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A Note on Selection of Time-Histories for Seismic Analysis of Bridges in Eurocode 8

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Eurocode 8 (EC8) allows the use of real earthquake records as an input for time-history analysis of structures. In its Part 2, the code discusses the preparation of seismic input for bridges; although referring to the same target spectral shapes of Part 1, which applies to buildings. The prescriptions are somewhat differently specified in the two drafts. However, the main requirement the chosen record set should satisfy in both cases, is the compatibility of the horizontal average spectrum with the target in a broad range of periods. The set has to be made of at least three recordings, but seven is the minimum set size to consider the mean structural response as the design value. The code, at least for bridges, seems to indicate real records as the principal source of ground-motions the practitioners should rely on; however the selection of real records is not straightforward. In another study, the authors discussed the record selection prescriptions of EC8 Part 1 with respect to the current best practice, and the actual possibility of finding real record sets compliant with EC8 spectra was investigated. This paper represents an extension of the same study to EC8 Part 2 and bridges. To this aim the European Strong-Motion Database is searched to identify real record sets matching the design spectral shapes for several hazard levels and site conditions in a broad range of periods up to 4s. It resulted that combinations well approximating the target may be found for some soil classes, at least for low-to-moderate seismicity sites and if the condition of matching specific source parameters is released and large record-to-record variability is accepted. Finally the record sets presented have been used to compare spectral compatibility prescriptions of EC8 Part 1 and Part 2, which have been found to be equivalent to some extent.

Keywords Real Records; Bridges; Seismic Isolation; Dynamic Analysis

1. Introduction

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 natural accelerograms, and they currently seem to be the most attractive option to define the seismic input in order to assess the structural performance. In spite this effort, in many seismic codes the guidelines about preparation of ground motion input for dynamic analysis are poor, especially in those cases when bi-directional loading is required [Beyer and Bommer, 2007]. Norms are similar worldwide, the minimum set size is typically from 3–7 records, and the main prescription is the compatibility with the design spectrum in a specified range of periods. Eurocode 8 (EC8) Part 1 [CEN, 2003], giving the prescriptions for buildings, requires that the average spectral ordinates of the

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chosen set should match the design spectrum with some lower-bound tolerance. Little, if any, specifications are given about the other features of the signal. EC8 Part 2 [CEN, 2005], referring to bridges, has similar requirements but more detailed: it refers to the same spectral shapes and site classifications given in Part 1 and still requires three-dimensional seismic input, but it specifies that the matching with the design spectrum should be carried out considering the square root summation of squares (SRSS) of the two horizontal spectra, independently of the vertical component. Other particular conditions about near source and spatial variability of seismic motion are also specifically considered in Part 2, as asynchronous ground-motion effects may be of some relevance for long bridges. In addition to spectral compatibility, both Part 1 and Part 2 ask for consistency of the chosen record set with the specific features of the seismic sources the site of interest is subjected to; however, the spectral shapes given are eventually related to the hazard at the site only via the anchoring value (a_g). EC8 does not provide anchor values for its non-dimensional spectral shapes, the determination of which is left to specific national authorities. The a_g values considered in the following correspond to the Italian case of OPCM 3274 [2003], according to which the seismic territory is divided into four zones representing different hazard levels.[1] The a_g values for the Zone 3, 2, and 1 are 0.15, 0.25, and 0.35 g, respectively. In fact, the if the peak ground acceleration (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].

In a previous study, the authors discussed the EC8 Part 1 requirements about seismic input with respect to the best current practice [Iervolino *et al.*, 2008] and the European Strong-Motion Database (ESD) was investigated to assess whether it is possible to find real record sets, suitable for moderate period buildings, complying as much as possible with the EC8 spectral requirements. The scope of the work herein presented is to extend the study to bridge structures. In the following, the critical issues in record selection for seismic analysis of structures and the main findings of the work carried out about EC8 Part 1 are briefly reviewed. Subsequently, the study proceeds focussing on EC8 provisions of Part 2, which are preliminarily compared to those of Part 1. The ESD dataset is investigated in order to find un-scaled (*original*) record sets, including the vertical component of the ground-motion, respecting as much as possible the spectral matching requirements in broad period ranges. Moreover, sets of scaled (*normalized*) code-compatible horizontal accelerograms are also considered in order to reduce the record-to-record variability of the spectra, and to obtain sets which are independent of the anchoring value of the code spectrum. Finally, some of the sets found under the working assumptions determined are discussed and used to practically compare the prescriptions of EC8 Parts 1 and 2.

2. Background of Record Selection for Seismic Structural Analysis

Structural assessment via dynamic analysis requires some characterization of the seismic input which should reflect the seismic hazard as well as the soil conditions at the site. Generally, the signals that can be used are of three types: (1) artificial waveforms; (2)

[1]In January 2008, a new seismic code was released in Italy [CS.LL.PP., 2008], which supersedes the seismic classification of the territory in zones considering the actual seismic hazard at the site to determine seismic actions on structures. Nevertheless, in other seismically prone European countries zone-classification is still enforced with similar anchoring values of the deisgn spectra [Garcia-Mayordomo *et al.*, 2003].

simulated accelerograms; and (3) natural records [Bommer and Acevedo, 2004]. Signals of the type (1) are generated recurring to the random vibrations theory to match some target spectral shape. Simulation records (2) are obtained via modelling of the seismological source and may account for path and site effects. The methods used in this approach range from simulation of point sources to dynamic models of rupture. Finally, of type (3) are ground-motion records from real events.

In the past, the lack of real ground motion records and the need to have seismic input closely representing a specific scenario to match, for example, in terms of a target spectral shape or a magnitude-distance pair (e.g., a design event), have supported the use of artificial records by means of which one can produce several signals with nominal characteristics of interest. On the other hand, the recently increasing accessibility to accerelograms recorded during real ground shaking via digital seismic networks has pointed the attention of research to investigate the issues related to the use of real records for seismic structural design and assessment. This is also because some types of artificial accelerograms have shown shortcomings in being a realistic representation of possible ground motion [Bazzurro and Luco, 2003].

When selection of real records for seismic design of structures is concerned, the current state of best engineering practice (i.e., in the US) is based on the uniform hazard spectrum (UHS) which is an elastic spectrum defined by means of the seismic hazard at the site where the structure is supposed to be located [Cornell, 2004, 2005]. The UHS is defined with the purpose that all its acceleration ordinates have the same exceeding probability in a time interval depending on the limit state of interest. In fact, seismic hazard curves for spectral acceleration (Sa) at different oscillation periods are all entered with the same probability (i.e., 10% probability of exceedance in 50 years) and the corresponding accelerations are read. Plotting each of these values versus the corresponding oscillation period results in the "10 in 50" UHS.

After the UHS is defined the record selection requires disaggregation of the seismic hazard [Bazzurro and Cornell, 1999] in terms of causative magnitude (M) and distance (R). In particular, the level of spectral acceleration given by the UHS at the first mode period of the structure is disaggregated. This procedure leads to a joint probability distribution of magnitude and source-to-site distance providing the frequency of occurrence of each M-R pair given the exccedance of the acceleration being disaggregated. It is possible, then, to identify the mean or modal values of M and R which, being those most contributing to the hazard, are assumed to represent the design or scenario event.

Then, an accelerograms' repository (e.g., an online database) is accessed and a number of records is selected to match within tolerable limits the values of M-R from disaggregation, site conditions and, eventually, expected style of faulting, duration of shaking, recording instrument housing, or any other parameter believed to be important for a correct estimation of the structural response. Finally the selected records are scaled to match precisely the UHS level at a period near that of the first mode of the structure. Waveforms obtained are considered to be consistent with the UHS and used as an input for nonlinear dynamic analysis aimed at evaluating the behavior of the structure.

It is worth noting here that several studies have investigated this procedure, and there is some evidence that all this care taken about the selected records' properties may be not justified. That is, although it may be prudent to cosider M and R or faulting style in record selection, it is not generally proven that these characteristics significantly influence linear or nonlinear response conditional to first-mode spectral acceleration [Iervolino and Cornell, 2005]. This conclusion seems also to hold for duration, which has been found to be statistically insignificant in the assessment of displacement demand at least for SDOF structures [Iervolino *et al.*, 2006], conversely it strongly affects, as expected, other demand parameters accounting for cyclic behavior such as hysteretic ductility or equivalent number of cycles.

Also, the amplitude scaling of records to match some spectral value has been the focus of a significant deal of research to assess whether it leads to a biased estimation of the seismic response. It has been found not to be the case at least to some extent and if the effect of *epsilon*, or the deviation of a record's spectrum at a specific period from the corresponding median ground motion prediction relationship, is accounted for appropriately [Baker and Cornell, 2006].

There are also cases for which the current practices of seismic hazard analysis and record selection do not apply or have to be properly adjusted. This is the case, for example, of near-source pulse-like ground motions. In fact, ground motion records affected by "directivity" may show unusual features in the signal resulting in low-frequency cycle pulses in the velocity time-history, especially in the fault-normal component. Such an effect causes the seismic demand for structures to deviate from that of, so-called, "ordinary" records. Current attenuation laws are not able to capture such effects well, if at all, and therefore current probabilistic seismic hazard analysis (PSHA) is not able to predict the peculiar spectral shape of records affected by directivity. This failure may possibly lead to an underestimation of, in particular, the nonlinear demand. Accounting for pulse-type records in earthquake engineering practice should be reflected both in the PSHA and in the record selection for seismic assessment of structures [Tothong *et al.*, 2007; Iervolino and Cornell, 2008].

In conclusion, the bulk of the work related to record selection seems to indicate that the most important proxy for ground-motion potential is the spectral shape. Other ground-motion characteristics may be less important given the spectral shape in the range of interest for the nonlinear structural response. Also, because of this, techniques have been developed to modify real ground-motions in a way that they match the design spectral shape. This approach makes use of *wavelets*, and signals obtained are considered to be a better option with respect to generate artificial records [Hancock *et al.*, 2006].

For further details on these issues one may see Iervolino *et al.* [2008] and references therein.

2.1. Code-Based Record Selection and Findings of the Study Regarding EC8 Part 1

Code-based record selection (i.e., in Europe) apparently tries to reproduce the approach discussed above. In fact, to design using an UHS corresponding to a small probability of exceedance is, in principle, analogous to choose a conservative value of the action in the load-resistance factor design and therefore is consistent with the common design philosophy of modern codes worldwide. It allows the practitioner to check the seismic structural performance in semi-deterministic conditions where the actions are amplified and the capacity is reduced on a probabilistic basis. However, the use of UHS for code-based design requires the seismic hazard at the site provided for all the national territory. In the US, for example, hazard curves and UHS may be downloaded by the USGS website (recently, also Italy has such a service by the Istituto Nazionale di Geofisica e Vulcanologia). This is not the case for many other countries where seldom engineers are able to easily obtain PSHA data for the site of interest. Therefore, the record selection procedure described above is often only approximated by codes as it happens, in fact, in the case of Eurocode 8.

It will be shown in the following that EC8 assigns a spectral shape, which may be considered an approximation of UHS, and prescribes to select records according to source parameters (i.e., magnitude and distance dominating the hazard at the site); finally, the selected records have to match in the average the target shape in a broad range of periods which may be considered somehow corresponding to the amplitude scaling of records. Nevertheless, the real records selection is not straightforward because: (i) the code spectrum is only indirectly related to the hazard for the site of interest, and 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 for the site under exam (which is often the case); (ii) the design spectra tend to overestimate the UHS and sometimes it may not be easy to find records severe enough to match them; (iii) the requirement that the average spectrum of a records' combination has to match the code spectrum in a broad range of periods seems to be also hard to satisfy, and this in principle favors, the use of artificial records which may be generated to have precisely the target spectral shape.

In fact, in a previous study [Iervolino *et al.*, 2008] the authors discussed the EC8 Part 1 requirements about seismic input with respect to the best current practice and recent research advances. In the same study, the European Strong-Motion Database (ESD) was investigated to find real record sets, suitable for moderate period structures and complying as much as possible with the EC8 spectra. The main purpose of the study was to investigate whether it is possible to find real record sets fulfilling the requirements of Eurocode 8 about the input for seismic analysis of spatial and plane structures.

The ESD was investigated for two types of combinations *compatible* with the EC8 spectra: un-scaled record sets and combinations of records requiring scaling to match in average sense the target spectrum. Some results, showing a good average agreement with the target shape were found for original records (except for the more severe design spectra and for very soft soil sites). However, to find results it was not possible to match any source parameter or to limit the very large record-to-record variability of spectra within a combination. This is why the dataset was searched for records to be scaled; in fact, this allows to select records with a spectral shape as much possible similar to that of the code and therefore to limit the individual scatter within a combination, but it may entail large linear scaling factors.

The study lead to conclude that, although some results may be found, EC8 Part 1 does not easily allow the use of the real records for nonlinear time-history analysis especially in those cases where the seismic actions (i.e., design spectra) are determined assigning each site to a seismic zone, which only indirectly reflects the actual hazard. Moreover, to not prescribe any limitation to the variability of individual spectra within a combination (as it happens for Part 1 where only the average spectrum is constrained) may lead to an uncertain assessment of the seismic response if only seven un-scaled records are employed.

A similar study regarding EC8 Part 2 is described in the following and, although some differences in prescriptions appear, the same conclusions have been found to hold.

3. Seismic Input for Time-History Analysis in EC8

3.1. Part 1 – Buildings

In EC8 the seismic input for time-history analysis is defined after the elastic response spectrum. In Part 1, the spectral shapes are given for both horizontal and vertical components of motion. *Section 3.2.2*[2] gives two spectral shapes defined as *type 1* and

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

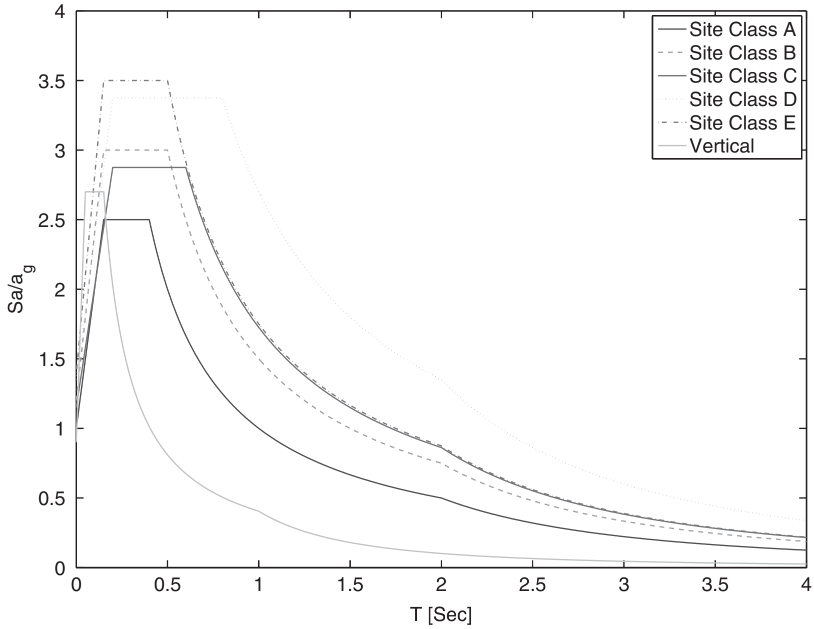


FIGURE 1 EC8 horizontal and vertical type 1 spectral shapes.

type 2. The latter applies *if the earthquakes that contribute most to the seismic hazard have surface-wave magnitude not greater than 5,5*; otherwise, the former should be used. The design spectral shapes for the vertical component have the same distinction. The anchoring value for the vertical elastic spectrum (a_{vg}) is defined by the suggested ratio $a_{vg}/a_g = 0.9$. In Fig. 1 the 5% damped type 1 elastic spectra (considered herein) for the five main site classes defined by EC8 are given as normalized with respect to the anchoring values.

To comply with Part 1, the set of accelerograms, whether 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;*
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.*

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 translational components of motion to be used (the two horizontal and the vertical one). However, in *Sec. 4.3.3.4.3*, the code allows the consideration of the mean effects on the structure, rather than the maximum, if at least seven nonlinear time-history analyses are performed. Moreover, the vertical component of the seismic action should be taken into account for base-isolated structures, and for some special cases in regular buildings, if the design vertical acceleration for the A-type site class (a_{vg}) is greater than 0.25 g. Finally, some prescriptions regarding duration are given for artificial accelerograms, and real 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*.

3.2. Part 2 – Bridges

EC8 Part 2 refers to the same spectral shapes of Part 1 in order to define the seismic input for time history analysis of bridges. However, the selection criteria are differently presented. In fact, the requirements for the seismic input for dynamic analysis are given in *Sec. 3.2.3*: *when a nonlinear time-history analysis is carried out, at least three pairs of horizontal ground-motion time-history components shall be used. The pairs should be selected from recorded events with magnitudes, source distances, and mechanisms consistent with those that define the design seismic action. When the required number of pairs of appropriate recorded ground-motions is not available, appropriate modified recordings or simulated accelerograms may replace the missing recorded motions.*

The relevant criteria the chosen set of accelerograms should match are:

a. *For each earthquake consisting of a pair of horizontal motions, the SRSS spectrum shall be established by taking the square root of the sum of squares of the 5%-damped spectra of each component.*
b. *The spectrum of the ensemble of earthquakes shall be formed by taking the average value of the SRSS spectra of the individual earthquakes of the previous step.*
c. *The ensemble spectrum shall be scaled so that it is not lower than 1,3 times the 5% damped elastic response spectrum of the design seismic action, in the period range between $0,2T_1$ and $1,5T_1$, where T_1 is the natural period of the fundamental mode of the structure in the case of a ductile bridge, or the effective period (T_{eff}) of the isolation system in the case of a bridge with seismic isolation*[3].
d. *When the SRSS spectrum of the components of a recorded accelerogram gives accelerations the ratio of which to the corresponding values of the elastic response spectrum of the design seismic action shows large variation in the period range in (c), modification of the recorded accelerogram may be carried out, so that the SRSS spectrum of the modified components is in closer agreement with the elastic response spectrum of the design seismic action.*
e. *When three component ground-motion time-history recordings are used for non-linear time-history analysis, scaling of the horizontal pairs of components may be carried out in accordance with previous step, independently from the scaling of the vertical components. The latter shall be effected so that the average of the relevant spectra of the ensemble is not lower by more than 10% of the 5% damped elastic response spectrum of the vertical design seismic action in the period range between $0,2T_v$ and $1,5T_v$, where T_v is the period of the lowest mode where the response to the vertical component prevails over the response to the horizontal components (e.g. in terms of participating mass)*[4].

[3]After this point the code also specifies that: *The scaling factor derived from the previous step shall be applied to all individual seismic motion components.*

[4]For example, Part 2, for the vertical component, has the same prescriptions of Part 1 for horizontal ground motion.

f. *The use of pairs of horizontal ground-motion recordings in combination with vertical recordings of different seismic motions, is also allowed. The independent scaling of the pairs of horizontal recordings and of the vertical recordings shall be carried out.*

In *Sec. 4.2.4.3*, the code allows the consideration of the mean effects on the structure, rather than the maximum, when nonlinear dynamic analysis is performed for at least seven independent ground motions.

Also, for what concerns Part 2 the vertical action has to be considered in special cases only. In *Sec. 4.1.7*, the code specifies that the effects of the vertical seismic component on the piers may be omitted in cases of low and moderate seismicity, while in zones of high seismicity these effects on the piers need only be taken into account in the following conditions: (a) *if the piers are subjected to high bending stresses due to vertical permanent actions of the deck*; (b) *when the bridge is located within 5 km of an active seismotectonic fault.* According to this section: *the effects of the vertical seismic component acting in the upward direction on prestressed concrete decks and the effects of the vertical seismic component on bearings and links, shall be always taken into account.*

EC8 Part 2 also has specific prescriptions for special cases as near-source conditions. In particular, the code prescribes that site-specific spectra considering near source effects shall be used, when the site is located horizontally within 10 km of a known active seismotectonic fault that may produce an event of moment magnitude larger than 6,5. The code also prescribes when the spatial variability of ground-motion has to be considered (*Sec. 3.3*): when the soil properties along the bridge vary to the extent that more than one ground types correspond to the supports of the bridge deck; or when soil properties along the bridge are approximately uniform, but the length of the continuous deck exceeds the distance beyond which the ground-motions may be considered uncorrelated. These special cases were not considered further in the present study as they are design-case-specific.

3.3. Differences in Requirements About Record Selection of EC8 Part 1 and Part 2

Parts 1 and 2 are generally similar in prescriptions about record selection although some differences appear. EC8 Part 2 indicates to use accelerograms of a different type (e.g., artificial) only when real records representing the peculiar feature of the case study of interest are not available. Thus, it seems EC8 Part 2 suggests real records as the primary source of input ground-motion the practitioner should rely on. Conversely, EC8 Part 1 seems not to prefer, at least in principle, one specific type of accelerograms with respect to others.

Parts 1 and 2 share the number of accelerograms to be used which is at least three (to be multiplied by the number of components of each recording), while seven is the number to assume the average response of the structure resulting from the analyses as the design value. Both guidelines prescribe to use contemporarily the two horizontal components of ground motion in the analysis of three-dimensional structures and to include also the vertical one in special cases. They both have the average spectral matching requirement, but the minimum intervals prescribed by Part 1 is $0{,}2T_1$ and $2T_1$, while it is $0{,}2T_1$ and $1{,}5T_1$ in Part 2. Moreover, Part 1 specifies that the average peak ground acceleration (PGA) of the combination should be not lower than that of the code, while Part 2 does not have such requirement.

The apparently main differences between the two guidelines is that Part 2 prescribes the spectrum to be considered is the SRSS of the two spectra of the horizontal components. Part 1 does not have such specifications and therefore, in the case of bi-directional horizontal loading, for example, the average spectrum of a combination may be obtained averaging 14 spectra, which are 7 pairs from 7 recording stations. EC8 Part 1 specifies that the average spectrum of the chosen set should not underestimate the code spectrum more than 10%. In Part 1 it is not explicitly stated if the average has to be computed on all 14 horizontal components of 7 ground-motion records, although this was the interpretation of Iervolino *et al.* [2008]. This choice seems to be somewhat confirmed by Part 2. In fact, the SRSS, in the ideal case of a record having equal horizontal spectra in the two directions, is equal to about one of the two spectra times 1.4, and to compare the average of the 7 SRSS spectra to 1.3 times the code spectrum is equivalent to compare the average of the 14 components to 0.9 times the code spectrum (this is further investigated in Sec. 6 herein).

Another difference between Parts 1 and 2 is that point (d) of Section 3.2 is not explicitly present in Part 1. It is an acknowledgement for the fact that, for the estimation of the seismic performance, may be important to control not only the deviation of the average spectrum with respect to the code spectrum, but also the individual spectral variability within a combination matters. However, no quantitative measure is given to account for this.

4. Applicability of Requirements and Considered Selection Criteria

The study presented in the following sections proceeded as Iervolino *et al.* [2008]; in particular, an online database was searched for code-spectrum matching real record sets with reference to prescriptions of EC8 Part 2. It has to be underlined at this point that both Parts 1 and 2 require the selected accelerograms to be selected considering source parameters. It seems that this prescription could be easily acknowledged via disaggregation of seismic hazard. However, the design spectrum is related to the hazard at the site through the a_g value only, therefore the code seems to suggest that the hazard of a_g should be the subject of disaggregation, although the current best practice in record selection suggests to disaggregate the spectral acceleration at near the first mode of the structure. Moreover, because to define the design spectrum for a site only the anchoring value is required and it is often provided by the national authorities; may be not the case for engineers involved in design of ordinary structures to have source parameters to match[5]. For these reasons, and also because this study does not refer to any site-specific case, herein it was not possible to search for natural records from events having source features consistent with those that define the design seismic action. Finally, it will be shown that, at least in some cases, trying to match other criteria than the spectral compatibility would eventually lead not to find any results, especially for the most severe spectra, which is a consistent finding with respect to the mentioned study carried out for buildings.

On the other hand, spectral matching requirements were considered along with additional criteria, which allowed to rank the record sets found. Two of the three criteria considered are aimed at controlling the scatter of individual and average spectra of a combination with respect to the target (i.e., the code spectrum), the third one is aimed at

[5]This may change in the future, and probabilistic hazard analysis may be easily available in an increasing number of countries. For example, the recent Italian hazard mapping of the Istituto Nazionale di Geofisica e Vulcanologia provides hazard curves and disaggregation of seismic hazard in terms of magnitude, distance and epsilon; although disaggregation is only available for the PGA (see http://esse1.mi.ingv.it/).

having, as much as possible, different earthquakes represented in a combination. These criteria are:

a. The deviation of the average spectrum with respect to the code spectrum (δ), which gives a measure of how much the mean spectrum of a records' combination deviates from the spectrum of the code. Definition of δ is given in Eq. (1), where: $Sa_{o,med}(T_i)$ is the ordinate of the average spectrum corresponding to the period T_i; $Sa_s(T_i)$ is the value of 1.3 [1.0] times the ordinate of the code spectrum at the same horizontal [vertical] spectrum period; and N is the number of values falling within the considered range of periods. Herein N is that of the spectra provided by the ESD (for example, N equals 67 and 116 for the 0.139–4 s and 0.04–2 s intervals, respectively).

   Selecting a record set with a low δ value may allow to obtain an average spectrum which is well approximating the target. The deviation δ was computed separately for the horizontal SRSS and the vertical components of motion, and indicated as δ_H and δ_V, respectively.

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

b. The maximum deviation of a single spectrum within a set with respect to the code spectrum ($\delta_{\max}$). It is defined as the maximum over a combination of Eq. (1) in which $Sa_{o,med}(T_i)$ is replaced by the ordinates of each single spectrum. Controlling this parameter may allow to choose combinations characterized by records having the individual spectra relatively close to the code spectrum, and therefore being narrowly distributed around it (which seems also to be relevant for condition (c) of Sec. 3.2).
c. The number of different events within a set. This criterion corresponds to the identification of combinations of records featuring the largest number of different events possible to prevent domination of a single earthquake, which could bias the estimation of the seismic response.

5. Waveform Database and Analyses

The investigated dataset id derived from the European Strong-Motion Database, the URL of which is http://www.isesd.cv.ic.ac.uk; see Ambraseys *et al.* [2000, 2004] for further information. The selected list of records is practically the same as that used in Iervolino *et. al* [2008] (website accessed in April 2005) except for the A site class accelerograms, for which the database was accessed again in April 2007. From the ESD all records and spectra were downloaded. Of the downloaded records, those without all three translational components (two horizontal and one vertical) were discarded. Moreover, only events characterized by a moment magnitude equal or larger than 5.8 (6.0 for site class A) have been retained. This pre-selection, ensures to have records coming from moderate-to-high magnitude events and also allows the dramatic reduction of the number of sets to be investigated. In fact, the possible combinations of seven from a list of more than 150 records is huge and may require an unfeasible computational effort.

For D site class, no reduction to retain moderate-to-high magnitude events only was made because of the shortage of stations for this site condition. The resulting numbers of

TABLE 1 Input dataset considered in the study

Local geology	X	Y	Z
A (rock)	134	134	134
B (stiff soil)	134	134	134
C (soft soil)	122	122	122
D (very soft soil)	28	28	28
E (alluvium)	29	29	29

records are given in Table 1, where the two horizontal and vertical components are conventionally indicated as X, Y, and Z, respectively.

The identified dataset was investigated for two classes of spectrum compatible sets. One class is made of *original* records, which means that these records (or at least their horizontal components) do not require scaling to satisfy the spectral compatibility criterion. The other class is made of *normalized* or *non dimesional* records, meaning that they require scaling to comply, via the SRSS average, with the design spectrum. This should allow to search for records featuring a spectral shape similar to that of the code.

These jobs were carried out via a specifically developed software, which analyzed all possible combinations of 5% damped horizontal SRSS spectra (and vertical in the case of *original* record sets) of the input list checking the match with the code shapes. The compatibility intervals were chosen to be 0.139–4 s and 0.04–2 s for horizontal and vertical components, respectively. These intervals, according to Sec. 3.2, render the record sets found suitable bridges with fundamental horizontal (T_1) vertical (T_v) periods in the range of 0.7 s $\div$ 2.7 s and 0.2 s $\div$ 1.3 s, respectively.

For each combination the software also computes the maximum deviation of individual spectra within the set and also the deviation of the average spectrum from the code spectrum, as defined above. Results of this search were manually ranked with respect to the additional criteria. In the following the total number of sets compatible with EC8 spectra is presented and selected results, referring to both original and normalized combinations are displayed. It has to be anticipated that for D and E soil types, no results were found. This is primarily due to the shortage of earthquake recordings on these soil sites in the database.

5.1. Sets of Un-Scaled (Original) Spectra

The chosen dataset has been investigated for sets made of seven un-scaled SRSS horizontal spectra first. It means that for each couple of horizontal components (X and Y) of seven recording stations a single spectrum is obtained computing at each period the square root of the sum of the two spectral accelerations squared. Therefore, from 14 records (corresponding to 7 stations), 7 spectra result. Then the average of the seven spectra of the combination is compared to the code spectrum to see whether it matches the target with the prescribed tolerance (to follow) in the range of period considered. To this aim, for each soil, all possible combinations of seven are considered for those recordings in Table 1.

A summary of the results is given in Table 2, which shows, for each site class and seismic zone for which combinations exist, the number of EC8 Part 2 spectrum-compatible sets found and the corresponding tolerance in matching the average spectrum imposed in the analyses. It is to recall here that the compatibility lower bound assigned by

TABLE 2 Compliant horizontal SRSS sets found

Ground	Zone	Compatibility lower bound[6]	Compatibility upper bound[7]	Sets found
A	1	30%	1000%	4
	2	30%	100%	127177
	3	30%	70%	380385
B	1	30%	1000%	53
	2	30%	80%	4179
	3	30%	80%	838263
C	1	*0%*	1000%	10
	2	30%	100%	167
	3	30%	80%	115307

EC8 is 30% above the code spectrum for the horizontal components, which means that the average of the 7 SRSS spectra should not be below 1.3 times the code spectrum in any point of the considered range of periods. An upper bound tolerance is not prescribed by the code; herein it was arbitrarily chosen and, if necessary, iteratively adjusted to find Eurocode spectra compatible sets.

As it is expected, the larger number of results corresponds to the lower hazard levels. It should also be noted that for the higher hazard levels of soil C, it was not possible to find results satisfying the EC8 prescriptions. In fact, the lower bound had to be released allowing a larger tolerance (with respect to that prescribed) in matching the code spectrum. Combinations found in this case do not comply with EC8 prescriptions. Nevertheless, sets found may be linearly scaled to comply with the code spectrum. In fact, the compatibility lower bound for Zone 1 of C site class is given as 0% in Table 2 meaning that a combination was considered acceptable if it was above 1.0 times the code spectrum in the considered range of periods. This value has been obtained iteratively changing (with a 10% step) the lower bound in the analyses starting from 30%. In other words it was not possible to find suitable results using 30, 20, and 10%, respectively.

For those combinations found and listed in Table 2, it has been verified whether the sets made of the vertical components also match the corresponding code spectrum. Results of this analysis are given in Table 3. For A and C ground types, it was not possible to find results satisfying the horizontal and vertical spectral matching requirements at the same time. For this reason, the lower bound was released. Again, vertical sets found may be linearly scaled to comply with the code spectrum.

As an example, selected results are given from Figs. 2–10. They correspond to all three hazard levels of A, B, and C site classes. In the figures the rough thick curve represents the average spectrum and the thick smooth curve represents the code spectrum. The dashed line is the compatibility limit prescribed by the code; thin lines are the individual (SRSS in the case of horizontal components) spectra within a set. In the legend of any figure the seven digits station code, as well as the earthquake code (EQ) from the ESD database, is given. The legend, when needed, also reports the amplitude scale factors (SF) to comply with EC8 spectra. It may be seen from the figures that although some of

[6]For example: 30% means that the average spectrum of a combination has to be above 1.3 times the code spectrum in the considered range of periods to be acceptable.

[7]For example: 100% means that the average spectrum of a combination has to be below 2 times the code spectrum in the considered range of periods to be acceptable.

TABLE 3 Compliant vertical component sets found

Ground	Zone	Compatibility lower bound[8]	Compatibility upper bound[7]	Sets found
A	1	*45%*	1000%	3
	2	*30%*	1000%	18
	3	*40%*	1000%	226
B	1	10%	1000%	7
	2	10%	1000%	41
	3	10%	1000%	8207
C	1	*55%*	1000%	3
	2	*30%*	1000%	1
	3	*30%*	1000%	99

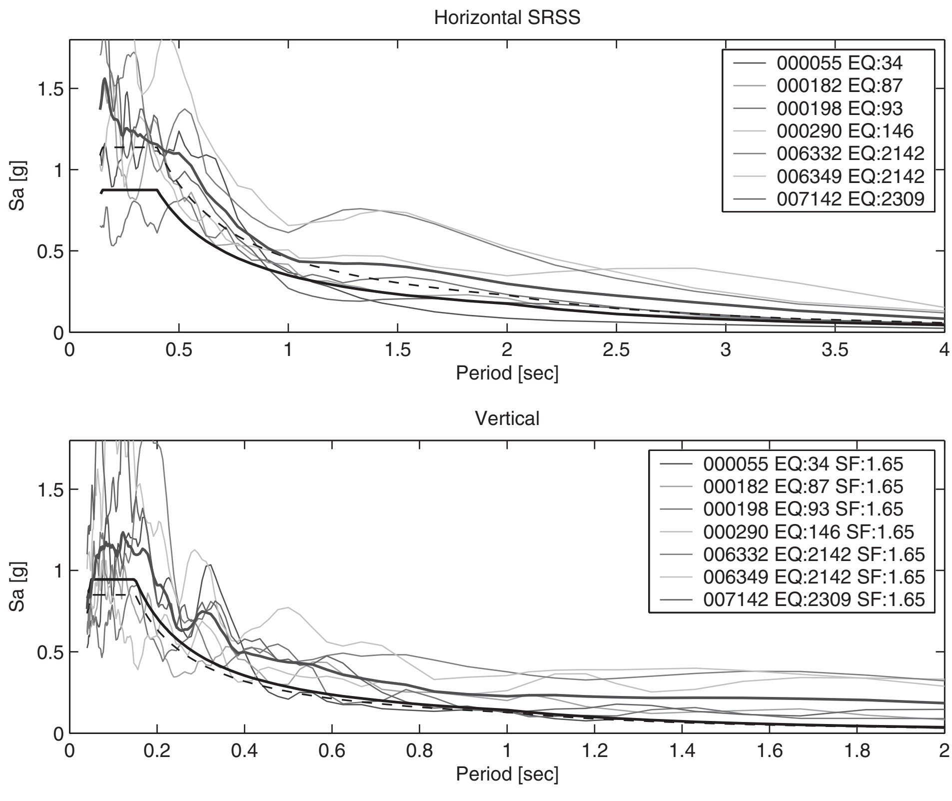


FIGURE 2 Site class A – Zone 1. Set found having the minimum deviation of the average horizontal spectrum with respect to the target spectrum (δ_H = 0.235).

the records displayed are those with the minimum individual variability with respect to the target, it may still be large. On the other hand, it is possible to find original records having an average good agreement with the code. For details about the records displayed see the Appendix where M_W is the moment magnitude and R is the epicentral distance.

[8]For example: 10% means that the average spectrum of a combination has to be above 0.9 times the code spectrum in the considered range of periods to be acceptable.

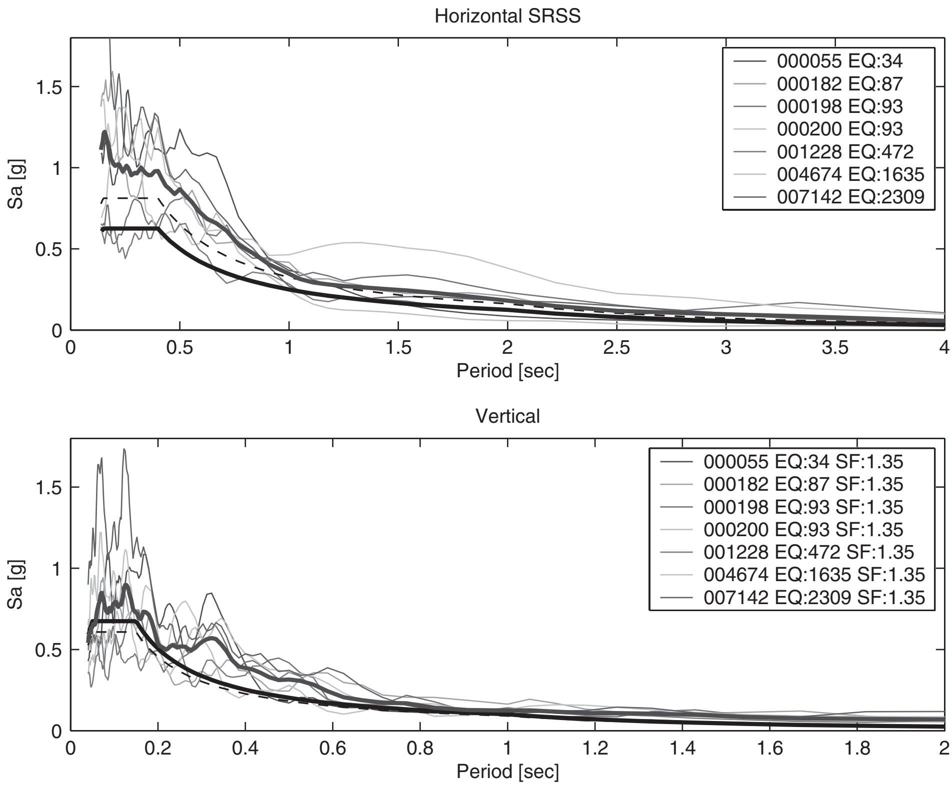


FIGURE 3 Site class A – Zone 2. Set found having minimum deviation of individual horizontal and vertical spectra in from their respective targets (δ_{Hmax} = 0.808; δ_{Vmax} = 0.513), and also having minimum deviation of the vertical average spectrum with respect to the target (δ_V = 0.231).

5.2. Normalized (Non-dimensional) Sets

In point (d) of Sec. 3.2, the EC8 Part 2 recognizes somewhat the importance that not only the mean spectrum is "close," but also that the individual spectra should be not too variable with respect to the target spectrum. It seems that the code suggests that the individual records are manipulated to match the target spectral shape (i.e., via wavelets). Herein, another strategy has been pursued in trying to identify record sets with a reduced record-to-record variability. The input database has also been examined for normalized horizontal records, which should allow to select records having a spectral shape similar to that of the code. However, this entails scaling the records, which was avoided as much as possible in the analyses presented in the previous sections. Here, the records have been rendered non-dimensional by dividing the spectral ordinates by their PGA.

After normalizing the spectra, the same analyses discussed above have been repeated. In fact, combinations of these spectra have been compared to the non-dimensional code spectra, and then the results are independent of the a_g values. From Figure 11 to Figure 13 some results for the horizontal SRSS components are given for A, B and C site classes. As expected normalization of spectra reduces the variability within a set (although it may remain large in some cases) and insures a good average matching with the code if large scale factors are allowed; see Table 4.

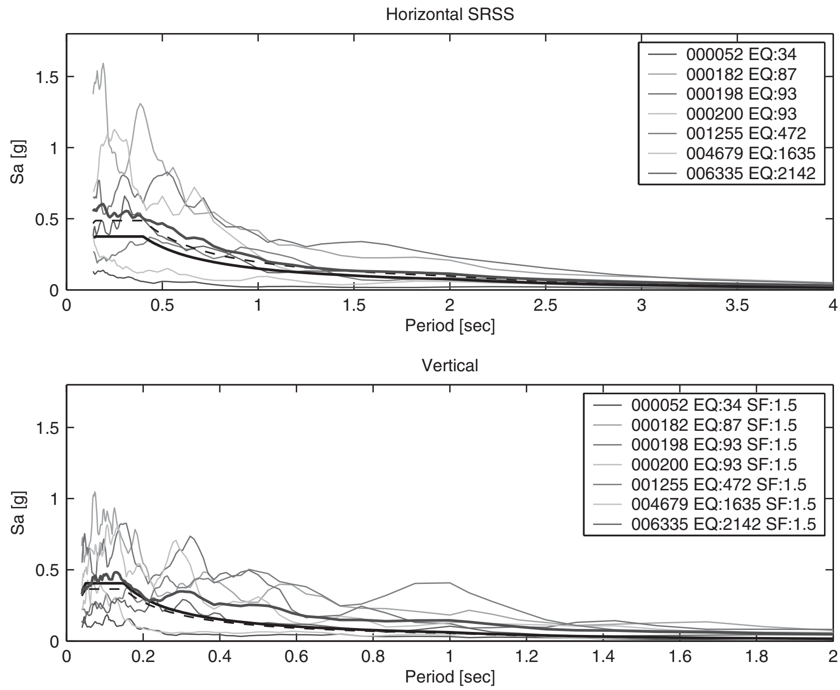


FIGURE 4 Site class A – Zone 3. Set found having minimum individual deviation of horizontal and vertical spectra from their respective targets ($\delta_{\text{Hmax}} = 1.336$; $\delta_{\text{Vmax}} = 0.799$).

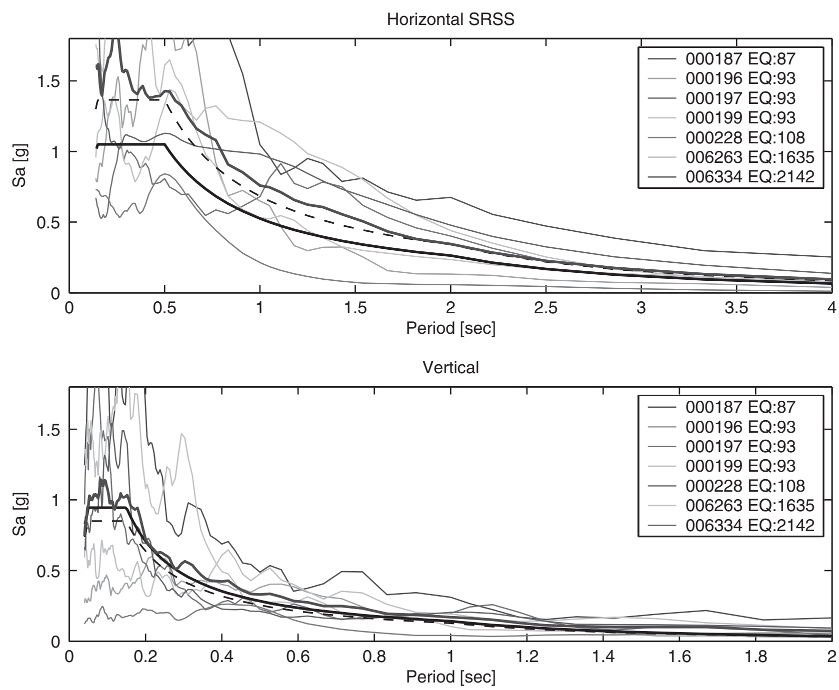


FIGURE 5 Site class B – Zone 1. Set found having minimum deviation of the horizontal and vertical average spectra from their respective targets ($\delta_{\text{H}} = 0.221$; $\delta_{\text{V}} = 0.171$).

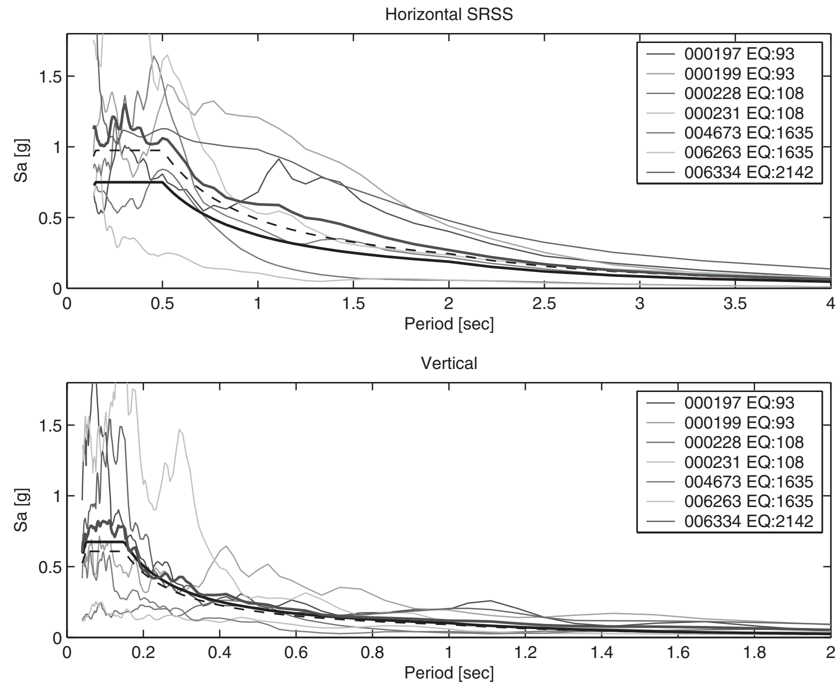


FIGURE 6 Site class B – Zone 2. Set found having the minimum deviation of the average vertical spectrum from the target ($\delta_V = 0.175$).

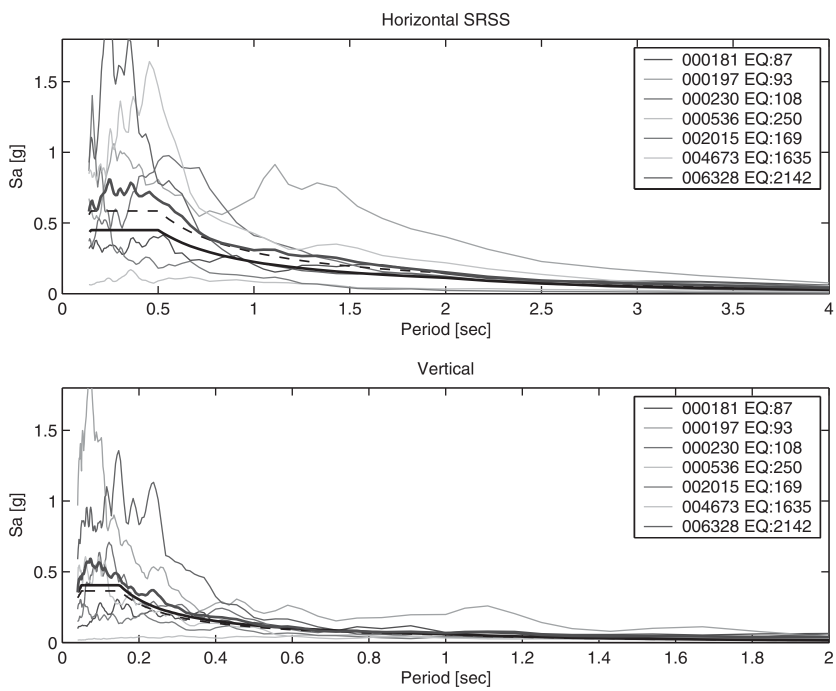


FIGURE 7 Site class B – Zone 3. Set found having the minimum deviation of the average vertical spectrum from the target ($\delta_V = 0.338$) and also featuring records from seven different earthquakes.

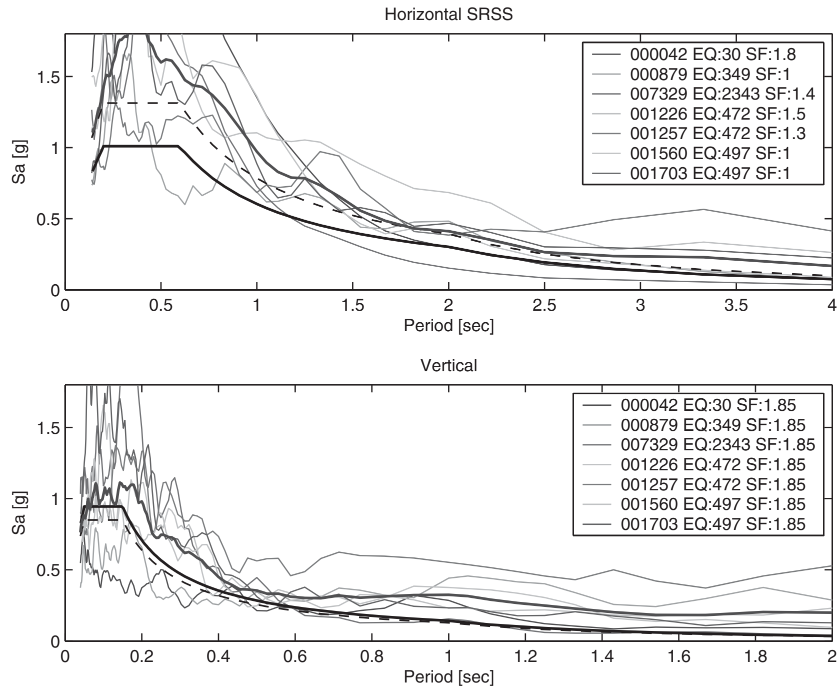


FIGURE 8 Site class C – Zone 1. Set with minimum deviation of individual spectra from the horizontal target spectrum ($\delta_{\mathrm{Hmax}} = 0.525$), and minimum deviation of the vertical average spectrum from the target spectrum ($\delta_{\mathrm{V}} = 0.125$).

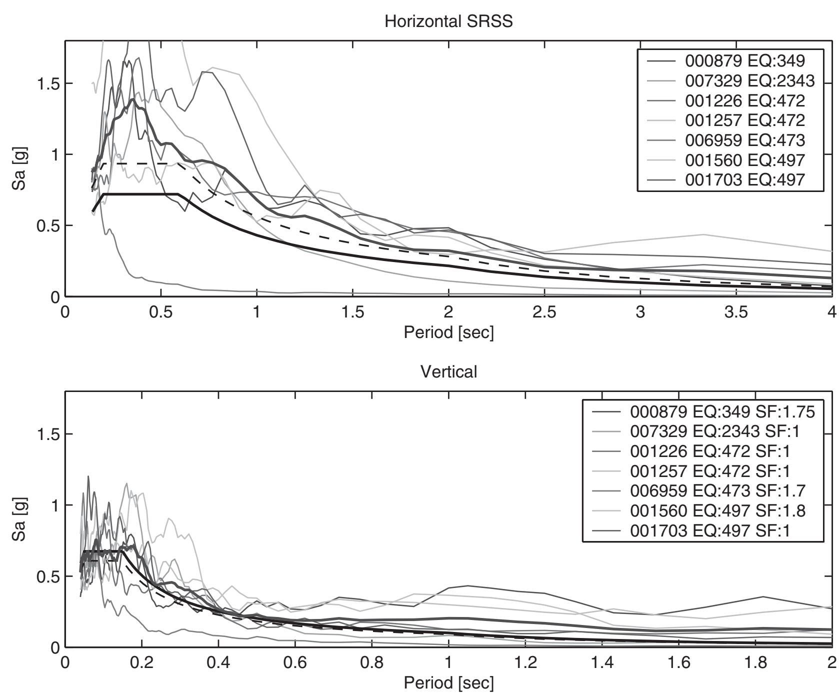


FIGURE 9 Site class C – Zone 2. The only un-scaled set found.

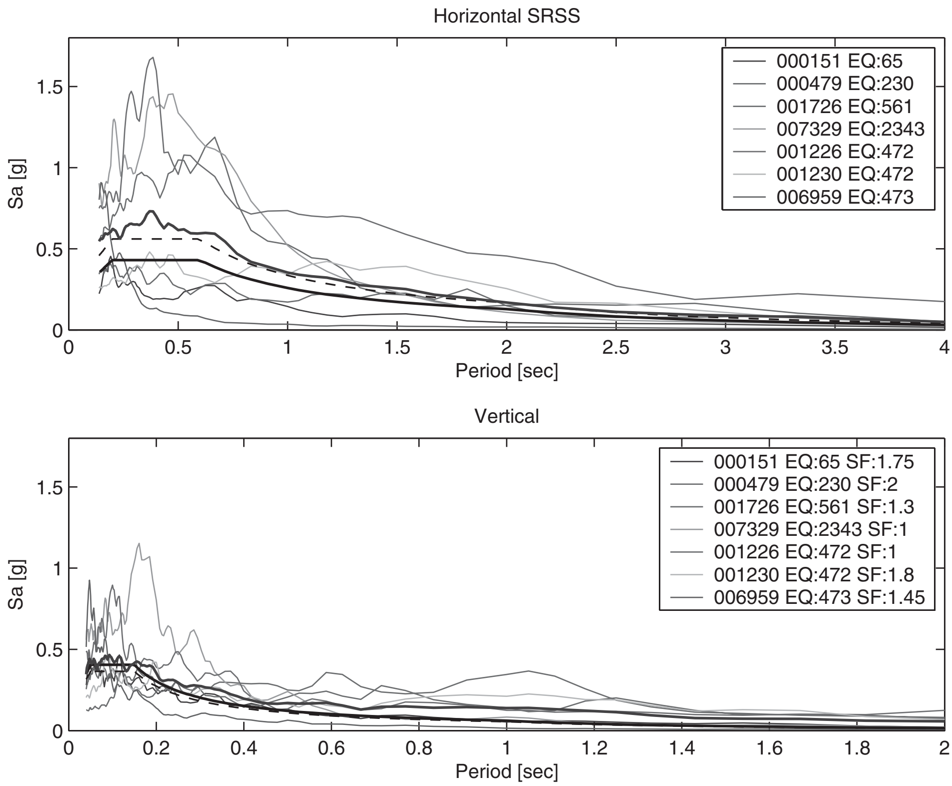


FIGURE 10 Site class C – Zone 3. Set with minimum deviation of individual spectra from the horizontal and vertical target spectra (δ_{Hmax} = 1.274; δ_{Vmax} = 1.163) and minimum deviation of the average spectrum from the horizontal target spectrum (δ_{H} = 0.147).

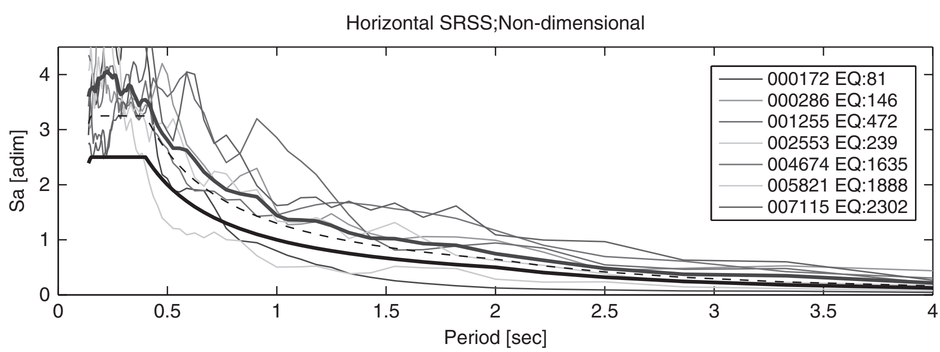


FIGURE 11 Site class A. Example of horizontal non-dimensional set (δ_{H} = 0.18) featuring records from seven different earthquakes.

6. Suitability of Results with Respect to Spectral Compatibility of EC8 Part 1

Other than the different upper bound prescribed for the period range in which the average spectral matching has to be insured, Parts 1 and 2 seem different because the latter prescribes that the SRSS has to be computed for horizontal components, while the former

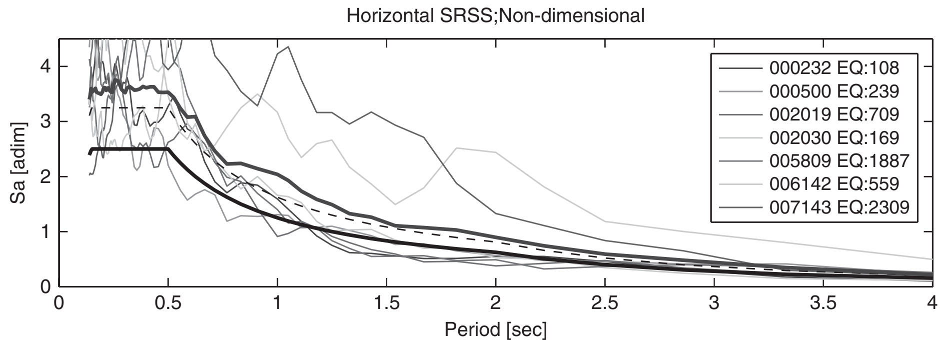


FIGURE 12 Site class B. Example of horizontal non-dimensional set (δ_H = 0.12) featuring records from seven different earthquakes.

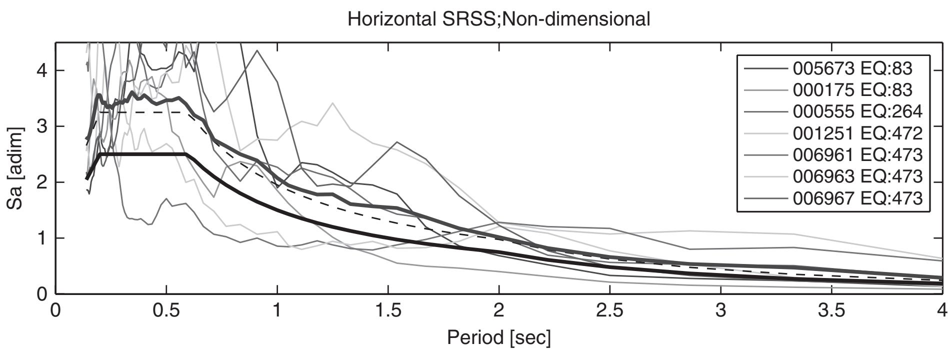


FIGURE 13 Site class C. Example of horizontal non-dimensional set (δ_H = 0.08).

TABLE 4 Average scaling factor of non-dimensional records to match the code spectra

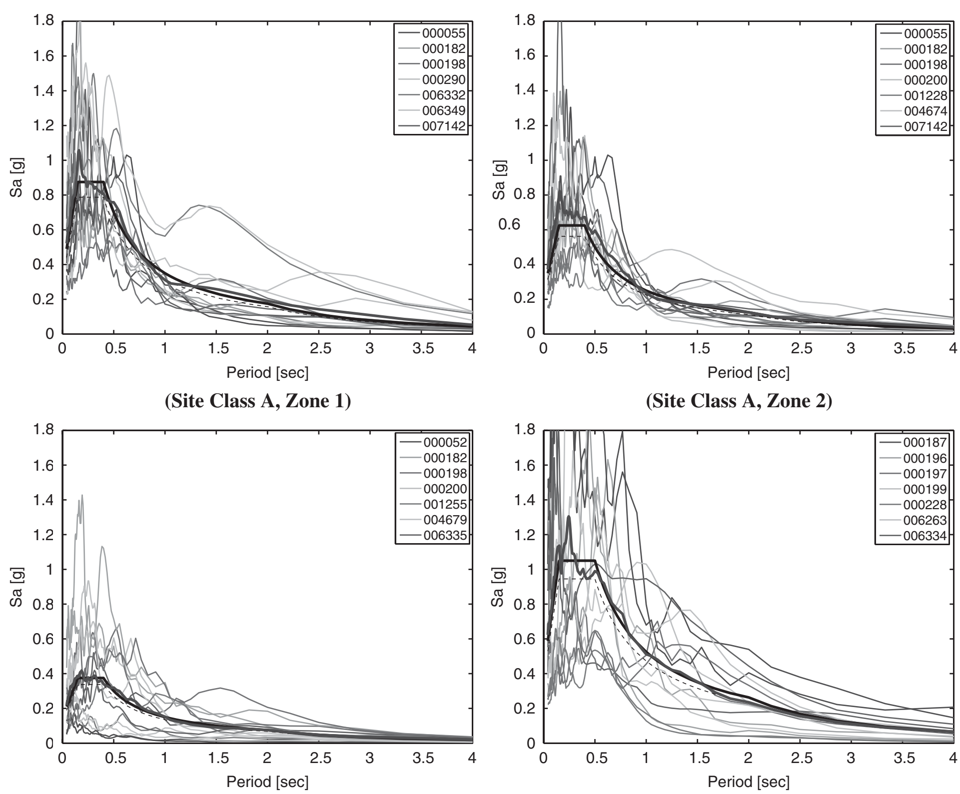
Site-Zone	a_g	Code PGA [g]	SF
A-1	0.35	0.35	18
A-2	0.25	0.25	13
A-3	0.15	0.15	8
B-1	0.35	0.42	24
B-2	0.25	0.30	17
B-3	0.15	0.18	10
C-1	0.35	0.40	11
C-2	0.25	0.29	8
C-3	0.15	0.17	5

do not give any specific information in that respect. In Iervolino *et al.* [2008], as an arbitrary interpretation of the code, the average was taken as the arithmetic mean of the spectra computed on all 14 ground motion components and then compared to the code spectra.

Herein, the horizontal SRSS' of the results presented have been recombined computing the average as just described. This may allow to check how much equivalent are the spectral matching requirements for building and bridges. In the panels of Figs. 14 and 15 the average spectra of the results presented in Sec. 5.1 are compared to the code spectra (even in a broader range of periods [0.04–4 s]). In the figures, the rough thick curve represents the arithmetic mean spectrum and the thick smooth curve represents the code spectrum. The dashed line is the compatibility lower bound limit prescribed by EC8 Part 1 (10% below the target spectrum); thin lines are the individual spectra of the 14 components of 7 recordings within a set. In the legend of any figure the seven digits station code is given.

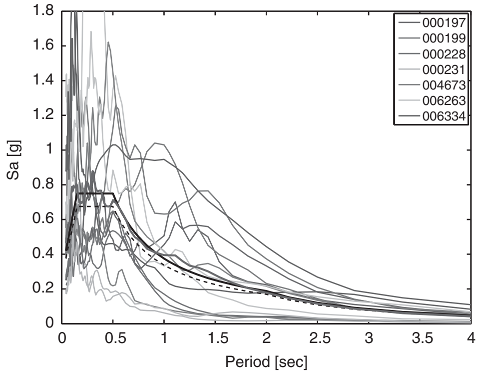
It is possible to see from the graphs that, except for the Zone 1 of the C site class where larger disagreement with the code spectrum was expected, the averages are in good agreement with the code spectrum and the 10% prescribed lower bound tolerance is generally respected. The same conclusion may be drawn from the normalized sets found, for which the average of all 14 components has also been compared to the non-dimensional code spectrum (Fig. 16). It is also observed that the individual variability of spectra for the normalized sets appears lower with respect to combinations in the panels of Figs. 14 and 15.

From these cases it may be concluded that sets compatible with spectral matching prescriptions of Part 2 are close to match also those of Part 1. This is mainly because, at

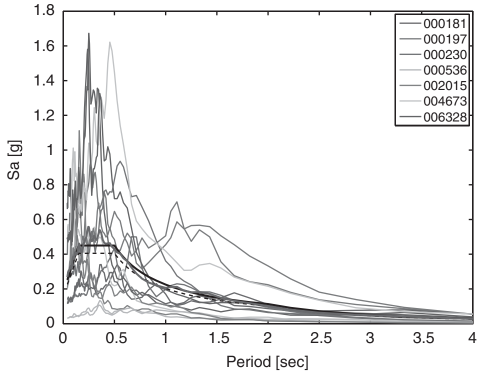


(Site Class A, Zone 1) (Site Class A, Zone 2)
(Site Class A, Zone 3) (Site Class B, Zone 1)

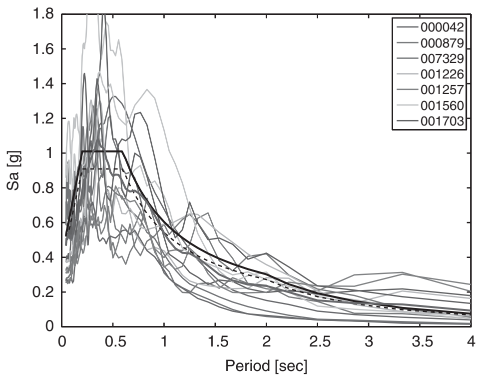
FIGURE 14 Sets given in Figs. 2–5 recombined to take the average on all 14 horizontal components and compared to the code spectra.



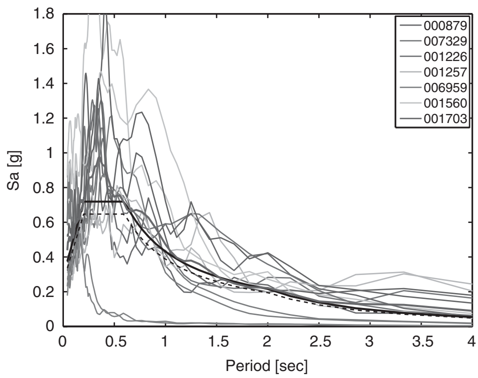
(Site Class B, Zone 2)



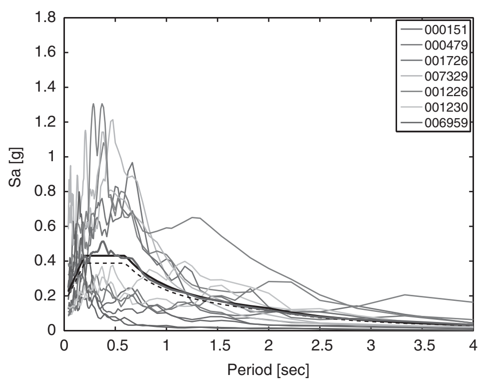
(Site Class B, Zone 3)



(Site Class C, Zone 1)



(Site Class C, Zone 2)



(Site Class C, Zone 3)

FIGURE 15 Sets given in Figs. 6–10 recombined to take the average on all 14 horizontal components and compared to the code spectra.

least in *far-source* conditions, some similarity between the spectra of the two orthogonal horizontal components of a recorded ground-motion is expected and to compare the average of the 7 SRSS spectra with 1.3 times the code spectrum is similar to compare the average of the 14 individual spectra to the 0.9 times the code spectrum.

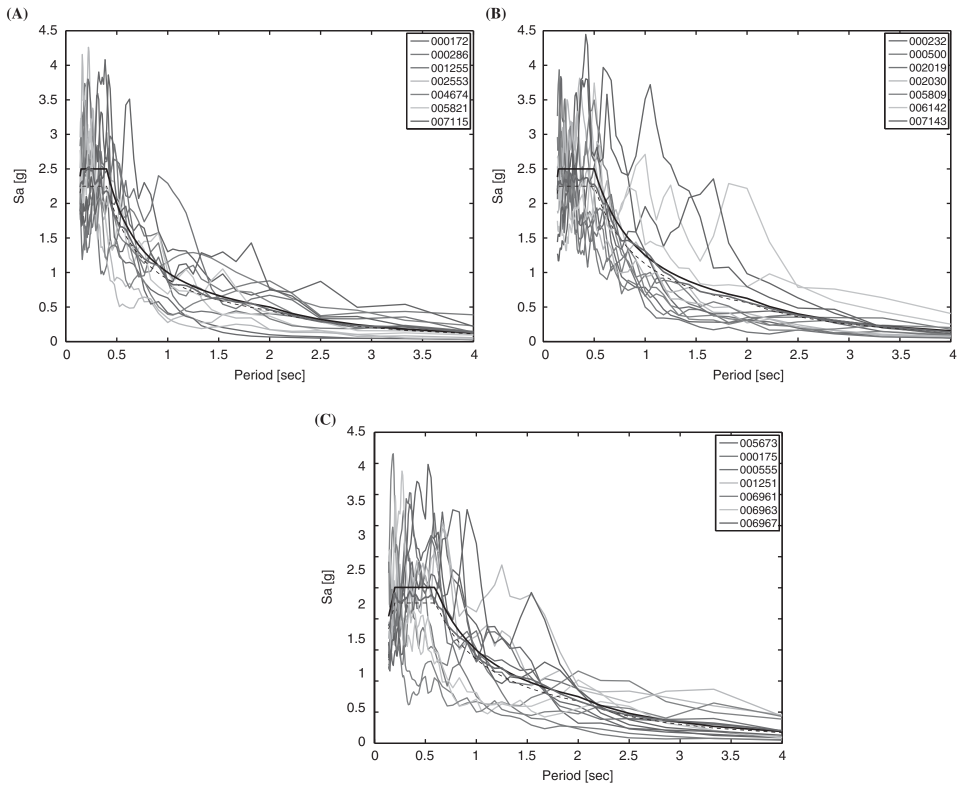


FIGURE 16 Sets given in Figs. 11–13 recombined to take the average on all 14 horizontal components and compared to the code spectra.

It may be now questioned whether some of these results may be used for the time-history analysis of moderate-to-long period buildings, as those provided with seismic isolation. EC8 Part 1 requires time-history analysis of isolated buildings when some conditions, for which the isolation system may not be represented by an equivalent linear model, apply (see Part 1, *Sec. 10.9.5*). It seems that no specific information are given for base-isolated buildings in terms of the spectral compatibility interval of condition (c) of Sec. 3.1 and therefore the range of periods where the spectral compatibility was verified herein is, in principle, applicable to buildings with a fundamental period in the range 0.7s ÷ 2.0s. One may argue that isolated buildings may have an effective period larger than 2.0 s; however, there are reasonable justifications to think that the actual range of compatibility may be reduced for isolated structures. In fact, other codes as the mentioned OPCM 3274 [2003] and the new Italian code [CS.LL.PP., 2008], for example, prescribe a less restrictive period range in which spectral matching has to be insured. In fact, although nonlinear dynamic analysis of base-isolated structures is necessary when the isolation system may hardly be modelled as a linear one, the superstructure is likely to remain elastic during the shaking. The isolation-structure system is designed to behave basically as a two degrees of freedom system. Therefore, one may argue that the more convenient strategy to select code spectrum-compatible records is to match the compatibility lower bound of the design spectrum in a region around the effective period of the isolated structure.

7. Conclusions

The study presented in the article extends a previous study of the authors which investigated the actual applicability to real records of EC8 Part 1 requirements about preparation of seismic input for dynamic structural analysis. The European Strong-Motion Database was investigated to search for record sets matching the EC8 Part 2 spectral requirements (found to be substantially equivalent to that of Part 1).

The considered sets are of two types: (1) combinations made of records (including horizontal and vertical components) which, if possible, do not require scaling to match the code spectrum compatibility provision; (2) horizontal records to be scaled to comply with the code spectral prescription, which may in principle reduce the variability within a set at the price of eventually high scaling factors.

These investigations confirm conclusions of the study referring to buildings, that is, although real records are considered, it may be hard to find un-scaled record sets matching the target shapes and at the same time satisfying other conditions, as vertical components' spectral compatibility or source parameters matching, at least for the more severe target spectra. In fact, code prescriptions do not easily allow for the application of current practice in real records selection also because the code spectrum may be only indirectly related to seismic hazard at the site and if specific software tools are not available to the practitioner. Under these conditions, the exercise performed allowed to find results, some of which are presented herein and are available online at http://www.reluis.it.

Results found well approximate the target, but are characterized by large individual spectral variability which may lead to an uncertain estimation (e.g., the structural response characterized by large record-to-record dispersion) if only seven recordings are used and, therefore, should be used with consciousness. In fact, EC8 Part 2 recommends to take care of such variability. Herein, the attempt to address this consisted of searching for non-dimensional spectra with shapes similar to that of the code. These non dimensional combinations have also the advantage to be independent of the anchoring value of the design shape, but require scaling to get the level of the target spectrum and the average scaling factor may be large.

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Appendix

In this Appendix, the details about the records presented in the paper are given as they come from the European Strong-motion Database website (http://www.isesd.cv.ic.ac.uk).

Table A1 A-type site class: record information for the un-scaled type sets, from http://www.isesd.cv.ic.ac.uk, (Figs. 2–4)

Site/Zone	Code	Event	Country	Date	Station	M_w	Mechanism	R [km]
A – 1	000055	Friuli	Italy	06/05/1976	Tolmezzo-Diga Ambiesta	6.5	thrust	23
	000182	Tabas	Iran	16/09/1978	Dayhook	7.3	oblique	12
	000198	Montenegro	Serbia & Montenegro	15/04/1979	Ulcinj-Hotel Albatros	6.9	thrust	21
	000290	Campano Lucano	Italy	23/11/1980	Sturno	6.9	normal	32
	006332	South Iceland (aftershock)	Iceland	21/06/2000	Thjorsartun	6.4	strike slip	6
	006349	South Iceland (aftershock)	Iceland	21/06/2000	Thjorsarbru	6.4	strike slip	5
	007142	Bingol	Turkey	01/05/2003	Bingol-Bayindirlik Murlugu	6.3	strike slip	14
A - 2	000055	Friuli	Italy	06/05/1976	Tolmezzo-Diga Ambiesta	6.5	thrust	23
	000182	Tabas	Iran	16/09/1978	Dayhook	7.3	oblique	12
	000198	Montenegro	Serbia & Montenegro	15/04/1979	Ulcinj-Hotel Albatros	6.9	thrust	21
	000200	Montenegro	Serbia & Montenegro	15/04/1979	Hercegnovi Novi-O.S.D. Pavicic School	6.9	thrust	65
	001228	Izmit	Turkey	17/08/1999	Gebze-Tubitak Marmara Arastirma Merkezi	7.6	strike slip	47
	004674	South Iceland	Iceland	17/06/2000	Flagbjarnarholt	6.5	strike slip	5
	007142	Bingol	Turkey	01/05/2003	Bingol-Bayindirlik Murlugu	6.3	strike slip	14
A - 3	000052	Friuli	Italy	06/05/1976	Feltre	6.5	thrust	108
	000182	Tabas	Iran	16/09/1978	Dayhook	7.3	oblique	12
	000198	Montenegro	Serbia & Montenegro	15/04/1979	Ulcinj-Hotel Albatros	6.9	thrust	21
	000200	Montenegro	Serbia & Montenegro	15/04/1979	Hercegnovi Novi-O.S.D. Pavicic School	6.9	thrust	65
	001255	Izmit	Turkey	17/08/1999	Heybeliada-Senatoryum	7.6	strike slip	78
	004679	South Iceland	Iceland	17/06/2000	Hveragerdi-Retirement House	6.5	strike slip	41
	006335	South Iceland (aftershock)	Iceland	21/06/2000	Selfoss-City Hall	6.4	strike slip	15

Table A2 B-type site class: record information for the un-scaled type sets, from http://www.isesd.cv.ic.ac.uk, (Figs 5–7)

Site/Zone	Code	Event	Country	Date	Station	M_w	Mechanism	R [km]
B - 1	000187	Tabas	Iran	16/09/1978	Tabas	7.3	oblique	57
	000196	Montenegro	Yugoslavia	15/04/1979	Petrovac-Hotel Oliva	6.9	thrust	25
	000197	Montenegro	Yugoslavia	15/04/1979	Ulcinj-Hotel Olimpic	6.9	thrust	24
	000199	Montenegro	Yugoslavia	15/04/1979	Bar-Skupstina Opstine	6.9	thrust	16
	000228	Montenegro (aftershock)	Yugoslavia	24/05/1979	Bar-Skupstina Opstine	6.2	thrust	33
	006263	South Iceland	Iceland	17/06/2000	Kaldarholt	6.5	strike slip	7
	006334	South Iceland (aftershock)	Iceland	21/06/2000	Solheimar	6.4	strike slip	11
B - 2	000197	Montenegro	Yugoslavia	15/04/1979	Ulcinj-Hotel Olimpic	6.9	thrust	24
	000199	Montenegro	Yugoslavia	15/04/1979	Bar-Skupstina Opstine	6.9	thrust	16
	000228	Montenegro (aftershock)	Yugoslavia	24/05/1979	Bar-Skupstina Opstine	6.2	thrust	33
	000231	Montenegro (aftershock)	Yugoslavia	24/05/1979	Tivat-Aerodrom	6.2	thrust	21
	004673	South Iceland	Iceland	17/06/2000	Hella	6.5	strike slip	15
	006263	South Iceland	Iceland	17/06/2000	Kaldarholt	6.5	strike slip	7
	006334	South Iceland (aftershock)	Iceland	21/06/2000	Solheimar	6.4	strike slip	11
B – 3	000181	Tabas	Iran	16/09/1978	Boshroyeh	7.3	oblique	68
	000197	Montenegro	Yugoslavia	15/04/1979	Ulcinj-Hotel Olimpic	6.9	thrust	24
	000230	Montenegro (aftershock)	Yugoslavia	24/05/1979	Budva-PTT	6.2	thrust	8
	000536	Erzincan	Turkey	13/03/1992	Tercan-Meteoroji Mudurlugu	6.6	strike slip	65
	002015	Kefallinia (aftershock)	Greece	23/03/1983	Argostoli-OTE Building	6.2	oblique	9
	004673	South Iceland	Iceland	17/06/2000	Hella	6.5	strike slip	15
	006328	South Iceland (aftershock)	Iceland	21/06/2000	Kaldarholt	6.4	strike slip	12

Table A3 C-type site class: record information for the un-scaled type sets, from http://www.isesd.cv.ic.ac.uk, (Figs. 8–10)

Site/Zone	Code	Event	Country	Date	Station	M_w	Mechanism	R [km]
C - 1	000042	Ionian	Greece	04/11/1973	Lefkada-OTE Building	5.8	thrust	15
	000879	Dinar	Turkey	01/10/1995	Dinar-Meteoroloji Mudurlugu	6.4	normal	8
	007329	Faial	Portugal	09/07/1998	Horta	6.1	strike slip	11
	001226	Izmit	Turkey	17/08/1999	Duzce-Meteoroloji Mudurlugu	7.6	strike slip	100
	001257	Izmit	Turkey	17/08/1999	Yarimca-Petkim	7.6	strike slip	20
	001560	Duzce 1	Turkey	12/11/1999	Bolu-Bayindirlik ve Iskan Mudurlugu	7.2	oblique	39
	001703	Duzce 1	Turkey	12/11/1999	Duzce-Meteoroloji Mudurlugu	7.2	oblique	8
C - 2	000879	Dinar	Turkey	01/10/1995	Dinar-Meteoroloji Mudurlugu	6.4	normal	8
	007329	Faial	Portugal	09/07/1998	Horta	6.1	strike slip	11
	001226	Izmit	Turkey	17/08/1999	Duzce-Meteoroloji Mudurlugu	7.6	strike slip	100
	001257	Izmit	Turkey	17/08/1999	Yarimca-Petkim	7.6	strike slip	20
	006959	Izmit (aftershock)	Turkey	13/09/1999	Adapazari Bahtiyat Topcu Evi	5.8	oblique	23
	001560	Duzce 1	Turkey	12/11/1999	Bolu-Bayindirlik ve Iskan Mudurlugu	7.2	oblique	39
	001703	Duzce 1	Turkey	12/11/1999	Duzce-Meteoroloji Mudurlugu	7.2	oblique	8
C - 3	000151	Friuli (aftershock)	Italy	15/09/1976	Buia	6	thrust	11
	000479	Manjil	Iran	20/06/1990	Rudsar	7.4	oblique	81
	001726	Adana	Turkey	27/06/1998	Ceyhan-Tarim Ilce Mudurlugu	6.3	strike slip	30
	007329	Faial	Portugal	09/07/1998	Horta	6.1	strike slip	11
	001226	Izmit	Turkey	17/08/1999	Duzce-Meteoroloji Mudurlugu	7.6	strike slip	100
	001230	Izmit	Turkey	17/08/1999	Iznik-Karayollari Sefligi Muracaati	7.6	strike slip	39
	006959	Izmit (aftershock)	Turkey	13/09/1999	Adapazari Bahtiyat Topcu Evi	5.8	oblique	23

Table A4 Record information for the non-dimensional type sets, from http://www.isesd.cv.ic.ac.uk, (Figs. 11–13)

Site	Code	Event	Country	Date	Station	M_w	Mechanism	R [km]
A	000172	Basso Tirreno	Italy	15/04/1978	Messina 1	6	oblique	58
	000286	Campano Lucano	Italy	23/11/1980	Arienzo	6.9	normal	78
	001255	Izmit	Turkey	17/08/1999	Heybeliada-Senatoryum	7.6	strike slip	78
	002553	Racha	Georgia	29/04/1991	Toros	6.8	thrust	167
	004674	South Iceland	Iceland	17/06/2000	Flagbjarnarholt	6.5	strike slip	5
	005821	Strofades (aftershock)	Greece	18/11/1997	Koroni-Town Hall (Library)	6	strike slip	93
	007115	Pulumur	Turkey	27/01/2003	Bingol-Bayindirlik Murlugu	6	strike slip	87
B	000232	Montenegro (aftershock)	Yugoslavia	24/05/1979	Kotor-Naselje Rakite	6.2	thrust	20
	000500	Racha	Georgia	29/04/1991	Bogdanovka	6.8	thrust	129
	002019	Off coast of Magion Oros peninsula	Greece	06/08/1983	Ierissos-Police Station	6.6	strike slip	87
	002030	Kefallinia (aftershock)	Greece	23/03/1983	Zakynthos-OTE Building	6.2	oblique	65
	005809	Strofades	Greece	18/11/1997	Argostoli-OTE Building	6.6	oblique	78
	006142	Aigion	Greece	15/06/1995	Patra-San Dimitrios Church	6.5	normal	43
	007143	Bingol	Turkey	01/05/2003	Elazig-Bayindirlik ve Iskan Mudurlugu	6.3	strike slip	120
C	005673	Volvi	Greece	20/06/1978	Pehcevo-Duvanski Kombinat	6.2	normal	119
	000175	Volvi	Greece	20/06/1978	Thessaloniki-City Hotel	6.2	normal	29
	000555	Kallithea	Greece	18/03/1993	Patra-OTE Building	5.8	thrust	41
	001251	Izmit	Turkey	17/08/1999	Bursa-Tofa Fabrikasi	7.6	strike slip	92
	006961	Izmit (aftershock)	Turkey	13/09/1999	Adapazari A.Babalioglu Evi	5.8	oblique	26
	006963	Izmit (aftershock)	Turkey	13/09/1999	Akyazi Gebes Koyu Imam Lojmani	5.8	oblique	38
	006967	Izmit (aftershock)	Turkey	13/09/1999	Ambarli-Termik Santrali	5.8	oblique	120