Definition of Spectrum-Compatible Natural Records for the Italian Territory

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SUMMARY
This paper presents SEISM-HOME (SElection of Input Strong Motion for HOmogeneous MEgazone), an interactive application created to support non-expert users to automatically define the seismic input required to carry out dynamic analyses of structures and/or geotechnical systems, at any desired site of the Italian territory, by simply specifying the geographical coordinates. The methodology upon which SEISM-HOME has been developed is based on implementing four main steps: sorting all the response spectra of the Italian territory in 40 homogeneous groups; defining a reference (parent) response spectrum for each group; selecting spectrum-compatible accelerograms using the parent response spectrum of each group; linearly scaling the accelerograms to satisfy spectrum-compatibility with respect to other response spectra of the group. SEISM-HOME is freely-available at www.eucentre.it/seismhome.html and it allows the user to select a set of 7 spectrum-compatible real accelerograms compliant with the requirements of the Italian building code for rocky sites (475 years return period).

Keywords: seismic input; mesozonation; time-history analysis; real accelerograms; spectrum compatibility

1. INTRODUCTION

The Italian building code (NTC08, 2008) defines the seismic action in terms of elastic acceleration response spectra using the results of the seismic hazard study carried out by the National Institute of Geophysics and Volcanology (INGV) for the whole Italian territory (Montaldo et al. 2007). The elastic response spectra are site-dependent and approximate the probabilistic uniform hazard spectra for 10751 nodes (located at a relative distance not larger than 10 km) of a reference grid and 9 return periods (ranging from 30 to 2475 years).

NTC08 gives also prescriptions about the use of accelerograms, which must be taken into account for the execution of non-linear dynamic analyses of structures and geotechnical systems. For instance, like other building codes worldwide, NTC08 allows the adoption of three categories of accelerograms namely natural, artificial and synthetic. 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 the use of real time-series as input to dynamic analyses of structures and geotechnical systems should be preferred over other types of signals and this for a variety of reasons including their 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, it does not allow the use of artificial records for the analysis of geotechnical systems. 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, the geotechnical conditions at the recording site, the magnitude, the distance from the source and the maximum horizontal acceleration expected at the site. According to the Commentary to NTC08 (Circ. NTC08, 2009) and Eurocode 8 (EN 1998-1, 2004), the spectrum-compatibility condition requires that no value of the average spectral ordinates of the selected records should be lower 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 0.15s÷2.0s and 0.15s÷2*T*, with *T* the elastic fundamental structural period, for ultimate limit states, and 0.15s÷1.5*T* for serviceability limit states. The Italian Commentary of the building code also states that the geological conditions of the site should be accounted for and that if records need to be linearly scaled to satisfy spectrum-compatibility, the scaling factors must be limited in case of accelerograms originated from small magnitude events.

The difficulty in properly defining the seismic input in terms of time-series is one of the reasons for which nonlinear dynamic analysis of structures and geotechnical systems is rarely carried out in the everyday engineering practice. Moreover, the variability of the spectral shapes defined by NTC08 for the Italian territory 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 the 10751 nodes of the reference grid.

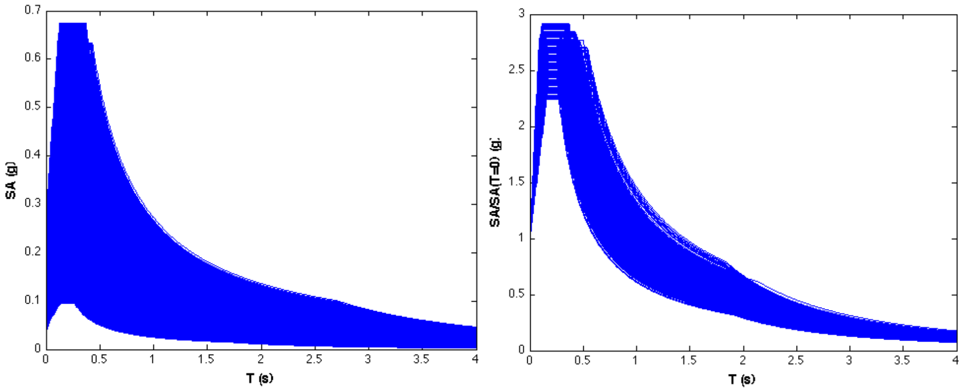
This paper aims at illustrating the details of a work that has been recently carried out in an attempt to contribute to the solution of this problem. A web-based application named SEISM-HOME (SElection of Input Strong-Motion for HOmogeneous MEsozones) has been created and is available at the web-site 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 7 real, spectrum- and seismo-compatible accelerograms recorded at outcropping rock sites with flat topographic surface, complying with the prescriptions of NTC08, for the return period of 475 years. Only the geographical coordinates of the site of interest are required as input by the user.

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 40 homogeneous groups characterised by acceleration response spectra with similar shapes and severity. This step required a quantitative definition of "similarity" among different spectral shapes;
2. for each homogeneous group defined at point 1 above, identification of the reference (parent) acceleration response spectrum, appropriately selected among the NTC08 spectra belonging to the same group;
3. selection and scaling of suites of 7 real accelerograms recorded on outcropping rock and flat topographic surface, with the constraint of being spectrum-compatible, on average, with the reference spectrum defined at point 2 above, using the ASCONA program (Corigliano et al., 2012);
4. linear scaling of the selected records to satisfy the spectrum-compatibility requirement with all the acceleration response spectra belonging to the same homogeneous group.

2. MESOZONATION OF THE ITALIAN TERRITORY

The horizontal acceleration response spectra defined by NTC08 for outcropping rock conditions (soil type A) and flat topographical surface for the 475 years return period at each of the 8948 nodes of the reference grid (nodes referring to lands inside the national borders) were used as input data for the study. Each response spectrum is characterized by an analytic expression consisting of four branches and depending on three parameters: the maximum horizontal ground acceleration, a_g, the maximum spectral acceleration normalized with respect to a_g (amplification factor), F_0 and the period indicating the beginning of the constant velocity branch of the spectrum, T_c^*. A plot of these spectra (Fig. 2.1a) shows a significant variability of the spectral ordinates, whereas a representation of the same spectra normalised to their value of a_g (Fig. 2.1b) shows a milder variability of spectral amplitude. This suggested the need to identify a minimum number of groups of spectral shapes that could be representative of the entire variability of all the response spectra. In other words, the first task of the study was the identification of homogeneous groups of spectra having similar shapes and descriptive parameters (so to carry out a seismic mesozonation of the Italian territory).



a) b)

Figure 2.1. (a) Graphical representation of the 8948 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 a_g

The homogeneous groups of response spectra were defined according to three criteria based on the average spectral deviation, δ, and on the parameters T_c* and F_0 prescribed by NTC08. The parameter δ is a quantitative measure of the deviation of a 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. The algorithm that was set-up consists in the implementation of the following steps:

a) identification of the spectrum (S_{max}) with the maximum value of the product $a_g \cdot F_0$;

b) computation, for each spectrum S_k, of the average spectral deviation δ with respect to S_{max}:

$$\delta = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{S_k(T_i) - S_{\max}(T_i)}{S_{\max}(T_i)}\right)^2} \tag{2.1}$$

where N represents the number of equally spaced periods, T_i, in which the spectrum was discretized. The value of δ is computed in the range of periods relevant for the condition of spectrum-compatibility, i.e. between 0.15s and 2s (after some trials and iterations an optimum value of δ equal to 0.2 was identified as a meaningful acceptable threshold);

c) identification of the spectra S_k with $\delta<0.2$;

d) selection of response spectra with values of T_c^* ($T_{c,k}^*$) sufficiently close (selected tolerance 0.05) to the corresponding value of the spectrum S_{max} ($T_{c,max}^*$). Formally:

$$\left|T^*_{c,\max} - T^*_{c,k}\right| \leq 0.05 \tag{2.2}$$

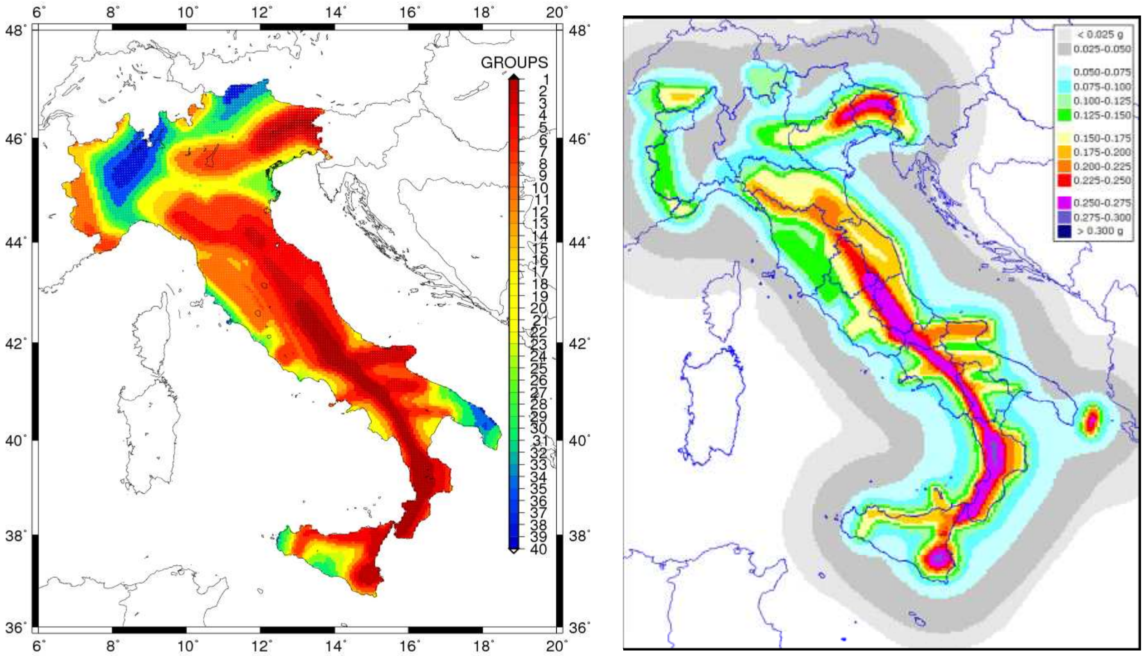
e) identification of the spectra with values F_0 and a_g ($F_{0,k}$ and $a_{g,k}$) sufficiently close (selected tolerance 0.5) to the corresponding values of the spectrum S_{max} ($F_{0,max}$ and $a_{g,max}$). Formally:

$$\left(a_{g,k} \cdot F_{0,k}\right) > a_{g,\max} \cdot \left(F_{0,\max} - 0.5\right) \tag{2.3}$$

f) definition of a first group of homogeneous response spectra which includes S_{max} and all the spectra simultaneously satisfying the three conditions described at points c), d) and e) above.

Threshold values associated with the conditions described at points c), d) and e) above derived from the need 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 (parent) 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 detail in the next sections).

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 a group. Using this approach, 40 groups were defined, each including a variable number of spectra. Fig. 2.2a shows the geographical distribution of the groups, each identified by a specific chromatic scale. The comparison of these results with 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, Fig. 2.2b) highlights a non-surprising good correspondence between the two maps.



a) b)

Figure 2.2. Comparison between (a) the result of the mesozonation of the Italian territory for 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)

3. DEFINITION OF THE PARENT SPECTRA

For each of the 40 groups of homogeneous spectra in which the 8948 response spectra were subdivided, a reference (or parent) spectrum was identified and then used for selecting real, spectrum-compatible accelerograms. The parent spectrum for each group was selected among the spectra belonging to the same group so to represent as closely as possible the characteristics of all the spectral shapes of the same group. The choice of the parent spectrum was based on the implementation of the following steps:

a) evaluation of the average response spectrum of the group, S_{av}:

$$S_{av}(T_i) = \frac{\sum_{k=1}^{n} S_k(T_i)}{n} \tag{3.1}$$

with n representing the number of spectra S_k of the group;

b) calculation of the average spectral deviation δ of each spectrum in the group, S_k, with respect to S_{av}:

$$\delta = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(\frac{S_k(T_i) - S_{av}(T_i)}{S_{av}(T_i)}\right)^2} \tag{3.2}$$

c) identification of the reference spectrum of the group as the one with the smallest value of δ.

Fig. 3.1 shows, as an example, the spectra belonging to group 15, with outlined the parent spectrum defined by means of the procedure previously discussed.

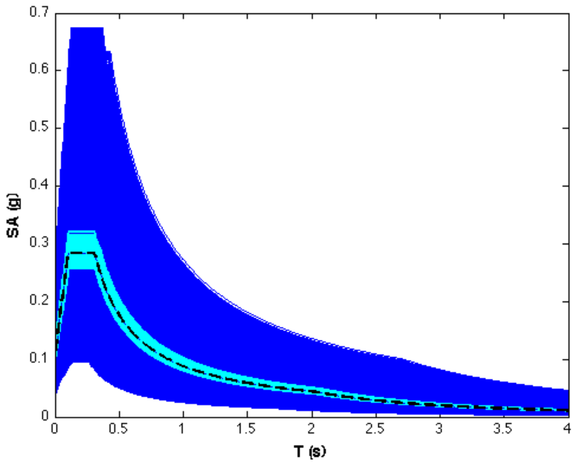


Figure 3.1. a) Definition of the parent spectrum of group 15: the blue lines represent all the spectra under consideration, the cyan lines indicate the spectra belonging to group 15, while the black dashed line is the parent (reference) spectrum for group 15

4. SELECTION OF REAL, SPECTRUM-COMPATIBLE ACCELEROGRAMS

Real, spectrum-compatible accelerograms were selected for the 40 identified parent response spectra using the ASCONA computer program (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/). 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.

The program ASCONA is based on the selection of a set of accelerograms that better satisfy some constraints imposed by the user with the additional requirement of spectrum-compatibility with a target response spectrum. In fact, ASCONA requires specification of pre-defined requisites which include the number of records to be included in the set, the interval of magnitude and epicentral distance, the maximum and minimum values of the scaling factor, the reference spectrum, 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 spectral deviation δ.
Then the algorithm generates a large number of combinations of real records satisfying the enforced requirements. Additional constraints are imposed by ASCONA to avoid having in the same set of accelerograms two components of the same record, more than one recorded at the same station during different events and accelerograms recorded during the same event. This is done to prevent the use of records that could be strongly correlated.
The average response spectrum of each set of records is computed and compared with the reference spectrum in terms of average (absolute value) and maximum negative difference, and average and maximum spectral deviation. When the maximum negative difference does not exceed a certain tolerance in a fixed range of periods, then the set of accelerograms is kept since it satisfies the spectrum-compatibility criterion, and the "best" set of accelerograms provided by ASCONA is chosen as the suite of records satisfying the spectrum-compatibility requirement and characterized by the minimum average difference.

In this study spectrum-compatibility was enforced according to the prescriptions of NTC08 and EC8-1 for artificial accelerograms, i.e. imposing that in the interval of structural periods between 0.15s and 2s, the average spectrum of the selected accelerograms does not exhibit a negative difference of more than 10% with respect to the reference spectrum. The size of the suite of accelerograms was 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.

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. 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. 4.1, 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.

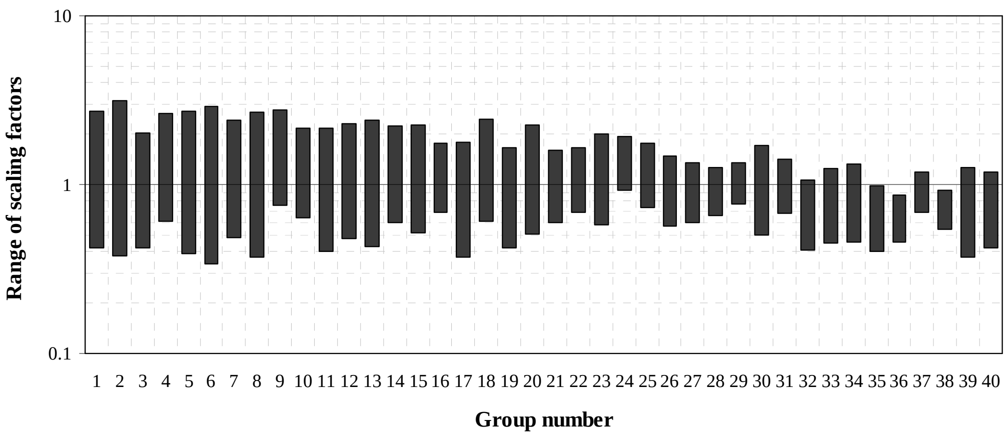
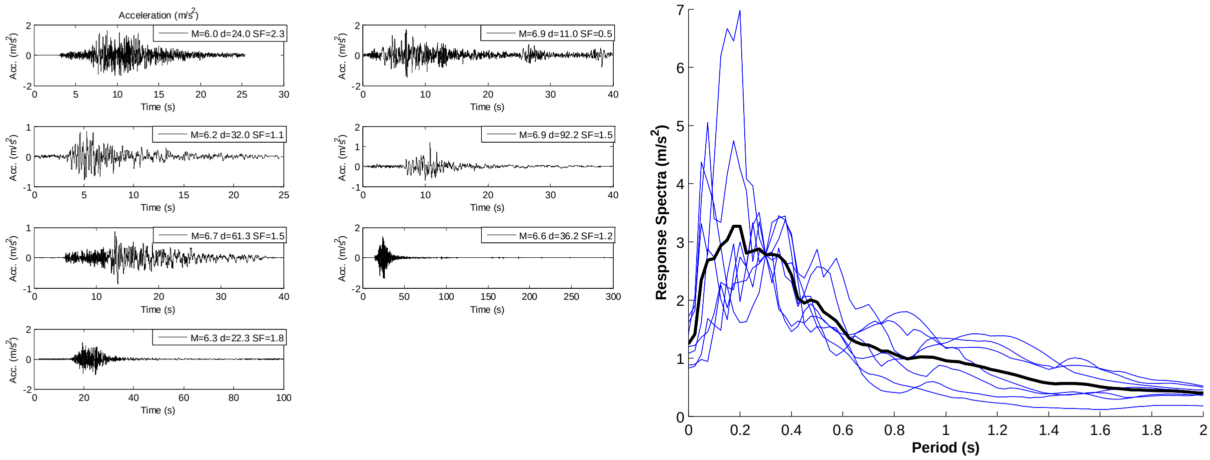


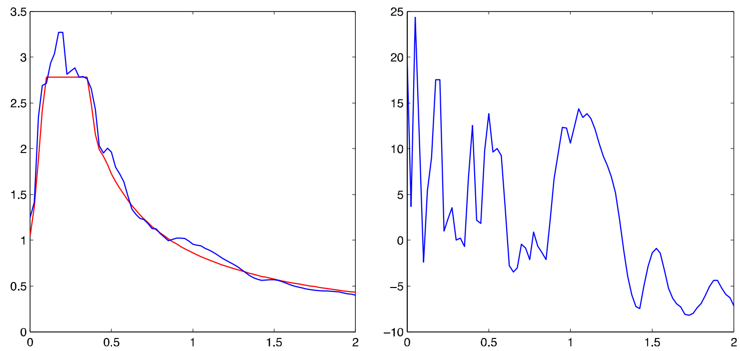
Figure 4.1. Variability of the scaling factors adopted for the set of 7 records of each group, to enforce spectrum-compatibility with the parent spectrum (logarithmic scale)

An example of the results obtained for the selection of accelerograms spectrum-compatible with the parent spectrum of group 15 is illustrated in the following figures. Specifically, Fig. 4.2a shows the selected records (scaled to the spectral value at the corner period T_c^*), whereas Fig. 4.2b illustrates the response spectra of each accelerogram together with the average response spectrum. For this case, the minimum and maximum scaling factors turned out to be 0.52 and 2.25, respectively, whereas the average scaling factor is equal to 1.39. Finally, Fig. 4.3 shows the enforced spectrum-compatibility, reporting a comparison between the average spectrum and the parent spectrum (Fig. 4.3a) and also the values of the percentage difference between the two spectra as a function of the structural period (Fig. 4.3b). It is noted that, for the case presented in the figure, spectrum-compatibility was enforced in the period interval 0.15-2 s. The average percentage difference turned out to be 6.30%, the maximum negative difference is 8.19%, the average spectral deviation is 0.077 and the maximum spectral deviation (referring to the response spectrum of each single record with respect to the parent spectrum) is 0.558.



a) **b)**

Figure 4.2. a) Group of 7 accelerograms spectrum-compatible, on average, with the parent spectrum of group 15. For each record, the legend reports the values of magnitude (M) and epicentral distance (d) of the event and the corresponding scaling factor (SF). b) Acceleration response spectra of the selected records (blue lines) and average spectrum (black line)



a) **b)**

Figure 4.3. a) Comparison between the average spectrum of the 7 records selected to be compatible with the parent spectrum of group 15 (blue line) and the reference spectrum itself (red line). b) Percentage difference between the two spectra.

5. LINEAR SCALING OF THE ACCELEROGRAMS

In the procedure describe above, the real accelerograms were only selected with the objective of being spectrum-compatible with the parent spectrum of each group. The spectrum-compatibility of the selected set of records with an arbitrary spectrum of the same group is not automatically guaranteed. Thus the latter was enforced for each group by further (linearly) scaling the records selected for the parent spectrum according to the procedure described as follows.

The mean spectrum of the accelerograms compatible with any spectrum of an arbitrary group was obtained by multiplying the mean spectrum of the records selected with respect to the parent spectrum of the same group times two scaling factors, SF1 and SF2. SF1 is the scaling factor needed to pass from the parent spectrum to the arbitrary spectrum of the same group, i.e. it is the ratio between the arbitrary spectrum and the parent spectrum at the spectral ordinate for which the records were scaled in ASCONA (i.e. corresponding either to a structural period T=0 or to 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 NTC08 only imposes the maximum negative difference to be within 10% in a given period interval, this additional scaling factor SF2 was defined as to guarantee that the maximum negative difference was exactly equal to 10%. 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 prescribed to be equal to one.

The range of variability of the product of the additional scaling factors SF1 and SF2 for each group is illustrated in Fig. 5.1, where the minimum and maximum values are shown.

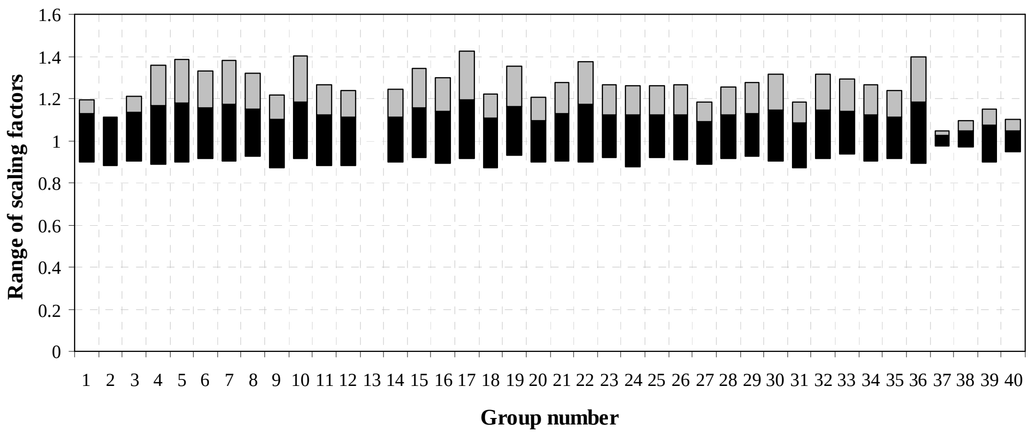


Figure 5.1. Variability (maximum and minimum values for each group) of the scaling factor SF1 (black) and of the product SF1·SF2 (grey) adopted to enforce spectrum-compatibility of the set of records with any arbitrary spectrum of the same group

6. SEISM-HOME WEB-GIS

The results of this work for the return period of 475 years 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 (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.

The software identifies the node of the reference grid adopted by NTC08 closest to the site of interest and supplies the associated set 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 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 located on a rocky site or, instead, it can be used as input for site response analyses in case of non-rocky sites.

7. 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 suites of real accelerograms for the time-history analysis 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 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 variety of reasons.

With the aim of real 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). Forty 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-derived methodology and a definition of similarity whose details were 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 a set of spectrum-compatible real accelerograms. Forty sets of 7 real accelerograms, spectrum-compatible, on average, with the corresponding parent spectrum were selected by means of the software ASCONA. Spectrum-compatibility, enforced according to the prescriptions of NTC08 for artificial records (or EC8-1), was achieved through a procedure based on a restricted linear scaling of the accelerograms. For each specific set 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 set of accelerograms and any individual spectrum belonging to a specific group.

Despite these operations, the final scaling factors, obtained as the product of the factors used in the selection for the parent spectrum and the two additional factors mentioned above, ended-up being within 0.31 and 3.5 for all the 40 groups. Also, the average final scaling factor for each group varied between 0.63 and 1.95 whereas, at the national level, the total scaling factors varied between 0.59 and 2.15, with an average value of 1.34. These ranges of scaling factors are a direct consequence of the limited scaling factors used by ASCONA and also of the rigorous criteria adopted for defining the groups of homogeneous spectra and the parent spectra of each group.

The results of the work are accessible through the SEISM-HOME (SElection of Input Strong-Motion for HOmogeneous MEsozones) Web-GIS application (www.eucentre.it/seismhome.html), from which it is possible to download, for any location on the national territory, a set of 7 real accelerograms spectrum-compatible, on average, with the acceleration response spectrum prescribed by the Italian building code for rock sites. SEISM-HOME constitutes a useful tool for practitioners and non-specialist users who need ready-to-use suites of real time-histories for seismic analyses of structures and geotechnical systems. In fact the downloaded accelerograms do not require any correction and can be directly used for applications without any further scaling. They have to be associated with soil type A of NTC08 since they were recorded on outcropping rocky sites.

Although the work was 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).

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