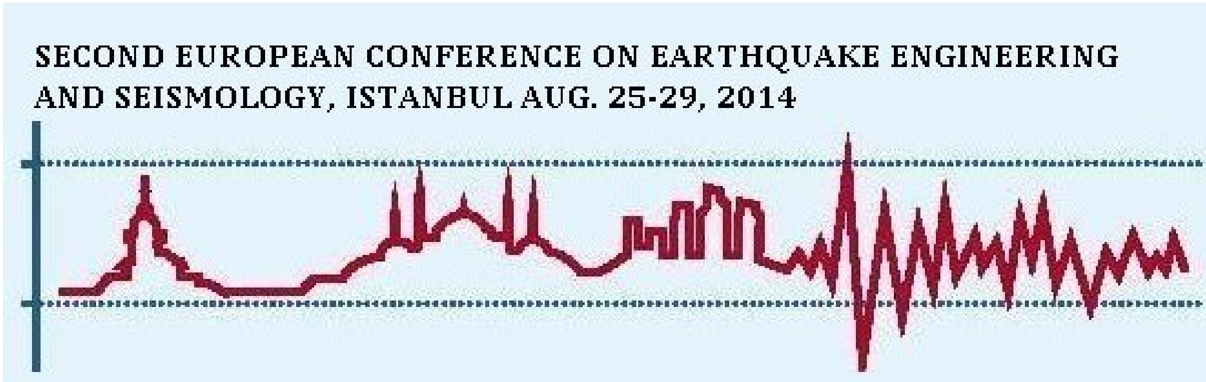

An Effective Method for Selection and Modification of Ground Motion for Dynamic Time History Analysis

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ABSTRACT

One of the most appropriate methods to estimate the seismic behavior of structures is the nonlinear dynamic time history analysis. In such a method, the momentary responses of a structure are calculated under an accelerogram of an earthquake. A prime factor affecting the accuracy of such calculations is an appropriate selection of the ground motion suit so that inconsistency of records can result in an unrealistic comprehension of the seismic behavior of the studied building.

In this study, first a three-step screening process is presented for selection of consistent earthquake records in which number of suitable earthquakes is quickly screened and reduced from a few thousands to a handful number for practical use in the time history analysis. Records that remain at the end of this screening process are the most appropriate for the studied structures meaning that they considerably reduce the dispersion of structural responses. Then, an effective method is presented for spectral matching and modification of the selected records. A number of commonly available methods for scaling of records are examined comparatively. 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. It is perceived that the selection and modification procedure presented, leads to less scatter hence more reliability of the nonlinear dynamic response values for structural design purposes.

INTRODUCTION

The nonlinear time history analysis possesses a special advantage over other dynamic analysis methods due to its ability to simulate a realistic seismic behavior of structures. To implement such an analysis, availability of suitable earthquake records is necessary. It is well known that the structural responses are quite sensitive to the selected earthquake records. On the other hand, any selected record is scaled to be consistent to the seismic environment under study. Various scaling methods are available. Among the methods, the one which results least scatter in nonlinear responses under the selected and scaled records can be relied upon more efficiently. Therefore, in a nonlinear dynamic analysis both of the selection and scaling procedures of the ground motions to be used are of prime importance. These are discussed in detail in the next sections.

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THE PROPOSED METHOD FOR RECORD SELECTION

In this research a three-phase screening method is presented for selection of seismic records. In such a procedure, from the first to the third screen, the selection criteria become more rigorous and the remaining records become rapidly smaller in number. These are called the loose, intermediate, and tight screens. At the loose-screen stage, general characteristics of ground motions are selected to be consistent. These are the: magnitude (M), epicentral distance (R), soil type (according to the shear wave velocity, V_s) and peak ground acceleration (normalized to g, PGA). For numerical analysis of this study, it is arbitrarily assumed that: $(6 \leq M \leq 8)$, $(10 \leq R \leq 90$ km), $(375 \leq V_S \leq 750\ m/s)$, $(0.20 \leq PGA \leq 1.2)$.

If the database of PEER is consulted [PEER, 2013], then the selected records will be 47 motions as shown in Table 1.

Table 1. The selected records after loose-screen.

Row	NGA NUM	M	R(km)	PGA (g)	PGV(cm/sec)	PGD(cm)	Vs30 (m/s)	Latitude	Longitude
1	NGA0033	6.19	24.90	0.2934	17.4500	3.6100	527.90	35.7100	-120.170
2	NGA0057	6.61	16.00	0.2994	19.8300	3.2900	450.30	34.5640	-118.642
3	NGA0125	6.50	13.00	0.3458	25.0600	4.5400	424.80	46.3820	12.9820
4	NGA0126	6.80	22.50	0.6438	61.5000	20.8000	659.60	40.3500	63.4700
5	NGA0265	6.33	30.00	0.5722	27.0600	10.8500	659.60	32.4210	-115.3010
6	NGA0288	6.90	47.00	0.2137	12.4100	2.4600	500.00	40.4580	15.63500
7	NGA0587	6.60	13.00	0.2926	21.0700	4.6000	424.80	-38.1150	176.8830
8	NGA0739	6.93	40.00	0.2385	19.5700	7.0300	488.80	37.1660	-121.6280
9	NGA0755	6.93	40.00	0. 4700	7.8400	4.6500	684.90	36.7650	-121.4460
10	NGA0787	6.93	40.00	0.2281	32.5600	9.5300	425.30	37.0407	-121.8830
11	NGA0801	6.93	40.00	0.2834	21.0200	11.1200	671.80	37.4200	-122.2100
12	NGA0809	6.93	40.00	0.3418	11.8100	5.1400	714.00	37.0010	-122.0620
13	NGA0810	6.93	40.00	0.4568	18.6300	4.4500	714.00	37.0010	-122.0600
14	NGA0811	6.93	40.00	0.5174	32.3200	7.4100	376.10	36.9720	-121.9950
15	NGA0864	7.28	71.70	0.2489	34.2400	11.8900	379.30	34.1300	-116.3140
16	NGA0952	6.69	18.00	0.5102	32.8200	6.6700	545.70	34.1270	-118.4050
17	NGA0963	6.69	18.00	0.4898	46.5100	13.5700	450.30	34.5640	-118.6420
18	NGA0974	6.69	18.00	0.2063	13.3000	2.1300	446.00	34.0880	-118.2220
19	NGA0991	6.69	18.00	0.2558	10.8300	1.8100	446.00	34.2000	-118.2310
20	NGA0993	6.69	18.00	0.2071	16.5100	2.9300	446.00	34.1150	-118.2440
21	NGA1006	6.69	18.00	0.3908	22.4100	5.1100	398.40	34.0680	-118.4390
22	NGA1007	6.69	18.00	0.3492	19.3900	2.3800	376.10	34.0620	-118.1980
23	NGA1009	6.69	18.00	0.2648	28.0200	9.7000	392.20	34.0520	-118.4510
24	NGA1010	6.69	18.00	0.3391	26.3700	6.7900	413.80	34.0520	-118.4510
25	NGA1020	6.69	18.00	0.2153	9.9700	4.4400	602.10	34.5710	-118.5600
26	NGA1039	6.69	18.00	0.2291	22.3100	4.1300	405.20	34.2880	-118.8810
27	NGA1049	6.69	18.00	0.3316	22.6500	5.9900	446.00	34.0420	-118.5540
28	NGA1055	6.69	18.00	0.2337	12.9800	1.2500	455.40	34.1680	-118.0780
29	NGA1070	6.69	18.00	0.2087	10.2300	2.2700	401.40	34.0910	-118.0930
30	NGA1089	6.69	18.00	0.2591	13.7600	3.1300	376.10	34.0840	-118.6000
31	NGA1198	7.62	88.00	0.2595	33.1100	20.7300	544.70	23.6135	120.5282
32	NGA1202	7.62	88.00	0.2602	41.9200	12.9000	473.90	23.5200	120.5840
33	NGA1205	7.62	88.00	0.4625	27.7300	9.8400	492.30	23.4388	120.5957
34	NGA1402	7.62	88.00	0.3852	26.3700	18.4400	375.30	24.6312	121.0005
35	NGA1485	7.62	88.00	0.4730	38.8900	25.5200	704.60	24.5412	120.9137
36	NGA1487	7.62	88.00	0.3643	38.1200	36.4200	520.40	24.6188	120.9387
37	NGA1506	7.62	88.00	0.2058	56.4500	51.0400	401.30	24.1960	120.5403
38	NGA1524	7.62	88.00	0.5283	56.2400	36.2800	446.60	24.6917	121.0135
39	NGA1633	7.37	71.60	0.5051	43.7800	18.9600	724.00	36.9200	48.95000
40	NGA1787	7.13	69.00	0.3062	34.2100	17.7100	684.90	34.8294	-116.3350
41	NGA2495	6.20	10.00	0.3342	47.2700	9.0100	553.40	23.5972	120.6777

42	NGA2622	6.20	10.00	0.2736	11.7600	1.7300	624.90	23.9855	120.7883
43	NGA2627	6.20	10.00	0.3363	39.2400	6.4100	615.00	23.9077	120.6757
44	NGA2658	6.20	10.00	0.6083	26.4800	4.8000	664.40	23.8783	120.6843
45	NGA2942	6.20	17.50	0.2461	10.2700	1.1800	427.70	23.7570	120.6062
46	NGA3217	6.20	17.50	0.3911	10.9200	1.0600	664.40	23.8783	120.6843
47	NGA3507	6.30	29.00	0.2565	13.5900	3.8800	664.40	23.8783	120.6843

At the intermediate-screen stage, the selected records are sorted according to their spectral intensity values. The spectral intensity is a measure of the earthquake energy absorbed by a structure during a certain interval of ground motion, as a function of the spectral velocity. It is defined as follows [Housner, 1952]:

$$SI = \int_{T_1}^{T_2} sv_x \, .dt \tag{1}$$

In the above equation, T_1 and T_2 are two distinct periods and are taken to be 0.1 and 2.5 sec, respectively. The criterion is that the more suitable records at this stage are those with spectral intensities nearer to that of the design spectrum at hand. If the ratio of the two above values is called RSI, earthquakes with RSI's near to unity are picked up at this stage. Based on this criterion, 20 earthquakes are selected out of the previous stage records. These are mentioned in Table 2 along with their RSI's.

Table 2. Seismic records selected at the intermediate-screen stage.

Row	NGA NUM	RSI	Row	NGA NUM	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

At the tight-screen stage, the records selected in the previous stage are again reduced in number using consistency of their response spectra with the conditional mean spectrum (CMS) [Baker, 2011].
The criteria for consistency are the sum of the squared errors (SSE) and the scale factor (SF) calculated as follows:

$$SSE = \sum_{j=1}^{n} \left(\ln Sa(T_j) - \ln Sa_{CMS}(T_j)\right)^2 \tag{2}$$

in which $\ln Sa(T_j)$ is the natural logarithm of the spectral acceleration of the record at period T_j and $\ln Sa_{CMS}(T_j)$ is the natural logarithm of the CMS value at the same period. Also:

$$\text{Scale Factor} = \frac{\sum_{j=1}^{n} Sa_{CMS}(T_j)}{\sum_{j=1}^{n} Sa(T_j)} \tag{3}$$

where $Sa(T_j)$ and $Sa_{CMS}(T_j)$ are the spectral accelerations of the record and the CMS at period T_j.

The final selected records are those with small (near to zero) SSE's and with SF's near to unity. With these criteria, 10 records are finally selected out of those of the previous stage. These are shown with their SSE's and SF's in Table 3.

Table 3. The records finally selected at the tight-screen stage.

Row	2-story building			4-story building			6-story building			8-story building			10-story building		
	NGA	S.F	SSE	NGA	S.F	SSE	NGA	S.F	S.F	NGA	SSE	S.F	NGA	SSE	S.F
1	0265	0.886	3.117	0265	0.856	3.252	0265	0.8634	0.886	0265	3.117	0.856	0755	3.662	0.9959
2	0755	1.026	2.038	0755	1.019	3.662	0755	0.9959	1.026	0755	2.038	1.019	0787	4.019	1.0139
3	0787	1.239	1.099	0787	1.048	4.019	0787	1.0139	1.239	0787	1.099	1.048	0864	14.50	0.7795
4	0864	1.092	5.933	0864	0.824	14.50	0864	0.7795	1.092	0864	5.933	0.824	0952	23.31	0.8526
5	1010	1.005	9.069	1010	1.044	8.170	1010	1.0645	1.005	0952	15.75	0.816	1010	8.170	1.0645
6	1198	1.124	6.547	1198	1.012	6.536	1198	0.9586	1.124	1010	9.069	1.044	1202	20.32	0.6943
7	1202	1.023	4.882	1487	0.783	7.479	1485	0.7885	0.725	1198	6.547	1.012	1485	12.82	0.7885
8	1487	0.861	1.023	1506	1.064	14.31	1487	0.7887	0.861	1485	1.389	0.781	1487	7.479	0.7887
9	1787	1.052	5.568	2495	0.629	45.86	1506	0.9623	1.239	1487	1.023	0.783	1787	18.35	0.8497
10	2627	0.909	2.126	2627	0.831	2.290	2627	0.822	0.909	2627	2.126	0.831	2627	2.290	0.8216

CHARACTERISTICS OF THE EXAMPLE BUILDINGS AND THE DESIGN SPECTRUM

Five example buildings having 2, 4, 6, 8 and 10 stories with steel moment frames both ways are selected for response analysis of this study. The structures have three bays in each direction with 5m spans and 3m story heights. The fundamental periods of the mentioned buildings are 0.4, 0.8, 1.0, 1.2 and 1.5sec, respectively. The design spectrum is constructed using the requirements of ASCE7-10 and is shown in Fig. 1.

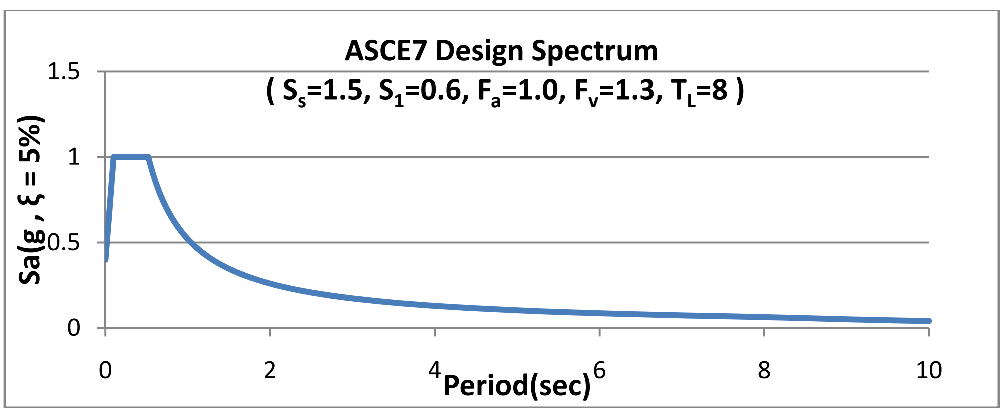

Fig. 1. The design spectrum.

MODIFICATION (SCALING) OF THE SELECTED RECORDS

In this paper five available methods are used for scaling of records. The first two methods belong to procedure of ASCE7-10 in which scaling is once performed based on the average spectrum of all records and once for each record separately. These are called the combinatorial ASCE and the separative ASCE, respectively. In the third method the CMS is used to scale the records. The fourth and fifth methods belong to a new procedure developed in this study called the Uniform Design Method (UDM). This new method can be implemented on the average response spectrum of earthquakes (combinatorial UDM, method 4) or on each individual record (separative UDM, method 5). The UDM will be described in the following sections.

Finally, the studied buildings are analyzed and their nonlinear dynamic responses are calculated under the selected earthquakes after each scaling method. The advantages of each method are discussed according to their ability to reduce scatter in the responses while being simple to implement.

SCALING ACCORDING TO ASCE7-10

In these methods a pair of response spectra is constructed using the horizontal components of each earthquake. The pair is combined to result in a single response spectrum using the square root of the sum of the squares (SRSS) method. The scale factor of the single spectrum is a number that when is multiplied by the spectral values, results in a scaled spectrum touching the design spectrum at the lowest in the period range of 0.2T-1.5T, where T is the fundamental period of the building. This method can be applied to the single spectrum of each earthquake (separative ASCE) or to a single spectrum averaged between all earthquakes (combinatorial ASCE). Tables 4 & 5 present the resulting scale factors of the selected earthquakes.

Table 4. The scale factors according to 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 5. The scale factors according to 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

SCALING ACCORDING TO THE CMS METHOD

In this method a CMS is constructed for each building as a target spectrum. The scale factor of each record is the ratio of the CMS values averaged in the period range of 0.2T-1.5T to the response spectral values of the record averaged in the same range, using Eq. (2). This should result in a response spectrum modified to become similar to the CMS in the mentioned period range. The scale factors are shown in Table 6.

Table 6. The scale factors according to 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

SCALING ACCORDING TO THE UDM

In the UDM, developed in this study, the original records are scaled such that all result in a similar structure when designed using the scaled response spectrum of the record. In this method, first the structure is designed using the response spectrum of the original record. The fundamental period of the resulted building is called T_1^e. Then the building is designed using the design spectrum. The fundamental period will be T_1^{code} in this case. Then the scale factor is calculated using Eq (4):

$$\text{Scale Factor} = \left({T_1^e}/{T_1^{code}} \right)^2 \tag{4}$$

It is expected that when the structure is designed using the response spectrum modified as above, its fundamental period becomes very similar to that of the same building designed using the design spectrum.
The above method is called the separative UDM. It can be easier to implement if Eq. (4) is used for the building designed using a single response spectrum averaged between all original selected records. Implemented this way, the method is called the combinatorial UDM.

The scale factors calculated using the above two versions of the UDM, are shown in Table 7 & 8.

Table 7. The scale factors computed using the combinatorial UDM.

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

Table 8. The scale factors computed using the separative UDM.

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

COMPARISON OF STRUCTURAL RESPONSE SCATTER

After scaling of the 10 selected earthquakes according to the different methods discussed, maximum responses of the structures are calculated under each modified earthquakes. The responses are selected to be story shears and drifts. For each scaling method, the scatter of response is calculated for each building under the modified earthquakes. There are different statistical criteria available for calculation of scatter. The ones that are more widely used are four criteria taken in this study. They are the: coefficient of variation (COV), logarithmic standard deviation (σ), difference of averages (DA), and half logarithmic difference of 16 and 84 percentiles (PA). The difference of averages is calculated using Eq (5):

$$DA=\frac{MEAN_{50}-MEAN_{10}}{MEAN_{50}} \quad (5)$$

In the above calculation, noting that 5 scaling methods with 10 records are used, the population is equivalent to 50 scaled records. Therefore, the average of the calculated responses is shown with $MEAN_{50}$. Since in each scaling method 10 records are used, the average response is shown by $MEAN_{10}$. Smaller values of Eq. (5) show that the results of the corresponding method are nearer to the total average hence are more suitable.

To calculate the difference of percentiles, Eq. (6) is utilized:

$$PA=\frac{\ln EDP_{84}-\ln EDP_{16}}{2} \quad (6)$$

where $\ln EDP_{84}$ and $\ln EDP_{16}$ are logarithms of the 84 and 16 percentiles, respectively, for the 10 selected records [5].

The scatter of the maximum responses are calculated using the above 4 criteria for the 5 buildings under the 10 records in each story. They are shown in Tables 9-16. In these tables, the smallest scatter criteria are shown with a grey background in each column. Tables 17-19 summarize the results with the percentages at which each method of scaling has resulted in the least scatter for each response quantity. These tables clearly show that the UDM and after that the code based method of scaling, have resulted in the least scatters among the cases considered.

Table 9. Values of the scatter criteria for the story drifts of the 2-story building.

	Modification Method	First Floor	Second Floor
C.O.V	Combinatorial ASCE	0.510663	0.457848
	Separative ASCE	0.732088	0.664811
	CMS	0.435066	0.422985
	Combinatorial UDM	0.374488	0.365207
	Separative UDM	0.619847	0.572101
σ	Combinatorial ASCE	0.590142	0.539423
	Separative ASCE	0.863172	0.787591
	CMS	0.5788	0.558377
	Combinatorial UDM	0.434614	0.401285
	Separative UDM	0.758051	0.738098
D.A	Combinatorial ASCE	0.147169	0.11795
	Separative ASCE	0.193625	0.148596
	CMS	0.421838	0.381921
	Combinatorial UDM	0.14276	0.120268
	Separative UDM	0.232621	0.231007
P.A	Combinatorial ASCE	0.472563	0.393128
	Separative ASCE	0.696995	0.629484
	CMS	0.403995	0.386545
	Combinatorial UDM	0.306268	0.299182
	Separative UDM	0.612571	0.557937

Table 10. Values of the scatter criteria for the story drifts of the 4-story building.

	Modification Method	First Floor	Second Floor	Third Floor	Forth Floor
C.O.V	Combinatorial ASCE	0.48102	0.54528	0.56453	0.57758
	Separative ASCE	0.58354	0.6038	0.6365	0.65131
	CMS	0.54988	0.60749	0.70486	0.62702
	Combinatorial UDM	0.4588	0.5191	0.4948	0.4694
	Separative UDM	0.619847	0.54778	0.62073	0.57758
σ	Combinatorial ASCE	0.45114	0.51301	0.50965	0.52434
	Separative ASCE	0.48654	0.50982	0.52532	0.53524
	CMS	0.43765	0.47893	0.50985	0.47143
	Combinatorial UDM	0.4957	0.5461	0.5857	0.5483
	Separative UDM	0.43022	0.48283	0.5095	0.52021
D.A	Combinatorial ASCE	0.0849	0.0984	0.1733	0.287
	Separative ASCE	0.2474	0.2317	0.1545	0.0437
	CMS	0.274	0.2825	0.3244	0.4053
	Combinatorial UDM	0.0695	0.0413	0.183	0.6262
	Separative UDM	0.181	0.1905	0.1602	0.0225
P.A	Combinatorial ASCE	0.44717	0.44696	0.41045	0.37781
	Separative ASCE	0.46399	0.47994	0.48504	0.48945
	CMS	0.4432	0.41639	0.48707	0.40474
	Combinatorial UDM	0.3803	0.4502	0.4025	0.386
	Separative UDM	0.52063	0.56546	0.5755	0.57673

Table 11. Values of the scatter criteria for the story drifts of the 6-story building.

	Modification Method	First Floor	Second Floor	Third Floor	Forth Floor	Fifth Floor	Sixth Floor
C.O.V	Combinatorial ASCE	0.578051	0.59524	0.645508	0.672463	0.67667	0.585778
	Separative ASCE	0.482146	0.513191	0.561925	0.604147	0.620382	0.503735
	CMS	0.52915	0.532508	0.551593	0.579823	0.576912	0.534585
	Combinatorial UDM	0.6964	0.6658	0.6515	0.6599	0.6192	0.5637
	Separative UDM	0.487625	0.513186	0.556399	0.576198	0.60491	0.50588
σ	Combinatorial ASCE	0.980698	1.103367	1.157842	1.209592	1.118799	0.936966
	Separative ASCE	0.623626	0.66425	0.759885	0.884929	1.188992	0.663252
	CMS	0.805176	0.795466	0.865939	0.973753	1.034004	0.738307
	Combinatorial UDM	0.7182	0.7936	0.8537	0.8626	0.8263	0.6815
	Separative UDM	0.575085	0.677172	0.846612	0.806236	0.783091	0.516186
D.A	Combinatorial ASCE	0.1744	0.1524	0.1959	0.2131	0.2545	0.3209
	Separative ASCE	0.0213	0.0024	0.0007	0.008	0.0171	0.0909
	CMS	0.3342	0.3113	0.3638	0.4366	0.4288	0.4064
	Combinatorial UDM	0.1984	0.1858	0.2759	0.3472	0.4503	0.6096
	Separative UDM	0.3316	0.2755	0.2831	0.3105	0.25	0.2086
P.A	Combinatorial ASCE	0.698372	0.701612	0.749281	0.767174	0.683147	0.540955
	Separative ASCE	0.602578	0.630746	0.721779	0.745358	0.771463	0.596023
	CMS	0.754043	0.70824	0.714906	0.742751	0.679246	0.579779
	Combinatorial UDM	0.5578	0.6675	0.733	0.7607	0.7261	0.6221
	Separative UDM	0.503402	0.633369	0.705311	0.678121	0.660438	0.40581

Table 12. Values of the scatter criteria for the story shears of the 6-story building.

	Modification Method	First Floor	Second Floor	Third Floor	Forth Floor	Fifth Floor	Sixth Floor
C.O.V	Combinatorial ASCE	0.538735	0.52724	0.526377	0.545919	0.524812	0.49441
	Separative ASCE	0.393164	0.39016	0.39999	0.438382	0.369045	0.337496
	CMS	0.497801	0.493615	0.493981	0.519207	0.488658	0.446816
	Combinatorial UDM	0.4459	0.4542	0.4519	0.4776	0.4471	0.4076
	Separative UDM	0.390277	0.376329	0.388884	0.42969	0.367769	0.336813
σ	Combinatorial ASCE	2.296341	2.318801	2.370688	2.375986	2.346035	2.324231
	Separative ASCE	0.554692	0.52551	0.588407	0.669678	0.504191	0.450773
	CMS	0.767964	0.748719	0.773875	0.845508	0.689432	0.593078
	Combinatorial UDM	0.5571	0.5971	0.6229	0.6417	0.6029	0.5024
	Separative UDM	0.525775	0.489098	0.545186	0.628414	0.461579	0.431824
D.A	Combinatorial ASCE	0.1264	0.1032	0.1221	0.1304	0.1673	0.2173
	Separative ASCE	0.036	0.0299	0.0621	0.058	0.0541	0.0193
	CMS	0.2323	0.2078	0.2483	0.2571	0.2748	0.3397
	Combinatorial UDM	0.1177	0.0996	0.1025	0.1163	0.144	0.264
	Separative UDM	0.205	0.1814	0.2059	0.2132	0.244	0.2737
P.A	Combinatorial ASCE	0.572452	0.574459	0.551231	0.559857	0.494627	0.420645
	Separative ASCE	0.388892	0.422795	0.407491	0.471408	0.356948	0.340845
	CMS	0.672693	0.659911	0.623311	0.618937	0.59797	0.519346
	Combinatorial UDM	0.4199	0.4689	0.5046	0.5212	0.5021	0.4133
	Separative UDM	0.40731	0.408246	0.414442	0.420074	0.322607	0.253252

Table 13. Values of the scatter criteria for the story drifts of the 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	0.461514	0.489759	0.57587	0.679395	0.845642	0.90208	0.697525	0.546229
	Separative ASCE	0.440211	0.48109	0.533038	0.632982	0.780646	0.772092	0.7402	0.537356
	CMS	0.467588	0.460703	0.509124	0.608928	0.743627	0.796406	0.615334	0.525

	Combinatorial UDM	0.5028	0.5226	0.569	0.6227	0.6651	0.6576	0.5669	0.5073
	Separative UDM	0.43583	0.424166	0.508739	0.553504	0.745538	0.700855	0.671093	0.494002
σ	Combinatorial ASCE	0.597466	0.569739	0.655205	0.679282	0.800794	1.117425	0.843998	0.684791
	Separative ASCE	0.529796	0.592569	0.630459	0.690221	0.755334	1.02047	0.913271	0.687278
	CMS	0.7030	0.618258	0.62515	0.728597	0.804566	1.207689	0.87039	0.630959
	Combinatorial UDM	0.6588	0.6301	0.6805	0.6799	0.7448	0.7502	0.698	0.6394
	Separative UDM	0.466058	0.45622	0.528429	0.546639	0.739564	0.907548	0.773562	0.612378
D.A	Combinatorial ASCE	0.0535	0.0639	0.0866	0.1191	0.1385	0.1939	0.1321	0.1905
	Separative ASCE	0.0802	0.0768	0.0592	0.0277	0.0093	0.0046	0.0582	0.0556
	CMS	0.2984	0.3128	0.3439	0.3666	0.4215	0.4435	0.3812	0.4259
	Combinatorial UDM	0.0802	0.1364	0.1878	0.3003	0.4696	0.5232	0.536	0.7116
	Separative UDM	0.1915	0.1634	0.1835	0.1577	0.0811	0.1188	0.0355	0.0397
P.A	Combinatorial ASCE	0.47744	0.536262	0.598526	0.680203	0.792345	1.168216	0.891989	0.676893
	Separative ASCE	0.456673	0.501774	0.583981	0.736295	0.750769	0.869448	0.976574	0.695415
	CMS	0.455814	0.496297	0.58447	0.658595	0.783795	1.339049	0.81926	0.619686
	Combinatorial UDM	0.5075	0.5373	0.6328	0.6742	0.7636	0.7128	0.5986	0.5375
	Separative UDM	0.316093	0.34857	0.454	0.603938	0.706468	0.777229	0.803832	0.540002

Table 14. Values of the scatter criteria for the story shears of the 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	0.427098	0.409377	0.411905	0.416168	0.454318	0.417825	0.369682	0.371992
	Separative ASCE	0.40202	0.380152	0.372644	0.376594	0.412631	0.383659	0.341572	0.352889
	CMS	0.44986	0.437948	0.448575	0.455426	0.481624	0.447081	0.479152	0.404917
	Combinatorial UDM	0.4137	0.4033	0.4009	0.3972	0.4164	0.3969	0.353	0.3432
	Separative UDM	0.360782	0.33985	0.312243	0.296203	0.339089	0.307936	0.25358	0.292742
σ	Combinatorial ASCE	0.562506	0.522251	0.520006	0.504656	0.585017	0.52093	0.463529	0.461297
	Separative ASCE	0.525603	0.483302	0.476906	0.461749	0.543287	0.474621	0.421367	0.43108
	CMS	0.634713	0.60122	0.607704	0.601295	0.673129	0.61028	2.636125	0.538796
	Combinatorial UDM	0.5445	0.5385	0.5387	0.4858	0.5256	0.4949	0.4338	0.4222
	Separative UDM	0.414731	0.377065	0.354535	0.326176	0.39789	0.35098	0.289205	0.315209
D.A	Combinatorial ASCE	0.0382	0.044	0.0516	0.0473	0.0565	0.0416	0.0385	0.0579
	Separative ASCE	0.0737	0.0671	0.059	0.062	0.0651	0.0487	0.0499	0.0515
	CMS	0.2561	0.2562	0.2489	0.237	0.2571	0.227	0.2244	0.2588
	Combinatorial UDM	0.0591	0.0706	0.08	0.0673	0.0894	0.0875	0.0873	0.1382
	Separative UDM	0.1615	0.1625	0.1615	0.1551	0.1591	0.1325	0.1256	0.1271
P.A	Combinatorial ASCE	0.424061	0.426346	0.432398	0.434967	0.514842	0.427234	0.37172	0.392092
	Separative ASCE	0.404702	0.385954	0.391191	0.40919	0.4845	0.405482	0.35340	0.379276
	CMS	0.445517	0.467563	0.502324	0.51969	0.562232	0.476205	0.42888	0.429316
	Combinatorial UDM	0.4081	0.3947	0.4128	0.4128	0.4635	0.4244	0.3285	0.3567
	Separative UDM	0.289738	0.25676	0.268288	0.309272	0.37344	0.314865	0.23532	0.308514

Table 15. Values of the scatter criteria for the story drifts of the 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	0.48412	0.45867	0.46839	0.51289	0.64377	0.73156	0.78979	0.72069	0.67645	0.44887
	Separative ASCE	0.51318	0.4712	0.4731	0.4896	0.6435	0.7109	0.71463	0.70858	0.6177	0.36324
	CMS	0.48198	0.49701	0.49078	0.48269	0.59582	0.65524	0.66443	0.66601	0.66269	0.56673
	Combinatorial UDM	0.5071	0.5091	0.5054	0.5019	0.5936	0.6295	0.6164	0.5834	0.5018	0.4309
	Separative UDM	0.39834	0.39491	0.43548	0.47483	0.64216	0.73398	0.81331	0.77413	0.59685	0.47835
σ	Combinatorial ASCE	0.74549	0.72481	0.85469	0.84046	0.91982	0.94079	0.95414	1.08652	1.24822	0.51114
	Separative ASCE	0.79358	0.7194	0.9017	0.7952	0.9486	0.9189	0.95872	1.01377	0.79083	0.50944
	CMS	0.71002	0.87934	0.91196	0.7993	0.94939	0.88554	1.03844	1.06066	1.04867	0.83939
	Combinatorial UDM	0.6463	0.6578	0.7226	0.7529	0.7984	0.8234	0.8134	0.7676	0.6898	0.6087
	Separative UDM	0.60251	0.59528	0.76486	0.69633	0.83955	0.87527	0.90118	0.96022	0.78236	0.60869

D.A	Combinatorial ASCE	0.0214	0.0008	0.0036	0.0141	0.0286	0.0582	0.09	0.1047	0.1223	0.1259
	Separative ASCE	0.1621	0.1683	0.172	0.1519	0.0735	0.0471	0.0209	0.0117	0.0596	0.0676
	CMS	0.1972	0.2116	0.2509	0.2827	0.2678	0.3186	0.331	0.3147	0.2672	0.2541
	Combinatorial UDM	0.0596	0.0727	0.0466	0.0106	0.1173	0.1856	0.2968	0.405	0.4538	0.5501
	Separative UDM	0.1162	0.1152	0.1219	0.1343	0.1056	0.144	0.1034	0.0262	0.0047	0.1026
P.A	Combinatorial ASCE	0.36357	0.39372	0.46658	0.62261	0.71993	0.88669	0.85411	1.09518	0.96743	0.40573
	Separative ASCE	0.499	0.4926	0.4742	0.5392	0.748	0.909	0.86152	0.93742	0.66953	0.23113
	CMS	0.36276	0.41694	0.48704	0.50739	0.69827	0.8673	0.74057	1.0286	1.04293	0.72888
	Combinatorial UDM	0.4736	0.4691	0.5232	0.5556	0.634	0.7005	0.7018	0.6389	0.5263	0.4076
	Separative UDM	0.31555	0.36084	0.39667	0.8445	0.76	0.92878	0.8445	1.04997	0.69361	0.31555

Table 16. Values of the scatter criteria for the story shears of the 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	0.4022	0.39506	0.39886	0.41115	0.4222	0.41515	0.41915	0.39808	0.36038	0.37411
	Separative ASCE	0.41475	0.3992	0.40107	0.40908	0.41735	0.40661	0.40935	0.39479	0.34774	0.41019
	CMS	0.43464	0.42852	0.42814	0.43258	0.4383	0.42826	0.43764	0.42132	0.41886	0.43853
	Combinatorial UDM	0.33143	0.32844	0.33694	0.35505	0.36	0.35924	0.36524	0.3335	0.28233	0.30765
	Separative UDM	0.537	0.3991	0.401	0.4045	0.414	0.4091	0.4121	0.4158	0.3754	0.392
σ	Combinatorial ASCE	0.63412	0.63922	0.67662	0.67182	0.631	0.62758	0.66716	0.59954	0.52113	0.49474
	Separative ASCE	0.61957	0.61688	0.65319	0.64438	0.599	0.59466	0.63313	0.56184	0.48004	0.48375
	CMS	0.72282	0.73455	0.76995	0.76043	0.7164	0.71192	0.74955	0.68544	0.62248	0.57848
	Combinatorial UDM	0.49337	0.48998	0.52607	0.52295	0.48362	0.48202	0.5301	0.46652	0.38615	0.3634
	Separative UDM	0.9284	0.5666	0.5924	0.63	0.6018	0.5797	0.588	0.5847	0.5385	0.5695
D.A	Combinatorial ASCE	0.0083	0.0013	0.002	0.0007	0.0014	0.0004	0.0011	0.0012	0.0126	0.0349
	Separative ASCE	0.1116	0.0918	0.0947	0.0859	0.074	0.075	0.0707	0.0529	0.0324	0.0466
	CMS	0.1335	0.1286	0.1327	0.1419	0.1464	0.1472	0.148	0.1368	0.1383	0.2037
	Combinatorial UDM	0.1082	0.0738	0.0745	0.0752	0.0915	0.0957	0.0922	0.0927	0.093	0.0669
	Separative UDM	0.0946	0.0383	0.0385	0.0185	0.0176	0.0239	0.0138	0.0076	0.0256	0.1251
P.A	Combinatorial ASCE	0.3316	0.307	0.32141	0.36274	0.43807	0.43746	0.40123	0.33634	0.2933	0.31982
	Separative ASCE	0.36961	0.35909	0.34693	0.37113	0.42979	0.43478	0.37249	0.29186	0.30433	0.3388
	CMS	0.34708	0.34331	0.36653	0.38667	0.44572	0.42133	0.42576	0.35895	0.37686	0.3897
	Combinatorial UDM	0.25494	0.24594	0.24082	0.29248	0.34882	0.33819	0.30466	0.25751	0.21634	0.2195
	Separative UDM	0.7131	0.3764	0.3821	0.3891	0.4129	0.48108	0.4346	0.3853	0.3408	0.381

Table 17. Percentages of each scaling method with the lowest scatter in maximum responses between earthquakes for the 6-story building.

Method	C.O.V.	σ	D.A.	P.A.
Combinatorial ASCE	0	0	0	0
Separative ASCE	16.67	16.67	100	25
CMS	16.67	0	0	0
Combinatorial UDM	0	0	0	0
Separative UDM	66.66	83.33	0	75

Table 18. Percentages of each scaling method with the lowest scatter in maximum responses between earthquakes for the 8-story building.

Method	C.O.V.	σ	D.A.	P.A.
Combinatorial ASCE	0	0	62.50	0
Separative ASCE	0	0	25	0
CMS	0	0	0	0
Combinatorial UDM	18.75	12.50	0	18.75
Separative UDM	81.25	87.50	12.50	81.25

Table 19. Percentages of each scaling method with the lowest scatter in maximum responses between earthquakes for the 10-story building.

Method	C.O.V.	σ	D.A.	P.A.
Combinatorial ASCE	0	0	70	0
Separative ASCE	5	0	20	0
CMS	0	0	0	5
Combinatorial UDM	75	80	5	75
Separative UDM	20	20	5	20

CONCLUSIONS

In this study first a three-stage screening process was presented for selection of consistent earthquake records. The stages were called the loose, intermediate and tight screens, in which general characteristics of ground motions, their spectral intensities and the similarity of their response spectra to the conditional mean spectrum were utilized as the main tools, respectively.

Then the existing scaling methods of the records were evaluated and a more effective method was presented for the same purpose. Through a vast numerical study, it was shown that the proposed scaling method resulted in the least scatter in nonlinear structural responses.

REFERENCES

Pacific Earthquake Engineering Research Center (PEER). 2013. Evaluation of Ground Motion Selection and Modification Methods: Predicting Median Interstory Drift Response of Buildings.

Housner, George W. Intensity of ground motion during strong earthquakes. *Office of Naval Research Report*. pp. 1-60, August 1952. http://resolver.caltech.edu/CaltechEERL:1952.EERL.1952.001 .

Baker, J. W. 2011. "Conditional Mean Spectrum: A tool for ground motion selection."*Journal of Structural Engineering*, 137(3), 322-331.

ASCE Standard ASCE/SEI 7-10.2010. Minimum design loads for buildings and other structures. *ISBN* 978-0-7844-1085-1.

Effect of Ground Motion Selection and Scaling on Engineering Demand Parameter Dispersion. *NIST GCR* 10-917-9.