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Selecting and scaling ground motion time histories according to Eurocode 8 and ASCE 7-05

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Abstract. Linear and nonlinear time history analyses have been becoming more common in seismic analysis and design of structures with advances in computer technology and earthquake engineering. One of the most important issues for such analyses is the selection of appropriate acceleration time histories and matching these histories to a code design acceleration spectrum. In literature, there are three sources of acceleration time histories: artificial records, synthetic records obtained from seismological models and accelerograms recorded in real earthquakes. Because of the increase of the number of strong ground motion database, using and scaling real earthquake records for seismic analysis has been becoming one of the most popular research issues in earthquake engineering. In general, two methods are used for scaling actual earthquake records: scaling in time domain and frequency domain. The objective of this study is twofold: the first is to discuss and summarize basic methodologies and criteria for selecting and scaling ground motion time histories. The second is to analyze scaling results of time domain method according to ASCE 7-05 and Eurocode 8 (1998-1:2004) criteria. Differences between time domain method and frequency domain method are mentioned briefly. The time domain scaling procedure is utilized to scale the available real records obtained from near fault motions and far fault motions to match the proposed elastic design acceleration spectrum given in the Eurocode 8. Why the time domain method is preferred in this study is stated. The best fitted ground motion time histories are selected and these histories are analyzed according to Eurocode 8 (1998-1:2004) and ASCE 7-05 criteria. Also, characteristics of both near fault ground motions and far fault ground motions are presented by the help of figures. Hence, we can compare the effects of near fault ground motions on structures with far fault ground motions' effects.

Keywords: selection of earthquake records; scaling of earthquake records; time domain scaling; frequency domain scaling

1. Introduction

In the past, many earthquakes occurred and caused death of a lot of people all over the world. With advances in seismic analysis and design of structures, these losses of lives and properties are minimized. One of the developments in engineering area is to carry out analysis of structures against recorded earthquakes or earthquakes in future. In general, earthquake forces are calculated by using either the equivalent lateral force method or spectral modal analysis. However, with advances in seismic analysis and computer technology, time history analysis has been used commonly for design and consideration of structures. One of the most important issues for such

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analysis is the selection and scaling of appropriate ground motion records. Also, ground motion records are preferred to evaluate the response of structures with regards to deformation, stability and dynamic site response. In literature, there are three different sources of acceleration time histories; artificial records, synthetic records and actual earthquake records. Due to the increase of the number of available strong ground motion database and accessibility, real earthquake ground motion records have been becoming the most common input for the time history analysis. Also, the advantage of using real accelerograms is that they carry all the ground motion characteristics such as amplitude, frequency, energy content and duration and reflect all the factors that influence accelerograms such as characteristics of the source, path and site. Note that geological and seismological conditions such as magnitude, fault distance and site condition are very important to be able to select appropriate real ground motion records in a certain site.

After criteria for matching time histories to a design spectrum are determined, a method should be preferred to scale strong ground motions. In general, two methods are used for scaling actual time histories to match a design spectrum; scaling in time domain method and in frequency domain method. Time domain procedure only scales the amplitude of the seed motions. It does not change the frequency content of the seed motions, whereas frequency domain procedure changes frequency content and time. The method of adding or subtracting wavelets to or from the original time history is used in time domain procedure. The wavelets are selected to provide a harmony between target spectrums and spectral acceleration of ground motions. RSPMATCH Abrahamson (1993) is an important software example for this method.

In this study, seven near fault motions and seven far fault motions are selected considering events of magnitudes, fault distance and site condition. The time domain scaling procedure is utilized to scale the available real records to match the proposed elastic design spectrum given in the Eurocode 8 (1998-1: 2004). The best fitted ground motion time histories are selected and scaling factors are obtained. These histories are analyzed according to ASCE 7-05 (2006) and Eurocode 8 (1998-1: 2004) criteria.

As a result of this study, scaling parameters such as scaling factor and proportional relative error are used commonly to carry out time history analyses are evaluated. Also characteristics of both near fault ground motions and far fault ground motions are presented by the help of figures. Hence, we can compare near fault ground motions with far fault ground motions in their effects on structures.

2. Background

Nonlinear and linear time history analysis have been used more common in civil engineering area for seismic evaluation of existing structures and design of new structures. One of the most important issues for such analysis is the selection and scaling of appropriate time histories. Artificial records compatible with design response spectrum, synthetic records obtained from seismological models and accelerograms recorded in real earthquakes are used as inputs for seismic analysis by Abrahamson (1993), Bommer and Acevedo (2004). It is very difficult that response spectrum of any earthquake becomes compatible with code design spectrum, so different methods are used to increase the harmony between response spectrum and target spectrum. In recent years, due to the increase of available strong ground motion database and accessibility, the number of studies about selection and scaling actual time histories has been increasing more and more. However, a method about selection of actual time histories accepted by most of the researchers cannot be still developed.

Previous researches on scaling methods have been related to intensity based methods. Intensity-based procedures preserve the original content of the actual earthquake records. Different intensity measures are used to determine the effects of strong ground motions on structural response. A vector-valued intensity measure has been considered for predicting the effects of pulse-like near fault ground motions by Baker and Cornell (2008). However, further studies are needed to demonstrate robustness of vector-valued intensity measure for predicting structural response quantities. Also, the housner intensity measure is proved to be the more effective intensity measure for selecting the seismic inputs by (Masi *et al.* 2011). Other scalar intensity measures (IMs) such as arias intensity, effective peak acceleration and effective peak velocity have been found inaccurate and inefficient by Kurama and Farrow (2003). The matching of ground motions to target peak ground acceleration is one of the earliest approaches about scaling procedure. This approach has been shown to produce inaccurate median engineering demand parameters, but one of the primary objectives of intensity based scaling methods minimizes the record to record variations in engineering demand parameters.

The selection of appropriate earthquake records is very important procedure to be able to carry out nonlinear and linear seismic analysis. Since a method about this procedure accepted by most of the researchers cannot be still developed, different methods based on national codes have been used for selection of appropriate records. For example, Eurocode 8 allows the use of real records as an input for nonlinear dynamic analysis (Iervolino *et al.* 2009). Different international codes specify different, similar and sometimes ambiguous guidelines and requirements on how the selection and scaling of the earthquake ground motion records to be performed (Hachem *et al.* 2010). However, the scarcity of real recordings with the desired characteristics has forced researchers to look for other ways to develop time histories. Lilhanand and Tseng (1988) developed a method for generation of realistic synthetic earthquake time histories compatible with multiple-damping design spectra. Important structures such as tall buildings need to be safe against more severe ground shakings than code-defined design earthquake hazards, so new method is essential for selecting design earthquake ground motions for tall buildings (Lee *et al.* 2000). Also a procedure based on drift and input energy demands is used for scaling earthquake records for tall buildings by Takewaki and Tsujimoto (2011). An iterative procedure, wavelet-based generation, has been proposed to modify a recorded accelerograms by Mukherjee and Gupta (2002). Recorded accelerogram becomes compatible with a given design spectrum by the help of this method. It is very difficult task to find appropriate records compatible with design spectrum among a lot of records in any database. However, a procedure based on using genetic algorithms is fast and reliable; also records obtained by using this method match the target spectrum with minimal tampering (Naeim *et al.* 2004). Ground motion time histories should be selected and classified taken into account the earthquake parameters and site conditions. The effects of these criteria on earthquake ground motions are very important research subjects. The dependence of structural response on common earthquake parameters such as the magnitude (M) and distance (R) are studied by Iervolino and Cornell (2005). Selected earthquake records should become compatible with code design spectrums. Also, Wang (2010) explained that these records should preserve the characteristics and alteatory variability of scenario earthquakes. Apart from these selection procedures mentioned above, some methods such as probabilistic method (Morales-Estaban *et al.* 2012), spectrum compatible earthquake ground motions by Morlet Wavelet Shama (2012) are used commonly for evaluation of existing structures and design of new structures.

After criteria for matching time histories to a design spectrum are determined, a method should be preferred to scale strong ground motions. Different methods examined by Fahjan (2010) such as ground motion scaling in time domain, spectral matching in frequency domain, spectral matching by wavelets and spectrum compatible artificial record generation are used to decrease record to record variations between spectral accelerations of earthquake records and target spectrums. In general, two methods are preferred for scaling actual time histories to match a design spectrum; scaling in time domain is used by Fahjan (2008); (Iervolino *et al.* 2009) and (Kayhan *et al.* 2011) and frequency domain is used by Bolt and Gregor (1993). However, many studies are conducted to be able to develop the most reasonable scaling approach for use when predicting nonlinear building response by Wood and Hutchinson (2012). The effectiveness of some parameters in reducing the scatter in estimated structural response is an important research subject about scaling procedure. Kurama and Farrow (2003) investigated ground motion scaling methods for different site conditions and structure characteristics.

For near fault sites, some of the above scaling procedures may not work very well Bozorgnia and Mahin (1998); Alavi and Krawinkler (2000), Baez and Miranda (2000), Chopra and Chintanapakdee (2004). Bazzuro and Luco (2004), Luco and Cornell, (2007) show that If nonlinear displacement spectrum of the first mode nonlinear single degree of freedom system is used for scaling, this problem has been overcome by using some methods . A new scaling model; modal-pushover-based ground motion scaling procedure has been developed by Kalkan and Kwong (2010), Kalkan and Chopra (2010). The modal-pushover-based scaling scales ground motions for using in a nonlinear analysis of buildings.

Martinez-Ruedai (1998), Chopra and Chinatanapakdee (2004) came up with that single degree of freedom systems have been used by most of the researchers for a long time on ground motion scaling procedures. Multi degree of freedom systems have been used on only a few studies by Shome and Cornell (1998), Alavi and Krawinkler (2000) Kurama and Farrow (2003) Kalkan and Chopra (2011).

3. Code-based scaling procedure

Engineers use information based on international codes to perform one or a combination of many types of seismic analyses including response spectrum analysis, nonlinear pushover analysis and linear or nonlinear response history analysis. These analyses require using ground motion records scaled to match the code's design spectrum. Different codes all over the world specify different, similar and sometimes ambiguous guidelines and requirements on how the selection and matching of the design records are to be performed (Hachem *et al.* 2010).

For two-dimensional analysis, ASCE/SEI 7 (2006) requires ground motion records scaled by using appropriate scale factors for seismic analysis of symmetric plan buildings. Average value of the 5% damped response spectra for the set of scaled records is not less than the code design response spectrum over the period range from $0{,}2T_n$ to $1{,}5T_n$, where T_n is the elastic first mode vibration period of the structure.

For three-dimensional analyses, ground-motions should consist of pairs of appropriate horizontal ground motion acceleration components. For each pair of horizontal ground motion components, a square root of the sum of the squares (SRSS) spectrum should be constructed by taking the SRSS of the 5% damped response spectra of the unscaled components. Each pair of motions are then scaled with the same scale factor such that the mean of the SRSS spectra from all horizontal component pairs does not fall below the corresponding ordinate of the target spectrum

in the period range from $0{,}2T_n$ to $1{,}5T_n$.
According to Eurocode 8, in the range of periods between $0{,}2T_1$ and $2T_1$, where T_1 is the fundamental period of the structure in the direction where the accelerogram will be applied; no value of the mean 5% damping elastic spectrum, calculated from all time histories, should be less than 90% of the corresponding value of the 5% damping elastic response spectrum.

4. Formulation of time domain method

In this procedure, accelerograms should only be scaled with regards to amplitude without changing the frequency content. The method is based on minimizing the differences between the scaled ground motion records response spectrum and target spectrum within a period range of interest. "Difference" is calculated as below by Fahjan (2008).

$$\left|\text{Difference}\right| = \int_{T_A}^{T_B} \left[a_{SF} \times S_a^{actual}(T) - S_a^{target}(T) \right]^2 dT \tag{1}$$

Where; S_a^{actual} is actual acceleration response spectrum, S_a^{target} is target acceleration response spectrum, a_{SF} scaling factor, T is period, T_A and T_B are lower and upper period of scaling, respectively.

The first derivative of difference function with respect to the scaling factor must be zero to be able to minimize the difference.

$$\min\left|\text{Difference}\right| = \frac{d\left|\text{Difference}\right|}{da} = 0 \tag{2}$$

When Eq. (2) is solved, the definition of scaling factor is obtained as below

$$a_{SF} = \frac{\sum_{T_A}^{T_B} \left(S_a^{actual}(T) \times S_a^{target}(T) \right)}{\sum_{T_A}^{T_B} \left(S_a^{actual}(T) \right)^2} \tag{3}$$

For each record, differences among amplitudes of response spectrum which belongs to target spectrum and scaled ground motion are calculated with Total Relative Error (TRE) equation between T_A and T_B.

$$\left|\text{TRE}\right| = \sum_{T_A}^{T_B} \left| \frac{a \times S_a^{actual}(T) - S_a^{target}(T)}{S_a^{target}(T)} \right| \tag{4}$$

$$\left|\text{PRE}(\%)\right| = \frac{1}{k}\left|\text{TRE}\right| ?\ \ 00 \tag{5}$$

where PRE denotes Proportional Relative Error, $k=(T_B-T_A)/\Delta T$ and ΔT is the number of period steps.

Finally, scaling factors and proportional relative errors are ranked from lowest to highest. The records matching with target spectrum best are selected for design.

5. Flow chart diagram of time domain method

Time domain method based on minimizing the differences between the scaled ground motion records response spectrums and target spectrum within a period range of interest is used commonly about scaling earthquake records. Steps of this procedure are mentioned by the help of a flow chart diagram in Fig. 1.

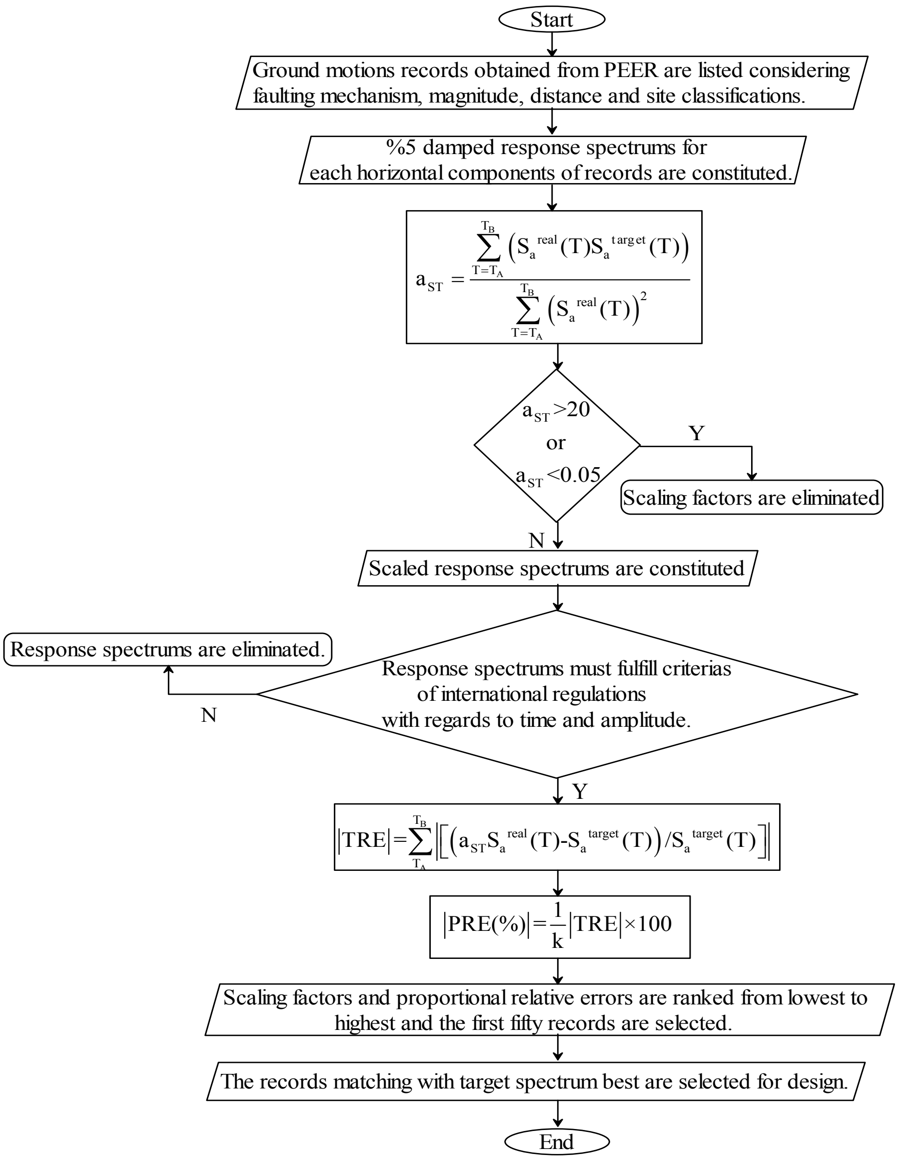

Fig. 1 Flow chart diagram of time domain method

6. Scaling ground motions using time domain method

The objective of this study is twofold: the first is to discuss and summarize basic methodologies and criteria for selecting and scaling ground motion time histories. The second is to analyze scaling results of time domain method according to ASCE 7-05 and Eurocode 8 (1998-1:2004) criteria.

Seven near-fault ground motions and seven far-fault ground motions are selected considering events of magnitudes, fault distance and site classification. These records are shown in Table 1 and Table 2. Moment magnitude and distance to fault rupture are represented by Mw and r respectively in Table 1 and Table 2. The time domain scaling procedure is utilized to scale the available real records to match the elastic design spectrum given in the Eurocode 8 (1998-1:2004). Target spectrum is selected in accordance with seed accelerograms with regards to site classification and shown in Fig. 2.

Scaling factors and proportional relative errors of ground motions are shown in Table 3 and Table 4. Note that scaling factor belongs to spectrum coefficient, but a_{AT} which belongs to spectral acceleration coefficient (A(T)) must be used to be able to scale ground motion records in these tables. There is an equation for this transformation:

$$a_{AT} = a_{ST} \times A_o \times I \tag{6}$$

where a_{AT} is scaling factor of A(T) used in analyses, a_{ST} is scaling factors of S(T), A_o is effective

Table 1 Far fault seed accelerograms for use in the scaling procedure

Record ID	Earthquake name	Date (D/M/Y)	Recording station	M_w	r (km)	Site condition
P0133	Friuli, Italy	15/09/1976	Forgaria Comino	5.7	13.50	B
P0188	Imperial Valley	15/10/1979	Parachute Test Site	6.5	14.20	B
P0779	Loma Prieta	18/10/1989	Saratoga-Aloha Ave	6.9	13.00	B
P0810	Cape Mendocino	25/04/1992	Rio Dell Overpass	7.1	18.50	B
P0865	Landers	28/06/1992	Coolwater	7.3	21.20	B
P1136	Chi-Chi, Taiwan	20/09/1999	CHY029	7.6	15.28	B
P1165	Chi-Chi, Taiwan	20/09/1999	CHY074	7.6	82.49	B

Table 2 Near fault seed accelerograms for use in the scaling procedure

Record ID	Earthquake name	Date (D/M/Y)	Recording station	M_w	r (km)	Site condition
P0225	Livermore	27/01/1980	Livermore	5.4	8.00	B
P0458	Morgan Hill	24/04/1984	Anderson Dam	6.2	2.60	B
P0519	N.Palm Springs	08/07/1986	Desert Hot Springs	6.0	8.00	B
P0530	N.Palm Springs	08/07/1986	North Palm Springs	6.0	8.20	B
P0729	Superstitn Hills(B)	24/11/1987	Superstition Mtn	6.7	4.30	B
P0745	Loma Prieta	18/10/1989	Corralitos	6.9	5.10	B
P1169	Chi-chi Taiwan	20/09/1999	CHY080	7.6	6.95	B

ground acceleration coefficient and I is building importance coefficient.

Unscaled and scaled records of far-fault ground motions and near-fault ground motions in Figs. 3-6. Average of scaled motions exhibits considerable variability with respect to the target spectrum. In Fig. 4, this variability appears appropriate for the long period range of the spectrum. However, low period spectral values of the average scaled motions are lower than the target. For near fault ground motions as seen in Fig. 6, scaled records appears appropriate for the long period range of the spectrum, but high period spectral values of the average scaled motions are lower than the target.

Fig. 2 Elastic response spectrum

Table 3 Scaling factors and proportional relative errors of far fault ground motions

Record ID	Earthquake name	Date (D/M/Y)	Scaling factor (a_{ST})	PRE (%)
P0133	Friuli, Italy	15/09/1976	5.283	9.170
P0188	Imperial Valley	15/10/1979	8.652	5.973
P0779	Loma Prieta	18/10/1989	3.251	3.887
P0810	Cape Mendocino	25/04/1992	2.222	8.011
P0865	Landers	28/06/1992	3.015	6.309
P1136	Chi-Chi, Taiwan	20/09/1999	4.990	5.632
P1165	Chi-Chi, Taiwan	20/09/1999	6.212	11.289

Table 4 Scaling factors and proportional relative errors of near fault ground motions

Record ID	Earthquake name	Date (D/M/Y)	Scaling factor (a_{SF})	PRE (%)
P0225	Livermore	27/01/1980	4.514	10.352
P0458	Morgan Hill	24/04/1984	3.624	6.521
P0519	N.Palm Springs	08/07/1986	3.174	6.698
P0530	N.Palm Springs	08/07/1986	2.111	7.674
P0729	Superstitn Hills(B)	24/11/1987	1.775	6.623
P0745	Loma Prieta	18/10/1989	2.062	6.348
P1169	Chi-Chi Taiwan	20/09/1999	1.406	6.261

After scaling procedure, as in Figs. 7-12, scaled records for near-fault and far-fault fulfill criteria of ASCE 7-05 and Eurocode 8 (1998-1:2004). When these criteria are not provided, to

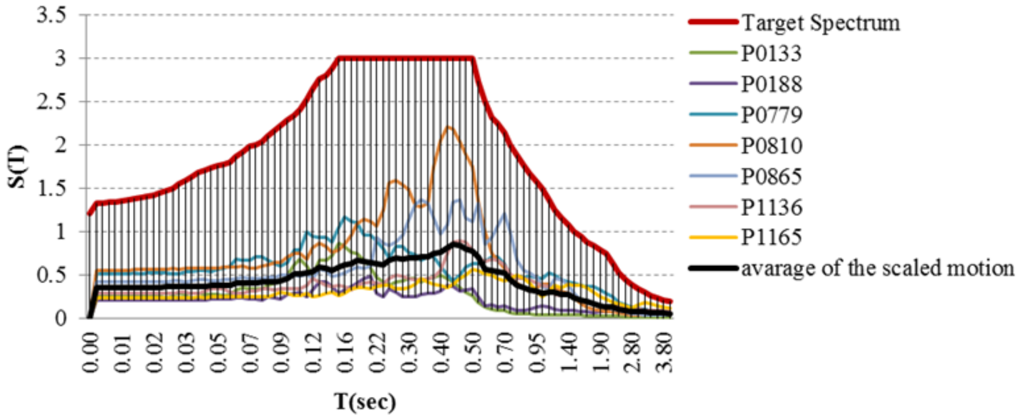

Fig. 3 Target spectrum and unscaled records of far fault ground motions

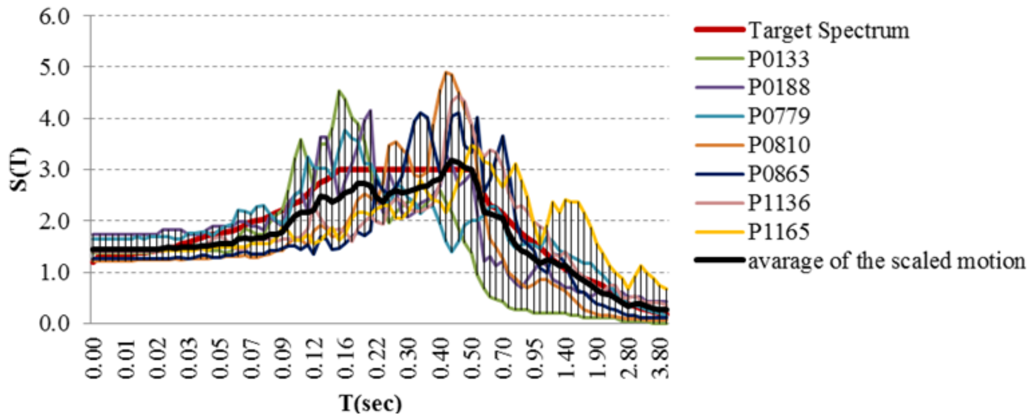

Fig. 4 Target spectrum and scaled records of far fault ground motions

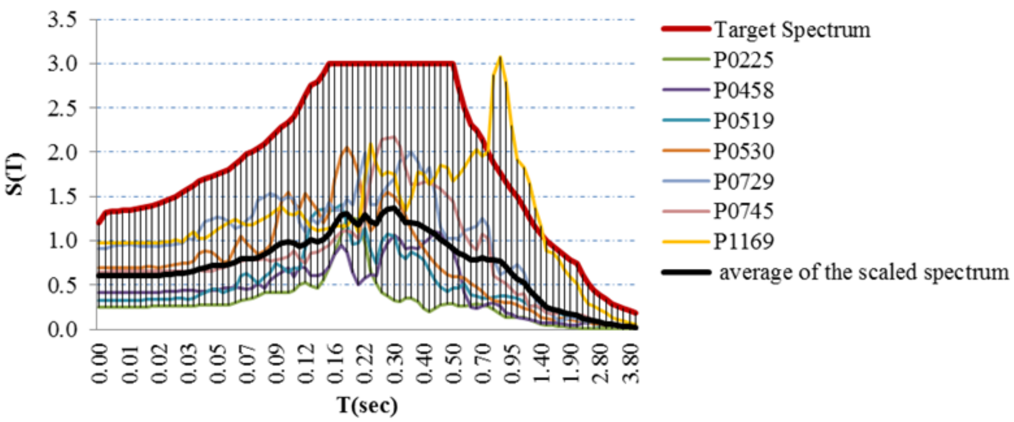

Fig. 5 Target spectrum and unscaled records of near fault ground motions

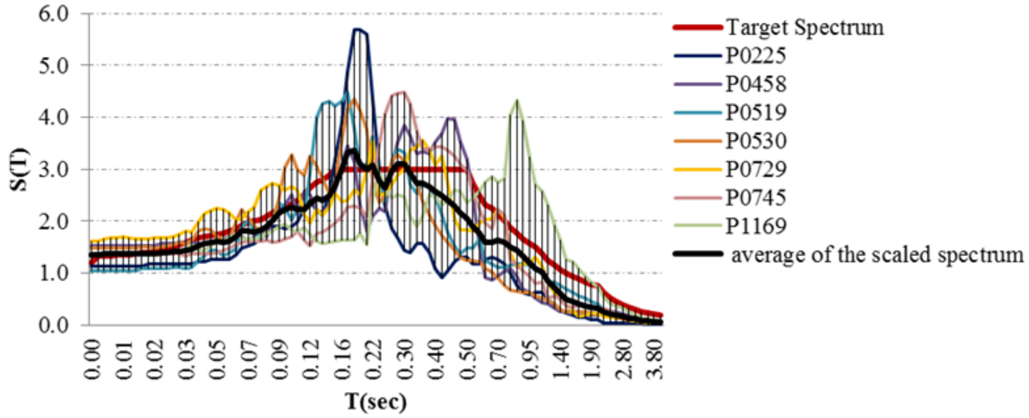

Fig. 6 Target spectrum and scaled records of near fault ground motions

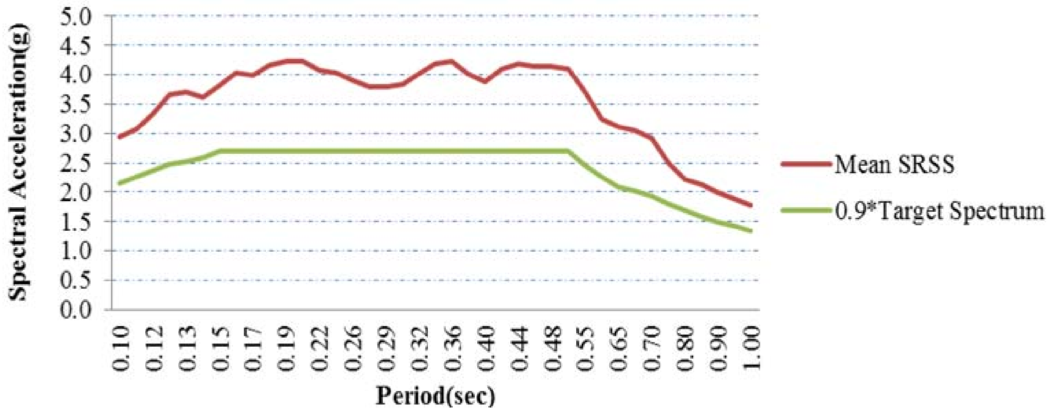

Fig. 7 Comparison of average far fault spectral accelerations with target spectrum in terms of Eurocode 8

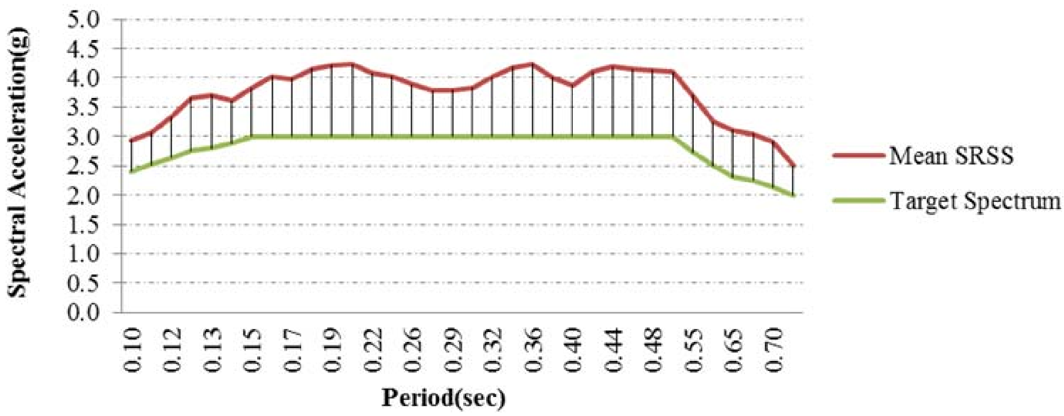

Fig. 8 Comparison of average far fault spectral accelerations with target spectrum in terms of ASCE 7 for two dimensional analysis

meet them, determine a scale factor a_1 that applies to all motions as scaled with a_{SF}. The final scale factor for each motion is the product $a_{ST}xa_{1.}$

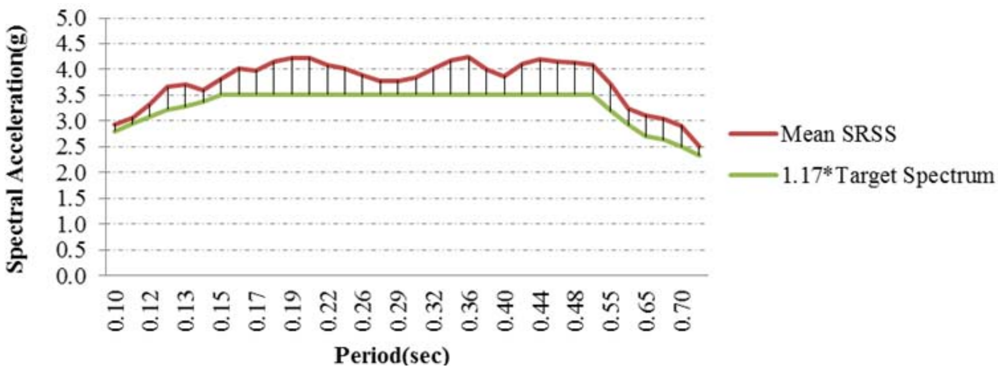

Fig. 9 Comparison of average far fault spectral accelerations with target spectrum in terms of ASCE 7 for three dimensional analysis

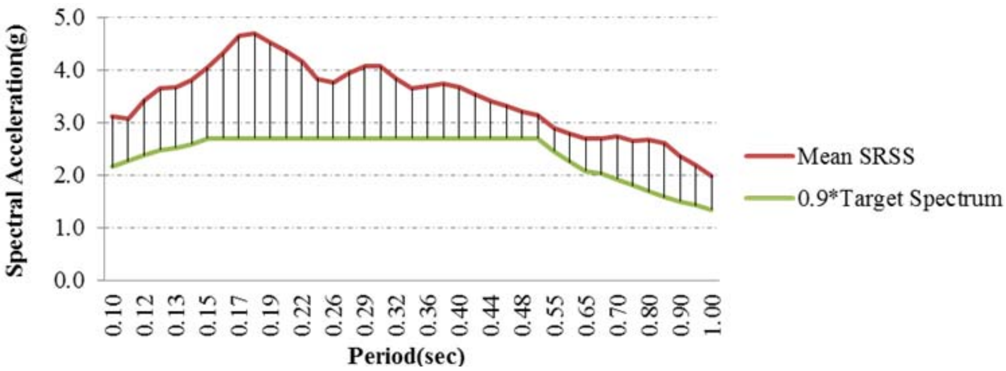

Fig. 10 Comparison of average near fault spectral accelerations with target spectrum in terms of Eurocode 8

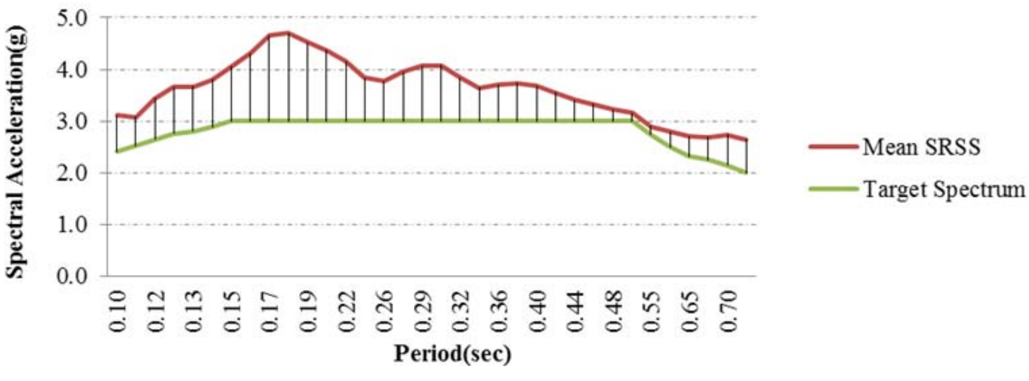

Fig. 11 Comparison of average near fault spectral accelerations with target spectrum in terms of ASCE 7 for two dimensional analyses

7. Conclusions

Selection and scaling strong ground motion time histories are critical and important to the time history analyses of structures. The time history scaling procedure is has the advantage that

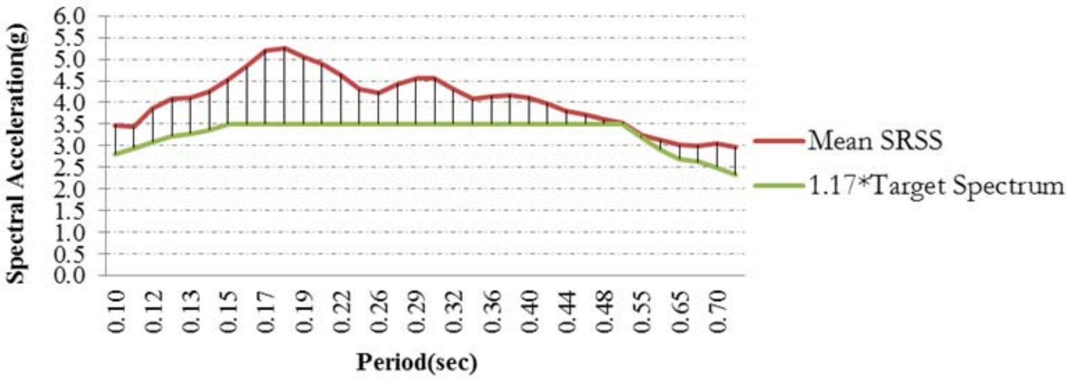

Fig. 12 Comparison of average near fault spectral accelerations with target spectrum in terms of ASCE 7 for three dimensional analyses

frequency contents of the records are not change. If the real accelerograms to fit the design spectra are scarce, frequency domain scaling can be used. Even though, the procedure is robust, the frequency contents and the spectral displacement response of the record are significantly changed. A less disturbance to the frequency contents and the spectral displacement response can be achieved by starting the procedure with records that response spectra are more compatible to the design spectra.

The objective of this study is twofold: in the first part, basic methodologies and criteria of selecting and scaling strong ground motion time histories are summarized. Which parameters should be considered for selecting actual ground motion records are mentioned briefly. In the second part, time domain scaling procedure is utilized to scale the available records and steps of this procedure are mentioned by the help of a flow chart diagram. The reason of using time domain method is that this method only scales the amplitude of the seed motions. It does not change the frequency content. Also, the scaling results of time domain method according to ASCE 7-05 and Eurocode 8 (1998-1:2004) criteria are analyzed.

Average of scaled both far fault ground motions and near fault ground motions exhibits considerable variability with respect to the target spectrum. For far fault ground motions, this variability appears appropriate for the long period range of the spectrum. However, low period spectral values of the average scaled motions are lower than the target. For near fault ground motions, scaled records appears appropriate for the long period range of the spectrum, but high period spectral values of the average scaled motions are lower than the target.

By using time domain method, scaling parameters such as scaling factor and proportional relative error are used to carry out time history analyses are obtained and these values are shown in Table 3 and Table 4. The best fitted ground motion records should be selected among the others and used for design of structures. The most appropriate three far fault ground motion records and three near fault ground motions are respectively; Loma Prieta(P0779), Cape Mendocino(P0810), Landers(P0865), Superstitn Hills(B)(P0729), Loma Prieta(P0745) and Chi-Chi Taiwan(P1169).

After scaling procedure, it is seen that scaled records for near-fault and far-fault fulfill criteria of ASCE 7-05 and Eurocode 8 (1998-1:2004). When these criteria are not provided, to meet them, determine a scale factor a1 that applies to all motions as scaled with a_{SF}. The final scale factor for each motion is the product $a_{ST}xa_1$.

It is know that near fault ground motion causes bigger response and energy demand than far fault ground motion on structures, but scaling factors of both near fault and far fault are similar.

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