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UNSCALED REAL RECORD SETS COMPLIANT WITH EUROCODE 8

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SUMMARY

Among all possible options, natural recordings are emerging as the more attractive input for non-linear dynamic analysis since accessible waveform databases are available and some evidences show that only a limited number of criteria have to be considered in selection to get unbiased estimation of seismic demand. The Eurocode 8 allows the use of real ground motions for the nonlinear seismic analysis of structures. The main constraint to be satisfied by the chosen record set is the matching, of the average spectral ordinates, with the elastic code spectra. In fact, the latter may not be underestimated more than by 10% in a broad range of periods. Code's spectral shape depends on the seismicity of the site, which may be obtained by national seismic surveys (Italian herein), and on the soil conditions.

The study presented in the paper investigated the European Strong Motion Database to establish whether combinations of unscaled records complying with the Eurocode 8 prescriptions, and also accounting for additive constraints believed to matter in the non-linear assessment of buildings, may be found. Results refer to soft soils, stiff soils and rock. The accelerogram sets obtained tend to overestimate as minimally as possible the code's spectrum for economical reasons; to have the minimum record-to-record variability; and are not manipulated (i.e. not scaled), to avoid "epsilon" related issues.

1. INTRODUCTION

International codes often allow the non-linear dynamic analysis as a tool for assessment of the seismic response of structures. This option requires some characterization of the seismic input which should reflect the hazard as well as the soil conditions at the site. Despite significant research effort in recent years attempted to discriminate scalar or vectorial parameters proxy for those signal features affecting the structural response, the codes often only prescribe some compatibility of the chosen records to a smooth design pseudo-acceleration spectrum and other minor requirements.

The earthquakes signals that can be used as input for non-linear analysis, are basically of three types: (1) Synthetic accelerograms; (2) Spectrum-compatible waveforms; (3) Natural records. Signals of the type (1) derive from computer-based simulation of the seismological source models and account for path and site effects. These models range from stochastic simulation of point or finite sources (*kinematic models*), to dynamic models of stress release (*pseudo-dynamic models*) [May and Beroza, 2000]. Simulation of source models, especially in those methods largely recurring to *random vibrations* theory [Boore, 2002], may lead to accelerograms which are unreal at least in terms of phasing of seismic waves; on the other side more advanced procedures accounting for extended faulting systems require arbitrary setting of some parameters as the *rise time. S*ome state-of-the-art approaches seem to overcome these shortcomings that may lead to unrealistic records but they're not yet readily available to the engineers.

Spectrum matching records (2) allow to manipulate recorded ground motions to match some smooth design spectrum. The target may obtained either by time or frequency domain modification methods such as the *wavelets* theory. The latter basically consists of using modulating functions located in time selectively to modify the spectrum of the signal where and how it is needed to get some target shape. Although these methods produce records perfectly compatible with code prescriptions, some studies shows that the number of cycles or energy

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carried on still does not reflect real earthquakes or, at least, they may lead to biased estimation of the seismic response [Carballo, 2000]. Furthermore both simulation of ground motion and spectral manipulation may require seismological competencies or software rarely available to the professionals.

Finally type (3) are ground motion records from real events. They are the more direct representation of the seismic threat and simple procedures have been developed to link the real ground motion to the hazard at the site for design purposes; e.g. by simple manipulation as linear amplitude scaling. In the past, one of the limits to the use of real records was their unavailability; nowadays the rapid development of digital seismic networks worldwide and online user friendly waveforms databases increased the accessibility. However, in many cases it is still very difficult to perform seismic assessment at a site by records from high intensity events from that same area and accelerograms from other regions have to be considered.

Seismic codes allow dynamic analysis however the guidelines on preparing ground motion input for full dynamic analysis are generally poor, partially because the research on the topic is developing fast in recent years and at lest a few time is required by regulations to take it in. Eurocode 8 (EC8), in particular, allows employment of all three kinds of accelerograms as an input for nonlinear seismic analysis of structures indifferently provided that they match the same prescriptions. They refer almost only to the matching to the design spectrum of the average spectral ordinate of the set of chosen records. The set has to be made of at least seven stations (both horizontal components if spatial analysis is concerned) to take the mean of the response, if the size of the set is three to six the maximum response is that to be considered for design or assessment. Little, if at all, prescriptions are given about other features of the signal.

Because of these conditions, the code prescriptions seem to favour spectrum-matching records. On the other hand, as discussed in the next section, real accelerograms are rising as the most attractive option for get unbiased yet accurate of the seismic demand. The study herein presented investigated the feasibility of defining real record sets matching the EC8 requirements and at the same time respecting as much as possible some addictive constraints, which may help for a correct estimation of the response.

The chosen waveform database is first investigated for unscaled sets because this may prevent from bias in the estimation of the demand if the residuals of the spectral ordinates in respect to the attenuation relationship are not accounted for or “epsilon” issue [Baker and Cornell, 2006]. Eurocode design spectra considered refer to the Italian case for several soil conditions and all three seismicity levels. The records vault considered is that of the European Strong Motion Database which contains accelerograms from European and Mediterranean events. Record from this database have been combined in all possible ways in group of seven and compared to the reference spectra. Results lead to a large number of sets, at least for low-to-moderate seismicity and stiff soil conditions, which are compliant with Eurocode 8 even though showing significant record-to-record spectral variability, which may only be reduced by linear scaling of records.

2. EUROCODE 8 PRESCRIPTIONS

The Eurocode 8 part 1 [ENV, 1998] recalls the seismic input for nonlinear dynamic analysis in *section 3.2.3*[2]: *The seismic motion may be represented in terms of ground acceleration time-histories and depending on the nature of the application and on the information actually available, the description of the seismic motion may be made by using artificial accelerograms (see 3.2.3.1.2) and recorded or simulated accelerograms (see 3.2.3.1.3).*

2.1 General requirements

The requirements for generating artificial accelerograms are: (i) the 5% damped code spectrum has to be matched; (ii) the duration of the accelerograms shall be consistent with the magnitude and the other relevant features of the seismic event, which affect the design ground acceleration on type A soil (a_g). Natural (recorded) and simulated accelerograms, produced through a physical simulation of the focal mechanism and travel path, the code prescribes that the sets are *adequately* qualified with regard to the seismogenetic features of the sources and to the soil conditions appropriate to the site. (While for simulated records an adequate qualification has a precise meaning, for natural accelerograms such statements may be interpreted. In common current practice records are selected to match a seismic scenario of interest in terms of magnitude, distance and soil condition [Bazzurro and Cornell, 1999], [Iervolino and Cornell, 2005].)

2.2 Spectral requirements and set sizes

The set of accelerograms, regardless they are natural, artificial or simulated should match the following criteria (see 3.2.3.1.2 – ENV, 1998):

[2] In the rest of the paper all citations of the Eurocode 8 will be simply indicated in italic (e.g. *section 3.2.3*)

a) a minimum of 3 accelerograms should be used;
b) the mean of the zero period spectral response acceleration values (calculated from the individual time histories) should not be smaller than the value of a_g.S for the site in question;
c) 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.

Herein, the comparison among the spectral target and the average of those coming from the recordings is realized for a range of periods between 0 and 2 seconds, which means that possible results apply to structures with fundamental oscillation period up to 1 sec, which is the case for many common structures.

In the case of spatial structures, the seismic motion shall consist of three simultaneously acting accelerograms representing the three spatial components of the shaking, then *3* of condition (a) shall be considered as the number of groups of records to be used (each group is made of the two horizontal and the vertical components of motion). Moreover, although three is the minimum number of groups to be used, in this case the demand to be taken corresponds to the maximum resulting from the seismic assessment; on the other hand, in *section 4.3.3.4.3*, the code allows to consider the mean effects on the structure, if at least seven non-linear time-history analyses are performed. In the following the investigated solutions are those consisting of seven groups of records.

In the already mentioned *section 4.3.3*, the code clarifies further that the vertical component should only be taken into account if a_g is greater than 0.25 g and in the following cases: for horizontal or nearly horizontal structural members with a span longer than 20 m; for horizontal or nearly horizontal cantilever components longer than 5 m; for horizontal or nearly horizontal pre-stressed components; for beams supporting columns; in base-isolated structures. Herein, because the many common structures are not included in the categories above indicated, than a group is considered to be made of only the two horizontal components.

2.3 Reference spectra

The spectra the selected record sets should be compared to are defined in *section 3.2.2.2*. The ordinates and shapes depend on the seismic hazard level and soil conditions respectively. The five stratigraphical profiles considered are:

A - Rock or other rock-like geological formation;
B - Deposits of very dense sand, gravel, or very stiff clay (Stiff Soil);
C - Deep deposits of dense or mediumdense sand, gravel or stiff clay (Soft Soil);
D - Deposits of loose-to-mediumcohesionless soil (Very Soft Soil);
E - A soil profile consisting of a surface alluvium layer (Alluvional);

The spectral shapes for these soil types are given in Figure 1. Other than those listed, two more special ground types, *S*1 and *S*2, exist. For such cases special studies for the definition of the seismic action are required, than they are not considered in the investigation.

The spectral shape is independent from the hazard which, is described in terms of a single parameter, i.e. the value of the reference peak ground acceleration on type A ground. Three hazard levels are possible, than fifteen spectra may be defined. The a_g values are to be chosen by the National Authorities with reference to the return period of the seismic action for the no-collapse limit state (or equivalently the reference probability of exceedance in 50 years). Italian values [OPCM 3274, 2003] herein used are given in Table 1.

Table 1. Ground accelerations values according to the Italian code

Hazard level/Zone	a_g
1	0.35g
2	0.25g
3	0.15g

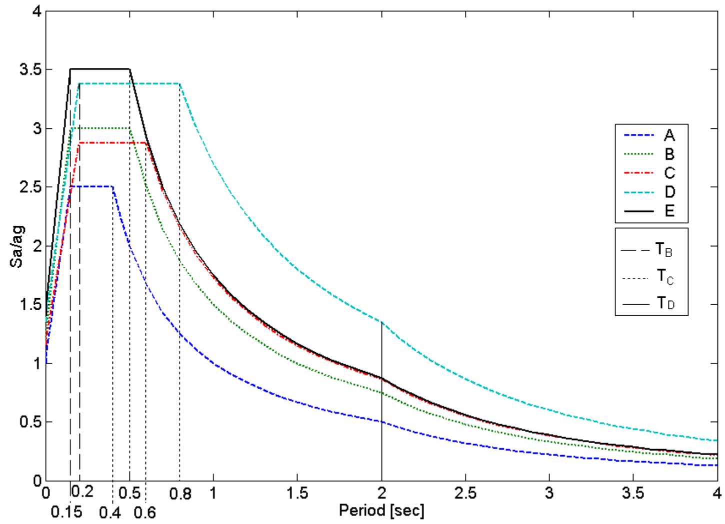

Figure 1: Spectral shapes for all soil types

2.4 Combinations of records in the case on one-dimension and spatial analyses

The code requires to use a number of groups records at least equal to three, but in the following the considered combinations are made of seven groups. This for three basic reasons: (1) It is possible to consider the average effects on the structure rather than the maximum; (2) The chance of finding accelerograms respecting the criteria of the code is enhanced if any combination is made of more records; (3) The use of only three groups of accelerograms may lead to an unreliable estimation of the variability of the seismic demand. It is worth to underline that a combination of seven groups is made of fourteen recordings (seven for each of the two directions). Then, condition (c) of section 2.4 (spectral requirements and set sizes) has been checked taking the average of all fourteen components of motion for the set under exam and comparing it with the reference spectrum in the period range from 0-2 s.

Since the same accelerogram may not be used simultaneously along both horizontal directions (*section 3.2.3.1.1*), the groups are made of the two horizontal components of the same recording station. In other words a set of records contains data from seven seismic instruments only.

3. ADDITIONAL CONSTRAINTS

Along with the conditions (a), (b), (c) of the paragraph 2.2, some additional parameters were considered, because they may matter for the non-linear response structures:

a) the deviation of the average spectrum in respect of the code spectrum (σ);
b) the maximum deviation of a single spectrum within a set in respect to the code spectrum (σ_{max});
c) records coming from different events within a set;
d) small variability of magnitude of events within a set.

a) The average spectrum deviation (σ) gives a quantitative measure of how much the mean spectrum of a combination of records deviates from the spectrum of the code. The definition of σ is given by Eq. (1).

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{Sa_{o,med}(T_i) - Sa_s(T_i)}{Sa_s(T_i)}\right)^2} \qquad (1)$$

where $Sa_{o,med}(T_i)$ represents the pseudo-acceleration ordinate related to the mean real spectrum corresponding to the period T_i, while $Sa_s(T_i)$ is the value of the spectral ordinate of the code spectrum at the same period and N is points number observed inside the considered range of periods (herein 0-2 sec). Selecting record sets with a low σ value allows to obtain average spectra, which are well approximating the code. This may prevent from over conservative design due to an overestimated spectral demand.

b) The maximum deviation (σ_{max}) of a single record within a set has been computed as in Eq. (1) replacing $Sa_{o,med}(T_i)$ with $Sa_o(T_i)$, which is the ordinate of a single component of the combination. Controlling this parameter may allow to choose combinations characterized by records having the individual spectra relatively close to the reference spectrum and then being narrowly distributed around it.

c) This criterion is corresponds to identify combinations of records which contain the largest number of different events possible. In fact, having many records from the same earthquake within a combination may prevent from a bias of the seismic demand because of a dominating earthquake.

d) This criterion is reflected in selecting records only within events with moderate to high magnitude for each soil. Moreover since it is recommended by many studies as Shome et al. [1998] to use recordings deriving about from the same magnitude of a scenario event. The analyses herein presented aimed to find sets of records made by records coming from several small ranges of magnitude. To limit the magnitude also allows to control the duration of the records [Stewart et al., 2001] if unscaled.

Unfortunately, since high magnitude events are rare, analyses almost failed in limiting the magnitude variation within the found solution. In fact, it will be discussed how it was not possible to find record sets optimizing more than one of these criteria and, at the same time, being compatible with the code. Moreover other parameters such as record duration and distance have not been regarded in selection, if not indirectly. This is also because some studies question importance of these features at least under some conditions [Iervolino et al., 2006].

4. INVESTIGATED DATABASE

Nowadays there are many source of ground motion records, most of them also have a directly accessible website. For the purposes of the present study the investigated database is that of the ESD (*European Strong-motion Database, http://www.isesd.cv.ic.ac.uk*); see Ambraseys et al. [2004] for further information. The database includes events since the Debar earthquake (Macedonia) happened on December 2 1967. Selecting the records within the database by the soil classification (rock, stiff soil, soft soil, very soft soil, alluvium) it was possible to first download all accelerograms belonging to each ground category (website accessed in April 2005). Such analysis resulted in finding components (North-South, East-West and Vertical directions) which, if only the horizontal axis of motion are considered, are given in Table 2. From these records, those station without both components have been discarded. Moreover, only events characterized by a moment magnitude equal or larger than 5.8 have been considered. For D soil type, any cut hasn't been made because of the lack of stations for that geological condition. The resulting numbers of records are given Table 3 where it is also shown the percentage of stations characterized by a source-to-site distance larger than 15 km which is a proxy (although weak) for the far field condition.

Table 2. Total number of the records in the database selected by soil type

Local Geology	East-West	North-South
GROUND A (rock)	575	570
GROUND B (stiff soil)	770	770
GROUND C (soft soil)	410	410
GROUND D (very soft soil)	28	29
GROUND E (alluvium)	105	103

Table 3. Total number of ground motion records considered in the analysis

Local Geology	Est-Ovest	Nord-Sud	Totale	Far field (>15Km)
GROUND A (rock)	111	111	222	87 %
GROUND B (stiff soil)	135	135	270	86 %
GROUND C (soft soil)	122	122	244	87 %
GROUND D (very soft soil)	28	28	56	96 %
GROUND E (alluvium)	29	29	58	100%

In Table 4, the records are referred to the countries they come from. As expected the most of the accelerograms are of Italian, Turkish and Greek events. This pre-selection, ensures to have records coming from moderate-to-high magnitude earthquakes and also allow to dramatically reduces the number of sets of records to investigate. In fact, the number of possible combinations of records goes with the binomial coefficient, which may require a huge computational effort.

Table 4. Seismic stations considered divided by country

Country	Rock (A)	Stiff soil (B)	Soft soil (C)	Very soft soil (D)	Alluvium (E)
Italy	47	11	16	11	14
Albania	-	-	-	2	-
Algeria	1	-	1	-	1
Armenia	-	-	1	-	-
Bosnia and Herzegovina	-	-	-	6	-
Croatia	-	-	-	2	-
Cyprus	-	-	1	-	-
Egypt	-	-	7	-	-
Georgia	5	2	3	-	-
Greece	20	29	20	-	4
Iceland	-	11	-	-	-
Iran	2	10	5	-	-
Israel	-	-	-	-	-
Macedonia	1	1	-	1	-
Portugal	-	-	2	-	1
Romania	3	1	-	2	-
Slovenia	-	-	-	-	4
Turkey	24	59	59	-	4
Yugoslavia	8	11	7	4	1
Total	**111**	**135**	**122**	**28**	**29**

5. ANALYSIS AND RESULTS

To find sets compatible with the Eurocode prescriptions, a specific computer code has been developed. It allows to determine all the possible combinations of seven groups of records and to compare each of them with reference spectrum for any soil condition and hazard level. (It is worth to recall that, for example, the number of non-ordered combinations of 111 elements (groups of two components of motions) in 7 bins is given by the *binomial coefficient* and it is 34 billions).

The computer code checks the compatibility of any set to code spectrum with some tolerance. The lower bound is prescribed to be 90% of the latter (see section 2 of this paper); the upper bound is not assigned, and in the analysis it was iteratively adjusted to contemporarily control the number of the results found and to limit the overestimation of the code spectrum. The final results, in terms of number of combination found, are given in Table 5. It is expected that the larger number of results correspond to the lower hazard level. In fact, the larger spectrum refers to a high magnitude-short distance or rare event. The upper bound is not uniform because the relaxation of this constraint allowed to find more results optimizing the additional criteria considered.

For the higher hazard level of all soil it was not possible to find results satisfying the EC8. Because of that, the lower bound had to be reduced. Sets found in this way are not suitable, but may be slightly linearly scaled to comply with the code. For D and E soil no solutions at all where found.

Table 5. Combinations found for spatial analyses

GROUND	ZONE	LOWER BOUND [%]	UPPER BOUND [%]	SETS FOUND
A	1	30	100	13
	2	10	100	452
	3	10	10	3673
B	1	20	100	3978
	2	10	30	20934
	3	10	20	24081
C	1	35	50	138
	2	10	∞	423
	3	10	15	12230

As an example, selected results for A soil are given in Figures 2 and 3. They correspond to the three hazard levels of that soil. The set in the Figure 2 is that characterized by the minimum σ in respect of the code spectrum. It is possible to see that the combination in the left plot does not comply with the code because at many periods the average spectral ordinates (red thick line) are below the 10% of the spectrum (thin solid black line). Combinations in the Figure 2 (right) and Figure 3 (left), still characterized by the smallest σ, also optimize the criterion of coming different earthquakes. Details about sets of the figures are given in Table 6.

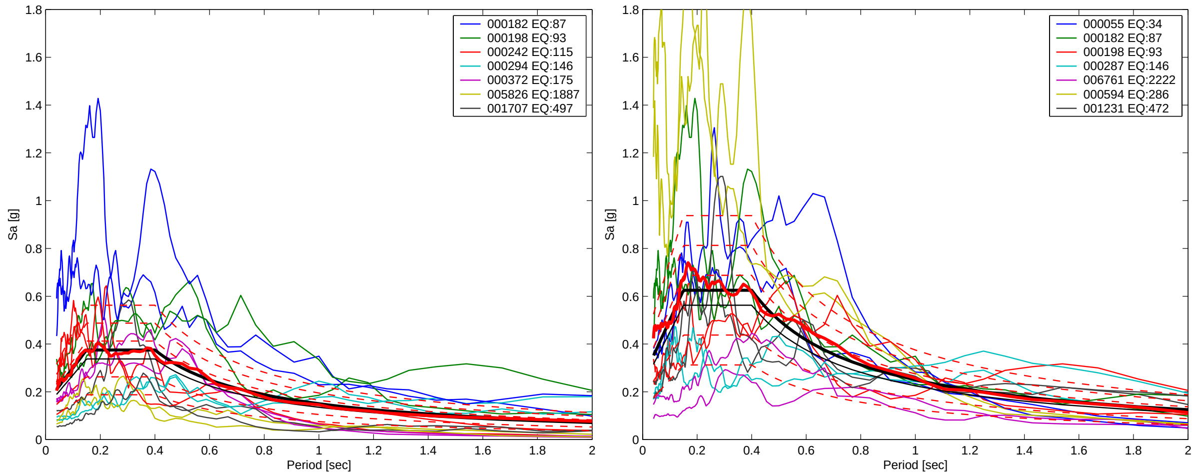

Figure 2: Spectral shapes for soil type A and a_g=0,15 g (left) and a_g=0,25 g (right)

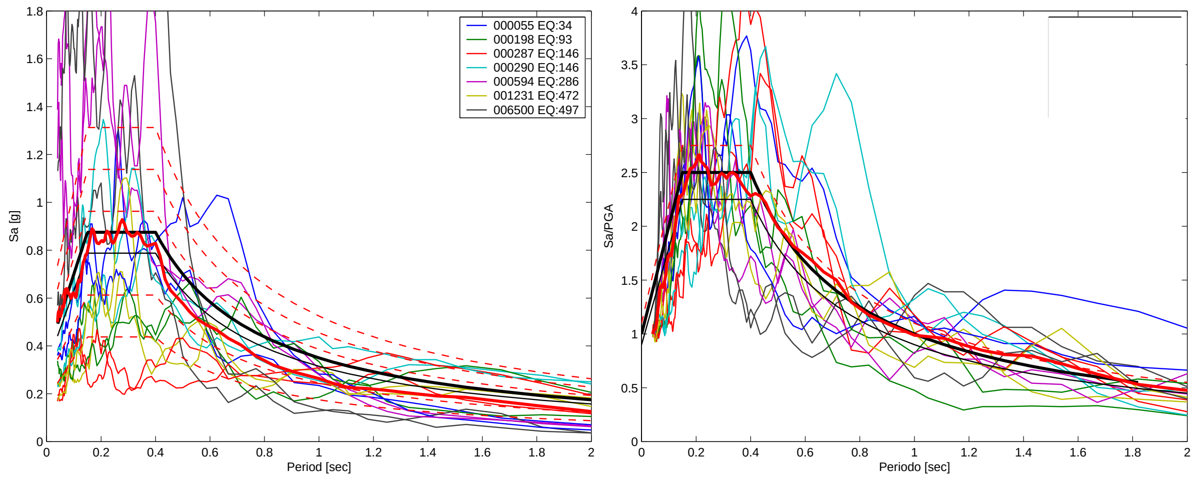

Figure 3: Spectral shapes for soil type A and a_g=0,35 g (left) and non-dimensional set (right)

Table 6. Records information

Soil & zone	code	Earthquake Name	Earthquake Country	Date	Local Geology	Magnitude	Fault distance (km)	station name	$PGA_{average}$ (g)
A3	000182	Tabas	Iran	16/09/1978	rock	7.4	11	Dayhook	0.2046
	000198	Montenegro	Yugoslavia	15/04/1979	rock	6.9	9	Ulcinj-Hotel Albatros	
	000242	Valnerina	Italy	19/09/1979	rock	5.8	1	Cascia	
	000294	Campano Lucano	Italy	23/11/1980	rock	6.9	19	Bisaccia	
	000372	Lazio Abruzzo	Italy	07/05/1984	rock	5.9	?	Scafa	
	005826	Strofades	Greece	18/11/1997	rock	6.6	65	Kyparrisia-Agriculture Bank	
	001707	Duzce 1	Turkey	12/11/1999	rock	7.2	34	Mudurnu-Kaymakamlik Binasi	
A2	000055	Friuli	Italy	06/05/1976	rock	6.5	6	Tolmezzo-Diga Ambiesta	0.4235
	000182	Tabas	Iran	19/09/1978	rock	7.4	11	Dayhook	
	000198	Montenegro	Yugoslavia	15/04/1979	rock	6.9	9	Ulcinj-Hotel Albatros	
	000287	Campano Lucano	Italy	23/11/1980	rock	6.9	6	Bagnoli-Irpino	
	006761	Vrancea	Romania	30/08/1986	rock	7.2	26	Vrancioaia	
	000594	Umbria Marche	Italy	26/09/1997	rock	6	4	Nocera Umbra	
	001231	Izmit	Turkey	17/08/1999	rock	7.6	8	Izmit-Meteoroloji Istasyonu	
A1	000055	Friuli	Italy	06/05/1976	rock	6.5	6	Tolmezzo-Diga Ambiesta	0.4984
	000198	Montenegro	Yugoslavia	15/04/1979	rock	6.9	9	Ulcinj-Hotel Albatros	
	000287	Campano Lucano	Italy	23/11/1980	rock	6.9	6	Bagnoli-Irpino	
	000290	Campano Lucano	Italy	23/11/1980	rock	6.9	14	Sturno	
	000594	Umbria Marche	Italy	26/09/1997	rock	6	4	Nocera Umbra	
	001231	Izmit	Turkey	17/08/1999	rock	7.6	8	Izmit-Meteoroloji Istasyonu	
	006500	Duzce 1	Turkey	12/11/1999	rock	7.2	9	LDEO Station No. C0375 VO	

It results from the analysis of the plots that the variability of the single records may be very large. On the other hand, may be desirable to have a low scatter [Malhotra, 2003]. This condition may be achieved searching for records having a spectral shape similar to that of the code and renouncing to have them unscaled. Then, according to the methodology proposed by Bommer and Acevedo [2004] the records have been rendered non-dimensional dividing their spectral ordinates by the PGA. Combination of these records have been compared to the code spectrum also rendered non-dimensional, which is than completely independent on the a_g value. An example of this kind of combination is given in Figure 3 (right) and the corresponding scaling factor to match the dimensional spectra of soil A are given in the Table 7.

Table 7. Average scaling factor to match the code spectra for the records of Figure 3 right

Hazard level/Zone	a_g	Average scaling factor to comply with the code (SF)
1	0.35g	21.0
2	0.25g	15.0
3	0.15g	9.0

6. FINAL REMARKS

The study presented in this paper intended to investigate whether it is possible to find natural and unscaled record sets fulfilling the requirements of Eurocode 8 about the seismic input of non-linear analysis of spatial structures. Considering unscaled records may be important to avoid bias in the estimation of the demand if the "epsilon" issue is not accounted for in the selection of accelerograms.

The records considered are those of the European Strong Motion Database. Among them only those coming from events of moderate-to-high magnitude have been selected. A specifically developed code analyzed the compatibility of all possible sets of these waveforms with the code prescriptions.

Several combinations compatible with the EC8 have been found, to rank them additional conditions have been considered. They refer to the similarity of the average spectrum with the reference spectrum; the record-to-record variability of the spectral ordinates; the prevention of event domination; and finally the range of magnitude within a set. It was not possible to satisfy all these criteria contemporarily, which may lead to a difficult choice of the combination to use.

Results were found for A, B and C soil types, while for very soft soil sites (D,E) it was not possible to retrieve possible solutions in the investigated database. This is because of two main reasons: (1) the lack of recordings for these soils in the ESD; (2) the spectra for soft soil is dependent on the stratigraphical features of the specific site and may not be referred to a standard shape.

Sets found are made of seven pairs of records (horizontal directions of seven seismic stations), which allows to consider, for design, the mean demand on the structure rather than the maximum as happens if only three groups are used. The vertical component of the motion is not considered.

Suitable results refer to hazard zones 2 and 3 characterized, according to the a_g values of the OPCM 3274, by a peak ground acceleration equal respectively to 0.25 g and 0.15 g. For Zone 1, it hasn't been possible to find set compatible with the normative limits, however light linear scaling of few records within the set may help in the matter.

Moreover, the condition of having unscaled record sets strictly matching the Eurocode 8 spectra, results in a large record-to-record variability of the spectral ordinates within the same set. This may be avoided selecting records with a spectral shape as much possible similar to that of the code, but this may lead to large linear scaling factors to get the spectral matching.

Finally, the results concerning the study presented in this paper, are available at the following link: http://www.reluis.unina.it/.

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