ACES Workshop on Performance-Based Earthquake Engineering
Corfù, Greece, 5-6 July 2009

# Real, scaled, adjusted and artificial records: a displacement and cyclic response assessment.

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**Abstract**

Different procedures to obtain sets of spectral matching records for nonlinear dynamic analysis of structures were compared in terms of post-elastic structural response. Six typologies of records were considered: un-scaled real records, real moderately linearly scaled, real significantly linearly scaled, real adjusted by wavelets, artificial generated by two different procedures. The study is spectral shape-based, that is, all the considered sets of records, either generated or selected, match, individually (artificial and adjusted) or on average (real records), the same design spectrum of a case-study site in Italy. Bilinear non-degrading single degree of freedom systems were used to evaluate the nonlinear response for the compared sets at different non-linearity levels; i.e., demand spectra in terms of peak and cyclic response were derived for two strength reduction factors. Results show that artificial or adjusted records may underestimate, at high non-linearity levels, the displacement-related non-linear response if compared to real records, which are considered as a benchmark. Conversely, if the cyclic response is considered, artificial record sets show a (more evident) overestimation of the demand, while wavelet-adjusted do not display a significant bias. Finally the two groups of linearly scaled records seem to show no systematic bias for both types of response considered suggesting, as expected, that scaling does not impair estimation of seismic response if the spectral shape is controlled.

## 1. Introduction

Seismic assessment of structures via non-linear dynamic analysis requires proper seismic input selection. Seismic codes suggest different procedures to select ground motion signals, most of those assuming spectral compatibility to the elastic design spectrum as the main criterion (Iervolino *et al.*, 2008). On the other hand, practitioners have several options to get input signals for their analysis; e.g., various types of synthetic, artificial, real or real-manipulated records (Bommer and Acevedo, 2004). Codes usually acknowledge the use of different types of records and may provide additional criteria or limitations for each of those. In the new Italian seismic code (CS.LL.PP., 2008), for example, artificial records should have duration of at least 10 seconds in their *pseudo-stationary* part, and they cannot be used in the assessment of geotechnical structures. Synthetic generated by simulation of earthquake rupture and propagation process should refer to a characteristic scenario for the site in terms of magnitude, distance and other source seismological characteristics; finally, real records should reflect the event *dominating* the hazard at the site. However, practitioners not always can accurately characterize the seismological threat to generate synthetic signals or it is not possible to find a set of real records that fits properly code requirements in terms of a specific hazard scenario (Convertito *et al.*, 2009). In fact, despite in the last decades the increasing availability of databanks of real accelerograms, the most sound representation of ground motion, has determined a spread use of this type of records to characterize seismic input, it may be very difficult to successfully apply code provisions to natural record sets, especially those regarding spectral compatibility, if appropriate tools are not available (Iervolino *et al.*, 2008). This is why the relatively easy and fast generation of artificial records (i.e., via *random vibration* procedures) perfectly compatible with an assigned design spectrum, has become very popular for both practice and research purposes. More recently, algorithms to get the spectral compatibility of real records by wavelets adjustment were proposed (Hancock *et al.* 2006). This kind of manipulation is an extension of the more simple linear scaling of real records to modify (e.g., to amplify) the spectral shape to get a desired intensity level (Iervolino e Cornell, 2005).

Although, several studies tried to assess the reliability of each of these procedures (e.g., Schwab and Lestuzzi, 2007), general conclusions seem hard to be derived from the literature. This work tries to address the spectral matching issue from the structural point of view in terms of non-linear peak and cyclic response, simply having as reference a code-based design spectrum. To this aim six categories of 28 accelerograms, each of which consisting of four sets, were considered: un-scaled real records (URR); moderately scaled real records (SF5); largely scaled real records (SF12); wavelet-adjusted real records (RSPMatch); type 1 artificial records (Belfagor); type 2 artificial records (Simqke).

The basis of this study is the elastic pseudo-acceleration design spectrum, that is, all sets are compatible with the same elastic code spectrum for a case study site in southern Italy (see following section). As structural response measures, or engineering demand parameters (EDPs), the peak inelastic displacement, the kinematic ductility and the equivalent number of cycles were considered to relate the structural response to both peak and cyclic content of ground motion.

Analysis of a large number of single degree of freedom (SDOF) systems with an elastic-plastic with hardening behavior aimed at assessing and comparing the bias, if any, associated to each typology of records for the three EDPs with respect to the un-scaled real ground motions which are considered as a benchmark.

## 2. Records

Six categories of records were selected assuming the same target spectrum built according to the new Italian seismic code for a case-study site (Avellino, southern Italy) having as geographical coordinates: lat. 40.914, long. 14.78. The 5% damped elastic spectrum considered is that related to the *life-safety* limit state of an ordinary construction with a nominal life of 50 years on A-type (stiff) soil class; see CS.LL.PP. (2008) for details.

For each category four spectrum compatible sets of seven records were selected (if real) or generated (if artificial). Assuming sets of seven records acknowledges the Italian and Eurocode 8 (CEN 2003) prescriptions allowing to consider the mean structural response from non-linear dynamic analyses if at least seven records are employed.

In the following the selection or generation of the sets are briefly reviewed.

URR, UN-SCALED REAL RECORDS - The sets of un-scaled real records were selected using REXEL, a software which allows to select combinations of multi-component real ground motion records, contained in the European Strong-Motion Data Base (ESD – http://www.isesd.cv.ic.ac.uk/ESD) and in the Italian Accelerometric Archive (ITACA – http://itaca.mi.ingv.it/ItacaNet), which on average match an arbitrary or code-based elastic spectrum (Iervolino *et al.*, 2009). Providing to the software the geographical coordinates of the site and the limit state of interest it was possible to select four sets of records matching on average the target spectrum in the 0.15s-2.0s range. Moment magnitude and source-to-site distance range between 5.6-7.8 and 0km-35km, respectively. In Figure 1a the four sets' means are represented along with individual records and target spectra. All the averages of the sets are within the [-10%, + 30%] tolerance interval with respect to the target spectrum, and in most of the compatibility interval they approximate very well the design spectral shape. The four URR sets have no registrations in common and come from 17 different earthquake events.

SCALED REAL RECORDS - Also linearly (amplitude) scaled records were selected with REXEL. In particular two categories of four scaled records sets each, differing for the average scaling factor (SF), were selected: (1) SF = 5; (2) and SF = 12. The intent is to compare the responses to records moderately and significantly scaled. The range of periods considered is the same as per URR.

SF5 - In the same magnitude and distance ranges chosen for un-scaled records, four sets of seven compatible accelerograms each of those has a mean SF equal to 5, thanks to a specific option of REXEL, were selected, Figure 1b. The 28 different records (9 records in common with URR) come from 15 earthquake events (10 of them are in common with URR). Note that the variability of the scaled sets is smaller than those un-scaled as expected (Iervolino *et al.*, 2008 and 2009).

SF12 - Using REXEL three sets of seven records whose average SF was 12, were also defined. Because it was not possible to find another set with the desired characteristics, the fourth set of seven accelerograms was "manually" selected so that its average scaling factor was similar to the other three sets selected with the computer software. These four sets have no events in common with the URR sets and come from 17 different earthquakes, Figure 1c.

RSPMATCH, WAVELET ADJUSTED RECORDS - RSPMatch2005 software (Abrahamson, 1992; Hancock *et al.*, 2006) was used to modify the URR sets; in this case the adjustment procedure was simply aimed at reducing the mismatch of individual records with respect to the target. The procedure was pursued only for the 5% damping factor in the range of period [0.15s-2.0s] in which records were already compatible on average and without the application of any linear scaling factor, Figure 1d.

ARTIFICIAL RECORDS - Generally speaking, generation procedures for artificial accelerograms are based on the random vibration theory and the spectral matching is carried out via an iterative adjustment of the Fourier spectrum (Pinto *et al.*, 2004). The two computer programs selected for this study generate different kind of signals: the first one, Belfagor (Mucciarelli *et al.*, 2004) produces non stationary signals; the second one Simqke (Gasparini and Vanmarke, 1976) produces stationary signals that are subsequently enveloped in a trapezoidal shape.
Belfagor records - Belfagor generates non stationary signals by using variable Fourier amplitudes empirically evaluated; in fact, the code asks for reference M, R values and soil type, even if the spectrum to match is a code spectrum. Using Belfagor 28 accelerograms were generated. They all have the same duration, 21.48 seconds and a sampling time step of 0.005 seconds. Records were arranged in four sets of seven records, Figure 1e.
Simqke records - A second group of four sets of artificial records was generated by Simqke. This well-known software generates groups of stationary artificial records in a way they fit the target spectrum. In this case 28 records were generated together and then they were split in four groups of seven, Figure 1f.

Each accelerogram of the six categories was also processed to evaluate characteristic (integral) parameters other than the spectral shape. Arias intensity ($I_A$), and the Cosenza and Manfredi index ($I_D$), Equation (2), computed as the mean of the sample of 28 records for each category, are reported in Figure 2. $I_D$ is defined as a factor times the $I_A$ divided by the peak ground acceleration (PGA) times the peak ground velocity (PGV), Iervolino *et al.* (2006).

$$I_D = \frac{2 \cdot g}{\pi} \cdot \frac{I_A}{PGA \cdot PGV} \tag{2}$$

It is possible to see that real records, both scaled and un-scaled, have close mean values of $I_D$ as well as RSPMatch records. Both categories of artificial records display higher values of $I_D$. The Simqke records show comparatively high values of $I_A$ and $I_D$. Belfagor records compare better to real records at least in terms of $I_A$.

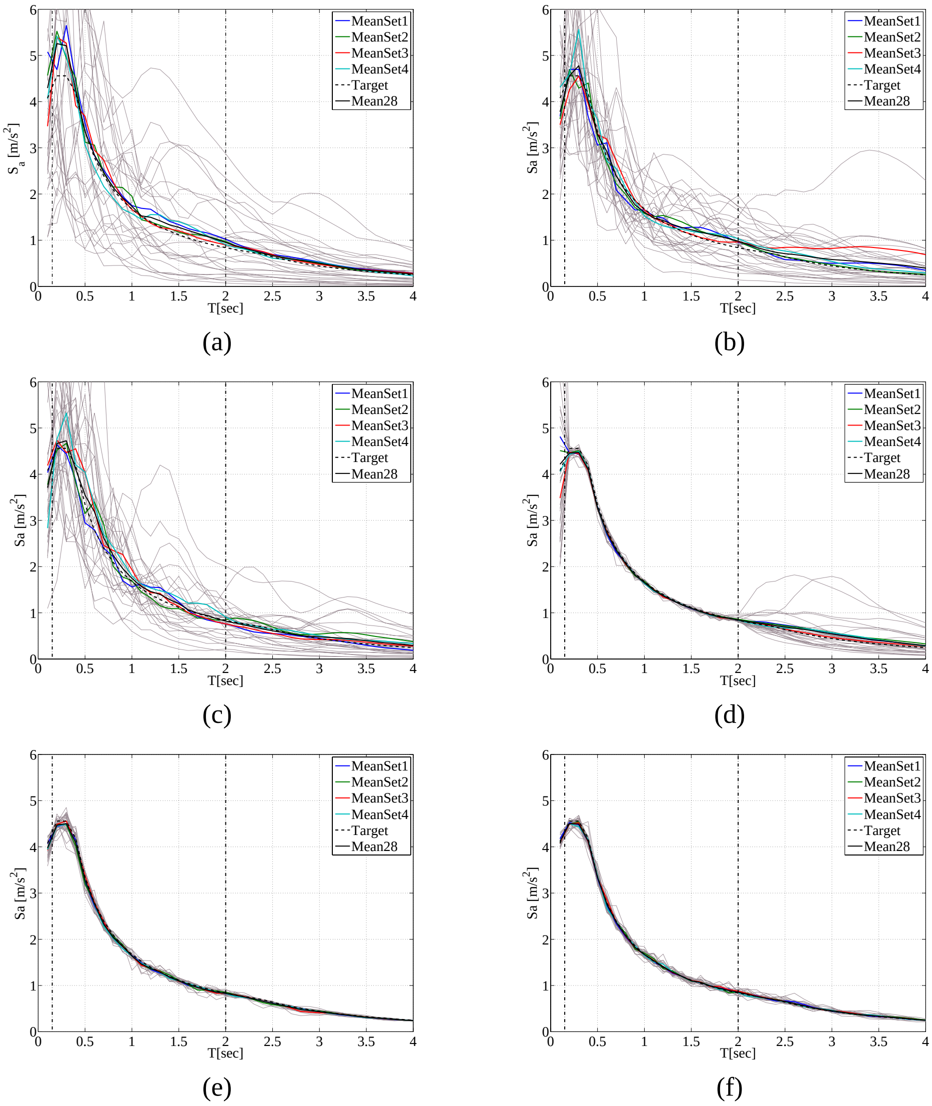



**Fig. 1 URR (a), SF5 (b), SF12 (c), RSPMatch (d), Belfagor (e), Simqke (f) acceleration response spectra.**

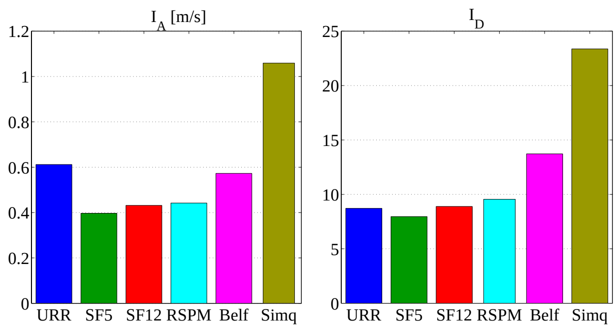



**Fig. 2 Average values of $I_A$ and $I_D$ computed as mean value of 28 records.**

## 3. Analyses and structural response measures

All records selected for each category were used as an input for non-linear dynamic analyses applied to 40 inelastic SDOFs, whose periods (T) vary linearly from 0.1 to 2 seconds. Inelastic SDOFs have an elastic-plastic with hardening backbone; post-yield hardening ratio was assumed as 0.03 times the initial stiffness ($k_{el}$). In Figure 3 SDOF behavior is represented, where $F_y$ and $\Delta_y$ are yielding force and displacement respectively.

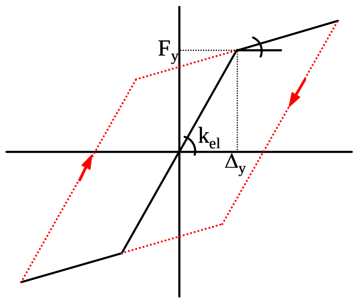



**Fig. 3 SDOF backbone curve.**

It is to recall that the peak elastic deformation experienced by an elastic structure is a ground-motion specific quantity. Therefore, one can achieve the same value of the strength reduction factor (R), either for each record in a dataset (*constant R* approach) or on an average sense for all the records, that is, relating the R factor to the target spectrum matched (*constant strength approach*) as in Equation (3) where $Sa_{e,t}$ is the acceleration ordinate in the code spectrum at the period of the SDOF and m is its mass. The latter approach was considered herein, to simulate the effect of different sets of accelerograms on the same structure; in particular two R values were chosen, 4 and 10, to cover a wide range of non-linearity levels.

However, it should be emphasized that the two different approaches may lead to different conclusions (Bazzurro *et al.*, 2004).

$$F_y = Sa_{e,t}(T) \cdot m/R \tag{3}$$

EDPs chosen were selected to investigate both peak and cyclic seismic response. Displacement-based parameters are: the peak inelastic displacement ($Sd_{R=i}$) and the kinematic ductility ($D_{kin}$) evaluated as the ratio of $Sd_{R=i}$ and the yielding displacement, Equation (4). The equivalent number of cycles ($N_e$) was also considered. It includes the hysteretic energy ($E_H$) normalized with respect to the largest cycle, decoupling ductility demand (already considered above) and cyclic demand, Equation (5).

$$D_{kin} = Sd_{R=i} / \Delta_y \tag{4}$$

$$N_e = E_H / \left[ F_y \cdot \left( Sd_{R=i} - \Delta_y \right) \right] \tag{5}$$

## 4. Results and discussion

PEAK RESPONSE – The peak displacements for the SDOF systems are presented as mean value on 28 records pooled per typology. Figures 4a and 4b show inelastic result for the two R values equal to 4 and 10. Additional results relative to other R values and other engineering demand parameters (EDP) can be found in De Luca *et al.* (2009). Generally, the adjusted and artificial records seem to show a systematic underestimation of the displacement response if compared to the URR for the higher non-linearity levels, and at least in the range of period of interest for the non-linear behavior of the most of common structures.

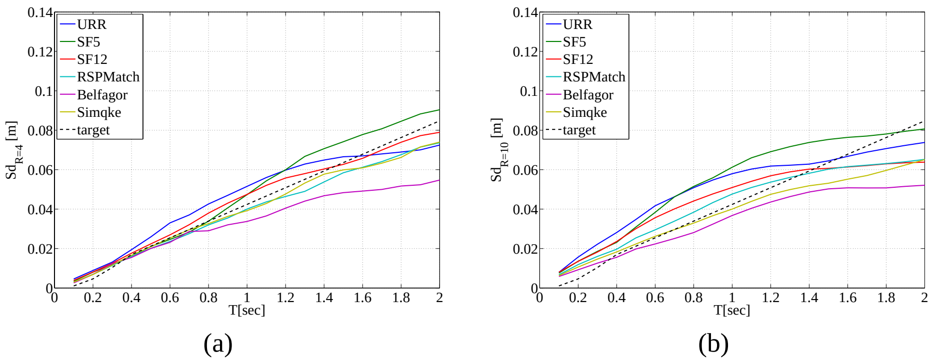
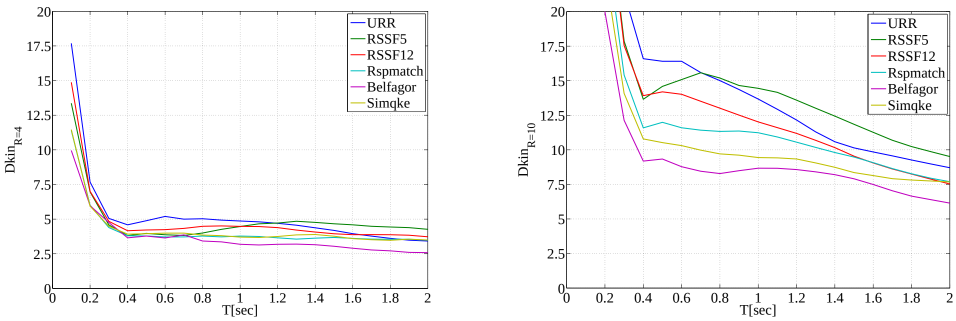



**Fig. 4 R = 4 (a) and R = 10 (b) displacements for each category (28 category).**

SF5 and SF12 do not show a systematic trend with the period. Belfagor records, in particular, lead systematically and for both R values, to average inelastic displacements lower than the elastic target spectra. However, hypothesis tests employed to assess quantitatively the significance of these results do not lead to the conclusions that any of these biases are statistically significant.

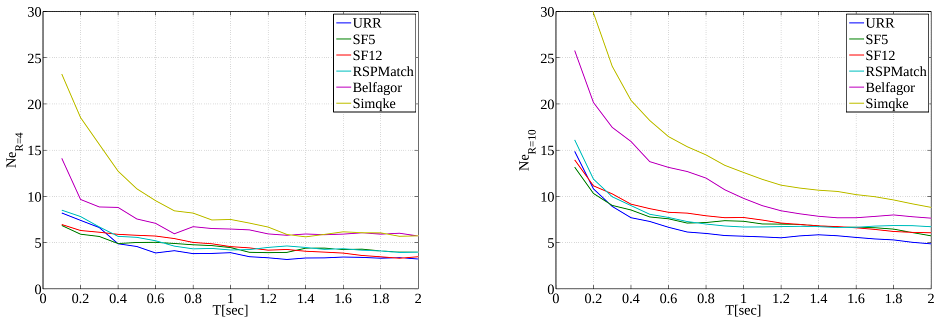
DUCTILITY DEMAND - The kinematic ductility may be useful to assess the absolute displacement demand. Figure 5a and Figure 5b show the same trend observed above, that is, artificial or adjusted records may show underestimation with respect to URR only at high non-linearity levels. Ductility demands for each category are very close to each other for R equal to 4; increasing the reduction factor leads to the same trend found for inelastic displacements. In this case URR ductility demand, for R equal to 10, in the moderate periods range, is about two times that of Belfagor records.




(a) (b)

**Fig. 5 R = 4 (a) and R = 10 (b) ductility demand (28 category).**

EQUIVALENT NUMBER OF CYCLES - More evident conclusions may be found when analyzing the trends of the equivalent number of cycles; Figure 6.




(a) (b)

**Fig. 6 R = 4 (a) and R = 10 (b) equivalent number of cycles (28 category).**

For all the non-linearity levels, a significant overestimation in terms of cyclic response may be observed for both adjusted and artificial records. In this case Simqke records show the highest $N_e$ values that in some cases can get over 200% with respect to the URR; Belfagor records have the same trend, although with a lower bias. Wavelet-adjusted records seem to not show a bias.
It is to note that trends found for $N_e$ could have been be predicted by the integral parameters discussed above; i.e., the $I_D$ values of the sets. Figure 7 show $N_e$ versus $I_D$ for the individual records for T equal to 0.6 seconds, for R equal to 4 (a) and 10 (b). The high values of $I_D$ of the artificial records seem to agree with the high $N_e$ values (more evidently for the Simqke records).

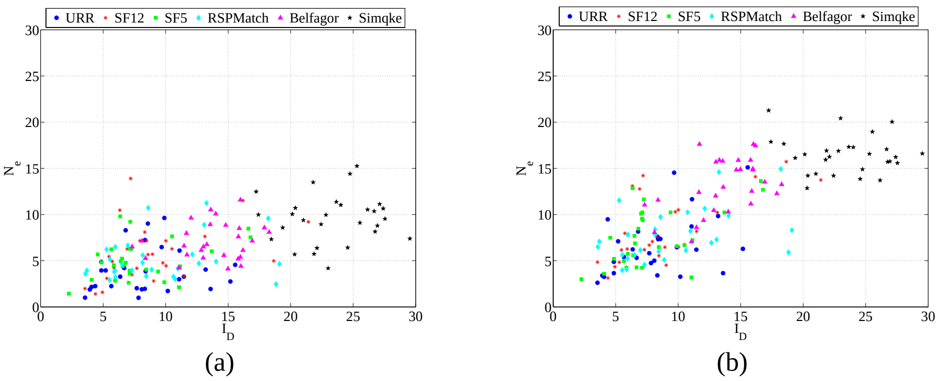



**Fig. 7 Ne versus $I_D$ for R = 4 (a) and R = 10 (b) and T = 0.6 seconds.**

## 5.Conclusions

In this work different ways to achieve spectral matching record sets were compared in terms of both peak and cyclic of inelastic seismic response of 40 non degrading SDOFs.
Six typologies of records were considered: real un-scaled, real with limited average scaling factor, real with large average scaling factor, real adjusted with wavelets, and two different types of artificial records. The benchmarks were the design elastic spectrum for a case study site in southern Italy and the response to unscaled records matching it on average.
Results seem to indicate that artificial and wavelet-adjusted records may underestimate peak displacement-related demand, although this is evident only for high R values and it was not found to be statistically significant. On the other hand, when cyclic response is of concern, artificial records show a strong overestimation with respect to real records and wavelet-adjusted records.
All the trends for the linearly scaled records seem to be non-systematic indicating that scaling does not bias the response if the spectral shape is a control factor.

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