Bull Earthquake Eng (2012) 10:1357–1375
DOI 10.1007/s10518-012-9369-4

ORIGINAL RESEARCH PAPER

Mesozonation of the Italian territory for the definition of real spectrum-compatible accelerograms

M. Rota · E. Zuccolo · L. Taverna ·
M. Corigliano · C. G. Lai · A. Penna

Received: 13 January 2012 / Accepted: 24 July 2012 / Published online: 10 August 2012

Abstract The Italian building code defines the seismic action in terms of elastic acceleration response spectra derived from the results of a probabilistic seismic hazard study performed for the whole national territory. This representation of the seismic input is insufficient for several situations (e.g. analysis of geotechnical systems or time-history analyses of structures), for which the seismic input needs to be specified in terms of accelerograms. This work illustrates a methodology for the seismic mesozonation of the Italian territory, with the aim of defining suites of 7 real accelerograms recorded at outcropping rock sites with flat topographic conditions and, most importantly, compatible with the elastic acceleration response spectrum defined by the Italian building code at any location in Italy. These accelerograms do not require any correction and can be directly used for nonlinear dynamic analyses of structures and geotechnical systems. The mesozonation is based on identification of groups of spectra with similar characteristics and shape. For each of these groups, a parent spectrum is defined and used for selecting real spectrum-compatible records. Limited linear scaling is then applied to these accelerograms to make them compatible with all the response spectra of the group. The results of this work for the 475-years return period are accessible through the SEISM-HOME Web-GIS (www.eucentre.it/seismhome.html) providing, for any site in Italy, a suite of 7 real accelerograms spectrum-compatible, on average, with the acceleration response spectrum prescribed by the Italian building code. SEISM-HOME is a useful tool for practitioners needing ready-to-use time-histories for seismic analyses.

M. Rota (✉) · C. G. Lai · A. Penna
European Centre for Training and Research in Earthquake Engineering, Via Ferrata 1, 27100 Pavia, Italy
e-mail: maria.rota@eucentre.it

E. Zuccolo · C. G. Lai · A. Penna
Department of Civil Engineering and Architecture, University of Pavia, Via Ferrata 1, 27100 Pavia, Italy

L. Taverna
Trevi, SpA, Italy

M. Corigliano
Pavia, Italy

Keywords Seismic input · Mesozonation · Time-history analysis · Real accelerograms · Spectrum-compatibility

1 Introduction

Several building codes worldwide define the seismic hazard of a country by subdividing the national territory in a discrete and limited number of homogenous seismic zones (usually constrained by the geographical boundaries) that are individually characterised by a fixed value of a probabilistically-defined reference ground motion parameter (e.g. horizontal peak ground acceleration having 0.10 probability of exceedance in 50 years on stiff soil and flat topographic surface). This is for example the case for Eurocode 8 Part 1 (EN 1998-1 2005 indicated in the following as EC8-1) and most internationally available seismic codes (e.g. International Building Code 2011).

The Italian building code (NTC08 2008) was instead inspired by a different philosophy, aiming at a more refined description of seismic hazard, both in geographical and temporal terms. From the geographical point of view, the seismic hazard is made independent from the administrative subdivisions of the Italian territory, i.e. it is not linked to the geographical borders of each municipality as it happened in the past. The definition of a single spectral shape, anchored to different values of a reference peak ground acceleration (PGA) for each municipality (depending on the seismic classification), has been replaced by elastic acceleration response spectra defined at each point of a reference grid consisting of 10,751 nodes, located at a relative distance not larger than 10 km. From a temporal point of view, the seismic action has been defined for 9 values of the return period, ranging from 30 to 2,475 years.

In this study, reference was made to the current Italian building code (NTC08 2008), firstly as the aim of the study is the definition of the seismic input for the Italian territory and secondly because the approach adopted by NTC08 could be viewed as a pioneer application towards a more refined definition of seismic hazard in other countries and transnational building codes such as for example the Eurocode 8.

Despite being a more detailed and accurate definition of seismic hazard with respect to the standard approach based on seismic zones, the practical application of NTC08 creates some difficulties in the definition of the seismic input to be adopted for nonlinear dynamic analyses. This method of analysis, which is the most accurate for the assessment of the seismic response of structures and geotechnical systems, requires the seismic input to be represented in terms of properly defined time-series (e.g. accelerograms), which need to be consistent with the seismic hazard at the site. This is often associated with the idea of "spectrum-compatibility", i.e. to the fact that the difference between the average spectrum of the selected accelerograms and the target spectrum cannot exceed a predefined tolerance in a specified interval of structural periods. It is important to emphasize however that the selected records also need to satisfy the requirement of "seismo-compatibility" which means that they must be consistent with the regional seismotectonic and seismogenic setting, as discussed for example in Corigliano et al. (2012).

The Italian building code allows using accelerograms belonging to one of the following categories:

- real (or natural) accelerograms, recorded during seismic events and available from accredited digital strong-motion databases, either national or international;
- artificial accelerograms, generated by stochastic algorithms and possibly constrained to be spectrum-compatible with a target response spectrum, which can be provided by a

code or obtained by means of probabilistic or deterministic seismic hazard analyses (e.g. Mukherjee and Gupta 2002; Boore 2005; Hancock et al. 2006; Al Atik and Abrahamson 2010);
- synthetic accelerograms, generated through a numerical simulation of the rupture mechanism typically based on a kinematic representation of the seismic source coupled with an elastodynamic scheme of wave propagation from the source to the site of interest (e.g. Mai and Beroza 2003; Halldorsson and Papageorgiou 2004).

In between the two last categories a hybrid procedure has been proposed by Motazedian and Atkinson (2005) providing accelerograms which are intermediate between artificial and synthetic ones.

The advantages and drawbacks of these categories of records are well-known and they have been widely discussed in the literature (e.g. Bommer and Acevedo 2004; Corigliano et al. 2012). In general, it can be stated that the use of real time-series as input to dynamic analyses of structures and geotechnical systems should be preferred, as they are realistic in terms of frequency content, duration, number of cycles, correlation among vertical and horizontal components and energy content in relation to seismogenic parameters. NTC08 also provides some prescriptions regarding the applicability of the three types of records for different problems and, in particular, NTC08 does not allow the use of artificial records for geotechnical applications. Regarding real records, NTC08 requires their selection to be representative of the seismicity at the site and adequately justified based on the seismogenic characteristics of the source and on the peak horizontal acceleration expected at the site. The Commentary (Circ. NTC08 2009) further specifies that the spectrum-compatibility requirement defined for artificial records can be used as a reference also for real accelerograms. This condition, which is also reported by EC8-1, requires that no value of the mean spectral ordinates of the selected records should be less than the ordinates of the corresponding code-based elastic response spectrum by more than 10 % in a predefined range of structural periods, calculated as the larger between the interval $0.15\,\mathrm{s} \div 2.0\,\mathrm{s}$ and $0.15\,\mathrm{s} \div 2T$, with T the elastic fundamental structural period, for ultimate limit states, and $0.15\,\mathrm{s} \div 1.5T$ for serviceability limit states. The Italian Commentary also states that if records need to be linearly scaled to satisfy spectrum-compatibility, the scaling factor must be limited in case of accelerograms originated from small magnitude events.

NTC08 defines the seismic action in terms of elastic acceleration response spectra using the results of the probabilistic seismic hazard study carried out by the National Institute of Geophysics and Volcanology (INGV, http://esse1.mi.ingv.it/) for a reference grid consisting of 10,751 nodes. The variability of the spectral shapes makes the selection of real spectrum-compatible records a cumbersome task, as an independent suite of records should in principle be selected for each of these 10,751 points. This difficulty in the definition of the seismic input as time-histories is one of the reasons for which nonlinear dynamic analyses of structures and geotechnical systems is rarely carried out in the everyday engineering practice.

This paper aims to illustrate the details of a work that has been recently carried out in an attempt to provide a contribution to the solution of this problem. A web application named SEISM-HOME (SElection of Input Strong-Motion for HOmogeneous MEsozones) has been created and is available at the internet site www.eucentre.it/seismhome.html. It allows an automatic and prompt definition, at any location over the entire Italian territory, of the seismic input represented by suites of real spectrum- and seismo-compatible accelerograms recorded at outcropping rock sites with flat topographic surface, complying with the prescriptions of NTC08.

The methodology used to develop SEISM-HOME is based on the implementation of a series of operations which can be summarized by the following steps:

1. mesozonation of the Italian territory to subdivide the nodes of the reference grid used for the definition of seismic hazard according to NTC08 into homogeneous groups, characterised by acceleration response spectra having similar shapes. This required a quantitative definition of the concept of "similarity" among different spectral shapes;
2. for each homogeneous group defined at point 1 above, identification of the parent (or reference) acceleration response spectrum, appropriately selected among the NTC08 spectra belonging to the same group;
3. selection of suites of real accelerograms recorded on outcropping rock and flat topographic surface, subjected to the constraint of being spectrum-compatible, on average, with the parent spectrum defined at point 2 above, using the software ASCONA described in Corigliano et al. (2012). The choice of focusing exclusively on accelerograms recorded on rock derives from considerations upon the significant uncertainties associated with the selection of accelerograms recorded at non-rocky sites, particularly if they are required to be spectrum-compatible with a code-based spectrum for non-rocky soils. Moreover, the accelerograms recorded on outcropping rock constitute the objective motion for site response analyses, which are needed for the definition of the seismic input, in terms of time-series, at non-rocky sites.
4. limited linear scaling of the selected records to satisfy the spectrum-compatibility requirement with all the acceleration response spectra belonging to the same homogeneous group.

SEISM-HOME (SElection of Input Strong-Motion for HOmogeneous MEsozones) allows downloading (from www.eucentre.it/seismhome.html) suites of 7 real spectrum-compatible accelerograms for any location of the Italian territory. The size of the suite of accelerograms has been established equal to 7, in agreement with NTC08 and EC8-1, which specify that the number of records in a set should be equal or larger than 7 if the user wishes to use the average results of the analyses instead of the most unfavourable ones.

SEISM-HOME does not require any information about the regional seismogenic characteristics or the seismic hazard at a specific site. These data have already been considered during the process of record selection. With respect to other procedures currently available in the literature for the definition of seismic input in terms of real spectrum-compatible accelerograms, such as for example those at the base of the computer programs ASCONA (Corigliano et al. 2012), REXEL (Iervolino et al. 2010), REXELite (Iervolino et al. 2011) and SigmaSpectra (Kottke and Rathje 2008), SEISM-HOME is not a general tool for selecting records compatible with a target response spectrum. Conversely, it directly provides pre-selected suites of spectrum-compatible accelerograms, only requiring the geographical coordinates of the site of interest in Italy. Furthermore, the accelerograms provided by SEISM-HOME have already being corrected and linearly scaled through scaling factors that have been kept as close as possible to unity.

2 Mesozonation of the italian territory

The initial data used for the work are the results of the probabilistic seismic hazard study carried out by INGV for the entire national territory, which were made available since 2004 (http://esse1.mi.ingv.it/). These results consist of seismic hazard maps depicting 11 values of spectral acceleration (for the horizontal component and for a structural damping ratio of

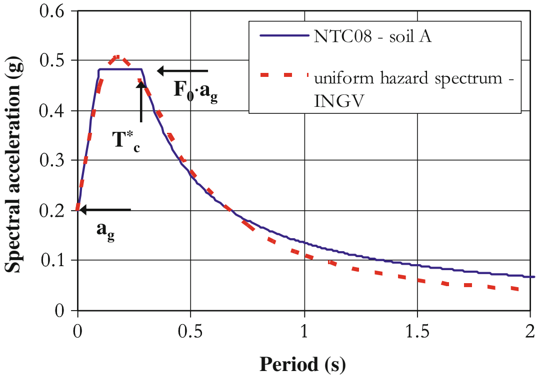


Fig. 1 Comparison between the uniform hazard spectrum computed by INGV and the NTC08 acceleration response spectrum for outcropping rock and for the return period of 475 years, for the site of Pontremoli, Tuscany (Lai et al. 2009)

5 %) on outcropping rock, for 9 return periods (from 30 to 2,475 years) and for three levels of reliability, for each node of a reference grid constituted by 16,921 nodes located at a relative distance smaller than 10 km.

The seismic action specified by the Italian building code (NTC08 2008) is based on the results of this study and defines, at each node of a reference grid consisting of 10,751 nodes, an elastic acceleration response spectrum characterised by an analytical expression which, in the absence of site effects, depends on three parameters: the peak horizontal ground acceleration (a_g), the maximum value of the amplification factor of the horizontal acceleration response spectrum (F_0) and the period indicating the beginning of the constant velocity branch of the horizontal acceleration response spectrum (T_c^*). For each node of the reference grid and for each of the 9 return periods, NTC08 provides values of the three parameters a_g, F_0 and T_c^* for the 50th percentile. In particular, values of a_g correspond to those derived in the INGV study, whilst values of F_0 and T_c^* were obtained by a least squares curve fitting procedure between the uniform hazard spectra calculated by INGV (for each site and for each return period) and the spectral shape described by the analytical expression of NTC08. An example of the comparison between a uniform hazard spectrum and the spectral shape of NTC08 for the site of Pontremoli (Tuscany) is illustrated in Fig. 1.

The work presented in this paper was carried out with reference to the elastic response spectra of NTC08 for the return period of 475 years and for outcropping rock conditions (soil type A) and flat topographical surface. Annex B of NTC08 contains a table where, for each node of the reference grid (described in terms of its geographical coordinates), the three parameters a_g, F_0 and T_c^* for the 50th percentile are reported. In this study, all points located at the sea and outside the national borders have been discarded from those included in Annex B, obtaining a total of 8,948 triplets of values for a_g, F_0 and T_c^* and thus 8,948 response spectra.

A plot of these spectra (Fig. 2a) shows a significant variability of the spectral ordinates, whereas a representation of the same spectra normalised to their value of a_g (Fig. 2b) and to their product $a_g \cdot F_0$ (Fig. 2c) shows the remarkable variability of spectral shapes. This suggested the need to identify a minimum number of spectral shapes which could be representative of all the response spectra. In other words, the first task of the study was the identification of homogeneous groups of spectra having similar shape and characteristics. The next step was the selection, for each homogeneous group, of a parent (or reference) spectrum to be used for the definition of real, spectrum-compatible accelerograms.

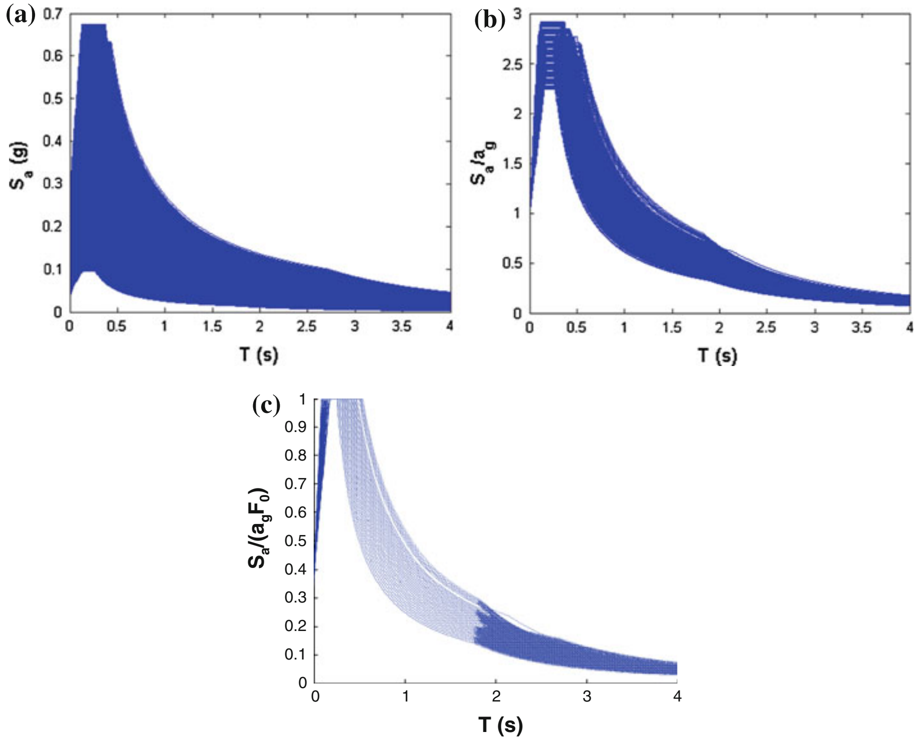


Fig. 2 **a** Graphical representation of the 8,948 acceleration response spectra considered in this study for the Italian territory (475 years return period and soil type A). **b** Same spectra normalised to the value of PGA (a_g) and **c** same spectra normalised to the product $a_g \cdot F_0$

2.1 Subdivision of the Italian territory in mesozones

Mesozonation of the Italian territory requires the identification of groups of response spectra with similar shape, amplitude and characteristics. Zini et al. (2011), with specific reference to the seismic hazard of Italy, proposed a few criteria to group the nodes of the reference grid based on consistency of spectral shapes and also on the differences between the prescriptions of NTC08 and the results of the hazard study performed by INGV. However the work by Zini et al. (2011) did not specifically focus on the selection of real accelerograms for engineering applications.

In the current work, the homogeneous groups of response spectra have been defined based on the values assumed by the parameters T_c^* and F_0 prescribed by NTC08 (Annex B) and of the average spectrum deviation δ as defined by Iervolino et al. (2008). The parameter δ is a quantitative measure of the deviation of the average spectrum from a target spectrum, whereas T_c^* controls the shape of the response spectra and F_0 affects the values of the record scaling factors, as discussed in the following. Threshold values of these three parameters were identified based on a trial and error approach, trying to find a trade-off between the number of independent homogeneous groups (which cannot be too large to limit the number of record selections) and the need for the reference spectrum to be adequately representative of all the spectra of the group (to ensure that the selected records are compatible with all the spectra in the group, as discussed in

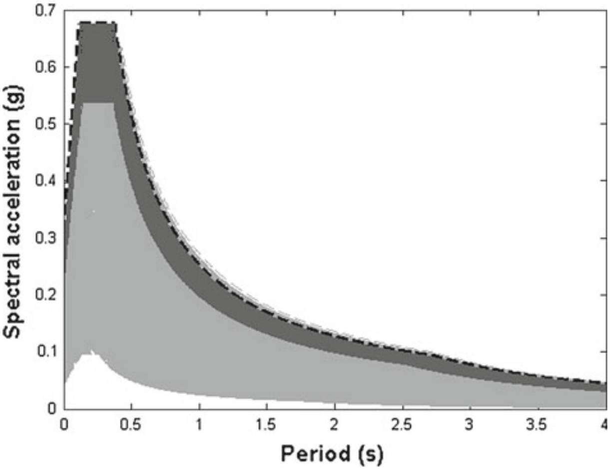


Fig. 3 Definition of group 1: the *dashed line* indicates the maximum response spectrum; the *light gray lines* represent all the considered spectra; the *dark grey lines* indicate the response spectra belonging to group 1

detail in the next sections). The algorithm consists in the implementation of the following steps:

1. identification of the spectrum (S_{max}) with the maximum value of the product $a_g \cdot F_0$;
2. for each spectrum S_k, evaluation of the average spectrum deviation δ with respect to S_{max} by:

$$\delta = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{S_k(T_i) - S_{\max}(T_i)}{S_{\max}(T_i)}\right)^2} \tag{1}$$

   where N represents the number of (equally spaced) periods used to discretize the spectrum. The value of δ is calculated in the same range of periods assumed relevant for spectrum-compatibility (in this study between 0.15 and 2 s);
3. identification of the spectra with $\delta < 0.2$;
4. selection of response spectra with values of T_c^* ($T_{c,k}^*$) sufficiently close (tolerance 0.05) to the corresponding value of the spectrum $S_{max}(T_{c,max}^*)$. Formally:

$$\left|T_{c,\max}^* - T_{c,k}^*\right| \le 0.05; \tag{2}$$

5. identification of the spectra with values F_0 and a_g ($F_{0,k}$ and $a_{g,k}$) sufficiently close (tolerance 0.5) to the corresponding values of the spectrum S_{max} ($F_{0,max}$ and $a_{g,max}$). Formally:

$$\left(a_{g,k} \cdot F_{0,k}\right) > a_{g,\max} \cdot \left(F_{0,\max} - 0.5\right); \tag{3}$$

6. definition of a first group of homogeneous response spectra which includes S_{max} and all the spectra simultaneously satisfying all the conditions described at points 3, 4 and 5 above (Fig. 3).

Once the first group, which includes n spectra, is defined, the second group is obtained by applying the same procedure to all the spectra not belonging to the first group (i.e. 8948-n spectra) and so on until all the response spectra are included in one of the groups.

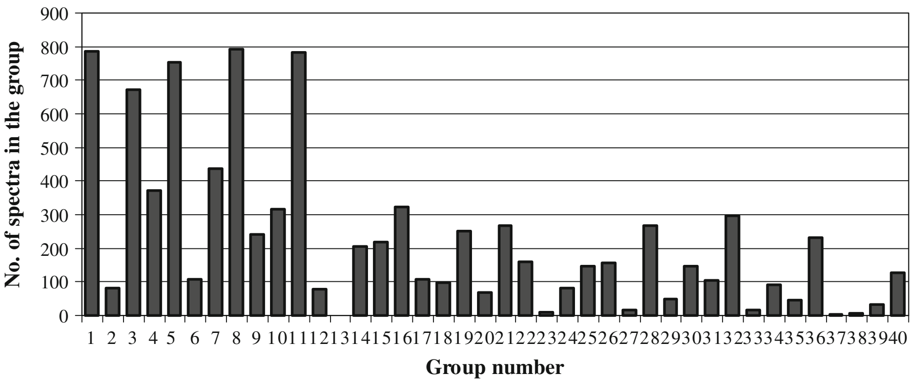


Fig. 4 Number of spectra belonging to each of the 40 groups

Using this approach, 40 groups were defined, each including a variable number of spectra, as depicted in Fig. 4. It can be noted that some of the groups consist of very few spectra, such as for example groups 13, 37 and 38, which include 1, 4 and 5 spectra, respectively. These groups correspond to spectral shapes that are significantly different from all the other spectra and hence require an ad hoc selection of accelerograms.

Figure 5 shows the geographical distribution of the groups of homogeneous spectra previously defined, each identified by means of a different colour. The overlapping of these results with the seismogenic zonation ZS9 (Meletti and Valensise 2004) used by INGV to calculate the seismic hazard of Italy (GdL MPS 2004), highlights a good correspondence between the two maps.

Furthermore Fig. 6 shows a good correlation between the mesozonation map and the spatial distribution of the PGA map of Italy (475 years return period, outcropping rock conditions and flat topographic surface) calculated by INGV (GdL MPS 2004).

2.2 Definition of the parent spectra

For each of the 40 groups of homogeneous spectra in which the 8,948 response spectra have been subdivided, a parent (or reference) spectrum has been identified and then used for selecting and linearly scaling real accelerograms. The parent spectrum for each group has been selected among the spectra belonging to the same group so to represent as much as possible the characteristics of all the spectral shapes of the group.

The choice of the parent spectrum was hence based on the following steps:

1. evaluation of the average response spectrum of the group, S_{av}:

$$S_{av}(T_i) = \frac{1}{n} \sum_{k=1}^{n} S_k\left(T_i\right) \tag{4}$$

   with n representing the number of spectra S_k of the group;
2. calculation of the average spectrum deviation δ of each spectrum in the group S_k, with respect to S_{av}:

$$\delta = \sqrt{\frac{1}{n} \sum_{i=1}^{n} \left(\frac{S_k(T_i) - S_{av}(T_i)}{S_{av}(T_i)} \right)^2} \tag{5}$$

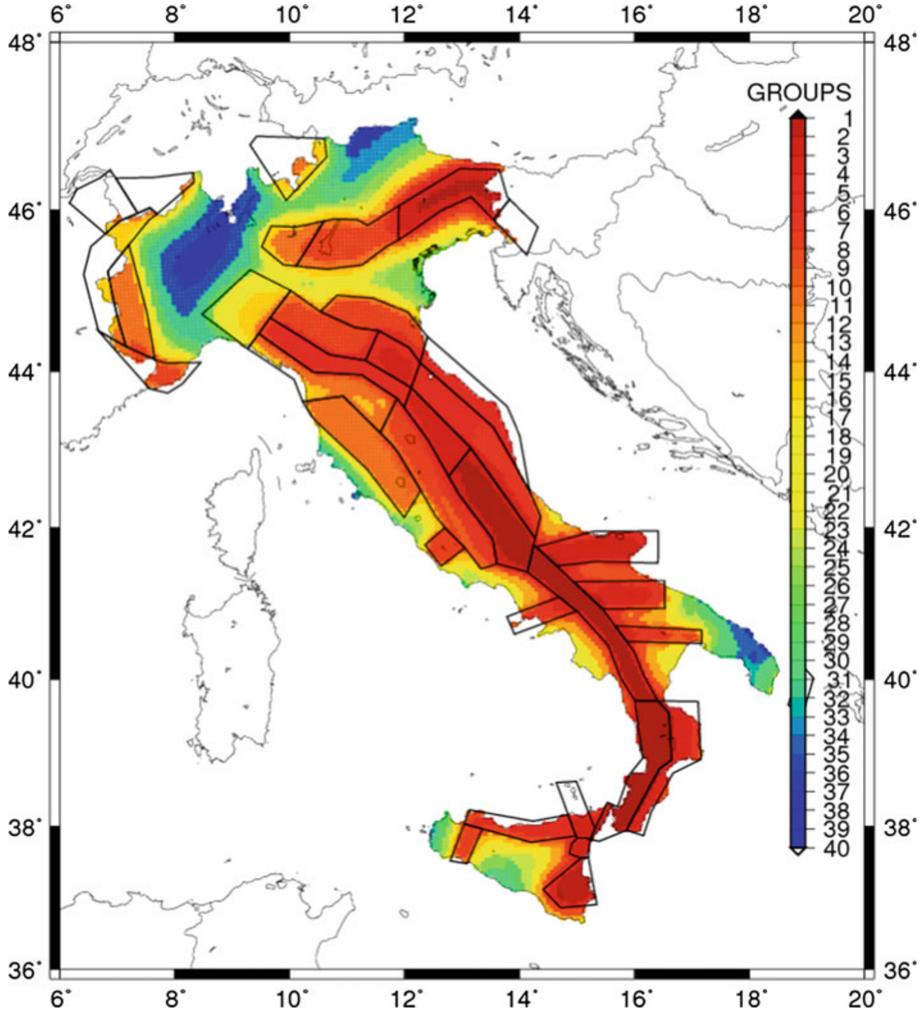
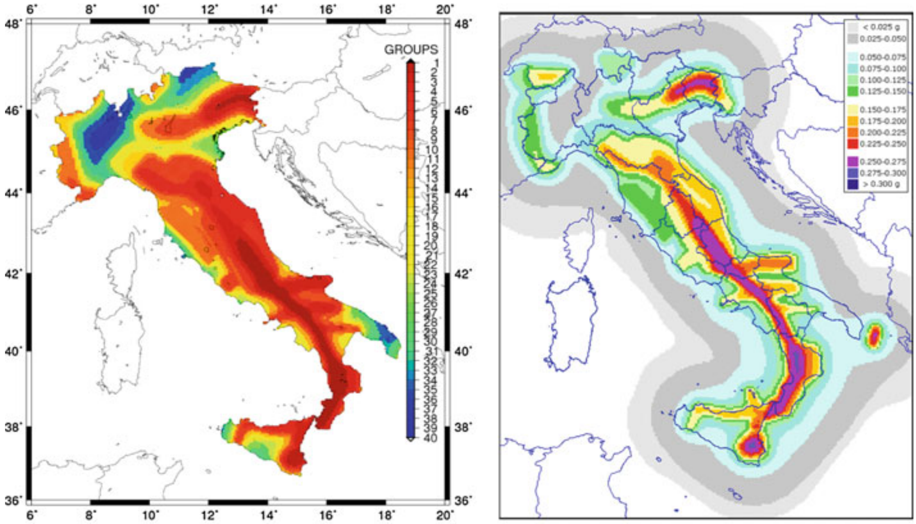


Fig. 5 Mesozonation of the Italian territory: geographical distribution of the 40 groups of homogeneous spectra (return period of 475 years). The numbering corresponds to the order of definition of the groups, starting from the one with the largest spectral ordinate. The mesozonation is overlapped with the seismogenic zonation ZS9 (Meletti and Valensise 2004) used by INGV for preparing the seismic hazard map of Italy (http://esse1.mi.ingv.it/)

3. selection of the parent spectrum of the group as the one with the smallest value of δ.

This procedure was already applied to a much smaller scale problem related to the definition of seismic input in territories within the Tuscany region in Central Italy (Zuccolo et al. 2011).

The main reason why the average spectrum of the group was not a suitable choice is that, according to EC8-1 and NTC08, spectrum-compatibility is required only in terms of maximum negative difference and not in terms of positive difference. This means that the average spectrum of the selected records is allowed to overestimate the reference



(a) (b)

Fig. 6 Comparison between **a** the results of the mesozonation of the Italian territory for the 475 years return period and **b** the seismic hazard map of Italy for the same return period expressed in terms of peak ground acceleration (horizontal component, soil type A) computed by INGV (GdL MPS 2004)

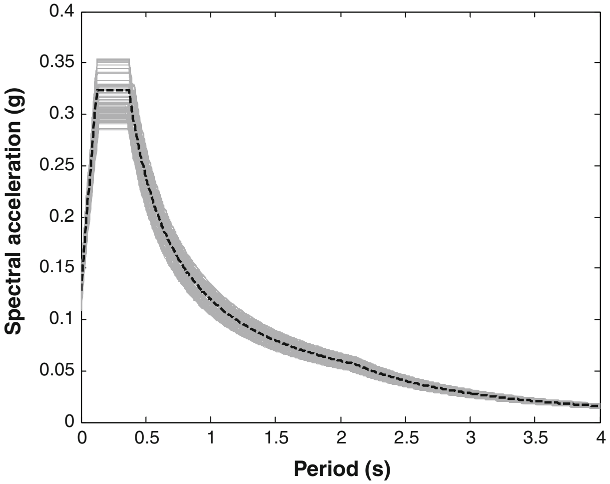


Fig. 7 Identification of the parent spectrum (*thick dashed line*) for group 12

spectrum, while it is not allowed to underestimate it by more than 10 %. For this reason, the choice of the average spectrum of the group as the parent spectrum would require the application of larger scaling factors than needed with the proposed definition of parent spectrum.

Figure 7 shows, as an example, the spectra belonging to group 12. The parent spectrum defined by means of the procedure discussed above is reported with a thick dashed line.

3 Selection of natural spectrum-compatible records

Natural accelerograms have been selected using the software ASCONA (Automated Selection of COmpatible Natural Accelerograms), which is described in detail in Corigliano et al. 2012. The program relies on a wide database of accelerograms, all recorded on outcropping rock, coming from accredited strong-motion databases such as the European Strong-motion Database (http://www.isesd.hi.is/), the PEER-NGA database (http://peer.berkeley.edu/nga/), the K-Net database (http://www.k-net.bosai.go.jp/) and ITACA (http://itaca.mi.ingv.it/ItacaNet/). As the different databases use different definitions of "rock", typically based on the value of the equivalent shear wave velocity of the upper 30 m of the profile ($V_{S,30}$), some assumptions were required. In particular, the ASCONA dataset includes only waveforms recorded by stations located on soil type A of EC8-1 ($V_{S,30} > 800$ m/s) or, alternatively, soil type A or B of NEHRP 2004 ($V_{S,30} > 1{,}500$ m/s and $V_{S,30} > 760$ m/s, respectively). The identification of the stations located on outcropping rock was more complicated for the K-Net seismic network, as it contains information on P and S waves' 1D velocity profiles of the stations up to a maximum depth of 20 m. The procedure followed in this case is described in detail in Corigliano et al. (2012).

The program ASCONA is based on a random procedure for determining the group of accelerograms better satisfying the requirements imposed by the user. The algorithm generates a large number of combinations of pre-selected real records satisfying certain pre-defined requisites, it calculates the average response spectrum of the selected records and compares it with the (acceleration or displacement) reference spectrum. The comparison is carried out in terms of average (absolute value) and maximum negative difference, and average and maximum spectrum deviation (as defined by Eq. 1).

ASCONA requires specification of pre-defined requisites which include the number of records to be included in the set (k), the tolerance of magnitude and epicentral distance, the maximum and minimum values of the scaling factor, the reference spectrum and the interval of structural periods over which spectrum-compatibility is enforced, the maximum value of the negative difference between the average spectrum of the selected records and the reference spectrum (in order for spectrum-compatibility to be satisfied) and the maximum acceptable value of spectrum deviation δ. Spectrum-compatibility can be enforced with reference to either an acceleration or a displacement response spectrum.

The program then selects records imposing additional constraints set to avoid having in the same group two components of the same record and accelerograms recorded during the same event. This is done to prevent the use of records that are strongly correlated. Figure 8 reports a flowchart of the algorithm implemented in ASCONA.

Real accelerograms have been selected for each of the 40 parent spectra of the 40 homogeneous groups identified for the return period of 475 years. Spectrum-compatibility has been enforced according to the prescriptions of NTC08 for artificial accelerograms (and EC8-1), i.e. imposing that in the interval of structural periods between 0.15 and 2 s, the average spectrum of the selected accelerograms does not present a negative difference of more than 10 % with respect to the parent spectrum. The number of accelerograms selected for each group was set equal to 7, as suggested by NTC08 and EC8-1.

The selected records were all linearly scaled to a spectral acceleration corresponding to a prescribed structural period of the parent spectrum. This was either the value of a_g (i.e. the PGA or the spectral acceleration associated with a period equal to zero), which was used as a first trial, or the spectral acceleration at the corner period T_c^* (indicating the beginning of the constant velocity branch of the horizontal acceleration response spectrum) when the first trial did not yield satisfactory results in terms of the values of the parameters quantifying the

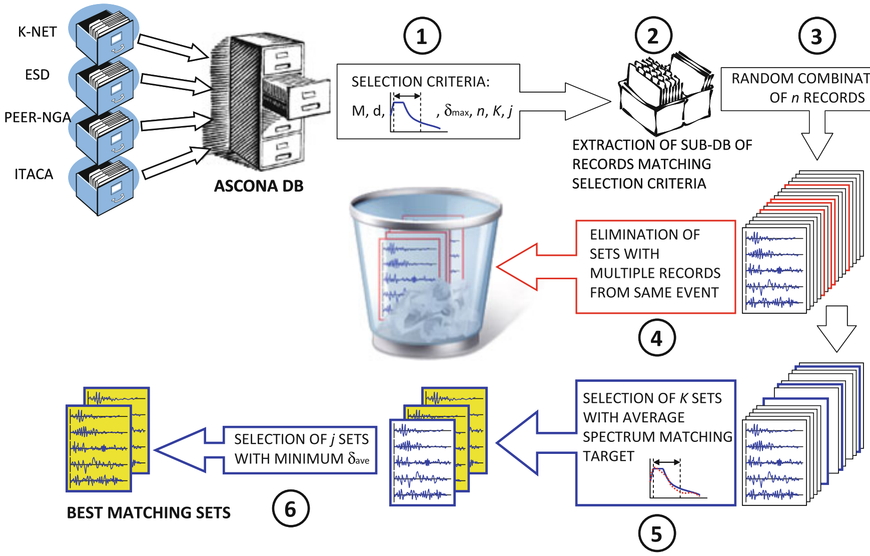


Fig. 8 Flowchart of the algorithm implemented in ASCONA (Corigliano et al. 2012)

goodness-of-fit between the average spectrum of the selected records and the parent spectrum. It is noted that, at the nodes of the reference grid located within the seismogenic zonation ZS9 (Meletti and Valensise 2004), scaling with respect to a_g is theoretically possible, provided the database of records is large enough. Conversely, this type of scaling is very difficult for all the nodes falling outside the seismogenic zones, for which scaling with respect to the ordinate corresponding to a higher period (e.g. T_c^*) is essentially necessary. This is a direct consequence of the probabilistic seismic hazard approach proposed by Cornell and McGuire (Cornell 1968; McGuire 1995) that was used to compute the uniform hazard response spectra. Indeed, the response spectra at the nodes located outside the seismogenic zones can be dominated by a distant event but, more likely, are a mixture of several events, coming from different sources. Both these situations are responsible of significant energy at long periods. These spectra have therefore a wide shape, with large spectral accelerations over a large range of periods. For this reason, it is in general more difficult to achieve spectrum-compatibility using records linearly scaled at the PGA. The recourse to the spectral acceleration corresponding to T_c^* may represent a possible solution to the problem, certainly not the only one, but there is currently no consensus in the technical community upon which value or range of values of spectral acceleration(s) is the most appropriate for linearly scaling natural records (e.g. Shome et al. 1998; Bradley 2010).

The values of the scaling factors adopted for the selected records to enforce spectrum-compatibility with the parent spectrum of each group were all kept reasonably close to unity, as shown in Fig. 9, where the range of variation of the scaling factors associated with each group (maximum and minimum values within the suite of 7 records) is plotted against the group number.

An example of the results obtained for the selection of accelerograms spectrum-compatible with the parent spectrum of group 12 is illustrated in the following figures. Specifically, Fig. 10 shows the selected records (scaled to the spectral value at the corner period T_c^*), whilst Fig. 11 illustrates the response spectra of each accelerogram together with the average

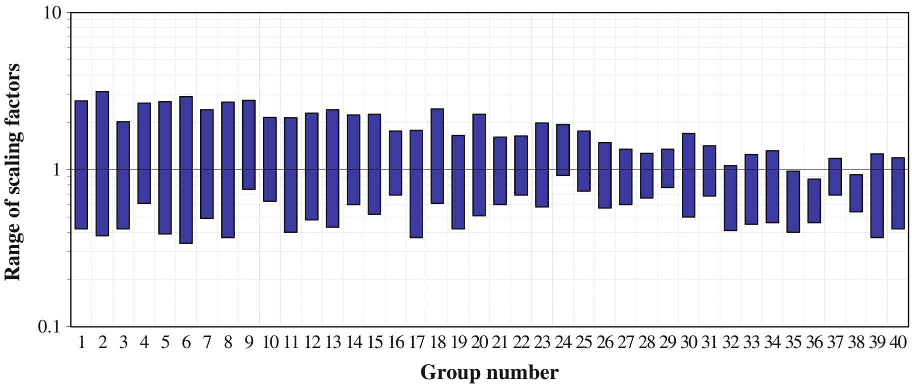


Fig. 9 Variability of the scaling factors adopted for the suite of 7 records of each group, to enforce spectrum-compatibility with the parent spectrum (logarithmic scale)

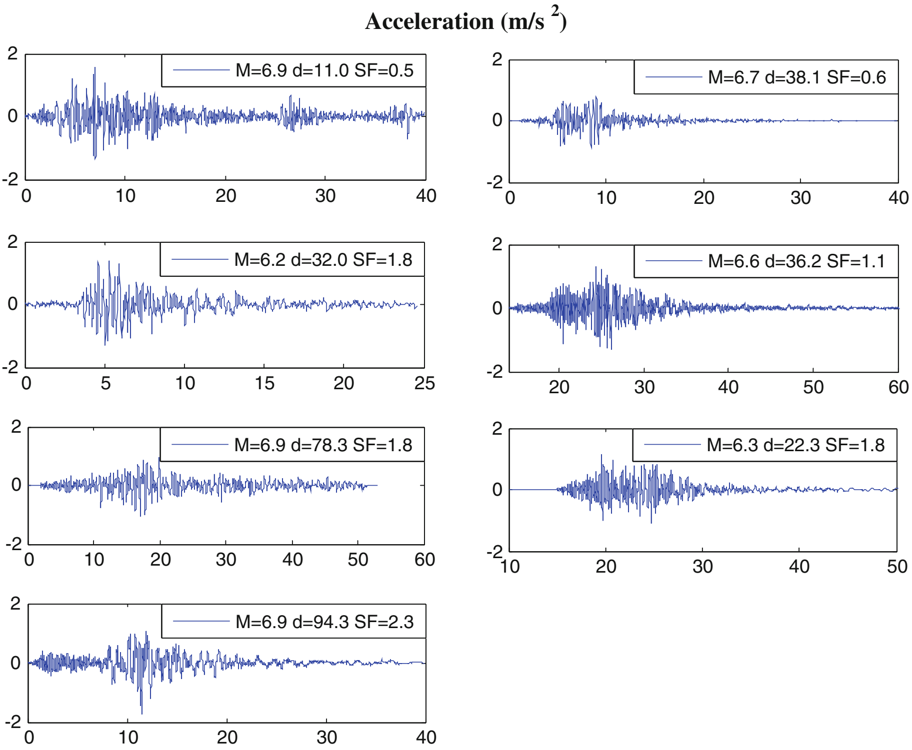


Fig. 10 Group of 7 accelerograms spectrum-compatible, on average, with the parent spectrum of group 12. For each record, the legend reports the values of magnitude (*M*) and epicentral distance (*d*) of the event and the corresponding scaling factor (*SF*)

response spectrum. Finally, Fig. 12 shows the enforced spectrum-compatibility, reporting a comparison between the average spectrum and the parent spectrum (Fig. 12a) and also the values of the percentage difference between the two spectra as a function of the structural period

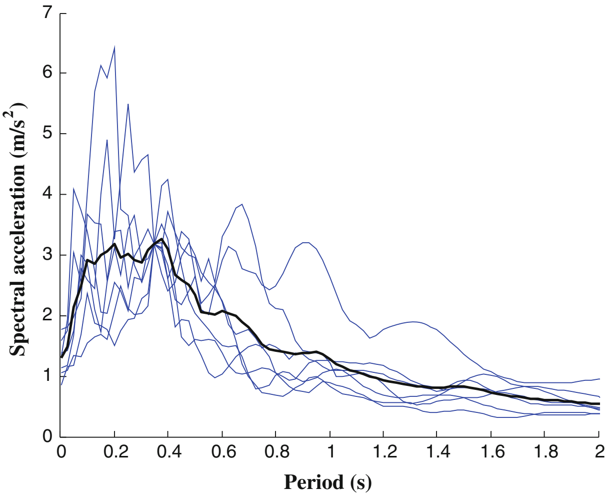


Fig. 11 Acceleration response spectra of the records selected for the parent spectrum of group 12 (*thin lines*) and average spectrum (*thick line*)

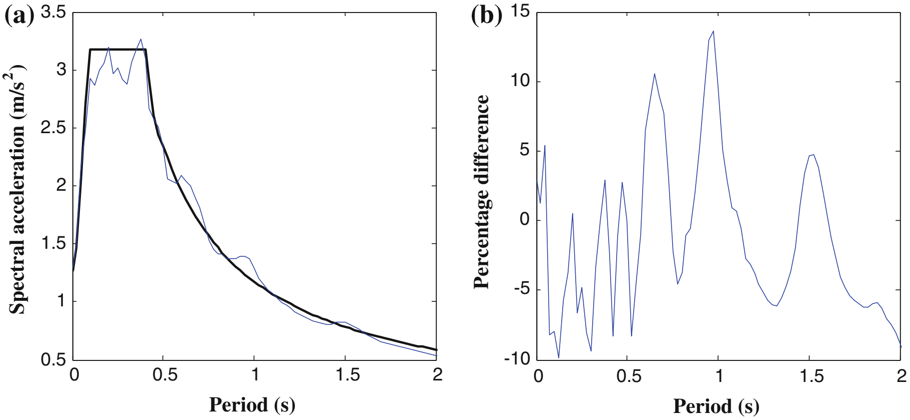


Fig. 12 **a** Comparison between the average spectrum of the 7 records selected to be compatible with the parent spectrum of group 12 (*thin line*) and the parent spectrum itself (*thick line*). **b** Percentage difference between the two spectra. Note that spectrum-compatibility has been enforced in the period interval 0.15–2 s

(Fig. 12b). This selection yielded a value of the average percentage difference (between the mean spectrum of the 7 accelerograms and the parent spectrum) of 4.86 %, a maximum negative difference of 9.85 %, an average spectrum deviation of 0.057 and a maximum spectrum deviation (referring to the response spectrum of each single record with respect to the parent spectrum) of 0.719. The minimum and maximum scaling factors obtained for this group were equal to 0.48 and 2.29, respectively, whereas the average scaling factor was equal to 1.41.

4 Further linear scaling of the accelerograms

In the procedure describe above, the real accelerograms have only been selected with the objective of being spectrum-compatible with the parent spectrum of each group. The

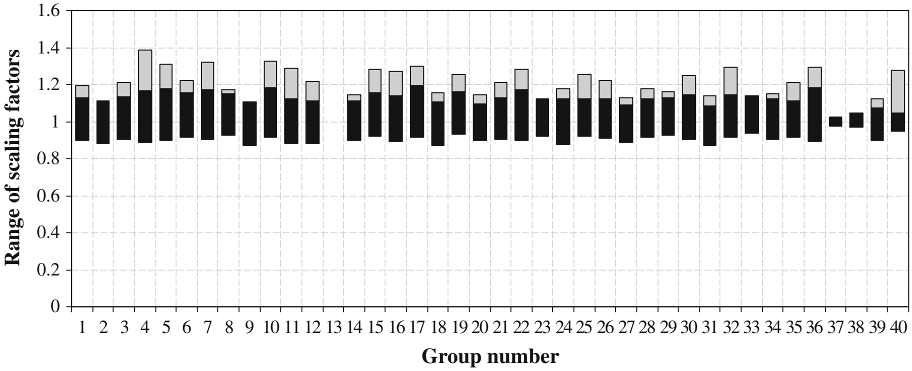


Fig. 13 Variability (maximum and minimum values for each group) of the scaling factor *SF1* (*black*) and of the product *SF1* · *SF2* (*grey*) adopted to enforce spectrum-compatibility of the suites of records with any arbitrary spectrum of the same group

spectrum-compatibility of the selected suite of records with each spectrum of the group is not automatically guaranteed. Thus it has been enforced for each group by further linearly scaling the records selected for the parent spectrum according to the procedure described below.

For each spectrum of each group, a suite of accelerograms, compatible on average with it, has been obtained by multiplying the average spectrum of the records selected with respect to the parent spectrum of the same group by two scaling factors, *SF1* and *SF2*. *SF1* is the scaling factor needed to pass from the parent spectrum to each spectrum of the same group, i.e. it is the ratio between each spectrum and the parent spectrum at the spectral ordinate for which the records have been scaled in ASCONA (i.e. spectral acceleration corresponding to a structural period $T = 0$ or T_c^*).

Since the shape of all the spectra belonging to a given homogeneous group is similar but not identical, in most cases the application of the scaling factor *SF1* was not sufficient to obtain accelerograms that were spectrum-compatible with all the spectra of the group. For this reason, an additional scaling factor (*SF2*) was introduced for all the spectra that did not satisfy spectrum-compatibility with *SF1* only. Considering that the spectrum-compatibility requirement of EC8-1 and NTC08 (for artificial records) only imposes the maximum negative difference to be within 10 % in a given period interval, this additional scaling factor *SF2* was defined, for each spectrum of the group, to guarantee that this maximum negative difference was exactly equal to 10 %. Hence *SF2* was calculated for the period (within the period interval used to enforce spectrum-compatibility) for which the difference between the two spectra was maximum, as the ratio between 90 % (1–10 %) and one minus the maximum negative difference (in percent) and then applied to the average spectrum of the selected records (i.e. to each of the seven selected records). However it is important to remark that the values adopted for *SF2* were all very close to unity and hence the ordinates of the response spectra were not significantly modified by the application of this additional scaling factor. For the spectra that directly satisfied spectrum-compatibility with *SF1*, *SF2* was obviously fixed to unity.

The range of variability of the product of the additional scaling factors *SF1* and *SF2* for each group is illustrated in Fig. 13, where the minimum and maximum values are shown.

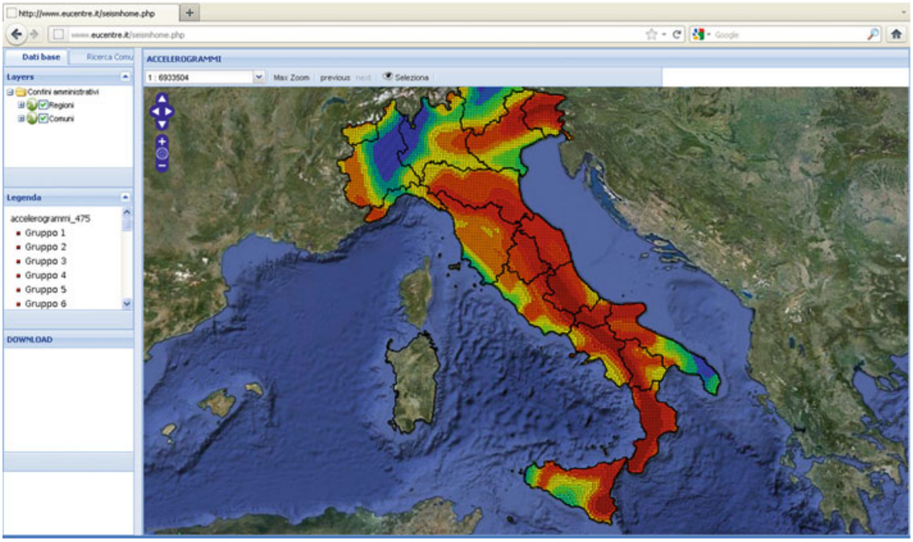


Fig. 14 Snapshot of the SEISM-HOME Web-GIS (www.eucentre.it/seismhome.html)

5 Seism-home Web-GIS

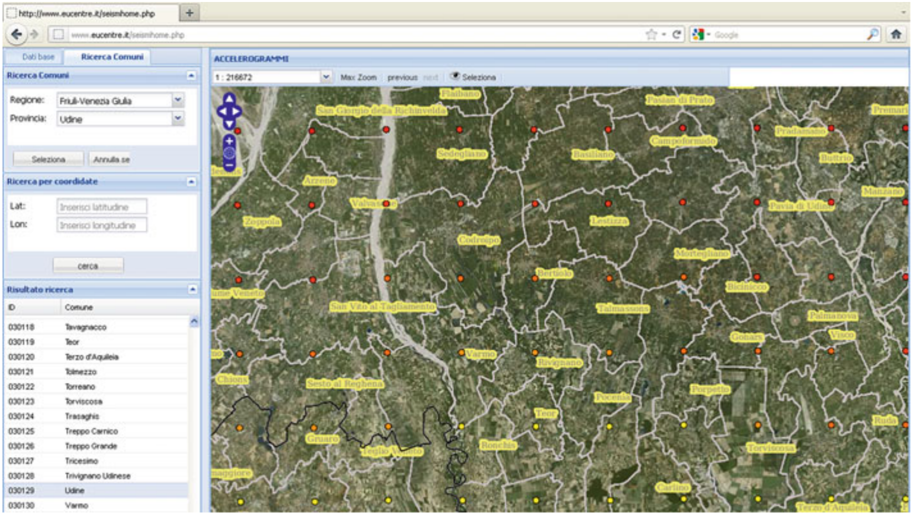
The results of this study for the return period of 475 years have been organised in an intuitive and user-friendly Web-GIS environment and are available online at www.eucentre.it/seismhome.html.

SEISM-HOME (SElection of Input Strong-Motion for HOmogeneous MEsozones) allows obtaining the seismic input at any site of the Italian territory, in terms of a suite of 7 real accelerograms spectrum-compatible with the acceleration response spectrum of the Italian building code (NTC08). The site of interest can be selected based alternatively on the name of the municipality, the geographical coordinates (latitude and longitude) or simply by directly picking it from an interactive geographical map of Italy (Fig. 14).

The software first identifies the node of the reference grid associated with Annex B of NTC08 closest to the site of interest (Fig. 15). Then it finds the spectral group to which the site must be linked. Next the program supplies a suite of 7 appropriately scaled real accelerograms, which are spectrum-compatible (on average) with the acceleration response spectra of NTC08 for that node and for the return period of 475 years. SEISM-HOME also returns a table containing important metadata including an identification code, the values of the scaling factors (*SF1*, *SF2* and the scaling factor used in ASCONA) and the main seismological characteristics of the selected records (e.g. magnitude, epicentral distance, original strong-motion database from which the signals were retrieved, etc). The seismic input defined by SEISM-HOME is then ready to be directly used for the seismic analysis of structures and geotechnical systems.

6 Conclusive remarks

This paper illustrates the results of a work aimed at contributing to the solution of a problem felt by civil engineers and practitioners in Italy, which is the need for ready-to-use and reliable



Ricerca Comuni

Regione: Friuli-Venezia Giulia
Provincia: Udine

Ricerca per coordidate

Lat: Inserisci latitudine
Lon: Inserisci longitudine

Risultato ricerca

ID	Comune
030118	Tavagnacco
030119	Teor
030120	Terzo d'Aquileia
030121	Tolmezzo
030122	Torreano
030123	Torviscosa
030124	Trasaghis
030125	Treppo Carnico
030126	Treppo Grande
030127	Tricesimo
030128	Trivignano Udinese
030129	Udine
030130	Varmo

1 : 216672

Fig. 15 Interactive selection of the site of interest from the SEISM-HOME Web-GIS (www.eucentre.it/seismhome.html)

suites of real accelerograms to be used for the seismic analyses of structures and geotechnical systems at any location of the national territory. The difficulty in retrieving records that are consistent with the expected seismic hazard and compatible with the regional seismotectonic and seismogenic setting at a given site is one of the reasons that make nonlinear time-history analysis of structures rarely used in the everyday engineering practice. In structural engineering, the problem can be partially mitigated by resorting to spectrum-compatible artificial accelerograms, but it is well-known that real records are far superior to artificial, synthetic or hybrid signals for a plurality of reasons.

With the aim of record selection, the Italian territory was subdivided into homogeneous areas from the point of view of the spectral shapes prescribed by NTC08, which vary from point to point (seismic mesozonation). 40 groups of elastic acceleration response spectra (horizontal component) were identified, each one constituted by spectra having similar shape and characteristics. The work was performed according to a purposely-devised methodology and a definition of similarity whose details are illustrated in the paper.

For each of the 40 groups of response spectra, a parent spectrum was selected as a reference for the definition of suites of spectrum-compatible real accelerograms. Forty suites of 7 real accelerograms, spectrum-compatible, on average, with the corresponding parent spectrum were selected with the software ASCONA (Corigliano et al. 2012). Spectrum-compatibility, enforced according to the prescription of NTC08 for artificial records (or EC8-1), was achieved through a restricted linear scaling of the accelerograms. For each specific suite of records, compatible with each of the 40 corresponding parent spectra, two additional scaling factors were introduced to enforce compatibility between the average spectrum of the suite of accelerograms and any individual spectrum belonging to a specific group.

Despite these operations, the final scaling factors, obtained from the product of the factors used in the selection for the parent spectrum and the two factors described above, ended up being within 0.31 and 3.5 for all the 40 groups. Also, the average scaling factor for the parent spectrum of each group varied between 0.63 and 1.95 whereas, at the national level, the final scaling factors varied between 0.59 and 2.15 for all the points of the grid, with an average value of 1.34. This range of scaling factors is a direct consequence of the limited scaling factors used by the software ASCONA and also of the rigorous criteria adopted for defining the groups of homogeneous spectra and the parent spectrum of each group.

The goodness of the fit between the average response spectrum of the suite of real records and the spectrum prescribed by the Italian building code (NTC08) was assessed for all the 8,948 nodes of the reference grid by means of specific misfit parameters such as the average spectrum deviation (ranging between 0.04 and 0.24), the maximum spectrum deviation (ranging between 0.35 and 0.96) and the absolute value of the average difference (ranging between 3.5 and 21.3 %). The ratio between the values of a_g of the record-based and NTC08-based spectra was also computed to avoid having an excessive overestimation of the peak ground acceleration on rock when scaling with respect to T_c^* (in EC8-1 this prescription is required). This ratio ended up varying between 0.9 and 1.6.

This work has been carried out for a level of severity of the seismic input corresponding to a return period of 475 years. Furthermore, the selected accelerograms have to be associated with soil type A of NTC08 since they were recorded on outcropping rocky sites. These accelerograms do not require any correction and can be directly used for applications without any further scaling.

The results of the work are accessible through the SEISM-HOME Web-GIS application (www.eucentre.it/seismhome.html), from which it is possible to download, for any location of the national territory, a suite of 7 real accelerograms spectrum-compatible, on average, with the acceleration response spectrum prescribed by the Italian building code. SEISM-HOME (SElection of Input Strong-Motion for HOmogeneous MEsozones) is a useful tool for practitioners and non-specialist users who need ready-to-use suites of real time-histories at any site of the Italian territory for seismic analyses of structures and geotechnical systems.

Although the work has been carried out for the return period of 475 years only, efforts are underway for an extension to other return periods, specifically those of interest for the seismic design of structures according to the Italian building code (NTC08). As previously mentioned, the results of this study can be directly used without the need for any correction in case of structures located on rock or as the seismic input for site response analyses of structures and geotechnical systems located on non-rocky soils. Finally, since spectrum-compatibility is enforced in a given range of periods (between 0.15 and 2 s), the selected and scaled records should be used for structures and geotechnical systems whose periods of vibration, at least in the elastic phase of the response, are well included in this range.

Acknowledgments This work has been carried out within the 2009–2012 EUCENTRE executive project E5/2 “Knowledge levels and confidence factors for existing masonry buildings and heritage structures”, funded by the Italian Department of Civil Protection. The work also took advantage of the coordination with a project funded by the Tuscany Region through the General Direction of Territorial and Environmental Policies in which a trial application of the same selection procedure was used to define input ground motions for the territories of Garfagnana, Lunigiana, Mugello, Val di Sieve and Montagna Fiorentina. Both contributions are gratefully acknowledged by the authors affiliated to EUCENTRE. A special word of gratitude goes to the ICT staff of EUCENTRE and in particular to Mr. Andrea Bianchi and Dr. Paolo Verri for the support provided in the development of the web application SEISM-HOME. The paper has significantly benefited from the useful suggestions of prof. Dario Slejko and an anonymous reviewer, who are gratefully acknowledged.

References

Al Atik L, Abrahamson NA (2010) An improved method for nonstationary spectral matching. Earthq Spectra 26(3):601–617

Bommer JJ, Acevedo AB (2004) The use of real earthquake accelerograms as input to dynamic analysis. J Earthq Eng 8(SI1):43–91

Boore DM (2005) SMSIM—fortran programs for simulating ground motions from earthquakes: version 2.3—a revision of OFR 96-80-A. U.S. Geological Survey open-file report

Bradley BA (2010) A generalized conditional intensity measure approach and holistic ground-motion selection. Earthq Eng Struct Dyn 39(12):1321–1342

Circ NTC (2009) Circolare, n.617, 2 febbraio 2009, del Ministero delle Infrastrutture e dei trasporti approvata dal Consiglio Superiore dei Lavori Pubblici *"Istruzioni per l'applicazione delle nuove norme tecniche per le costruzioni di cui al D.M. 14 gennaio 2008"* (in Italian)

Corigliano M, Lai CG, Rota M, Strobbia C (2012) ASCONA: Automated Selection of Compatibile Natural Accelerograms. Earthq Spectra (in press)

Cornell CA (1968) Engineering seismic risk analysis. Bull Seism Soc Am 58:1583–1606

EN 1998-1 (2005) Eurocode 8: design of structures for earthquake resistance—part 1: general rules, seismic actions and rules for buildings

GdL MPS (2004) Redazione della mappa di pericolosità sismica prevista dall'Ordinanza PCM 3274 del 20 marzo 2003, Rapporto conclusivo per il dipartimento di Protezione Civile, INGV, Milano—Roma, 65 pp. +5 appendici. Website: http://zonesismiche.mi.ingv.it/elaborazioniinItalian.

Halldorsson B, Papageorgiou AS (2004) Region specific ground motion simulations using the specific barrier model. Draft user manual for SGMSv5

Hancock J, Watson-Lamprey J, Abrahamson NA, Bommer JJ, Markatis A, McCoy E, Mendis R (2006) An improved method of matching response spectra of recorded earthquake ground motion using wavelets. J Earthq Eng 10(SI1):67–89

Iervolino I, Maddaloni G, Cosenza E (2008) Eurocode 8 compliant real record sets for seismic analysis of structures. J Earthq Eng 12:54–90

Iervolino I, Galasso C, Cosenza E (2010) REXEL: computer aided record selection for code-based seismic structural analysis. Bull Earthq Eng 8: 339–362. doi:10.1007/s10518-009-9146-1

Iervolino I, Galasso C, Paolucci R, Pacor F (2011) Engineering ground motion record selection in the ITalian ACcelerometric Archive. Bull Earthq Eng 9: 1761–1778. doi:10.1007/s10518-011-9300-4

2012 International Building Code (2011) International Code Council, 690 pp

Kottke A, Rathje EM (2008) A semi-automated procedure for selecting and scaling recorded earthquake motions for dynamic analysis. Earthq Spectra 24(4):911–932

Lai CG, Foti S, Rota M (2009) Input Sismico e Stabilità Geotecnica dei Siti di Costruzione. IUSS Press, Pavia

Mai PM, Beroza GC (2003) Hybrid method for calculating near-source, broadband seismograms: application to strong motion prediction. Phys Earth Planet Inter 137:183–199

McGuire RK (1995) Probabilistic seismic hazard analysis and design earthquakes: closing the loop. Bull Seism Soc Am 85(5):1275–1284

Meletti C, Valensise G (2004) Zonazione Sismogenetica ZS9—App.2 al Rapporto Conclusivo, Appendice 2 al documento "Redazione della Mappa di Pericolosità Sismica prevista dall'Ordinanza PCM del 20 marzo 2003, n. 3274, All. 1—Rappsorto Conclusivo, Istituto Nazionale di Geofisica e Vulcanologia. http://zonesismiche.mi.ingv.it/-inItalian

Motazedian D, Atkinson GM (2005) Stochastic finite-fault modeling based on a dynamic corner frequency. Bull Seism Soc Am 95:995–1010

Mukherjee S, Gupta VK (2002) Wavelet-based characterisation of design ground motions. Earthq Eng Struct Dyn 31(5):1173–1190

NEHRP (2004) Recommended provisions for seismic regulations for new buildings and other structures (FEMA 450) part 1: provisions. Building Seismic Safety Council, National Institute of Building Sciences, Washington, D.C

NTC (2008) Norme tecniche per le costruzioni, Ministero delle Infrastrutture e dei Trasporti, Decreto Ministeriale del 14 gennaio 2008, Supplemento ordinario alla G.U. n. 29 del 4 febbraio 2008

Shome N, Cornell CA, Bazzurro P, Carballo JE (1998) Earthquakes, records, and nonlinear responses. Earthq Spectra 14(3):469–500

Zini A, Rinaldis D, Pugliese A (2011) Raggruppamento della pericolosità sismica del territorio nazionale attraverso parametri statistici. In: Proceedings of 14th Italian conference on earthquake engineering, Bari (in Italian)

Zuccolo E, Corigliano M, Taverna L, Lai CG (2011) Meso-zonazione di un territorio per la definizione di accelerogrammi reali spettro-compatibili. In: Proceedings of 14th Italian conference on earthquake engineering, Bari (in Italian)