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RESEARCH ARTICLE

Ground Motion Selection and Scaling in Practice

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Abstract

This paper provides and evaluates a very simple and practical procedure for selecting ground motions in addition to compare two common scaling methods based on the uniform hazard spectrum (UHS) method and presents scale factors of the selected ground motions associated with these methods. Evaluation of the proposed approach of record selection demonstrates the efficiency of the proposed method. It also presents proper method of scaling for each soil condition and engineering demand parameter and the obtained scale factors could be utilized directly from this paper in the other studies in this field without any excessive calculational attempts.

Keywords

Record Selection · Record Scaling · Uniform Hazard Spectrum · Efficiency · Soil Condition

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1 Introduction

Seismic provisions in current building codes and standards include rules for design of structures using nonlinear response history analysis in some conditions. Due to the lack of recorded data for the design level earthquakes (which are usually rare events), it is critical to develop systematic methods and useful tools to select and modify from current ground motion databases to provide a group of earthquake motions that can realistically represent important aspects of the design motion controlling the nonlinear response of civil engineering facilities [1]. The best method for selecting and scaling ground motions will depend on the type of assessment being performed. ATC-58-1 identifies three types of performance assessment: intensity, scenario, and time-based. Intensity-based assessments are the most common of the three types and compute the response of a building and its components for a specified intensity of ground shaking (this approach is the focus of this paper). A scenario-based assessment computes the response of a building to a user specified earthquake event, which is typically defined by earthquake magnitude and the distance between the earthquake source and the building site. A risk-based (referred to as time-based assessment in ATC-58-1) assessment provides information on response over a period of time (e.g., annual rates). This is the most comprehensive type of assessment and involves a number of intensity-based assessments over the range of ground motion levels of interest [2]. Despite the scenario-based assessment which computes the response of a building based on a specific earthquake event, intensity and time-based assessments have been conducted subjecting to a group of records. Time-based assessment acquires information of all occurred earthquakes which have been utilized to adjust hazard curve of the assessed region; so, as much as records could be provided, the confidence level will promote, so many researchers attempts to enlarge records category to reduce record-by-record variations incorporated in this type of assessment. However, intensity-based assessment deal with number of records represented by intensity measures (IM), like peak ground acceleration, spectral acceleration on fundamental period of the model or etc., which are scaled associated to the intensity assumed target spectrum. Therefore, although enlargement in the number of incorporated records can reduce record-by-record variations, the scaling factors associated to the other records should be adjusted to the selected ground motions entirely that will cause some growing trend in deviations of structural responses [3]. To reply this requirement, some methods of ground motion selection have been recommended by researchers like random selection or selecting based on some spectral magnitudes which are going to be discussed further in this paper. On the other hand, if ground motions scaling factors are adjusted based on the large selected number of records, nonlinear time history analysis of the model is going to be computationally too expensive and time-consuming; as all the records incorporated in scaling procedure should be included in analysis too. Additionally, this intense computational expenses occurred in the place of very little upturn in confidence level. Unfortunately, there is currently no consensus in the earthquake engineering community on how to appropriately select and scale earthquake ground motions for code-based design and seismic performance assessment of buildings using nonlinear response history analysis [4]. Despite the current practices of record selection according to a specific magnitude-distance scenario and scaling to a common level, neither aspect of this process has received significant research attention to ascertain the benefits or effects of these practices on the conclusions [5]. In addition to the notification of the type of analysis, the analyst must have a clear understanding of the goals of analyzing before choosing procedures to select and scale ground motions [4]. Nonlinear response-history analysis is performed for a number of reasons, including: (1) designing new buildings with non-conforming lateral force resisting systems; (2) designing new buildings equipped with seismic isolators or energy dissipation devices; (3) designing seismic upgrades of existing buildings per ASCE/SEI 41-06; and (4) assessing performance of new or existing buildings per ATC-58-1 [2]. Also, The appropriate method for selecting and scaling ground motions will depend on the structural response parameter(s) of interest, whether record-by-record variability in structural response is to be predicted (in addition to mean response), and whether maximum responses or collapse responses are to be predicted [4]. ATC-58-1, one of very common standards in building performance evaluation, recommends two methods for record scaling. The first is the uniform hazard spectrum (UHS) and the second is the conditional mean spectrum (CMS) which encounters some limitations in application. Although many researchers confirmed efficiency of CMS in comparison with the UHS method, it could not be considered as a general method [2, 6–8]. This study addresses the question of selecting and amplitude scaling of accelerograms for predicting nonlinear seismic response of structures that supports either design or performance assessment. It provides a very simple and practical procedure for choosing ground motions in addition to compare two methods of scaling based on the UHS method, and presents scale factors for the selected ground motion in view of these two methods considering different types of soil. The scale factors and the selected records could be directly utilized from this paper in the other studies in this field without any excessive calculational attempts.

2 Ground motion selection

The selection and scaling of earthquake ground motions have a key role in seismic load definition that will be applied to a structure during structural analysis, and serves as the interface between seismology and engineering [9]. Ground motions must be either selected from previous recorded earthquake events or supplemented by physics-based simulations where there is a lack of appropriate recordings, such as large magnitude earthquakes at short site-to-source distances [5].

For assessing the frequently used methods of selecting and scaling, it is better to provide a brief explanation about the parameter of ε. Magnitude and distance are familiar quantities to any earthquake engineer, but understanding of the ε parameter may be less common. Epsilon is defined by engineering seismologists studying ground motion as the number of standard deviations by which an observed logarithmic spectral acceleration differs from the mean logarithmic spectral acceleration of a ground-motion prediction (attenuation) equation. Epsilon is computed by subtracting the mean predicted $\ln \mathrm{Sa}(T_1)$ from the record's $\ln \mathrm{Sa}(T_1)$, and dividing by the logarithmic standard deviation (as estimated by the prediction equation). Epsilon is defined with respect to the unscaled record and will not change in value when the record is scaled [10].

Researchers recommend four methods for selecting records in primarily list as follow [9]:

1 Select records at random from a record library, without attempting to match any specific record properties. This will be abbreviated as the 'AR Method,' as it uses Arbitrary Records. The importance of capturing the variability in seismic analysis is reflected in the recent ATC-58-1 guideline [6], which recommended randomly gathering eleven ground motions from the chosen magnitude and distance bin and then scaling them to match the targeted spectrum value at the fundamental period of the structure. However, the randomness nature in the selection procedure makes it difficult to represent the true variability of ground motions [1].

2 Select records with magnitude and distance values representative of the site hazard, without attempting to match the ε values. This will be abbreviated as the 'MR-BR Method,' as it uses M, R-Based Records.
Besides the spectral shape, the ground-motion characteristics important to the seismic response of the facility may also include the significant duration, number of strong shaking cycles, near-field directivity effects and pulse sequencing etc. It is necessary to specify the ranges of parameters over which searches are to be conducted and other limits and restrictions on the searches [1].

3 Select records with ε values representative of the site hazard, without attempting to match the magnitude and distance values. This will be abbreviated as the 'ε-BR Method,' as it uses ε-Based Records.

4 Select records with spectral shapes that match the target spectrum, usually defined by the method of conditional mean, but make no further attempt to directly match the target M, R or ε values. This will be abbreviated as the 'CMS-ε Method,' as it uses the Conditional Mean Spectrum, considering ε.

Preliminary results from COSMOS 2007 workshop concluded that for a first-mode dominated structure, such as tall buildings, time histories that closely match target spectrum conditioned on the period of the first mode of the structure can yield good estimate of the median response of EDPs (eg. Maximum inter-story drift ratio) for that scenario [11].

For distant sites (not near-field), the most important factor in selecting ground motions for scaling to a target spectrum is spectral shape over the period range of interest (currently $0.2\,T_1$ to $1.5\,T_1$ in ASCE/SEI 7-10, where T_1 is the first mode translational period). Selecting pairs of motions whose spectral shapes are similar to the target spectrum minimizes the need for scaling and modification. In addition, selecting records based on their spectral shape and design spectral acceleration increases the accuracy and efficiency of the procedure [12].

For near-field sites, another significant factor in selecting ground motions for scaling to a target spectrum is the possible presence of velocity pulses. Velocity pulses are present in many near-fault ground motion recordings, especially in the forward directivity region. A relationship is proposed for estimating the appropriate number of pulse motions in a suite of design motions in Appendix C of the report of NIST/GCR 11-917-15 [13]. Disaggregation of the seismic hazard curve will identify the combinations of earthquake magnitude, site-to-source distance, and ε that dominate the hazard around the period of the building; this can aid the selection of pulse periods and thus seed ground motions for later scaling.

Regarding the number of ground motions, typical practice in structural design is to use seven motions according to ASCE05-7 and eleven ground motions according to ATC, but the appropriate number of motions is still a topic of needed research. According to the ASCE/SEI-7 [14], if at least seven ground motions are analyzed, the design values of engineering demand parameters (EDPs) are taken as the average of the EDPs determined from the analyses. If fewer than seven ground motions are analyzed, the design values of EDPs are taken as the maximum values of the EDPs. It is demonstrated that the ASCE/SEI-7 scaling procedure is conservative if less than seven ground motions are employed. Current ground motion selection and modification (GMSM) efforts are mainly focused on predicting the median response of the engineering demand parameters (EDP) under a prescribed seismic demand. Since there are no experimental validation studies available up to date, the effectiveness of these methods can only be assessed using numerical simulations [15]. Pointing out that the ground motions may exhibit significant variability in frequency content and amplitude, small dispersion (variability) of EDPs is desired as it provides an acceptable confidence level.

2.1 Proposed approach of record selection (step-by step)

Considering all the advantages of selecting ground motion based on their spectral characteristics that have been discussed earlier, this selection procedure causes some bias in scaling procedure and the gained scaling factors. This scaling bias is more intense if intensity measure is dependent to spectral characteristics of the building (For example spectral acceleration) [9]. In addition, this procedure of selection requires assuming a predictive model prior to conducting record selection; consequently scaling records by means of this method results in dependency of scaling factors to the model specifications as it is necessary to know the response spectrum associated with ground motions having the target ground motion intensity; Therefore, for a new model the amounts of scaling factors should be modified in a try-and-error procedure. However, the well-known Uniform Hazard Spectrum (UHS) is unappealing for this application, as it is an envelope of spectral values associated with multiple ground motions, rather than a description of a single ground motion. Problems with treating the UHS as the spectrum of a single ground motion have been also noted by some other researchers [16–18].

To overcome the mentioned problems noted above there is two strategies; the first strategy is to modifying target spectrum which results in Conditional Mean Spectrum (CMS) that was initially proposed with an emphasis on the mean spectrum and less attention was paid to the variability in the spectrum and considers variability is termed the "Scenario Spectrum" or "Conditional Spectrum" (CS). Another recent extension of the approach has been to consider conditional values of any ground motion properties (e.g., duration), rather than just response spectral values [7, 8]. To address the mentioned problem with the Uniform Hazard Spectrum, the Conditional Mean Spectrum instead conditions the spectrum calculation on spectral acceleration at a single period, and then computes the mean (or distribution of) spectral acceleration values at all other periods. This conditional calculation ensures that the resulting spectrum is reasonably likely to occur, and that ground motions selected to match the spectrum have appropriate properties of naturally occurring ground motions for the site of interest.

The second strategy is random selection of records that is utilized as the main approach for record selection up to now.

The procedure proposed in this paper employ random selection by consideration of minimizing deviations around the geometric mean of natural logarithmic spectral acceleration values to reduce the effect of record-by-record variations in structural responses. The efficiency of this method is going to be revealed by comparison of standard deviations of engineering demand parameters (EDP) subjected to the selected records by the proposed approach of this study and some arbitrary choose of records.

This is fine to mention, it could not be claimed that the group of records selected by the proposed method of this paper is the most efficient one, but we could illustrate that employing this technique for record selection could apparently reduce the deviation of structural responses in comparison to one merely randomly selected.

2.1.1 Step 1: Determining primarily list of records

For ground motion selection, a primarily list of records is required which the records are going to be selected from it. The number of records incorporated in the primarily list and their characteristics depend on the purpose of assessment in addition to the hazard analysis of the site and records characteristics like the fault mechanism, its frequency, maximum amount of its acceleration, distance between the site and the faults and some other seismological factors. Many researchers prefer to randomly set records in primarily list and some other recommends choosing records as a list comprises records with all groups of specification according to their hazard possibilities. How to choose primarily list of records and any advantages and disadvantages of each method is beyond the focus of this study.

In this paper, one of very frequently developed primarily list of records has been utilized. The records of this list have been carefully selected by Medina and Krawinkler from the Pacific Earthquake Engineering Research (PEER) center strong motion database and it has been employed in many previous researches in PEER and SAC centers and could be used for many studies in this field too. Recorded motions are derived from a bin of recorded motions from databases of PEER NGA database [19], COSMOS [20] or K-NET [21]. It is fine to mention that any arbitrary list of records could be substituted and the record selection procedure proposed in this paper does not have any partiality to the list.

The proposed primarily list of records by Medina and Krawinkler contains 79 earthquake ground motions recorded in various earthquakes in California. All ground motions were recorded on free-field sites that can be classified as site class D according to NEHRP seismic provision [22]. Most of the design codes like ASCE05-7 and seismic performance provisions like ATC-58-1 allow using this class of soil when the specification of the soil has not been studied; so, this list could be used when the site class has not been determined too. For the sites with the other types of soil, modifications in target spectrum should be done that have been also performed in this study and corresponding scale factors gained according to the site specifications were presented. The earthquake magnitude in the list ranges in magnitude from 5.8 to 6.9 with the closest distance to rupture ranging from 13 km to 60 km.

2.1.2 Step 2: Choosing a representative record for each earthquake event

The primarily list consists of twelve different earthquake events in different stations and since the frequency content and other seismological characteristics of each earthquake differ with the other ones, it is prefer to choose one ground motion for each of the earthquake event; subsequently by this technique, twelve ground motions in two directions were acquired. The procedure proposed in this paper for selecting appropriate station for each group of earthquake events is choosing the station with the least standard deviation in natural logarithmic of the spectral acceleration values as a represent for the group to minimize record-by-record variations. The selected records for each of the ground motion set are presented in Table 1. By this proposed technique, records would be selected for analyzing the structure which could conclude little deviation in EDP results as they have the least distance from the mean values of the spectral acceleration values point by point.

2.1.3 Step 3: Selecting minimum number of records

As nonlinear dynamic analyzing is too time consuming, one tries to decrease the number of records as it is possible. A suite of 11 pairs of ground motions is the minimum recommended by the ATC-58-1 as well as it is going to be served in this study. Such a suite will provide a 75% confidence that the predicted median response from will be with ±20% of the true median value of response given the spectrum (for an assumed dispersion of 0.5). Better estimates of the median response can be achieved by using larger suites of motions [2]. Since we have twelve records in two directions, one of the records has been omitted from the secondary list. For this purpose, records' natural logarithmic standard deviations were calculated and the record with the maximum amount of standard deviation has been omitted. Table 2 demonstrates the amounts of logarithmic standard deviation for each of the selected twelve records; as it is illustrated in this table the record of Livermore station has the maximum value of standard deviation and should be omitted from the list.

Also, if elastic spectral diagrams of the records were plotted against the values of structural period, one could reach to the diagrams of Fig. 1 that presents not locating Livermore record in the domain of 2.5% up to 97.5% of the record's mean value in most of the period domain. By all the above assessments record of Livermore station has been chosen to be omitted from the selected list of records. Eleven records are available in this stage providing a somewhat different prediction of the response quantities used to assess building performance and were displayed in Table 3. The intent is to obtain an unbiased estimate of the structural response, given the target spectrum, with limited error.

3 Scaling ground motions

Current performance-based design and evaluation methodologies prefer intensity-based methods to scale ground motions over spectral matching techniques that modify the frequency

Tab. 1. Twelve selected records

Number	Record ID	Event	Year	Station	Mw	R (km)	Mech	PGA (g)
1	IV79e13	Imperial Valley	1979	El Centro Array #13	6.53	21.90	Strike-slip	0.139
2	LV80srm	Livermore	1980	San Ramon - Eastman Kodak	5.80	17.60	Strike-slip	0.076
3	MH84g02	Morgan Hill	1984	Gilroy Array #2	6.20	15.10	Strike-slip	0.162
4	PM73phn	Point Mugu	1973	Port Huen-eme	5.80	25.00	Reverse-slip	0.112
5	PS86psa	N.Palm Spring	1986	Palm Springs Airport	6.00	16.60	Strike-slip	0.187
6	WN87wat	Whittier Narrows	1987	Carson - Water St	6.00	24.50	Reverse	0.104
7	SF71pel	San Fer-nando	1971	LA - Hol-lywood Store Lot	6.60	21.20	Reverse-slip	0.174
8	SH87pls	Superstition Hill	1987	Plaster City	6.70	21.00	Strike-slip	0.186
9	BM68elc	Borrego Mountain	1968	El Centro Array #9	6.70	46.00	Strike-slip	0.057
10	LP89slc	Loma Prieta	1989	Palo Alto - SLAC Lab	6.90	36.30	Reverse-oblique	0.194
11	NR94del	Northridge	1994	Lakewood - Del Amo Blvd	6.70	59.30	Reverse-slip	0.137
12	CO83c05	Coalinga	1983	Parkfield - Cholame 5W	6.40	47.30	Reverse-oblique	0.131

content or phasing of the record to match its response spectrum to the target spectrum. In contrast, intensity-based scaling methods preserve the original non-stationary content and only modify its amplitude. The primary objective of intensity-based scaling methods is to provide scale factors for a small number of ground motion records so that nonlinear response history analysis (RHA) of the structure for these scaled records has sufficient reliability. It provides an accurate estimate in the median value of the engineering demand parameters (EDPs), and minimizes the record-to-record variations in the EDP magnitudes.

Scaling ground motions to match a target value of peak ground acceleration (PGA) is the earliest approach to the problem, which produces inaccurate estimates with large dispersion in EDP values [23–26]. Other scalar intensity measures (IMs) such as: effective peak acceleration, Arias intensity and effective peak velocity have also been found to be inaccurate and inefficient [27]. Indeed, spectral shape is a record property that directly affects the structural responses [28].

Including a vibration property of the structure led to improved methods to scale ground motions, e.g., scaling records to a target value of the elastic spectral acceleration, from the code-based design spectrum or (Probabilistic Seismic Hazard Analysis) PSHA-based uniform hazard spectrum at the fundamental vibration period of the structure, T_1, provides improved results for structures whose response is dominated by their first-mode [23]. However, this scaling procedure becomes less accurate and less efficient for structures responding significantly in their higher vibration modes or far into the inelastic range [29–31]. To consider higher mode response, a scalar IM that combines the spectral accelerations at the first two periods T_1 and T_2 and vector IM comprised of T_1 and the ratio of T_1/T_2 have been developed [32, 33]. Although this vector IM improves accuracy, it remains inefficient for near-fault records with a dominant velocity pulse [34].

In addition to different scaling methodologies, International Building Code (IBC) [35] and California Building Code (CBC)

Tab. 2. Record's natural logarithmic standard deviations

Earthquake	σ (Ln(Sa(T)))
Borrego Mountain	11.05
Coalinga	12.38
Imperial Valley	9.51
Livermore	25.96
Loma Prieta	19.57
Morgan Hill	8.64
N.Palm Spring	4.19
Northridge	3.50
Point Mugu	7.30
San Fernando	16.50
Superstition Hill	10.53
Whittier Narrows	9.89

[36] require earthquake scaling according to the ASCE05-7 provisions [14].

Since there are no experimental validation studies available up to date, the effectiveness of these methods can only be assessed using numerical simulations. These simulations require development of realistic computer models. In this respect, structural monitoring plays a key role in providing recorded motions on existing structures which can be used to create their well-calibrated (in terms of modal periods, modal shapes, modal damping etc.) computer models. The good agreement between the computed and recorded displacements indicates that the computer model is adequate for assessing the ASCE05-7 ground motion scaling method [37].

This paper employs two common methods for scaling recorded earthquakes according to different class of soils. The outcomes could be directly used as the scaling ratio in related researches.

The first that has been recommended by the ATC-58-1 and ASCE05-7 is also recommended by many provisions like IBC2006 and CBC2007 for use in nonlinear RHA of structures.

For two-dimensional analysis of symmetric-plan buildings, ASCE05-7 requires intensity-based scaling of ground motion records using appropriate scale factors; so that the average value of the 5 percent-damped response spectra for the set of scaled records is not less than the design response spectrum over the period range from $0.2\,T_1$ to $1.5\,T_1$. The design value of an engineering demand parameter (EDP) is taken as the average value of the EDP over seven (or more) ground motions, or its maximum value over all ground motions, if the system is analyzed for fewer than seven ground motions [14]. The ASCE05-7 scaling procedure does not insure a unique scaling factor for each record; obviously, various combinations of scaling factors can be defined to insure that the average spectrum of scaled records remains above the design spectrum (or amplified spectrum in case of 3-D analyses) over the specified period range. Because it is desirable to scale each record through the smallest possible factor, an algorithm is developed and used in applying the code-scaling procedure which is available at [37, 38].

The ASCE/SEI-7 procedure is found to be conservative as compared to the benchmark responses from hazard compatible unscaled records using a larger catalog of ground motions. It is neither efficient nor consistent if less than seven ground motions are utilized, thus penalizing the analyst for employing less than seven ground motions for nonlinear RHAs [12].

The second method that is very frequently used by designers and also has been applied in ATC-58-1 example section is scaling the ground motion only in the fundamental period of the structure.

Early quantitative investigations into ground motion scaling indicated that a suite of ground motions may be safely scaled to the suite's median spectral acceleration value, at a period T, without biasing the median response of a structure having the same first-mode period T [5, 29]. But recent work suggests that in some other situations record scaling may induce some bias in structural response [39, 40]. This bias appears to result from the scaled ground motions having inappropriate values of spectral shape or the parameter ε, which is an indirect measure of spectral shape [9, 41].

In this paper, the scale factors were provided for a short-rise building with a fundamental period equal to one. After providing scale factors in two methods, the evaluation and comparison of these two methods will be done and considering all the conditions these scaling factors could be employed directly in other studies.

3.1 Definition of Target Spectra for Scaling Ground Motions

Although 5%-damped spectral acceleration, S_a, has several limitations and is not directly related to the nonlinear response of a building, it is broadly utilized in researches as well as this study.

There are three primary types of horizontal spectral acceleration: (1) arbitrary component (Sa_{arb});

(2) Geometric mean ($Sa_{g.m.}$); and (3) maximum direction (Sa_{maxDir}). These three definitions are discussed in the NIST report more comprehensively [13]. Any of these definitions can be used, and the performance prediction will not depend on the choice, but it is imperative that the procedure used to select and scale motions be consistent with the definition used for the target spectrum [10].

There are two common methods for providing target spectrum, uniform hazard spectrum (UHS) and conditional mean spectrum (CMS). This paper utilized UHS method for the purpose of target spectrum definition that is more common rather than CMS method and has been applied in all design and performance codes as the main method of achieving target spectrum.

The Uniform Hazard Spectrum is based on a given hazard level by enveloping the results of seismic hazard analysis (for a given probability of exceedance) for each period. The probability of observing all of those spectral amplitudes in any single ground motion is unknown. Consequently, it will generally be a conservative target spectrum, especially for large and rare

Tab. 3. Eleven selected records

Number	Record ID	Event	Year	Station	Mw	R (km)	Mech	PGA (g)
1	IV79e13	Imperial Valley	1979	El Centro Array #13	6.53	21.90	Strike-slip	0.139
2	MH84g02	Morgan Hill	1984	Gilroy Array #2	6.20	15.10	Strike-slip	0.162
3	PM73phn	Point Mugu	1973	Port Hueneme	5.80	25.00	Reverse-slip	0.112
4	PS86psa	N.Palm Spring	1986	Palm Springs Airport	6.00	16.60	Strike-slip	0.187
5	WN87wat	Whittier Narrows	1987	Carson - Water St	6.00	24.50	Reverse	0.104
6	SF71pel	San Fernando	1971	LA - Hollywood Store Lot	6.60	21.20	Reverse-slip	0.174
7	SH87pls	Superstition Hill	1987	Plaster City	6.70	21.00	Strike-slip	0.186
8	BM68elc	Borrego Mountain	1968	El Centro Array #9	6.70	46.00	Strike-slip	0.057
9	LP89slc	Loma Prieta	1989	Palo Alto - SLAC Lab	6.90	36.30	Reverse-oblique	0.194
10	NR94del	Northridge	1994	Lakewood - Del Amo Blvd	6.70	59.30	Reverse-slip	0.137
11	CO83c05	Coalinga	1983	Parkfield - Cholame 5W	6.40	47.30	Reverse-oblique	0.131

ground motion, unless the structure responds elastically in only its first translational mode. This inherent conservatism comes from the fact that the spectral values at each period are not likely to all occur in a single ground motion. This limitation of the Uniform Hazard Spectrum has been noted in many works e.g. in [16–18].

3.2 Definition of target spectrum for scaling ground motions by uniform hazard method

In this part of study, the target spectrum in two levels of maximum credible earthquake (MCE) and design earthquake (DE) is going to be obtained according to ASCE05-7 procedure. These two levels respectively represent 2% and 10% probability of occurrence of earthquake by the assumed intensity measure in 50 years. The amounts of longitude and latitude of the picked out stations and their spectral amounts for short and long periods (S_s, S_l) and their modification factors (F_a, F_v) according to ASCE05-7 have been obtained and displayed in Table 4. Through calculating geomean between the maximum credible earthquake spectrums for each station, the target maximum spectrum will be achieved and also according to ASCE05-7, 10% Probability of occurrence target spectrum could be simply got through applying target maximum spectrum values by the factor of 0.667.

3.3 Scaling ground motions

This paper employs two common methods for record scaling based on the uniform hazard spectra (UHS) for a short-rise building by the typical period equal to one located in diverse classes of soil.

The first method, recommended by the ATC-58-1 and ASCE05-7 in company with the many other provisions like IBC2006 and CBC2007 for use in nonlinear RHA of structures, suggest to scale record so that the average value of the 5 percent-damped response spectra for the record is not less than the target design spectrum over the period range from 0.2 T_1 to 1.5 T_1. This method is going to be called in this study "provision method".

The second method that is very frequently used by designers and also has been applied in ATC-58-1 example section is scaling the ground motion only in the fundamental period of the structure which is going to be called in this study "design method".

The obtained scale factors for different types of soil according to the two methods have been present in Tables 5 to 12. Also, the scaled response spectrum of each record according to target design spectrum has been exhibited for soil type D in Figs. 2 and 3.

4 Evaluation of the proposed method for record selection

For evaluating the proposed method in record selection, structural responses of a generic model under three sets of randomly selected records in addition to the records selected due to the proposed method were considered and presented in Table 13. Then the records have been scaled based on the design method of scaling regarding a certain target spectrum for all of the four sets of records which has been mentioned previously in Fig. 2.

Tab. 4. Langitude and latitude of the selected stations and their spectral amounts for short and long periods (S_s , S_l) and their modification factors (F_a , F_v) according to ASCE05-7

Earthquake	Station	Latitude	Longitude	S_s g	S_l g	Fa	F_v	S_{as}	S_{al}	T_S (s)
				According to ASCE05-7						
Borrego Mountain	El Centro Array #9 - 1968	32.795	-115.550	1.500	0.600	1	1.5	1.50	0.90	0.60
Coalinga	Park field-Cholame-1983	36.138	-120.363	1.500	0.557	1	1.5	1.50	0.84	0.56
Imperial Valley	El Centro Array #13 - 1979	32.709	-115.683	1.406	0.554	1	1.5	1.41	0.83	0.59
Livermore	San Ramon - Eastman Kodak-1980	37.780	-121.980	1.998	0.751	1	1.5	2.00	1.13	0.56
Loma Prieta	Palo Alto - SLAC Lab- 1989	37.419	-122.205	2.427	1.006	1	1.5	2.43	1.51	0.62
Morgan Hill	Gilroy Array #2 -1984	36.980	-121.556	1.500	0.700	1	1.5	1.50	1.05	0.70
N.Palm Spring	Palm Springs Airport - 1986	33.925	-116.548	2.085	1.001	1	1.5	2.09	1.50	0.72
Northridge	Lakewood - Del Amo Blvd - 1994	34.229	-118.528	1.848	0.669	1	1.5	1.85	1.00	0.54
Point Mugu	Port Hueneme - 1973	34.110	-119.056	2.131	0.877	1	1.5	2.13	1.32	0.62
San Fernando	LA - Hollywood Store Lot - 1971	34.058	-118.301	2.054	0.696	1	1.5	2.05	1.04	0.51
Superstition Hill	Plaster City - 1987	32.793	-115.858	1.500	0.600	1	1.5	1.50	0.90	0.60
Whittier Narrows	Carson - Water St -1987	34.033	-118.068	2.035	0.708	1	1.5	2.04	1.06	0.52

Tab. 5. Scale factors for soil type D according to the "Design Method" for a building by T = 1.0 (s)

Scale factor for 10% probability of occurrence in 50 years (Design) level	Scale factor for 2% probability of occurrence in 50 years (Maximum Credible Earthquake) level	Earthquake
4.66	6.98	Borrego Mountain
6.83	10.24	Coalinga
6.43	9.64	Imperial Valley
1.41	2.11	Loma Prieta
8.00	12.00	Morgan Hill
4.37	6.55	N.Palm Spring
5.91	8.86	Northridge
4.60	6.89	Point Mugu
3.59	5.38	San Fernando
5.02	7.53	Superstition Hill
5.03	7.55	Whittier Narrows

Tab. 6. Scale factors for soil type D according to the "Provision Method" for a building by T = 1.0 (s)

Scale factor for 10% probability of occurrence in 50 years (Design) level	Scale factor for 2% probability of occurrence in 50 years (Maximum Credible Earthquake) level	Earthquake
5.25	7.87	Borrego Mountain
4.26	6.40	Coalinga
5.91	8.87	Imperial Valley
2.00	3.00	Loma Prieta
6.45	9.68	Morgan Hill
4.89	7.34	N.Palm Spring
5.13	7.70	Northridge
5.52	8.28	Point Mugu
3.60	5.40	San Fernando
3.32	5.00	Superstition Hill
4.93	7.40	Whittier Narrows

Tab. 7. Scale factors for soil type C according to the "Design Method" for a building by T = 1.0 (s)

Scale factor for 10% probability of occurrence in 50 years (Design) level	Scale factor for 2% probability of occurrence in 50 years (Maximum Credible Earthquake) level	Earthquake
4.03	6.05	Borrego Mountain
5.92	8.88	Coalinga
5.57	8.36	Imperial Valley
1.22	1.83	Loma Prieta
6.93	10.40	Morgan Hill
3.78	5.68	N.Palm Spring
5.12	7.68	Northridge
3.98	5.97	Point Mugu
3.11	4.66	San Fernando
4.35	6.53	Superstition Hill
4.36	6.54	Whittier Narrows

Tab. 8. Scale factors for soil type C according to the "Provision Method" for a building by T = 1.0 (s)

Scale factor for 10% probability of occurrence in 50 years (Design) level	Scale factor for 2% probability of occurrence in 50 years (Maximum Credible Earthquake) level	Earthquake
4.77	7.15	Borrego Mountain
3.87	5.81	Coalinga
5.37	8.06	Imperial Valley
1.81	2.72	Loma Prieta
5.86	8.80	Morgan Hill
4.45	6.67	N.Palm Spring
4.66	7.00	Northridge
5.02	7.52	Point Mugu
3.27	4.90	San Fernando
3.02	4.53	Superstition Hill
4.48	6.71	Whittier Narrows

Tab. 9. Scale factors for soil type B according to the "Design Method" for a building by T = 1.0 (s)

Scale factor for 10% probability of occurrence in 50 years (Design) level	Scale factor for 2% probability of occurrence in 50 years (Maximum Credible Earthquake) level	Earthquake
3.10	4.66	Borrego Mountain
4.55	6.83	Coalinga
4.28	6.43	Imperial Valley
0.94	1.40	Loma Prieta
5.33	8.00	Morgan Hill
2.91	4.36	N.Palm Spring
3.94	5.91	Northridge
3.06	4.61	Point Mugu
2.39	3.59	San Fernando
3.35	5.02	Superstition Hill
3.35	5.03	Whittier Narrows

Tab. 10. Scale factors for soil type B according to the "Provision Method" for a building by T = 1.0 (s)

Scale factor for 10% probability of occurrence in 50 years (Design) level	Scale factor for 2% probability of occurrence in 50 years (Maximum Credible Earthquake) level	Earthquake
3.90	5.85	Borrego Mountain
3.17	4.75	Coalinga
4.40	6.60	Imperial Valley
1.48	2.22	Loma Prieta
4.80	7.19	Morgan Hill
3.63	5.45	N.Palm Spring
3.81	5.72	Northridge
4.10	6.16	Point Mugu
2.67	4.01	San Fernando
2.47	3.71	Superstition Hill
3.66	5.50	Whittier Narrows

Tab. 11. Scale factors for soil type A according to the "Design Method" for a building by T = 1.0 (s)

Scale factor for 10% probability of occurrence in 50 years (Design) level	Scale factor for 2% probability of occurrence in 50 years (Maximum Credible Earthquake) level	Earthquake
2.48	3.72	Borrego Mountain
3.64	5.46	Coalinga
3.43	5.14	Imperial Valley
0.75	1.12	Loma Prieta
4.27	6.40	Morgan Hill
2.33	3.49	N.Palm Spring
3.15	4.72	Northridge
2.45	3.67	Point Mugu
1.91	2.87	San Fernando
2.68	4.02	Superstition Hill
2.68	4.02	Whittier Narrows

Tab. 12. Scale factors for soil type A according to the "Provision Method" for a building by T = 1.0 (s)

Scale factor for 10% probability of occurrence in 50 years (Design) level	Scale factor for 2% probability of occurrence in 50 years (Maximum Credible Earthquake) level	Earthquake
3.12	4.68	Borrego Mountain
2.54	3.80	Coalinga
3.52	5.28	Imperial Valley
1.19	1.78	Loma Prieta
3.84	5.76	Morgan Hill
2.91	4.37	N.Palm Spring
3.05	4.58	Northridge
3.28	4.92	Point Mugu
2.14	3.21	San Fernando
1.98	2.96	Superstition Hill
2.93	4.40	Whittier Narrows

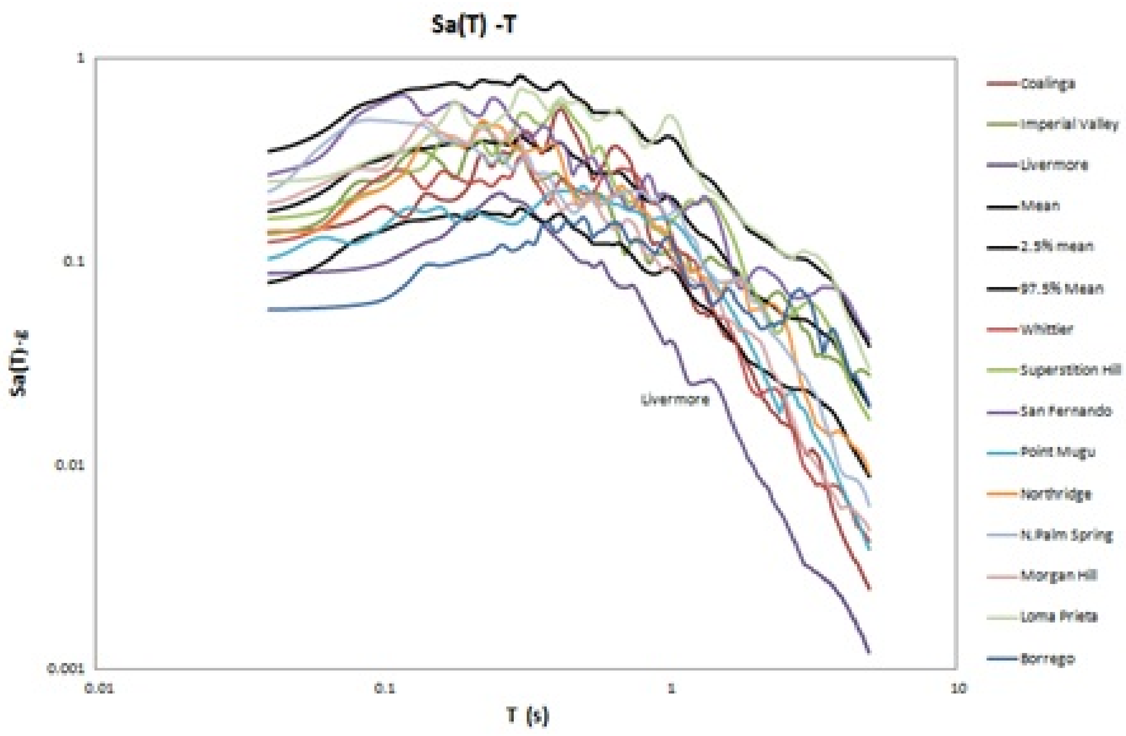

Fig. 1. Elastic spectral diagrams for different records

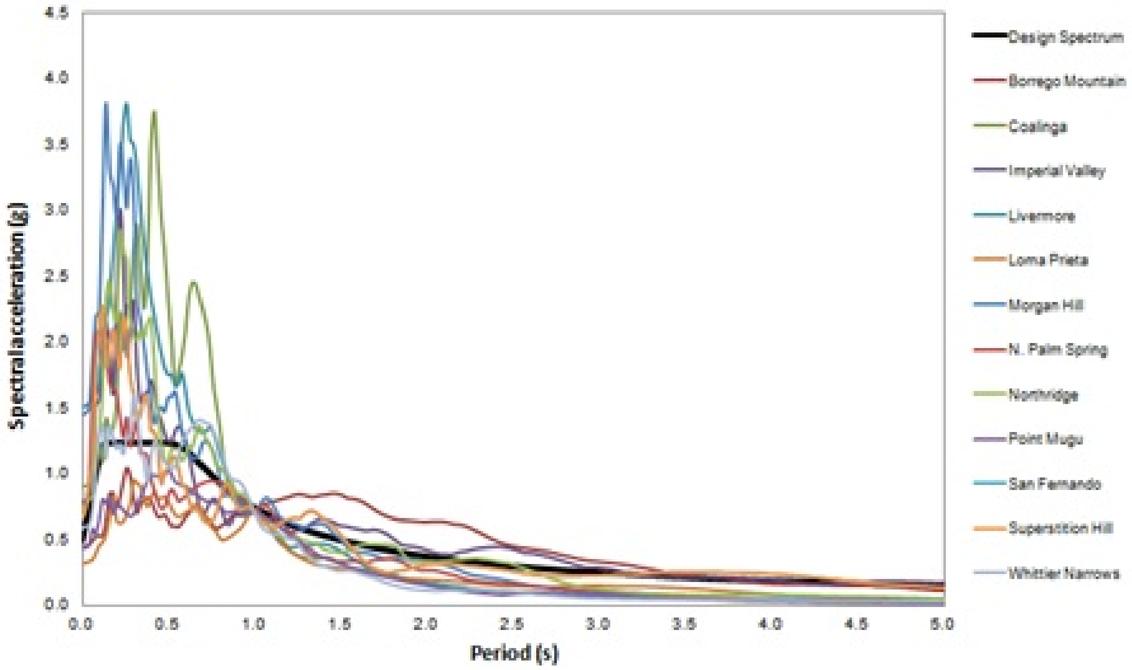

Fig. 2. Scaled Spectrums associated with the target design spectrum for soil type D according to the "Designers' Method" for a building by T = 1.0(s)

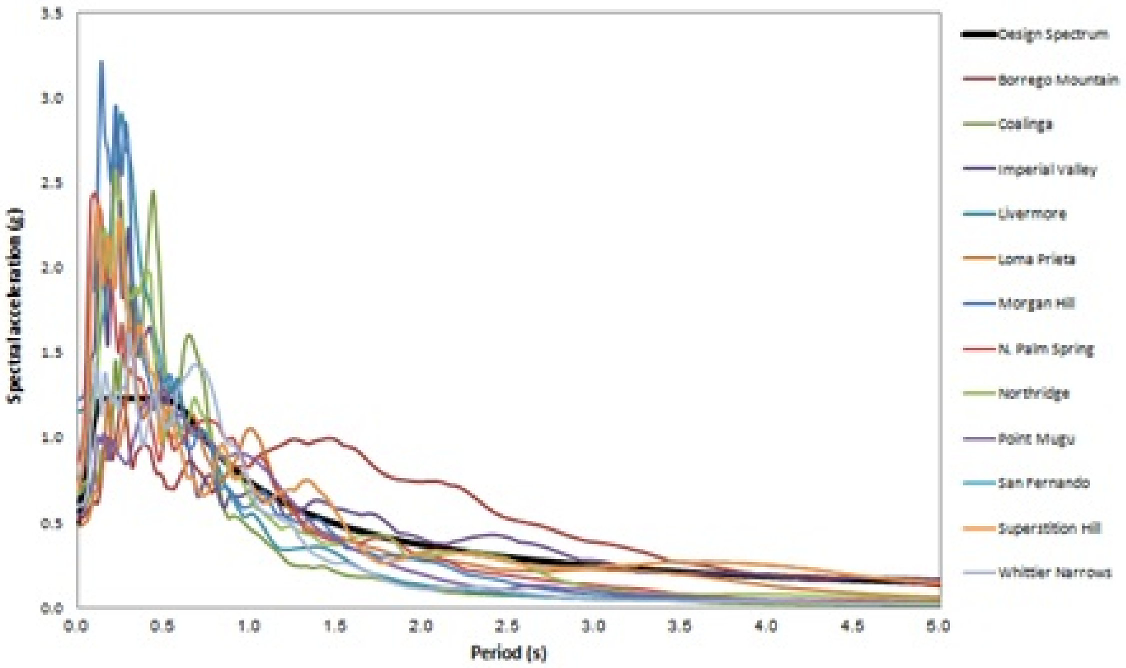

Fig. 3. Scaled Spectrums associated with the target design spectrum for soil type D according to the "Provisions' Method" for a building by T = 1.0 (s)

Tab. 13. Incorporated record IDs for three sets of random selection and proposed method of record selection

Number of sets	Incorporated record IDs
1 (Random selection)	NR94pic, MH84g02, WN87sse, WN87stc, NR94php, WN87wat, NR94cen, SH87icc, IV9vct, LP89sjw, NR94sse
2 (Random selection)	NR94cen, NR94del, SH87wsm, LP89slc, BM68elc, NR94del, NR94nya, WN87wat, LP89svl, WN87cas, IV79e01
3 (Random selection)	MH84g02, NR94glp, NR94sor, SH87wsm, MH84g03, IV79wsm, PM73phn, WN87cat, LP89hch, NR94fle, PS86ino
4 (Proposed method)	IV79e13, MH84g02, PM73phn, PS86psa, WN87wat, SF71pel, SH87pls, BM68elc, LP89slc, NR94del, CO83c05

Tab. 14. Logarithmic standard deviation of the EDPs subjected to four sets of records

Number of sets	σ (Ln(IDR))			σ (Ln(PFA))		
	Story 1	Story 2	Story 3	Story 1	Story 2	Story 3
1 (Random selection)	4.97	5.76	6.93	4.97	4.98	4.46
2 (Random selection)	4.65	5.93	6.50	4.13	4.53	4.23
3 (Random selection)	4.86	5.38	5.96	4.48	4.57	4.19
4 (Proposed method)	3.18	3.80	4.17	2.10	2.39	2.92

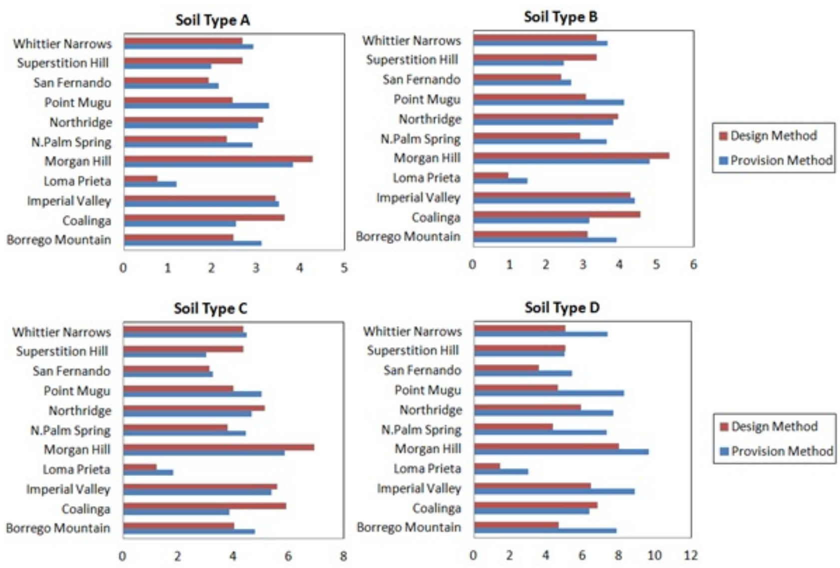

Fig. 4. Comparison of the scale factors according to the two assessed methods for different records and types of soil.

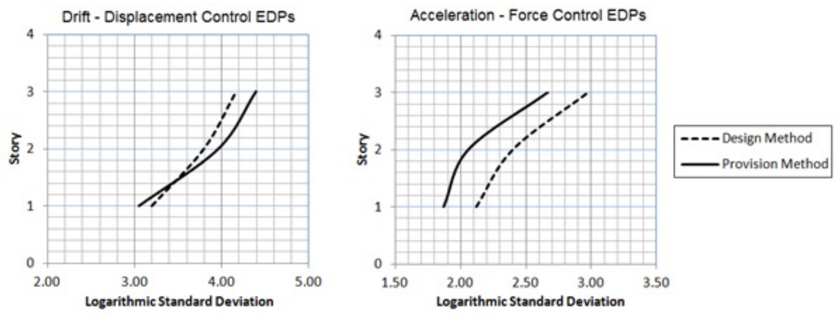

Fig. 5. Schematic presentation of the Logarithmic standard deviation of EDPs according to Design level scale factors in two methods

Tab. 15. Logarithmic standard deviation of EDPs according to Design level scale factors in two methods

Method	Drift			Acceleration		
	1st Story	2nd Story	3rd Story	1st Story	2nd Story	3rd Story
Design Method	3.20	3.80	4.17	2.12	2.40	2.98
Provision Method	3.05	3.96	4.39	1.87	2.06	2.67

The selected EDPs in structural response assessment are usually inter-story drift ratios (IDR) and peak floor acceleration (PFA) as well as in this paper. In this research, the median and standard deviation of the natural logarithm of EDP parameters were reported as statistical parameters and probability distribution of EDPs were assumed lognormal with the median and standard deviations gained from the outcomes of nonlinear dynamic analyses.

4.1 Description of structural systems used for evaluation

On account of the need for generality of the results, the structural frame models are not intended to represent a specific structure. For this purpose, a very typical 3-story model were utilized with one bay in long and one in width for each story that has been designed according to the ASCE05-7 as special steel moment frame (SMRF). The long of bays in both directions are equal to 6 m and the height of each story is equivalent to 3 m. Loading and complete designing of the model were carried out according to Iran's seismic code (2800), [42], much similar to UBC97, [43], and Iran's Steel Design Code, [44], much similar to AISC2005, [45].

Nonlinear response analyzing was accomplished by the help of the open system for earthquake engineering simulation (Opensees) [46]. Plastification was modelled, using nonlinear material gained from parallel aggregation of some elastoplastic materials which their definition were performed according to FEMA273 [47]. All the nonlinear dynamic analyses are conducted as Direct Integration Transient time history analyses using Direct Integration in Hilber, Hughes and Taylor's method by consideration of P-Δ effects and damping ratio for all modes equal to 5%.

4.2 Engineering Demand Results (EDP) subjected to different sets of records

Following the procedure mentioned above for design method of scaling, the scaling factors have been attained and by the means of them nonlinear analyses of the models were performed and EDP parameters achieved.

Magnitudes of the logarithmic standard deviation of the EDPs are presented in Table 14. As it could be seen utilizing the simple modification in record random selection could significantly reduce the amounts of EDPs' standard deviations and could improve the efficiency of the selected records in estimating structural responses taking in to account no-expensive computational efforts for performing the proposed modifications in record selection.

5 Evaluation and comparison of the scaling methods

Comparison of the scale factor results according to the two assessed methods for different records, archived by the means of proposed method for record selection, and types of soil are displayed in Fig. 4. It could be inferred that by reducing shear wave velocity in the soil classes (going from class A (hard rock) to D (stiff soil)) the differences between two methods increased and provision method becomes more conservative. For evaluation of the methods from the aspect of efficiency, logarithmic standard deviation of engineering demand parameters (EDP) have been assessed. The assumed EDPs are maximum acceleration and drift of each story that represent force control and displacement control EDPs respectively and the amounts of scale factors derived from Tables 5 and 6 for soil type D. Table 15 serves the logarithmic standard deviation of EDPs according to 10% probability of occurrence based on the two scaling methods. The results of this table are plotted in Fig. 5.

It could be realized that the provision method is the more efficient method of scaling for force control EDPs; though for displacement control EDPs, design method seems to be slightly more efficient for the upper stories. However, for assessing higher mode effects and mode participation results in the efficiency evaluation of scaling methods it is recommended to use models with more number of stories in the future researches.

6 Conclusions

- This research proposed a simple and practical method for selecting required records for nonlinear time history analysis of a model based on the least standard deviation in natural logarithmic acceleration spectral values. The superiority of the proposed method has been demonstrated by much less magnitudes of standard deviations in engineering demand parameters in comparison with randomly sets of records.
- This paper employs two common methods for scaling recorded earthquake data based on provisions requirements and designers experiences according to diverse class of soils. The results could be directly used as the scaling factors in related researches.
- Evaluation and comparison of the results deduce that by reduction in shear wave velocity in the soil classes (going from class A (hard rock) to D (stiff soil)) the differences between

two methods increased and provision method becomes more conservative.

- It recognized that the provision method (the method in which record scaling has been accomplished so that the average value of the 5 percent-damped response spectra for the record is not less than the target design spectrum over the period range from $0.2\,T_1$ to $1.5\,T_1$), is the more efficient method for record scaling in terms of force control EDPs; though for displacement control EDPs, design method (the method based on the scaling ground motion only in the fundamental period of the structure) seems to be slightly more efficient for the upper stories.

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