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Selection of spectrum- and seismo-compatible accelerograms for the Tuscany region in Central Italy

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ABSTRACT

This article illustrates the results of a study aimed at developing a methodology for the automatic identification of the seismic input at outcropping rock sites and flat topographic conditions necessary to carry out non-linear dynamic analysis of structures and geotechnical systems. The seismic input is provided in terms of a set of 7 natural accelerograms recorded on outcropping rock and satisfying the average spectral compatibility requirements prescribed by the Italian seismic code (NTC08).

The study focuses on the territory encompassing Tuscany region in Central Italy and it has been carried out for six return periods, which are 50, 75, 101, 475, 712 and 949 years. The procedure involved four main steps: (1) grouping of the response spectra with similar features; (2) definition of the reference response spectrum for each group; (3) selection of spectrum-compatible accelerograms using the reference response spectrum of each group; and (4) linear scaling of the accelerograms to satisfy the compatibility requirement with respect to other response spectra of the group. The last step is implemented through an interactive, user-friendly program named SCALCONA 2.0, which provides the seismic input in agreement with the site location and return period specified by the user. The program is freely available at the following web site: http://www.rete.toscana.it/sett/pta/sismica/01informazione/banchedati/input_sismici/progettazione/index.htm.

1. Introduction

Nonlinear, time-history analysis represents the most advanced method to assess the response of structures and geotechnical systems to seismic loading. Despite the computational and modelling improvements achieved during the last decade, the use of nonlinear dynamic analysis is still restricted in most circumstances to the solution of research problems. This despite certain typologies of structures would require the adoption of such type of analysis. On the other hand, the assessment of ground response is becoming increasing widespread in the engineering practice. For instance, local administrators require the use of ground response analysis for the purpose of microzonation of a territory. The seismic input for nonlinear dynamic analysis is represented by properly defined time series (e.g., accelerograms), which need to be defined consistently with the expected seismic hazard at the site of interest. The selection of time series is a fundamental activity also because the results of non-linear dynamic analyses of structures and geotechnical systems are strongly affected by the adopted input signal. However, the identification of a group of accelerograms complying with the seismic hazard expected at a site is a complicated matter. It requires skills in engineering seismology and usually it is very time consuming.

The current Italian building code (NTC08 [1]) and its Commentary [2], defines the seismic action in terms of acceleration response spectra specified over a grid of points covering the entire Italian territory. However, their use is limited to pseudo-static and dynamic linear analyses. To encourage the use of nonlinear dynamic analyses, several regional administrations in Italy have funded research projects aimed at defining, in their territory, appropriate sets of spectrum-compatible natural records.

This paper describes a methodology developed in the framework of one of these projects, specifically the project funded by Tuscany Region, aimed at identifying the seismic input in the Tuscan territory in agreement with the prescriptions of the Italian building code [1,2]. The seismic input has been defined, for each location within the Tuscany Region, in terms of sets of 7 natural accelerograms recorded on outcropping rock (i.e., soil category A as per NTC08 [1]), spectrum-compatible with the response spectrum of

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the Italian building code [1,2]. The number of accelerograms in a set has been restricted to 7 in accordance with the prescriptions of the NTC08 [1], which permits to use the mean results of the analysis instead of the most unfavourable ones if the analysis carries out at least 7 independent dynamic analyses. The study has been carried out considering the following 6 return periods: 50, 75, 101, 475, 712 and 949 years.

Like other building codes worldwide, NTC08 [1] allows the adoption of three categories of accelerograms, namely natural, artificial and synthetic records. Natural (or real) accelerograms are signals recorded during real seismic events and they are available from accredited strong-motion databases. Artificial accelerograms are signals generated using stochastic algorithms and possibly constrained to be spectrum-compatible with a target response spectrum. This category includes also hybrid accelerograms, which are records obtained by appropriately modifying real seismograms in such a way to enforce spectrum-compatibility. Finally, synthetic accelerograms are signals generated through a kinematic and/or dynamic model of the seismic source coupled with an elastodynamic idealization of the Earth crust from the source to the site of interest.

The superiority of natural accelerograms over artificial and synthetic records is widely recognized in the scientific community for both structural and geotechnical applications. Natural accelerograms have a correct duration in relation to the earthquake scenario, frequency content and correlation between the vertical and horizontal components of ground motion and between the phase and the amplitude of the record [3,4]. For these reasons, some buildings codes like the NTC08 [1], do not allow the use of artificial records for the assessment of local site effects, slope stability and other geotechnical applications.

According to NTC08 [1], recorded accelerograms to be used for dynamic analysis need to be representative of the seismicity of the site and adequately justified in terms of the characteristics of the seismic source, the geological and geotechnical conditions of the recording site, the expected magnitude, the distance from the source and the peak horizontal acceleration expected at the site. They may be linearly scaled to match the code-based elastic response spectrum in the range of periods of interest for the problem under examination.

These prescriptions represent the current practice in the selection of natural records, in which the accelerograms should reflect the magnitude, distance and other earthquake-related parameters that are believed to dominate the hazard at the site. However, some studies [5] demonstrated that, in some cases, compliance with the magnitude and the epicentral distance of the earthquake scenario, which might be named *seismo-compatibility*, is not a sufficient criterion to guarantee a correct estimation of the structural response and the *spectrum-compatibility* also needs to be enforced. For these reasons, the Commentary [2] of the NTC08 [1] recommends that the selection of natural accelerograms should take into account the compatibility of the average spectrum of the selected records with respect to the code-based elastic spectrum, within a prescribed range of periods. Specifically, the code states that no value of the average response spectrum computed from the selected accelerograms 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. The latter is calculated as the larger between the interval 0.15 s ÷ 2.0 s and 0.15 s ÷ 2*T*, for ultimate limit states, or 0.15 s ÷ 1.5*T*, for serviceability limit states, with *T* the elastic fundamental structural period. Furthermore, the Commentary [2] of the NTC08 [1] prescribes that, if the records are linearly scaled to satisfy spectrum-compatibility, the scaling factor must be limited in case of accelerograms originated from events characterized by small magnitude.

The identification of the seismic input for the Tuscan territory would require a selection of time series for each response spectrum defined by the NTC08 [1] within the region, for each of the 6 return periods considered in this study, resulting in over 5500 selections. Therefore, a procedure to reduce this computational effort has been developed. The methodology is based on the implementation of a number of steps which can be summarized as follows: (1) grouping of the response spectra in clusters with similar shape and amplitude; (2) definition of a reference response spectrum for each cluster; (3) selection of a set of 7 accelerograms spectrum-compatible with the reference response spectra only; and (4) linear scaling of the selected accelerograms so to satisfy the spectrum-compatibility at a specific site, where the code-based response spectrum is generally different from the reference spectrum, although it belongs to the same cluster. A Fortran code, named SCALCONA 2.0 (SCALing of COmpatible Natural Accelerograms, version 2.0) has been purposely developed and it is available at the following web site: http://www.rete.toscana.it/sett/pta/sismica/01informazione/banchedati/input_sismici/progettazione/index.htm. In a matter of few seconds, SCALCONA 2.0 yields the seismic input at a specific site and for a specific return period prescribed by the user.

The methodology is based on linearly scaling real accelerograms. However, big efforts have been made to obtain acceptable values for the adopted scaling factors. It is well known, in fact, that the duration of ground shaking and the frequency content of a seismogram are both strongly dependent on the magnitude–distance pair to which they are referred. Therefore, it is highly desirable to adopt scaling factors as close to unity as possible [4]. Formally, neither the NTC08 [1] nor the Eurocode 8 [6] prescribe specific bounds for the factors to be used to scale real accelerograms.

2. Definition of the target response spectra

2.1. Seismic input according to the Italian building code

The NTC08 [1] and its Commentary [2] define the seismic action in terms of elastic response spectra, using the results of the probabilistic seismic hazard assessment study for the Italian territory performed by the Italian Institute of Geophysics and Volcanology (INGV) in the framework of Project S1 [7]. The seismic hazard is estimated at 16921 nodes of a regular grid with a spatial distance among the nodes equal to 0.05°, corresponding to an average distance of about 5–6 km. For each node, the seismic hazard is represented in terms of peak ground acceleration (PGA) and 10 different spectral ordinates between 0.1 and 2 s of structural period. The uniform hazard response spectra are defined for rock outcropping conditions and flat topographic surface and for 9 return periods (i.e. 30, 50, 72, 101, 140, 201, 475, 975 and 2475 years). All the data can be retrieved at the following web site http://esse1.mi.ingv.it. Disaggregation of the seismic hazard for the PGA has also been performed by INGV. The results of the study [8] are available in terms of magnitude, *M*, epicentral distance, *d*, and number, ε, of (logarithmic) standard deviations by which the (logarithmic) ground motion deviates from the median value predicted by a specific ground motion prediction relation for a given *M*–*d* pair.

The elastic response spectra defined by NTC08 [1] are site-dependent and match the probabilistic uniform hazard spectra for 10751 nodes of the reference grid and the 9 return periods adopted for the seismic hazard study. Moreover, for the islands belonging to the Italian territory, with the exception of Sicily, Ischia, Procida and Capri, a unique spectral shape has been defined throughout the territory of each island. Each response spectrum is defined, in the absence of site effects, by an equation depending on

3 parameters: the horizontal peak 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 and for each return period, the three parameters have been obtained looking at the corresponding median results of the seismic hazard study performed by INGV. Specifically, the parameter a_g corresponds to the horizontal PGA, whereas F_0 and T_c^* have been obtained by minimizing (in the least-squares sense) the misfit between the uniform hazard spectra and the spectral shapes described by the equation of the NTC08 [1]. Response spectra for different return periods can be obtained through interpolation of the parameters associated with the 9 return periods considered by the seismic hazard, as prescribed by NTC08 [1].

The input data used for this study are the horizontal acceleration response spectra of NTC08 [1], defined for rock site conditions (soil category 'A') and flat topographic surface at the nodes of the reference grid located within the Tuscany region and at the islands of the Tuscan archipelago. Six return periods have been considered, namely 50, 75, 101, 475, 712 and 949 years.

Concerning the inland territory of Tuscany region, a total of 923 nodes have been used. They include the nodes located inside the regional boundaries plus those located within a distance of 0.1 degrees from the outermost ones (see Fig. 1). Fig. 2 shows the 475-year return period response spectra associated with the 923 considered nodes. The response spectra illustrated in Fig. 2a are anchored to the value of a_g specified by NTC08 [1] and show a large variability in spectral ordinates. To highlight the difference in spectral shape, Fig. 2b displays the same response spectra normalized to the value of a_g, revealing a small variability in spectral shape. This trend has been observed also for the 5 remaining return periods. In this situation, selecting a set of spectrum-compatible accelerograms for each response spectrum would result in an extremely time-consuming and unnecessary work in light of the fact that the shapes of the various spectra are similar. As a matter of fact, the total number of selections would be equal to 5538 (that is 923 nodes times 6 return periods). On the other hand, the variability of spectral accelerations cannot be overlooked, as shown in Fig. 2a, especially at large return periods. This suggested the need to identify, for each return period independently, a minimum number of spectral shapes that would be representative of the totality of the response spectra. Therefore, the first step of the study consisted in the identification of groups of spectra having similar shape and amplitudes, while the second step was the definition, for each group, of a reference response spectrum to be used for the selection of spectrum-compatible accelerograms (step 3).

This approach allowed to achieve a considerable reduction in the total number of records selections. The criteria adopted for both the identification of the groups of spectra and the definition of the reference response spectra are two key aspects of the proposed methodology. In fact, they control the scaling factors that are subsequently applied to the selected records (step 4 of the procedure) to enforce their compatibility with the response spectra of the group different from the reference spectrum, on which the selection is based. The first three steps have been applied only for 4 return periods out of 6, namely 75, 475, 712 and 949 years. In fact, since the three return periods from 50 to 101 years show a limited variability in the spectral ordinates, it was decided to consider only one return period (i.e. 75 years) representative of all three, in order to further reduce the total number of records selections.

Concerning the islands of the Tuscan archipelago, the NTC08 [1] defines a single spectral shape for each return period. The response spectra associated with the 6 return periods considered in this study are shown in Fig. 3. They have been directly used for the selection of the natural records, for a total of 6 selections.

2.2. Groups of response spectra

The grouping of the 923 response spectra in clusters with similar shape and amplitude has been performed independently for the return periods of 75, 475, 712 and 949 years. The groups have been defined according with the values assumed by the parameter T_c^* [1], the product $a_g F_0$ [1] and the average spectral deviation δ, as defined by [9]. The parameter δ is a quantitative

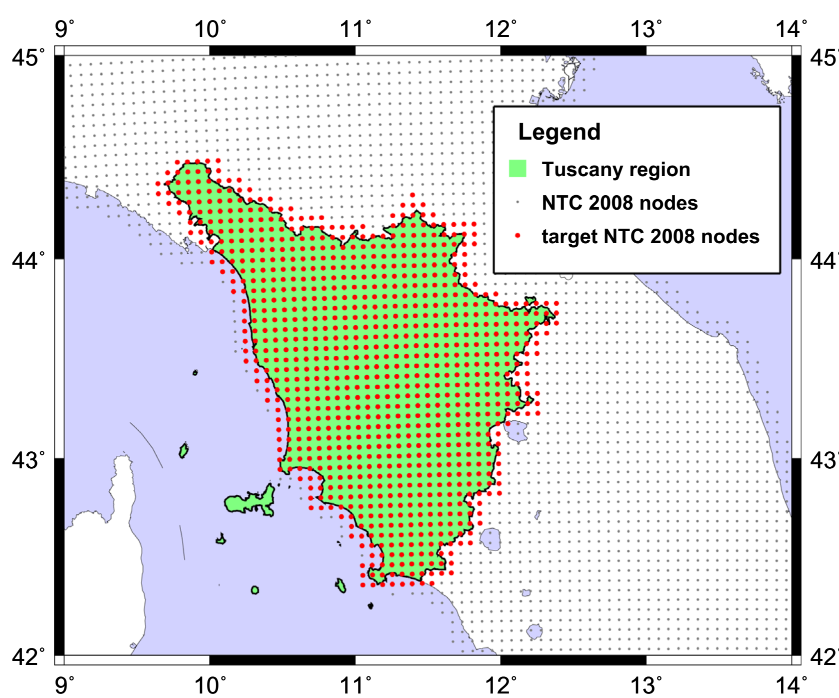

Fig. 1. Reference grid considered by NTC08 [1] (grey points). The 923 nodes of the reference grid used in this study are highlight in red. The territory of Tuscany Region is enhanced in green. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

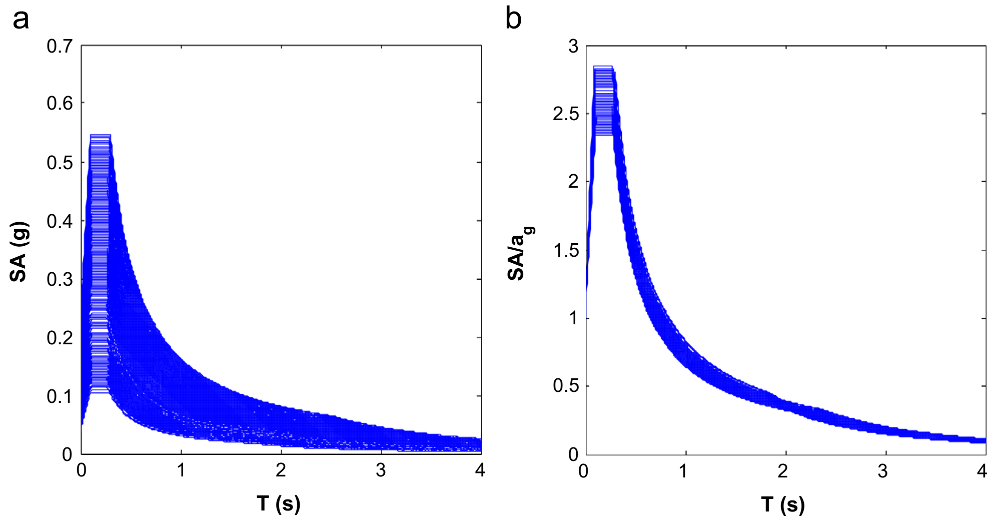

Fig. 2. Response spectra associated with the 923 nodes of the reference grid located within Tuscany region, associated with the return period of 475 years: (a) response spectra anchored to the value of a_g defined by NTC08 [1] and (b) response spectra normalized to the value of a_g.

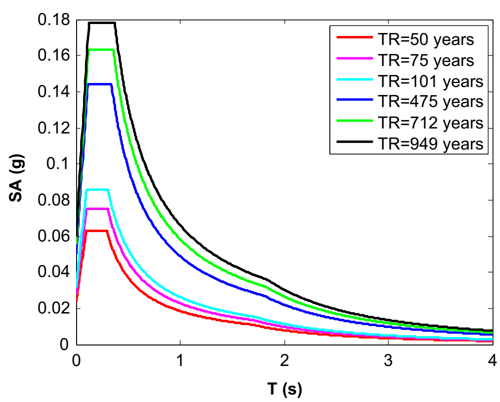

Fig. 3. Response spectra defined by NTC08 [1] for the islands of the Tuscan archipelago, for the 6 return periods (TR) considered in this study.

measure of the misfit between one arbitrary spectrum and a target spectrum, within a prescribed range of periods, whereas T_c^* controls the shape of the response spectrum and a_gF_0 affects the amplitudes. An iterative procedure has been developed, which starts from the identification of the spectrum (S_{max}) characterized by the maximum spectral acceleration (given by the product a_gF_0). The first group of response spectra is formed by S_{max} and by all the response spectra, S_k, simultaneously satisfying the following three conditions:

$$\delta = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\frac{S_k(T_i)-S_{max}(T_i)}{S_{max}(T_i)}\right)^2} < 0.2 \quad (1)$$

where N represents the number of (equally-spaced) structural periods, T_i, in which the spectrum is discretized (the sampling step adopted in this study is 0.005 s). The value of δ is computed in the range of periods assumed relevant for spectrum-compatibility (i.e., between 0.15 s and 2 s)

$$|T^*_{c,\,max} - T^*_{c,k}| \le 0.05 \quad (2)$$

where $T^*_{c,max}$ represents the value of T_c^* associated with the spectrum S_{max} and $T^*_{c,k}$ is the corresponding value of the spectrum S_k

$$(a_{g,k}F_{0,k}) > a_{g,\,max}(F_{0,\,max} - 0.5) \quad (3)$$

where $F_{0,max}$ and $a_{g,max}$ are, respectively, the values of F_0 and a_g associated with the spectrum S_{max}, whereas $F_{0,k}$ and $a_{g,k}$ are the corresponding values of the spectrum S_k.

Threshold values for the three quantities have been identified based on a trial and error procedure, attempting to find a proper balance between the number of groups, which cannot be too large to limit the number of records selections, and the need for the reference spectrum to be adequately representative of all the spectra of the group, so to ensure that the selected records are compatible with all the spectra in the group. After having defined the first group, characterized by m spectra, the second group is determined using the same criteria described above, excluding from the analysis the response spectra belonging to the first group (i.e. considering the remaining 923-m response spectra). The procedure is then repeated until the completion of all spectra. To avoid the formation of groups constituted by a small number of spectra, or in the extreme case by a single spectrum, the minimum number of spectra required to form a group is set equal to 4. Therefore, if $m < 4$, a group is not formed, and the spectra of this "*not-formed*" group are included in the previous group.

The application of this procedure to the inland territory of Tuscany region allowed the identification of 8 groups for the return period of 75 years and 9 groups for the return periods of 475, 712 and 949 years. The geographical distribution of the groups is shown in Fig. 4. The figure reveals that the position of the groups reflects the spatial pattern of the values of PGA of the probabilistic hazard maps associated with each return period (http://esse1.mi.ingv.it).

2.3. Definition of the reference response spectra

The choice of the reference response spectrum for each group plays a crucial role in the selection of spectrum-compatible natural accelerograms. In fact, according with the proposed procedure, the selection of the accelerograms for the inland territory of Tuscany region has to be carried out only for the reference response spectrum of each group. The spectrum-compatibility requirement for the remaining response spectra of the group is subsequently achieved by linearly scaling the selected set of accelerograms. Therefore, the reference response spectrum should be as much as possible representative of the characteristics of all the spectral shapes belonging to the same group.

It has been defined as the spectrum of the group closest (in terms of δ) to the average spectrum of the group itself. The choice of considering one spectrum of the group, instead of the average response spectrum, is due to the advantage of analytically identifying it by the three parameters a_g, F_0 and T_c^*. The main characteristics

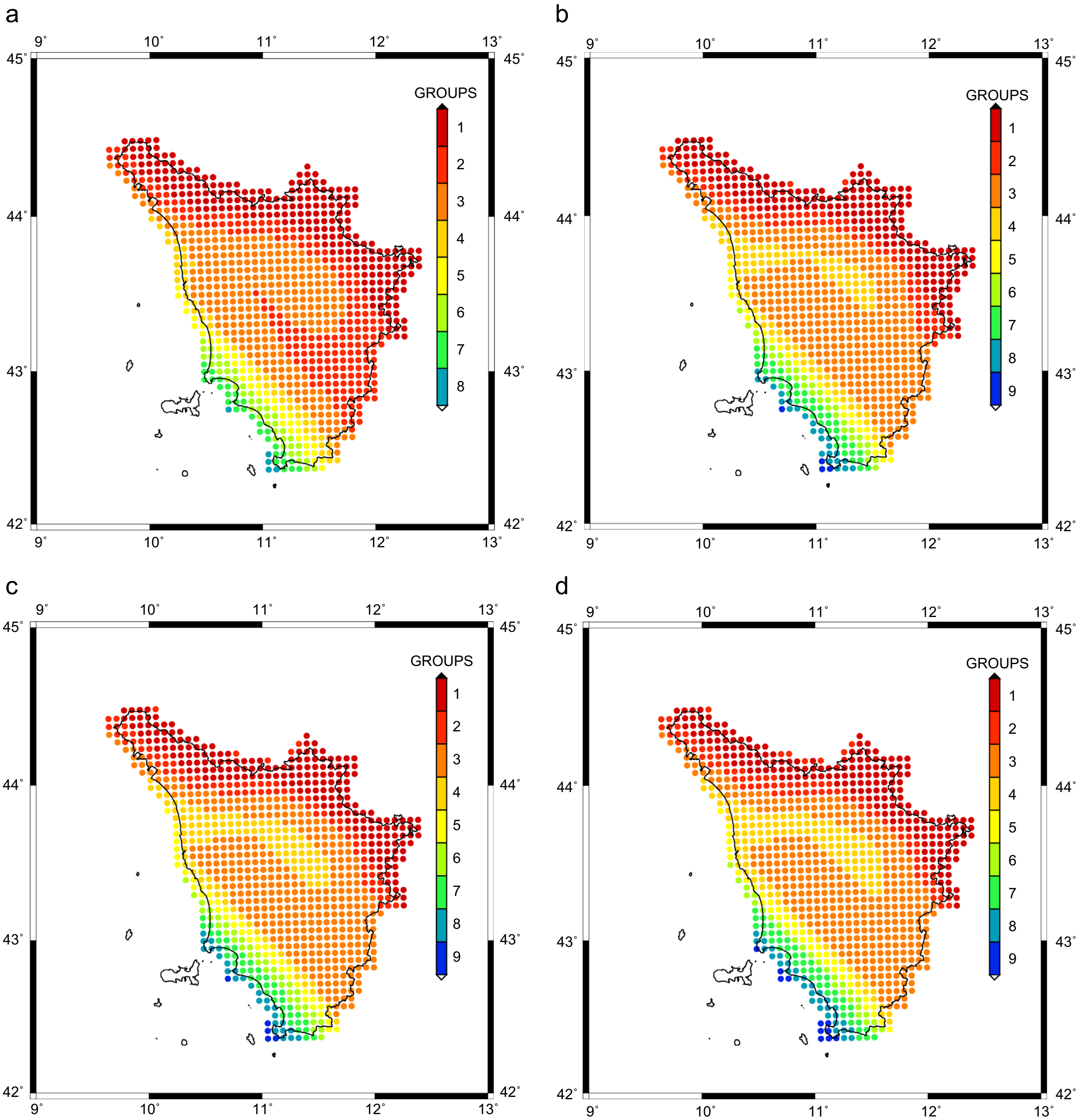

Fig. 4. Geographical distribution of the groups of response spectra identified for the return period of (a) 75 years, (b) 475 years, (c) 712 years, and (d) 949 years. The numbering corresponds to the order adopted in the definition of the groups, which starts from the one with the largest spectral ordinate.

of the 35 identified reference response spectra are given in Table 1, while the reference response spectra for the return period of 475 years are shown in Fig. 5.

3. Selection of natural accelerograms

The selection of natural accelerograms has been performed using the computer program ASCONA (Automated Selection of COmpatible Natural Accelerograms [10]). The code provides a set of n natural recordings satisfying several criteria, with the additional requirement of compatibility with a target spectrum, in a specified range of periods. Recordings are taken from an internal database composed by accelerograms recorded on outcropping rock. They come from accredited international accelerometric databanks, 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 criteria that must be fulfilled by the selected recordings can be subdivided between user pre-defined requisites and constraints enforced by the code.

Table 1
Main characteristics of the reference response spectra for each group and return period (RT): identification number (ID), longitude (Lon) and latitude (Lat) of the node of the reference grid; a_g, F_0 and T_C^* parameters (NTC08 [1]).

RT (years)	Group	ID	Lon (°E)	Lat (°N)	a_g (g)	F_0	T_C^* (s)
75	**1**	18505	11.262	44.114	0.097	2.42	0.27
	2	19161	10.574	43.949	0.075	2.47	0.27
	3	19381	10.438	43.895	0.064	2.54	0.26
	4	25167	11.452	42.617	0.051	2.55	0.25
	5	24051	11.034	42.859	0.042	2.64	0.23
	6	24717	11.040	42.709	0.034	2.69	0.22
	7	25383	11.046	42.559	0.029	2.72	0.21
	8	26272	11.122	42.360	0.025	2.72	0.17
475	**1**	18728	11.334	44.065	0.205	2.38	0.29
	2	20064	11.621	43.770	0.173	2.38	0.29
	3	24280	11.513	42.818	0.139	2.48	0.28
	4	20270	10.517	43.697	0.117	2.48	0.28
	5	24498	11.242	42.763	0.086	2.63	0.28
	6	25833	11.457	42.467	0.067	2.77	0.29
	7	25608	11.252	42.513	0.054	2.79	0.29
	8	25160	10.976	42.607	0.045	2.80	0.29
	9	26049	11.052	42.409	0.039	2.77	0.29
712	**1**	18729	11.403	44.066	0.233	2.43	0.30
	2	18267	10.147	44.138	0.205	2.41	0.29
	3	22505	11.569	43.219	0.157	2.51	0.29
	4	19825	10.443	43.795	0.141	2.37	0.29
	5	24944	11.382	42.666	0.103	2.61	0.29
	6	24942	11.246	42.663	0.074	2.80	0.30
	7	24717	11.040	42.709	0.060	2.82	0.30
	8	25383	11.046	42.559	0.050	2.82	0.30
	9	26049	11.052	42.409	0.043	2.80	0.30
949	**1**	18729	11.403	44.066	0.255	2.45	0.30
	2	18267	10.147	44.138	0.227	2.42	0.29
	3	21841	11.702	43.371	0.177	2.45	0.29
	4	19826	10.512	43.797	0.157	2.39	0.29
	5	25835	11.592	42.469	0.115	2.60	0.29
	6	24497	11.174	42.762	0.088	2.75	0.29
	7	24049	10.898	42.856	0.069	2.85	0.30
	8	23601	10.621	42.949	0.058	2.84	0.30
	9	25827	11.050	42.459	0.048	2.84	0.31

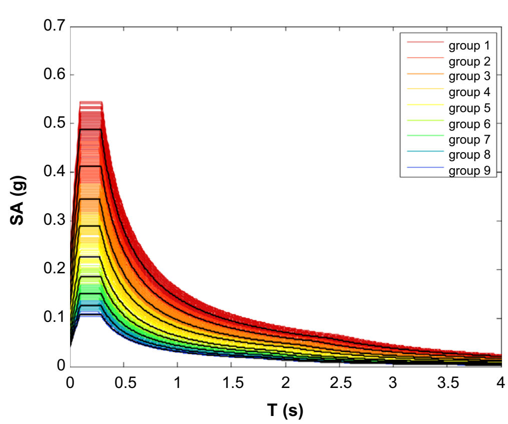

Fig. 5. Response spectra associated with the 923 nodes of the reference grid (coloured lines) and reference response spectra (black lines). The considered return period is 475 years. Each colour corresponds to a group. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

User pre-defined requisites include the number of records to be included in the set (n), the target response spectrum, the structural period at which to scale the accelerograms, the maximum and minimum values of the scaling factor, the maximum acceptable value of the spectral deviation δ [9], the range of magnitude and epicentral distance (i.e., seismological constraints), the interval of structural periods over which to evaluate spectrum-compatibility and the maximum value of the negative difference between the average spectrum of the selected records and the target spectrum. The first operation performed by ASCONA [10] is the linear scaling of the accelerograms at the spectral acceleration of the target spectrum corresponding to the structural period specified by the user. This is done in order to ensure a better match between the average response spectrum of the selected records and the target spectrum. A large number of sets of n accelerograms satisfying the requirements imposed by the user are then generated through a random, automatic process based on Monte Carlo simulation.

Two additional constraints are enforced by ASCONA [10] itself to avoid having in the same set two ground motion components of the same recording and accelerograms recorded during the same seismic sequence (i.e., main event, foreshocks or aftershocks). This is done to prevent the use of records that are strongly correlated. The identification of the sets of records is carried out with reference to a single horizontal ground motion component. Alternatively, other criteria could have been chosen like the geometric mean of the two horizontal components.

Next, ASCONA [10] computes the average response spectrum of the selected records and assess whether it complies with the spectrum-compatibility criterion prescribed by NTC08 [1]. Among the sets of n accelerograms satisfying the spectrum-compatibility requirement, the set selected by ASCONA [10] is that characterized by the minimum average misfit between the mean response spectrum of the recordings and the target spectrum.

In this study, we have prescribed n equal to 7 according to NTC08 [1]. Also in accordance to NTC08 [1], the spectrum-compatibility has been assessed by verifying that the negative misfit between the average response spectrum of the selected accelerograms and the target response spectrum does not exceed the threshold of 10% within the range of periods 0.15–2.0 s. The 35 reference response spectra identified for the inland territory of Tuscany region (whose characteristics are listed in Table 1) plus the 6 response spectra defined for the islands of Tuscan archipelago (shown in Fig. 3) have been used as target response spectra.

Two options have been considered for the structural period at which scale the accelerograms: as a first trial, the time series have been scaled at the spectral acceleration associated with a period equal to zero (i.e., the value of a_g); when the goodness-of-fit between the average spectrum of the selected records and the target spectrum was not satisfactory (i.e., the average misfit between the mean response spectrum of the recordings and the target spectrum was larger than 10%), the spectral acceleration at the corner period T_C^* [1] has been used. Concerning the range of magnitude and epicentral distance, reference was made to the disaggregation of the Italian territory performed by INGV [8]. Specifically, the results obtained by [8] have been used as a lower bound of the ranges of magnitude and distance. In fact, the disaggregation has been conducted by [8] only with respect to a_g. However, the earthquake scenario varies with the structural period chosen for the disaggregation [11], and in general more than one single scenario controls the hazard at a site, especially if the latter is influenced by more than one source. Therefore, to proper identify the intervals of magnitude and distance that contribute the most to the definition of the uniform hazard spectrum, it would be necessary to perform disaggregation for values of spectral acceleration corresponding to a sufficiently large range of periods. The size of the range depends on the shape of the response spectrum and thus on the regional seismogenic and attenuation characteristics [12]. In particular, with the increase of the structural period, the magnitude-distance pair that mostly affects the hazard is represented by an event of larger magnitude and greater epicentral distance.

As an example, Fig. 6 shows the set of 7 accelerograms selected for the group 1 associated with the return period of 475 years. The response spectra associated to the selected accelerograms and their average spectrum are shown in Fig. 7, along with the reference response spectrum.

4. SCALCONA 2.0

The last step of the adopted methodology consists in a linear scaling of the selected records in order to enforce the spectrum-compatibility for each response spectrum prescribed by NTC08 [1] within the Tuscany territory. A user-friendly computer program has been purposely developed to scale the accelerograms selected for the reference response spectra (step 3 of the procedure) and to provide a set of 7 spectrum-compatible natural accelerograms at any site of the Tuscany territory, for the 6 return periods (i.e. 50, 75, 101, 475, 712 and 949 years) considered in this study. The code is named SCALCONA 2.0 (SCALing of COmpatible Natural Accelerograms – version 2.0) and it can be freely downloaded from the following web site: http://www.rete.toscana.it/sett/pta/sismica/01informazione/banchedati/input_sismici/progettazione/index.htm. The first version of the program was a prototype limited to the Tuscan territories of Lunigiana, Garfagnana, Mugello, Val di Sieve and Montagna Fiorentina. Further details can be found in [13]. SCALCONA 2.0 allows the user to specify the site location and the return period of interest and it yields in few seconds the seismic input compatible with NTC08 [1] and associated Commentary [2], both in terms of spectrum-compatible accelerograms and response spectra.

The site location can be specified alternatively in terms of geographical coordinates (decimal degrees) or by the name of the municipality. Only the 6 return periods considered in this study are allowed. Depending on the site location, the program distinguishes whether the site is located inland or on an island of the Tuscan archipelago. For an island site, the code directly provides the set of 7 natural accelerograms selected for the response spectrum of Fig. 3 associated with the return period of interest. Instead, for an inland site, more calculations are actually carried

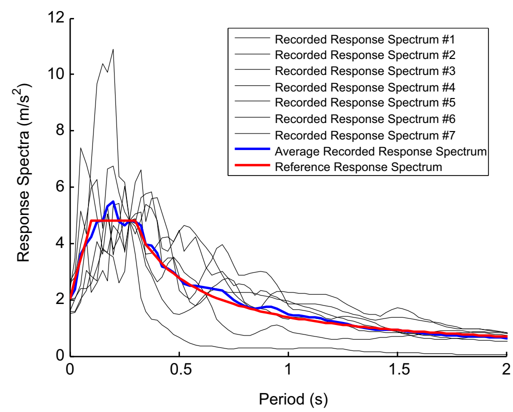

Fig. 7. Response spectra of the 7 accelerograms selected for the group 1 associated with the return period of 475 years (black lines) along with the mean spectrum (blue line) and the reference spectrum (red line). The average misfit between the spectral ordinates of the mean spectrum and the reference spectrum in the range of periods [0.15–2.0 s] is 6.07%, while the maximum negative misfit in the same range of periods is 9.46%. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

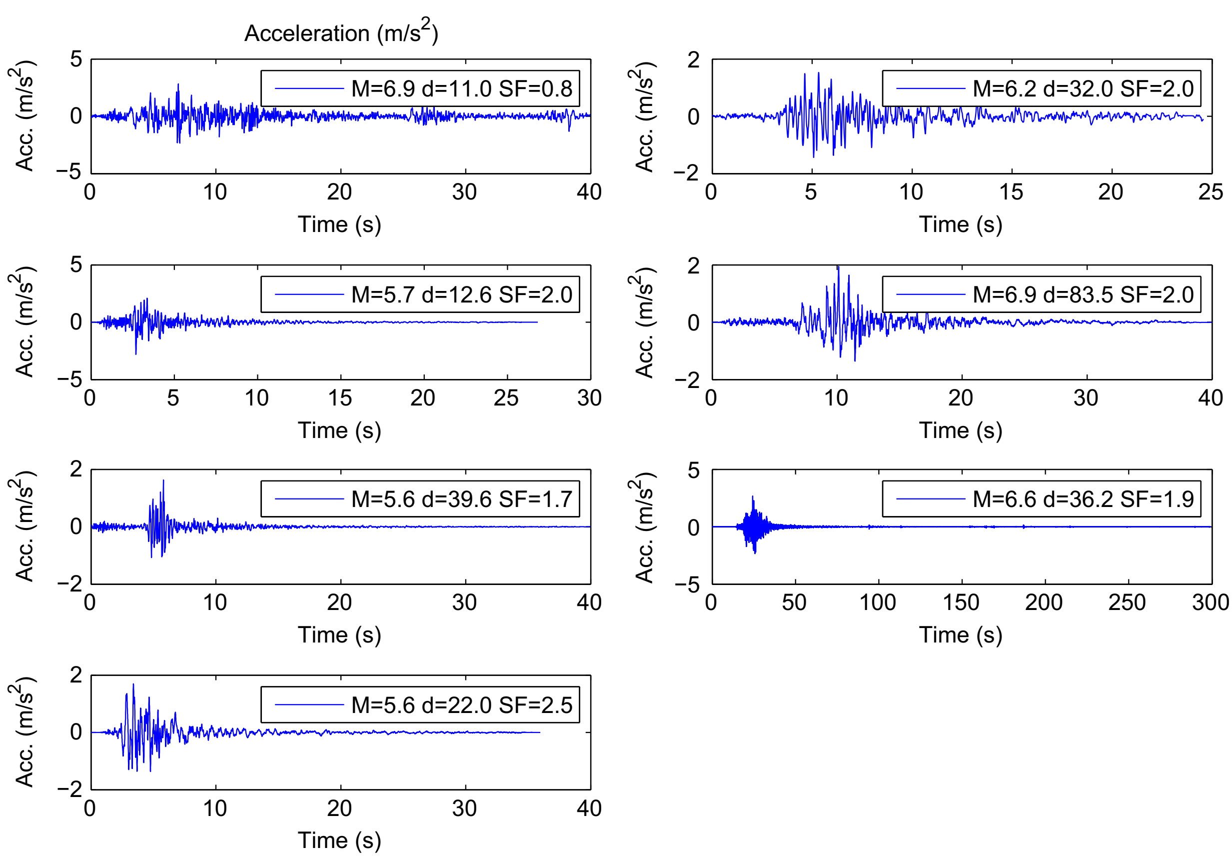

Fig. 6. Group of 7 accelerograms (horizontal components) satisfying the average spectrum-compatibility criterion with respect to the reference spectrum of the group 1 associated with the return period of 475 years. Above each accelerogram, the scaling factor (SF) between the spectral ordinate at $T=T_C^*$ of the reference spectrum and the corresponding value of the recorded response spectrum is also reported.

out, as shown in the following example related to the city of Florence (43.769N, 11.257E) and the return period of 475 years.

At first, the program identifies the node of the reference grid (NTC08 [1]) closest to the site of interest and then: (a) calculates the elastic response spectrum, S_{site}, prescribed by NTC08 [1] for the identified node and the selected return period; and (b) seeks for the reference group in order to retrieve the response spectra and the accelerograms selected for its reference spectrum, S_{ref}. If the return period of interest is 50 or 101 years, the group is searched among the groups associated with the return period of 75 years. In case of the example, the node closest to the city of Florence is the node 20059 (NTC08 [1]), which is characterized by a_g=0.1302 g, F_0=2.4, T_c^*=0.3 s and belongs to group 3. Since the selection of accelerograms has been carried out only for the reference spectrum of the group, the spectrum-compatibility of the selected set of records with the response spectrum prescribed for Florence is not automatically guaranteed. In fact, the negative misfit between the average response spectrum of the selected accelerograms and S_{site} can exceed the threshold of 10% [1].

SCALCONA 2.0 enforces the spectrum-compatibility by linearly scaling the selected records. Two scaling factors are considered, *SF1* and *SF2*. *SF1* is the scaling factor needed to pass from S_{ref} to S_{site}. It is computed as the ratio between S_{site} and S_{ref} at the spectral period used to scale the accelerograms in ASCONA [10] (i.e., $T=0$ or $T=T_c^*$). In case of Florence, $T=T_c^*$ and *SF1*=0.91. Since the shape of S_{site} is similar to that of S_{ref}, but not identical, in most cases the application of *SF1* alone is not sufficient to guarantee the spectrum-compatibility, especially at long periods. In these cases, an additional scaling factor, *SF2*, is used, which has specifically the purpose to enforce the spectrum-compatibility. *SF2* is computed by identifying the spectral period (within the period interval used to evaluate spectrum-compatibility, i.e. between 0.15 and 2.0 s) where the negative misfit is maximum and imposing a maximum negative difference, between the average response spectrum scaled by *SF1* and S_{site}, equal to 9.999%. It is important to notice that the values of *SF2* are very close to unity and therefore the ordinates of the average response spectrum are not significantly modified by the application of this second scaling factor. In the analyzed case, *SF2*=1.06 (computed at $T=1.4$ s). Both the response spectra and the set of 7 accelerograms selected for S_{ref} are then multiplied by the total scaling factor *SF*=*SF1***SF2*, thus allowing SCALCONA 2.0 to provide a seismic input compatible with NTC08 [1]. Of course, if the spectrum-compatibility is verified with *SF1* alone, *SF2* is set equal to 1. Instead, when the geographical coordinates of the node closest to the desired site coincide with those of the reference response spectrum of the group (Table 1) and, additionally, the return period of interest is 75, 475, 712 or 949 years, obviously it will be *SF*=1.

Due to (a) the criteria adopted for both the identification of the groups of spectra and the definition of the reference response spectra and (b) the threshold scaling factors enforced in ASCONA [10], the scaling factors applied by SCALCONA 2.0 to the original accelerograms vary between 0.28 and 3.74. The range of variation as a function of the return period is shown in Table 2. The number of cases in which the scaling factor ranges between 2/3 and 1.5 is also reported, showing that for the short return periods more than 50% of the scaling factors are close to unity. The percentage decreases as the return period increases, reflecting the difficulty in selecting spectrum-compatible records with low scaling factors for the longer return periods. This can be related to the lack of recordings on rock characterized by large values of PGA.

Summing up, SCALCONA 2.0 allows the user to specify the site location and the return period of interest. Then, the code properly scales the results of the selection of accelerograms previously carried out by the authors using ASCONA [10], to directly provide the seismic input required in non-linear dynamic analyses of structures and geotechnical systems, with no need of any further processing.

Table 2
Minimum, maximum and mean value of the scaling factor (SF) applied by SCALCONA 2.0 to the original accelerograms, for each return period (RT). The percentage of cases with SF between 2/3 and 1.5 is also reported.

RT (years)	*SF*			% of cases with *SF* between 2/3 and 1.5
	Min	Max	Mean	
50	0.28	1.87	0.83	59
75	0.29	2.27	0.99	69
101	0.35	2.59	1.12	63
475	0.36	2.91	1.33	48
712	0.40	3.33	1.53	35
949	0.37	3.74	1.71	30

5. Conclusions

This paper proposes a methodology for the identification of the seismic input, described in terms of spectrum-compatible real accelerograms, at an extended territory. The final product of the study is represented by a user-friendly software, called SCALCONA 2.0, which provides the time series to be used in non-linear dynamic analyses of structures and geotechnical systems in Tuscany region in Central Italy. The purpose is to help non-specialists users in obtaining the seismic input, avoiding the need to directly carry out the selection of spectrum-compatible records, which is a non-trivial operation. In fact, it requires the availability of accredited strong-motion databases and it is time-consuming, especially when the selection has to be carried out at several locations within an extended territory and for different return periods.

The adopted methodology involves four main steps. The first step consists in grouping the response spectra with similar shapes, followed by the identification of a reference response spectrum for each group. The third step concerns the selection of spectrum-compatible real records with respect to the reference response spectrum of each group. The final step consists in linearly scaling the selected accelerograms, to guarantee the spectrum-compatibility with respect to other spectra of the group different from the reference response spectrum. This step is implemented internally by SCALCONA 2.0, which provides in few seconds the seismic input required by the user for a specified site location and return period. The seismic input is represented by a set of 7 natural accelerograms, along with their response spectra (5% damping), satisfying the spectrum-compatibility requirements prescribed by NTC08 [1] and associated Commentary [2]. The procedure has been set for 6 return periods, namely 50, 75, 101, 475, 712 and 949 years.

Although purposely developed for the territory of Tuscany region, the proposed methodology is general and it could be easily applied to other regions of Italy or other Countries, or even to a national territory (see [14] for the 475-years return period).

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