RECORD SELECTION AND SEISMIC INPUT DEFINITION FOR STRUCTURAL ANALYSIS

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1 INTRODUCTION

Since several years, seismic input definition is one of the hot topics of earthquake engineering because of its influence on simulations for estimating seismic structural performance. Herein, the efforts of the ReLUIS 2010-2013 project toward the development of practice-ready tools for hazard consistent seismic input definition aimed at seismic structural analysis is shown. Determination of design seismic actions in seismic codes mostly relies on a target spectrum, which is, therefore, also the basis for record selection in seismic input definition when performing nonlinear structural analysis. Since a rational performance target should account for the seismic hazard at the site of interest, the uniform hazard spectrum (UHS), or an approximation of it, is often used as the design spectrum. The UHS is built entering the elastic spectral acceleration, $S_a(T)$, hazard curves for several $T$ values at a specified probability of exceedance of (e.g., 10% in 50 years or, equivalently, 475 years return period, $T_r$), and plotting the corresponding ordinates versus $T$.

Generally, the signals that can be used for structural simulation are of three types: (1) artificial waveforms; (2) simulated accelerograms; and (3) natural records. Signals of type (1) are often obtained via random vibration theory. Simulation records (2) are obtained via modelling of the seismological source and may account for path and site effects. Finally of type (3) are ground-motion records from real events (Bommer and Acevedo, 2004).

As far as it regards real records, given the UHS for the structural limit-state of interest (i.e., the UHS corresponding to a $T_r$), current or advanced (depending on the context where it is applied) practice today, which may require aid by a seismologist, would select a set of records reflecting the likely magnitudes (M), source-to-site distances (R), and other earthquake parameters thought to drive the probabilistic seismic hazard analysis (PSHA) for the site (McGuire, 2004), and which are believed to matter with respect to structural response (This information comes from a procedure called disaggregation of PSHA). Finally, the records are usually manipulated to match the UHS, individually or in average sense, at the period of the first mode of the structure ($T^*$), Figure 1, or in an interval around it (e.g., Iervolino and Cornell, 2005).

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1 Many researchers contributed to the work described in this paper, all the authors of the paper in the ReLUIS reference list should be considered a co-authoring also this chapter.

2 Although the use of UHS was only recently acknowledged by engineering practice and/or codes for design and assessment purposes (e.g., in Italy), some studies have already investigated the shortcomings of this kind of representation of ground motion and propose more sound alternative (see, e.g., Baker, 2011).
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Figure 1. Steps to define seismic action according to the hazard at the site, from left to right: (1) UHS for the site and limit-state of interest; (2) hazard disaggregation for the spectral ordinate of interest ($T^*$); (3) selection of a set of records compatible to disaggregation and matching the target spectrum at $T^*$.

It has been discussed (e.g., Iervolino et al., 2008 and 2009) that international codes, at least in principle, may be seen as not very far from that approach. In fact, once the target spectrum has been defined, the main criterion is that the records have to match, or exceed it, in a range of periods. Codes often also require the selected records to reflect some characteristic of the relevant seismic sources (e.g., magnitude and distance) jointly with the design spectrum; this for example applies to ASCE Standard ASCE/SEI 7-10 (ASCE, 2010) and Eurocode 8 or EC8 (CEN, 2003). Therefore, the mainstream of the practice-related research on the topic deals, on seismological side, with linking the code approach to record selection to the probabilistic seismic hazard for the construction site and, on the structural side, with the characterization of the sample to capture the seismic response. In other words, to select samples, of different possible size, of real records matching arbitrary design spectra is the basic alternative which can be improved coupling spectrum compatibility with disaggregation (respecting distance-magnitude design range in record selection) or vector valued intensity measures (e.g., adding relation to ground motion duration besides the acceleration spectrum).

This motivated the part of the ReLUIS research dealing with real records, which lead to the inclusion in the last version (3.5) of REXEL (Iervolino et al., 2010a), the ReLUIS record selection software, of several additional features with respect to previous versions (see section 3). Moreover, as the databases of records are continuously improving with new events and improved processing, it may be worthwhile to have a REXEL-like code-related waveform selection tool operating directly on an online-repository of real waveforms. This sparked the development of REXELite (Iervolino et al., 2010g and 2011a) which has the REXEL search engine, but it operates on the portal of the Italian Accelerometric Archive or ITACA, the database of Italian seismic records of the Istituto Nazionale di Geofisica e Vulcanologia (INGV), which is also one of the main results of the project, as described in the following. One of the key features added to REXEL is the database of design earthquakes from disaggregation of probabilistic seismic hazard in terms of spectral ordinates for the whole Italy (Iervolino et al., 2011b), which allows a more hazard-constrained code-based record selection. The disaggregation results, are also available online, in form of a webgis, as an input for REXELite. Finally, to match the needs of recently proposed new paradigms of earthquake engineering such as the displacement-based seismic design and assessment (see the work by Calvi and Sullivan in this same book), one of the results of the project is also REXEL-DISP (Smerzini et al., 2014), which is the equivalent of REXEL, yet selection records based on the matching of a hazard-derived displacement elastic spectrum rather than an acceleration one.
As it regards the other options available to practitioners to define the seismic input to seismic structural analysis, that is artificial and simulated records, different issues motivated the research within the RELUS (2010-2013) project. The basic issue to be addressed is that artificial and simulated ground motions have to be proven equivalent to real records prior to be used as an alternative to them. In a context related to code-based practice, such an equivalence has to be measured in terms of structural response, and it should be evaluated provided that the artificial records at least match the same conditions (i.e., design spectrum) of an equivalent ideal ground motion set made of real records. This was the basis of the work in Iervolino et al. (2010b), where different types of artificial and real records matching the same design scenario, where compared in terms of structural response they induce.

As mentioned, simulated records also need validation, but in this case it can be carried out comparing the structural response of simulated records when the latter try to replicate historical seismic events (Galasso et al., 2012a-c and 2013). In this case the real-records benchmark is provided by the real ground motions from the recorded earthquake. Another possible form of validation of simulated records is to compare the non-linear response on simple single degree of freedom (SDOF) systems to what expected from a ground motion prediction equation (GMPE) developed in terms of nonlinear response as well, but based on real records (De Luca et al., 2011 and 2014). Finally, it is clear that, once validated, in a repository of simulated records is required for engineering practice in the long run. A prototype of such a database, perfectly analogous to those of real records, was developed within the project; indeed, it will be illustrated how the Synthesis database is intended to become a proof of concept for selection of scenario-based simulated records.

2 RESEARCH STRUCTURE

The research deployed on different lines, partly in continuation of the previous ReLUIIIS 2008-2010 project. Three main lines of action (tasks) were identified and pursued:

(1) practice-ready record selection software for seismic structural analysis;

(2) practice-ready tools for hazard-informed record selection;

(3) validation of simulated/artificial ground motion for seismic structural analysis;

(1) led to the further refinement of the already existing ReLUIIIS product REXEL as well as the extension of the REXEL family via the development of other record selection softwares with specific features (to follow). All the developed REXEL-based tools are currently available for practitioners to use. (2) basically concerned the identification, for Italy, of design earthquakes from probabilistic hazard disaggregation, that is the mapping of reference magnitude and source-to-site distance pairs, which control the seismic hazard at the return periods of interest to the construction code (CS.LL.PP., 2008) at any site in the country. Finally, (3) was related with a large effort, also developed in collaboration with international projects on the same topic, regarding engineering validation of artificial and simulated ground motions. As it regards artificial records, the validation was based on spectrum compatibility and in comparison to the nonlinear SDOF response to real records. As it regards simulated records, the result of this activity was twofold: (i) a series of studies of different kind to
assess, using as a benchmark nonlinear SDOF response GMPEs or MDOF response to some historical earthquakes, the possible bias induced by some ground motion simulation/generation techniques; (ii) the development of a prototypal online repository of simulated ground motions for engineering use.

The research structure reflects a coordinated and multi-disciplinary effort to get the deliverables. In fact, three research units mainly contributed to it. One belonging to the University of Naples Federico II (UNINA) and coordinated by the author of this article, one belonging to the Polytechnic of Milan (POLIMI) and coordinated by professor Roberto Paolucci, and finally one of the INGV (Milan section) coordinated by Dr. Francesca Pacor. These groups strongly collaborated and complemented each other. Indeed, UNINA took care of the REXEL and REXEL-related developments as well as the disaggregation study, POLIMI provided the database for the REXEL-DISP software as well as the displacement design spectra derived from long-period hazard assessment for Italy. The INGV contributed to the integrations of the developed tools (i.e., REXELite) in ITACA, as well as the validation of simulated ground motions and development of the Synthesis portal. Finally, the project benefitted of a fruitful collaboration with the University of California at Irvine and the Southern California Earthquake Center who had similar interests on the engineering validation of simulated ground motions.

3 MAIN RESULTS

3.1 REXEL 3.5

In a series of investigations, developed between 2005 and 2006, to assess the practicability of code provisions (with particular focus on the Eurocode 8), an algorithm was developed to analyze all possible combination of seven elastic spectra within a list, to find those having the average compatible with a target spectrum in a range of periods and with some upper- and lower-bound tolerance. That algorithm was employed to find sets compatible to EC8 spectral shapes, and to draw the conclusions depicted in the papers by Iervolino et al. (2008) and (2009). Subsequently, with the introduction in Italy of a new Building Code or NTC08 (CS.LL.PP., 2008), the algorithm at its second generation of development, was given of a graphic user interface (GUI), named REXEL 2.0 (beta), and released publicly at the RELUIS website.

The original procedure implemented for record selection deploys in four basic steps:

a) definition of the target horizontal and/or vertical spectra the set of records has to match on average; the spectra can be built based on some code provisions or may be arbitrary;

b) list and plot of the records contained in the database and embedded in REXEL which fall into the magnitude and distance bins specified by the user for a specific site class;

c) assigning the period range where the average spectrum of the set has to be compatible with the reference spectrum, and specification of tolerances in compatibility;

d) running the search for combinations of seven records which include one, two of all three components of motion and that, on average, match the design spectrum with parameters
specified in step c; the records may be original (unscaled) or linearly scaled in amplitude.

One of the most important improvements of REXEL v 2+, Iervolino et al. (2009, 2010a, 2010d, 2010f), with respect to the first generation, was that the search algorithm was optimized to return, as fast as possible (i.e., within seconds), the combination with the smallest record-to-record variability with respect to the target spectrum. As it is well known, that large variability, which may result from such kind of search (e.g., Iervolino et al., 2008 and 2009), may affect significantly the confidence in the estimation of structural response if only seven records are used as an input for structural analysis. At that stage, the software enabled basically step 1 and 3 depicted in Figure 1, missing the link with the design earthquakes from disaggregation of hazard the design spectrum derives from. This has been possible in the third generation of the software (v 3+). In fact, a comprehensive disaggregation study (for Italy so far; Iervolino et al., 2011b and 2012), now suggests M and R ranges consistent with the hazard for the design spectral ordinates of interest (i.e., step 2 of Figure); see also section 3.4. The same design earthquakes embedded may also be used, via the conditional hazard approach (Iervolino et al., 2010c and 2010e) also implemented, to select records matching the design spectrum and at the same time reflecting likely (in a probabilistic sense) other ground motions intensity measures; e.g., cyclic content of ground motion for duration sensitive structures.

REXEL v 3+ defines target spectra according to several international codes – (1) NTC08; (2) EC8 (Type 1 and Type 2 spectra); (3) ASCE/SEI 7-10 and (4) user-defined spectral shape – and the sets may be searched among three records databases embedded. The spectrum matching waveforms may be preliminarily selected, alternatively to M, R and epsilon (another, well known disaggregation result; Iervolino et al., 2011b) by bins of peak and integral ground motion intensity measures (IMs); i.e., step (c) above may be now also according to ground motion IMs and not only magnitude and distance. Finally, other options as displacement spectrum compatibility check, and repeating record sets’ search excluding undesired records, further improve the selection.

In this section, a brief report of how the new features and enhancements of the last REXEL release (v 3.5) (Figure 2) allows an informed and practice-ready record selection, is given.

3.1.2. Embedded databases

REXEL had built in the records belonging to the European Strong Motion Database or ESD (last accessed July 2007 at http://www.isesd.hi.is/). Recently, Italian free-field records of earthquakes with M larger than 4 from ITACA (http://itaca.mi.ingv.it, updated to April 2011) and worldwide free-field records of earthquakes with M larger than 5 from the Selected Input Motions for displacement-Based Assessment and Design database, or SIMBAD, were also embedded. SIMBAD was developed in the framework of ReLUIS 2010-2013 Project, task Displacement Based Approaches for Seismic Assessment of Structures, as a strong ground motion database suitable for displacement-based design and assessment (Smerzini et al., 2012 and 2014). It contains at more than 400 three-component accelerograms from earthquakes worldwide (Figure 3).
3.1.3. Preliminary search parameters
To make sure the selected set of spectrum matching records has the desirable characteristic, the user can limit the search to waveforms falling in specific M and R bins or M, R and \( \epsilon \) bins. If the spectrum is hazard-based, as it happens in Italy where the code assigns design spectra which are basically UHS, the selection of such bins can follow disaggregation of seismic hazard for the region of the target spectrum of interest (to follow). Alternatively, REXEL 3.5 introduces pre-selection in bins from a specific range of a selected IM. More specifically, the user may select the records in the databases corresponding to a given range horizontal peak ground acceleration (PGA), peak ground velocity (PGV), the Cosenza and...
Manfredi index ($I_D$) (selection according to this parameter may be guided by conditional hazard, see section 3.1.5), Arias Intensity ($I_A$), and, finally, $N_p$ (Bojorquez and Iervolino, 2011).

A parameter that is desirable to include in record selection is the site classification. However, specifying a close match for this parameter in record selection may not always be feasible, because for some soft soils only a few records may be available. Moreover, if the spectral shape is assigned by the code, the site class of real records may be of secondary importance (e.g., Galasso and Iervolino, 2011). In light of these considerations, there may be cases in which it may be useful to relax the matching criteria for site classification. Therefore, in REXEL 3.5 beta it is now possible to select records from *same as target spectrum* soil or from *any site class*. The latter option, as shown in the following, could help to find spectrum matching sets when insufficient records are available for a specific site condition.

After M-R (or IM) bins and site classification are defined, the software returns the number of records, and the corresponding number of originating earthquake events, available in the intervals. This list constitutes the inventory of records in which to search for sets compatible, via their average, with the target spectrum. Spectra of records from preliminary database search may also be plotted along with the target spectrum (i.e., the *preliminary plot* option) to have a picture of the spectra REXEL will search among. This, in most of the cases, enables to immediately understand if the search for spectrum matching sets will be successful.

### 3.1.4. Design earthquakes from disaggregation

When the design spectrum is derived from PSHA (e.g., a UHS as it happens in the Italian code), the *disaggregation* procedure allows to identify, from a probabilistic point of view, the contribution to the hazard of each source (in terms, for example, of M, R and *epsilon*). In particular, *epsilon* ($\varepsilon$) is defined as the number of standard deviation by which the logarithmic ground motion (in terms of spectral ordinates) departs from the median predicted by the chosen attenuation relationship; Ambraseys et al. (1996) for this specific study. Such an information can address the identification of scenarios relevant for design; i.e., the *design earthquakes* which are dependent on the spectral ordinate of interest and on return period the spectrum refers to. In fact, as briefly reviewed in the introduction, most of the codes requires to account in record selection for the features of the seismic sources of interest for hazard at the site, and this may be rationally referred to disaggregation.

To address this issue, a comprehensive disaggregation analysis for the pseudo-accelerations hazard (in terms of four return periods (Tr): 50, 475, 975, and 2475 yr) has been carried out for more than 10000 Italian sites considering four spectral periods: PGA, $S_a(0.5s)$, $S_a(1s)$, and $S_a(1.5s)$. The first half of IMs are considered representative for the short period portion of the response spectrum, while the latter half has been found adequate for moderate-to-long period structures; details may be found in section 3.4 as well as in Chioccarelli (2010) and Iervolino et al. (2011b). Results of the analyses are implemented in REXEL which now provides, for each site, together with the design spectrum, a plot of disaggregation distribution in terms of magnitude and source-to-site distance corresponding to the closer return period and structural period with respect to those of interest. This is to guide the definition of M and R bins in which to find spectrum matching sets; i.e., linking all steps of Figure 1.

### 3.1.5. $I_D$ and PGV conditional hazard

When seismic analysis of structures sensitive to cyclic content of ground motion or to PGV is concerned, to match the design spectrum may be insufficient to properly characterize the set of records used as an input (e.g., Iervolino et al., 2006).

A way to account for multiple IMs (acceleration and one related to duration or PGV in this case) at the same time, is to compute the so-called vector-valued hazard analysis for the site
Although computationally demanding, this analysis allows to compute the joint hazard for more than one IM. However, if in a vector of two, one IM is seen most important with respect to another, an alternative, easy yet hazard-consistent way of including secondary intensity measures in record selection is represented by the conditional hazard (Iervolino et al., 2010c and Chioccarelli et al., 2012). This consists of computing hazard curves of the secondary IM conditional to a specific value of the primary IM. Conditional hazard is especially appropriate if the primary IM is the design acceleration value (for example PGA) provided by the code, and one wants to include in selection the likely value of the secondary IM conditional to it. In fact, two applications of conditional hazard are implemented in REXEL where PGA is assumed as the primary IM and the Cosenza and Manfredi index ($I_D$), which is considered a proxy for the cyclic content of ground motion, Equation (1), or PGV are the secondary IMs. In Equation (1), $a(t)$ is the acceleration time-history, $t_E$ is the total duration of the ground motion recording.

$$
I_D = \frac{1}{\text{PGA} \cdot \text{PGV}} \int_0^{t_E} a^2(t) \, dt
$$

Having conditional hazard implemented for Italian sites, REXEL suggests to the user the distribution (in terms of complementary cumulative density functions) of $I_D$, or PGV, given the design PGA. This allows improving seismic input selection including, in a probabilistically consistent manner, care for PGV or cyclic content, without having to change the code design hazard.

### Set size and set modification

In the previous releases of REXEL, it was possible a selection of seven records each of those featuring one, two or three components of motion. This was because seven is a reference set size in many codes. Now REXEL allows the search for sets comprised of one, seven, or thirty records. The new option has been included as one may be interested in one record individually matching a spectrum, as well as large group of records (i.e., thirty) for an analysis in which structural response is assessed with more confidence with respect to use seven records only.

After a spectrum matching set if any size is found, the analyst may want to exclude a particular record. In fact, REXEL finds sets matching the target spectrum via their average, thus a particular record may have a spectral shape the user wants to disregard for some reason. To address this issue, REXEL now includes the option Repeat search excluding a station, which allows to repeat the performed analysis by excluding any record from an already found solution. This allows to refine the selection in an iterative yet very fast way as it is guided by visual inspection of individual spectra in a found set.

### REXELite

The availability of internet strong-motion databases as the ITalian ACelerometrica Archive (Luzi et al., 2008), developed by INGV for seismological purposes, is of certain interest also to the earthquake engineering community, as it facilitates seismic input definition for dynamic structural analysis by means of real records. However, as discussed, seismic structural codes, regarding the ground motion selection issue, often require that the suite of records has to “match” the design spectrum for the site and for the limit state of interest. This, along with other provisions, makes selection of real records hardly feasible for the practitioner if not adequately aided, as demonstrated by REXEL. While REXEL is a standalone software, in the RELUIS 2010-2013 project a web-based version, REXELite, with the same record selection
REXELite has the significant advantage to be constantly synchronized with the continuing evolution of ITACA, including new records, updated site classifications and new or revised information on existing waveforms.

REXELite (Figure 4) allows to search for horizontal combinations of seven 1- or 2-horizontal components strong motion records, compatible on average with a specified target (code) spectrum, in a range of periods of interest and with arbitrary tolerances. The target spectra may be defined according to NIBC or to EC8. For this purpose, it is necessary to enter the geographical coordinates of the site, latitude and longitude in decimal degrees, and to specify the Site Class (according to EC8 classification), the Topographic Category (as in EC8), the Nominal Life, the Functional Type, and the Limit State of interest. For EC8 spectra, it is necessary to specify only the anchoring value of the spectrum (and therefore may be used for engineering projects outside Italy) and the site class because, as mentioned, the design spectrum is only function of $a_g$ and $S$.

REXELite allows one to search for records within ITACA belonging to the same site class of the defined spectrum or to any site class (i.e., records referring to different site conditions may show up in the same set matching the target spectrum; see next section) and corresponding to magnitudes and epicentral distances of interest. In fact, the intervals $[M_{\text{min}}, M_{\text{max}}]$ (moment and/or local magnitude) and $[R_{\text{min}}, R_{\text{max}}]$ (epicentral distance, in km), in which to search for sets of accelerograms, have to be defined. Because when selecting a set of accelerograms for structural analysis the main objective is to reflect the relevant hazard scenarios at the site, for example from disaggregation (e.g., Iervolino et al., 2011b),
REXELite allows to select suites which also belong to user-defined magnitude and source-to-site distance bins, and to the same site class of the location of the structure, or to any site class. Also the recording instrument features may be specified, e.g., whether late-triggered and/or analogue recordings should be or not included in the search. For an introduction and discussion on the quality of ITACA records, and specifically of the late-triggered records, see Paolucci et al. (2011) and Pacor et al. (2011). Once these options have been defined, REXELite returns the number of records (and the corresponding number of events and recording stations) available in ITACA. The spectra of the records returned by this preliminary search are used by RESEE to find a combination of seven accelerograms, whose average is compatible with the defined target spectrum and some tolerance in an arbitrary interval of periods [T₁, T₂] between 0s and 4s (Figure 4). ITACA may be searched for spectrum-matching sets of records which are original (unscaled) or ground motions linearly scaled in amplitude. Finally, RESEE not only ensures the set resulting from the search has its average matching the target spectrum, but also that it is the one with the smallest individual record-to-record variability (as in RESEE).

3.3. RESEE-DISP

Recent performance-based approaches to seismic design gave an increasing emphasis on the definition of the seismic demand at long periods. This is even more important when one refers to the definition of seismic demand in terms of displacement response spectra, such as in the capacity-spectrum (FEMA, 2005) and the direct displacement-based design approaches (Priestley et al., 2007), where the availability of reliable earthquake ground motions up to long periods is required. This stimulated several research works concerning, on one hand, the development of improved displacement design spectra based on independent evaluations of long period spectral ordinates rather than on the use of the standard pseudo-spectral rule (Faccioli et al., 2004) and, on the other hand, the definition of simple criteria to assess the reliability of digital strong motion data (Paolucci et al., 2008). Such advances supported the calibration of up-to-date empirical ground motion prediction tools extending to long periods (Cauzzi and Faccioli, 2008), the improved quantification of site effects at long periods (e.g., Figini and Paolucci, 2009), the formulation of new seismic hazard maps at long periods in Italy (Faccioli and Villani, 2009).

In the framework of performance-based seismic design and assessment, a relevant issue is the selection of a suitable set of ground motion records to represent the design seismic excitation for nonlinear dynamic analysis. According to the vast majority of international codes, such as the Eurocode 8, or EC8 (CEN, 2003), the current Italian seismic code, or NTC08 (CS.LL.PP, 2008), and US ASCE 7-10 (ASCE, 2010) provisions, the selected suite of records needs to match, within prescribed tolerance limits, the target design spectrum. Moreover, acceleration histories shall be obtained from records having magnitudes, distances and source mechanisms consistent with those controlling the target spectrum in the range of periods of interest for a given application. While tools designed for the selection of earthquake ground motions compatible with design acceleration response spectra for earthquake engineering purposes are progressively becoming available, e.g., RESEE and RESEE lite, tools for the selection of displacement-spectrum compatible accelerograms are still very limited and at research stage. Therefore, a user-friendly software, namely RESEE-DISP (Figure 5), which allows to automatically select suites of real ground motion records compatible with a target displacement spectrum, was developed.
The need to provide reliable displacement spectral ordinates over a broad range of vibration periods, e.g., up to about 10 s, led to embed in REXEL-DISP an *ad hoc* strong motion database, the discussed SIMBAD (Selected Input Motions for displacement-Based Assessment and Design) dataset, consisting of high quality three-component acceleration recordings from shallow crustal earthquakes worldwide in near field conditions. An innovative feature of REXEL-DISP is the definition of the target displacement spectra: besides the design spectra from the NTC08 and EC8 codes, an alternative target displacement spectrum for Italian sites is introduced. The latter combines the norm prescriptions at short periods and the main results of the PSHA study for Italy of Faccioli and Villani (2009) at long periods.

REXEL-DISP, available at [http://www.reluis.it/index_eng.html](http://www.reluis.it/index_eng.html), allows one to search for combinations of horizontal accelerograms whose average is compatible with a target displacement spectrum, and in which individual records have the shape as similar as possible with that of the target in a prescribed period range. Records may also reflect desired magnitude and source-to-site distance bins or specific ranges of some peak and integral ground motion intensity measures.

In the definition of the analysis constraints, REXEL-DISP allows to search for records within SIMBAD belonging to magnitudes and epicentral distances from pre-defined bins or to selected ranges of: i) PGA; ii) peak ground velocity or $PGV$; iii) $I_D$; iv) Arias Intensity ($IA$).

Once the selection options are defined, REXEL-DISP returns the number of records (and the corresponding number of events) available in SIMBAD, which match these. The spectra of the records returned by this preliminary search are used by REXEL-DISP to find sets of record (one, seven, or thirty), whose average is compatible with the defined target spectrum in an arbitrary interval of periods $[T_1, T_2]$ between 0 s and 10 s. Spectrum matching is ensured with some tolerance also defined by the user as an analysis’ option.
The compatible record set found can be either comprised of single-component accelerograms, hence to be applied in one horizontal direction for analysis of bi-dimensional (plan) structures, or of pairs of horizontal components (therefore, for example, if one searches for a set, of seven ground motions, the software actually returns fourteen records) for the analysis of three-dimensional structures.

REXEL-DISP allows one to obtain combinations of accelerograms compatible with the code spectrum that do not need to be scaled, but it also allows one to choose sets of accelerograms compatible with the target spectrum, if scaled linearly (in this case, the individual records scale factors (SFs) are also provided). If this second option is chosen, the user has to check the Scaled records box, and the spectra of the preliminary search are normalized dividing the spectral ordinates to the value at 10 s. Combinations of these spectra are compared to the non-dimensional target spectrum. If this option is selected, it is also possible to specify the maximum mean scale factor allowed.

3.4. Engineering design earthquakes for Italy

It was illustrated that REXEL has embedded, to drive record selection, disaggregation of seismic hazard of four different spectral ordinates for the whole Italy. The disaggregation was developed in a specific study (Iervolino et al., 2011b) that is described in this section. Given the characterization of seismic sources and once a ground motion IM is chosen, PSHA allows to identify, for each considered site, the probability of exceedance of different IM values in a time interval of interest. Choosing a return period, and assuming as IM the elastic spectral acceleration at different structural periods, it is possible to build the UHS; i.e., the response spectrum with a constant exceedance probability for all ordinates (Reiter, 1990). In the most advanced seismic codes, the UHS currently is the basis for the definition of design seismic actions on structures. On the other hand, for example when dealing with record selection, accelerograms not only are recommended to match such a spectrum, but also to be compatible with the earthquakes dominating the hazard at the site (e.g., Eurocode 8); see Figure 1.

PSHA, for its integral nature, combines the contribution to the hazard from all considered sources. The event most important for the occurrence or exceedance of an IM value may be identified via disaggregation of seismic hazard (Convertito et al., 2009). In fact, once the UHS has been defined, it is possible to identify one or more earthquakes; i.e. the values of magnitude source-to-site distance and $\varepsilon$ (number of standard deviations that the ground motion parameter is away from its median value estimated by the assumed attenuation relationship) providing the largest contributions to the hazard in terms of exceeding a specified IM value. These events may be considered as the earthquakes dominating the seismic hazard in a probabilistic sense, and may be used as design earthquakes; e.g., Iervolino (2010).

Analytically, disaggregation results is the joint probability density function (PDF) of magnitude, distance and $\varepsilon$ given the exceedance of an IM level; i.e., the values of these parameters most frequent in those cases the IM level chosen is exceeded, as described in the following equation:

$$f(m,r,\varepsilon|IM > IM_0) = \frac{\sum_{i=1}^{N} \nu_i \cdot I[IM > IM_0]\cdot f_{M,R,\varepsilon}(m,r,\varepsilon)}{\sum_{i=1}^{N} E_i(IM > IM_0)}$$

where: $N$ is the number of seismic sources which affect hazard at the site of interest; $\nu_i$ is the mean annual rate of occurrence of earthquakes at each of the considered sources; $E_i(IM > IM_0)$
is the mean annual rate of exceedance of a given $IM_0$ value (result of the hazard integral) and $I$ is an indicator function that equals to 1 if $IM$ exceeds $IM_0$ for a given distance $r$, a given magnitude $m$ and a given $\varepsilon$, whose joint PDF is represented by $f_{m,r,\varepsilon}(m,r,\varepsilon)$. From equation (2) it is possible to observe that disaggregation depends on $IM_0$ (i.e., the hazard level being disaggregated, or the return period of the IM) and on the definition of the IM itself. If the spectral acceleration of interest is $Sa(T)$, then disaggregation, and therefore the design earthquakes, also depends on $T$. In fact, UHS for different return periods is characterized by different design earthquakes, and, within a given UHS, short and long period ranges may display different $M$, $R$ and $\varepsilon$ from disaggregation (Reiter, 1990; Convertito et al., 2009).

In Italy, INGV provides disaggregation, for nine return periods between 30 and 2475 year, but for PGA only (see http://esse1-gis.mi.ingv.it/). Within this project, disaggregation of all Italian sites for structural periods equal to 0 sec (PGA), 0.5 sec, 1.0 sec and 1.5 sec was carried out. Disaggregation for these four periods is intended to help in identifying design earthquakes for the short, moderate and long period ranges of the UHS related to the life safety limit-state of ordinary constructions. Four different return periods were considered (2475, 975, 475 and 50 years) corresponding to the main limit states for civil and strategic structures, however, only results for $Tr$ equal to 475 years will be shown in the following.

Disaggregation requires PSHA first; then, exceedance probabilities were computed for thirty values of the IMs equally distributed between 0.001g and 1.5g. All the analyses have been performed by a FORTRAN program specifically developed and also used in Convertito et al. (2009). The modelling of seismogenic zones is that proposed by Meletti et al. (2008), also adopted by INGV. Seismicity parameters of each zone are those used by Barani et al. (2009). The considered grid for Italy is the same of that from INGV and used in the Italian seismic code. All the analyses refer to rock site conditions. According to Ambraesys et al. (1996), which is the GMPE considered, magnitude is that of surface waves ($M_s$). Because of seismogenic zones modelling, the hazard software assumes a uniform distribution of possible epicentres, then epicentral distance is converted (Gruppo di Lavoro, 2004) in closest distance to the projection of the fault rupture ($R_{jb}$), as defined by Joyner and Boore (1981). Because the used GMPE is valid for $R_{jb}$ up to 200 km, the influence of sources with larger $R_{jb}$ was neglected in the hazard analysis for each site.

The hazard results, computed in terms of PGA and spectral acceleration at $T = 1.0$ sec are in fair agreement with those of INGV, and they are considered as the basis for disaggregation analyses presented in this section. The joint PDFs of $M$, $R$ and $\varepsilon$ given the exceedance of $IM_0$ with an exceedance return period of 475 years were computed, for each site of the grid, via simulation and using bins of $M$, $R$ and $\varepsilon$ equal to 0.05, 1.0 and 0.5, respectively. Minimum and maximum values used for $\varepsilon$ are -3 and +3. Subsequently the first two modes of the joint PDF from disaggregation were extracted. The first mode is identified as the $M$, $R$ and $\varepsilon$ vector giving the maximum contribution to the hazard, while the second mode corresponds to second higher relative maximum contribution, identified if the differences between first and second mode are 5.0, 0.25 or 0.25 in terms of $M$, $R$, or $\varepsilon$ respectively. Figure 6 and Figure 7 show the modes of disaggregation distributions. In the map referring to the second mode, white zones indicate that the hazard contribution of second mode is negligible or zero.

Looking at disaggregation results for PGA, it was possible to identify general trends: (i) the first mode corresponds to an earthquake caused by the closer source (or the source the site is enclosed into) and with low-to-moderate magnitude, and (ii) the influence of the more distant zones is accounted for by the second mode, which is usually a larger magnitude one. For a few sites, the particular combination of geometrical condition and seismic parameters of each source can determine an inversion of disaggregation results, and in such sites the sources
influencing the first mode can be more distant than that related to the second mode. Other exceptions are represented by sites with a single mode; i.e., one design earthquake. These sites are enclosed or close to zones with high seismicity with respect to the surrounding zones and the hazard contribution from other zones is negligible (see also Convertito et al., 2009). Considering $T = 1.0$ sec disaggregation results, the general conclusions of PGA are confirmed. However, changing from PGA to Sa($T=1.0$) the contribution of the second mode increases. Finally, analyses show that almost all sites are characterized by two different modal values of disaggregation. This means that, from a design point of view, for each site may be useful to know not only the first mode, but also the second one, in definition of seismic action on structures.

It is finally to note that this disaggregation information are available to the public also through the ReLUIS website (http://193.206.66.17/egeos/web/reluis; user name and password “reluis”). Once the design earthquakes are selected for a specific site in Italy then they can be automatically passed to the REXELite website and used as a selection constraint for spectrum-matching records.

Figure 6. Map of disaggregation results represented by first ($M^1_s$) and second ($M^2_s$) modal values of $M_s$ for PGA (left) and Sa(1.0sec) (right) and for $Tr = 475$ year.
Figure 7. Map of disaggregation results represented by first ($R_{jb}^1$) and second ($R_{jb}^2$) modal values of $R_{jb}$ and $\epsilon$ for PGA (left) and Sa(1.0sec) (right) and for $Tr = 475$year.
3.5. Spectrum-based evaluation of seismic response to artificial and real-manipulated records

Engineering practitioners have several options to get (spectrum-matching) input signals for their analysis; e.g., real or real manipulated records and various types of synthetic and artificial accelerograms. All these options are usually acknowledged by codes which may provide additional criteria or limitations for some of them. In the Italian seismic code, for example, artificial records, generated recurring to random vibration theory, should have duration of at least 10s in their pseudo-stationary part, and cannot be used in the assessment of geotechnical structures. Synthetic records, generated by simulation of earthquake rupture process, should refer to a characteristic scenario for the site in terms of magnitude, source-to-site distance and seismological source characteristics; finally real records should reflect the earthquake dominating the hazard at the site. However, practitioners not always can accurately characterize the seismological threat to generate synthetic signals or it is not possible to find a set of real records that fits properly code requirements in terms of a specific hazard scenario. In fact, despite in the last decades the increasing availability of databanks of real accelerograms has determined a spread use of this type of records, it may be very difficult to successfully apply code provisions to obtain code-compliant real record sets. In particular, provisions regarding spectral compatibility are hard to match if appropriate tools are not available. This is why the relatively easy and fast generation of artificial records, perfectly compatible with an assigned design spectrum, is still very popular for both practice and research purposes. More recently, procedures to get the spectral compatibility of real records by wavelets adjustment were proposed (e.g., Grant et al., 2008). This kind of manipulation is conceptually an extension of the more simple linear scaling of real records to modify (e.g., to amplify) the spectral shape to get a desired intensity level.

Although several studies tried to assess the reliability of each of these procedures (e.g., Schwab and Lestuzzi, 2007), many of them are relatively narrow in scope without giving a general overview of the spectral compatibility issue. Iervolino et al. (2010b) tried to address the spectral matching matter from the structural point of view in terms of ductility and cyclic response, having as reference a code-based design spectrum. To this aim six classes of 28 accelerograms, each of those comprised of four sets of 7, were considered: (1) unscaled real records (URR - Figure 8a); (2) moderately linearly scaled real records (SF5 - Figure 8b); (3) significantly linearly scaled real records (SF12 - Figure 8c); (4) wavelet-adjusted real records (RSPMatch - Figure 8d; Abrahamson, 1992); (5) (Belfagor - Figure 8e; Mucciarelli et al., 2004) stationary artificial records; (6) (SIMQKE - Figure 8f; Gasparini and Vanmarke, 1976) non stationary artificial records. All sets are compatible with the elastic design spectrum for a case study in southern Italy.

The seismic responses of a large number of SDOF systems, with different backbones, hysteretic relationships, and with various strength reduction factors (R), were considered. As structural response measures, or engineering demand parameters (EDPs), the ductility normalized with respect to the strength reduction factor and the equivalent number of cycles were considered to relate the ground motions to both peak and cyclic structural demand (Manfredi, 2001). Analyses aimed at comparing the differences, if any, in the EDPs associated to each class of records with respect to the unscaled real records, considered as a benchmark. Hypothesis tests on selected samples were also carried out to assess the statistical significance of the results found in terms of both peak and cyclic response.
Figure 8. URR (a), SF5 (b), SF12 (c), RSPMatch (d), Belfagor (e), and Simqke (f) acceleration elastic spectra, compared to the target spectrum.

While a more comprehensive summary of the work and the results may be found in Iervolino et al. (2010b), as an example of the results of this study Figure 9 shows kinematic ductility demand (D_{kin}) normalized with respect to the different R values investigated referring to one
of the SDOFs investigated; i.e., the EPH (elastic-plastic with hardening) system. For low \( R \), normalized ductility seems to be similar for all six classes of records. The cases for high \( R \) values (Figure 9c and Figure 9d) emphasize an apparent underestimation of ductility for artificial records with respect to real records classes. In particular, results for \( R \) equal to 10 show different underestimation levels for adjusted and artificial classes of records: Belfagor class is followed by Simqke and RSPMatch. Ductility response indicates that wavelet adjusting procedure gives a lower bias. On the other hand, it should be recalled that RSPMatch records are the same records as URR to which the adjustment procedure was applied. Linearly scaled records, indifferently if moderately or significantly, seem to show no trends with respect to URR. The large scattering of real records with respect to the target, leads to large variability of the average estimated response from class-to-class of real records; e.g., Figure 9c and Figure 9d.

Figure 9. Average values of kinematic ductility demand for EPH system computed as mean value of 28 records.

3.6. Scenario- and GMPE-based evaluation of seismic response to simulated records and the Synthesis repository

Modern common earthquake resistant design procedures are based on inelastic deformation of structures as the primary source of seismic energy dissipation. On the other hand, design actions are based on PSHA, which refers to elastic acceleration response spectrum ordinates.
According to the analysis method employed, the elastic acceleration response spectrum represents the link between hazard and vulnerability of structures. Recently, earning interest is the possibility to develop PSHA directly in terms of nonlinear structural response to improve accuracy in definition of structural design targets. This may require a prediction equation (also referred to as attenuation law) for the structural response measure of interest. The possibility to develop an attenuation law for nonlinear SDOF systems’ responses based on the Italian Accelerometric Archive was explored. Peak and cyclic inelastic structural response parameters were considered for the development of such attenuation laws, useful for both design or assessment aims (see De Luca, 2011).

Prediction equations in terms of inelastic peak and cyclic inelastic response can also be employed as a benchmark for the engineering validation of simulated records; i.e., those ground motions obtained simulating source, path, and site effects in one earthquake. The validation made in terms of prediction equations has its main basis in the fact that as long as simulated records are employed in nonlinear dynamic analyses as substitutes of real records, the main target is that they lead to the same conclusion in terms of risk assessment.

A preliminary validation example, referred to the case of four sites for the 1980 Irpinia, M 6.9 earthquake was carried out focusing on the comparison of validation made by means of prediction equations with the more typical simulated-to-real validation approach. The synthetic records refer to 54 simulations of the Irpinia event at those seismic station (BGI, BSC, BNV, BVN in ITACA) where a real counterpart was recorded in the event. Three finite-fault simulation techniques were adopted to produce synthetics: purely stochastic, hybrid deterministic-stochastic with approximated Green’s, broadband integral-composite. For all simulations, a normal fault-plane, embedded in 1D propagation medium, 35 km long and 15 km wide, with 315° strike and 60° dip, was assumed. On this fault, 54 different rupture models were simulated by varying the main source kinematic parameters such as: position of the nucleation point, rupture velocity, and final slip distribution (Ameri et al., 2011).

In the example provided, SODF’s inelastic displacements, and equivalent number of cycles (Manfredi, 2001), for different strength reduction factors, were controlled as informative intensity measures for peak and cyclic response to be employed in the validation (see Figure 10 and Figure 11). In fact, for these, inelastic GMPEs were developed (those of De Luca, 2011). The first, expected, conclusion is that considering nonlinear response rather than the only elastic one can provide additional significant results to the validation procedure (see De Luca et al., 2014, for details).

The preliminary validation shows that the simulations have an underestimation trend mostly in terms of cyclic response with respect to the median estimates of the prediction equations. On the other hand, in the case of inelastic displacements the simulation are between the one standard deviation bands of the prediction equations. The underestimation trends of the simulated records, have different causes for equivalent number of cycles and spectral displacements. For cyclic response, the underestimation can be partially ascribed to the simplified simulation model with respect to the actual 3-dimensional crustal structure. For peak values, the simulations are lower than mean predictions but in better agreement with the observed data, thus suggesting that synthetics capture specific features related to the Irpinia earthquake, that are not predicted by the GMPE, developed for the whole national territory. The underestimation of observed peak spectral displacement is similar, while the underestimation trend in terms of cyclic response is opposite, to what found in previous studies for spectrum-compatible artificial records. Notwithstanding the preliminary character
of the results provided, given the small sample of records considered, the validation approach through prediction equations of peak and cyclic inelastic response is a first step towards a systematical engineering validation of physics-based simulated accelerograms.

Finally, the activity related to simulated records produced a prototype for synthetic seismograms database, called SYNTHESIS (http://synthesis.mi.ingv.it/); Figure 12. It is based on the structure and the tables of ITACA, made and managed to distribute strong-motion data recorded in Italy. SYNTHESIS is a fully relational data base, which can be accessed through user friendly interfaces which allow the user to perform queries to select scenarios, sites, and waveform parameters, in order to download the synthetic seismograms. The main interfaces are three: one for the seismic scenarios, one for the sites and one for synthetic seismograms. The database can be explored through searchable key fields: 13 for the stations, 11 for the seismic scenarios and 13 for the waveforms. The basic idea is that separated queries can be performed for three distinct data base blocks (stations, events and waveforms). Each query (event, station and waveform) returns a list and the single outcome can be explored in detail. Figure 8 shows and example of detail-page relative to the selection...
of a seismic scenarios. Both sites and events are mapped through the Google-Map data©, which allows to display point data alternatively on a satellite image or a basic map (or both). A gallery of images is also included in the database, illustrating input data and results from the scenarios study, such as distribution of slip on the fault or map of simulated peak values corresponding to a specific scenarios.

Although synthesis is intended to host records from eventually simulated earthquakes, it was originally populated with three sets of simulated accelerograms, each of them composed by about 4500 waveforms, computed for the Irpinia fault, that caused the 1980, M 6.9, Irpinia earthquake. A common name and file format were selected to write the files containing the synthetics.

It is worth to mention also that the work related to validation of simulated ground motion, thanks to a collaboration with the University of California at Irvine (for what concerns the structural analysis part) and the Southern California Earthquake Center (for the part concerning the simulation of ground motions), also referred to simulations for historical events recorded in the US. In particular, a comparison between simulated and recorded GMs in terms of elastic and post-elastic seismic response was carried out. This was pursued by considered elastic and inelastic SDOF systems and generalized linear MDOF buildings. Four historical earthquakes in California have been considered (see Figure 12). Several engineering demand parameters have been considered and an example of comparison is shown in Figure 13; details may be found in Galasso et al. (2012a-c and 2013).
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Figure 12. Maps of the considered earthquakes. The star is the epicenter and the grey triangles are recording stations of the NGA database for which the simulations are available. The red triangles are recording stations considered in this study.

Figure 13. Simplified model used (left) and ratios of the medians of the generalized maximum interstory drift ratio (MIDR) spectra for simulated GMs to the corresponding quantity computed for the recorded GMs in the Imperial Valley earthquake.

4. DISCUSSION

The work described herein was an integrated effort to comply with code-based requirements for record selection, yet rendering it as much as possible hazard-informed. In other words, the aim of the bulk of the research carried out was entirely devoted to enrich seismic-code-related record selection with relevant research results on the topic. Another driver was the development of tools that may be directly applicable by the practitioners. Therefore, large part of the research was devoted to the update and extension of the REXEL software. The latter
was released with new features, which integrate new hazard-related information such as disaggregation and conditional hazard. Moreover, other versions of REXEL with specific purposes, that is to work online on the ITACA records repository, or to comply with a displacement spectrum for displacement-based earthquake engineering were developed. This effort of having practice-ready tool also produced an online repository of disaggregation of seismic hazard to provide design earthquakes for the whole Italy. This database is directly linked to REXELite so that once the site is selected the design earthquakes are automatically input as magnitude and distance constraints for record selection in ITACA.

The second part of the work was aimed at understating the features of simulated and artificial records that may impact structural response. This is important, indeed, because, once proven, applicable these records may provide an alternative for all those cases in which real records are not available. Two issues were faced in particular. First of all, it was assessed the bias, if any, induced by artificial records when the criterion is matching a design spectrum, that is code-based selection. The response of different kinds of artificial records and manipulated real records were compared to a reference real records case. Different structural response measures were considered, believing that artificial records may induce different seismic response with respect to real records also depending on the engineering demand parameters. Finally, simulated ground motions (i.e., those obtained via simulation of source path and site effects) were also considered and tested in terms of non-linear structural response versus their real counterpart. This was carried out for some Italian and US historical earthquakes and in terms of single and multiple degrees of freedom systems in a joint effort with the University of California at Irvine and the Southern California Earthquake Center. Finally, the prototype of a repository for simulated ground motions for engineering uses was developed. The long term goal is to have a database of simulated earthquake scenarios for earthquake engineering practice that would allow one to select specific situations that may not always be represented by recordings.

5. VISIONS AND DEVELOPMENTS

The described research takes for granted the selection criteria given in the seismic codes (with a specific focus on Italy) and tries to account as much as possible for the research results on the topic of seismic input for seismic structural analysis without changing those. However, it is recognized that there are some issues which may require update of selection criteria and consequently research in the field. For example, the intrinsic limits of the uniform hazard spectrum, which does not represent the spectrum of any specific event, may be overpassed by more recent alternatives. Also the control of the uncertainty in the estimated structural response via the number of ground motions employed should be explicitly investigated. Moreover, some specific, yet relevant, situations, such as near-source pulse-like effects are not yet accounted for by record selection practice. Also record selection for geotechnical engineering requires further effort. In particular the consistent consideration of relevant intensity measures beyond spectral ordinates as well as the use of artificial or simulated ground motions.

To address all these issues substantial aid may come from simulated ground motions, which in principle may provide great flexibility to address a broad variety of engineering needs. Therefore, a large coordinated effort of seismologist and earthquake engineers (both structural and geotechnical) should be devoted to the validation of simulations for engineering purposes.
as well as to render easily available for practice this kind of ground motions. On the other hand, the selection of real records is nowadays a quite established methodology, which may be refined but will unlikely undergo under changes of paradigm in the near future.

6. MAIN REFERENCES

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7. RELUIS REFERENCES


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