16th World Conference on Earthquake Engineering, 16WCEE 2017
Santiago Chile, January 9th to 13th 2017
Paper N° 2021
Registration Code: S-O1450529484

EFFECT OF NUMBER OF RECORDS AND THEIR PROPERTIES ON THE ESTIMATION OF SEISMIC DEMANDS BY NONLINEAR ANALYSIS

J.E. Martínez-Rueda(1)

(1) *Senior Lecturer, University of Brighton – SET – Civil Engineering, jem11@bton.ac.uk*

Abstract

Design codes tend to recommend a minimum number of scaled natural earthquake accelerograms as an option to model the seismic input for time-history analysis. However there is still debate as to what that minimum number of records must be to obtain meaningful results when dealing with non-linear inelastic analysis. This article addresses the issues related to the stability of assessed seismic demands as affected by the number of accelerograms used (and their properties) for time-history analysis. To that effect, a large number of inelastic analyses are conducted using a representative inelastic MDOF system. The seismic input is modelled using a database of accelerograms recorded on rock which have been previously used for the calibration of ground motion prediction equations in Europe and the Middle East. The seismic input is scaled to match the intensity of the standard EC8 design spectrum. Scaling criteria used in the study include amplitude and dual scaling (amplitude + time scaling) to comply with EC8 recommendations related to spectrum matching, as well as, by using an optimum spectrum intensity scale. Results are assessed in terms of the stability of the predicted seismic demands as affected by the size of the family of accelerograms used for the analyses (*i.e.* families made of 3,4,5,…,11 accelerograms), and by the degree of fitting between the design spectrum and the mean response spectrum of the scaled records of the family and by the scaling criterion.

Keywords: nonlinear time-history analysis, selection of earthquake records, amplitude scaling, time scaling, dual scaling.

1. Introduction

The robust assessment of seismic demands of inelastic structures makes use of nonlinear time-history analysis. And the seismic input of this type of analysis plays a major role in the validity of the results. To get reliable demands, a suite of earthquake records (*i.e.* a family of accelerograms) rather than a single accelerogram is called for; hence seismic codes around the world recommend the use of scaled natural accelerograms as one way to define the seismic input. Although not extensive guidance is provided, the code normally recommends that the records of the family are selected to match as close as possible the seismological parameters that control the target design spectrum. Normally, accelerograms are scaled in amplitude to match the geometry of a region of the design spectrum, accounting for the fundamental period of the structure but neglecting the influence of the inelastic strength of the structure. This scaling criterion is adopted in EC8 [1] and in ASCE/SEI-7 [2]. Other scaling criteria are based on the concept of matching the intensity implicitly associated to the design spectrum while accounting for the combination of both the fundamental period and the inelastic strength of the structure [3]. This with the aim of optimizing the degree of association between the intensity of ground motion and the expected displacement ductility demand.

It is generally accepted that natural records that require scale factors close to 1 are the most ideal to use. Natural accelerograms can be also scaled in time domain to improve the resemblance between the response and the design spectrum. Hence a dual scaling process (amplitude + time scaling) [4,5] can be used as an additional tool to define the seismic input for nonlinear analysis.

The question of what is the acceptable minimum number of accelerograms to be used for nonlinear time-history analysis remains an open research question and is one of the main motivations behind this article. Most past works on practical methods to scale natural accelerograms to match a smooth design spectrum have relied on the assessment of seismic demands using stable nonlinear inelastic single degree-of-freedom systems [3-7].

1.1 Objectives and scope

The main objective of this article is to find an indication of what the minimum number of accelerograms one could use for nonlinear time-history analysis, without having a major risk of underestimating the peak seismic demands of structures that behave inelastically under the action implicit in a prescribed design spectrum. A secondary objective is the visualization of the benefits of dual scaling to specify the seismic input.

To achieve the above objectives, an inelastic structure is studied under the action of a number of families of natural accelerograms of increasing size. The accelerograms are not chosen randomly; instead, they are initially selected by identifying a reduced set of accelerograms that best resemble the geometry of the design spectrum; then they are scaled to match the ground motion intensity implicit in the design code. Four different scaling criteria (two based on amplitude scaling + two based on dual scaling) are studied in detail.

2. Analysis of an inelastic structure under the action of scaled natural accelerograms

2.1 Structure under study

The structure under study is an inelastic 3 storey shear building. The building properties of strength and stiffness were calibrated using a number of available push-over analysis results of a real 3 storey RC framed building [8], that has been modelled in the past using nonlinear fibre elements [9]. Table 1 summarizes the storey properties including the initial stiffness k_o, the stiffness of the deformation softening branch k_{ds}, the yield strength H_y, the peak strength H_u, the yield displacement Δ_y and the displacement at peak strength Δ_u. A standard Takeda rule was adopted to model the hysteric lateral response of the storeys. The standard storey height of the real building is 3.5 m; hence when assessing seismic response one has to be mindful that an interstorey displacement equal to 0.07 m is equivalent to a drift of 2%. An eigenvalue analysis of the building based on the initial stiffness of the building revealed that its fundamental period is about 0.43 sec. Based on the push over response of the building the yield seismic coefficient was found to be $C_y = 0.20$. Mild viscous damping was included in the model using a Rayleigh damping model by assigning 5% damping to the 1st mode and 1% to the 3rd mode.

Table 1. Summary of properties of the shear building

	H_y [kN]	H_u [kN]	Δ_y [m]	Δ_u [m]	k_o [kN/m]	k_{ds}[kN/m]	Mass [Tonnes]
1st storey	559.17	745.56	0.0073	0.0182	115,000.0	-4,320.7	100
2nd storey	458.42	611.22	0.0082	0.0234	84,333.3	-984.6	100
3rd storey	256.92	342.55	0.0056	0.0223	69,000.0	0	85

2.1 Seismic action

The design spectrum (target spectrum) is the so-called *horizontal elastic response spectrum* of EC8 for rock (soil Type A), spectrum shape Type 1 with periods T_b = 0.15 sec, T_c = 0.4 sec & T_d = 2.0 sec, anchored to a peak ground acceleration PGA = 0.3 g.

An ensemble of strong earthquake ground motion (SEGM) used in the past to investigate the degree of association between ground motion parameters and ductility demands [10] was selected for the current study. The ensemble is made of natural accelerograms and is part of the dataset used by Ambraseys *et al.* [11] for the derivation of a ground motion prediction equation for spectral acceleration in Europe and the Middle East. For each available record on rock in this dataset, only the stronger horizontal component with PGA greater than 0.10*g* was chosen. This lead to an ensemble of 68 natural accelerograms of SEGM.

A ranking of the elements of the above SEGM ensemble was implemented. This with the aim of assessing the goodness of fit between the design spectrum and each response spectrum of the ensemble, both normalized with respect to the *PGA* of each spectrum. The goodness of fit was assessed by ε^2 defined by:

$$\varepsilon^2 = \Sigma \left[PSA_d(T)/PGA_d - PSA_r(T)/PGA_r \right]^2 \tag{1}$$

where $PSA_d(T)$ is the pseudoacceleration of the design spectrum at period T; $PSA_r(T)$ is the pseudoacceleration of the response spectrum of the natural accelerogram at period T; PGA_d is the PGA of the design spectrum and PGA_r is the PGA of the response spectrum. The summation range of the above formula covered the period interval $[0.2T_1; 2T_1]$, where T_1 is the fundamental period of the structure. This period interval is the one used in EC8 to condition the response spectrum of the scaled natural accelerogram to have ordinates with values of at least 90% of those defined by the design spectrum. In this study, this condition is referred to as the *EC8 constraint*. Fig. 1 shows the variation of the ε^2 calculated for the spectra of the ensemble.

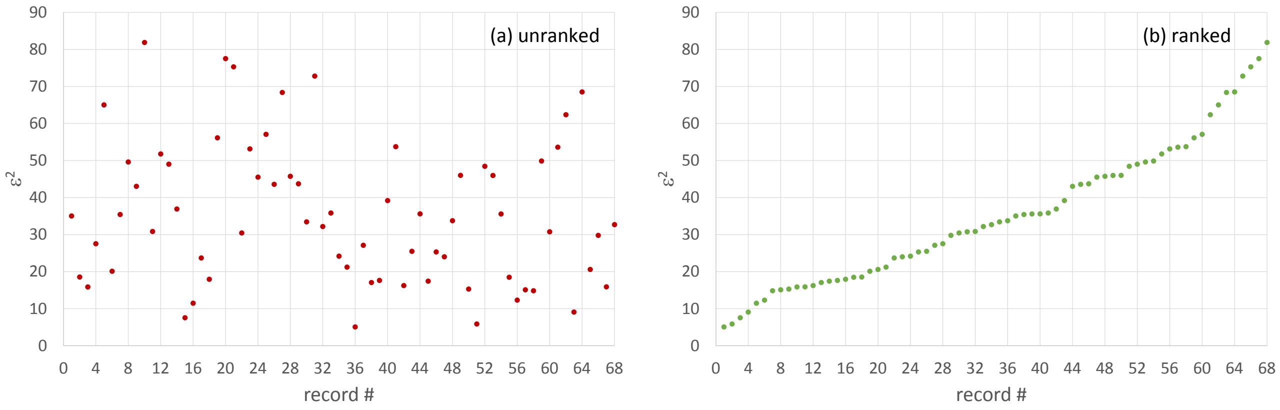

Fig. 1 - Variability of ε^2 for the accelerograms of the ensemble of SEGM used in the study

Table 2. Family of 11 accelerograms selected for the study
(M_w is Moment Magnitude and d is distance to the surface projection of the fault)

code	PGA [m/sec^2]	M_w	d [km]	Date [d/m/y]	Country	Station
001228x	2.340	7.6	30	17/08/1999	Turkey	Gebze-Tubitak Marmara Arastirma Merkezi
000055x	3.350	6.5	7	06/05/1976	Italy	Tolmezzo-Diga Ambiesta
000594y	5.433	6.0	1	26/09/1997	Italy	Noce Umbra
006713x	1.422	5.0	10	21/03/1998	Italy	Sellano Est
000665x	1.837	6.0	14	26/09/1997	Italy	Assisi-Stallone
000182y	3.744	7.3	14	16/09/1978	Iran	Dayhook
000200y	2.546	6.9	17	15/04/1979	Serbia-Montenegro	Herceg Novi-O.S.D.Pavicic
000198y	2.106	6.9	11	15/04/1979	Serbia	Ulcinj-Hotel Albatros
007142x	5.387	6.3	14	01/05/2003	Turkey	Bingol-Bayindirlik Murlugu
000290y	3.044	6.9	14	23/11/1980	Italy	Sturno
006500y	8.750	7.2	9	12/11/1999	Turkey	LDEO station No. CO375 VO

Once the elements of the ensemble of SEGM were ranked, a family of 11 accelerograms were finally chosen as the main source of seismic input for this study. The acelerograms chosen are the best 11 according to the ranking shown in Fig. 1(b) (*i.e.* the first 11 records). Table 2 summarizes the properties of the family of 11 accelerograms. Other families of accelerograms of increasing size were then formed. The family of 3 accelerograms contained the accelerograms with ranking 1st to 3rd, the family of 4 was made of the accelerograms with ranking 1st to 4th , and so on. In total, 9 families were created (*i.e.* families made of 3,4,5,…, 11 accelerograms).

2.2 Scaling criteria.

Four scaling criteria were studied and here are simply referred to as:

- EC8 scaling
- SIm scaling
- EC8 dual scaling
- SIm dual scaling

The EC8 scaling criterion is based on amplitude scaling with the aim of satisfying the constraint defined by EC8 in section 3.2.3.1.3 for recorded or simulated accelerograms.

SIm scaling refers to amplitude scaling with the aim of matching not the geometry of the design spectrum but an optimum spectrum intensity accounting for the fundamental period and the inelastic strength of the structure. With the aim of identifying an optimum degree of association between displacement ductility demand and spectrum intensity, a past study [3] identified the system of spectrum intensity scales recommended to use for amplitude scaling. From this study, and in the interest of simplicity, the criterion of Matsumura [12] to define spectrum intensity (SI_m) was chosen in the current study; namely:

$$SI_m = \frac{1}{T_y} \int_{T_y}^{2T_y} PSV(T,\xi)\, dT \tag{2}$$

where $PSV(T,\xi)$ is the pseudovelocity spectrum for a given damping ratio ξ ; T_y is the fundamental period of the structure at first yield (estimated here as the fundamental period of the structure calculated using the storey stiffnesses at yield).

The EC8 dual scaling criterion is defined here as a combination of amplitude and time-scaling. To this effect accelerograms were first scaled in time domain to improve their degree of fitting with respect to the design spectrum. The time-scaling factors (SF_t) were found by iteration with the aim of identifying the optimum SF_t for each accelerogram. With the exception of just one accelerogram, which required a SF_t = 0.55, the other accelerograms required factors close to 1 or even no factor at all (*i.e.* SF_t = 1). The quality of the time-scaled records was investigated to confirm no anomalies were introduced by the scaling. The time-scaled accelerograms were then subjected to amplitude scaling to comply with EC8 requirements (*i.e.* the same requirements used in the EC8 scaling criterion).

For SIm dual scaling criterion the same SF_t factors were used, but the amplitude scaling of the time-scaled accelerograms was perform using the same approach as in the SIm scaling.

2.3 Spectral shapes

Figs. 2 and 3 compare the mean spectrum with the design spectrum for different scaling criteria. It is observed that the application of the *EC8 constraint* observed in Figs. 2(a),(c) and 3(a),(c) has a negative effect on the degree of fitting between the target and the mean spectrum. In general, at first glance, no major differences are perceived between the mean spectra generated by different scaling criteria.

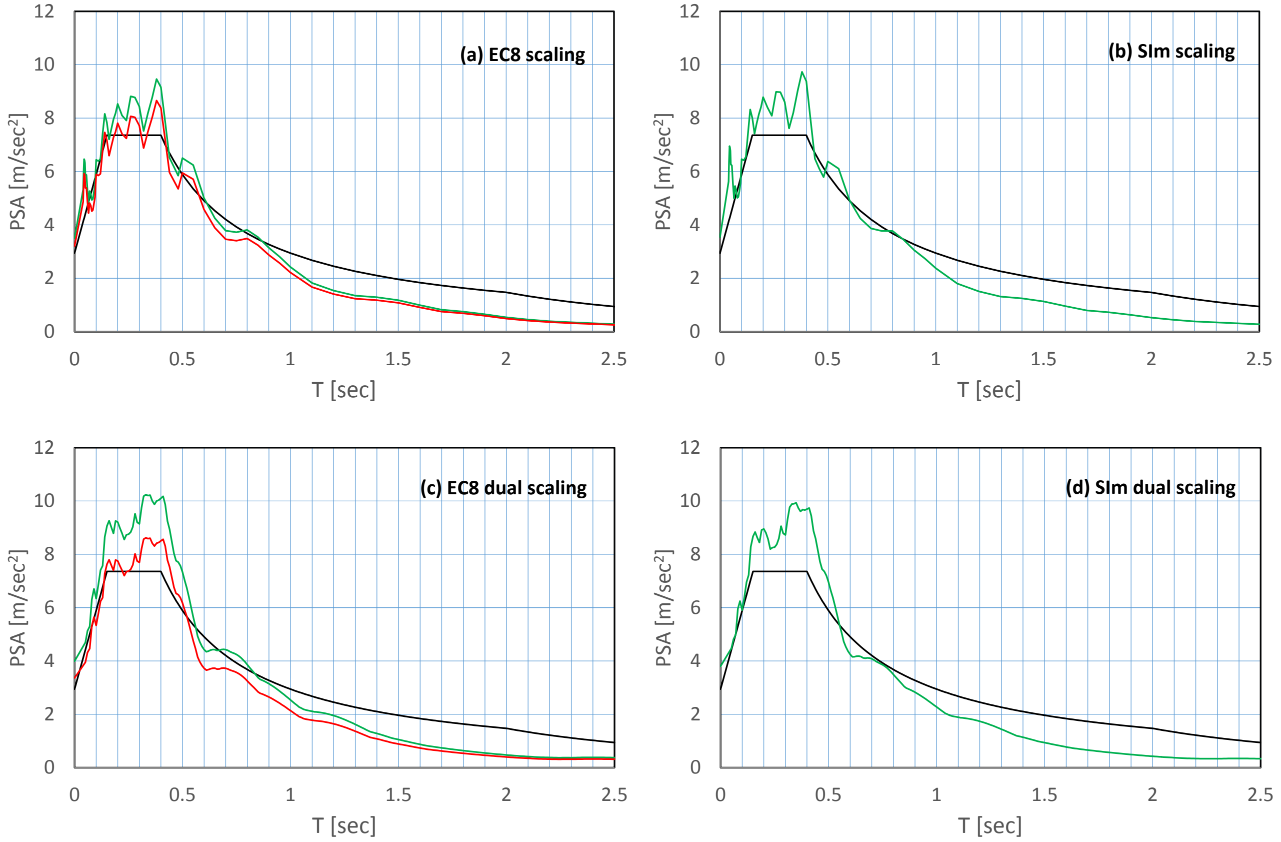

Fig. 2 - Comparison between target spectrum and mean response spectrum for the family of best 3 accelerograms for different scaling criteria [plots (a) & (c) include the mean response spectrum with and without the application of the *EC8 constraint*]

Further comparison between Figs. 2 and 3 reveals that the effect of increasing the number of records in the family has a ‘negative’ effect on the degree of fitting between the target and the mean response spectrum. This was expected and it is consistent with the way each family was formed (*i.e.* the larger the number of records in the family the larger the average value of ε^2).

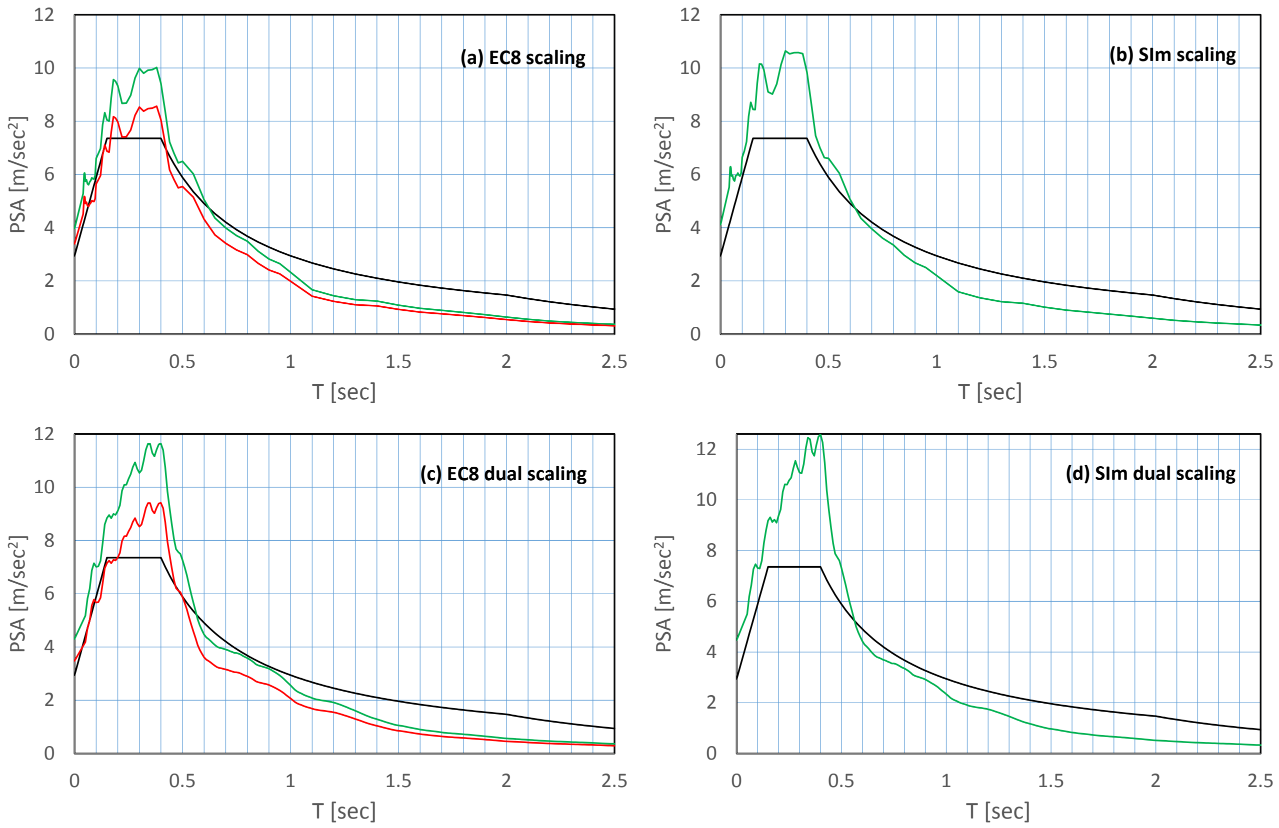

Fig. 3 - Comparison between target spectrum and mean response spectrum for the family of best 7 accelerograms for different scaling criteria [plots (a) & (c) include the mean response spectrum with and without the application of the *EC8 constraint*]

3. Analysis of seismic demands obtained by nonlinear time-history analysis

Fig. 4 exemplifies the type of results obtained for the storeys of the structure under the action of the scaled accelerograms. Results obtained for each family of accelerograms were processed with the aim of identifying possible indications of 'convergence' of the statistics in terms of maxima and central tendencies. As each family has a different size it is difficult to make objective comparisons by using mean values. On the other hand, it is well known that median values are less susceptible to the influence of outliers. For the above reasons, when describing central tendency values, the median rather than the mean was used to assess the stability of the central tendency of the results as affected by the size of each family.

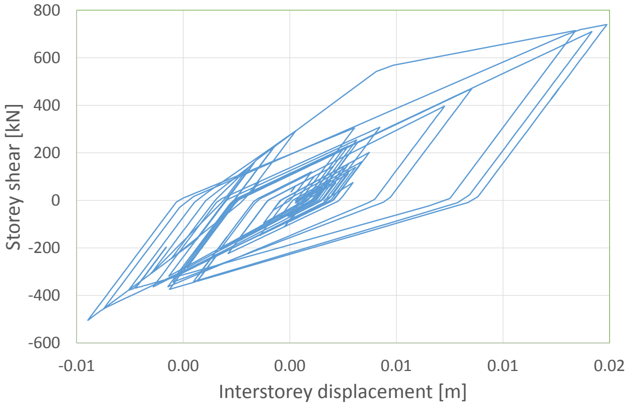

Fig. 4 - Hysteretic response of the first storey of the building under study when subjected to the accelerogram 200y scaled according to the EC8 dual scaling criterion.

3.1 Interstorey displacements

Fig. 5 summarizes the central tendency of the interstorey displacements obtained from the non-linear time history analyses. It is evident that the 2nd storey is the critical one showing in general greater interstorey displacements. The more stable trends are those associated with SIm scaling and with SIm dual scaling. It is important to note that in 3 of the 4 scaling criteria under study, the critical displacement (*i.e.* maximum median interstorey displacement) occurs when 6 records are used for analysis. A notable exception is the SIm dual scaling criterion where the peak occurred when using the family of 5 records. In other words, keeping in mind the way that records were assigned to each family, one could argue that, in general, the use of less than 7 records increases the chances of missing the above critical displacement (except when using SIm dual scaling where only 6 records would be needed to identify the above critical value, *i.e.* the peak occurred between the family 4 and the family of 6).

It is interesting to note that, for a given family, the mean response spectrum when using SIm scaling does not comply with the EC8 constraint. Nevertheless, the seismic demands obtained with SIm are consistently higher than those seen for EC8 scaling. Hence, not complying with the standard scaling procedure recommended in EC8 does not necessarily mean that one obtains unsafe results.

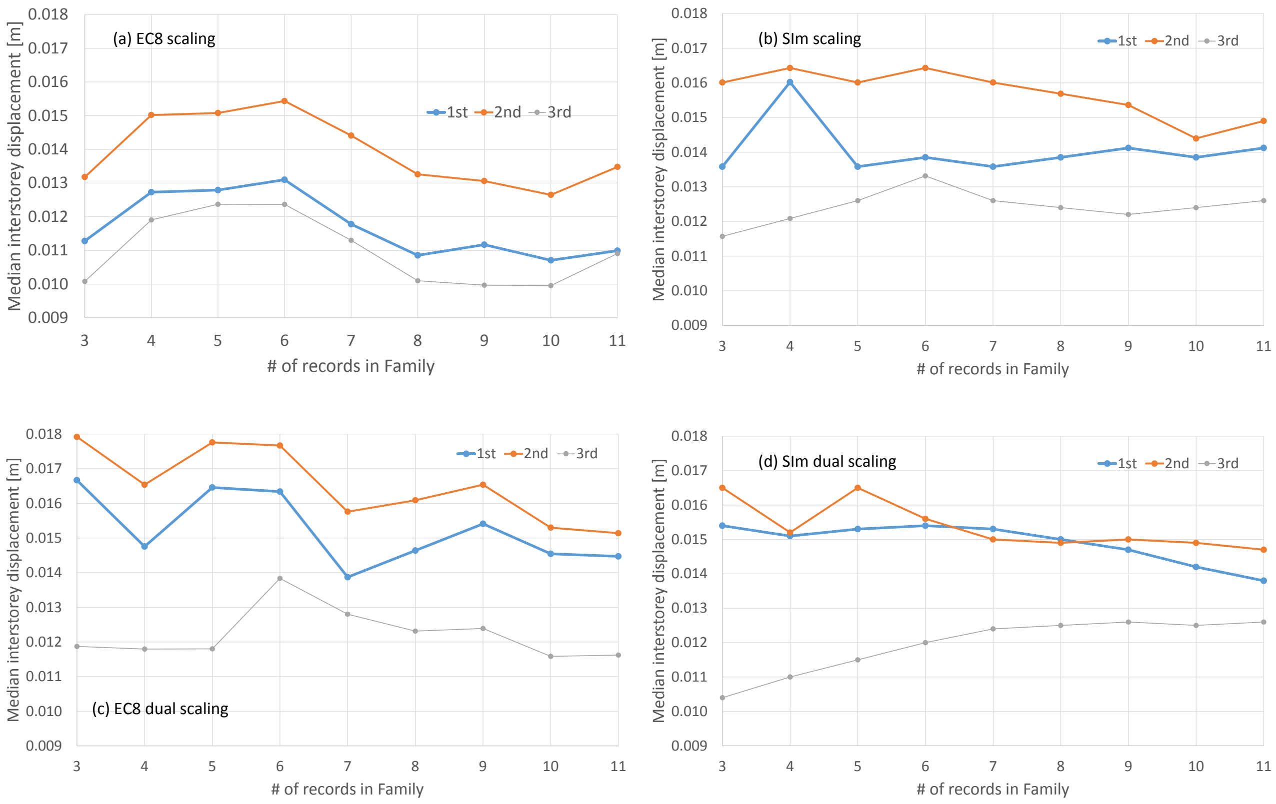

Fig. 5 - Effect of family size on the median interstorey displacement

3.2 Maximum interstorey displacement

When using a small number of records to assess seismic demands, some analysts prefer to use the maximum value rather than a central tendency value. Fig. 6 shows the variation of the maximum interstorey displacements as affected by the number of records used as seismic input. Note that with the exception of the EC8 scaling criterion, the rest of the scaling criteria are able to capture the seismic demand imposed by the critical accelerogram (*i.e.* that associated with the maximum interstorey displacement of the critical storey) for families of 6 or less accelerograms. In fact, one would need at least 7 records to be able to identify the peak demand when using a scaling criterion involving dual scaling, and only 5 records would be needed when using SIm scaling. The benefit of dual scaling is perceived while comparing the two plots associated with dual scaling [Figs. 6(c) and 6(d)] which reveal smaller differences between them than those observed between plots for amplitude scaling [Figs. 6(a) and 6(b)].

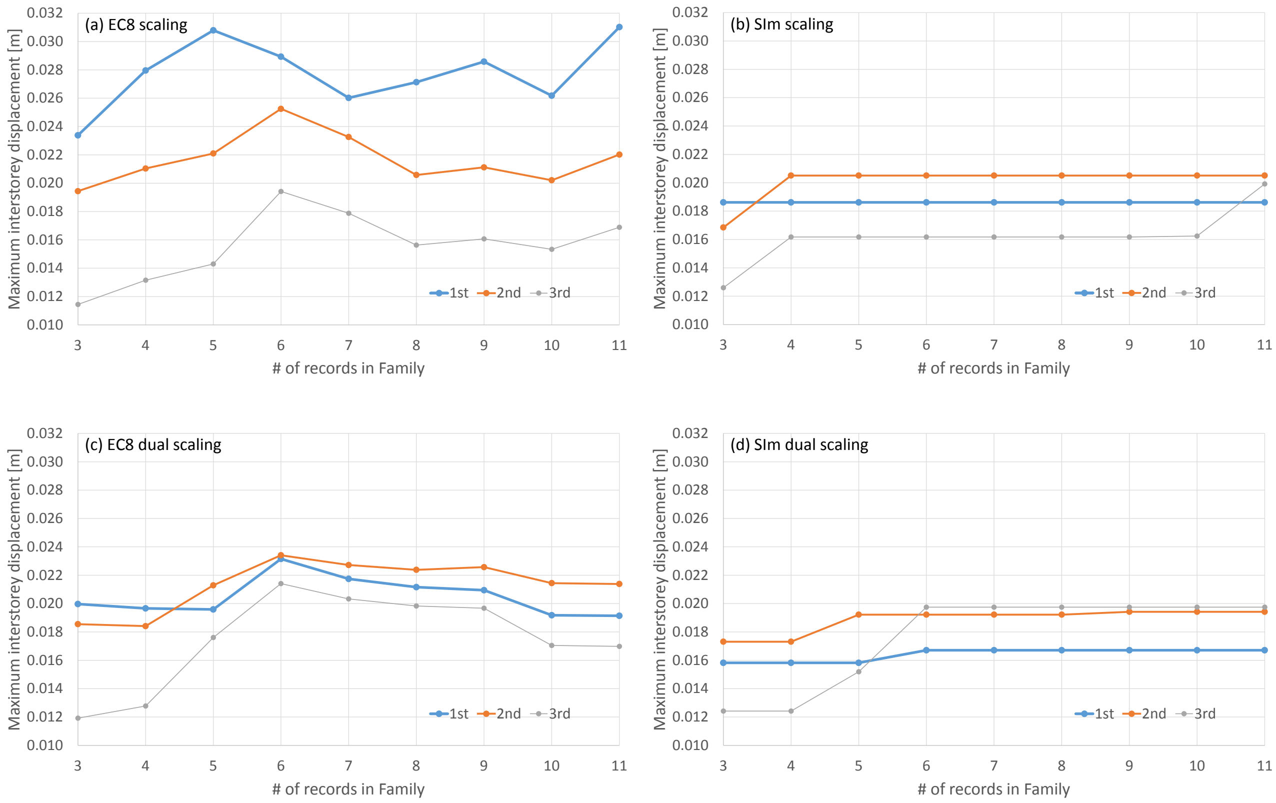

Fig. 6 - Effect of family size on the maximum interstorey displacement

3.3 Storey ductility demands

Detailed analysis of results showed that all scaled records of every family lead to inelastic response, regardless of the adopted scaling criterion. As the storeys of the structure under study have different yield displacements, the plots of Fig. 7 show similar individual trends when compared to those of Fig. 6 but in a scaled fashion. Fig. 7 reveals that in general, the ductility demands were rather mild. At first glance it appears as if the 3rd storey is the critical one; however, this is only apparent as the 3rd storey has the highest ductility capacity as it is not susceptible to deformation softening (see Table 1). Accordingly, the observations in terms of an acceptable minimum number of records that were presented in section 3.1 remain valid.

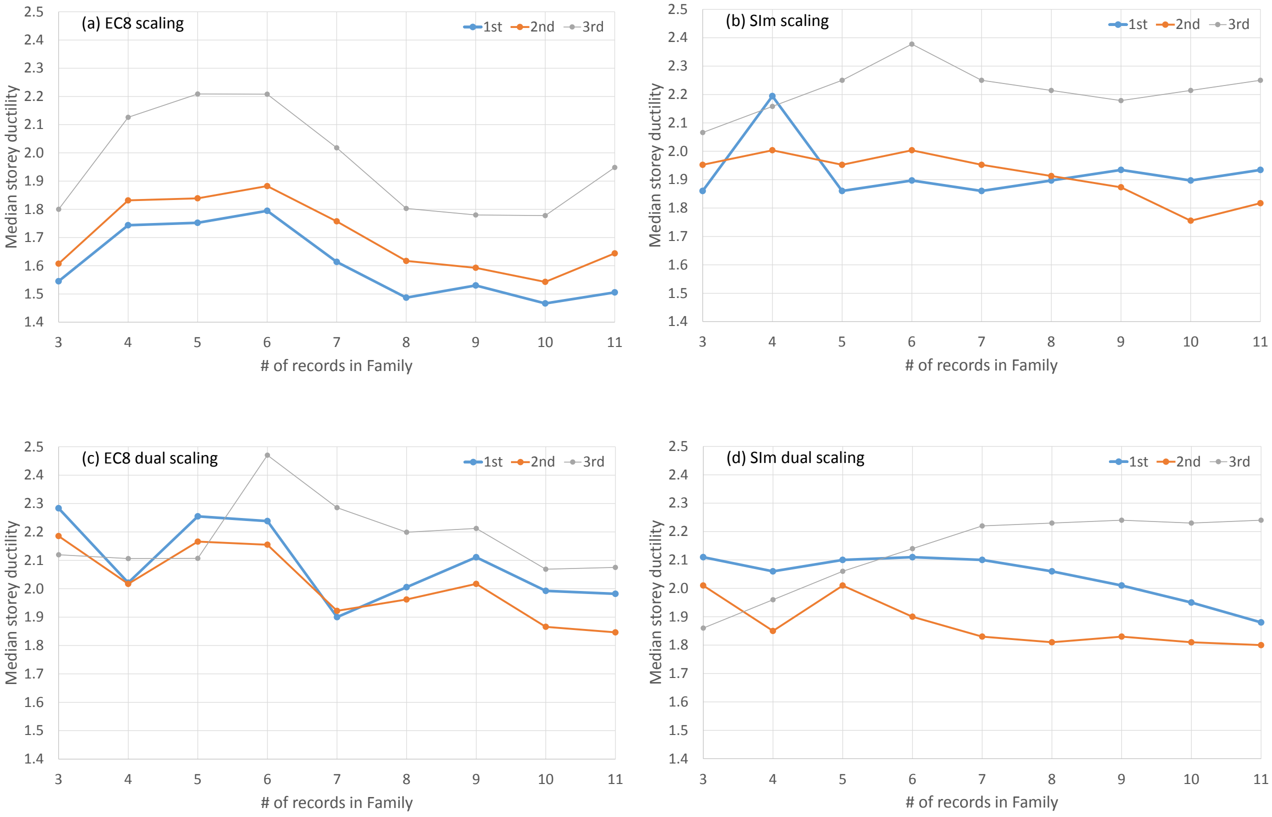

Fig. 7. Effect of family size on median storey ductility demand

4. Concluding remarks

This study introduced a methodology to systematically select a family of natural accelerograms for nonlinear time-history analysis. In this methodology accelerograms are not selected at random but based on their assessed goodness of fit with respect to the design spectrum. If accelerograms are selected in this way, the study on the effect of the family size on the assessed seismic demands suggests that a minimum of 7 records improves greatly the chances of being able to capture the accelerogram expected to inflict maximum response. Penalizing the analyst to use the maximum demand if only 3 or 4 accelerograms are used, is not a guarantee against underestimating seismic demands. Based on the case study reported here, it is also concluded that the use of dual scaling improves significantly the stability of results even when following the EC8 recommendations for amplitude scaling.

5. References

[1] European Committee for Standardisation. *Eurocode 8: Design of Structures for Earthquake Resistance* 2008.

[2] American Society of Civil Engineers. *ASCE-SEI-7-10 Minimum Design Loads for Buildings* 2010.

[3] Martínez-Rueda JE (1998): Scaling procedure for natural accelerograms based on a system of spectrum intensity scales. *Earthquake Spectr*a, **14**(1), 135-152.

[4] Martínez-Rueda JE (2012): Analysis of practical engineering approaches to guide the dual scaling of earthquake ground motion for non-linear time-history analysis. *15th World Conference on Earthquake Engineering,* Lisbon, Portugal.

[5] Martínez-Rueda JE, Hamedi F (2014): Dual *vs.* amplitude scaling in nonlinear time-history analysis. *10th U.S. National Conference on Earthquake Engineering*, Anchorage, U.S.A.

[6] Fahjan Y, Ozdemir Z (2008): Scaling of earthquake accelerograms for nonlinear dynamic analyses to match the earthquake design spectra. *14th World Conference on Earthquake Engineering*, Beijing, China.

[7] Reyes JC, Kalkan E (2012): How many records should be used in an ASCE/SEI-7 ground motion scaling procedure? *Earthquake Spectr*a, **28**(3), 1223-1242.

[8] Hoffmann GW, Kunnath AM, Reinhorn, AM, Mander JB (1990): Gravity-load-designed reinforce concrete buildings: seismic evaluation of existing construction and detailing strategies for improved seismic resistance. *Technical report NCEER-92-0016.* National Center for Earthquake Engineering Research, New York, USA.

[9] Martinez-Rueda JE (1997): Energy dissipation devices for seismic upgrading of RC structures. *PhD Thesis*. Imperial College of Science, Technology and Medicine, London, UK.

[10] Martinez-Rueda JE, Vlachos T (2010): Instrumental earthquake intensities *vs.* ductility demand: correlation study using data from Europe and the Middle East. *7th International Conference on Urban Earthquake Engineering and 5th International Conference on Earthquake Engineering*, Tokyo, Japan.

[11] Ambraseys NN, Douglas J, Sarma K, Smit PM (2005): Equations for the estimation of strong ground motions from shallow crustal earthquakes using data from European and Middle East: horizontal peak ground acceleration and spectral acceleration. *Bulletin of Earthquake Engineering* 2005, **3**(1), 1-53.

[12] Matsumura K (1992): On the intensity measure of strong motions related to structural failures. *10th World Conference on Earthquake Engineering*, Madrid, Spain.