Ground Motion Record Selection Based on Broadband Spectral Compatibility

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The increasing interest in performance-based earthquake engineering has promoted research on the improvement of hazard-consistent seismic input definition and on advanced criteria for strong motion record selection to perform nonlinear time history analyses. Within the ongoing research activities to improve the representation of seismic actions and to develop tools as a support for engineering practice, this study addresses the selection of displacement-spectrum-compatible real ground motions, with special reference to Italy. This involved (1) the definition of specific target displacement spectra for Italian sites, constrained—both at long and short periods—by results of probabilistic seismic hazard analyses; (2) the compilation of a high-quality strong ground motion database; and (3) the development of a software tool for computer-aided displacement-based record selection. Application examples show that sets of unscaled, or lightly scaled, accelerograms with limited record-to-record spectral variability can also easily be obtained when a broadband spectral compatibility is required. [DOI: 10.1193/052312EQS197M]

INTRODUCTION

Performance-based approaches to seismic design and assessment, together with the ever-increasing availability of high-quality digital strong ground motion (GM) records, have raised research interest in improved criteria for the selection and scaling of waveforms to perform nonlinear dynamic analyses of structures.

For example, the ASCE/SEI 7-10 Standard (ASCE 2010), recommends that input ground motions for linear and nonlinear seismic analyses of structures shall be selected from actual recorded events "having magnitude, fault distance, and source mechanism that are consistent with those that control the maximum considered earthquake . . . . The ground motions shall be scaled such that the average value of the 5% damped response spectra for the suite of motions is not less than the design response spectrum for the site for periods ranging from 0.2 T to 1.5 T where T is the fundamental period of the structure in the fundamental mode for the direction of response being analyzed." The latter requirement recognizes that spectral compatibility should be enforced in a period range large enough to account for the sensitivity of nonlinear structural response to spectral ordinates at periods larger than the fundamental one, and to the higher modes' contribution at shorter periods. Particularly, the importance to constrain not only the spectral ordinate at the fundamental period of the structure, but the

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response spectral shape itself in a sufficiently large period range has been remarked by several authors (e.g., Baker and Cornell 2006, Haselton et al. 2009, Bojorquez and Iervolino 2011). Particularly, ground motion selection based on conditional spectra—that is, the conditional mean spectrum (Baker 2011) and the conditional spectrum (Jayaram et al. 2011)—has gained a growing relevance, although its applicability is still disputed for cases where large nonlinear effects and/or participation of higher modes in structural response may affect the choice of the conditioning period. Recently, the U.S. National Institute of Standards and Technology (NIST) funded a project to improve guidance to the earthquake engineering profession for selecting and scaling earthquake ground motions for the purpose of nonlinear response-history analyses in performance-based seismic engineering (NIST 2011).

Requirement for broadband compatibility, including long periods, may be especially important for specific classes of earthquake engineering applications among which: (1) seismic design approaches relying on a proper definition of spectral displacements at long periods, such as the direct displacement-based design method (e.g., Priestley et al. 2007), (2) dynamic analyses involving nonlinear soil-structure interaction effects, such as for the seismic response of underground structures, or for soil stability assessment. In the latter applications, the response is not dominated by the inertial properties of the structure around its natural vibration periods, but by the spectral characteristics of the ground motion itself in a wide frequency range. Furthermore, results of numerical simulations of the dynamic response may be significantly affected by the long-period noise of input ground motion, especially when dealing with records from analog instruments, with potential non-physical drifts of the velocity and displacement time series (e.g., Foti and Paolucci 2012). As a matter of fact, long-period noise on recorded ground motions has traditionally limited the reliability of response spectral ordinates for structural periods up to a maximum of 3–4 s.

To address these limitations, in the last decade a significant effort has been made toward a better characterization of long-period ground motion for seismic design (Faccioli et al. 2004), by taking advantage of the ever-increasing number of high quality digital GM records from worldwide earthquakes. A common objection to the determination of long-period spectral ordinates from digital GM records, is that appropriate displacement traces cannot be generally retrieved upon simple double integration of the uncorrected accelerations and that high-pass filtering is typically required. An answer to this objection has been given by a growing number of recent studies, starting with Boore (2001), which have shown that long-period spectral ordinates of digital accelerograms depend only weakly on the adopted baseline correction procedures, in opposition to the dramatic effect of those operations on the displacement waveforms. Even more pervasive, with respect to this issue, is the evidence, pointed out by Wang et al. (2007) and by Paolucci et al. (2008), that spectral ordinates, calculated from co-located GM and broadband records, coincide up to at least 10 s.

Advances to assess the reliability of long-period response spectral ordinates have supported the calibration of up-to-date empirical ground motion prediction equations (GMPEs) extending to long periods (Cauzzi and Faccioli 2008), the improved quantification of site effects (Figini and Paolucci 2009), and the formulation of new seismic hazard maps at long periods in Italy (Faccioli and Villani 2009).

Research activities for an improved determination of seismic input at long periods continued recently with a collaboration among the authors of this study, to combine, on one side, the expertise on long-period ground motion characterization with earthquake record selection for engineering applications on the other side. The starting point was a software tool, REXEL (Iervolino et al. 2010), which enables the selection of suites of multi-component ground motions compatible with either code-based or user-defined pseudo-acceleration response spectra. Spectrum compatibility will be referred to hereafter as the condition for which the average response spectrum of the selected set of records approaches the target spectrum within a prescribed tolerance level, and scatter of individual spectra with respect to the target spectrum is limited as much as possible[1]. To achieve the goal of spectral compatibility at long periods, two basic ingredients were introduced: (1) a target spectrum suitable up to long periods, constrained by results of short-period and long-period probabilistic seismic hazard analyses (PSHA) in Italy; (2) a strong GM database consisting of high-quality accelerograms, covering, in a way as homogeneous as possible, the magnitude, distance range, and site conditions of interest for Italian sites. In fact, the psuedo-spectral rule, that is, the simple multiplication of the acceleration spectrum, S_a, by $(T/2\pi)^2$, where T is the vibration period, to obtain displacement spectral ordinates, S_d, may not provide accurate results if the target spectrum has not been properly constrained at long periods. On the other hand, the use of accelerograms with an insufficient signal-to-noise ratio at long periods precludes the success of the search.

The first part of this paper illustrates the substantial differences among several seismic regulations, in terms of elastic design spectra at long periods, which may have consequences when such spectra are used as targets for GM selection. Afterward, the following topics are addressed: a hazard-based target displacement spectrum for Italian sites; a specifically developed GM database; and the REXEL-DISP software, in which the previous two ingredients are implemented together with a search engine. Finally, the application examples provide a key to the second objective of this research, that is, showing that the combination of an appropriate target spectrum both at short and long periods, together with a high-quality database, allows one to achieve consistent spectrum compatibility of selected GM records in a broad period range, either in terms of accelerations or displacements. Although such results are obtained for the Italian context, the approach presented in this paper has a general value and may easily be applied to other parts of the world, provided that PSHA studies at long periods are available.

RESPONSE SPECTRA AT LONG PERIODS

DISPLACEMENT SPECTRA FROM INTERNATIONAL SEISMIC CODES

This section reviews the specifications of seismic actions at long periods according to four international seismic codes: Eurocode, or EC8 (CEN 2004); the Italian Building code, or NTC08 (CS.LL.PP. 2008); the U.S. seismic provisions ASCE 7-10 (ASCE 2010), and the New Zealand seismic standards, or NZS 1170 (NZS 2004). Results will be compared in terms of displacement spectra, which are more suitable to highlight differences at long periods. For all these codes, displacement spectra are defined (at least up to a certain corner period) by

[1] This is because two different sets, equivalent in terms of average spectral fit, can still provide very different results in the estimate of seismic response, depending on the record-to-record variability with respect to the target spectrum (e.g., Iervolino et al. 2010).

converting the corresponding elastic acceleration design spectra through the pseudo-spectral relationship mentioned in the introduction.

The key feature that controls the shape and amplitude of the spectrum at long periods is the corner period, T_D, denoting the beginning of the maximum spectral displacement plateau (*MSD*; see Figure 1), which was determined in the previously mentioned codes according to different criteria. In particular, in NZS 1170, a constant value $T_D = 3.0\,\text{s}$ is defined, regardless of the seismic hazard associated with the selected site. Similar to NZS 1170, EC8 defines a constant value of T_D, but an indirect dependence on magnitude is introduced by assigning $T_D = 2.0\,\text{s}$ for the Type 1 spectrum (i.e., seismic hazard associated with earthquakes of surface-wave magnitude $M_S \geq 5.5$) and $T_D = 1.2\,\text{s}$ for Type 2 ($M_S < 5.5$). In NTC08, the corner period T_D (equal to $a_g/g \cdot 4 + 1.6$) is made dependent on the maximum ground acceleration at rock (a_g), the latter being related to the return period under consideration through the PSHA results (Montaldo et al. 2007). Finally, the ASCE 7-10 guidelines define the long-period branch of the response spectra by providing maps of the long-period transition period T_L (equivalent to T_D), as illustrated in Figure 1b, as a function of the modal magnitude (M_d) of each region, determined by *disaggregation* of PSHA for probability of exceedence of 2% in 50 years at $T = 2\,\text{s}$ (Crouse et al. 2006). Mapped values of T_L for the conterminous United States show a large variability, ranging from 4 s (for M_d in the 6.0–6.5 range) up to 16 s (M_d in the 8.0–8.5 range). As a final remark, it is worth noting that in all these codes, T_D (or T_L) does not depend on site conditions.

With regard to the features of the displacement spectrum for periods beyond T_D (or T_L), while NZS 1170 and ASCE 7-10 assume the spectral displacement to be constant with period (see Figure 1b), understanding that beyond T_D the spectral ordinate approaches the peak ground displacement, EC8 and NTC08 limit the application of the pseudo-spectral rule up to a corner period, T_E, ranging between 4.5 s and 6.0 s, as a function of the ground category. Beyond T_E, a linear decreasing branch of the spectrum is defined, up to the control period $T_F = 10\,\text{s}$, beyond which the spectral displacement tends to have a constant value (d_{max}, as depicted in Figure 1a). The latter is computed in both EC8 and NTC08 by the following relationship:

$$d_{max} = 0.025 a_g S T_C T_D = 0.025 a_{max} T_C T_D \tag{1}$$

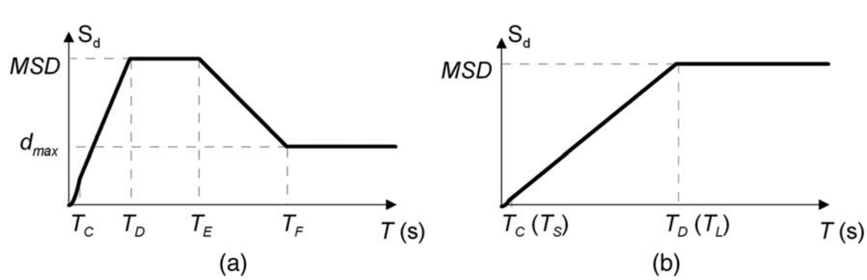

Figure 1. Elastic displacement design spectral shape according to (a) the Italian Building Code and Eurocode 8 and (b) the New Zealand and U.S. standards.

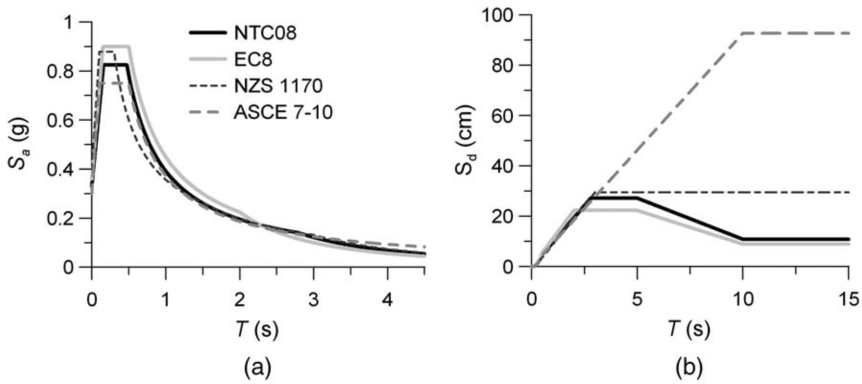

Figure 2. Elastic design acceleration (a) and displacement (b) spectra according to the Italian, European, New Zealand and U.S. seismic codes for 475-yr return period on ground category B (for NTC08 and EC8) and C (for NZ 1170 and ASCE 7-10). The spectra are anchored to the value of peak ground acceleration on exposed bedrock a_g equal to 0.30 g.

where a_{max} (equal to a_g times S) is the design peak ground acceleration, S is the soil amplification factor and T_C is the control period marking the start of the constant velocity branch of the design spectrum. Thus, Equation 1 explicitly, albeit rather arbitrarily, constrains the long-period spectral ordinates to the short-period ones (i.e., a_{max} and T_C) and to the corner period T_D. A consequence of such constraint is that the ratio MSD/d_{max} is equal to the ratio MSA/a_{max}, MSA being the maximum response spectral acceleration. This ratio is 2.5 according to EC8, while NTC08 denotes it by F_0 and provides its values, based on the results of short-period PSHA at a national scale.

To illustrate the effect of the previous assumptions on design spectra, Figure 2 shows (a) the spectral elastic accelerations and (b) displacements for an arbitrary site on similar ground types, either B (for NTC08 and EC8) or C (for NZS 1170 and ASCE 7-10). For the purpose of comparison, the design spectra are anchored to the same value of maximum ground acceleration on rock, $a_g = 0.30$ g. This results in a hazard factor $Z = 0.30$ g for NZS 1170 and spectral accelerations $S_S = 1.125$ g and $S_1 = 0.4$ g, at 0.2 s and 1.0 s, respectively, for ASCE 7-10, which serve to define the design spectra in these codes. While spectral accelerations appear to be relatively close, differences are much clearer in terms of spectral displacements at long periods, mainly because of the heterogeneous criteria for the definition of the corner period T_D. Even if such differences may not be relevant for specification of seismic actions for design, unless periods larger than about 3 s are of interest, the consequences in terms of ground motion selection may be more important, since it is clear that records approaching the ASCE 7-10 displacement spectrum at long periods will correspond in general to a different magnitude level than those approaching the EC8 or NTC08 spectra.

DISPLACEMENT SPECTRA FROM LONG-PERIOD SEISMIC HAZARD STUDIES: THE ITALIAN EXPERIENCE

To provide a rationale framework for the characterization of long-period ground motion for design, Faccioli and Villani (2009) illustrated a novel representation of long-period seismic hazard for Italy, based on the findings of the S5-Project "Seismic Input in Terms of Expected Spectral Displacements," funded by the Department of Civil Protection from 2005 to 2007. This study produced new probabilistic seismic hazard maps for Italy in terms of horizontal displacement response spectral ordinates in a wide range of vibration periods, from 0.05 s up to 20 s, taking advantage, on one side, of the broadband ground motion attenuation relationship developed by Cauzzi and Faccioli (2008) and, on the other side, of the criteria for the reliability of long-period response spectral ordinates from digital data introduced by Paolucci et al. (2008).[2]

Specifically, this work provided, throughout the Italian territory and for all local municipalities, mapped values of the 5% damped displacement response spectral ordinates (16th, 50th, and 84th percentiles), for $T = 2\,\text{s}$, 5 s, 10 s and for the return periods: $T_R = 72\,\text{yr}$, 475 yr and 975 yr. Based on these results, Faccioli and Villani (2009) proposed a simplified bilinear approximation for the displacement response spectra on exposed rock, defined as follows:

$$S_d(T) = \begin{cases} \frac{D_{10}}{T_D} T & T \le T_D \\ D_{10} & T > T_D \end{cases} \tag{2}$$

where D_{10} is the displacement response spectral ordinate at $T = 10\,\text{s}$ and T_D is the corner period separating the constant displacement branch of the spectrum from the constant velocity one. The latter is computed as follows:

$$T_D = \frac{2\pi D_{10}}{\max\limits_T PSV} \tag{3}$$

where PSV denotes the pseudo-velocity response spectrum, obtained from the uniform hazard (UH) displacement spectra using the pseudo-spectral approximation rule.

As underlined by the authors of the hazard assessment, the bilinear approximation of Equation 2 cannot be used to estimate the seismic actions in terms of acceleration at short periods via the pseudo-spectral relationship, as it would not lead in general to spectral ordinates compatible with those prescribed by the current seismic code.

A Target Displacement Spectrum for Italian Sites (TDSI)

To satisfy the short-period prescriptions of the NTC08, on one side, and, on the other side, the results of long-period PSHA from Project S5, the following target displacement spectrum for Italy, referred to as TDSI hereafter (see Figure 3), is introduced:

[2] This hazard study is not yet implemented in NTC08, which is currently based on PSHA at short periods.

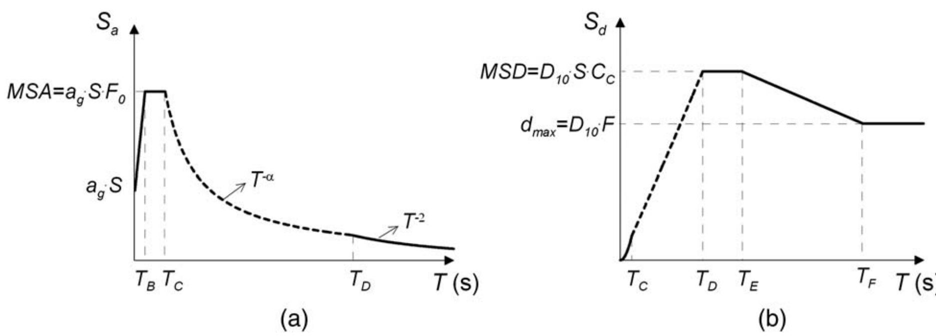

Figure 3. Target displacement spectrum for Italy (TDSI, see Equation 4) in the (a) short- and (b) long-period range, based on the results of the PSHA at long periods developed by Faccioli and Villani (2009). Representation in the short-period range (left side) is given in terms of spectral acceleration.

$$S_d(T) = \begin{cases} T \le T_B & a_g \eta S F_0 \left[\frac{T}{T_B} + \frac{1}{\eta F_0}\left(1 - \frac{T}{T_B}\right)\right] \frac{T^2}{4\pi^2} \\ T_B < T \le T_C & a_g \eta S F_0 \frac{T^2}{4\pi^2} \\ T_C < T \le T_D & a_g \eta S F_0 \left(\frac{T_C}{T}\right)^{\alpha} \frac{T^2}{4\pi^2} \\ T_D < T \le T_E & D_{10} \eta S C_c \\ T_E < T \le T_F & D_{10} \eta F + D_{10} \eta (S C_c - F) \frac{T_F - T}{T_F - T_E} \\ T > T_F & D_{10} \eta F \end{cases} \quad (4)$$

where:

- D_{10} and T_D are defined in Equations 3 and 4, based on the mapped values of long-period PSHA (Faccioli and Villani 2009).
- a_g is the design ground acceleration on rock for a given return period; $F_0 = MSA/a_{max}$, S and C_c are the soil factors as a function of ground type; T_C, T_E, T_F are corner periods; and η is the damping correction factor ($\eta = 1$ for 5% viscous damping). All the previous parameters are defined according to NTC08.
- $\alpha = log(\frac{4\pi^2 D_{10} C_c}{a_g F_0 T_D^2}) / log(T_C/T_D)$ is the factor introduced to ensure matching between the short- and long-period branches of the proposed spectral shape (see dotted line in Figure 3). Values of α for Italy range approximately between 0.85 and 1.4, the largest values being typically found in low-seismicity regions, while regions of high seismicity are characterized by values close or slightly less than unity.
- $F = (800/V_{S30})^{0.375}$—$V_{S30}$ being the site shear wave velocity averaged over the top 30 meters—is the site factor for long periods, as obtained in the framework of Project S5 (Cauzzi et al. 2007).

Since the results of the long-period PSHA are given for three return periods alone (i.e., $T_R = 72$ yr, 475 yr, 975 yr) values of D_{10} and T_D as a function of the return period T_R are computed through a linear interpolation of logarithms. Note that due to the poor dependence of T_D on the return period, as emerged from the seismic hazard studies, a constant value of T_D was assumed at all sites for simplicity's sake. For the computation of the long-period site factor F, the average values of V_{S30} within the variability range of each site class have been considered, namely: $V_{S30} = 800\,\text{m/s}$ for site class A ($F = 1.0$); $V_{S30} = 580\,\text{m/s}$ for class B ($F = 1.13$); $V_{S30} = 270\,\text{m/s}$ for classes C and E ($F = 1.5$); $V_{S30} = 140\,\text{m/s}$ for class D ($F = 1.9$).

The key features of the proposed TSDI target spectrum can be summarized as follows:

- The maximum spectral displacement plateau MSD for periods $T_D \le T \le T_E$—the latter being inherited from NTC08 (i.e., $T_E = 4.5$ s for ground type A, $T_E = 5.0$ s for ground type B, and $T_E = 6.0$ s for other soil classes)—and the constant spectral displacement d_{max}, reached at periods $T \ge T_F = 10$ s, are calculated based on the long-period PSHA of Project S5.
- To match the NTC08 spectra when site factors are accounted for, we have considered the same site factor SC_c, as in the NTC08, between T_C and T_E, while the long-period site factor F from Project S5 was adopted for periods $T \ge T_F$; for intermediate periods, a linear variation of the site factor was assumed.
- The MSD/d_{max} ratio is equal to SC_c/F, thus leading rock sites (soil class A) to a constant displacement branch ($SC_c/F = 1$) for periods beyond T_D, while leading other soil classes to a more gentle decay of spectral displacements between T_E and T_F with respect to NTC08 (since in general, $SC_c/F < F_0$).

To highlight the effects of different assumptions on site factors, Figure 4 shows the ratio between the spectral ordinates for soil class C and those for soil class A, computed according to the NTC08 design spectrum (black thick line) and to the TDSI of Equation 4 (gray dotted line). Up to T_E, the spectral amplification factors coming from NTC08 and from Equation 4 are the same, while for $T > T_E$, the spectral amplification factor in Equation 4 decreases linearly until it reaches the value of F at the corner period T_F.

Figure 5 shows the comparison between the NTC08 design displacement spectrum (black line) and the TDSI (dotted gray line) for the return period $T_R = 475$ yr both on ground type A

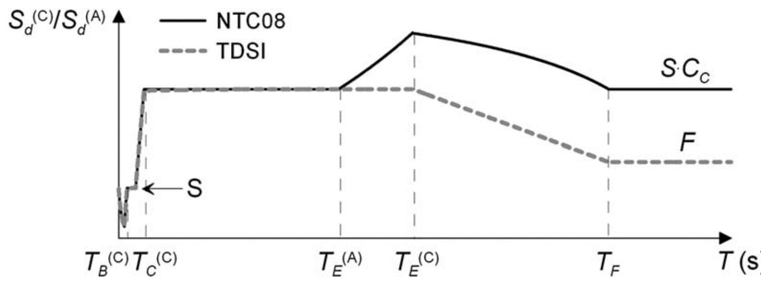

Figure 4. Ratio of the spectral ordinates for soil class C with respect to soil class A, according to NTC08 (black line) and to the proposed representation, TDSI (gray dashed line).

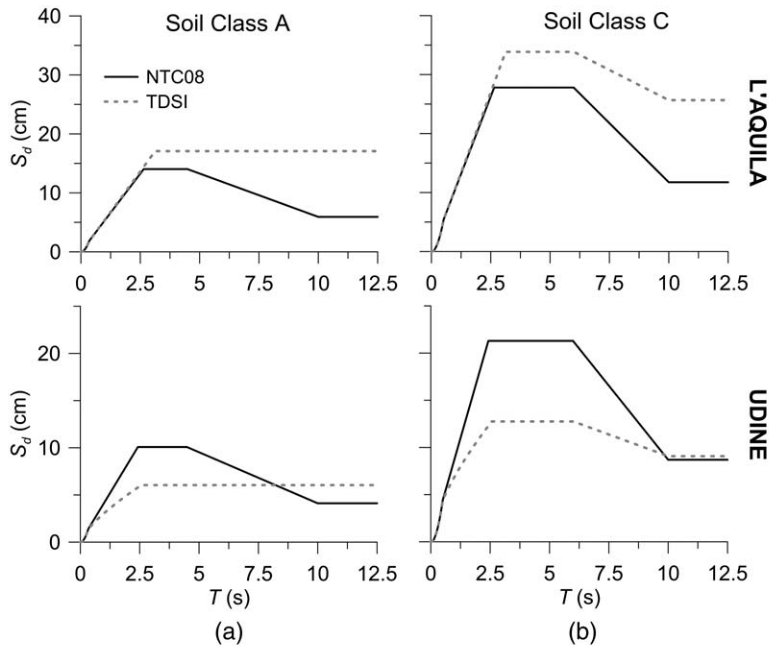

Figure 5. Comparison of the displacement response spectra coming from NTC08 (black line) and from this work, TDSI (gray dashed line), for 475-yr return period, at two representative sites, namely L'Aquila (top panel) and Udine (bottom panel), on ground types (a) A and (b) C.

(Figure 5a) and C (Figure 5b), at L'Aquila, central Italy (top panel) and at Udine, northeastern Italy (bottom panel). A general feature highlighted by this example is that for high seismicity regions in Italy, such as L'Aquila, the spectral ordinates at long periods are generally underestimated by the NTC08 design spectrum with respect to the TDSI, while, for low-to-medium seismic regions, such as Udine, they may be significantly overestimated by the NTC08, especially in terms of *MSD*. As remarked previously, the decay of spectral ordinates for periods between T_E and T_F is much more pronounced in the code spectra than observed in the TDSI.

DATABASE FOR ENGINEERING ANALYSES OF LONG-PERIOD GROUND MOTION

DATA SELECTION

After introducing the target spectrum for displacement-based seismic analyses in Italy, the second step is the compilation of the strong GM database, mainly consisting of digital recordings suitable for displacement-based applications.

The SIMBAD database (Selected Input Motions for displacement-Based Assessment and Design) was created by assembling records from different strong ground motion databases worldwide, with the main objective of providing records of engineering relevance for the most frequent design conditions in Italy. For this reason, only records from shallow crustal earthquakes, at epicentral distance R_{epi} approximately less than 35 km, with moment magnitude, M_W, ranging from 5 to 7.3, were considered. These are the conditions generally governing seismic hazard throughout Italy, for most return periods of practical interest.

For the scope of this study, the selected records should be accurate at long periods. In fact, most records (about 90%) included in the database are from digital instruments, while a limited number of analog records was retained, typically from large magnitude earthquakes, for which a good signal to noise ratio at long periods could be achieved.

In general, raw acceleration time histories were processed according to the procedure devised by Paolucci et al. (2011) and applied to the ITalian ACcelerometric Archive (ITACA, http://itaca.mi.ingv.it). One of the features of the aforementioned procedure is that single and double integration of processed acceleration records provides velocity and displacement waveforms without non-physical baseline trends, and no further correction is required. For each record, the same filter band was selected and applied to the three spatial components. Except for a few exceptions, records were included in SIMBAD only if the high-pass filter frequency was not larger than 0.15 Hz.

Only for the ground motions derived from ITACA or from U.S. providers (the PEER, CESMD, and NSMP databases; see Table 1), processed records were included in SIMBAD as disseminated by the data provider, without reprocessing raw records.

Table 1. Source of strong ground motion records included in the SIMBAD database

Country	# records	Data provider
Japan	220	K-NET[a]
		KiK-net[a]
Italy	83	ITalian ACcelerometric Archive ITACA[b1]
		Department of Civil Protection[b2]
New Zealand	77	Institute of Geological and Nuclear Sciences: GNS[c]
United States	44	Center for Engineering Strong Ground Motion Data: CESMD[d]
		PEER Strong Motion Database[e]
		U.S. Geological Survey National Strong Motion Project: NSMP[f]
Europe	18	European Strong-Motion Data Base: ESMD[g]
Turkey	15	Turkish National Strong Motion Project: T-NSMP[h]
Greece	7	Institute of Engineering Seismology and Earthquake Engineering[i]
Iran	3	Iran Strong Motion Network ISMN[j]

[a] *http://www.kyoshin.bosai.go.jp/*.
[b1] *http://itaca.mi.ingv.it/*.
[b2] *http://www.protezionecivile.gov.it/*.
[c] *http://www.geonet.org.nz*.
[d] *http://strongmotioncenter.org/*.
[e] *peer.berkeley.edu/products/strong_ground_motion_db.html*.
[f] *http://nsmp.wr.usgs.gov/*.
[g] *http://www.isesd.hi.is/*.
[h] *http://daphne.deprem.gov.tr*.
[i] *http://www.itsak.gr/en/head*.
[j] *http://www.bhrc.ac.ir/*.

A further requirement for records to be included in SIMBAD is the availability of V_{S30} at the recording station. We retained records only for some cases where the ground classification according to the EC8 (or, equivalently, NTC08) was available, even without direct V_{S30} measurements.

Table 1 provides a list of the worldwide ground motion networks used for assembling the SIMBAD database. Most records come from the Japanese strong motion networks K-NET and KiK-net of the National Research Institute for Earth Science and Disaster Prevention (NIED), which provide a valuable source of high-quality digital data, with detailed information on subsoil conditions.

DATABASE ORGANIZATION

The metadata associated to the waveforms included in the SIMBAD database are organized into three main sections related to: (1) earthquake: event name and date, area, M_W, focal mechanism, event latitude and longitude, focal depth, fault solutions (when available); (2) station: station code and name, station latitude and longitude, elevation, site class according to EC8, V_{S30} measurements, type of instrument, analog/digital recorder, data source; (3) record: R_{epi} (other source-to-site distance metrics are included when available), low- and high-cut filter values and type of filter used for record processing. Sites were classified into five ground categories according to the European and Italian seismic norms: A ($V_{S30} \geq 800\,\mathrm{m/s}$), B ($360 \leq V_{S30} < 800\,\mathrm{m/s}$), C ($180 \leq V_{S30} < 360\,\mathrm{m/s}$), D ($V_{S30} < 180\,\mathrm{m/s}$) and E (site C or D with thickness smaller than 20 m over rigid rock).

The SIMBAD database presently consists of 467 three-component acceleration time histories from 130 earthquakes worldwide. Most records come from Japan (47%), Italy (18%), New Zealand (17%), and United States (9%), with minor contributions from Greece, Turkey, Iran, and other European countries (9%), as shown in Figure 6. In the selection of records for the database, priority was given to achieve an approximately uniform distribution in the

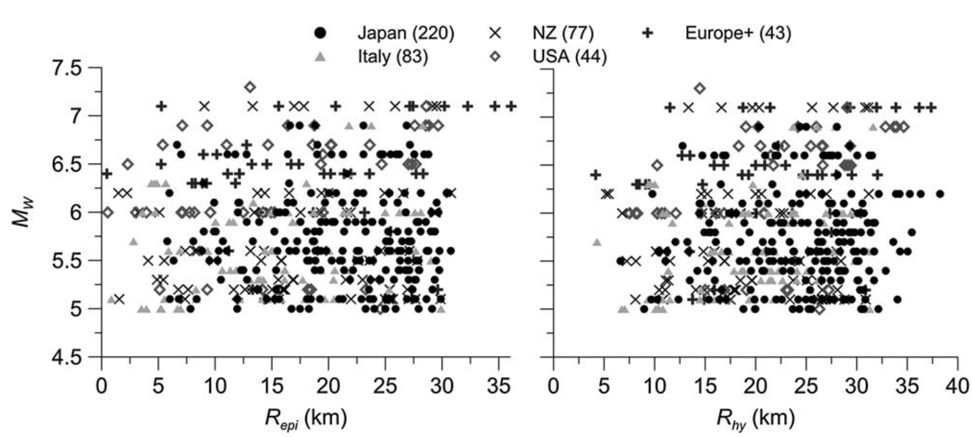

Figure 6. Distribution M_W, R_{epi} (left panel) and M_W, R_{hy} (right panel), with indication of the geographical origin of the records included in SIMBAD. R_{epi} and R_{hy} denote the epicentral and hypocentral distance, respectively.

magnitude and distance ranges defined in the previous section, while an extension of the database to cover a wider range of magnitude and source-to-site distance, as well as specific near-fault conditions, such as directivity and fault mechanisms, was considered secondary and then was not explicitly addressed. Inclusion of new records in the database aims presently at filling in the less represented regions, in terms of magnitude, distance, and site conditions. The latter point is probably the most critical issue, since most records are representative of soils B (44%) and C (43%), while only a few of them are registered on rock (8%), or soft soils D (4%) and E (1%), as depicted in Figure 7.

DEPENDENCE OF T_D ON MAGNITUDE AND SITE CONDITIONS

As pointed out in the previous section, significant discrepancies exist among different seismic codes worldwide in the criteria used to define the corner period T_D and its dependence on magnitude and site conditions. The main differences are summarized in Table 2. Because this is relevant to the selection of displacement spectrum–compatible GM record sets, the corner periods, as estimated on the SIMBAD database, are investigated in this section. To this end, the median horizontal displacement response spectra of the SIMBAD records have been computed for different equally spaced magnitude ranges, namely $M_W = 5.0-5.4$, 5.5–5.9, 6.0–6.4, 6.5–6.9. Records have been grouped according only to ground categories B and C of the EC8, due to the scarcity of records belonging to soil classes A, D, and E (see Figure 7). For each magnitude range, the corner period T_D marking the beginning of the constant displacement branch of the spectrum is evaluated using Equation 3, where D_{10} is approximated here by the average spectral displacement in the period range 5–10 s.

Figure 8 illustrates the median horizontal (geometric mean of the two horizontal components) displacement response spectra of the SIMBAD records as a function of the soil conditions (soil class B, left-hand side, and C, right-hand side) for the four magnitude ranges under consideration. On each plot of Figure 8, the bilinear approximation for the median displacement spectrum, computed according to Equation 3, is also superimposed

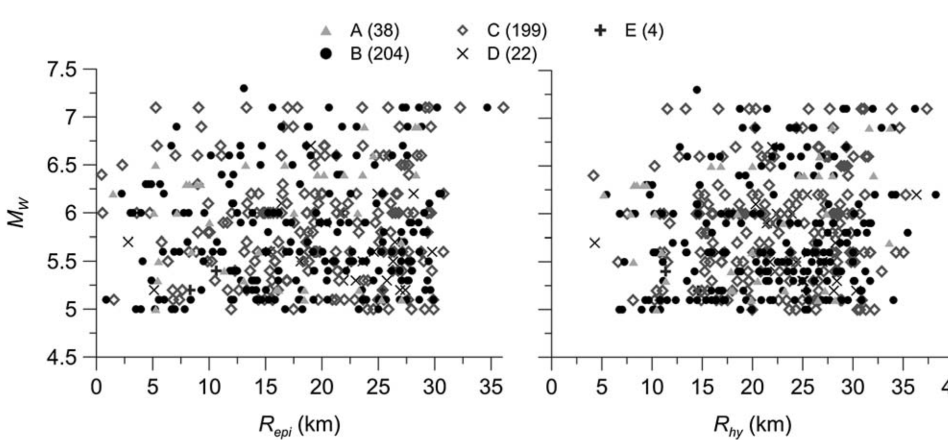

Figure 7. Distribution M_W, R_{epi} (left panel), and M_W, R_{hy} (right panel) with indication of the ground category (EC8-NTC08 soil classification) of the records included in SIMBAD.

Table 2. Range of variability of the corner period T_D according to selected seismic norms worldwide and the proposed TDSI (Equation 4)

Displacement spectrum	Range of variability of T_D
EC8	1.2 s, for $M < 5.5$; 2.0 s, for $M \geq 5.5$
NTC08	Ranging from about 1.8 s (for $a_g/g = 0.05$) to 2.8 s (for $a_g/g = 0.30$)
NZS 1170	3.0 s
ASCE 7-10	Ranging from about 4 s (for $M = 6.0-6.5$) to 16 s (for $M = 8.0-8.5$)
TDSI	3.7 s median value, $\pm\sigma = 1.4$ s

(thin line). T_D is found to vary from about 0.60 s in the 5.0–5.4 magnitude range, up to about 2.1 s for $M_W = 6.5 - 6.9$, with a slight dependence on site conditions.

Based on the summary of Table 2, it is interesting to clarify the reasons, on one side, of the relatively good agreement of these results with the EC8 provisions, that is, $T_D = 1.2$ s for low-seismicity regions in Europe ($M < 5.5$) and $T_D = 2.0$ s for high-seismicity regions ($M \geq 5.5$), and, on the other side, the mismatch with respect to the Italian code NTC08 and the proposed target spectrum TDSI (Equation 4). As a matter of fact, while the EC8 spectra are mainly based on the envelope of observed spectral shapes from GM records, the Italian spectra derive either from the UH spectra proposed for the Italian territory (Montaldo et al. 2007), in the case of NTC08, or from the PSHA at long periods introduced by Faccioli and Villani (2009), in the case of the TDSI spectrum. Therefore, since the UH spectra are a combination of different earthquake sources—either small-magnitude and short-distance or large-magnitude and long-distance—typically in the short- and long-period ranges, respectively, T_D from UH spectra typically tends to be larger than the corresponding value calculated from GM records.

Finally, it emerges from Figure 8 (bottom panel) that the median spectral displacements of SIMBAD records are in good agreement with the corresponding median from the GMPE by Cauzzi and Faccioli (2008), confirming that the database is unbiased.

REXEL-DISP: COMPUTER-AIDED DISPLACEMENT-BASED RECORD SELECTION

The availability of a high-quality digital strong motions database, along with target spectra constrained both at short and long periods, may allow a more rational GM record selection for engineering applications. To this aim, a user-friendly software, REXEL-DISP (Figure 9), based on the same core algorithms of REXEL (Iervolino et al. 2010) and REXELite (Iervolino et al. 2011), was developed. Although the basic features of REXEL are described in the aforementioned papers, a brief discussion herein is still worthwhile because significant enhancements in the interface and options are now available with respect to what was described in former publications.

REXEL-DISP has been freely available at http://www.reluis.it since January 2012. The software allows one to select combinations of (multi-component) horizontal accelerograms

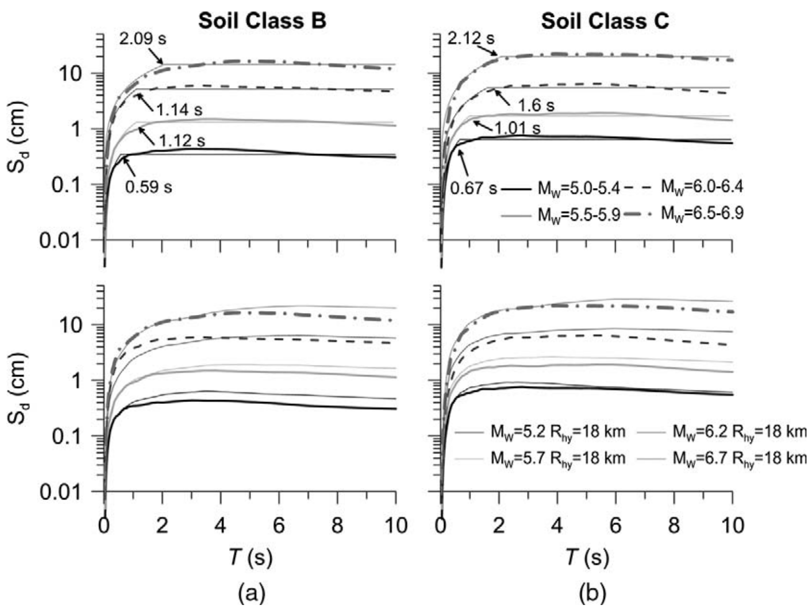

Figure 8. Median horizontal (geometric mean) displacement response spectra of the SIMBAD records as a function of soil conditions according to EC8-NTC08 ((a): soil type B; (b): soil type C) for four different magnitude ranges. Top panel: the superimposed thin lines denote the bilinear approximation used for the determination of the corner period T_D (see labels indicated by the arrows). Bottom panel: comparison with the median spectrum as predicted by the GMPE of Cauzzi and Faccioli (2008) for representative values of magnitude and hypocentral distance ($R_{hy} = 18\,\text{km}$).

whose average response spectrum is compatible with a target displacement spectrum in an arbitrary period range. The record search is carried out such that the response spectral shape of individual records is as similar as possible to the target one in the same period interval.

Spectrum-compatible record set selection is based on four main steps:

1. The first is the definition the target spectrum; the latter may be: TDSI for Italy, the design spectra according to NTC08 and EC8, or an arbitrarily defined one (typically a UH spectrum entered by the user).
2. The second step, to be followed only in case of the TDSI and the NTC08, is the definition of additional input parameters, namely, geographical coordinates of the site, *latitude* and *longitude* in decimal degrees, *Site Class* (according to NTC08/EC8 classification), *Topography Category* (as in NTC08/EC8), *Nominal Life*, *Functional Type*, and *Limit State*. These parameters are required to calculate the elastic design spectrum according to these codes.
3. The third step involves the definition of the bins in which the software will search for spectrum-compatible sets. In fact, the software allows one to search for records

within SIMBAD belonging to the same site class of the target spectrum, or to *any site class* (i.e., recordings from different site conditions may fit the target spectrum and be selected). Moreover, the user may select records corresponding to prescribed magnitude and source-to-site distance intervals, or to selected ranges of several GM intensity measures. Once the selection options are defined, the software returns the number of records, along with the corresponding number of events, available in the SIMBAD database.

4. The spectra returned by the preliminary search in Step 3, are then used by REXEL-DISP to find suites of records (of sizes 1, 7, or 30), whose average response spectrum is compatible with the target one in an arbitrary period range, $[T_1, T_2]$, between 0 s and 10 s. Spectral compatibility is ensured within a tolerance band defined by the user (upper and lower tolerances to be provided); for example, 0% lower tolerance should be set to ensure that the average spectrum is not lower than the target one, as specified by the ASCE 7–10 recommendations quoted previously.

The sets of compatible records may consist either of single-component or of pairs of horizontal component accelerograms. In the latter case, the software will return 14 (from 7 recording stations) or 60 (from 30 recording stations) records time histories to be used, for example, for the analysis of three-dimensional structures.

It is worth underlining that to select spectrum-compatible records, the software analyzes all possible combinations of spectra identified in the preliminary search (Step 3) and checks whether each combination approaches—in an average sense and within the assigned tolerances—the target spectrum.

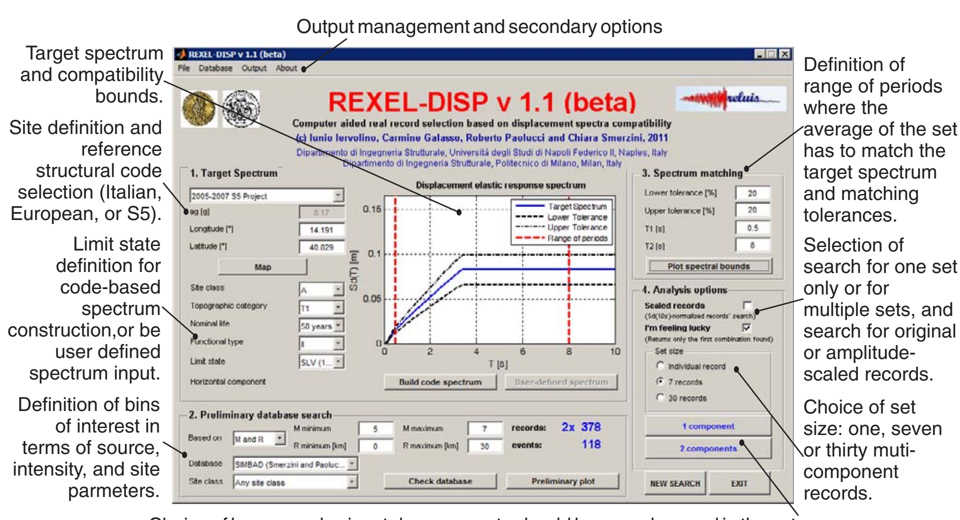

Figure 9. Graphic user interface of REXEL-DISP and main required information or record selection options.

An especially important feature of REXEL and REXEL-DISP is that the list of records determined in Step 3 is sorted in ascending order with respect to the following parameter:

$$\delta_j = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[\frac{S_{d,j}(T_i) - S_{d,target}(T_i)}{S_{d,target}(T_i)}\right]^2} \tag{5}$$

where $S_{d,j}(T_i)$ denotes the spectral ordinate of record j at period T_i, $S_{d,target}(T_i)$ is the value of the displacement target spectrum at the same period, and N is the number of periods within the considered range. The parameter δ_j in Equation 5 measures the deviation of the spectrum of an individual record from the target one. Preliminary ordering ensures that the first combinations found are those with the smallest individual scattering with respect to the target spectrum (i.e., Iervolino et al. 2008). In fact, the *I'm feeling lucky* option can be used to stop the analysis as soon as the first combination is found, which is expected to be one of the best record sets according to this criterion.

REXEL-DISP allows one to obtain sets of either unscaled or scaled accelerograms compatible with the target spectrum. When the scaling option is chosen, a search for spectrum-compatible scaled record sets is carried out in terms of non-dimensional values, by normalizing both record and target spectra by the corresponding value at 10 s. When a combination is found, the normalization factor is returned to the user as the scale factor for the specific record in the set and is applied uniformly to all spectral ordinates (i.e., linear scaling). In this case, it is also possible to specify the maximum mean scale factor (SF) allowed, and the software will discard combinations with an average SF larger than that assigned.

Quality measures for the output record sets may be derived from Equation 5. Indeed, δ_{avg} is introduced as a measure of average spectrum matching by replacing the spectral ordinate of individual spectra with that of the average spectrum of the output combination, while δ_{max} is defined as the largest value from Equation 5 among those computed for all records in a given combination. Therefore, the former is a measure of average spectral goodness of fit, while the latter is a measure of record-to-record variability within a combination (Iervolino et al. 2010).

As for other REXEL software, complementing functions of REXEL-DISP are related to: visualization of results; the return of selected waveforms, spectra, and metadata to the user; repetition of the search excluding an undesired waveform from an output combination; or visualization of acceleration spectra compatibility for the selected set. Applications in the next section will show how, in fact, this software may render record displacement-based records selection feasible and practice-ready.

APPLICATION EXAMPLES

Some applications for representative Italian sites are presented hereafter to clarify the performance of ground motion selection, depending on the selected target spectrum, on the seismicity level of the site of interest and on the period range bounds.

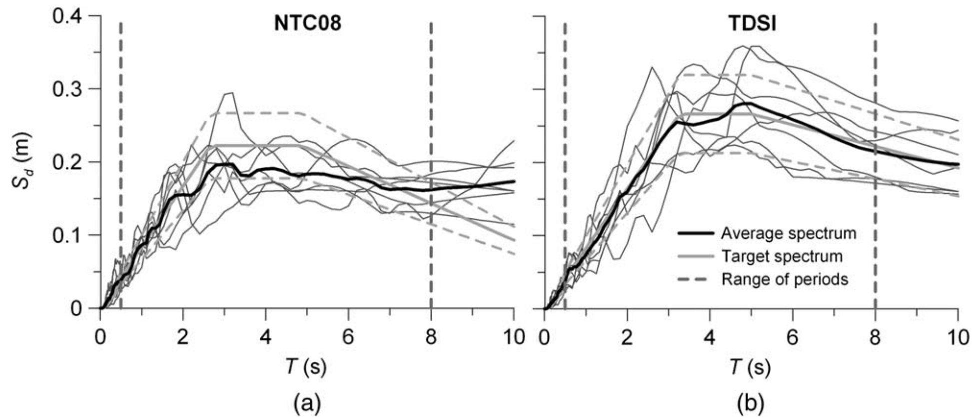

Figure 10. Displacement response spectra, at 5% damping, of the set of 7 unscaled horizontal ground motions compatible with the NTC08 design spectrum (a) and the TDSI of Equation 4 (b) for the reference site of L'Aquila (soil class B) and for $T_R = 475$ yr. The thin solid lines represent the individual displacement response spectra of the selected accelerograms, the thick black line denotes the average spectrum of the output combination, while the thick gray line indicates the target displacement spectrum along with the corresponding lower and upper tolerances (dashed gray lines). The vertical dashed lines denote the range of periods where spectral compatibility of the average is ensured.

EFFECT OF TARGET SPECTRAL SHAPE

As a first example, REXEL-DISP is used to select seven horizontal ground motions compatible either with the NTC08 design spectrum or with the TDSI (Equation 4). Reference is made to the city of L'Aquila for a return period $T_R = 475$ yr, soil class B, and no topography special conditions. Selection criteria involve a broadband spectrum compatibility in the period range from $T_1 = 0.5$ s to $T_2 = 8$ s, with 20% lower and 20% upper tolerance. It is worth underlining that no scaling factor is introduced, and no specific magnitude and distance interval, nor site class, have been specified.

With the above parameters, the software returns the best suites of seven accelerograms compatible with the NTC08 spectrum and with the TDSI presented in Figures 10a and 10b, respectively. A reasonable agreement is found between the average displacement spectrum and the NTC08 spectrum, resulting in a maximum spectral deviation δ_{max} of the individual accelerograms limited to less than 30% and an average spectral deviation δ_{avg} of around 10%, even in case no scaling factors are applied to the selected records. However, the response spectral ordinates of selected records divert significantly from the decreasing branch of the design spectrum, starting from 5 s.

The agreement with selected records improves when considering the TDSI (Figure 10b), with a reduced scatter of the mean spectrum ($\delta_{avg} \sim 6\%$). Furthermore, it is noted that the target spectral shape fits the trend of spectral ordinates of GM records, especially beyond 5 s, much better. This is a common finding for all considered Italian sites, confirming that the sharply decreasing trend proposed both by the EC8 and by the NTC08 spectra is not suitable for long periods, as already pointed out by Faccioli et al. (2004).

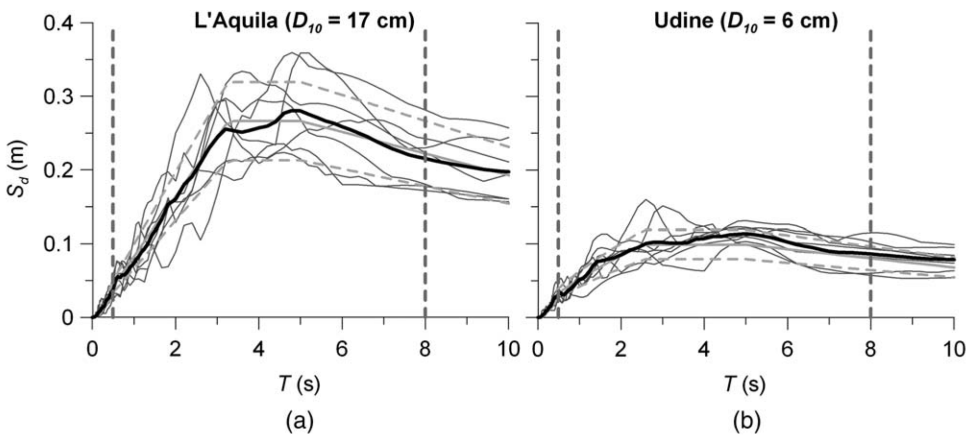

Figure 11. Output combinations of real ground motions compatible with the TDSI for $T_R = 475$ yr at L'Aquila (a) and at Udine (b).

EFFECT OF HAZARD LEVEL

To evaluate the influence of the level of seismicity on the ground motion selection procedure, the Udine site is considered, which is characterized by lower hazard with respect to L'Aquila. The selected target spectrum is TDSI, while the other parameters are the same as in the previous search. The output combination returned by the software at L'Aquila and Udine are compared in Figures 11a and 11b, respectively. A good agreement is achieved in Udine as well, leading to values of δ_{avg} and δ_{max} of about 9% and 28%, respectively.

It is worth noting that the average moment magnitude and epicentral distance of the output suite of strong motion records is about 6.6 and 12 km in L'Aquila and about 6.5 and 20 km in Udine. These values are in good agreement with the disaggregation results at both sites obtained by the long-period PSHA analyses (M. Villani, *pers. comm.*), namely modal M in the range 6.4–6.7 and R of 10 km (L'Aquila), 6.2–6.5 and 20 km (Udine). Note that such an agreement has been obtained with unscaled records and with no specification of the magnitude and distance range. Therefore, it turns out, as a major achievement, that GM record selection based on displacement-spectrum compatibility tends to naturally fit the proper magnitude and distance ranges, provided that the target spectrum at long periods is constrained by a suitable seismic hazard analysis.

EFFECT OF PERIOD RANGE FOR SPECTRUM COMPATIBILITY

In this example, the proposed approach is explored, considering different period ranges where spectral compatibility is ensured. For this purpose, we consider the same example at L'Aquila (class B) for the TDSI ($T_R = 475$ yr) and compare the results using three different period ranges, namely, (a) $T = [0.5, 3]$ s, (b) [0.5, 8] s, and (c) [0.15, 10] s, with a upper and lower tolerance of 20%. The results are illustrated in Figure 12, not only in terms of displacement response spectra (left-hand side), but in terms of acceleration spectra as well (right-hand side). By examination of these results, some interesting comments can be derived on the use of the software:

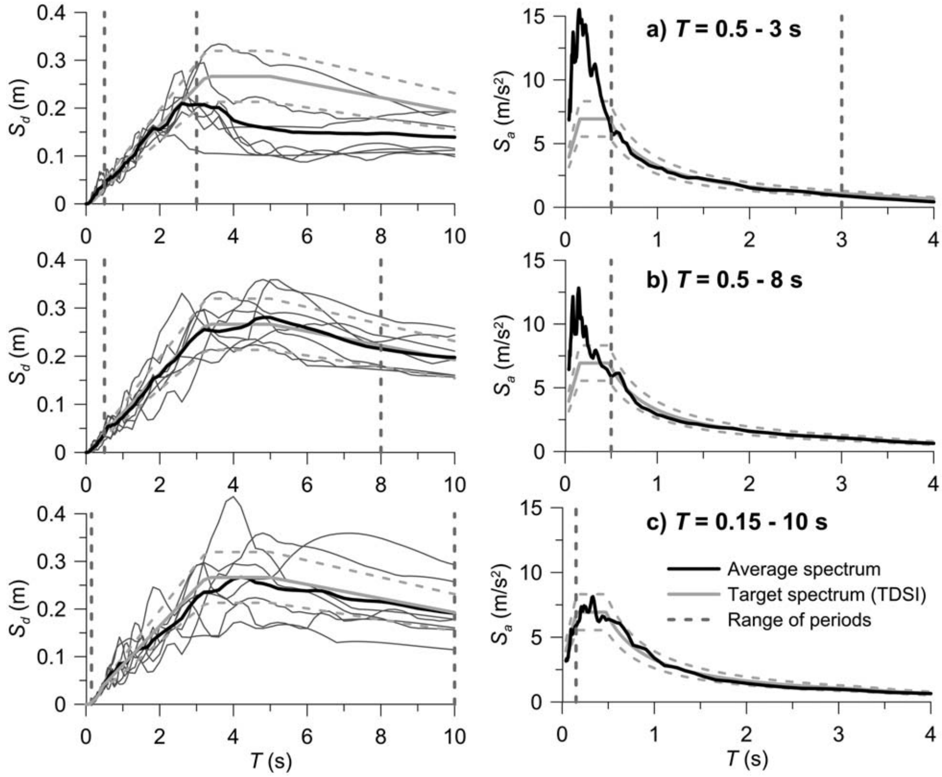

Figure 12. Displacement (left-hand side) and acceleration (right-hand side) response spectra of the record sets compatible with the TDSI ($T_R = 475$ yr) for an ideal site in the city of L'Aquila considering three different ranges of vibration periods: (a) $T = 0.5-3$ s, (b) $T = 0.5-8$ s, and (c) $T = 0.15-10$ s. For clarity in the right panel only the average spectrum of the selected accelerograms is shown along with the target spectrum.

- Restricting the period range of spectrum compatibility improves the search performance in the selected range, but returns a set of accelerograms with large variability at longer (and shorter) periods, thus involving a reduced homogeneity of the suite in terms of magnitude.
- Extending the period range to include short periods involves a moderate decrease of search performance in terms of maximum error ($\delta_{avg} = 8\%$ and $\delta_{max} = 40\%$), but it allows one to achieve a *broadband* spectrum compatibility, without scaling the ground motion records.

CONCLUSIONS

In the framework of ongoing research activities to improve the representation of the seismic action in Italy, this study addressed the selection of displacement-spectrum compatible earthquake ground motions from real accelerograms. The following tasks were achieved:

- After comparing the provisions from several seismic codes worldwide, target design spectra for Italian sites (TDSI), tailored to fit results of PSHA both at short and long periods, were proposed.
- A high-quality strong-motion database, SIMBAD, was set up, consisting of digital recordings from shallow crustal earthquakes with epicentral distances of less than about 30 km, with the purpose of covering as homogenously as possible the magnitude and distance ranges of interest for seismic hazard at Italian sites.
- The REXEL-DISP software was developed, as a byproduct of REXEL, and specifically featured to search for displacement-spectrum compatible records from the SIMBAD database.

Application examples at some representative Italian sites suggest that the combination of (i) a target spectrum calibrated both at long and short periods from seismic hazard studies and (ii) a digital strong-motion database covering in a relatively homogeneous way the ranges of magnitude, distance and site conditions which dominate seismic hazard, together with the search engine implemented in the REXEL-DISP software, allow in most cases to obtain sets of unscaled, or lightly scaled, records sets closely approaching the target spectrum in a broad period range. Furthermore, the magnitude and distance ranges of the selected records are consistent with the seismicity levels deduced from the hazard disaggregation study. This means that such selected records may be used with a similar level of confidence, either in terms of acceleration or of displacement spectrum, for a variety of applications, where constraining compatibility of records within a limited period range may not be satisfactory, such as for nonlinear time history analyses of structures with large participation factors of higher modes, for nonlinear dynamic soil-structure interaction problems, and for seismic soil stability studies.

Finally, it is noted that this approach was applied to Italian sites; however, it can be easily extended to any other site for which a reliable definition of long-period ground motion for seismic design is available.

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