. Similar to the previous cases, the records with scaling factors closest to unity is used to sort the selected ground motions.

5. Comparison of the six methods

5.1. Evaluation criteria

The effects of ground motion selecting and scaling methods on the prediction of the inter-story drift ratio is investigated by comparing with the benchmark results provided in Section 3.

The average value Δ of the EDP is calculated by Eq. (2)

$$\Delta_i = \frac{\sum_{i=1}^{n} x_i}{n} \tag{2}$$

where x_i is EDP value obtained from the i^{th} ground motion, and n is the number of selected ground motions.

In order to compare the structural responses against the benchmark results, three dimensionless indexes from local, global and maximum perspectives are used as shown by Eq. (3) ~ Eq. (5)

$$r_i(\Delta) = \frac{\Delta_i}{\Delta_{i0}} \tag{3}$$

$$E(\Delta) = \frac{1}{n}\sum_{i=1}^{n}\left|r_i(\Delta) - 1\right| \tag{4}$$

$$E_m(\Delta) = \max or \min\left[r_i(\Delta) - 1\right] \tag{5}$$

where $r_i(\Delta)$ is calculated by the i^{th} story response divided by the corresponding benchmark result, Δ_{i0} is considered as a local evaluation index whose value closer to unity implying the higher accuracy of the method; $E(\Delta)$ is the average error for all stories, which is considered as a global evaluation index whose value closer to zero implying the higher accuracy of the method; $E_m(\Delta)$ is equal to the maximum error (max corresponds to positive error and min corresponds to negative error) among all stories to represent the maximal difference of the calculated response against the benchmark result, whose value closer to zero implying a reliable prediction of the maximum response. In order to compare the cases of average EDP plus 1 and 2 standard derivations (σ), the Δ in Eq. (3) ~ Eq. (5) can be changed to $\Delta+\sigma$ and $\Delta+2\sigma$.

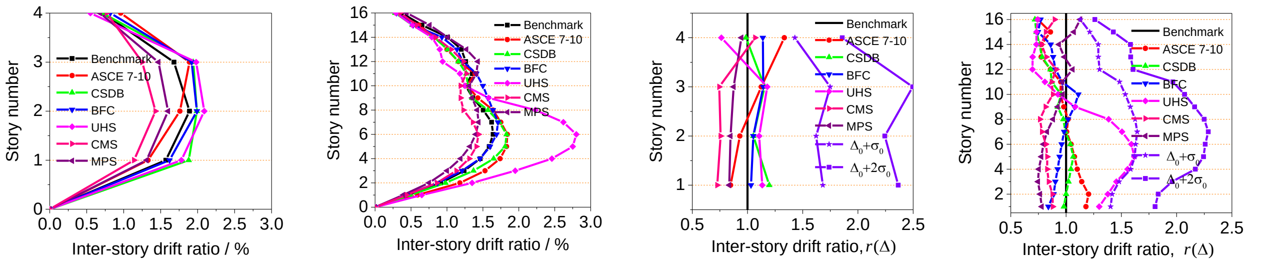
5.2. Comparison results

The average inter-story drift ratio obtained by 7-ground-motion set for the six methods, and the corresponding $r(\Delta)$ are illustrated in Fig. 7. For the inter-story drift ratio obtained by 7-ground-motion set, the maximum inter-story drift ratios arise at almost the same story with different methods. In most cases, the CMS method provides smaller predictions on the inter-story drift ratio, while the UHS method provides larger predictions. The predicted inter-story drift ratio by the six methods are around the benchmark response (average results by 400 ground motions), however, far smaller than results with 84% and 96% confidence intervals, i.e., average + 1 and 2 standard deviations.

Table 2 shows the errors of inter-story drift ratio obtained by 7-ground-motion set (average values). The figure shows that the CSDB and BFC methods have smaller errors in a global perspective, i.e., $E(\Delta)$, both are within 10% compared with the benchmark results. For the $E_m(\Delta)$ results, it seems that the maximum error of a single story can be up to -0.27~0.33 for the 4-story frame and -0.28~0.62 for the 16-story frame. However, the conservative or un-conservative predictions are not totally consistent for the 4-story and 16-story frames. The UHS method gives relative larger error for both the two frames, where 24% underestimates the inter-story drift ratio for the 4-story frame at top story and 62% overestimates the inter-story drift ratio for the 16-story frame around the bottom stories.

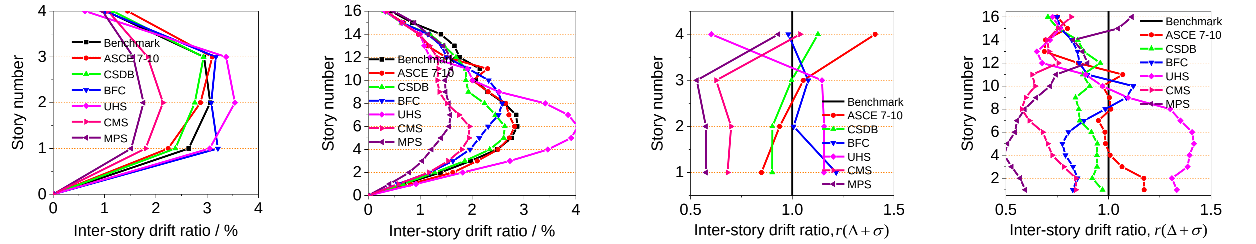
The average results of 7-ground-motion set plus 1 and 2 standard deviations and corresponding global and local error indexes are shown in Fig. 8, Fig. 9, and Table 2. These results are compared with the benchmark results, which are the average results plus 1 and 2 standard deviations obtained by 400 ground motions. It seems that the accuracy becomes lower when the confidence interval increases and these methods commonly give more unconservative results. Another important observation is that, if consideration of each story, none of these six methods can give totally conservative predictions, i.e., conservative results for all stories, this problem is even existed in the prediction of average result (50% confidence interval), but becomes more serious in the predictions of average results plus 1 and 2 standard derivations.

The maximum inter-story drift ratio obtained by 3-ground-motion set for the six methods, and corresponding $r(\Delta)$, $E(\Delta)$, and $E_m(\Delta)$ are illustrated in Fig. 10 and Table 2. These results show the accuracy of these methods by using maximum result of 3-ground-motions set is generally larger than that in the case of the average result of 7-ground-motion set. In most cases, the $E(\Delta)$ results are larger than results obtained by average result of 7-ground-motion set. More methods have larger and positive $E_m(\Delta)$ than that in the case of average result of 7-ground-motion set, which indicates more conservative results are obtained.



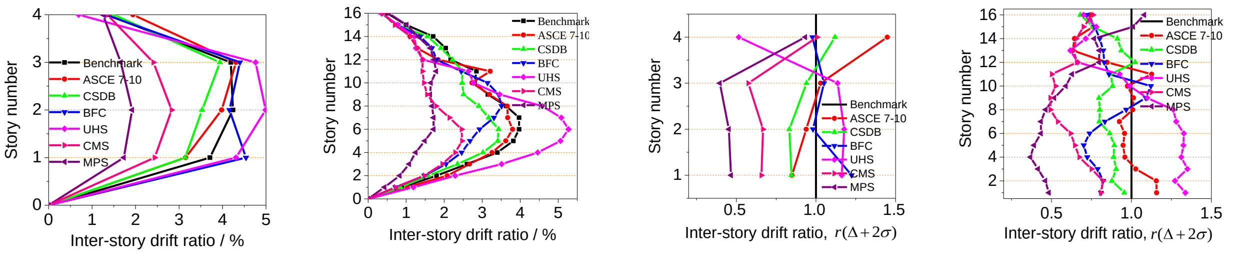
(a) 4-story frame (b) 16-story frame (c) 4-story frame (d) 16-story frame

Fig. 7 – The inter-story drift ratio obtained by 7-ground-motion set (average results)



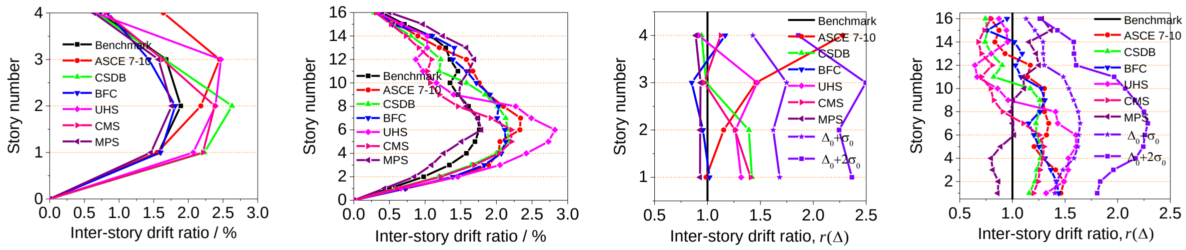
(a) 4-story frame (b) 16-story frame (c) 4-story frame (d) 16-story frame

Fig. 8 – The inter-story drift ratio obtained by 7-ground-motion set (average values + 1 standard deviation)



(a) 4-story frame (b) 16-story frame (c) 4-story frame (d) 16-story frame

Fig. 9 – The inter-story drift ratio obtained by 7 ground motion set (average values + 2 standard deviation)



(a) 4-story frame (b) 16-story frame (c) 4-story frame (d) 16-story frame

Fig. 10 – The inter-story drift ratio obtained by 3-ground-motion set (maximum values)

Table 2 – The errors of inter-story drift ratio obtained by 7- and 3-ground-motion sets

	7-ground-motion set												3-ground-motion set			
	$E(\Delta)$		$E_m(\Delta)$		$E(\Delta+\delta)$		$E_m(\Delta+\delta)$		$E(\Delta+2\delta)$		$E_m(\Delta+2\delta)$		$E(\Delta)$		$E_m(\Delta)$	
Frame	4	16	4	16	4	16	4	16	4	16	4	16	4	16	4	16
ASCE	0.17	0.12	0.33	-0.26	0.17	0.11	0.41	-0.31	0.17	0.13	0.45	-0.37	0.48	0.27	1.28	0.49
CSDB	0.10	0.10	0.20	-0.28	0.08	0.12	0.13	-0.30	0.13	0.14	-0.17	-0.32	0.22	0.24	0.42	0.28
BFC	0.09	0.10	0.14	-0.25	0.08	0.16	0.22	-0.25	0.08	0.19	0.22	-0.30	0.09	0.19	0.17	0.44
UHS	0.16	0.35	-0.24	0.62	0.21	0.29	-0.40	0.42	0.24	0.26	-0.49	-0.38	0.28	0.33	0.47	0.61
CMS	0.21	0.12	-0.27	-0.24	0.26	0.29	-0.47	-0.42	0.28	0.36	-0.42	-0.51	0.21	0.23	0.41	-0.32
MPS	0.12	0.14	-0.17	-0.25	0.35	0.32	-0.37	-0.51	0.44	0.41	-0.60	-0.68	0.08	0.14	-0.11	0.37

Note: $E(\cdot)$: Average errors of inter-story drift ratio; $E_m(\cdot)$: Maximum errors of inter-story drift ratio; Δ, $\Delta+\delta$, and $\Delta+2\delta$: Corresponding to 50% (average values), 84% (average values + 1 standard deviation), and 96% (average values + 2 standard deviation) confidence intervals.

6. Discussion on ground motion selecting and scaling method

Providing results of the structural seismic responses with 50% confidence interval, the designers don't know whether the structure is safe or not in a future earthquake, but may only qualitatively detect the potential adverse deformation modes in serious earthquakes. Therefore, to guarantee the safety, the prediction of the structural seismic responses with higher confidence intervals, i.e., 84% and 96% confidence intervals, is essential in some cases. This study illustrates that that a promising ground motion selecting and scaling method should has small $E(\Delta)$, $E_m(\Delta)$, $E(\Delta+\sigma)$ and $E_m(\Delta+\sigma)$ values (or even has small $E(\Delta+2\sigma)$ and $E_m(\Delta+2\sigma)$ values). As only a few numbers of ground motions (e.g., 7-ground-motion set) usually adopted in the seismic response verification for practical building project due to the computational cost issue, a simple strategy for choosing the ground motion selecting and scaling methods is: ① In order to better predict the average results, the method having small $E(\Delta)$ and $E_m(\Delta)$ can be adopted; then ② When using this method to select the records, in order to better predict the results with higher confidence intervals, the selected records in the 7-ground-motion set is advised to lead large dispersions in the structural seismic response.

7. Conclusions

This study intends to investigate the reliability of six commonly used ground motion selecting and scaling methods for the seismic demand estimation. The inter-story drift ratio is verified with case studies of a 4-story and a 16-story frames. With the aim of giving structural response benchmarks, a total of 400 real ground motions are selected from PEER strong motion database based on the seismology characteristics of the assumed site. A series of ground motion sets are selected from the 400 ground motions by each method considered. In summary, according to the analysis results based on the two example structures, some observations are made as follows.

(1) For the prediction of the structural seismic responses with 50% confidence interval (average results), all the six methods provide acceptable results, and the BFC and MPS methods are the best alternatives for predicting the global structural responses, although the MPS method may underestimate the local structural responses in a few cases. The use of maximum results of 3-ground-motion set is observed more conservative than the use of average results of 7-ground-motion set.

(2) For the prediction of the structural seismic responses with higher confidence intervals, i.e., 84% and 96% confidence intervals (average values + 1 and 2 standard deviation), it is demonstrated that when average results of 7-ground-motion set plus 1 or 2 standard deviations are used, compared with the prediction of the structural seismic responses with 50% confidence interval, most methods have the tendency to become inaccurate and declining conservation. The BFC method still gives better prediction results, but the accuracy of the MPS method reduces. It is also observed that, if considering all stories of a structure, i.e., whether conservative result for each story, almost none of the six methods can grantee a conservative prediction of the inter-story drift ratio. Using only 7-ground-motion set to estimate the structural responses with higher confidence interval may get unconservative results, because in this case a small number of ground motions may not characterize the large dispersion of the realistic earthquake scenario, although it can provide acceptable results in prediction of the structural responses with 50% confidence interval. The maximum value of 3-ground-motion set is not suitable to evaluate the structural seismic responses with higher confidence intervals because it has indirect relationship to the confidence issue.

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