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# A rapid screening method for selection and modification of ground motions for time history analysis

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**Abstract.** A three-step screening process is presented in this article for selection of consistent earthquake records in which number of suitable ground motions is quickly screened and reduced to a handful number. Records that remain at the end of this screening process considerably reduce the dispersion of structural responses. Then, an effective method is presented for spectral matching and modification of the selected records. Dispersion of structural responses is explored using different statistical measures for each scaling procedure. It is shown that the Uniform Design Method, presented in this study for scaling of earthquake records, results in most cases in the least dispersion measure.

**Keywords:** ground motion selection; screening process; modification; nonlinear time history analysis; scatter of response

## 1. Introduction

The nonlinear time history analysis of structures under earthquake motions has been known as the most rigorous analysis method for determining the seismic responses. The basic prerequisite for accomplishment of such an analysis is a suite of consistent earthquake records. By consistency, earthquakes recorded on the same soil type, in the same distance range, and having similar peak ground accelerations (PGA's), among other characteristics, are purposed. On the other hand, the final results of analysis with the selected suite of records, i.e., the structural responses, should not be too different between the earthquakes. In other words the scattering of responses must be kept small enough by appropriate selection and modification of ground motions.

Many alternatives have been proposed in the past for the same purpose mentioned above. Procedures suggested for the ground motion selection can generally be categorized in three groups regarding their level of complexity. In group 1 simply the general seismicity and seismotectonic characteristics of the region are considered. Parameters such as the fault mechanism, earthquake magnitude, distance to the causative fault, etc., have been used for sorting of earthquakes. This approach is very simple and needs no calculations. It has been adopted mainly by the public databases of earthquake records on the Internet, such as the PEER NGA strong motion data bank (Peer 2009).

In group 2, similarity of spectral shapes is the basis of selection. For this purpose, the response spectrum of the record at hand is compared with the design spectrum. If enough similarity is satisfied, the record is selected for dynamic analysis. As the basis of comparison, the code-based constant-shape design spectrum, the uniform hazard spectrum (UHS), and the conditional mean spectrum (CMS) have been used. The design spectrum is usually derived by a smoothing process of the average acceleration spectrum of a consistent suite of ground motions and/or using the attenuation relations. Therefore, the uniformity of hazard probability along its curve is not guaranteed. The UHS has been derived accounting for the same probability of a certain hazard at all periods. However, the resulting shape is not much different from that of the design spectrum. On the other hand, obviously a single earthquake cannot produce a response spectrum matching the UHS within a wide band of frequencies. The CMS has been developed considering the above reality. For constructing a CMS, a target spectral acceleration and a spectral shape parameter are necessary (Baker 2011). The target acceleration is usually selected to be the value of the design spectral acceleration at the fundamental frequency of the studied structure. The shaping parameter determines the CMS at other periods with calculation of the average and standard deviation of logarithm of the response spectrum with respect to the target (design) spectrum.

To determine how similar a response spectrum is to a basis spectrum, many options are available. When using the design or UHS spectra as the basis, the area under the response and basis spectra, or else the average of deviations from the basis spectrum between two certain periods are calculated and compared.

When the basis is a CMS, a spectral shape parameter called "$\varepsilon$" is used as a deviation index. Recently a more effective deviation index called "$\eta$" has been proposed (Mousavi *et al*. 2011). It uses a combination of spectral acceleration and velocities for evaluating an earthquake.

The criteria used in the third group are generally called

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the advanced intensity measures. They usually combine the spectral characteristics of a ground motion, calculated with linear analysis of simple systems, with certain nonlinear responses of multi-story structures. For instance, the intensity measure of inelastic spectral displacement, utilizes the response spectrum displacement at the fundamental mode and the maximum inelastic displacement of an elastic-perfectly-plastic model of the real building at the first mode (Luco and Cornell 2007). After computing the above intensity measure (IM) for many records, those with IM's nearer to the average IM are selected.

Another proposed method in the same group is the method of priority list (Azarbakht and Dolsek 2011). This method has mainly been developed in response to the need for minimizing the number of ground motions, hence the computation time, in an incremental dynamic analysis (IDA). In this method, first an IDA is implemented on a nonlinear equivalent single-degree-of-freedom (SDF) system with many earthquake records. An average IDA curve is then calculated and used for record selection based on how a specific IDA curve deviates from the average (Azarbakht and Dolsek 2007).

When a record is scaled, the main idea is to minimize deviation of its response spectrum from the target (basis) spectrum in a certain period range. If it can be assumed that the elastic response of the structure under study is mainly dependent on its fundamental mode, the period range can be defined using $T_1$, the period of the first mode of vibration. It is usually taken to be extending from $0.2\,T_1$ to $1.5\,T_1$ to include both the effects of higher modes and the nonlinear response of structure (ASCE-2010). In the spectral balancing method (Behnamfar and Nafarieh 2004).the scale factor is determined such that the area under the response spectrum becomes equal to that of the target spectrum in the mentioned period range. In the CMS method (Baker 2011) derivation of the scale factor is targeted at equalizing sum of the spectral amplitudes in the required period range from the CMS to that of the response spectrum. Genetic algorithm approaches are also available in which several groups of records are selected and the group characteristics are evolved during matching with each other until reaching a best generation of records (Michael 1999, Naeim *et al.* 2001, Pezeshk *et al.* 2000).

There have been several studies on the effects of different selection and scaling methods on the calculated nonlinear dynamic behavior of structures. Among them, one may refer to the studies of Takewaki and Tsujimoto on tall buildings (Takewaki and Tsujimoto 2011), Wood and T.C. Hutchinson on higher mode responses (Wood and Hutchinson 2012), Ergun and Ates on comparison of Eurocode8 and ASCE 7-05 regulations (Ergun and Ates 2013) and on comparative effects of scaled and unscaled earthquakes (Ergun and Ates 2014), Camataa and Cantagallo on directionality effects (Cantagallo *et al*. 2015), Bayati and Soltani on the collapse behavior of RC frames (Bayati and Soltani 2016), Kayhan on uni-directional and bi-directional dynamic analysis (Kayhan 2016), and Pavel and Vacareanu on Romania earthquakes (Pavel and Vacareanu 2016).

Scaling of records can also be accomplished using code-based prescribed procedures. For instance, FEMA 440 presents a method called the scaled nonlinear analysis procedure (FEMA 440). In this method, it is aimed to scale a record such that the maximum displacement of the mass center at the roof in a nonlinear dynamic analysis with the desired record is identical to the target displacement. Clearly, this method needs several trial and errors and can be too time-consuming and costly. ASCE7-10 requires that the scale factor be determined such that the average response spectrum of the suite of records does not fall below the design spectrum in the mentioned period range.

As observed, a large variety of methods exists for selection and scaling of ground motions, without a general consensus on the appropriate method. The aim of this research is to sort out a suitable methodology for earthquake record selection and modification. The final purpose of such a procedure is applying the records in a nonlinear dynamic analysis. Therefore, the main criterion for recognizing the suitability of the method is chosen to be having a minimum scatter in nonlinear structural responses.

## 2. The proposed method for selection of ground motions

In this study, a three-stage procedure for screening of earthquake records is presented. During the stages, the selection criteria become more strict and number of records that pass each screen sharply decreases. In other words, more strict measures are logically used with a smaller number of records resulting in much time saving. The three stages are called loose, medium and tight screens. They are explained in the following sections.

### 2.1 Stage 1: The loose screen

In stage 1, some global characteristics of earthquakes are utilized as the basis of record selection. These are: earthquake magnitude ($M$), source-to-site distance ($R$), soil type or the shear wave velocity ($V_s$), and peak horizontal acceleration at the ground surface (PGA).

For illustration, the following values are chosen to get forward with the next stages:

$$6 \le M \le 8\ ,\ 10 \le R \le 90\ \ Km\ ,$$
$$375 \le Vs \le 750\ {}^{m}/_{s}\ ,\ \ 0.2 \le PGA \le 1.2\ \ \ g\ .$$

Use of the above search criteria within the PEER ground motion database (Peer 2009), results in 47 ground motions, as shown in Table 1.

### 2.2 Stage 2: The medium screen

For the medium screen, the more promising option, after testing several procedures, seemed to be the spectrum intensity approach.

In this method the records with spectral intensities nearer to that of the design spectrum are picked up for the next screen. The spectrum intensity, $SI$, is calculated using Eq. (1)

$$SI = \int_{0.1}^{2.5} PSV\ dT \tag{1}$$

in which $PSV$ is the pseudo spectral velocity. This method

Table 1 Characteristics of the ground motions after the loose screen

| Row | NGA No. | *M* | *R* (km) | PGA (g) | $V_{s30}$ (m/s) |
|---|---|---|---|---|---|
| 1 | NGA0033 | 6.19 | 24.90 | 0.2934 | 527.90 |
| 2 | NGA0057 | 6.61 | 16.00 | 0.2994 | 450.30 |
| 3 | NGA0125 | 6.50 | 13.00 | 0.3458 | 424.80 |
| 4 | NGA0126 | 6.80 | 22.50 | 0.6438 | 659.60 |
| 5 | NGA0265 | 6.33 | 30.00 | 0.5722 | 659.60 |
| 6 | NGA0288 | 6.90 | 47.00 | 0.2137 | 500.00 |
| 7 | NGA0587 | 6.60 | 13.00 | 0.2926 | 424.80 |
| 8 | NGA0739 | 6.93 | 40.00 | 0.2385 | 488.80 |
| 9 | NGA0755 | 6.93 | 40.00 | 0. 4700 | 684.90 |
| 10 | NGA0787 | 6.93 | 40.00 | 0.2281 | 425.30 |
| 11 | NGA0801 | 6.93 | 40.00 | 0.2834 | 671.80 |
| 12 | NGA0809 | 6.93 | 40.00 | 0.3418 | 714.00 |
| 13 | NGA0810 | 6.93 | 40.00 | 0.4568 | 714.00 |
| 14 | NGA0811 | 6.93 | 40.00 | 0.5174 | 376.10 |
| 15 | NGA0864 | 7.28 | 71.70 | 0.2489 | 379.30 |
| 16 | NGA0952 | 6.69 | 18.00 | 0.5102 | 545.70 |
| 17 | NGA0963 | 6.69 | 18.00 | 0.4898 | 450.30 |
| 18 | NGA0974 | 6.69 | 18.00 | 0.2063 | 446.00 |
| 19 | NGA0991 | 6.69 | 18.00 | 0.2558 | 446.00 |
| 20 | NGA0993 | 6.69 | 18.00 | 0.2071 | 446.00 |
| 21 | NGA1006 | 6.69 | 18.00 | 0.3908 | 398.40 |
| 22 | NGA1007 | 6.69 | 18.00 | 0.3492 | 376.10 |
| 23 | NGA1009 | 6.69 | 18.00 | 0.2648 | 392.20 |
| 24 | NGA1010 | 6.69 | 18.00 | 0.3391 | 413.80 |
| 25 | NGA1020 | 6.69 | 18.00 | 0.2153 | 602.10 |
| 26 | NGA1039 | 6.69 | 18.00 | 0.2291 | 405.20 |
| 27 | NGA1049 | 6.69 | 18.00 | 0.3316 | 446.00 |
| 28 | NGA1055 | 6.69 | 18.00 | 0.2337 | 455.40 |
| 29 | NGA1070 | 6.69 | 18.00 | 0.2087 | 401.40 |
| 30 | NGA1089 | 6.69 | 18.00 | 0.2591 | 376.10 |
| 31 | NGA1198 | 7.62 | 88.00 | 0.2595 | 544.70 |
| 32 | NGA1202 | 7.62 | 88.00 | 0.2602 | 473.90 |
| 33 | NGA1205 | 7.62 | 88.00 | 0.4625 | 492.30 |
| 34 | NGA1402 | 7.62 | 88.00 | 0.3852 | 375.30 |
| 35 | NGA1485 | 7.62 | 88.00 | 0.4730 | 704.60 |
| 36 | NGA1487 | 7.62 | 88.00 | 0.3643 | 520.40 |
| 37 | NGA1506 | 7.62 | 88.00 | 0.2058 | 401.30 |
| 38 | NGA1524 | 7.62 | 88.00 | 0.5283 | 446.60 |
| 39 | NGA1633 | 7.37 | 71.60 | 0.5051 | 724.00 |
| 40 | NGA1787 | 7.13 | 69.00 | 0.3062 | 684.90 |
| 41 | NGA2495 | 6.20 | 10.00 | 0.3342 | 553.40 |
| 42 | NGA2622 | 6.20 | 10.00 | 0.2736 | 624.90 |
| 43 | NGA2627 | 6.20 | 10.00 | 0.3363 | 615.00 |
| 44 | NGA2658 | 6.20 | 10.00 | 0.6083 | 664.40 |
| 45 | NGA2942 | 6.20 | 17.50 | 0.2461 | 427.70 |
| 46 | NGA3217 | 6.20 | 17.50 | 0.3911 | 664.40 |
| 47 | NGA3507 | 6.30 | 29.00 | 0.2565 | 664.40 |

only needs the response velocity spectrum of each earthquake and the design velocity spectrum and therefore is simpler then the above method based on *ε*. Moreover, numerical analysis in this study has shown that selecting based on SI results in less scattering of structural responses compared with other methods (Talebi 2014) (not shown for brevity). For selection of earthquakes in this stage, the ratios of spectral intensities of the records at hand to that of the design spectrum are calculated. The earthquakes with ratios nearer to unity are selected. The design spectrum, $S_a$, used for this analysis is that of ASCE7-10 introduced in Eq. (2)

$$
\begin{aligned}
S_a &= S_{DS}(0.4+0.6\frac{T}{T_0}): && T \le T_0 \\
S_a &= S_{DS}: && T_0 \le T \le T_S \\
S_a &= \frac{S_{D1}}{T}: && T_S \le T \le T_L \\
S_a &= S_{D1}(\frac{T_L}{T^2}): && T \ge T_L
\end{aligned} \tag{2}
$$

where $S_{DS}$ and $S_{D1}$ are the spectral accelerations at short periods and at 1 second, and $T_0$, $T_S T_0$, $T_1$ and $T_L$ are anchor periods with $T_0 < T_s < T_l$ $T_0 \le T \le T_L$ determining the edges of different parts of the spectrum, respectively. They are calculated as follows

$$
\begin{aligned}
S_{DS} &= \frac{2}{3}F_a S_S \\
S_{D1} &= \frac{2}{3}F_V S_1 \\
T_0 &= 0.2\frac{S_{D1}}{S_{DS}} \\
T_S &= \frac{S_{D1}}{S_{DS}}
\end{aligned} \tag{3}
$$

in which $F_a$ and $F_V$ are the local soil factors, and $S_S$ and $S_1$ are the short period and 1 sec spectral accelerations on bedrock, respectively.

Sample values of the above parameters for a seismically active area with a medium soil in the western North America are: $S_S$=1.5, $S_1$=0.6, $F_a$=1.0 and $F_V$=1.3. Also, $T_l$ is a long period parameter varying between 4 and 16 in different regions. It is taken to be 8 sec in this research.

The above assumptions result in the design spectrum shown in Fig. 1.

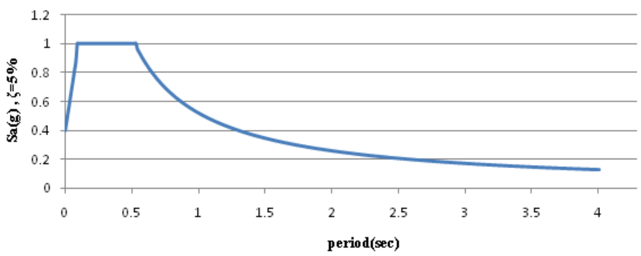
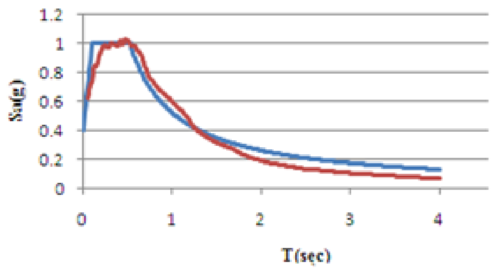


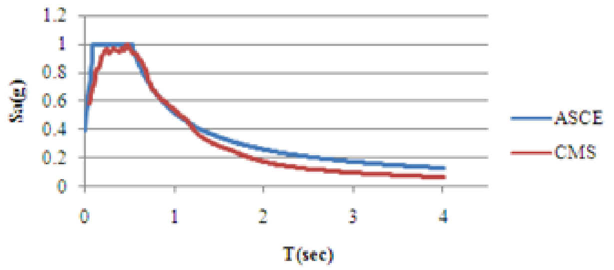

Fig. 1 The design spectrum

Table 2 Earthquakes selected after the medium screen and their spectral intensity ratios (RSI)

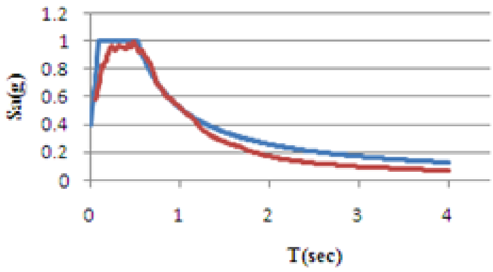
| Row | NGA No. | RSI | Row | NGA No. | RSI |
|---|---|---|---|---|---|
| 1 | 0126 | 0.5961 | 11 | 1202 | 0.4968 |
| 2 | 0265 | 0.3459 | 12 | 1205 | 0.3171 |
| 3 | 0755 | 0.3072 | 13 | 1485 | 0.3540 |
| 4 | 0787 | 0.3258 | 14 | 1487 | 0.3957 |
| 5 | 0811 | 0.3779 | 15 | 1506 | 0.3691 |
| 6 | 0864 | 0.4137 | 16 | 1524 | 0.3733 |
| 7 | 0952 | 0.3213 | 17 | 1633 | 0.5061 |
| 8 | 0963 | 0.6227 | 18 | 1787 | 0.3777 |
| 9 | 1010 | 0.2916 | 19 | 2495 | 0.5658 |
| 10 | 1198 | 0.3408 | 20 | 2627 | 0.3944 |



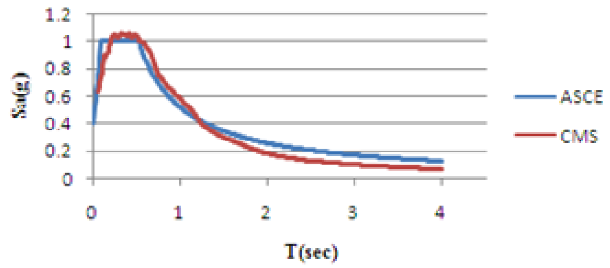

(a) 2-story



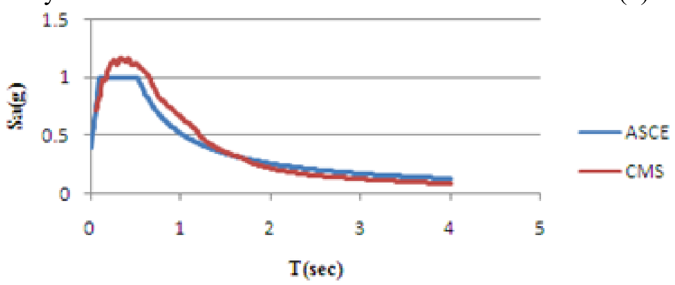

(b) 4-story




(c) 6-story




(d) 8-story




(e) 10-story building

Fig. 2 The conditional mean spectra

Value of the spectrum intensity of the design spectrum is 1.811 m. Based on Eq. (1) and Fig. 1, 20 earthquakes with spectral intensity ratios closer to unity are selected and shown in Table 2.

### *2.3 Stage 3: The tight screen*

Among the methods suitable for a tight screen, referred to in Sec.1, the CMS method is selected for analysis. Of course use of more advanced intensity measures is possible too, but they have been left aside after examining, for their unwanted complexity (Talebi 2014).

The CMS method needs a design spectrum and involves constructing a mean spectrum with the condition that it intersects with the design curve at a certain period. This period is taken to be the fundamental period of the buildings under study. These are introduced next.

#### *2.3.1 Buildings studied*

The structures designed for the purposes of this study, are 2, 4, 6, 8 and 10 story two-way steel moment resisting frames. There are three bays each way spanning 5 m between columns. The floor-to-floor heights of stories are uniformly 3 m. The fundamental periods of 2 to 10-story buildings are determined to be 0.42, 0.79, 1.07, 1.23 and 1.52 sec, respectively, using eigen value analysis by the design software.

#### *2.3.2 The conditional mean spectra*

The CMS must be constructed for each fundamental vibration period corresponding to each case study building. It is determined as follows:

1) Calculation of the mean, $\mu(Ln\,S_a)$ and standard deviation, $\sigma(LnS_a)$, of the natural logarithm of the spectral accelerations.

For the 20 earthquakes selected out the medium screen (Table 2), $\mu(Ln\,S_a)$ and $\sigma(Ln\,S_a)$ are calculated at each period $T$ as follows

$$\mu_{\ln S_a}(M,R,T) = (1/20)\sum_{i=1}^{20} \ln S_a(T)_i \quad (4)$$

$$\sigma_{\ln S_a}(T) = \sqrt{(1/19)\sum_{i=1}^{20}(lnS_a(T) - \mu_{lnS_a}(M.R.T))_i^2} \quad (5)$$

2) Determination of$\varepsilon$and the correlation factor $\rho$.

The spectral shape parameter $\varepsilon$ is calculated using Eq. (6) at the fundamental period $T$.

$$\varepsilon(T) = \frac{\ln Sa(T) - \mu_{\ln Sa}(M,R,T)}{\sigma_{\ln Sa}(M,R,T)} \quad (6)$$

The $\rho$ factor is determined using Eq. (7) (Baker 2011)

$$\rho(T_{\min},T_{\max}) = 1 - \cos(\frac{\pi}{2} - (0.359 + 0.163 I_{T_{\min}<0.189}$$

$$< \ln\frac{T_{\min}}{0.189}) \ln\frac{T_{\max}}{T_{\min}}) \tag{7}$$

where $I$ equals unity for $T_{\min} < 0.189$ and zero elsewhere. Also, for periods less than $T$, $T_{\min}$ is the desired period and $T_{\max} = T$. For periods larger than T, The above definition is reversed.

3) Calculation of CMS.

The conditional mean spectrum is calculated using Eq. (8)

$$CMS\,(T_L) = Exp\left\{\mu_{\ln S_a}(M, R, T_i) + \rho(T_i, T^*)\varepsilon(T^*)\sigma_{\ln S_a}(T_i)\right\} \tag{8}$$

where $(T_i)$ is the desired period.

Fig. 2 shows the CMS for each building along with the design spectrum.

### *2.3.3 Selection based on CMS*

The similarity of each response spectrum to the CMS is measured in this method using the SSE and SF indices, introduced as follows (Baker 2011)

$$SSE = \sum_{j=1}^{n} (\ln Sa(T_j) - \ln S_{aCMS}(T_j))^2 \tag{9}$$

$$Scale\,Factor = \frac{\sum_{j=1}^{n} S_{aCMS}(T_j)}{\sum_{j=1}^{n} Sa(T_j)} \tag{10}$$

where $Sa(T_j)$ is the value of the response spectrum at the descried period $T_i$ and $S_{aCMS}$ the CMS value at the same period. It is obvious that SSE and SF measure deviation of the response spectrum at hand from the CMS in two different ways. Then, 10 records with smaller SSE's and with SF's closer to unity are finally picked up for structural analysis. Table 3 lists the final earthquakes selected after the tight screen. Also, the response spectra of the selected earthquakes are shown in Fig. 3, for example, for the 2-story building along with the design spectrum.

## 3. Scaling of the selected ground motions

In this study a new scaling method is presented and evaluated for discrepancy along with two other more widespreadly used methods introduced in Sec. 1, namely the CMS and the code-based (prescribed) methods.

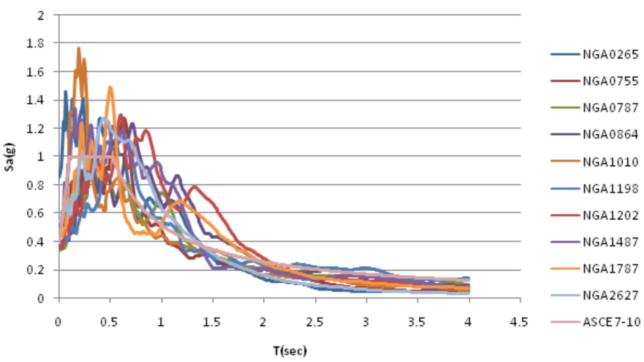



Fig. 3 Response spectra of the ground motions selected for nonlinear analysis of the 2-story building

Table 3 Final earthquakes selected after the tight screen stage

| Row | 2-story | 4-story | 6-story | 8-story | 10-story |
|---|---|---|---|---|---|
| 1 | NGA 0265 | NGA 0265 | NGA 0265 | NGA 0265 | NGA 0755 |
| 2 | NGA 0755 | NGA 0755 | NGA 0755 | NGA 0755 | NGA 0787 |
| 3 | NGA 0787 | NGA 0787 | NGA 0787 | NGA 0787 | NGA 0864 |
| 4 | NGA 0864 | NGA 0864 | NGA 0864 | NGA 0864 | NGA 0952 |
| 5 | NGA 1010 | NGA 1010 | NGA 1010 | NGA 0952 | NGA 1010 |
| 6 | NGA 1198 | NGA 1198 | NGA 1198 | NGA 1010 | NGA 1202 |
| 7 | NGA 1202 | NGA 1487 | NGA 1485 | NGA 1198 | NGA 1485 |
| 8 | NGA 1487 | NGA 1506 | NGA 1487 | NGA 1485 | NGA 1487 |
| 9 | NGA 1787 | NGA 1787 | NGA 1506 | NGA 1487 | NGA 1787 |
| 10 | NGA 2627 | NGA 2627 | NGA 2627 | NGA 2627 | NGA 2627 |

As mentioned in Sec.1, ASCE7-10 requires that earthquake records be scaled for each building such that their individual or mean spectra do not fall below the design spectrum in the periods range 0.2T-1.5T, with $T$ being the fundamental period of the building. In this study, the quality of ASCE7-10 scaling is evaluated with two versions. If the individual response spectra are used, it is called the separative ASCE method, but if the mean response spectrum is utilized, the method will be called the combinatorial ASCE. In CMS, the scale factor is determined by Eq. (12).

The new method presented in this study for modification or scaling of the selected ground motions is called the Uniform Design Method (UDM). This method is presented in two versions, called separative and combinatorial. It will be seen that the second version is much more practical with a similar or superior accuracy.

### *3.1 The separative UDM*

In this method first the building under study is designed for the response spectrum of the original (unmodified) earthquake record along with other loads. By design, here it is meant the result of determining only the section dimensions of the structural members including beams and columns in order to be able to calculate the fundamental vibration period of each building. Determining other structural details is not needed for this purpose. The fundamental period of the designed structure is called $T_1^e$. The same building is again designed but this time using the design spectrum of the building code. The fundamental period in this case is called $T_1^{code}$. In general, $T_1^e \neq T_1^{code}$. In order to arrive at a uniform (similar) design both with the response and the design spectra, similarity of design forces (spectral accelerations) resulting in similar lateral stiffnesses and similar fundamental periods is considered. Since stiffness is proportional to square of period, a scale factor is proposed as follows

$$Scale\,Factor = \left(\frac{T_1^e}{T_1^{code}}\right)^2 \tag{11}$$

### *3.2 The combinational UDM*

The separative UDM has the drawback that it is too

Table 4 The scale factors of the separative ASCE method

| Row | 2-story building | | 4-story building | | 6-story building | | 8-story building | | 10-story building | |
|---|---|---|---|---|---|---|---|---|---|---|
| | NGA | S.F. | NGA | S.F. | NGA | S.F. | NGA | S.F. | NGA | S.F. |
| 1 | 0265 | 1.078 | 0265 | 1.228 | 0265 | 1.228 | 0265 | 1.427 | 0755 | 1.449 |
| 2 | 0755 | 1.624 | 0755 | 1.420 | 0755 | 1.449 | 0755 | 1.449 | 0787 | 1.349 |
| 3 | 0787 | 2.164 | 0787 | 1.582 | 0787 | 1.582 | 0787 | 1.493 | 0864 | 1.481 |
| 4 | 0864 | 2.434 | 0864 | 1.758 | 0864 | 1.542 | 0864 | 1.481 | 0952 | 2.134 |
| 5 | 1010 | 1.637 | 1010 | 1.637 | 1010 | 1.637 | 0952 | 1.695 | 1010 | 1.636 |
| 6 | 1198 | 2.278 | 1198 | 2.203 | 1198 | 1.777 | 1010 | 1.637 | 1202 | 1.237 |
| 7 | 1202 | 2.220 | 1487 | 1.103 | 1485 | 1.520 | 1198 | 1.737 | 1485 | 1.593 |
| 8 | 1487 | 1.103 | 1506 | 2.995 | 1487 | 1.628 | 1485 | 1.593 | 1487 | 1.628 |
| 9 | 1787 | 1.583 | 2495 | 1.542 | 1506 | 2.552 | 1487 | 1.628 | 1787 | 1.542 |
| 10 | 2627 | 1.668 | 2627 | 1.417 | 2627 | 1.191 | 2627 | 1.355 | 2627 | 1.955 |

Table 5 The scale factors of the combinatorial ASCE method

| Row | 2-story building | | 4-story building | | 6-story building | | 8-story building | | 10-story building | |
|---|---|---|---|---|---|---|---|---|---|---|
| | NGA | S.F. | NGA | S.F. | NGA | S.F. | NGA | S.F. | NGA | S.F. |
| 1 | 0265 | 1.50 | 0265 | 1.193 | 0265 | 1.154 | 0265 | 1.301 | 0755 | 1.379 |
| 2 | 0755 | 1.50 | 0755 | 1.193 | 0755 | 1.154 | 0755 | 1.301 | 0787 | 1.379 |
| 3 | 0787 | 1.50 | 0787 | 1.193 | 0787 | 1.154 | 0787 | 1.301 | 0864 | 1.379 |
| 4 | 0864 | 1.50 | 0864 | 1.193 | 0864 | 1.154 | 0864 | 1.301 | 0952 | 1.379 |
| 5 | 1010 | 1.50 | 1010 | 1.193 | 1010 | 1.154 | 0952 | 1.301 | 1010 | 1.379 |
| 6 | 1198 | 1.50 | 1198 | 1.193 | 1198 | 1.154 | 1010 | 1.301 | 1202 | 1.379 |
| 7 | 1202 | 1.50 | 1487 | 1.193 | 1485 | 1.154 | 1198 | 1.301 | 1485 | 1.379 |
| 8 | 1487 | 1.50 | 1506 | 1.193 | 1487 | 1.154 | 1485 | 1.301 | 1487 | 1.379 |
| 9 | 1787 | 1.50 | 2495 | 1.193 | 1506 | 1.154 | 1487 | 1.301 | 1787 | 1.379 |
| 10 | 2627 | 1.50 | 2627 | 1.193 | 2627 | 1.154 | 2627 | 1.301 | 2627 | 1.379 |

Table 6 The scale factors of the CMS method

| Row | 2-story building | | 4-story building | | 6-story building | | 8-story building | | 10-story building | |
|---|---|---|---|---|---|---|---|---|---|---|
| | NGA | S.F. | NGA | S.F. | NGA | S.F. | NGA | S.F. | NGA | S.F. |
| 1 | 0265 | 0.925 | 0265 | 0.864 | 0265 | 0.829 | 0265 | 0.931 | 0755 | 1.172 |
| 2 | 0755 | 1.071 | 0755 | 1.029 | 0755 | 0.959 | 0755 | 1.032 | 0787 | 1.136 |
| 3 | 0787 | 1.293 | 0787 | 1.058 | 0787 | 0.978 | 0787 | 1.038 | 0864 | 0.891 |
| 4 | 0864 | 1.140 | 0864 | 0.832 | 0864 | 0.753 | 0864 | 0.811 | 0952 | 1.200 |
| 5 | 1010 | 1.049 | 1010 | 1.054 | 1010 | 1.015 | 0952 | 0.945 | 1010 | 1.030 |
| 6 | 1198 | 1.174 | 1198 | 1.022 | 1198 | 0.926 | 1010 | 1.135 | 1202 | 0.808 |
| 7 | 1202 | 1.068 | 1487 | 0.790 | 1485 | 0.758 | 1198 | 0.973 | 1485 | 0.977 |
| 8 | 1487 | 0.899 | 1506 | 1.074 | 1487 | 0.759 | 1485 | 0.834 | 1487 | 0.937 |
| 9 | 1787 | 1.098 | 2495 | 0.903 | 1506 | 0.931 | 1487 | 0.834 | 1787 | 1.001 |
| 10 | 2627 | 0.948 | 2627 | 0.839 | 2627 | 0.791 | 2627 | 0.875 | 2627 | 1.009 |

lengthy because each building must be designed once for each original record. The combinatorial UDM overcomes this difficulty with using the mean response spectrum of the original records for design. Therefore in this method the building is once designed using the mean response spectrum of the original records, with the resulting period $T_1^e$, and once with the design spectrum, resulting in period $T_1^{code}$. Then the scale factor is calculated using Eq. (11).

### 3.3 The scale factors

The scale factors using the methods mentioned above, namely the separative and combinatorial ASCE and UDM,

Table 7 The scale factors of the separative UDM approach

| Row | 2-story building | | 4-story building | | 6-story building | | 8-story building | | 10-story building | |
|---|---|---|---|---|---|---|---|---|---|---|
| | NGA | S.F. | NGA | S.F. | NGA | S.F. | NGA | S.F. | NGA | S.F. |
| 1 | 0265 | 2.57 | 0265 | 1.49 | 0265 | 2.49 | 0265 | 1.82 | 0755 | 1.32 |
| 2 | 0755 | 1.72 | 0755 | 1.65 | 0755 | 2.39 | 0755 | 1.86 | 0787 | 1.80 |
| 3 | 0787 | 1.66 | 0787 | 1.85 | 0787 | 2.40 | 0787 | 1.72 | 0864 | 1.76 |
| 4 | 0864 | 2.50 | 0864 | 1.59 | 0864 | 2.02 | 0864 | 1.54 | 0952 | 1.59 |
| 5 | 1010 | 1.95 | 1010 | 2.52 | 1010 | 1.99 | 0952 | 1.91 | 1010 | 1.67 |
| 6 | 1198 | 1.89 | 1198 | 1.84 | 1198 | 1.95 | 1010 | 1.67 | 1202 | 1.95 |
| 7 | 1202 | 1.70 | 1487 | 1.61 | 1485 | 1.90 | 1198 | 1.46 | 1485 | 2.06 |
| 8 | 1487 | 1.19 | 1506 | 1.35 | 1487 | 2.10 | 1485 | 2.45 | 1487 | 2.17 |
| 9 | 1787 | 1.22 | 2495 | 1.53 | 1506 | 1.87 | 1487 | 2.52 | 1787 | 1.52 |
| 10 | 2627 | 1.94 | 2627 | 1.62 | 2627 | 1.57 | 2627 | 1.36 | 2627 | 1.43 |

Table 8 The scale factors of the combinatorial UDM approach

| Row | 2-story building | | 4-story building | | 6-story building | | 8-story building | | 10-story building | |
|---|---|---|---|---|---|---|---|---|---|---|
| | NGA | S.F. | NGA | S.F. | NGA | S.F. | NGA | S.F. | NGA | S.F. |
| 1 | 0265 | 2.176 | 0265 | 1.507 | 0265 | 1.727 | 0265 | 1.542 | 0755 | 1.411 |
| 2 | 0755 | 2.176 | 0755 | 1.507 | 0755 | 1.727 | 0755 | 1.542 | 0787 | 1.411 |
| 3 | 0787 | 2.176 | 0787 | 1.507 | 0787 | 1.727 | 0787 | 1.542 | 0864 | 1.411 |
| 4 | 0864 | 2.176 | 0864 | 1.507 | 0864 | 1.727 | 0864 | 1.542 | 0952 | 1.411 |
| 5 | 1010 | 2.176 | 1010 | 1.507 | 1010 | 1.727 | 0952 | 1.542 | 1010 | 1.411 |
| 6 | 1198 | 2.176 | 1198 | 1.507 | 1198 | 1.727 | 1010 | 1.542 | 1202 | 1.411 |
| 7 | 1202 | 2.176 | 1487 | 1.507 | 1485 | 1.727 | 1198 | 1.542 | 1485 | 1.411 |
| 8 | 1487 | 2.176 | 1506 | 1.507 | 1487 | 1.727 | 1485 | 1.542 | 1487 | 1.411 |
| 9 | 1787 | 2.176 | 2495 | 1.507 | 1506 | 1.727 | 1487 | 1.542 | 1787 | 1.411 |
| 10 | 2627 | 2.176 | 2627 | 1.507 | 2627 | 1.727 | 2627 | 1.542 | 2627 | 1.411 |

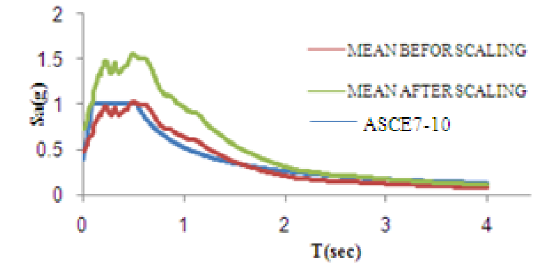
and the CMS procedures, are calculated for the records mentioned in Table 3, corresponding to the buildings introduced in Sec.2.3.1. The results are given in Tables 4-8.

As an example, Fig. 4 shows the mean spectra before and after scaling in different methods along with the design spectrum, for the 2-story building.

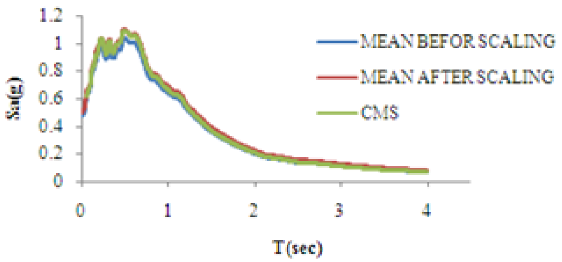
## 4. Nonlinear dynamic analysis

Quality of the scaling methods mentioned in Sec. 3 is evaluated in this section with determination of the structural responses by a nonlinear dynamic analysis under each scaled earthquake and calculating the scattering of results. The analysis is implemented within Opensees (Mazzoni *et al*. 2007). The structural steel members are modeled with nonlinear hinges to be concentrated at their ends. At such a location, the $M - \theta$ curve is calculated with discritizing the section into a number (usually 100-200) of fibers. Each fiber has a longitudinal one-dimensional nonlinear stress-strain relation assigned to it. For this purpose, the Steel02 material of Opensees for a St37 (European) or A36 (American) standard steel, accounting for the strain hardening and Bauschinger effects, is used.

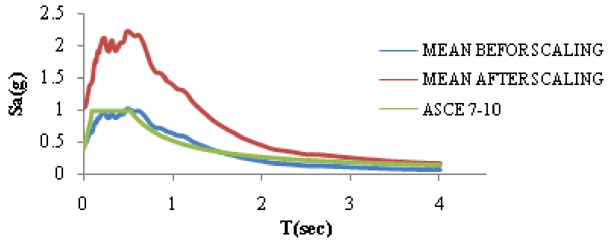
In the nonlinear analysis, story drifts and shear forces are calculated and their scattering among ground motions is measured. No consensus exists in the literature on a single measure of scattering of results. In this study, four more




(a) The combinatorial ASCE




(b) The CMS




(c) The combinatorial UDM

Fig. 4 The mean spectra before and after scaling, for the 2-story building

widespreadly used measures are utilized for the same purpose (NIST. 2011) The measures used are the coefficient of variation (COV), the logarithmic standard deviation ($\sigma$), relative difference of the averages (DA), and average of the 84 and 16 logarithmic percentiles of the responses (PA). Note that PA is an average, as well. If the distribution is close to normal, PA approaches to $\sigma \times COV$. The above parameters are determined based on Eqs. (12)-(15)

$$COV = \frac{\sigma}{\mu} \tag{12}$$

$$\sigma = \exp\left\{\sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(x_i - \bar{x})^2}\right\} \tag{13}$$

$$DA = \frac{MEAN_{50} - MEAN_{10}}{MEAN_{50}} \tag{14}$$

$$PA = \frac{\ln X_{84} - \ln X_{16}}{2} \tag{15}$$

where MEAN50, refers to mean of response for 50 scaled records (5 scaling methods for 10 records), and MEAN10 refers to mean of responses under10 records for each scaling method. Also, $X$ is the response considered, being the story drift or shear force in this study. The scattering measures introduced in Eqs. (12)-(15) are calculated for each method of scaling, as of Sec. 3, for each building and each story response parameter. The results are mentioned in Tables 9-18 where in each column the method resulting in the least scatter, associated with the smallest value of the measure is highlighted in dark color. Percentage of a measure being a minimum for a scaling method using data of drifts and story shears for all buildings altogether is also shown in Tables 19-23.

Values of the scatter measures as mentioned in Tables 9-18 and the percentages mentioned in Tables 19-23 clearly show that the combinatorial uniform design method have resulted in the least scattering of nonlinear structural

Table 9 Values of the scatter measures for different scaling methods, story drifts, 2-story building

| | Modification Method | First Floor | Second Floor |
|---|---|---|---|
| C.O.V | Combinatorial ASCE | 0.511 | 0.458 |
| | Separative ASCE | 0.732 | 0.665 |
| | CMS | 0.435 | 0.423 |
| | Combinatorial UDM | 0.374 | 0.365 |
| | Separative UDM | 0.620 | 0.572 |
| σ | Combinatorial ASCE | 0.590 | 0.539 |
| | Separative ASCE | 0.863 | 0.788 |
| | CMS | 0.579 | 0.558 |
| | Combinatorial UDM | 0.435 | 0.401 |
| | Separative UDM | 0.758 | 0.738 |
| D.A | Combinatorial ASCE | 0.147 | 0.118 |
| | Separative ASCE | 0.194 | 0.149 |
| | CMS | 0.422 | 0.382 |
| | Combinatorial UDM | 0.143 | 0.120 |
| | Separative UDM | 0.233 | 0.231 |
| P.A | Combinatorial ASCE | 0.473 | 0.393 |
| | Separative ASCE | 0.697 | 0.629 |
| | CMS | 0.404 | 0.387 |
| | Combinatorial UDM | 0.306 | 0.299 |
| | Separative UDM | 0.613 | 0.558 |

Table 10 Values of the scatter measures for different scaling methods, story drifts, 4-story building

| | Modification Method | First Floor | Second Floor | Third Floor | Forth Floor |
|---|---|---|---|---|---|
| C.O.V | Combinatorial ASCE | 0.481 | 0.545 | 0.565 | 0.578 |
| | Separative ASCE | 0.584 | 0.604 | 0.637 | 0.651 |
| | CMS | 0.550 | 0.607 | 0.705 | 0.627 |
| | Combinatorial UDM | 0.459 | 0.519 | 0.495 | 0.469 |
| | Separative UDM | 0.620 | 0.548 | 0.621 | 0.578 |
| σ | Combinatorial ASCE | 0.451 | 0.513 | 0.510 | 0.524 |
| | Separative ASCE | 0.487 | 0.510 | 0.525 | 0.535 |
| | CMS | 0.438 | 0.479 | 0.510 | 0.471 |
| | Combinatorial UDM | 0.496 | 0.546 | 0.586 | 0.548 |
| | Separative UDM | 0.430 | 0.483 | 0.510 | 0.520 |
| D.A | Combinatorial ASCE | 0.085 | 0.098 | 0.173 | 0.287 |
| | Separative ASCE | 0.247 | 0.232 | 0.155 | 0.044 |
| | CMS | 0.274 | 0.283 | 0.324 | 0.405 |
| | Combinatorial UDM | 0.070 | 0.041 | 0.183 | 0.626 |
| | Separative UDM | 0.181 | 0.191 | 0.160 | 0.023 |
| P.A | Combinatorial ASCE | 0.447 | 0.447 | 0.410 | 0.378 |
| | Separative ASCE | 0.464 | 0.480 | 0.485 | 0.489 |
| | CMS | 0.443 | 0.416 | 0.487 | 0.405 |
| | Combinatorial UDM | 0.380 | 0.450 | 0.403 | 0.386 |
| | Separative UDM | 0.521 | 0.565 | 0.576 | 0.577 |

Table 11 Values of the scatter measures for different scaling methods, story drifts, 6-story building

| | Modification Method | First Floor | Second Floor | Third Floor | Forth Floor | Fifth Floor | Sixth Floor |
|---|---|---|---|---|---|---|---|
| C.O.V | Combinatorial ASCE | 0.578 | 0.595 | 0.646 | 0.672 | 0.677 | 0.586 |
| | Separative ASCE | 0.482 | 0.513 | 0.562 | 0.604 | 0.620 | 0.504 |
| | CMS | 0.529 | 0.533 | 0.552 | 0.58 | 0.577 | 0.535 |
| | Combinatorial UDM | 0.696 | 0.666 | 0.652 | 0.66 | 0.619 | 0.564 |
| | Separative UDM | 0.488 | 0.513 | 0.556 | 0.576 | 0.605 | 0.506 |
| σ | Combinatorial ASCE | 0.981 | 1.103 | 1.158 | 1.21 | 1.119 | 0.937 |
| | Separative ASCE | 0.624 | 0.664 | 0.76 | 0.885 | 1.189 | 0.663 |
| | CMS | 0.805 | 0.795 | 0.866 | 0.974 | 1.034 | 0.738 |
| | Combinatorial UDM | 0.718 | 0.794 | 0.854 | 0.863 | 0.826 | 0.682 |
| | Separative UDM | 0.575 | 0.677 | 0.847 | 0.806 | 0.783 | 0.516 |
| D.A | Combinatorial ASCE | 0.174 | 0.152 | 0.196 | 0.213 | 0.255 | 0.321 |
| | Separative ASCE | 0.021 | 0.002 | 0.001 | 0.008 | 0.017 | 0.091 |
| | CMS | 0.334 | 0.311 | 0.364 | 0.437 | 0.429 | 0.406 |
| | Combinatorial UDM | 0.198 | 0.186 | 0.276 | 0.347 | 0.450 | 0.610 |
| | Separative UDM | 0.332 | 0.276 | 0.283 | 0.311 | 0.250 | 0.209 |
| P.A | Combinatorial ASCE | 0.698 | 0.702 | 0.749 | 0.767 | 0.683 | 0.541 |
| | Separative ASCE | 0.603 | 0.631 | 0.722 | 0.745 | 0.771 | 0.596 |
| | CMS | 0.754 | 0.708 | 0.715 | 0.743 | 0.679 | 0.580 |
| | Combinatorial UDM | 0.558 | 0.668 | 0.733 | 0.761 | 0.726 | 0.622 |
| | Separative UDM | 0.503 | 0.633 | 0.705 | 0.678 | 0.660 | 0.406 |

Table 12 Values of the scatter measures for different scaling methods, story drifts, 8-story building

| | Modification Method | First Floor | Second Floor | Third Floor | Forth Floor | Fifth Floor | Sixth Floor | Seventh Floor | Eight Floor |
|---|---|---|---|---|---|---|---|---|---|
| C.O.V | Combinatorial ASCE | 0.462 | 0.490 | 0.576 | 0.679 | 0.846 | 0.902 | 0.698 | 0.546 |
| | Separative ASCE | 0.440 | 0.481 | 0.533 | 0.633 | 0.781 | 0.772 | 0.740 | 0.537 |
| | CMS | 0.468 | 0.461 | 0.509 | 0.609 | 0.744 | 0.796 | 0.615 | 0.525 |
| | Combinatorial UDM | 0.503 | 0.523 | 0.569 | 0.623 | 0.665 | 0.658 | 0.567 | 0.507 |
| | Separative UDM | 0.436 | 0.424 | 0.509 | 0.554 | 0.746 | 0.701 | 0.671 | 0.494 |
| σ | Combinatorial ASCE | 0.597 | 0.570 | 0.655 | 0.679 | 0.801 | 1.117 | 0.844 | 0.685 |
| | Separative ASCE | 0.530 | 0.593 | 0.630 | 0.690 | 0.755 | 1.020 | 0.913 | 0.687 |
| | CMS | 0.703 | 0.618 | 0.625 | 0.729 | 0.805 | 1.208 | 0.870 | 0.631 |
| | Combinatorial UDM | 0.659 | 0.630 | 0.681 | 0.680 | 0.745 | 0.750 | 0.698 | 0.639 |
| | Separative UDM | 0.466 | 0.456 | 0.528 | 0.547 | 0.740 | 0.908 | 0.774 | 0.612 |
| D.A | Combinatorial ASCE | 0.054 | 0.064 | 0.087 | 0.119 | 0.139 | 0.194 | 0.132 | 0.191 |
| | Separative ASCE | 0.080 | 0.077 | 0.059 | 0.028 | 0.009 | 0.005 | 0.058 | 0.056 |
| | CMS | 0.298 | 0.313 | 0.344 | 0.367 | 0.422 | 0.444 | 0.381 | 0.426 |
| | Combinatorial UDM | 0.080 | 0.136 | 0.188 | 0.300 | 0.470 | 0.523 | 0.536 | 0.712 |
| | Separative UDM | 0.192 | 0.163 | 0.184 | 0.158 | 0.081 | 0.119 | 0.036 | 0.040 |
| P.A | Combinatorial ASCE | 0.477 | 0.536 | 0.599 | 0.680 | 0.792 | 1.168 | 0.892 | 0.677 |
| | Separative ASCE | 0.457 | 0.502 | 0.584 | 0.736 | 0.751 | 0.869 | 0.977 | 0.695 |
| | CMS | 0.456 | 0.496 | 0.584 | 0.659 | 0.784 | 1.339 | 0.819 | 0.620 |
| | Combinatorial UDM | 0.508 | 0.537 | 0.633 | 0.674 | 0.764 | 0.713 | 0.599 | 0.538 |
| | Separative UDM | 0.316 | 0.349 | 0.454 | 0.604 | 0.706 | 0.777 | 0.804 | 0.540 |

Table 13 Values of the scatter measures for different scaling methods, story drifts, 10-story building

| | Modification Method | First Floor | Second Floor | Third Floor | Forth Floor | Fifth Floor | Sixth Floor | Seventh Floor | Eight Floor | Ninth Floor | Tenth Floor |
|---|---|---|---|---|---|---|---|---|---|---|---|
| C.O.V | Combinatorial ASCE | 0.484 | 0.459 | 0.468 | 0.513 | 0.644 | 0.732 | 0.790 | 0.721 | 0.676 | 0.449 |
| | Separative ASCE | 0.513 | 0.471 | 0.473 | 0.490 | 0.644 | 0.711 | 0.715 | 0.709 | 0.618 | 0.363 |
| | CMS | 0.482 | 0.497 | 0.491 | 0.483 | 0.596 | 0.655 | 0.664 | 0.666 | 0.663 | 0.567 |
| | Combinatorial UDM | 0.507 | 0.509 | 0.505 | 0.502 | 0.594 | 0.630 | 0.616 | 0.583 | 0.502 | 0.431 |
| | Separative UDM | 0.398 | 0.395 | 0.435 | 0.475 | 0.642 | 0.734 | 0.813 | 0.774 | 0.597 | 0.478 |
| σ | Combinatorial ASCE | 0.745 | 0.725 | 0.855 | 0.840 | 0.920 | 0.941 | 0.954 | 1.087 | 1.248 | 0.511 |
| | Separative ASCE | 0.794 | 0.719 | 0.902 | 0.795 | 0.949 | 0.919 | 0.959 | 1.014 | 0.791 | 0.509 |
| | CMS | 0.710 | 0.879 | 0.912 | 0.799 | 0.949 | 0.886 | 1.038 | 1.061 | 1.049 | 0.839 |
| | Combinatorial UDM | 0.646 | 0.658 | 0.723 | 0.753 | 0.798 | 0.823 | 0.813 | 0.768 | 0.690 | 0.609 |
| | Separative UDM | 0.603 | 0.595 | 0.765 | 0.696 | 0.840 | 0.875 | 0.901 | 0.960 | 0.782 | 0.609 |
| D.A | Combinatorial ASCE | 0.021 | 0.001 | 0.004 | 0.014 | 0.029 | 0.058 | 0.090 | 0.105 | 0.122 | 0.126 |
| | Separative ASCE | 0.162 | 0.168 | 0.172 | 0.152 | 0.074 | 0.047 | 0.021 | 0.012 | 0.060 | 0.068 |
| | CMS | 0.197 | 0.212 | 0.251 | 0.283 | 0.268 | 0.319 | 0.331 | 0.315 | 0.267 | 0.254 |
| | Combinatorial UDM | 0.060 | 0.073 | 0.047 | 0.011 | 0.117 | 0.186 | 0.297 | 0.405 | 0.454 | 0.550 |
| | Separative UDM | 0.116 | 0.115 | 0.122 | 0.134 | 0.106 | 0.144 | 0.103 | 0.026 | 0.005 | 0.103 |
| P.A | Combinatorial ASCE | 0.364 | 0.394 | 0.467 | 0.623 | 0.720 | 0.887 | 0.854 | 1.095 | 0.967 | 0.406 |
| | Separative ASCE | 0.499 | 0.493 | 0.474 | 0.539 | 0.748 | 0.909 | 0.862 | 0.937 | 0.670 | 0.231 |
| | CMS | 0.363 | 0.417 | 0.487 | 0.507 | 0.698 | 0.867 | 0.741 | 1.029 | 1.043 | 0.729 |
| | Combinatorial UDM | 0.474 | 0.469 | 0.523 | 0.556 | 0.634 | 0.701 | 0.702 | 0.639 | 0.526 | 0.408 |
| | Separative UDM | 0.316 | 0.361 | 0.397 | 0.845 | 0.760 | 0.929 | 0.845 | 1.050 | 0.694 | 0.316 |

Table 14 Values of the scatter measures for different scaling methods, story shears, 2-story building

| | Modification Method | First Floor | Second Floor |
|---|---|---|---|
| C.O.V | Combinatorial ASCE | 0.264 | 0.258 |
| | Separative ASCE | 0.352 | 0.335 |
| | CMS | 0.305 | 0.298 |
| | Combinatorial UDM | 0.184 | 0.159 |
| | Separative UDM | 0.316 | 0.244 |
| σ | Combinatorial ASCE | 0.349 | 0.312 |
| | Separative ASCE | 0.491 | 0.455 |
| | CMS | 0.435 | 0.406 |
| | Combinatorial UDM | 0.200 | 0.172 |
| | Separative UDM | 0.447 | 0.254 |
| D.A | Combinatorial ASCE | 0.044 | 0.019 |
| | Separative ASCE | 0.039 | 0.066 |
| | CMS | 0.209 | 0.191 |
| | Combinatorial UDM | 0.061 | 0.040 |
| | Separative UDM | 0.153 | 0.183 |
| P.A | Combinatorial ASCE | 0.159 | 0.144 |
| | Separative ASCE | 0.307 | 0.265 |
| | CMS | 0.219 | 0.218 |
| | Combinatorial UDM | 0.148 | 0.099 |
| | Separative UDM | 0.213 | 0.271 |

Table 15 Values of the scatter measures for different scaling methods, story shears, 4-story building

| | Modification Method | First Floor | Second Floor | Third Floor | Forth Floor |
|---|---|---|---|---|---|
| C.O.V | Combinatorial ASCE | 0.346 | 0.363 | 0.370 | 0.369 |
| | Separative ASCE | 0.403 | 0.412 | 0.425 | 0.432 |
| | CMS | 0.419 | 0.437 | 0.461 | 0.465 |
| | Combinatorial UDM | 0.312 | 0.322 | 0.323 | 0.312 |
| | Separative UDM | 0.333 | 0.335 | 0.363 | 0.380 |
| σ | Combinatorial ASCE | 0.301 | 0.317 | 0.306 | 0.297 |
| | Separative ASCE | 0.313 | 0.321 | 0.319 | 0.336 |
| | CMS | 0.332 | 0.345 | 0.350 | 0.327 |
| | Combinatorial UDM | 0.368 | 0.373 | 0.398 | 0.371 |
| | Separative UDM | 0.292 | 0.296 | 0.312 | 0.318 |
| D.A | Combinatorial ASCE | 0.055 | 0.048 | 0.065 | 0.114 |
| | Separative ASCE | 0.117 | 0.134 | 0.118 | 0.061 |
| | CMS | 0.185 | 0.174 | 0.174 | 0.240 |
| | Combinatorial UDM | 0.016 | 0.032 | 0.009 | 0.194 |
| | Separative UDM | 0.138 | 0.120 | 0.130 | 0.099 |
| P.A | Combinatorial ASCE | 0.288 | 0.279 | 0.251 | 0.265 |
| | Separative ASCE | 0.278 | 0.257 | 0.213 | 0.270 |
| | CMS | 0.312 | 0.299 | 0.317 | 0.226 |
| | Combinatorial UDM | 0.232 | 0.234 | 0.210 | 0.249 |
| | Separative UDM | 0.328 | 0.308 | 0.321 | 0.300 |

Table 16 Values of the scatter measures for different scaling methods, story shears, 6-story building

| | Modification Method | First Floor | Second Floor | Third Floor | Forth Floor | Fifth Floor | Sixth Floor |
|---|---|---|---|---|---|---|---|
| C.O.V | Combinatorial ASCE | 0.539 | 0.527 | 0.526 | 0.546 | 0.525 | 0.494 |
| | Separative ASCE | 0.393 | 0.39 | 0.400 | 0.438 | 0.369 | 0.337 |
| | CMS | 0.498 | 0.494 | 0.494 | 0.519 | 0.489 | 0.447 |
| | Combinatorial UDM | 0.446 | 0.454 | 0.452 | 0.478 | 0.447 | 0.408 |
| | Separative UDM | 0.390 | 0.376 | 0.389 | 0.430 | 0.368 | 0.337 |
| σ | Combinatorial ASCE | 2.296 | 2.319 | 2.371 | 2.376 | 2.346 | 2.324 |
| | Separative ASCE | 0.555 | 0.526 | 0.588 | 0.670 | 0.504 | 0.451 |
| | CMS | 0.768 | 0.749 | 0.774 | 0.846 | 0.689 | 0.593 |
| | Combinatorial UDM | 0.557 | 0.597 | 0.623 | 0.642 | 0.603 | 0.502 |
| | Separative UDM | 0.526 | 0.489 | 0.545 | 0.628 | 0.462 | 0.432 |
| D.A | Combinatorial ASCE | 0.126 | 0.103 | 0.122 | 0.130 | 0.167 | 0.217 |
| | Separative ASCE | 0.036 | 0.030 | 0.062 | 0.058 | 0.054 | 0.019 |
| | CMS | 0.232 | 0.208 | 0.248 | 0.257 | 0.275 | 0.340 |
| | Combinatorial UDM | 0.118 | 0.100 | 0.103 | 0.116 | 0.144 | 0.264 |
| | Separative UDM | 0.205 | 0.181 | 0.206 | 0.213 | 0.244 | 0.274 |
| P.A | Combinatorial ASCE | 0.572 | 0.574 | 0.551 | 0.560 | 0.495 | 0.421 |
| | Separative ASCE | 0.389 | 0.423 | 0.407 | 0.471 | 0.357 | 0.341 |
| | CMS | 0.673 | 0.660 | 0.623 | 0.619 | 0.598 | 0.519 |
| | Combinatorial UDM | 0.420 | 0.469 | 0.505 | 0.521 | 0.502 | 0.413 |
| | Separative UDM | 0.407 | 0.408 | 0.414 | 0.420 | 0.323 | 0.253 |

Table 17 Values of the scatter measures for different scaling methods, story shears, 8-story building

| | Modification Method | First Floor | Second Floor | Third Floor | Forth Floor | Fifth Floor | Sixth Floor | Seventh Floor | Eighth Floor |
|---|---|---|---|---|---|---|---|---|---|
| C.O.V | Combinatorial ASCE | 0.427 | 0.409 | 0.412 | 0.416 | 0.454 | 0.418 | 0.370 | 0.372 |
| | Separative ASCE | 0.402 | 0.380 | 0.373 | 0.377 | 0.413 | 0.384 | 0.342 | 0.353 |
| | CMS | 0.450 | 0.438 | 0.449 | 0.455 | 0.482 | 0.447 | 0.479 | 0.405 |
| | Combinatorial UDM | 0.414 | 0.403 | 0.401 | 0.397 | 0.416 | 0.397 | 0.353 | 0.343 |
| | Separative UDM | 0.361 | 0.340 | 0.312 | 0.296 | 0.339 | 0.308 | 0.254 | 0.293 |
| σ | Combinatorial ASCE | 0.563 | 0.522 | 0.520 | 0.505 | 0.585 | 0.521 | 0.464 | 0.461 |
| | Separative ASCE | 0.526 | 0.483 | 0.477 | 0.462 | 0.543 | 0.475 | 0.421 | 0.431 |
| | CMS | 0.635 | 0.601 | 0.608 | 0.601 | 0.673 | 0.610 | 2.636 | 0.539 |
| | Combinatorial UDM | 0.545 | 0.539 | 0.539 | 0.486 | 0.526 | 0.495 | 0.434 | 0.422 |
| | Separative UDM | 0.415 | 0.377 | 0.355 | 0.326 | 0.398 | 0.351 | 0.289 | 0.315 |
| D.A | Combinatorial ASCE | 0.038 | 0.044 | 0.052 | 0.047 | 0.057 | 0.042 | 0.039 | 0.058 |
| | Separative ASCE | 0.074 | 0.067 | 0.059 | 0.062 | 0.065 | 0.049 | 0.050 | 0.052 |
| | CMS | 0.256 | 0.256 | 0.249 | 0.237 | 0.257 | 0.227 | 0.224 | 0.259 |
| | Combinatorial UDM | 0.059 | 0.071 | 0.080 | 0.067 | 0.089 | 0.088 | 0.087 | 0.138 |
| | Separative UDM | 0.162 | 0.163 | 0.162 | 0.155 | 0.159 | 0.133 | 0.126 | 0.127 |
| P.A | Combinatorial ASCE | 0.424 | 0.426 | 0.432 | 0.435 | 0.515 | 0.427 | 0.372 | 0.392 |
| | Separative ASCE | 0.405 | 0.386 | 0.391 | 0.409 | 0.485 | 0.405 | 0.353 | 0.379 |
| | CMS | 0.446 | 0.468 | 0.502 | 0.520 | 0.562 | 0.476 | 0.429 | 0.429 |
| | Combinatorial UDM | 0.408 | 0.395 | 0.413 | 0.413 | 0.464 | 0.424 | 0.329 | 0.357 |
| | Separative UDM | 0.290 | 0.257 | 0.268 | 0.309 | 0.373 | 0.315 | 0.235 | 0.309 |

responses in a large majority of cases. The separative UDM, and the combinational ASCE rank the next levels. Overall, the scaling method of CMS has performed inferior to other methods. While the combinatorial UDM associates with the least scatter of responses, it is very simple to use as mentioned in Sec. 3.2. In this method, the fundamental period resulting only from two different designs of a building, once using the mean spectra of original records, and once with the design spectrum, are needed. Therefore it can be a practical and accurate enough alternative for scaling of earthquake records.

## 4. Conclusions

In this paper a three-stage method for selection of earthquake ground motions suitable for nonlinear dynamic analysis of structures, along with a new scaling method for modification of the selected records were presented. The selection method uses the general characteristics of earthquakes as used in online databases for an initial selection. Then it uses two stricter measures for finally picking up the suitable records. It is a fast method. It has the advantage that the stricter measures are used with a far less number of records. In the presented scaling method it was

Table 18 Values of the scatter measures for different scaling methods, story shears, 10-story building

| | Modification Method | First Floor | Second Floor | Third Floor | Forth Floor | Fifth Floor | Sixth Floor | Seventh Floor | Eight Floor | Ninth Floor | Tenth Floor |
|---|---|---|---|---|---|---|---|---|---|---|---|
| C.O.V | Combinatorial ASCE | 0.402 | 0.395 | 0.399 | 0.411 | 0.422 | 0.415 | 0.419 | 0.398 | 0.360 | 0.374 |
| | Separative ASCE | 0.415 | 0.399 | 0.401 | 0.409 | 0.417 | 0.407 | 0.409 | 0.395 | 0.348 | 0.410 |
| | CMS | 0.435 | 0.429 | 0.428 | 0.433 | 0.438 | 0.428 | 0.438 | 0.421 | 0.419 | 0.439 |
| | Combinatorial UDM | 0.331 | 0.328 | 0.337 | 0.355 | 0.360 | 0.359 | 0.365 | 0.334 | 0.282 | 0.308 |
| | Separative UDM | 0.537 | 0.399 | 0.401 | 0.405 | 0.414 | 0.409 | 0.412 | 0.416 | 0.375 | 0.392 |
| σ | Combinatorial ASCE | 0.634 | 0.639 | 0.677 | 0.672 | 0.631 | 0.628 | 0.667 | 0.600 | 0.521 | 0.495 |
| | Separative ASCE | 0.620 | 0.617 | 0.653 | 0.644 | 0.599 | 0.595 | 0.633 | 0.562 | 0.480 | 0.484 |
| | CMS | 0.723 | 0.735 | 0.770 | 0.760 | 0.716 | 0.712 | 0.750 | 0.685 | 0.622 | 0.578 |
| | Combinatorial UDM | 0.493 | 0.490 | 0.526 | 0.523 | 0.484 | 0.482 | 0.530 | 0.467 | 0.386 | 0.363 |
| | Separative UDM | 0.928 | 0.567 | 0.592 | 0.630 | 0.602 | 0.580 | 0.588 | 0.585 | 0.539 | 0.570 |
| D.A | Combinatorial ASCE | 0.008 | 0.001 | 0.002 | 0.001 | 0.001 | 0.000 | 0.001 | 0.001 | 0.013 | 0.035 |
| | Separative ASCE | 0.112 | 0.092 | 0.095 | 0.086 | 0.074 | 0.075 | 0.071 | 0.053 | 0.032 | 0.047 |
| | CMS | 0.134 | 0.129 | 0.133 | 0.142 | 0.146 | 0.147 | 0.148 | 0.137 | 0.138 | 0.204 |
| | Combinatorial UDM | 0.108 | 0.074 | 0.075 | 0.075 | 0.092 | 0.096 | 0.092 | 0.093 | 0.093 | 0.067 |
| | Separative UDM | 0.095 | 0.038 | 0.039 | 0.019 | 0.018 | 0.024 | 0.014 | 0.008 | 0.026 | 0.125 |
| P.A | Combinatorial ASCE | 0.332 | 0.307 | 0.321 | 0.363 | 0.438 | 0.437 | 0.401 | 0.336 | 0.293 | 0.320 |
| | Separative ASCE | 0.370 | 0.359 | 0.347 | 0.371 | 0.430 | 0.435 | 0.372 | 0.292 | 0.304 | 0.339 |
| | CMS | 0.347 | 0.343 | 0.367 | 0.387 | 0.446 | 0.421 | 0.426 | 0.359 | 0.377 | 0.390 |
| | Combinatorial UDM | 0.255 | 0.246 | 0.241 | 0.292 | 0.349 | 0.338 | 0.305 | 0.258 | 0.216 | 0.220 |
| | Separative UDM | 0.713 | 0.376 | 0.382 | 0.389 | 0.413 | 0.481 | 0.435 | 0.385 | 0.341 | 0.381 |

Table 19 Percentage of a measure being a minimum for a scaling method, 2-story building

| Method | C.O.V | Σ | D.A | P.A |
|---|---|---|---|---|
| Combinatorial ASCE | 0 | 0 | 50 | 0 |
| Separation ASCE | 0 | 0 | 25 | 0 |
| CMS | 0 | 0 | 0 | 0 |
| Combinatorial UDM | 100 | 100 | 25 | 100 |
| Separation UDM | 0 | 0 | 0 | 0 |

Table 20 Percentage of a measure being a minimum for a scaling method, 4-story building

| Method | C.O.V | Σ | D.A | P.A |
|---|---|---|---|---|
| Combinatorial ASCE | 0 | 25 | 0 | 12.50 |
| Separation ASCE | 0 | 0 | 25 | 0 |
| CMS | 0 | 25 | 0 | 25 |
| Combinatorial UDM | 100 | 0 | 62.50 | 62.50 |
| Separation UDM | 0 | 50 | 12.50 | 0 |

aimed to equalize the fundamental period of the studied building designed under the scaled response spectrum of the record and under the design spectrum.

With calculation of four different scatter measures for nonlinear responses of five steel structures ranging from 2 to 10 stories under the 10 selected and scaled earthquake

Table 21 Percentage of a measure being a minimum for a scaling method, 6-story building

| Method | C.O.V | Σ | D.A | P.A |
|---|---|---|---|---|
| Combinatorial ASCE | 0 | 0 | 0 | 0 |
| Separation ASCE | 16.67 | 16.67 | 100 | 25 |
| CMS | 16.67 | 0 | 0 | 0 |
| Combinatorial UDM | 0 | 0 | 0 | 0 |
| Separation UDM | 66.66 | 83.33 | 0 | 75 |

Table 22 Percentage of a measure being a minimum for a scaling method, 8-story building

| Method | C.O.V | Σ | D.A | P.A |
|---|---|---|---|---|
| Combinatorial ASCE | 0 | 0 | 62.50 | 0 |
| Separation ASCE | 0 | 0 | 25 | 0 |
| CMS | 0 | 0 | 0 | 0 |
| Combinatorial UDM | 18.75 | 12.50 | 0 | 18.75 |
| Separation UDM | 81.25 | 87.50 | 12.50 | 81.25 |

Table 23 Percentage of a measure being a minimum for a scaling method, 10-story building

| Method | C.O.V | Σ | D.A | P.A |
|---|---|---|---|---|
| Combinatorial ASCE | 0 | 0 | 70 | 0 |
| Separation ASCE | 5 | 0 | 20 | 0 |
| CMS | 0 | 0 | 0 | 5 |
| Combinatorial UDM | 75 | 80 | 5 | 75 |
| Separation UDM | 20 | 20 | 5 | 20 |

records, it was shown that the proposed method resulted in the least scatter in most cases and retained a small value in the remaining cases. The quality of the ASCE and CMS scaling methods were shown to be ranked afterwards.

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