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Comparing of the effects of scaled and real earthquake records on structural response

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Abstract. Time history analyses have been preferred commonly in earthquake engineering area to determine earthquake performances of structures in recent years. Advances in computer technology and structural analysis have led to common usage of time history analyses. Eurocode 8 allows the use of real earthquake records as an input for linear and nonlinear time history analyses of structures. However, real earthquake records with the desired characteristics sometimes may not be found, for example depending on soil classes, in this case artificial and synthetic earthquake records can be used for seismic analyses rather than real records. Selected earthquake records should be scaled to a code design spectrum to reduce record to record variability in structural responses of considered structures. So, scaling of earthquake records is one of the most important procedures of time history analyses. In this paper, four real earthquake records are scaled to Eurocode 8 design spectrums by using SESCAP (Selection and Scaling Program) based on time domain scaling method and developed by using MATLAB, GUI software, and then scaled and real earthquake records are used for linear time history analyses of a six-storied building. This building is modeled as spatial by SAP2000 software. The objectives of this study are to put basic procedures and criteria of selecting and scaling earthquake records in a nutshell, and to compare the effects of scaled earthquake records on structural response with the effects of real earthquake records on structural response in terms of record to record variability of structural response. Seismic analysis results of building show that record to record variability of structural response caused by scaled earthquake records are fewer than ones caused by real earthquake records.

Keywords: selection of earthquake records; scaling of earthquake records; time domain scaling method; SESCAP

1. Introduction

The most important task of the earthquake engineering is to protect structures against earthquake forces, so different seismic analysis methods have been used to determine structural responses and make design of structures under earthquake forces. Generally, equivalent lateral force method and spectral modal analysis are preferred to be able to obtain the effects of earthquake forces on structural responses. However, time history analyses have been used commonly in earthquake engineering area to determine earthquake performances of structures in recent years. Advances in computer technology and structural analysis have led to common usage

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of this seismic analysis type.

One of the most important advantages of time history analysis than the other seismic analyses is that real earthquake records are used for seismic analysis of structures. Because, real earthquake records reflect seismic characteristics of ground motions such as frequency, energy content, amplitude and duration and carry characteristics of the certain site such as source and path, thereby more realistic results can be obtained from time history analysis. Selection of appropriate earthquake records is one of the most important procedures of time history analysis. However, a selection method accepted by most of the researchers cannot be still created, so international seismic codes have been used for selection appropriate earthquake records. For example; Eurocode 8 allows the using of real earthquake records as an input for time history analyses of structures (Iervolino *et al*. 2009). Principles and necessities about how the selection of earthquake ground motion records are specified by international seismic codes (Hachem *et al*. 2010). Also, (Ergun and Ates 2013) selected and scaled ground motion time histories according to Eurocode 8 and ASCE 7-05. However, real earthquake records with the desired characteristics sometimes may not be found for seismic analyses, in this case artificial records compatible with design response spectrum, synthetic records obtained from seismological models can be used as an input for seismic analyses (Abrahamson 1993, Bommer and Acevedo 2004). Therefore, a great number of studies have been conducted by researchers for years to generate artificial and synthetic earthquake records. For example; a method generating realistic synthetic earthquake records compatible with multiple-damping design spectra was developed by (Lilhanand and Tseng 1988). (Mukherjee and Gupta 2002) presented an iterative procedure to modify a recorded accelerograms. Also, (Shama 2012) generated spectrum compatible earthquake ground motions using Morlet Wavelet. Apart from these selection procedures mentioned above, (Heo *et al*. 2011) investigated two methods called by magnitude scaling and spectrum matching about selection of earthquake records. (Naeim *et al*. 2004) developed a selection procedure based on genetic algorithms. Appropriate earthquake records must be selected depending on some parameters such as magnitude (M) and distance (R) (Iervolino and Cornell 2005) to be able to carry out time history analyses, but there is much uncertainty and challenges about this subject, therefore researchers have studied to be able to develop selection methods accepted by the literature for years.

Since responses of structures under earthquake forces can be compared with each other, design spectrums and a guide for earthquake engineering, earthquake records must be scaled to any code design spectrum. Different scaling methods such as time domain scaling method used by (Iervolino *et al*. 2009) and (Kayhan *et al*. 2011), frequency domain scaling method used by (Bolt and Gregor 1993), spectral matching by wavelets and spectrum compatible artificial record generation (Fahjan 2010) are preferred for scaling earthquake records to match a design spectrum. The effect of these various ground motion scaling approaches are explored using three reinforced concrete prototypical building models by (Wood and Hutchinson 2012). The most important difficulty of scaling procedure is to should develop computer software. Software programs should be developed by using theoretic methods to be able to obtain scaling parameters fast such as scaling factor and proportional relative error. For example; (Grant 2011) presented RspMatchBi program based on RspMatch2005 (Hancock *et al*. 2006) that scales one of the components of earthquake records.

In this study, four real earthquake records are selected from Pacific Earthquake Engineering Research Center (PEER) considering geological and seismological conditions such as magnitude, fault distance, site condition and spectral shape, and then these records are scaled to Eurocode 8 design spectrums by using SESCAP (Selection and Scaling Program) based on time domain scaling method and developed by using MATLAB, GUI software. Scaled and real earthquake records are used as an input for linear time history analysis of a six-storied building modeled as spatial by SAP2000 software. Basic procedures and criteria of selecting and scaling earthquake records are summarized in the first part of the paper. In the second part, how the selected earthquake records are scaled to code design spectrum by SESCAP is introduced and the effects of scaled earthquake records on structural response are compared with the effects of real earthquake records on structural response in terms of record to record variability of structural response in the latest part of the paper. Seismic analysis results of building show that record to record variability of structural response caused by scaled earthquake records are fewer than ones caused by real earthquake records.

2. Code-based selection and scaling procedure

International seismic codes specifying principles and requirements on how the selection and scaling of the earthquake records (Hachem *et al*. 2010) are used by engineers to make seismic analyses such as response spectrum analyses, nonlinear pushover analyses, linear and nonlinear time history analyses.

2.1 Guidelines and requirements for buildings according to Eurocode 8

- Minimum of 3 accelerograms should be used.
- The mean of the zero period spectral response acceleration values should not be smaller than the value of $a_g S$ for the site in question.
- In the range of periods between $0{,}2T_1$ and $2\ T_1$, 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.

3. Formulation of time domain scaling method

Time domain scaling method is based on minimizing the differences between the scaled response spectrums of earthquake ground motion records and code target spectrums within a period range of interest. "Difference" is calculated as below (Ozdemir and Fahjan 2007).

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

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.

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

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

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

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 $T_{B.}$

$$\left|TRE\right| = \sum_{T_A}^{T_B}\left|\frac{aS_a^{actual}(T) - S_a^{target}(T)}{S_a^{target}(T)}\right| \qquad (4)$$

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

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

4. Flow chart diagram of time domain scaling method

Steps of time domain scaling procedure (Ozdemir and Fahjan 2007) are presented by the help of a flow chart diagram in Fig. 1. SESCAP software is developed by using this diagram.

5. Scaling of earthquake records with SESCAP

In this part of the paper, four real earthquake records are firstly obtained from Pacific Earthquake Engineering Research Center (PEER) considering geological and seismological characteristics and then scaled to Eurocode 8 design acceleration spectrums by using SESCAP software.

By the help of Buildings and Bridges buttons, users can arrive in subwindows where scaling procedures required for linear and nonlinear time history analyses of buildings and bridges are realized. In this study, building part of the SESCAP is only used to scale real earthquake records since selected earthquake records are used for linear time history analyses of a six-storied building.

Selected real earthquake records with some their characteristics are given in Table 1.

Scaling factors for S(T) and A(T), total relative errors (TRE) and proportional relative errors (PRE %) of scaled earthquake records can be shown in Figs. 3-6. Scaling factors obtained by SESCAP are belong to spectrum coefficient (S(T)). If seismic zone, effective ground acceleration coefficient (A_0) and building importance coefficient (I) are taken into account in time history

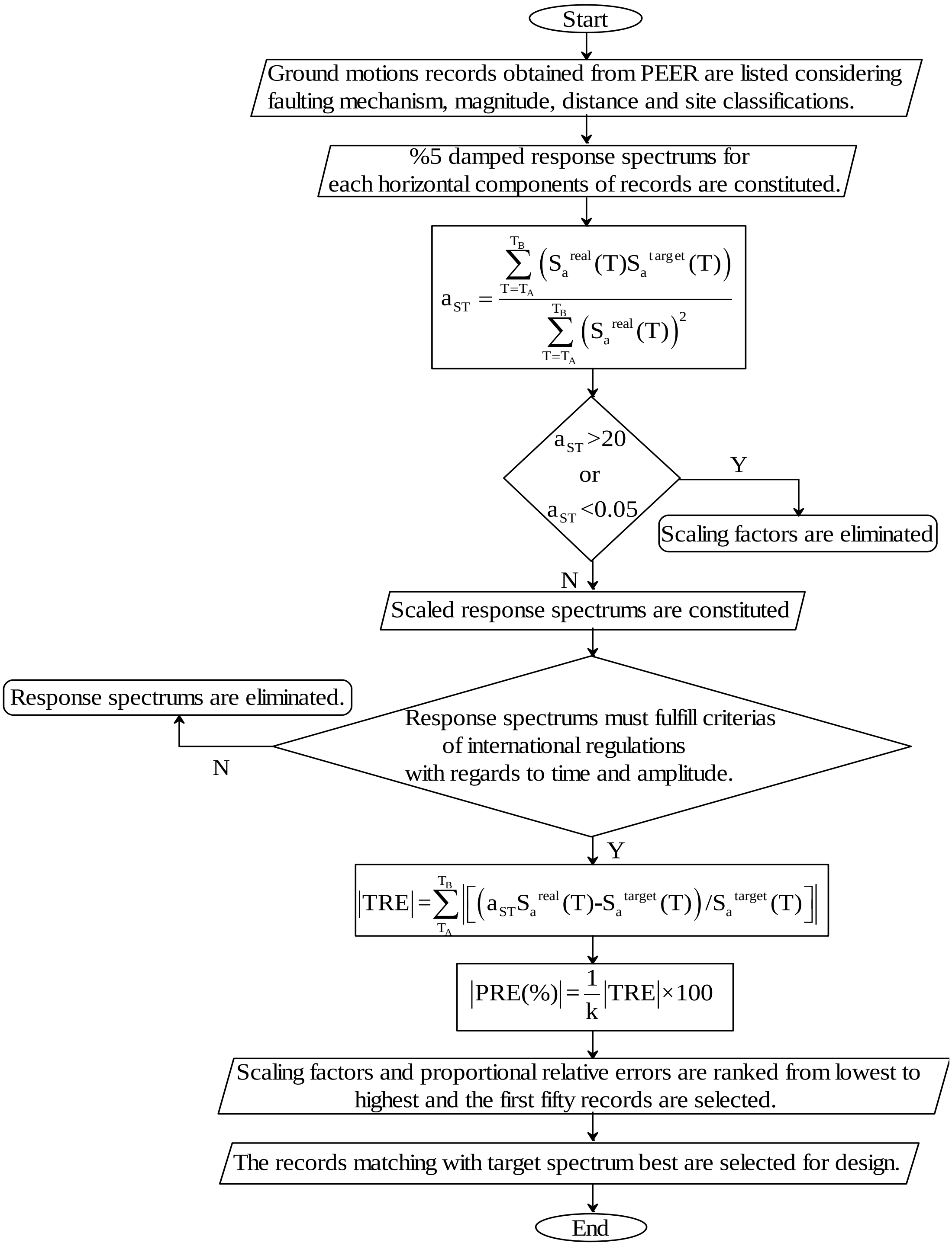


Fig. 1 Flow chart diagram of time domain scaling method

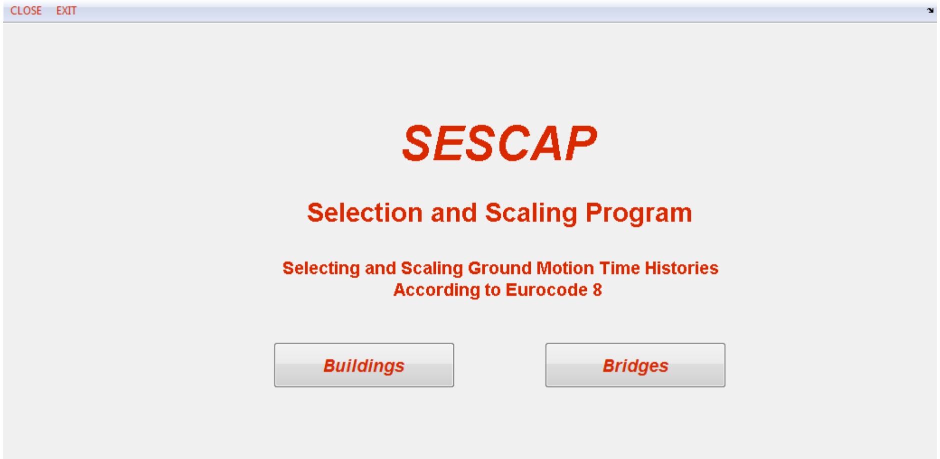


Fig. 2 The main window of SESCAP

Table 1 Real earthquake records for time history analyses of building

Record ID	Earthquake name	Date (D/M/Y)	Recording station	Record	M_W	r (km)	Site condition
P0161	Imperial Valley	15/10/1979	5054 Bonds Corner	H-BCR230	6,9	2,5	C
P0319	Westmorland	26/04/1981	5169 Westmorland	WSM180	5,8	13,3	C
P0736	Loma Prieta	18/10/1989	47381 Gilroy Array #3	G03000	7,1	14,4	C
P0452	Morgan Hill	24/04/1984	57382 Gilroy Array #4	G04360	6,1	12,8	C

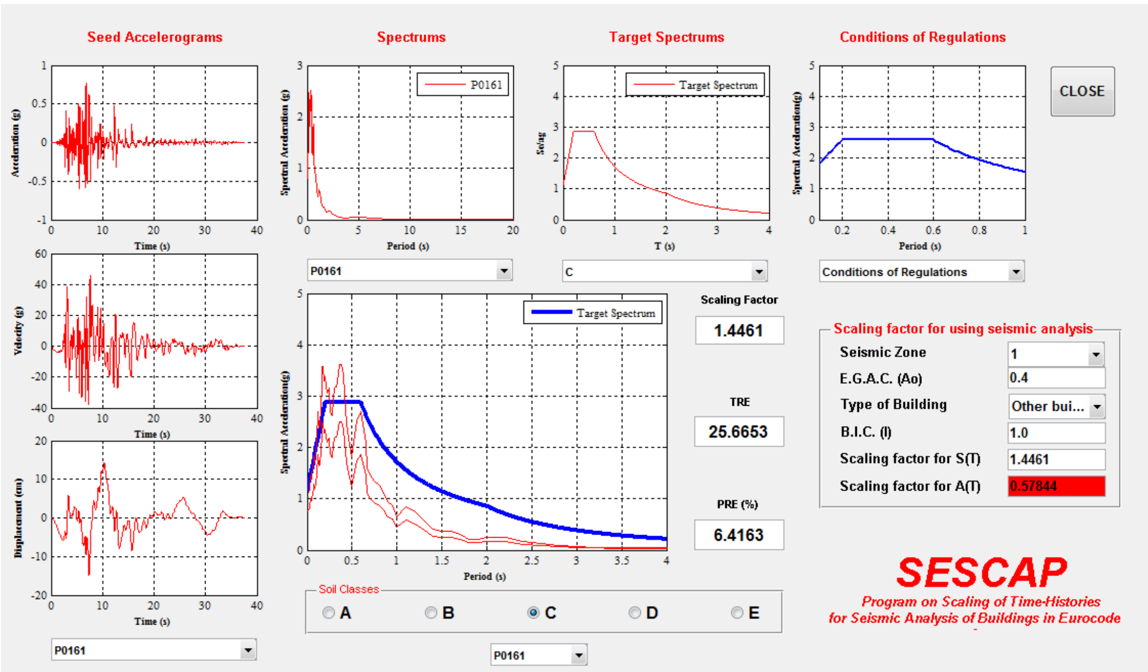


Fig. 3 Scaling results of Imperial Valley earthquake

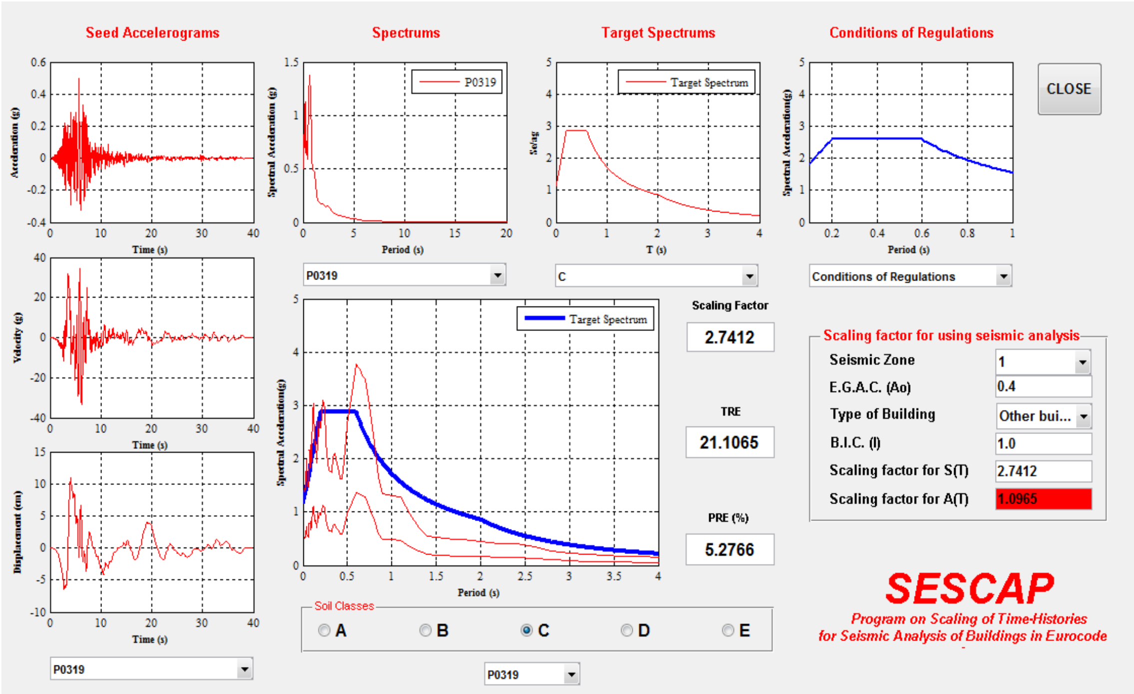


Fig. 4 Scaling results of Westmorland earthquake

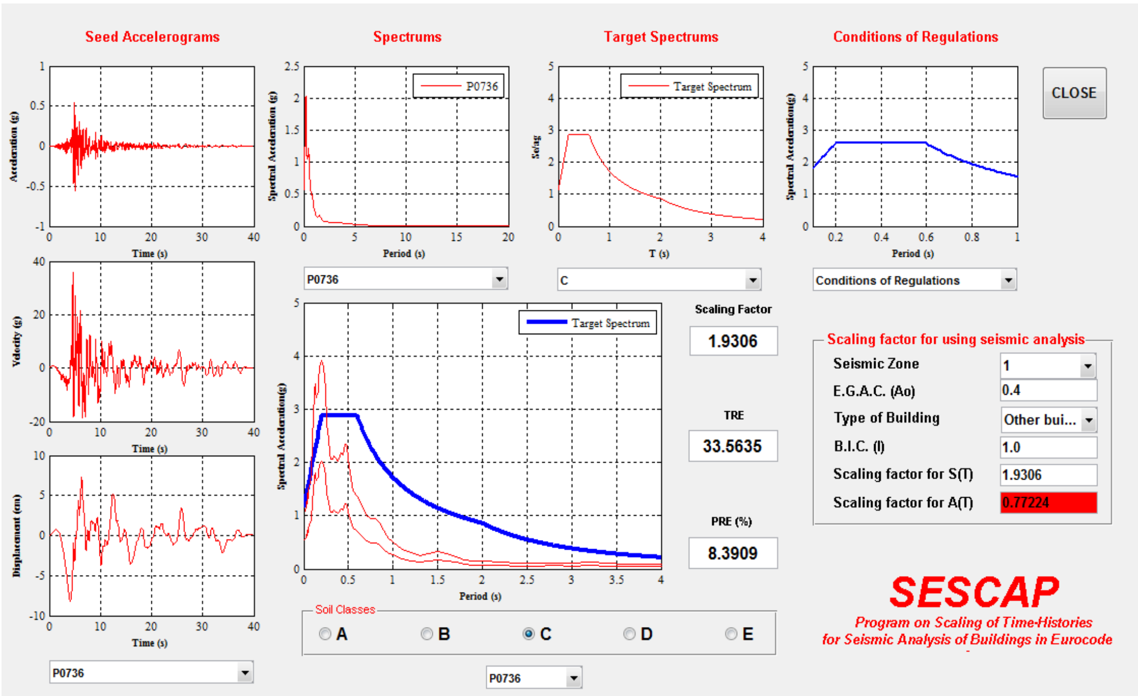


Fig. 5 Scaling results of Loma Prieta earthquake

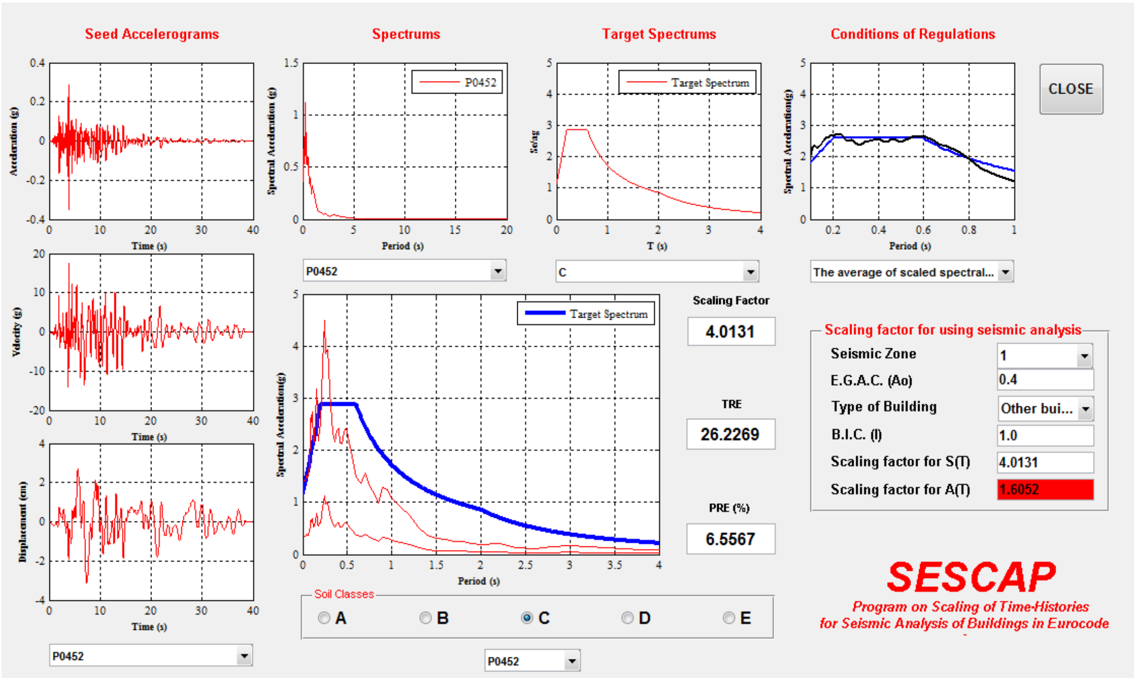


Fig. 6 Scaling results of Morgan Hill earthquake

analyses, earthquake records are scaled by scaling factors belong to spectral acceleration coefficient (A(T)). As is seen from Figs. 3-6, these scaling factors can be obtained easily by the help of Scaling factor for using seismic analysis section of SESCAP.

Condition of Regulation section of SESCAP informs users about whether scaled earthquake records satisfy the conditions of buildings of Eurocode 8 or not. It is seen easily from Fig. 6 that mean of spectral accelerations of scaled earthquake records satisfy substantially conditions of Eurocode 8 mentioned in the second part of the paper within a period range of interest.

In this study, only single horizontal component of earthquake records is selected and scaled to code design acceleration spectrum. Which component is used for seismic analyses can be shown easily for each earthquake record in Table1. However, if earthquake records compatible with code design spectrum well and desired characteristics are scarce then both horizontal components of earthquake records can be used for time history analyses.

Table 2 Scaled earthquake records for time history analyses of building

Record ID	Earthquake Name	Date (D/M/Y)	Recording Station	Scaling Factor (a_{ST})	Scaling Factor (a_{AT})	PRE (%)
P0161	Imperial Valley	15/10/1979	5054 Bonds Corner	1,4461	0,5784	6,4163
P0319	Westmorland	26/04/1981	5169 Westmorland	2,7412	1,0965	5,2766
P0736	Loma Prieta	18/10/1989	47381 Gilroy Array #3	1,9306	0,7722	8,3909
P0452	Morgan Hill	24/04/1984	57382 Gilroy Array #4	4,0131	1,6052	6,5567

Scaling results of earthquake records used for time history analyses of building are given in Table 2.

Real and scaled earthquake acceleration records used for linear time history analyses of building are shown in Figs. 7-10.

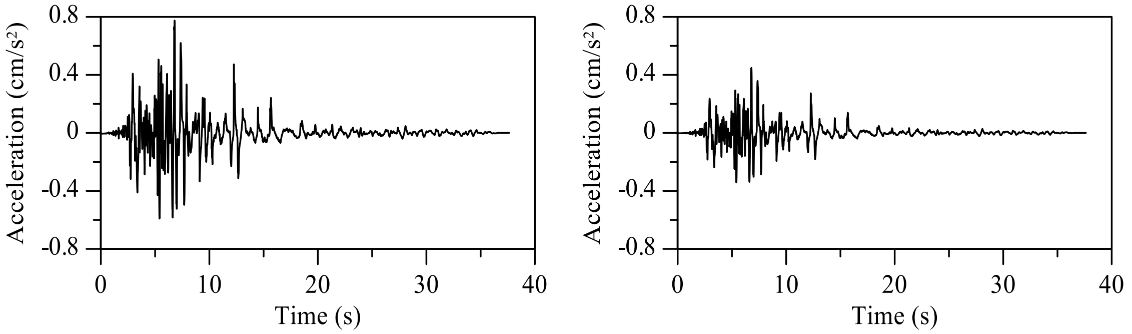


Fig. 7 Real and scaled acceleration records of Imperial Valley earthquake

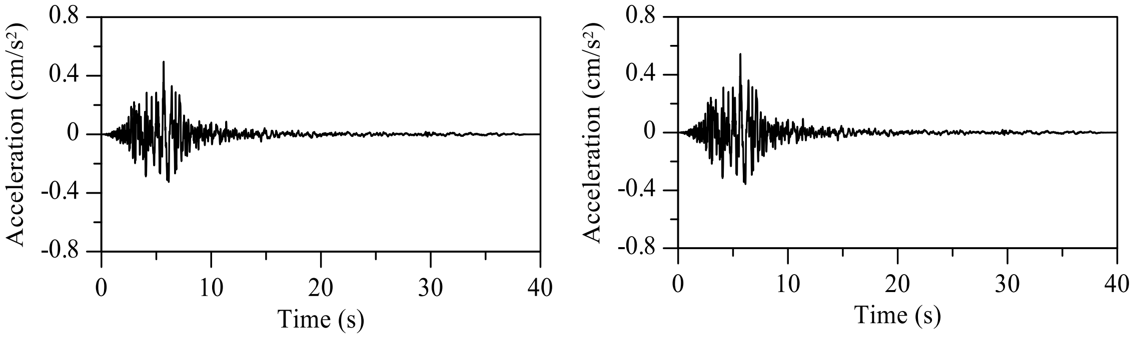


Fig. 8 Real and scaled acceleration records of Westmorland earthquake

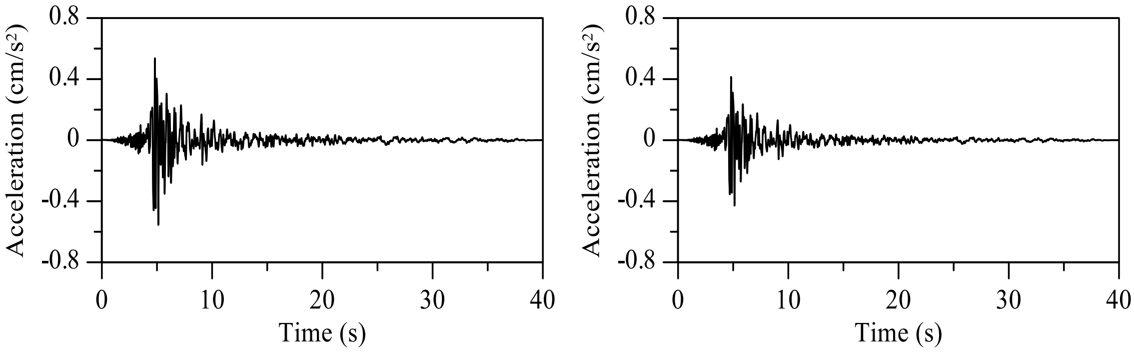


Fig. 9 Real and scaled acceleration records of Loma Prieta earthquake

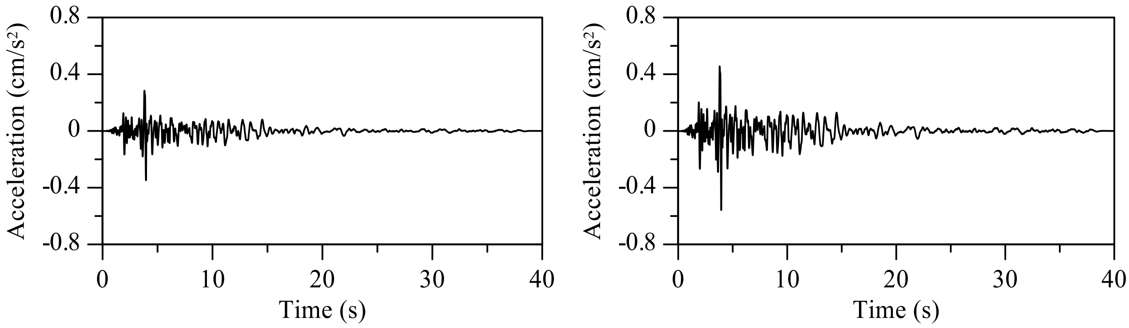


Fig. 10 Real and scaled acceleration records of Morgan Hill earthquake

6. Analytical study

In this study, a six-storied building is used as an example to be able to observe record to record variability in structural responses of under real and scaled earthquake records. The building is modeled as spatial by SAP2000 software. Cross sections of vertical bearing elements are constants along with building height and story heights of the building are three meters. The building is located in the first-degree seismic zone and building importance coefficient (I) is one. Material and cross-section properties of building elements are given in Table 3 and Table 4.

Table 3 Material properties of building elements

Concrete Grade	C20
Modulus of Elasticity (kN/m^2)	28000000
Poisson's Ratio	0,2
Weight Per Unit of Volume (kN/m^3)	25
Modulus of Subgrade Reaction (kN/m^3)	20000

Table 4 Cross-section properties of building elements

Element	Shape	B (m)	H (m)	Area (m^2)
Beam	Rectangular	0,25	0,50	0,125
Column	Rectangular	0,35	0,60	0,210
Column	Rectangular	0,35	0,70	0,245
Column	Rectangular	0,25	1,40	0,350
Column	Rectangular	0,30	1,40	0,420
Shear wall	Rectangular	0,25	3,60	0,900
Shear wall	Rectangular	0,25	1,80	0,450
Shear wall	Rectangular	0,25	2,00	0,500
Shear wall	Rectangular	0,25	2,40	0,600

Bar elements for beams and columns, area elements for shear walls, floors and raft foundation and springs for the soil are used to model the building with SAP2000. Three-dimensional analytical model, three-dimensional finite element model and mode shapes of building can be shown respectively in Figs. 11, 12 and 13.

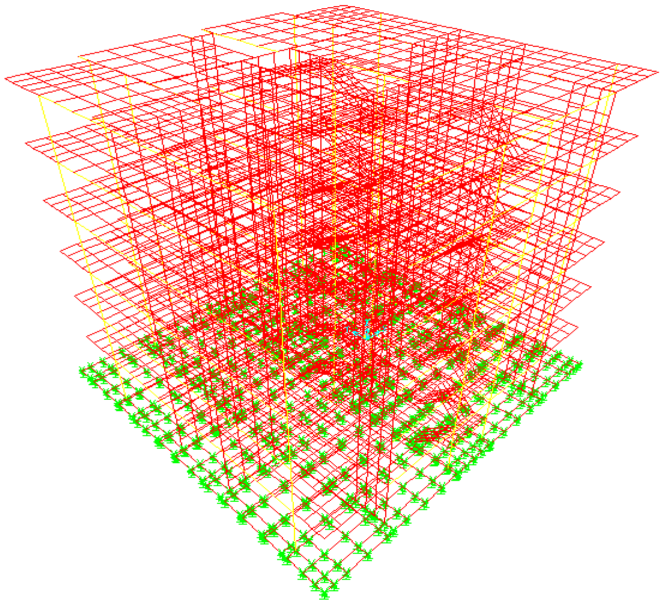


Fig. 11 Three-dimensional finite element model of the building

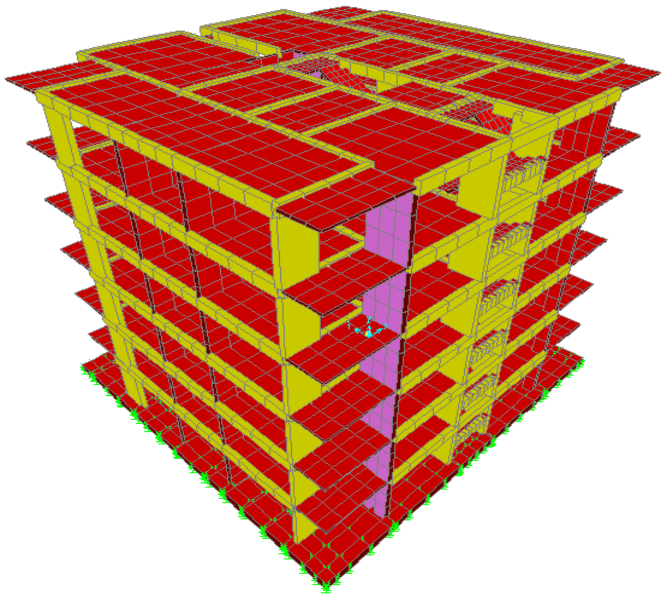
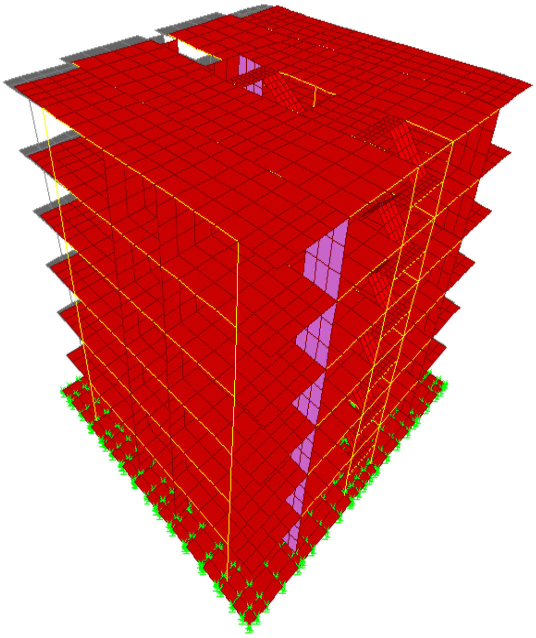
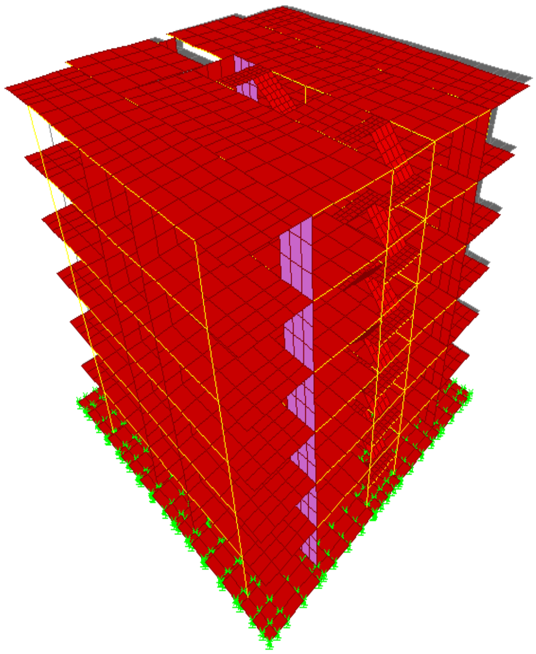


Fig. 12 Three-dimensional extruded view of the building

Mode 1
Frequency: 1,783 Hz
Period: 0,561 s



Mode 2
Frequency: 1,961 Hz
Period: 0,510 s



Mode 3
Frequency: 2,155 Hz
Period: 0,464 s

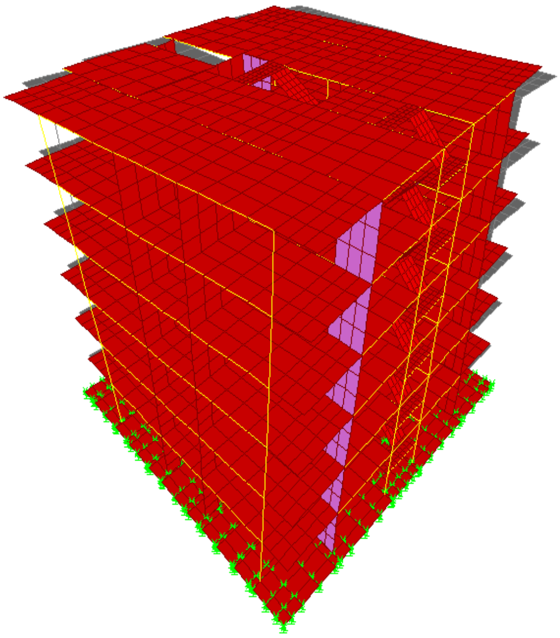


Fig. 13 Periods, frequencies and mode shapes of the building

7. Numerical results

The effects of real and scaled earthquake records on responses of the building in terms of record to record variability in structural response are examined by the help of SAP2000 software. Earthquake records are applied along both x and y axes of the building. Floor displacements and relative floor displacements of each story along both x and y axes of the building are taken into account as structural response after linear time history analyses. Floor displacements of the building under real and scaled earthquake records are given in Figs. 14 and 15.

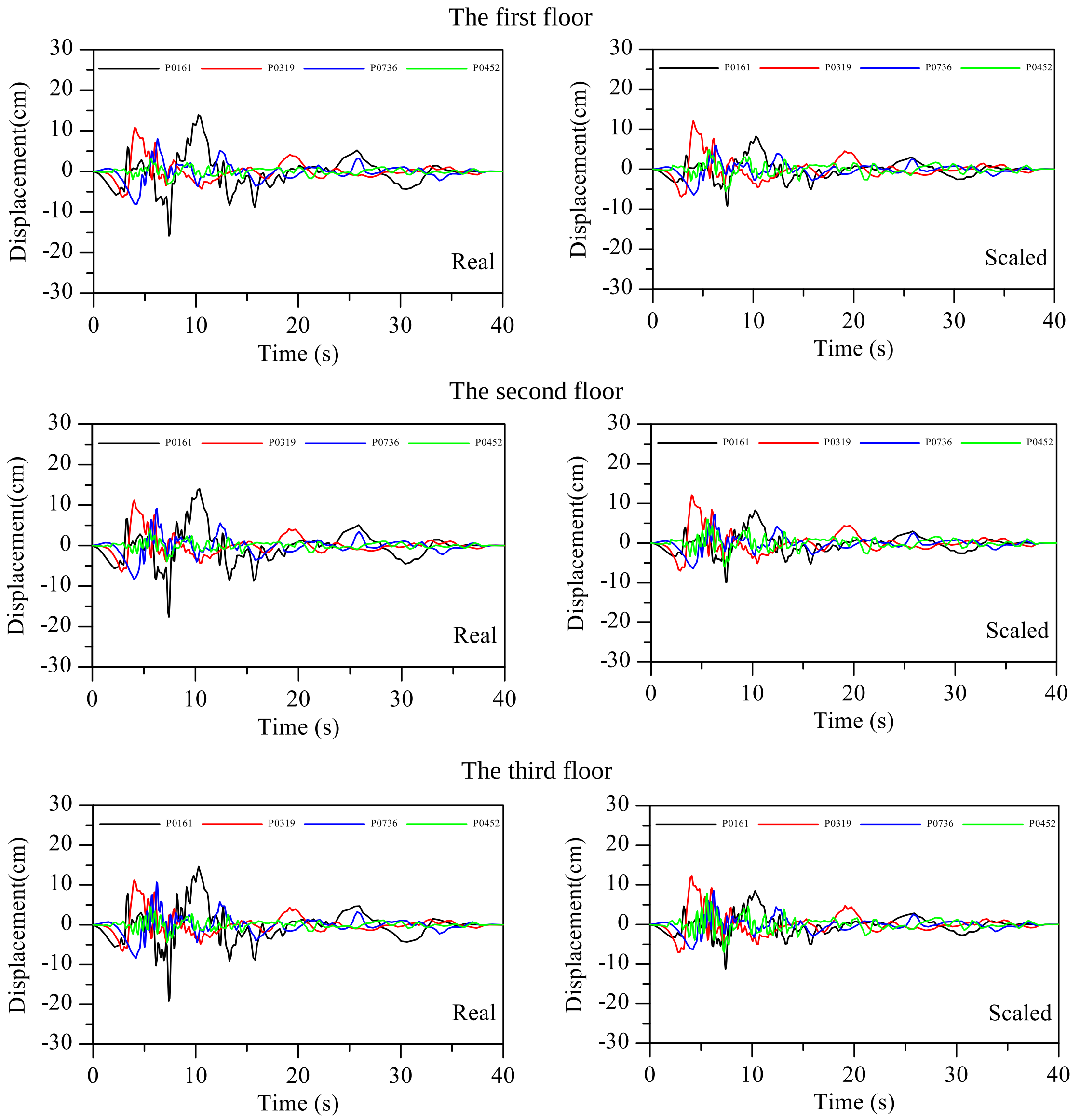


Fig. 14 Variations of displacements on the floors of the building along x axis under the effects of earthquake records

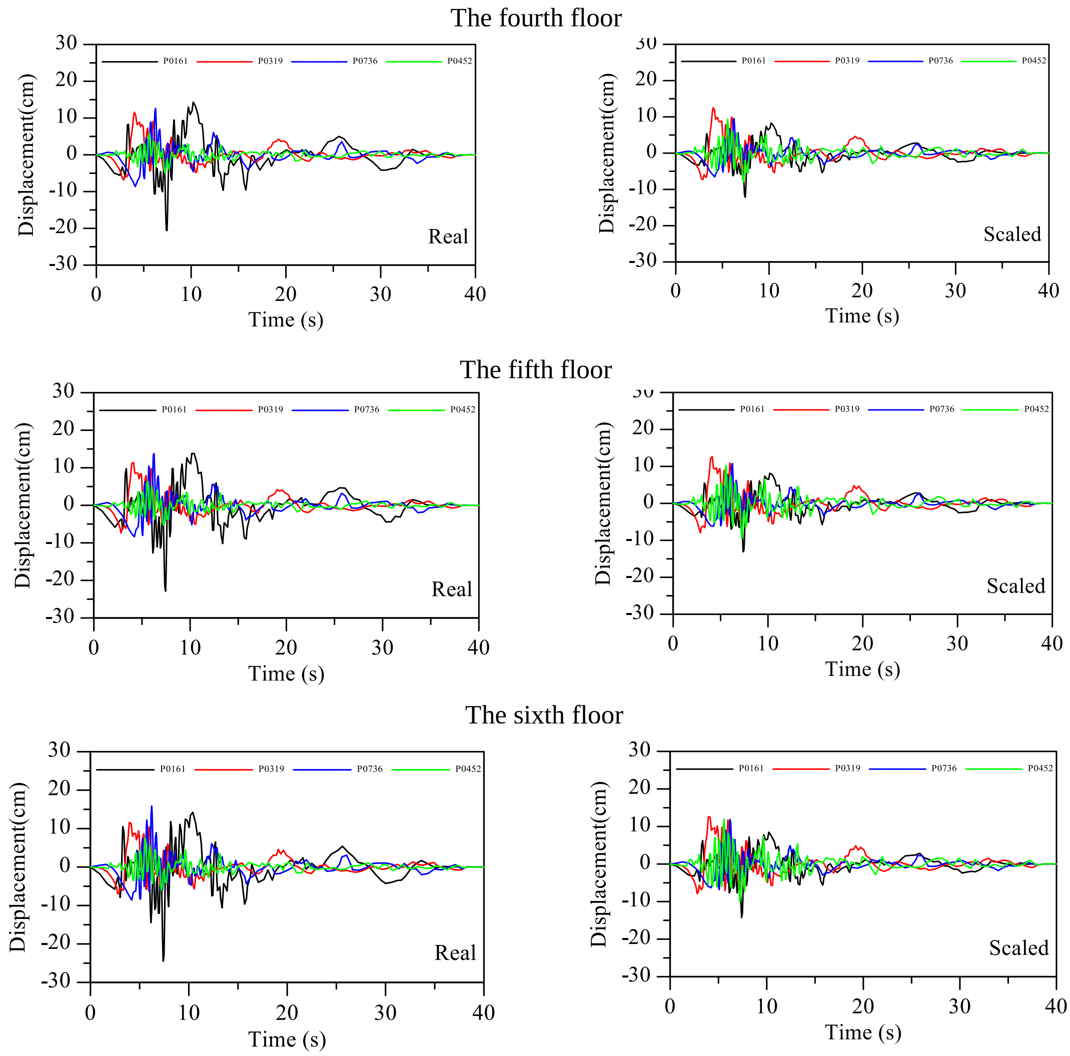


Fig. 14 Continued

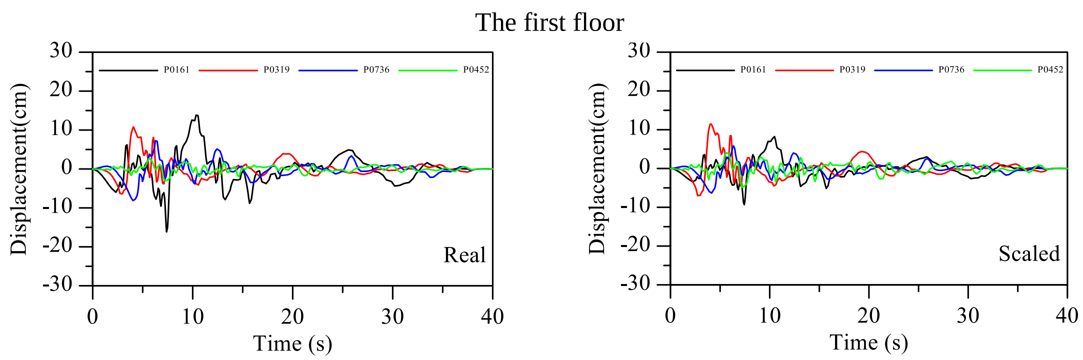


Fig. 15 Variations of displacements on the floors of the building along y axis under the effects of earthquake records

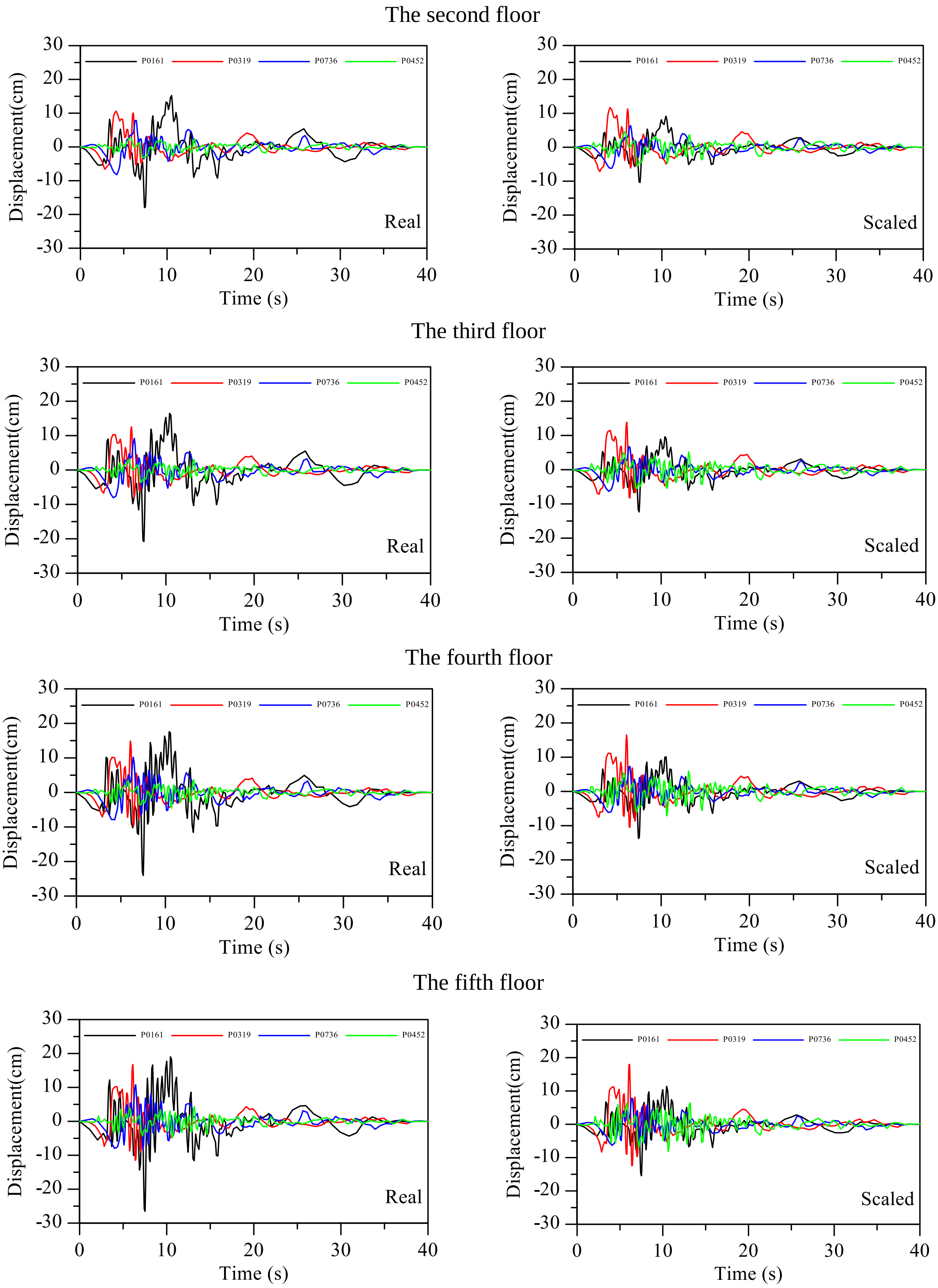


Fig. 15 Continued

The sixth floor

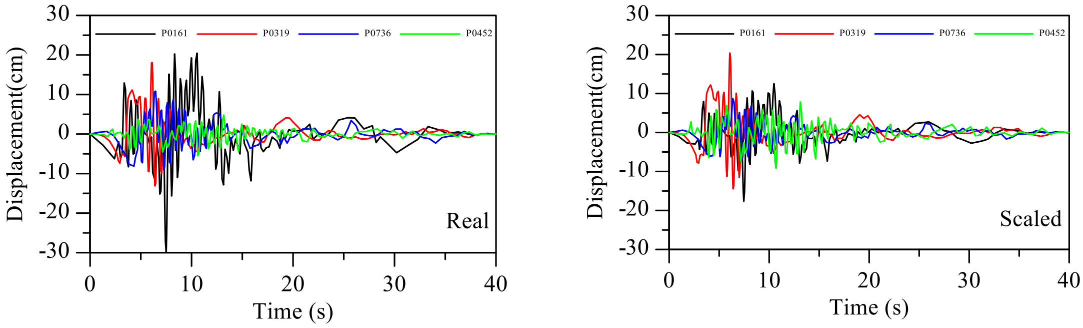


Fig. 15 Continued

Relative floor displacements of the building under real and scaled earthquake records are given in Figs. 16-17.

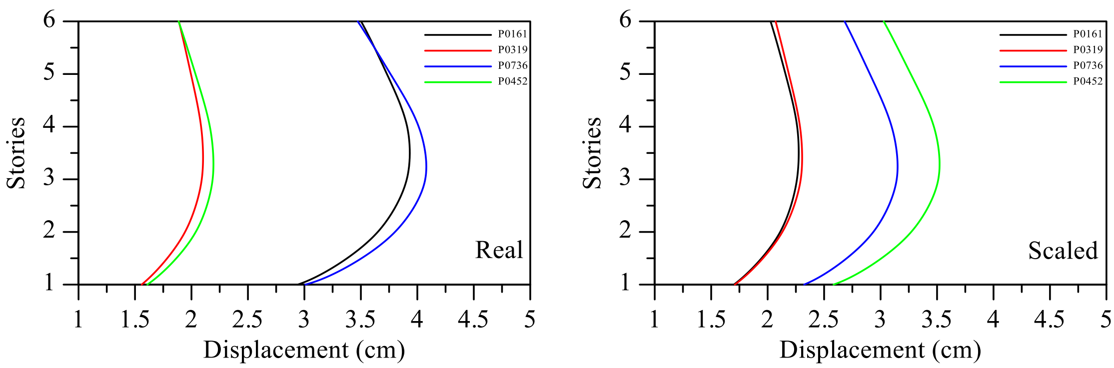


Fig. 16 Variations of relative displacements along x axis and the height of the building under the effects of earthquake records

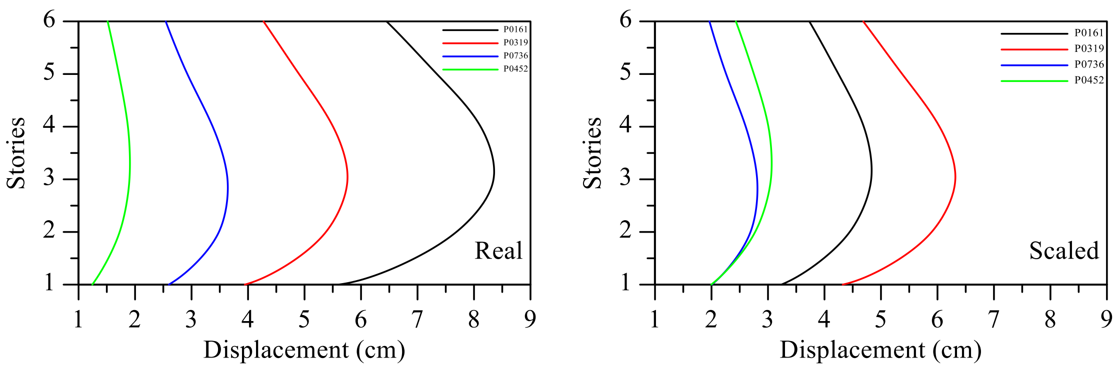


Fig. 17 Variations of relative displacements along y axis and the height of the building under the effects of earthquake records

8. Conclusions

Earthquake records for time history analyses should be scaled to code design acceleration spectrums to able to minimize differences of structural response changed from record to record by reducing amplitude variability at records.

The aim of this study is to examine the effects of real and scaled earthquake records on responses of the structures in terms of record to record variability in structural response. A six-storied building is selected as an example. Floor displacements and relative floor displacements of each story along both x and y axes of the building are taken into account as structural response after linear time history analyses.

As is seen in Figs. 14-15, floor displacements changed from record to record on both x and y axes of the building caused by scaled earthquake records are fewer than ones caused by real earthquake records. Similarly, it can be shown easily in Figs. 16-17, variations of relative displacements along both x and y axes and the height of the building under the effects of scaled earthquake records are more compatible with each other than ones of real earthquake records.

The numerical results of this study show that if unscaled earthquake records are used to make seismic analyses of any structure, structural responses depend on the effects of each earthquake record. However, structural response must reflect characteristics of seismic region, therefore earthquake records should be scaled to code design acceleration spectrums to be able to compare structural responses with each other, design spectrums and be guide in earthquake engineering.

References

Abrahamson, N.A. (1993), *Non-stationary spectral matching program RSPMATCH*, User Manual.

Bolt, B.A. and Gregor, N.J. (1993), "Synthesized strong ground motions for the seismic condition assessment of the eastern portion of the San Francisco bay bridge", Report UCB/EERC-93/12, University of California, Earthquake Engineering Research Center, Berkeley, CA.

Bommer, J.J. and Acevedo, A. (2004), "The use of real earthquake accelerograms as input to dynamic analysis", *J. Earthq. Eng.*, **8**(1), 43-91.

CEN. Eurocode 8. (2003), *Design of structures for earthquake resistance. Part 1: General rules, seismic actions and rules for buildings*, Final Draft prEN 1998, European Committee for Standardization, Brussels.

Ergun, M. and Ates, S. (2013), "Selecting and scaling ground motion time histories according to Eurocode 8 and ASCE 7-05", *Earthq. Struct.*, **5**(2), 129-142.

Fahjan, Y.M. (2010), "Selection, scaling and simulation of iput ground motion for time history analysis of structures", Seminar and Lunch on Earthquake Engineering and Historic Masonry.

Grant, D.N. (2011), "Response spectral matching of two horizontal ground-motion components", *J. Struct. Eng.*, **137**(3), 289-297.

Hachem, M.M., Mathias, N.J., Wang, Y.Y., Fajfar, P., Tsai, K.C., Ingham, J.M., Oyarzo-Vera, C.A. and Lee, S. (2010), "An international comparison of ground motion selection criteria for seismic design", *Joint IABSE–fib Conference*, May 3-5, Dubrovnik, Croatia.

Hancock, J., Watson-Lamprey, J.A., Abrahamson, N.A., Bommer, J.J., Markatis, A., McCoy, E. and Mendis, R. (2006), "An improved method of matching response spectra of recorded earthquake ground motion using wavelets", *J. Earthq. Eng.*, **10**(1), 67-89.

Heo, Y., Kunnath, S.K. and Abrahamson, N. (2011), "Amplitude-scaled versus spectrum-matched ground motions for seismic performance assessment", *J. Struct. Eng.*, **137**(3), 278-288.

Iervolino, I. and Cornell, C.A. (2005), "Record selection for nonlinear seismic analysis of structures", *Earthq. Spectra*, **21**(3), 685-713.

Iervolino, I., Cosenza, E. and Galasso, C. (2009), "Shedding some light on seismic input selection in Eurocode 8", *Eurocode 8 Perspectives from the Italian Standpoint Workshop*, 3-12, Doppiavoce, Napoli, Italy.

Kayhan, A.H., Korkmaz, K.A. and Irfanoglu, A. (2011), "Selecting and scaling real ground motion records using harmony search algorithm", *Soil Dyn. Earthq. Eng.*, **31**, 941-953.

Lilhanand, K. and Tseng, W.S. (1988), "Development and application of realistic earthquake time histories compatible with multiple-damping design spectra", *Proceedings of 9th World Conference on Earthquake Engineering*, August 2-9, Tokyo-Kyoto, Japan, II: 819-824.

MathWorks (2010), Graphical user interfaces in MATLAB, The Language of Technical Computing, Version 7.10.0.499 (R2010a).

Mukherjee, S. and Gupta, V.K. (2002), "Wavelet-based generation of spectrum-compatible time-histories", *Soil Dyn. Earthq. Eng.*, **22**(9), 799-804.

Naeim, F., Alimoradi, A. and Pezeshk, S. (2004), "'Selection and scaling of ground motion time histories for structural design using genetic algorithms", *Earthq. Spectra*, **20**(2), 413-426.

Ozdemir, Z. and Fahjan, Y.M. (2007), "Comparision of time and frequency domain scaling of real accelerograms to match earthquake design spectra", *Sixth National Conference on Earthquake Engineering*, Istanbul, Turkey.

Pacific Earthquake Engineering Research (PEER) Center (2006), PEER strong motion database, http://peer.berkeley.edu/smcat.

SAP2000 (2008), *Integrated finite element analysis and design of structures*, Computers and Structures Inc, Berkeley, California, USA.

Shama, A. (2012), "Spectrum compatible earthquake ground motions by Morlet wavelet", *20th Analysis and Computation Specialty Conference*, ASCE.

Wood, R.L. and Hutchinson, T.C. (2012), "Effects of ground motion scaling on nonlinear higher mode building response", *Earthq. Struct.*, **3**(6), 869-887.

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