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Eurocode 8 Compliant Real Record Sets for Seismic Analysis of Structures

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Among all the possible options to define the seismic input for structural analysis, natural recordings are emerging as the most attractive. Easily accessible waveform databases are available and evidence shows that only a relatively limited number of criteria has to be considered in selection and scaling to get an unbiased estimation of seismic demand. Like many codes worldwide, Eurocode 8 (EC8) allows the use of real ground-motion records for the seismic assessment of structures. The main condition to be satisfied by the chosen set is that the average elastic spectrum does not underestimate the code spectrum, with a 10% tolerance, in a broad range of periods depending on the structure's dynamic properties. The EC8 prescriptions seem to favour the use of spectrum-matching records, obtained either by simulation or manipulation of real records. The study presented herein investigates the European Strong-Motion Database with the purpose of assessing whether it is possible to find real accelerogram sets complying with the EC8 spectra, while accounting for additional constraints believed to matter in the seismic assessment of buildings, as suggested by the current best practice. Original (un-scaled) accelerogram sets matching EC8 criteria were found, for the case of one-component (P-type) and spatial sets (S-type), for the spectra anchored to the Italian peak acceleration values. The average spectra for these sets tend to be as close as possible to the code spectrum. Other sets, requiring scaling, have been found to match the non dimensional (country-independent) EC8 spectral shape. These sets have also the benefit of reducing, in respect to the un-scaled sets, the record-to-record variability of spectra. Combinations referring to soft soil, stiff soil, and rock are presented here and are available on the internet at http://www.reluis.it/

Keywords Record Selection; Dynamic Analysis; Eurocode 8

1. Introduction

The assessment of the structural response via dynamic analysis requires some characterization of the seismic input which should reflect the hazard as well as the near-surface geology at the site. Generally, the signals that can be used for the seismic structural analysis are of three types: (1) artificial waveforms; (2) simulated accelerograms; and (3) natural records [Bommer and Acevedo, 2004].

Spectrum-compatible signals of type (1) are obtained, for example, generating a power spectral density function from the code response spectrum, and deriving signals compatible to that. However, this approach may lead to accelerograms not reflecting the real phasing of seismic waves and cycles of motion, and therefore energy.

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Simulation records (2) are obtained via modeling of the seismological source and may account for path and site effects. These methods range from stochastic simulation [Boore, 2003] of point or finite sources to dynamic models of rupture.

Synthetics may be the only way to obtain appropriate records for rare scenarios, such as large magnitude events "close" to the site and give the benefit that one can produce from them large samples of nominally similar events. However, effort should be employed to insure that their spectra are appropriate for nonlinear analysis, e.g., non smooth [Cornell, 2004]. Moreover, they often require setting of some rupture parameters, such as the *rise-time*, which are hard to determine. *S*ome state-of-the-art simulation methods seem to overcome these shortcomings, but they are not yet readily available to engineers.

Finally, of type (3) are ground-motion records from real events. The availability of on-line, user-friendly, databases of strong-motion recordings, and the rapid development of digital seismic networks worldwide, have increased the accessibility to recorded accelerograms. However, due to the large variability in records representing a scenario, a number of points arise regarding the criteria for appropriate selection and manipulation of such records. In particular, an issue regarding the use of real recordings, whose spectra are generally non smoothed, is the selection of a set compatible with a code-specified spectrum. To overcome this, various approaches have been developed to manipulate real records to match a target spectral shape, either by frequency-domain or by time-domain modification methods such as the *wavelet* transform. The wavelet transform basically consists of using modulating functions, selectively located in time to modify the spectrum of the signal, where and when it is needed in order to match the target spectrum (see Hancock et al., 2006, for details). Although these methods produce records perfectly compatible with code's prescriptions and have the additional advantage of reducing the dispersion in the response, and hence the required sample size, some studies show that they may lead to a non conservative estimation of the seismic response [Carballo and Cornell, 2000; Bazzurro and Luco, 2003]. Therefore, earthquake engineering research has focused lately on the selection of real ground-motions for non-linear structural analysis and relatively simple and effective procedures have been developed to link records to the hazard at the site.

In seismic codes, the guidelines about preparation of ground-motion input for dynamic analysis are generally poor, as also pointed out by Bommer and Ruggeri [2002]. This is partially because research on the topic is developing fast and at least a few years are required by regulations to take it in. For example, the code-based prescriptions for records often require compatibility with a smooth design acceleration spectrum together with few other minor requirements. Eurocode 8 (EC8) [CEN, 2003], in particular, allows employment of all three kinds of accelerograms listed above as an input for seismic structural analysis. The EC8 prescriptions ask for matching of the average spectral ordinates of the chosen record set to the target code-based spectral shape. The set has to consist of at least seven recordings (each of which includes both horizontal components of a recorded motion if spatial analysis is concerned) to consider the mean of the response. Otherwise, if the size of the set is from three to six, the maximum response to the records within the sets needs to be considered. Little, if any, prescriptions are given about other features of the signal. Therefore, the code requirements seem to have been developed having spectrum-compatible records in mind. On the other hand, real accelerograms are becoming the most attractive option to get unbiased estimations of the seismic demand.

The study presented herein investigates the feasibility of finding real record sets complying as much as possible with EC8 spectra. EC8 does not provide anchor values (a_g) for its non dimensional spectral shapes, leaving it up to the European national authorities to determine the values of a_g, which is associated to the Peak Ground Acceleration (PGA) on rock with a certain probability of exceedance at the site of interest. The a_g values employed herein correspond to the Italian case, where the seismic territory is divided into four zones representing different hazard levels, where seismic resistant design is mandatory only in the upper three zones.[1]

The chosen ground-motion spectra dataset is extracted from the European Strong-Motion Database, which contains accelerograms from both European and Mediterranean events. Original spectra from this database have been combined in all possible suites of seven in order to find EC8 compliant sets of un-scaled records. Moreover, sets of scaled code-compatible accelerograms were also considered in order to reduce to record-to-record variability in the response, and to obtain sets which are independent on the anchoring value of the code spectrum.

Finally, sets compatible with Eurocode 8 spectra, for plane and spatial analysis of buildings, are found and some of them are discussed herein. The selected records refer to rock or stiff soil site classes and are available on the internet on the website of the Italian consortium of earthquake engineering laboratories: *Rete dei Laboratori Universitari di Ingegneria Sismica – ReLUIS* [http://www.reluis.it/]. On the same website, similar results and discussion for the selection of ground-motions suitable for dynamic analysis and compatible with the recent Italian seismic code prescriptions (slightly different from those of EC8), are also given [Iervolino *et al.*, 2006a].

2. Current Best Practice and Critical Issues in Record Selection and Manipulation

Among the possible approaches, reviewed by Beyer and Bommer [2007], in selecting real accelerograms for assessing the nonlinear demand of structures, the current state of best practice [Cornell, 2005] is based on first disaggregating the seismic hazard at the site [Bazzurro and Cornell, 1999], by causative magnitude (M) and distance (R), for the level of spectral acceleration (at the first mode period of the structure) at a specified probability (say a 10% chance of exceedance in 50 years). The records are then chosen to match within tolerable limits the mean or modal value of the M and R and site conditions, i.e., the expected value or most likely value of these characteristics given that exceedance. The records may also be selected for the expected style of faulting, duration, instrument housing, etc. Finally, they are scaled to match, in some average sense, the uniform hazard spectrum (UHS) or, as it is often recommended, precisely to the UHS level at a period near that of the first period of the structure.[2] Based on the studies that have investigated this procedure, there is some evidence that all this care taken about the selected records' earthquake properties may be not justified [Iervolino and Cornell, 2005]. That is, it is not proven that record characteristics such as M and R significantly influence linear or nonlinear response conditioned to first mode spectral acceleration or another *sufficient*[3] ground-motion intensity measure (IM). Moreover, the scaling of records to match some spectral value does not seem to bias the response estimate if the deviation from the median ground-motion prediction relationship effect is accounted for appropriately [Baker and Cornell, 2006a].

[1]The a_g values for the Zones 3, 2, and 1 are 0.15 g, 0.25 g, and 0.35 g, respectively. These values are related to the probabilistic seismic hazard analysis (PSHA) [McGuire, 1995] for the site of interest. In fact, if the PGA (on rock) with a 10% exceeding probability in 50 years falls in one of the intervals]0.25g, 0.35g],]0.15g, 0.25g], or]0.05g, 0.15g], then the site is classified as Zone 1, 2, or 3, respectively [OPCM 3519, 2006].

[2]Many authors have recently questioned the use of UHS as target spectrum, see for example Baker and Cornell [2006a].

[3]Sufficiency of an intensity measure is discussed in detail in the next section.

When following Eurocode 8 criteria (described next), these procedures for record selection are not readily applicable because: (i) the code spectrum is related to the hazard for the site of interest only through the anchoring value, which is related to the PGA with a 10% exceedance probability in 50 years on a rock site, therefore it is not possible to apply common disaggregation procedures or to match any source parameter if a site-specific probabilistic seismic hazard analysis (PSHA) is not available; (ii) the requirement to match, in the average, the code spectrum in a broad range of periods seems to be very hard to satisfy. In the following, a brief review of recent developments and relevant literature on the topic of record selection for dynamic analysis is given because it may matter to understand the applicability of the results found and will help to discuss the EC8 prescriptions.

2.1. Sufficiency and Efficiency of a Ground-Motion Intensity Measure

A *sufficient* IM renders the structural response, conditioned on that IM, independent, of earthquake ground-motion characteristics such as magnitude and distance [Cornell, 2004]. At the same time, a certain IM is defined as *efficient* if the structural response, conditioned on IM, has comparatively small dispersion. The spectral acceleration (Sa), at the fundamental period of oscillation of the structure, is often implicitly assumed to be both a sufficient and efficient IM. This is in part due to the availability of Sa hazard curves; however, for inter-story drift response, Sa is at the very least more sufficient and efficient than PGA.

First-mode spectral acceleration has also been proven to be sufficient in respect to duration, at least for single degree of freedom (SDOF) structures [Iervolino *et al*., 2006b]. In fact, although there is a debate on the influence of duration in seismic assessment of structures, as reviewed by Hancock and Bommer [2006], duration has been found to be statistically insignificant to displacement ductility demand; conversely, it strongly affects, as expected, other demand parameters accounting for cyclic behavior such as hysteretic ductility or equivalent number of cycles. Therefore, at least for the purposes of displacement-related demand assessment, it seems that one should not take too much care in selecting records from a particular duration bin given that they have (or are scaled to) a common Sa level (e.g., matching of the target spectral shape at some frequency).

A sufficient and efficient IM also allows the estimation of the response (i.e., median) requiring a smaller sample size to get a given standard error. It has been demonstrated, in fact, that if Sa is concerned, the uncertainty on the estimation can be dramatically reduced if records are scaled to a common Sa level [Shome *et al*., 1998]. However, it is worth noting that it has also been recently demonstrated that Sa may not be particularly efficient, nor sufficient, for some structures. If long periods of oscillation are called into question, the higher modes typically play a larger role in the seismic response and Sa has less prediction power than for first-mode dominated structures. It may indeed be insufficient because it is not able to capture the spectral shape in a range of frequencies where the latter depends on the magnitude. For soft-soil or near-source records Sa may also be insufficient. At the same time, PGA may be a better IM for peak floor acceleration, which is an important response variable for non structural response, since non structural elements are often sensitive to applied inertia forces. The lack of efficiency, or insufficiency, of first mode Sa may be explained by the iconoclastic statement: “only spectral shape matters” in the estimation of nonlinear seismic response of structures. This means that in the case of systematic spectral shape deviations, Sa may be found to be insufficient. Several studies propose alternative IMs trying to capture spectral shape in a range of interest to some structural types. They include scalar and vectors, linear and nonlinear quantities; however, they are still not included in common practice.

2.2. Epsilon

It has been briefly reviewed above why in seeking for characteristics to mirror in the record selection one should look to any systematic effect on spectral shape. For example, it is prudent to avoid selecting records from soft soil sites or from near-source records showing directivity effects. Baker and Cornell [2005, 2006a] recently demonstrated that one source of systematic effect is that of the deviation of a record's Sa from the value predicted by the ground-motion prediction equation. That deviation is called *epsilon*[4] or "normalized residual." High epsilon values are associated with peaks in the spectrum (Fig. 1), and hence with more benign nonlinear structural behavior. In fact, during the shaking the effective period of the structure lengthens descending the peak toward a less energetic portion of the frequency content.

Even though some researchers believe that epsilon is not an intrinsic ground-motion feature, PSHA disaggregation for epsilon often shows that high IM levels, contributing directly to rare maximum interstory drift ratio (MIDR) levels, are associated with high values of epsilon. Therefore, when selecting records for analyses at these high IM levels, one should consider choosing them among those having the *right* epsilon, in order to have the *correctly deviating* spectral shape around the period of interest, for a more efficient

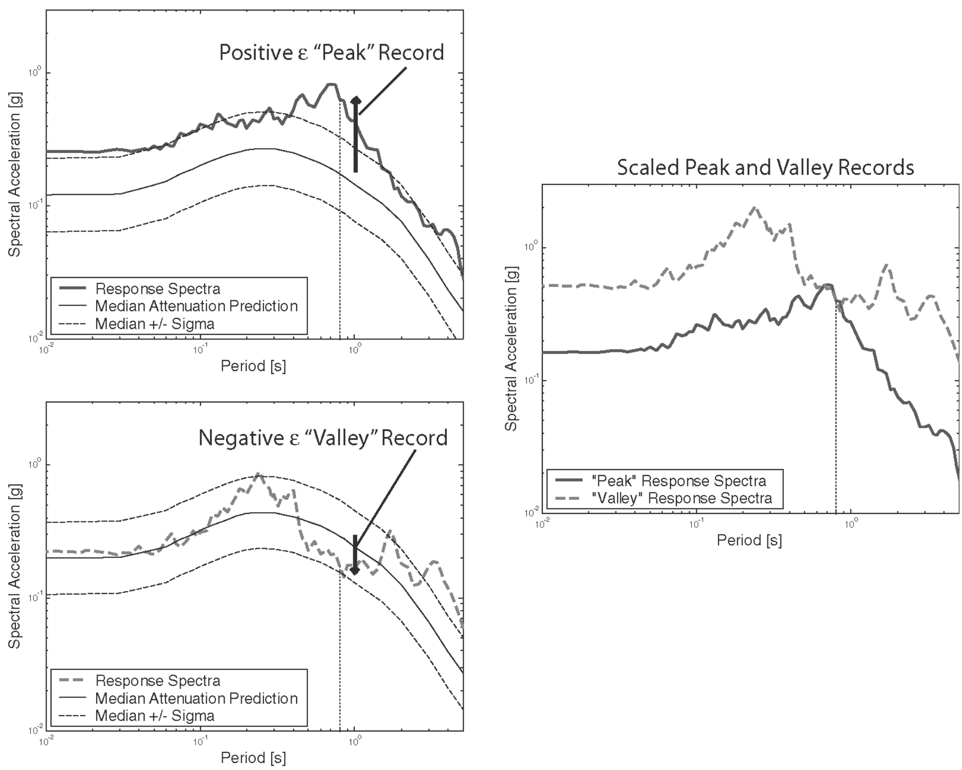

FIGURE 1 Scaling a negative ε record and a positive ε record to the same spectral acceleration at the period of 0.8 s. Courtesy of Jack W. Baker; see Baker and Cornell [2005] for details.

[4]Epsilon (ε) is defined as the difference between the log of the spectral acceleration, at a given period, of a record and that predicted by an ordinary ground-motion prediction equation divided by the standard deviation of the residuals.

and unbiased estimation of structural response. This is more important than matching records with scenario M and R values. It is also worth noting that the epsilon issue affects the scaling procedure; in fact, for example, scaling down a positive epsilon record would introduce an un-conservative bias in the demand estimation because, due to the lengthening of the period during the shaking, the structure will be sensitive to a part of the spectrum which is away from the peak; conversely, scaling up a negative epsilon record could lead to an overestimation of the seismic response (Fig. 1).

A method has also been proposed [Baker and Cornell, 2006a] to develop a target spectrum which accounts for the effect of magnitude, distance, and epsilon. This spectrum allows the selection of records that only have a spectral shape that matches the mean spectrum from the causal event, without taking care of appropriate magnitude, distance, and specific epsilon. The proposed target spectrum is compared to an UHS, and seen to be more appropriate for obtaining unbiased estimates of structural response.

2.3. Consistent Sa

In performing seismic assessment of structures via dynamic analysis it is important to bear in mind that structural engineers and seismologists sometimes intend Sa differently. This mismatch is due to the decomposition of ground-motion by projection along two directions [Baker and Cornell, 2006b]. For the aims of nonlinear seismic assessment of structures, Sa is considered as the one along a single axis. Conversely, seismologists may compute ground-motion prediction equations using the geometric mean of the spectral accelerations in the two directions; using one arbitrary component would lead to a larger dispersion of hazard curves. Both uses of Sa are legitimate, but inconsistent if combined for the probabilistic seismic assessment of structures. Therefore, it is preferable to define the same Sa in both the hazard and response. This means either that in the seismic risk analysis of structures one should use hazard curves that use one-component Sa, or estimating structural response using the geometric mean of the two components as an IM. This latter method has the advantage of not requiring new ground-motion prediction equations for hazard analysis. However, it will introduce additional dispersion into the response prediction and Sa will result less efficient. Alternatively, if the structural response is estimated using a single axis Sa, while hazard refers to the mean of the two components, the dispersion of the response may be inflated, as proposed by the cited authors, to reflect that which would have been seen if the mean Sa had been used as the intensity measure.

2.4. Near-Source

Finally, it should briefly be mentioned that a site located close to the source of a seismic event may be in a geometrical configuration, in respect to the propagating rupture, which may favor the constructive interference of waves (synchronism of phases causing building up of energy) traveling to it, which may result in a large velocity pulse. This situation, for dip-slip faults, requires the rupture going toward the site and the alignment of the latter with the dip of the fault, whereas for strike-slip faults the site must be aligned with the strike; if these conditions are met the ground-motion at the site may show *forward directivity* effects [Somerville *et al*., 1997]. Parameters driving the amplitude of the pulses are related to the above-discussed rupture-to-site geometry, while empirical models positively correlating the earthquake's magnitude to the period of the pulse have been proposed by seismologists [Somerville, 2003]. Pulse-type records are of interest for structural engineers because they: (1) may induce unexpected demand into structures having the fundamental period equal to a certain fraction of the pulse period; and (2) such demand may not be adequately captured by the current, best-practice, ground-motion intensity measures such as first mode spectral acceleration.

Common record selection practice and classical PSHA do not apply in the near-source. In fact, the latter requires ground-motion prediction relationships able to capture the peculiar spectral shape driven by the pulses, while the former should produce record sets reflecting the pulse features compatible with the near-source PSHA. Extended discussion and results on the topics of near-source hazard analysis and seismic assessment in near-source conditions may be found in the work by Tothong [2007].

3. Eurocode 8 Prescriptions for Record Selection

Eurocode 8, part 1, outlines the requirements for the seismic input for dynamic analysis in *Sec. 3.2.3:*[5] *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).*

The set of accelerograms, regardless if they are natural, artificial, or simulated, should match the following criteria:

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;*[6]
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*.[7]

Some duration prescriptions are given for artificial accelerograms, while recorded or simulated records should be *adequately qualified with regard to the seismogenetic features of the sources and to the soil conditions appropriate to the site, and their values are scaled to the value of a_g S* (PGA) *for the zone under consideration*. Regarding the former part of the sentence: it has to be noted that the code spectrum is not related to any specific feature of the source and, therefore, this prescription could not be accounted for herein. The latter part was not considered as well because: (1) it is not very clear what scaling the values of the records means; (2) if it means to scale the PGA of the individual records to the PGA value of the code, then the condition (b) above seems to make this statement useless (in fact, many codes such as the Italian one do not have this statement, although they have very similar prescriptions including (b) above).

According to the code, 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

[5]In the rest of the article, all calls and verbatim citations of Eurocode 8 will be simply indicated in italic.

[6]Many national codes in Europe have the EC8 as a main reference. The recent Italian seismic code [OPCM 3274, 2003], for example, has very similar prescription for record selection. However, this (b) criterion is not present.

[7]The upper limit accounts for the lengthening of period due to the nonlinear structural behavior, while the lower considers the contribution of higher modes to structural response. The recent Italian seismic code prescribes the lower period range limit as 0.15 s.

records to be used (each group is made up of the two horizontal and the vertical components of motion). However, in *Sec. 4.3.3.4.3*, the code allows the consideration of the mean effects on the structure, rather then the maximum, if at least seven nonlinear time-history analyses are performed. In the following, the investigated solutions are those consisting of seven groups of records.

3.1. Record Set Definition and Size

To better understand what is recommended by Eurocode about the number of records within a set, it is necessary to discuss a little more about what is intended herein as a group of records. A group is made of the two horizontal and the vertical recording of a single seismic station, therefore it is made of the three components of motion. However, the vertical component of the seismic action should be taken into account if the design vertical acceleration for the A-type site class (a_{vg}) is greater than 0.25 g and only in the following cases:[8]

- *for horizontal or nearly horizontal structural members spanning 20 m or more*;
- *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*.

In *Sec. 3.2.2.3* the suggested values of a_{vg} is defined as 0.9 times a_g, then the vertical component is only to be considered, for those cases listed, for the Zone 1 sites. Moreover, since most common structures do not fall into the listed cases, it is assumed herein that a group of records is only made up of the two horizontal components of a recorded signal.

The code requires the use of a number of groups at least equal to three, but in the following the considered combinations are made of seven groups. This has been done for three basic reasons: (1) in this case the code allows the consideration of the average effects on the structure rather than the maximum; (2) the chance of finding record sets respecting the criteria of the code is enhanced if a combination is made of more records; (3) the use of only three groups of accelerograms may lead to an estimation of the seismic demand with large uncertainty (which, however, may not even be correctly estimated by seven records).

In the case of analysis for spatial structures, the code prescribes (*Sec. 3.2.3.1.1*): *When a spatial model is required, the seismic motion shall consist of three simultaneously acting accelerograms. The same accelerogram may not be used simultaneously along both horizontal directions*. Therefore, sets for analysis of spatial structures (identified as *spatial type* or S-type) are made up of 14 records and, herein, as an arbitrary interpretation of the code, condition (c) of Sec. 3 has been checked taking the average of all fourteen spectra of motion for the set under consideration and comparing it with the reference spectrum. This means that the average spectrum computed taking 7 components out of the 14 records, for example, to use them as the seismic input along a specific direction of the structure, may not respect condition (c), although it is expected (and verified for those sets given in the following) to be similar to the average taken on all 14 recordings.

Since the same accelerogram may not be used simultaneously along both horizontal directions, 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.

For analysis of plane structures it seems that if a group of records should be made of only one component of motion, then a set should be made of seven accelerograms. The

[8]In the Italian code the condition on the a_{vg} does not exist while the rest is the same.

input database has also been investigated for this kind of combinations (identified as *plane type* or P-type).

3.2. Reference Spectra

The spectra the selected record sets should be compared to are defined in *Sec. 3.2.2.* Eurocode assigns the spectral shape distinguishing between low and high magnitude events. The spectral shape[9] for the latter is given by Eq. (1).

$$\begin{cases} 0 \le T \le T_B : S_a(T) = a_g \; S\left[1 + \dfrac{T}{T_B}(\eta\, 2.5 - 1)\right] \\ T_B \le T \le T_C : S_a(T) = a_g \; S\, \eta\, 2.5 \\ T_C \le T \le T_D : S_a(T) = a_g \; S\, \eta\, 2.5\left[\dfrac{T_C}{T}\right] \\ T_D \le T \le 4s : S_e(T) = a_g \; S\, \eta\, 2.5\left[\dfrac{T_C T_D}{T^2}\right] \end{cases}, \qquad (1)$$

where T is the vibration period of a linear SDOF; a_g is the design ground acceleration on type A site class; S is the soil factor; T_B, T_C are the limiting periods of the spectrum's plateau; T_D is the lowest period of the constant displacement spectral portion; η is the damping correction factor, and it is equal to one for 5% viscous damping.

The ordinates and shapes depend on the seismic hazard level and site class respectively. The five[10] stratigraphical profiles considered are summarized in Table 1 where the shear-wave velocity in the upper 30 m (Vs_{30}) range is given for each of them. In Table 2, the specific values to determine the spectral shapes are given, the resulting curves are plotted in Fig. 2.

TABLE 1 Vs_{30} values for main site classes according to EC8

Site class	Vs_{30} [m/s]
A – Rock or other rock-like geological formation	> 800
B – Deposits of very dense sand, gravel, or very stiff clay (Stiff Soil)	360 – 800
C – Deep deposits of dense or medium-dense sand, gravel or stiff clay (Soft Soil)	180 – 360
D – Deposits of loose-to-medium cohesionless soil (Very Soft Soil)	< 180
E – A soil profile consisting of a surface alluvium layer (Alluvional)	Vs *values of type C or D and thickness varying between about 5 m and 20 m, underlain by stiffer material with* Vs > 800 m/s

[9]The Italian code has a coincident spectral shape for Type A site class, whereas for other soil conditions it changes.

[10]Other than those listed, two more special ground types, S1 and S2, exist. For such cases, special studies for the definition of the seismic action are required, and they are not considered in the investigation.

TABLE 2 Spectral shape controlling parameters according to EC8

Site class	S-factor	T_B (s)	T_C (s)	T_D (s)
A	1	0.15	0.4	2.0
B	1.2	0.15	0.5	2.0
C	1.15	0.20	0.6	2.0
D	1.35	0.20	0.8	2.0
E	1.4	0.15	0.5	2.0

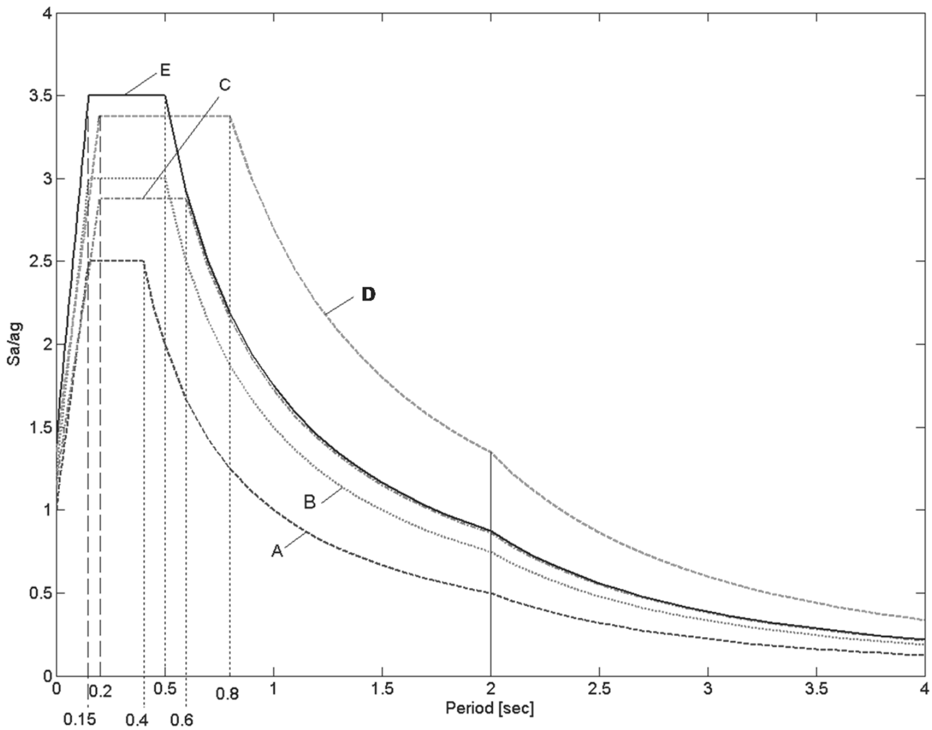

FIGURE 2 Spectral shapes for main site classes.

The spectral shape is almost[11] independent of the hazard which is described in terms of a single parameter, i.e., the reference value of PGA on Type A ground. As discussed, three hazard levels are possible, therefore 15 spectra may be defined. The a_g values are to be chosen by the national authorities; Italian values [OPCM 3274, 2003], herein used, are given in Table 3.

Once the instructions to define the code spectra have been given in terms of shape and spectral ordinate values, it is worthwhile to briefly comment on the criteria listed in Sec. 3. As discussed in Sec. 2, the EC8 prescriptions do not allow the implementation of current

[11]EC8 defines two types of spectral shapes to be selected depending on the magnitude of the earthquakes contributing most to the seismic hazard, this also sets an indirect connection between the design spectrum and the hazard. In the following only Type 1 spectra, which apply for surface-wave magnitude larger than 5.5, are given.

TABLE 3 Ground acceleration values according to the Italian code

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

best practices for estimation of the seismic demand on structures. Moreover, other basic aspects of the EC8 prescriptions have been challenged, for example by Bommer and Pinho [2006], as they seem to be directly derived from other codes without a specific revision or adjustment to the European case. One example of this is the choice of the 10% probability of exceedance in 50 years as a reference value.

Moreover, anchoring the spectra to a_g values with a certain exceedance probability, sets the connection between the code spectrum and the seismic hazard. Therefore, it may be argued that the code spectrum represents a crude approximation of the uniform hazard spectrum. Working with UHS makes it difficult to control performance assessment criteria which are stated in terms of mean annual frequency of exceeding a structural response threshold instead of a ground-motion hazard value. In fact, if a record set is chosen to match the code spectrum only in terms of averaged spectral ordinates, the residual variability of the records' spectra within the set does not allow to directly control the exceeding probability associated to the response estimated in that way. This is the reason why the database considered has also been investigated for specific record sets having relatively small individual spectra variability with respect to the code spectrum (Sec. 6.3).

Because of these considerations, it has to be underlined that results presented herein are conditioned to the EC8 prescriptions' intrinsic limits, although some additional selection criteria have been considered (see following section) in the analyses.

4. Additional Selection Parameters

Along with conditions (a), (b), (c) discussed in Sec. 3, additional parameters considered in the investigation, because they may matter for structural response assessment, are:

a. the deviation of the average spectrum in respect to the code spectrum (δ);
b. the maximum deviation of a single spectrum within a set in respect to the code spectrum ($\delta_{\max}$);
c. the number of different events for records within a set;
d. the variability of magnitude of events within a set.

a. The average spectrum deviation (δ) gives a quantitative measure of how much the mean spectrum of a records' combination deviates from the spectrum of the code. The definition of δ is given by Eq. (2).

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

a. where $Sa_{o,med}\ (T_i)$ represents the pseudo-acceleration ordinate of the average 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 the number of values within the considered range of periods. Selecting a record set with a low δ value allows to obtain of an average spectrum, which is well approximating the code. This may prevent overestimation of seismic demand.a.

b. The maximum deviation ($\delta_{\max}$) of a single record within a set has been computed as in Eq. (3) replacing $Sa_{o,med}\ (T_i)$ with $Sa_o\ (T_i)$, which is the ordinate of a single spectrum of the combination. Controlling this parameter may allow choosing combinations characterized by records having the individual spectra relatively close to the reference spectrum, and therefore being narrowly distributed around it.

$$\delta_{\max} = \max_{in\ a\ set}\left\{\sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{Sa_o\,(T_i) - Sa_s\,(T_i)}{Sa_s\,(T_i)}\right)^2}\right\} \tag{3}$$

c. This criterion corresponds to the identification of combinations of records which contain the largest number of different events possible, because it is believed that having many records from the same earthquake within a set may bias the estimation of the seismic demand.

d. This criterion should be reflected by selecting records only within events featuring a moderate-to-high magnitude for each site class. Since it is recommended by many studies such as Shome *et al*. [1998] to use recordings having about the same magnitude of the scenario of interest, the analyses herein presented aimed to find sets featuring small ranges of magnitude (to have several sets each of those representing a different magnitude scenario). Moreover, limiting the magnitude also allows the control of the duration of the records [Stewart *et al*., 2001].

Unfortunately, since high magnitude events are rare, the analyses almost failed in limiting the magnitude variation within the solutions found. In fact, it will be discussed how it was hardly possible to find record sets optimizing more than one of these criteria and, at the same time, being compatible with the code.

Other parameters such as record's duration and distance have not been considered in the selection, at least not directly. This is also because referenced studies have questioned the importance of these features, at least for the estimation of certain response parameters.

5. Investigated Waveform Database

Nowadays there are many sources of ground-motion records; most of them also have an accessible website. A review of the available waveforms databases may be found in Bommer and Acevedo [2004]. For the purposes of the present study the investigated dataset is the *European Strong-motion Database*[12] (ESD), whose URL is http://www.isesd.cv.ic.ac.uk; see Ambraseys *et al*. [2000, 2004] for further information. The criteria for record search within the ESD are summarised in Table 4.

Selecting the records within the database ordered by the site class (rock, stiff soil, soft soil, very soft soil, alluvium) allows to download of all the spectra of accelerograms

[12]This particular database was chosen because the European origin of the considered code. However, as shown in the following, it was only possible to find record sets each of those consisting of ground-motions from different countries and seismic areas. This weakens the motives behind the choice of that specific database; therefore, other waveform depositories could have been considered.

TABLE 4 Record selection criteria of the European Strong Motion Database website

Earthquake criteria	Station criteria	Waveform criteria
Earthquake Name	Station Name	Epicentral-Distance
Earthquake Country	Station Country	Fault-Distance
Date	Location (Lat. & Lon.)	Source-Station Azimuth
Epicentre (Lat. & Lon.)	Building Type	Local Intensity
Focal Depth	Local Geology	PHA & PVA (peak horizontal and vertical accelerations)
Magnitude (M_w, M_s, M_L)	Vs_{30m}	
Epicentral Intensity		
Fault Mechanism		

TABLE 5 Total number of the records found listed by site class

Local Geology	X	Y
A (rock)	575	570
B (stiff soil)	770	770
C (soft soil)	410	410
D (very soft soil)	28	29
E (alluvium)	105	103

belonging to each ground category (website accessed in April 2005). In Table 5 the number of retrieved spectra, divided by the two horizontal[13] components (conventionally indicated as X and Y), is given. The latter shows that the number of spectra available is significantly different among site classes especially for those referring to soft soil sites. Besides, those records without both components were discarded. Moreover, only events characterized by a moment magnitude equal or larger than 5.8 have been retained, which allows the use of the spectrum discussed in Sec. 3.1, since it is applicable for a surface-wave magnitude larger than 5.5. For site class D, no reduction to the initial list was made because of the shortage of stations for that geological condition. The resulting numbers of horizontal records are given in Table 6. In the table, the percentage of stations which have a source-to-site distance larger than 15 km (this criterion is a proxy, although weak, for indicating the far-source condition) is also listed. It has been verified that the instrument housing was of the free-field type for the most of the stations (Table 6). In Table 7, the records are classified by the countries they come from; in

Table 8 the events most represented are listed. As expected, the majority of accelerograms is from Italian, Turkish, and Greek earthquakes.

This pre-selection ensures having records coming from moderate-to-high magnitude events and also allows the reduction of the number of sets to be investigated. Otherwise, since the number of possible combinations of records would increase by the binomial coefficient, this would lead to a very large set of possible combinations; for example: the number of non-ordered combinations of 111 elements, groups of 2 components of motions, in 7 bins is given by the binomial coefficient and it is 34 billions.

[13]For many of the records in the ESD the X and Y correspond to the east-west and north-south components of motion.

TABLE 6 Total number of records with moment magnitude larger than 5.8 (except D-type site class)

Local Geology	X	Y	Total	Far Field	Free Field
A (rock)	111	111	222	87%	87%
B (stiff soil)	135	135	270	86%	89%
C (soft soil)	122	122	244	87%	91%
D (very soft soil)	28	28	56	96%	100%
E (alluvium)	29	29	58	100%	83%

TABLE 7 Records with moment magnitude larger than 5.8 listed by country

	Local Geology				
Nation	Rock	Stiff soil	Soft soil	Very soft soil	Alluvium
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	—	—
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**

TABLE 8 Events most represented in the selected database

Earthquake name	Country	Records (both horizontal components)
Campano-Lucano	Italy	42
Duzce 1	Turkey	92
Friuli	Italy	60
Izmit	Turkey	124
Montenegro	Yugoslavia	76

6. Analyses and Results

The identified database of records was investigated in order to find sets that consist of: (i) of 7 records (one-component or P-type sets); and (ii) 7 groups of records each of those including both horizontal components (sets made of 14 records for spatial analyses or S-type sets), for all 5 site classes. As prescribed by the code, special care was taken so that a combination is made only of records coming from the same site condition as that of the considered code spectrum.

To find sets compatible with Eurocode spectra, a specific computer code was developed. It examined all possible combinations of spectra of the input list given in the previous section, checking the matching with the code shapes. The compatibility interval was chosen to be 0.04–2 s. This interval, according to condition (c), in Sec. 3, renders the record sets found suitable for structures with T_1 in the range 0.2–1 s, which is the case for many common buildings. Since 0.04 s is the first period given in the spectra of the ESD, condition (b) of Sec. 3 has been checked approximating[14] the PGA of any record with Sa(0.04s).

The lower bound for the deviation from the code spectrum is prescribed to be 10% (see Sec. 3); the upper bound is not assigned, and in the analyses, it was iteratively adjusted to control the number of the results found and, at the same time, to limit the overestimation of the code spectrum. For each combination, the computer code also computes the deviation of every single spectrum within the set and also the deviation of the average spectrum from the code spectrum. Results of this search were manually[15] ranked with respect to the additional criteria given in Sec. 4. The highest-ranking results are outlined in Sec. 6.

Searches for sets of type P and S were performed to search for both un-scaled and sets to be scaled. In this last case the spectra were normalized, in order to make them comparable with the non dimensional code spectrum. This allows for the search for records with a spectral shape similar to the code; moreover, it reduces the spectral variability within a combination.

In the following sections the total number of sets compatible with EC8 spectra is presented and selected results, referring to both un-scaled and non dimensional records, are classified for spatial and one-component cases. For D and E soil types, no results at all were found. This is primarily due to the shortage of recordings on these soils in the database, but also because the spectra for soft soil are dependent on the stratigraphical features of the specific site and may not be referred to a standard shape.

6.1. Type S – Sets of Both Horizontal Components of Seven Stations

The chosen dataset has been investigated for S-type sets made of un-scaled records first. This means that the average has been calculated on the basis of 14 original (un-scaled) records, which are the *X* and *Y* components of seven signals.

A summary of results is given in Table 9, which shows, for any site class and seismic zone for which combinations exist, the number of spectrum-compatible sets found and their corresponding relative tolerance in matching the average spectrum. As it is expected, a larger number of results correspond to the lower hazard levels.

[14]Condition (b), checked with the actual PGA values, was always verified for randomly sampled resulting sets, indicating that this approximation seems acceptable.

[15]Another more refined option to carry out this job via genetic algorithms is that proposed by Naeim *et al*. [2004].

TABLE 9 Compliant sets for spatial analyses found

Ground	Zone	Maximum Lower Tolerance	Maximum Upper Tolerance	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

The upper bound for the deviation from the code spectrum is adjusted adaptively to allow to find more Eurocode-compatible sets.[16] It should also be noted that for all Zone 1 cases, the lower tolerance (assigned by EC8 to be 10% maximum) had to be overridden. Otherwise, for the higher hazard levels, it would not have been possible to find results satisfying the EC8 prescriptions. Specifically, the lower bound had to be reduced in such cases described; sets found may be slightly linearly scaled to comply with the code spectrum.

As an example, selected results are given from Figs. 3–11. They correspond to the all three hazard levels of all site classes. In the figures the rough thick curve represents the average spectrum and the thick smooth curve represents the code spectrum; the thin black line is the 10% tolerance limit prescribed by the code; the dashed line is 10% above the code spectrum; the other thin lines are the individual spectra of the records within a set; two components of the same station share the same line feature. In the legend of any figure the six digits station codes, as well as the earthquake codes (EQ), from the ESD database are given. For details about the records displayed see the Appendix.

All records shown are those characterized by the minimum δ with respect to the code spectrum; thus they have the smallest average deviation from the EC8 in the range of periods investigated (additional criterion a). It turns out that satisfying this criterion leads to large spectral variability. In order to measure such large record-to-record variability of the spectra within each set, δ_{max} was computed. The sets displayed in Figs. 6, 7, and 9 are also those combinations characterized by the lowest scatter of individual records in respect to the code spectrum (additional criterion b), but the variability is still large. Some of the sets shown are made of records coming from seven different events (additional criterion d).

For Zone 1 sets (all site classes), where scaling was necessary, the scaling factors (SF) are given in the legend. SFs were chosen manually with the scope of reducing as much as possible the number of records to be scaled within a set, and to limit the scaling factors of those records which are scaled. (In fact, for the results shown they are not larger than 1.6.) It could also happen that combinations referring to different hazard levels, optimizing the deviation from the code spectrum, share some records (see, for example, Figs. 6 and 7).

[16]The lower bounds for Zone 1 of A, B, C site classes are given in Table 9; 30, 20, and 35%, are the minimum lower bounds to find results. These levels have been obtained iteratively increasing (with a 5% step) the lower bound in the analyses. In other words it was not possible to find suitable results using 15, 25, and 30%, respectively. The upper bounds have been chosen arbitrarily to obtain a significant number of resulting record sets.

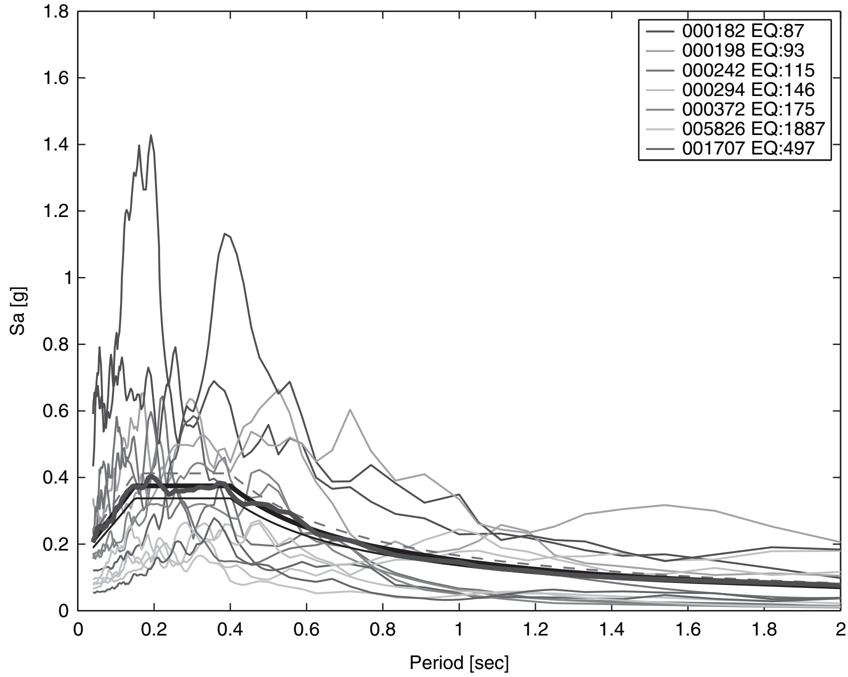

FIGURE 3 Site class A – Zone 3. Set with minimum average deviation from the target spectrum ($\delta = 0.041$) with records coming from seven different events.

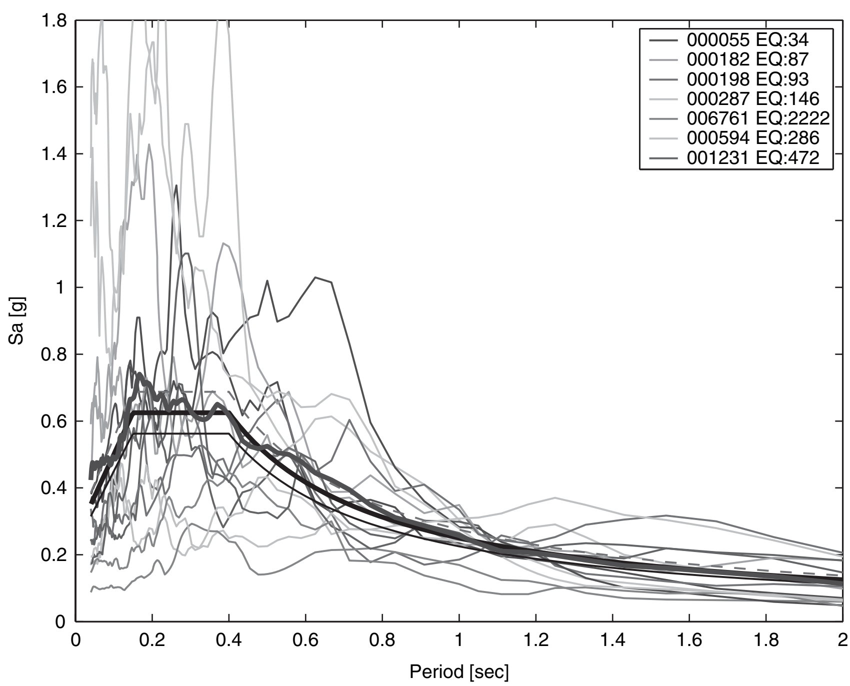

FIGURE 4 Site class A – Zone 2. Set with minimum average deviation from target spectrum ($\delta = 0.122$) with records coming from seven different events.

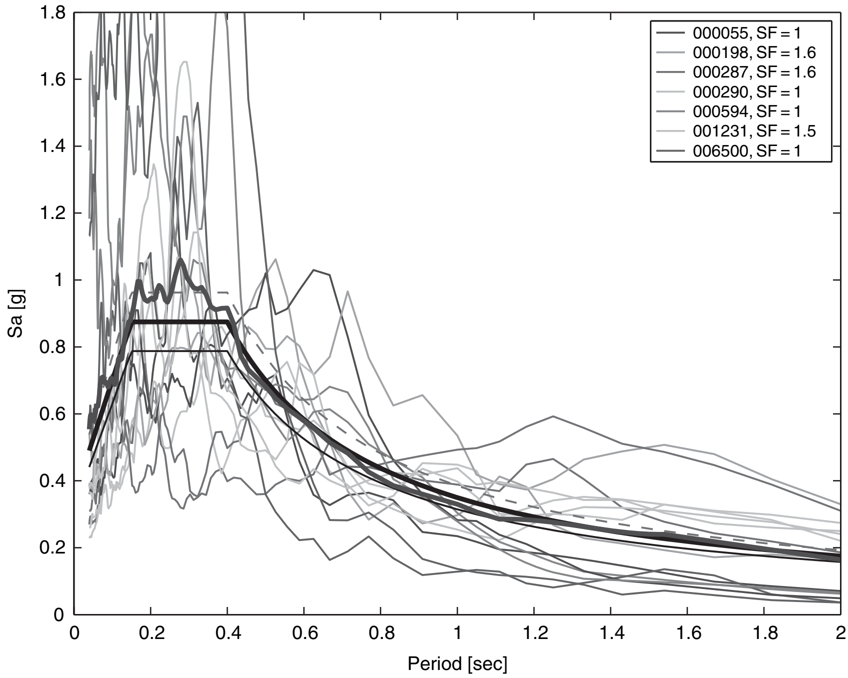

FIGURE 5 Site class A – Zone 1. Set with minimum average deviation from target spectrum ($\delta = 0.12$). SF is the individual scale factor.

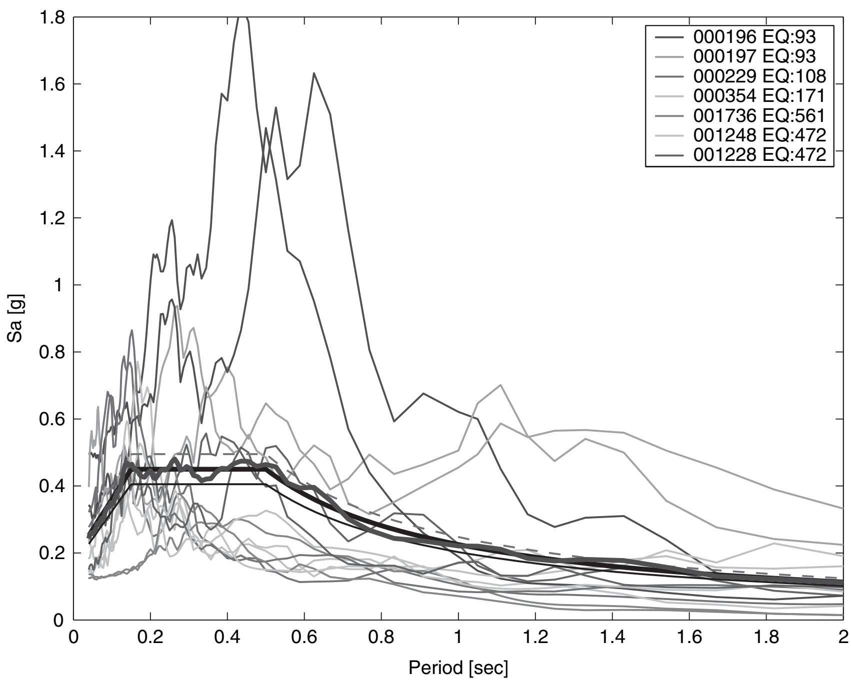

FIGURE 6 Site class B – Zone 3. Set with minimum average deviation from the target spectrum ($\delta = 0.04$) and minimum single-record deviation from the target ($\delta_{max} = 1.3$).

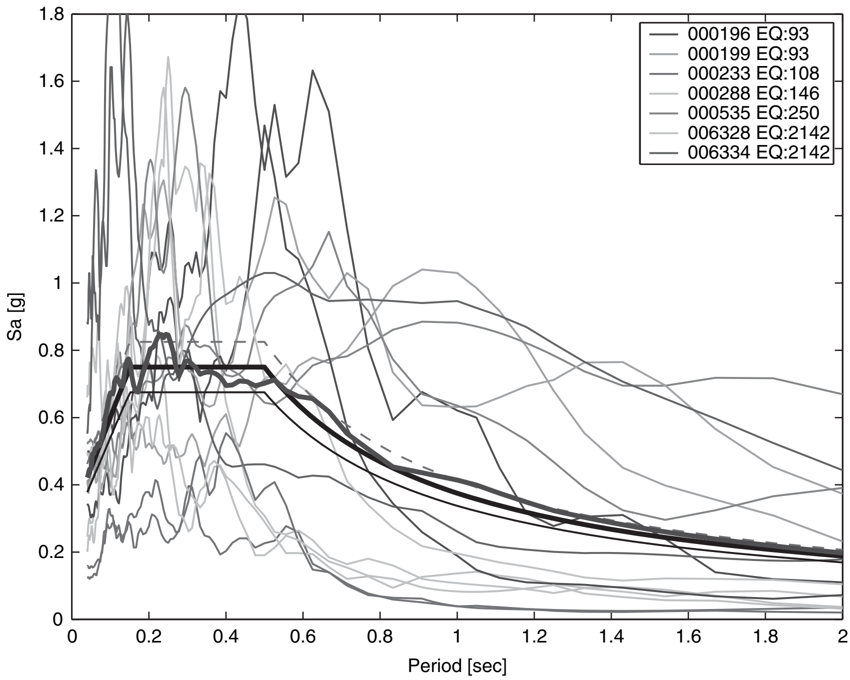

FIGURE 7 Site class B – Zone 2. Set with minimum average deviation from the target spectrum ($\delta = 0.07$) and minimum single-record deviation from the target ($\delta_{max} = 1.0$).

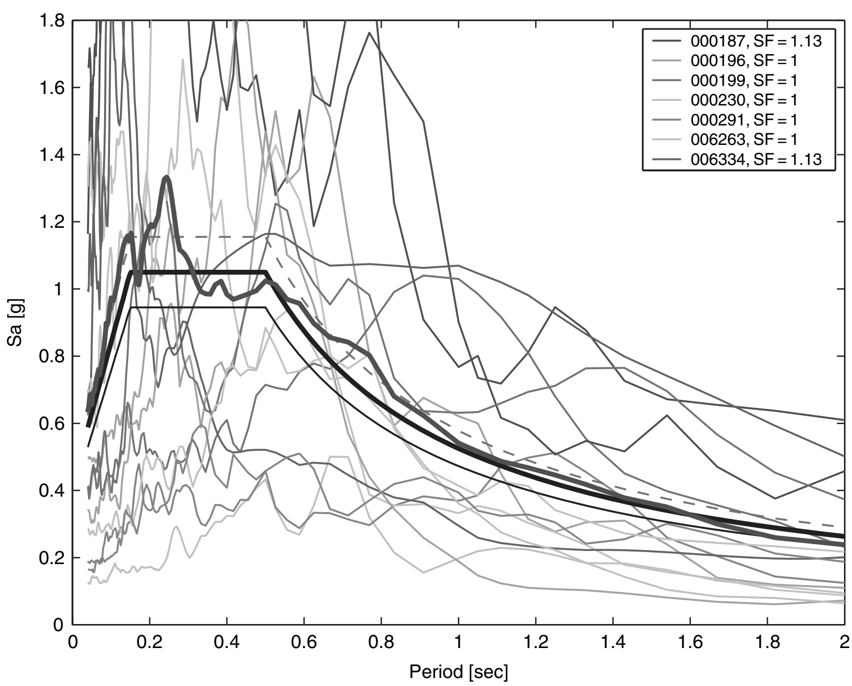

FIGURE 8 Site class B – Zone 1. Set with minimum average deviation from target spectrum ($\delta = 0.07$). SF is the individual scale factor.

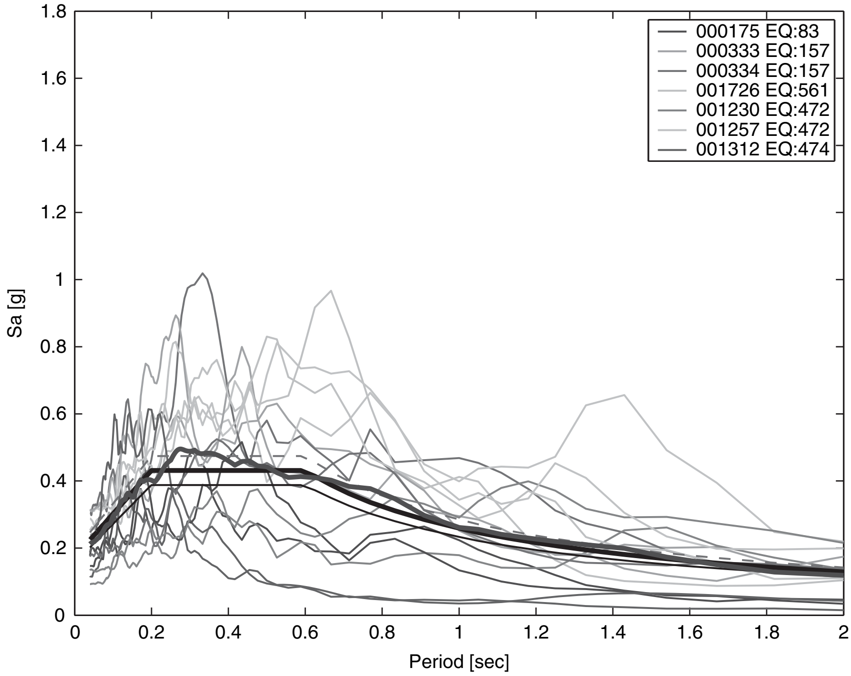

FIGURE 9 Site class C – Zone 3. Set with minimum average deviation from the target spectrum ($\delta = 0.07$) and minimum single-record deviation from the target ($\delta_{max} = 0.572$).

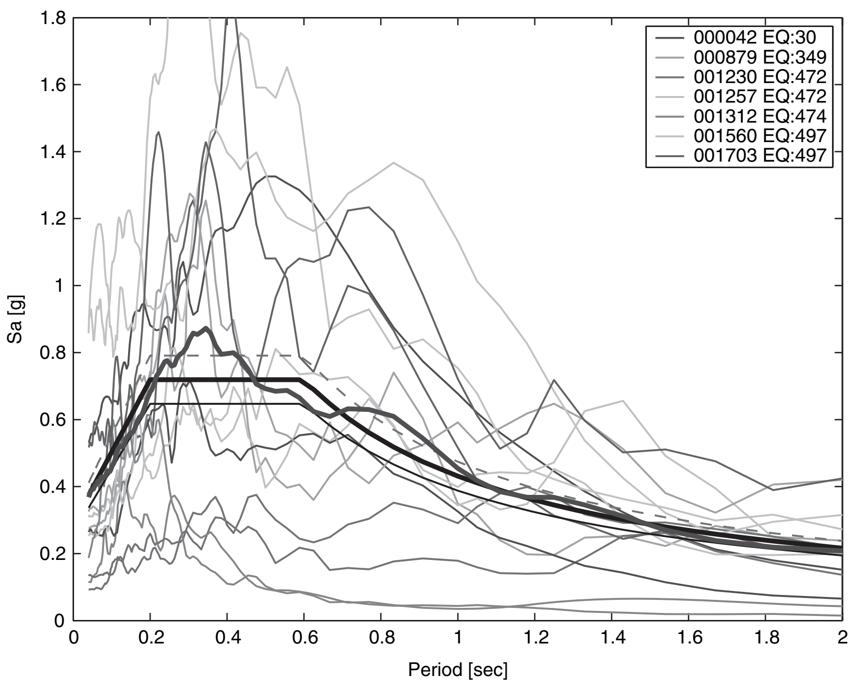

FIGURE 10 Site class C – Zone 2. Set with minimum average deviation from target spectrum ($\delta = 0.08$).

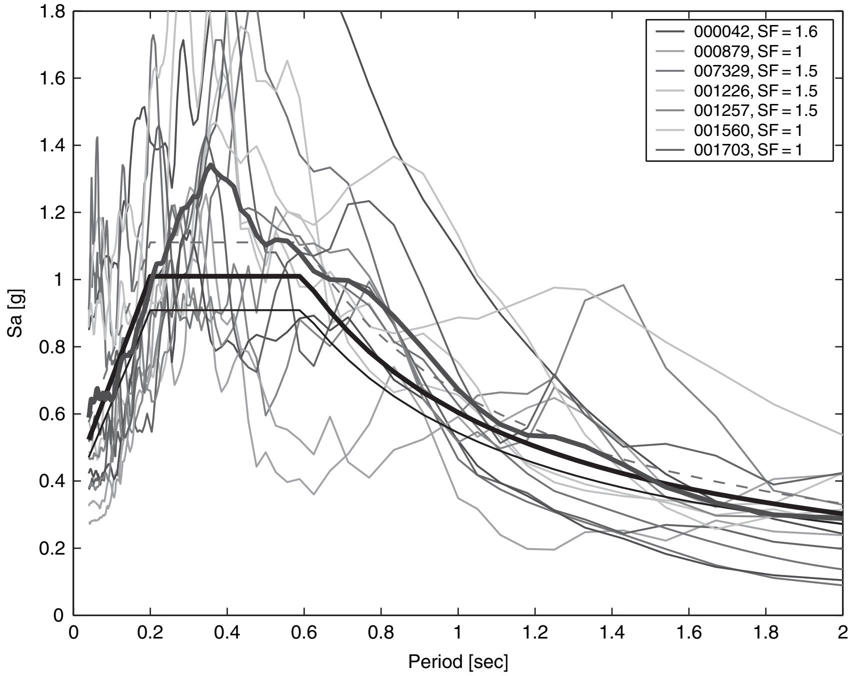

FIGURE 11 Site class C – Zone 1. Set with minimum average deviation from target spectrum ($\delta = 0.173$). SF is the individual scale factor.

What finally emerges from these results is that to have the best average spectral compatibility, it is hard to reduce the variability of the records keeping them un-scaled. Alternatively, it also could be possible to allow the scaling of all records, which is the approach followed for results presented in Sec. 6.3.

6.2. Type P – Sets of Seven Stations' Single Component

In this section the results of investigating the input dataset for P-type sets, then those made of seven groups of one component only, are summarized. Table 10 gives the number of combinations found for all zones for which results exist. The same considerations made

TABLE 10 Number of compliant sets for plane analyses found

Ground	Zone	Maximum Lower Tolerance	Maximum Upper Tolerance	Sets Found
A	1	*25%*	1000%	124
	2	10%	20%	831
	3	10%	20%	551
B	1	*20%*	1000%	79
	2	10%	20%	101
	3	10%	20%	1859
C	1	*20%*	1000%	337
	2	10%	20%	115
	3	10%	10%	177

for spatial sets still apply in terms of both number and type of results found. The sets are characterized by large record-to-record variability of the spectra, while showing good agreement with the code spectrum. For the more severe spectra (Zone 1), the P-type sets still require slight linear scaling in order to comply with the code. Some of the results, which are the best combinations found in terms of one or more additional constraints, are displayed from Figs. 12–20.

6.3. Non Dimensional Sets

It is generally desirable to reduce the record-to-record spectral variability within a set, as also discussed in Sec. 3.1. Therefore, the database has also been examined for records having a spectral shape similar to that of the code [Bommer and Acevedo, 2004]. However, this normally entails scaling the record, which was avoided, if possible, in the analyses presented in the previous sections. Here, the records have been rendered non dimensional by dividing the spectral ordinates to their spectral acceleration at T = 0.04 s (assumed to be an approximation of the PGA). Combinations of these spectra have been compared to the non dimensional code spectrum, and then the results may be considered country-independent.

It was not possible to find non dimensional sets compliant with the code in the initial period range. Then the investigated interval has been reduced to 0.147–2 s, which, according to the code, is appropriate for structures with a first mode period falling in the 0.735–1 s interval. This allowed to find results: the number of S-type combinations found is 8810, with 10% (lower) and 100% (upper) tolerance bounds. Examples are given in Figs. 21 and in 22 for the A-type site class.

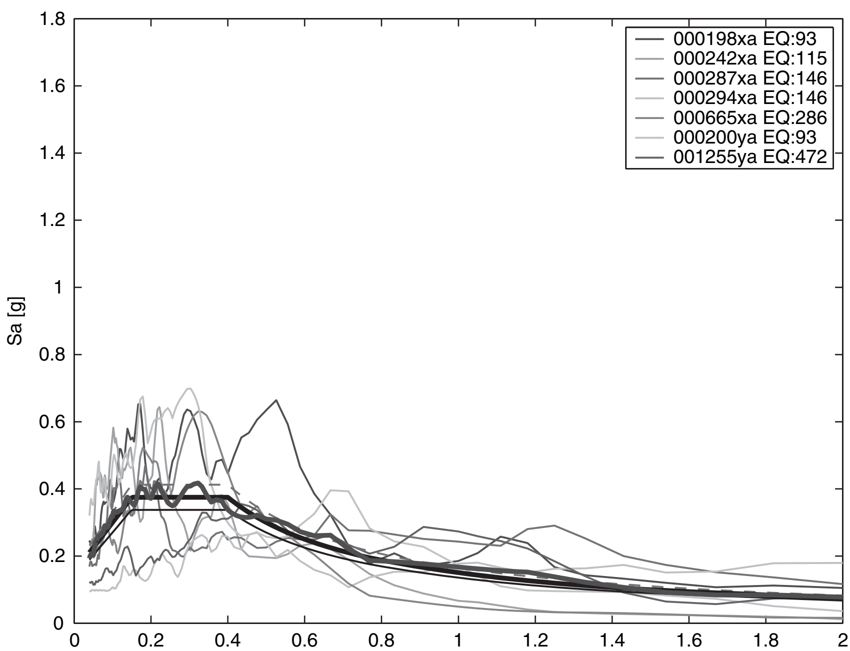

FIGURE 12 Site class A – Zone 3. Set with minimum average deviation from the target spectrum (δ = 0.07) and minimum single-record deviation from the target (δ_{max} = 0.58).

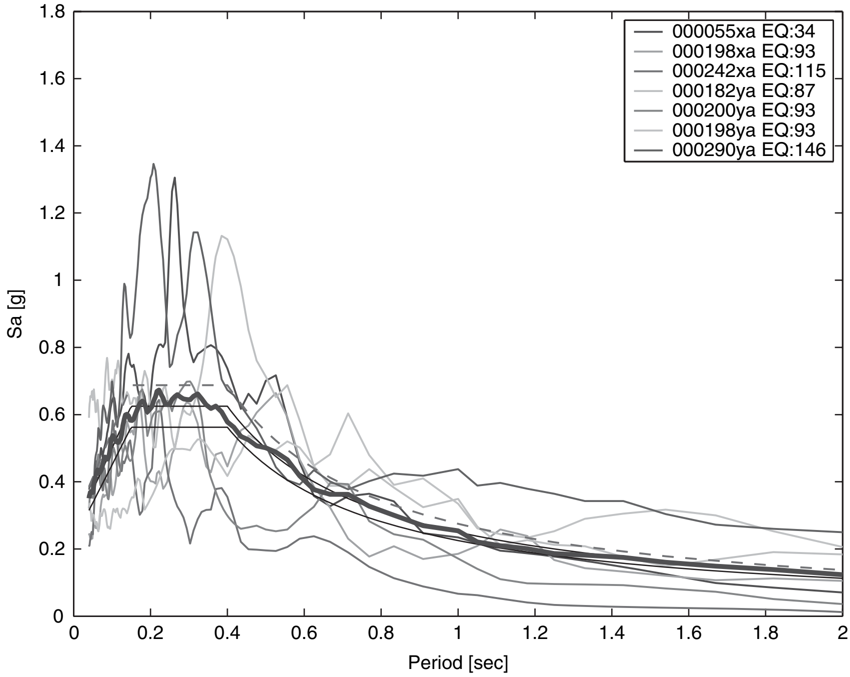

FIGURE 13 Site class A – Zone 2. Set with minimum average deviation from the target spectrum (δ = 0.04) and minimum single-record deviation from the target (δ_{max} = 0.51).

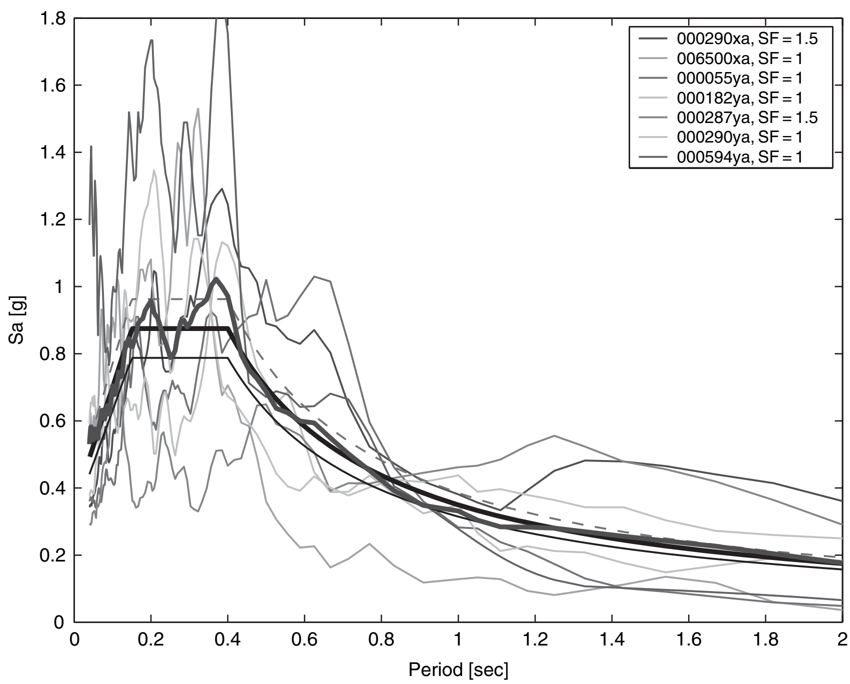

FIGURE 14 Site class A – Zone 1. Set with minimum average deviation from target spectrum (δ = 0.1). SF is the individual scale factor.

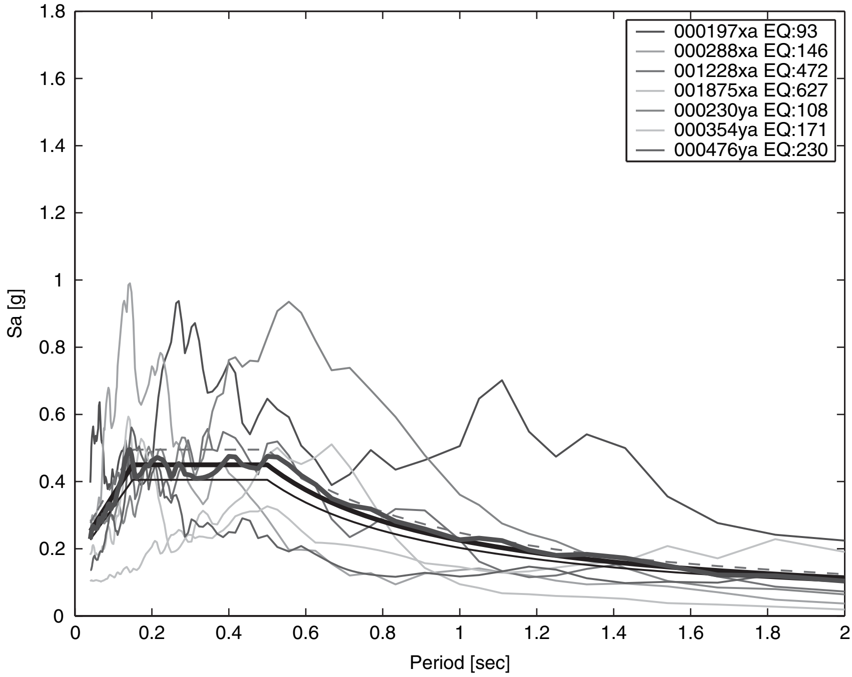

FIGURE 15 Site class B – Zone 3. Set with minimum average deviation from target spectrum ($\delta = 0.06$).

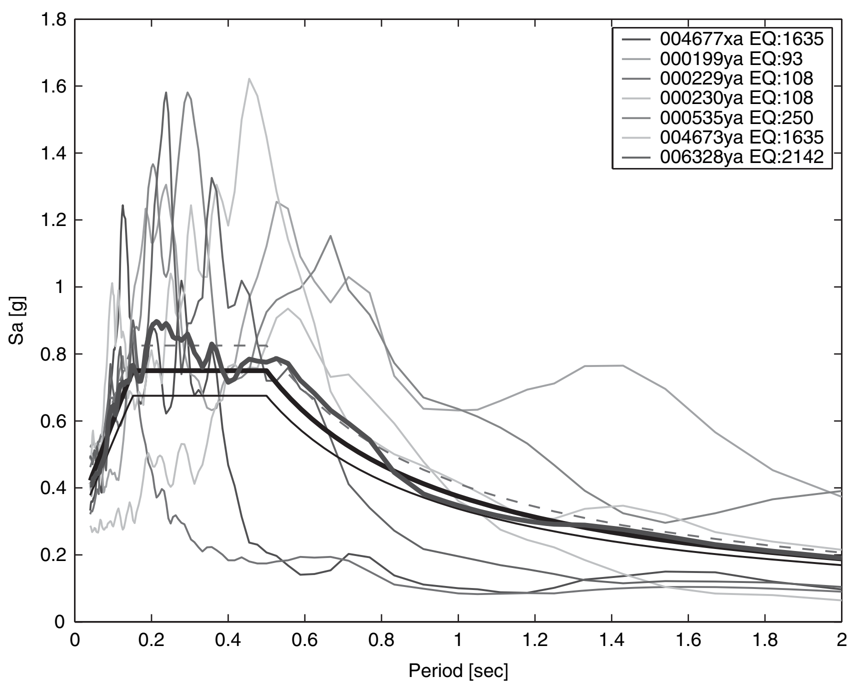

FIGURE 16 Site class B – Zone 2. Set with minimum average deviation from the target spectrum ($\delta = 0.09$) and minimum single-record deviation from the target ($\delta_{max} = 0.55$).

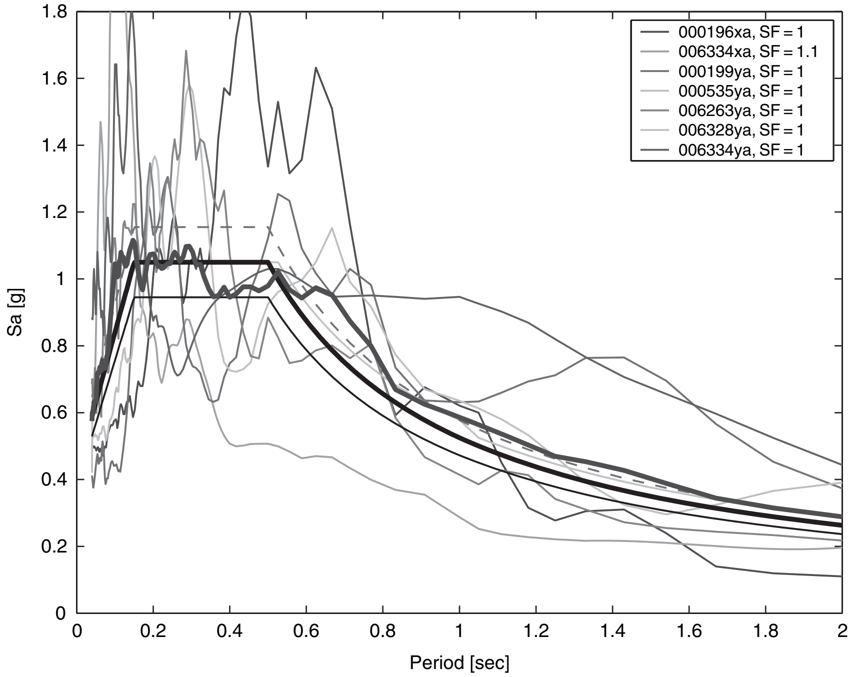

FIGURE 17 Site class B – Zone 1. Set with minimum average deviation from target spectrum ($\delta = 0.07$). SF is the individual scale factor.

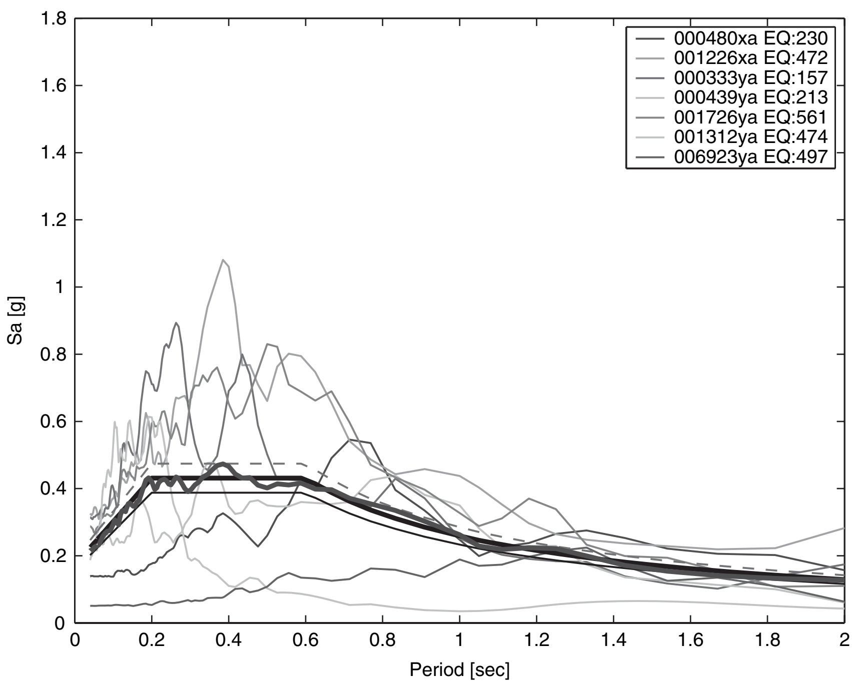

FIGURE 18 Site class C – Zone 3. Set with minimum single-record deviation from the target spectrum ($\delta_{max} = 0.77$).

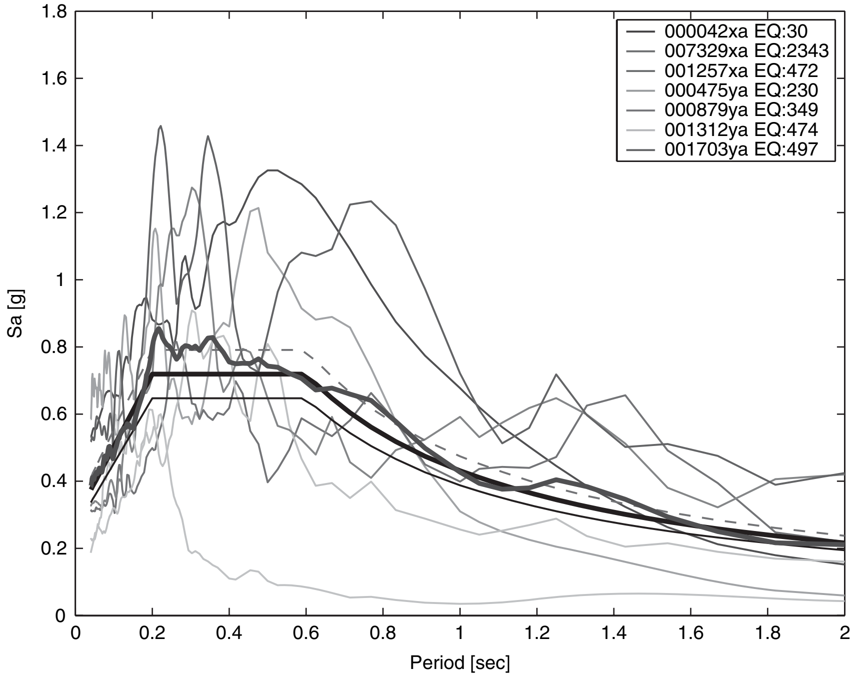

FIGURE 19 Site class C – Zone 2. Set with minimum average deviation from the target spectrum (δ = 0.08) and minimum single-record deviation from the target ($\delta_{\max}$ = 0.54).

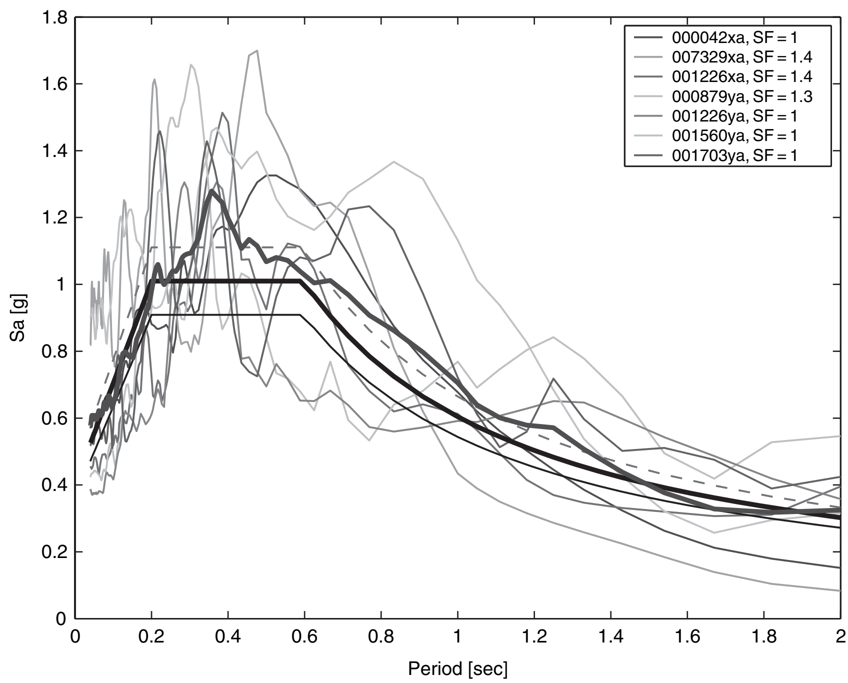

FIGURE 20 Site class C – Zone 1. Set with minimum average deviation from the target spectrum (δ = 0.11) and minimum single-record deviation from the target ($\delta_{\max}$ = 0.45). SF is the individual scale factor.

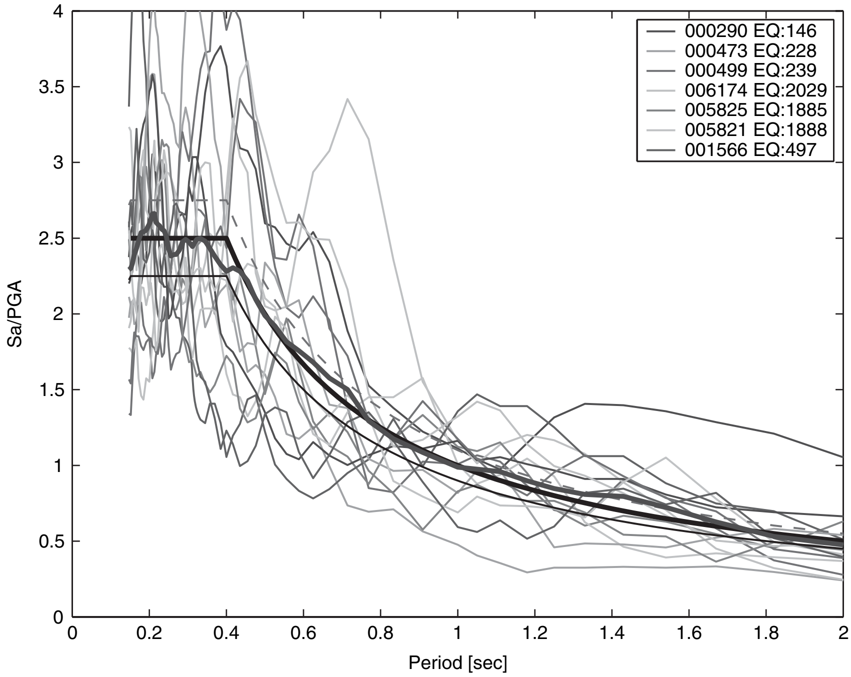

FIGURE 21 Site class A – S-type. Set with minimum average deviation from the target spectrum ($\delta = 0.047$) with records coming from seven different events.

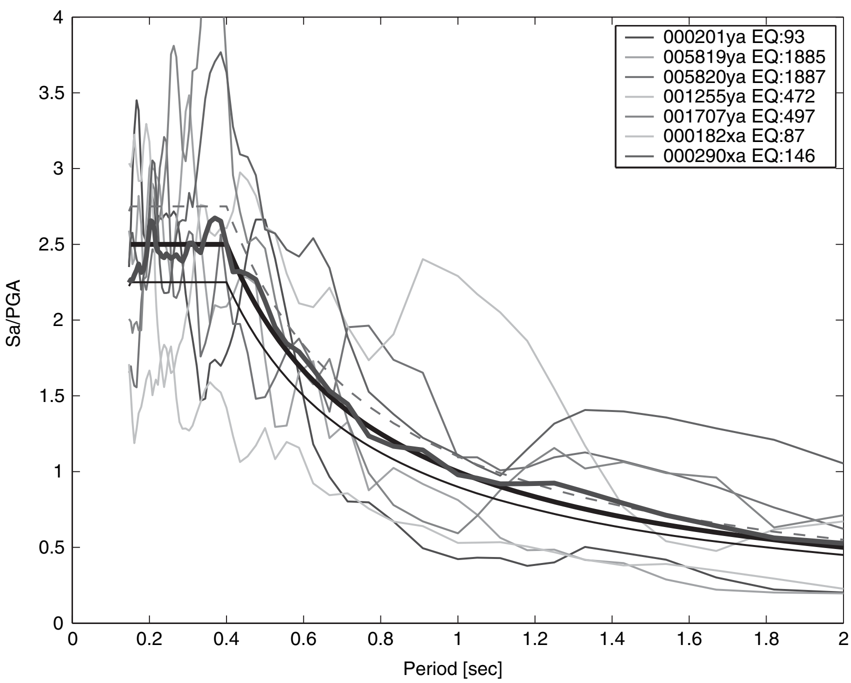

FIGURE 22 Site class A – P-Type. Set with minimum average deviation from the target spectrum ($\delta = 0.058$) with records coming from seven different events.

TABLE 11 Average scaling factor to match the code spectra of non dimensional records of A-type site class

		Non dimensional records of A-type site class	
Zone	a_g	S-type set (Figure 21)	P-type set (Figure 22)
1	0.35g	21	3.2
2	0.25g	15	2.3
3	0.15g	9	1.4

Normalization of spectra, as expected, reduces the spectral variability within a set while keeping a good average matching with the code. For example, the average SF values (rounded for presentation purposes) with respect to the Italian a_g values are given in Table 11. From the table it is possible to see that the average scaling factor is relatively limited for the P-type set, while it is very large for the spatial, S-type, set. However, there are different opinions on whether large scaling factors may be tolerated in seismic assessment; some other results have shown that large scaling factors do not bias the estimation of non-linear demand (see also on Watson-Lamprey and Abrahamson, 2006, on the topic).

7. Summary and Conclusions

The study presented in this article aims to investigate whether it is possible to find unscaled record sets fulfilling, as much as possible, the requirements of Eurocode 8 with respect to the seismic input for dynamic (time-history) analysis of spatial and plane structures. The European Strong-Motion Database is chosen as the database from which the spectra are taken. Only those recordings coming from events of moderate-to-high magnitude have been selected. A computer code was developed to verify the average compatibility of all possible sets of these spectra with the code spectra.

The dataset was searched for two different types of solutions: (1) sets made of seven single-component of motion for analysis of plane structures, namely P-type sets; and (2) sets made of seven groups of both horizontal components of the same recording station (S-type sets), for analysis of buildings. Having a set of at least seven ground-motions allows the practitioner to consider the mean structural response. Otherwise, one has to consider the maximum if three to six recordings are used. The vertical component of the motion was not considered because, according to the code, it has to be accounted for in special cases and for Zone 1 sites only. Sets resulting from the searching have also been ranked in terms of additional criteria. They not only refer to the similarity of the average spectrum with the reference spectrum, but also to the record-to-record variability of the spectral ordinates; to the prevention of a single-event domination; and finally to the range of magnitudes within a set. It was not possible to satisfy all these criteria simultaneously by the record sets found.

Results were found for A, B, and C site classes, while for very soft soil sites (D and E) it was not possible to retrieve solutions. This is because of two main reasons: (1) the shortage of recordings for these site classes 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.

Combinations found generally show a good average matching of the EC8 target spectral shape. Suitable results refer to hazard Zones 2 and 3, characterized according to the a_g values of the Italian seismic code; that is, by a peak ground acceleration on rock equal, respectively, to 0.25 g and 0.15 g. For Zone 1 (a_g = 0.35 g), it was not possible to find a set compatible with the EC8 spectra, however slight linear scaling of a few records within the set was found helpful in the matter. Moreover, the condition of having un-scaled record sets strictly matching Eurocode 8 spectra resulted in a large record-to-record variability in the spectral ordinates within the same set. This may be avoided by selecting records with a spectral shape as similar as possible to that of the code, but this may lead to large linear scaling factors.

Finally, based on this and other studies reviewed, it seems that EC8 may be significantly improved regarding the selection of real records as an input for structural performance assessment. In fact, it emerges that prescriptions do not easily allow for following the current best practice on the topic as it was presented in the first part of the paper; moreover, it may be hard for practitioners to search databases for real record sets, at least as it was done within this study. Finally, it may be stated that the prescriptions favor use of spectral matching accelerograms. For all these issues, the record sets found within this study, are conditioned to the code's constraints that were considered, and it still needs to be established whether: (i) the number of records in a set is sufficient to capture with acceptable confidence the seismic response and its record-to-record variability, and (ii) the sets found in this way are suitable to get an unbiased estimation of the nonlinear structural response, at the least at the level the best practice allows.

Acknowledgments

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Appendix

In this appendix the details about the records presented in the article, as they come from the European Strong Motion Database website, are given. Both components from the same station code should be considered for the spatial analyses sets, while the single component falling in to the set is indicated *(xa; ya)* for plane analyses sets.

TABLE 12 A-type site class: record information for the un-scaled S-type sets. From Figs. 3–5

Site/Zone	δ	Code	Event Name	Country	Date	Station name
A – 3	0.04	000182	Tabas	Iran	16/09/1978	Dayhook
		000198	Montenegro	Yugoslavia	15/04/1979	Ulcinj-Hotel Albatros
		000242	Valnerina	Italy	19/09/1979	Cascia
		000294	Campano Lucano	Italy	23/11/1980	Bisaccia
		000372	Lazio Abruzzo	Italy	07/05/1984	Scafa
		005826	Strofades	Greece	18/11/1997	Kyparrisia-Agriculture Bank
		001707	Duzce 1	Turkey	12/11/1999	Mudurnu-Kaymakamlik Binasi
A – 2	0.12	000055	Friuli	Italy	06/05/1976	Tolmezzo-Diga Ambiesta
		000182	Tabas	Iran	19/09/1978	Dayhook
		000198	Montenegro	Yugoslavia	15/04/1979	Ulcinj-Hotel Albatros
		000287	Campano Lucano	Italy	23/11/1980	Bagnoli-Irpino
		006761	Vrancea	Romania	30/08/1986	Vrancioaia
		000594	Umbria Marche	Italy	26/09/1997	Nocera Umbra
		001231	Izmit	Turkey	17/08/1999	Izmit-Meteoroloji Istasyonu
A – 1	0.12	000055	Friuli	Italy	06/05/1976	Tolmezzo-Diga Ambiesta
		000198	Montenegro	Yugoslavia	15/04/1979	Ulcinj-Hotel Albatros
		000287	Campano Lucano	Italy	23/11/1980	Bagnoli-Irpino
		000290	Campano Lucano	Italy	23/11/1980	Sturno
		000594	Umbria Marche	Italy	26/09/1997	Nocera Umbra
		001231	Izmit	Turkey	17/08/1999	Izmit-Meteoroloji Istasyonu
		006500	Duzce 1	Turkey	12/11/1999	LDEO Station No. C0375 VO

TABLE 13 B-type site class: record information for the un-scaled S-type sets. From Figs. 6–8

Site/Zone	δ	Code	Event Name	Country	Date	Station name
B – 3	0.04	000196	Montenegro	Yugoslavia	15/04/1979	Petrovac-Hotel Oliva
		000197	Montenegro	Yugoslavia	15/04/1979	Ulcinj-Hotel Olimpic
		000229	Montenegro (aftershock)	Yugoslavia	24/05/1979	Petrovac-Hotel Rivijera
		000354	Panisler	Turkey	30/10/1983	Horasan-Meteoroloji Mudurlugu
		001736	Adana	Turkey	27/06/1998	Mersin-Meteoroloji Mudurlugu
		001248	Izmit	Turkey	17/08/1999	Gebze-Arcelik
		001228	Izmit	Turkey	17/08/1999	Gebze-Tubitak Marmara Arastirma Merkezi
B – 2	0.07	000196	Montenegro	Yugoslavia	15/04/1979	Petrovac-Hotel Oliva
		000199	Montenegro	Yugoslavia	15/04/1979	Bar-Skupstina Opstine
		000233	Montenegro (aftershock)	Yugoslavia	24/05/1979	Kotor-Zovod za Biologiju Mora
		000288	Campano Lucano	Italy	23/11/1980	Brienza
		000535	Erzincan	Turkey	13/03/1992	Erzincan-Meteorologij Mudurlugu
		006328	South Iceland (aftershock)	Iceland	21/06/2000	Kaldarholt
		006334	South Iceland (aftershock)	Iceland	21/06/2000	Solheimar
B – 1	0.07	000187	Tabas	Iran	16/09/1978	Tabas
		000196	Montenegro	Yugoslavia	15/04/1979	Petrovac-Hotel Oliva
		000199	Montenegro	Yugoslavia	15/04/1979	Bar-Skupstina Opstine
		000230	Montenegro (aftershock)	Yugoslavia	24/05/1979	Budva-PTT
		000291	Campano Lucano	Italy	23/11/1980	Calitri
		006263	South Iceland	Iceland	17/06/2000	Kaldarholt
		006334	South Iceland (aftershock)	Iceland	21/06/2000	Solheimar

TABLE 14 C-type site class: record information for the un-scaled S-type sets. From Figs. 9–11

Site/Zone	δ	Code	Event Name	Country	Date	Station name
C – 3	0.07	000175	Volvi	Greece	20/06/1978	Thessaloniki-City Hotel
		000333	Alkion	Greece	24/02/1981	Korinthos-OTE Building
		000334	Alkion	Greece	24/02/1981	Xilokastro-OTE Building
		001726	Adana	Turkey	27/06/1998	Ceyhan-Tarim Ilce Mudurlugu
		001230	Izmit	Turkey	17/08/1999	Iznik-Karayollari Sefligi Muracaati
		001257	Izmit	Turkey	17/08/1999	Yarimca-Petkim
		001312	Ano Liosia	Greece	07/09/1999	Athens 2 (Chalandri District)
C – 2	0.08	000042	Ionian	Greece	04/11/1973	Lefkada-OTE Building
		000879	Dinar	Turkey	01/10/1995	Dinar-Meteoroloji Mudurlugu
		001230	Izmit	Turkey	17/08/1999	Iznik-Karayollari Sefligi Muracaati
		001257	Izmit	Turkey	17/08/1999	Yarimca-Petkim
		001312	Ano Liosia	Greece	07/09/1999	Athens 2 (Chalandri District)
		001560	Duzce 1	Turkey	12/11/1999	Bolu-Bayindirlik ve Iskan Mudurlugu
		001703	Duzce 1	Turkey	12/11/1999	Duzce-Meteoroloji Mudurlugu
C – 1	0.02	000042	Ionian	Greece	04/11/1973	Lefkada-OTE Building
		000879	Dinar	Turkey	01/10/1995	Dinar-Meteoroloji Mudurlugu
		007329	Faial	Portugal	09/07/1998	Horta
		001226	Izmit	Turkey	17/08/1999	Duzce-Meteoroloji Mudurlugu
		001257	Izmit	Turkey	17/08/1999	Yarimca-Petkim
		001560	Duzce 1	Turkey	12/11/1999	Bolu-Bayindirlik ve Iskan Mudurlugu
		001703	Duzce 1	Turkey	12/11/1999	Duzce-Meteoroloji Mudurlugu

TABLE 15 A-type site class: record information for the un-scaled P-type sets. From Figs. 12–14

Site/Zone	δ	Code	Event Name	Country	Date	Station name
A – 3	0.07	000198xa	Montenegro	Yugoslavia	15/04/1979	Ulcinj-Hotel Albatros
		000242xa	Valnerina	Italy	19/09/1979	Cascia
		000287xa	Campano Lucano	Italy	23/11/1980	Bagnoli-Irpino
		000294xa	Campano Lucano	Italy	23/11/1980	Bisaccia
		000665xa	Umbria Marche	Italy	26/09/1997	Assisi-Stallone
		000200ya	Montenegro	Yugoslavia	15/04/1979	Hercegnovi Novi-O.S.D. Pavicic School
		001255ya	Izmit	Turkey	17/08/1999	Heybeliada-Senatoryum
A – 2	0.04	000055xa	Friuli	Italy	06/05/1976	Tolmezzo-Diga Ambiesta
		000198xa	Montenegro	Yugoslavia	15/04/1979	Ulcinj-Hotel Albatros
		000242xa	Valnerina	Italy	19/09/1979	Cascia
		000182ya	Tabas	Iran	19/09/1978	Dayhook
		000200ya	Montenegro	Yugoslavia	15/04/1979	Hercegnovi Novi-O.S.D. Pavicic School
		000198ya	Montenegro	Yugoslavia	15/04/1979	Ulcinj-Hotel Albatros
		000290ya	Campano Lucano	Italy	23/11/1980	Sturno
A – 1	0.10	000290xa	Campano Lucano	Italy	23/11/1980	Sturno
		006500xa	Duzce 1	Turkey	12/11/1999	LDEO Station No. C0375 VO
		000055ya	Friuli	Italy	06/05/1976	Tolmezzo-Diga Ambiesta
		000182ya	Tabas	Iran	19/09/1978	Dayhook
		000287ya	Campano Lucano	Italy	23/11/1980	Bagnoli-Irpino
		000290ya	Campano Lucano	Italy	23/11/1980	Sturno
		000594ya	Umbria Marche	Italy	26/09/1997	Nocera Umbra

TABLE 16 B-type site class: record information for the un-scaled P-type sets. From Figs. 15–17

Site/Zone	δ	Code	Event Name	Country	Date	Station name
B – 3	0.06	000197xa	Montenegro	Yugoslavia	15/04/1979	Ulcinj-Hotel Olimpic
		000288xa	Campano Lucano	Italy	23/11/1980	Brienza
		001228xa	Izmit	Turkey	17/08/1999	Gebze-Tubitak Marmara Arastirma Merkezi
		001875xa	Griva	Greece	21/12/1990	Edessa-Prefecture
		000230ya	Montenegro (aftershock)	Yugoslavia	24/05/1979	Budva-PTT
		000354ya	Panisler	Turkey	30/10/1983	Horasan-Meteoroloji Mudurlugu
		000476ya	Manjil	Iran	20/06/1990	Qazvin
B – 2	0.09	004677xa	South Iceland	Iceland	17/06/2000	Selsund
		000199ya	Montenegro	Yugoslavia	15/04/1979	Bar-Skupstina Opstine
		000229ya	Montenegro (aftershock)	Yugoslavia	24/05/1979	Petrovac-Hotel Rivijera
		000230ya	Montenegro (aftershock)	Yugoslavia	24/05/1979	Budva-PTT
		000535ya	Erzincan	Turkey	13/03/1992	Erzincan-Meteorologij Mudurlugu
		004673ya	South Iceland	Iceland	17/06/2000	Hella
		006328ya	South Iceland (aftershock)	Iceland	21/06/2000	Kaldarholt
B – 1	0.07	000196xa	Montenegro	Yugoslavia	15/04/1979	Petrovac-Hotel Oliva
		006334xa	South Iceland (aftershock)	Iceland	21/06/2000	Solheimar
		000199ya	Montenegro	Yugoslavia	15/04/1979	Bar-Skupstina Opstine
		000535ya	Erzincan	Turkey	13/03/1992	Erzincan-Meteorologij Mudurlugu
		006263ya	South Iceland	Iceland	17/06/2000	Kaldarholt
		006328ya	South Iceland (aftershock)	Iceland	21/06/2000	Kaldarholt
		006334ya	South Iceland (aftershock)	Iceland	21/06/2000	Solheimar

TABLE 17 C-type site class: record information for the un-scaled P-type sets. From Figs. 18–20

Site/Zone	δ	Code	Event Name	Country	Date	Station name
C – 3	0.05	000480xa	Manjil	Iran	20/06/1990	Tonekabun
		001226xa	Izmit	Turkey	17/08/1999	Duzce-Meteoroloji Mudurlugu
		000333ya	Alkion	Greece	24/02/1981	Korinthos-OTE Building
		000439ya	Spitak	Armenia	07/12/1988	Gukasian
		001726ya	Adana	Turkey	27/06/1998	Ceyhan-Tarim Ilce Mudurlugu
		001312ya	Ano Liosia	Greece	07/09/1999	Athens 2 (Chalandri District)
		006923ya	Duzce 1	Turkey	12/11/1999	Hilal (Yalova)
C – 2	0.08	000042xa	Ionian	Greece	04/11/1973	Lefkada-OTE Building
		007329xa	Faial	Portugal	09/07/1998	Horta
		001257xa	Izmit	Turkey	17/08/1999	Yarimca-Petkim
		000475ya	Manjil	Iran	20/06/1990	Abhar
		000879ya	Dinar	Turkey	01/10/1995	Dinar-Meteoroloji Mudurlugu
		001312ya	Ano Liosia	Greece	07/09/1999	Athens 2 (Chalandri District)
		001703ya	Duzce 1	Turkey	12/11/1999	Duzce-Meteoroloji Mudurlugu
C – 1	0.11	000042xa	Ionian	Greece	04/11/1973	Lefkada-OTE Building
		007329xa	Faial	Portugal	09/07/1998	Horta
		001226xa	Izmit	Turkey	17/08/1999	Duzce-Meteoroloji Mudurlugu
		000879ya	Dinar	Turkey	01/10/1995	Dinar-Meteoroloji Mudurlugu
		001226ya	Izmit	Turkey	17/08/1999	Duzce-Meteoroloji Mudurlugu
		001560ya	Duzce 1	Turkey	12/11/1999	Bolu-Bayindirlik ve Iskan Mudurlugu
		001703ya	Duzce 1	Turkey	12/11/1999	Duzce-Meteoroloji Mudurlugu

TABLE 18 Record information for the non dimensional sets. From Figs. 21–22

Site/Analysis	δ	Code	Event Name	Country	Date	Station name
A – Plane	0.05	000201ya	Montenegro	Yugoslavia	15/04/1979	Dubrovnik-Pomorska Skola
		005819ya	Kalamata	Greece	13/10/1997	Koroni-Town Hall (Library)
		005820ya	Strofades	Greece	18/11/1997	Koroni-Town Hall (Library)
		001255ya	Izmit	Turkey	17/08/1999	Heybeliada-Senatoryum
		001707ya	Duzce 1	Turkey	12/11/1999	Mudurnu-Kaymakamlik Binasi
		000182xa	Tabas	Iran	19/09/1978	Dayhook
		000290xa	Campano Lucano	Italy	23/11/1980	Sturno
A – Spatial	0.06	000290	Campano Lucano	Italy	23/11/1980	Sturno
		000473	Vrancea	Romania	31/05/1990	Vrancioaia
		000499	Racha	Georgia	29/04/1991	Akhalkalaki
		006174	Kozani	Greece	13/05/1995	Veria-Cultural Center
		005825	Kalamata	Greece	13/10/1997	Kyparrisia-Agriculture Bank
		005821	Strofades (aftershock)	Greece	18/11/1997	Koroni-Town Hall (Library)
		001566	Duzce 1	Turkey	12/11/1999	Sakarya-Bayindirlik ve Iskan Mudurlugu