Italian design earthquakes: how and why

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ABSTRACT
Ground motion records for engineering seismic analysis of structures are often required by codes to reflect the hazard at the site and also, at least in Europe, to be consistent with the features of the seismic sources in the region. The former issue is usually addressed via a prescribed design spectrum while for the latter, if the design spectrum is derived from probabilistic seismic hazard analysis, disaggregation may be helpful allowing to identify the contribution to the hazard of each source (in terms, for example, of source-to-site distance, magnitude, and ε). Such an information can address the identification of scenarios relevant for design; i.e., the design earthquakes.
The paper discusses the identification of code-consistent engineering design earthquakes referring to the Italian case. Because disaggregation results change with the spectral ordinate and return period, the considered hazard refers to peak ground acceleration and 1s spectral acceleration with four exceedance return periods between 50 and 2475 years. Identification of design earthquakes starting from the disaggregation distributions of each site, by means of which the country is sampled, is discussed. Issues, such as sites with multiple design earthquakes and dependence of disaggregation results from structural features and design limit state, are also addressed, and possible applications discussed.

1 INTRODUCTION

In international codes seismic input is mostly represented by design spectra which are usually computed by probabilistic assessment. In fact, for a given seismic-source model and one or more ground motion prediction equations (GMPEs), probabilistic seismic hazard analysis (PSHA) is used to obtain the average return period of ground motions exceeding a given intensity measure (IM) threshold at the considered site (McGuire, 2004). If the IM is the elastic spectral acceleration at different structural periods, it is possible to build the uniform hazard spectrum (UHS); i.e., the response spectrum with a constant exceedance probability for all ordinates. Such type of spectrum (or a simplified approximation) is usually assumed as design spectrum. For example, Italian design code spectra (CS.LL.PP., 2008) are a very close approximation of UHS computed by Instituto Nazionale di Geofisica e Vulcanologia (INGV) over a grid of more than 10000 points for 9 return periods (Tr) from 30yr to 2475yr, and 10 spectral ordinates, from 0.1s to 2.0s (Stucchi et al., 2011).

UHS implicitly includes information about the features of the seismogenic sources determining the hazard at the site, but, prudently, the practitioner is often required by codes (e.g., Eurocode 8; CEN, 2003) to also account explicitly for them when, for example, selecting records for nonlinear dynamic analysis of structures. Because it is unlikely that the engineer has the information and/or is able to qualify the input ground motions with respect to the seismological features of the seismic sources, an useful tool to be used is the so-called *disaggregation* analysis (Bazzurro and Cornell, 1999). It identifies the values of some earthquake characteristics providing the largest contributions to the hazard. These may be referred to as the earthquakes dominating the seismic hazard in a probabilistic sense, and may be used as *design earthquakes* (DEs), as introduced by McGuire (1995).

Herein, Italian DEs are discussed for two different spectral acceleration ordinates[1], Sa, at 0s (i.e., peak ground acceleration or PGA), and 1s in order to account for short and moderate period regions of the response spectrum. Considered return periods are: 50, 475, 975 and 2475 years. Disaggregation was computed in terms of magnitude (M), source to site distance (R) and ε (the number of standard deviations that the ground motion parameter is away from its median value estimated by the assumed attenuation relationship).

Although analyses refer to Italian sites, general issues regarding identification of DEs and their dependency on structural and return periods are investigated, and conclusions are drawn. Finally some suggestions for practical engineering applications of DEs are provided.

2 FRAMEWORK

For the purposes of this study, the seismic hazard for the two chosen spectral ordinates was computed first. Hazard (and disaggregation) analyses have been performed by a computer program specifically developed and also used in (Convertito et al., 2009 and Iervolino et al., 2011).

The whole country was discretized using the same grid of about 10760 points adopted by INGV and, therefore, by the Italian seismic code. The seismogenic sources are that of Meletti et al. (2008), adopted also by INGV and sketched in Figure 1. Minimum and maximum magnitude (M_{min} and M_{max}), annual rate of earthquake occurrence above M_{min} (ν) and negative slope of Gutenberg and Richter (1944) relationship (b) are the seismic parameters associated to each zone. Numerical values are those used by Barani et al. (2009)[2].

Considered GMPE is that of Ambraseys et al. (1996) and used magnitude is that of surface waves (Ms). All the analyses refer to rock soil conditions.

A uniform epicenter distribution in each seismogenic zones was assumed and, according to distance applicability limits of the GMPE, contributions to hazard distant more than 200km from each site were neglected. No background seismicity was included because its significance is expected to be negligible (see Stucchi et al. 2011 for details).

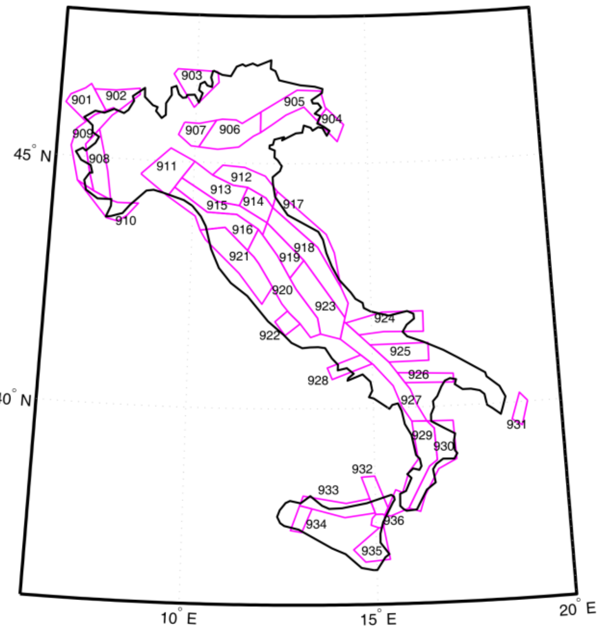

Figure 1. Seismogenic zones considered for Italy.

Once PSHA has been performed, disaggregation allows identification of the hazard contribution of each {M, R, ε} vector. Analytically disaggregation distribution is the four dimensional joint probability distribution represented by the following equation:

$$f\left(m,r,\varepsilon \middle| IM > IM_0\right) = \frac{\sum_{i=1}^{n} \nu_i \cdot I\left[IM > IM_0 \middle| m,r,\varepsilon\right] \cdot f\left(m,r,\varepsilon\right)}{\lambda_{IM_0}} \qquad (1)$$

in which $f\left(m,r,\varepsilon \middle| IM > IM_0\right)$ is the joint probability density function[3] (PDF) of {M, R, ε} conditional to the exceedance of an IM threshold (IM_0), I is an indicator function that equals 1 if IM is larger than IM_0 for a given distance r, magnitude m, and ε; n is the number of seismic

[1] INGV also provides data about the seismic scenarios mostly contributing to the hazard, but only referring to peak ground acceleration.

[2] An erratum (Barani et al., 2010) to this reference reports b values for zones 903, 920 and 922 different with respect to those considered in this study. However, given differences between correct and incorrect values and geographical location of zones, it is believed that changing these parameters should have minor influence on results presented in the following.

[3] In principle other source features may considered in disaggregation (e.g., faulting style, hanging/foot wall, etc) yet their relevance with respect to engineering practice is not fully proven to date.

sources relevant for the hazard at the site, ν_i is the earthquake occurrence probability for the source i; $f(m,r,\varepsilon)$ is the joint PDF of {M, R, ε} and λ_{IM_0} is the hazard for IM_0.

3 MAPS OF DESIGN EARTHQUAKES

Disaggregation PDF (Eq. 1) for each site was rendered a discrete function by the software assuming bins of 0.05, 1.0km and 0.5 for M, R and ε respectively (ε varies between -3 and +3). Moreover, because PDF is a four dimensional surface providing the contribution to hazard of M, R and ε variables for each site, return period and spectral ordinate, some criteria for synthetic identification of DEs have to be chosen. Herein, the first DE is defined as the *mode* of the disaggregation PDF; i.e., the vector {M*, R*, ε*} with the largest contribution to the exceedance of the IM threshold corresponding to the considered return period.

Because analyses show that in many cases disaggregation PDF has more than a single mode significantly contributing to hazard, as extensively discussed in Iervolino et al. (2011), a second DE is defined as the second relative maximum of the $f(m,r,\varepsilon|IM > IM_0)$ distribution. To ensure the second DE to be of practical relevance, two additional (arbitrary) conditions[4] were imposed: (1) the second mode is identified as an event different from the first DE if the two differ more than 5.0km in distance and/or 0.25 in magnitude; (2) the second DE is considered as such if the second mode of the disaggregation PDF gives a contribution to hazard larger than 10^{-4}.

As an example, maps of DEs for a return period equal to 475 years are reported in Figure 2 and Figure 3 assuming, as an IM, PGA or Sa(1s), respectively. (Maps for other return periods are provided in Iervolino et al., 2011)

Analyzing the figures, it is possible to identify some 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, (ii) the second mode accounts for the influence of the more distant zones usually with larger magnitude, and (iii) moving from PGA to Sa, the number of sites with two DEs increases. As consequence of (ii) and (iii), it can be inferred that the influence of more distant zones is higher for Sa(1s) than for PGA.

Each of these conclusions will be examined further in the following via case-studies referring to specific sites. Results for such cases are reported in term of M and R distribution from disaggregation. In fact, marginalization on ε is always performed for a clearer graphical representation, Eq. 2. Despite this pictorial choice, modal values presented are always computed on the complete disaggregation surface.

$$f(m,r|IM > IM_0) = \int_{\varepsilon} f(m,r,\varepsilon|IM > IM_0) \cdot d\varepsilon \quad (2)$$

It is to note that it can be anticipated how all disaggregation results can be motivated looking at GMPE and seismogenic model adopted and, because most of the ordinary GMPEs show similar dependencies with respect to magnitude and distance, while several different options may underlie modeling of seismic sources, changing GMPE may change the results without losing general trends, conversely, changing the seismic source model can alter results dramatically.

4 STRUCTURAL PERIOD AND DESIGN EARTHQUAKES

Disaggregation results can change significantly with the considered structural period the spectral ordinate refers to. This conclusion was anticipated introducing DEs maps and it can be further analyzed for a specific site. Here the site of Matera (16.603° E, 40.669° N) is considered. In Figure 4 disaggregation distributions in terms of M and R are reported for a Tr equal to 475 year and for the two spectral ordinates considered. In each diagram, also the geographical position of the site is sketched (with a triangle) together with all the seismogenic zones influencing the hazard.

Hazard of Matera is mostly influenced by zones 926 and 927; associated seismic parameters in terms of M_{min}, M_{max}, ν and b are respectively [4.3, 5.8, 0.061, 1.017] and [4.3, 7.3, 0.362, 0.557]. Influence of the other close zones, although not negligible in terms of hazard assessment, do not modify significantly the shape of disaggregation distributions.

[4] These criteria are helpful in avoiding as much as possible to neglect significant contribution to hazard of some sources. However, because PDFs can have very different shapes in a way that a unique set of conditions may not satisfy all the cases, identification of DEs should be carried out analyzing individual distribution for each site (see Chioccarelli, 2010 for further details).

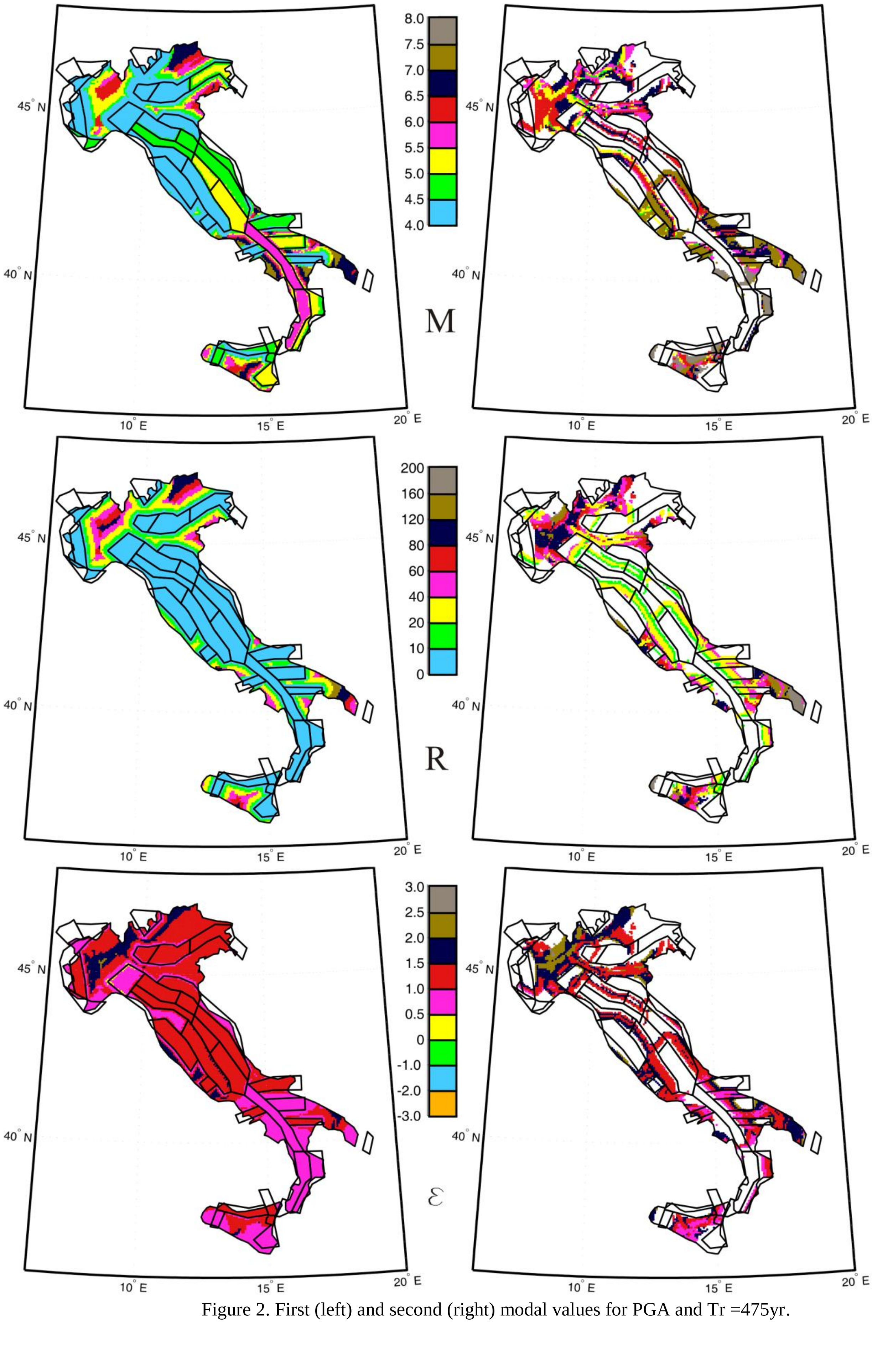

Figure 2. First (left) and second (right) modal values for PGA and Tr =475yr.

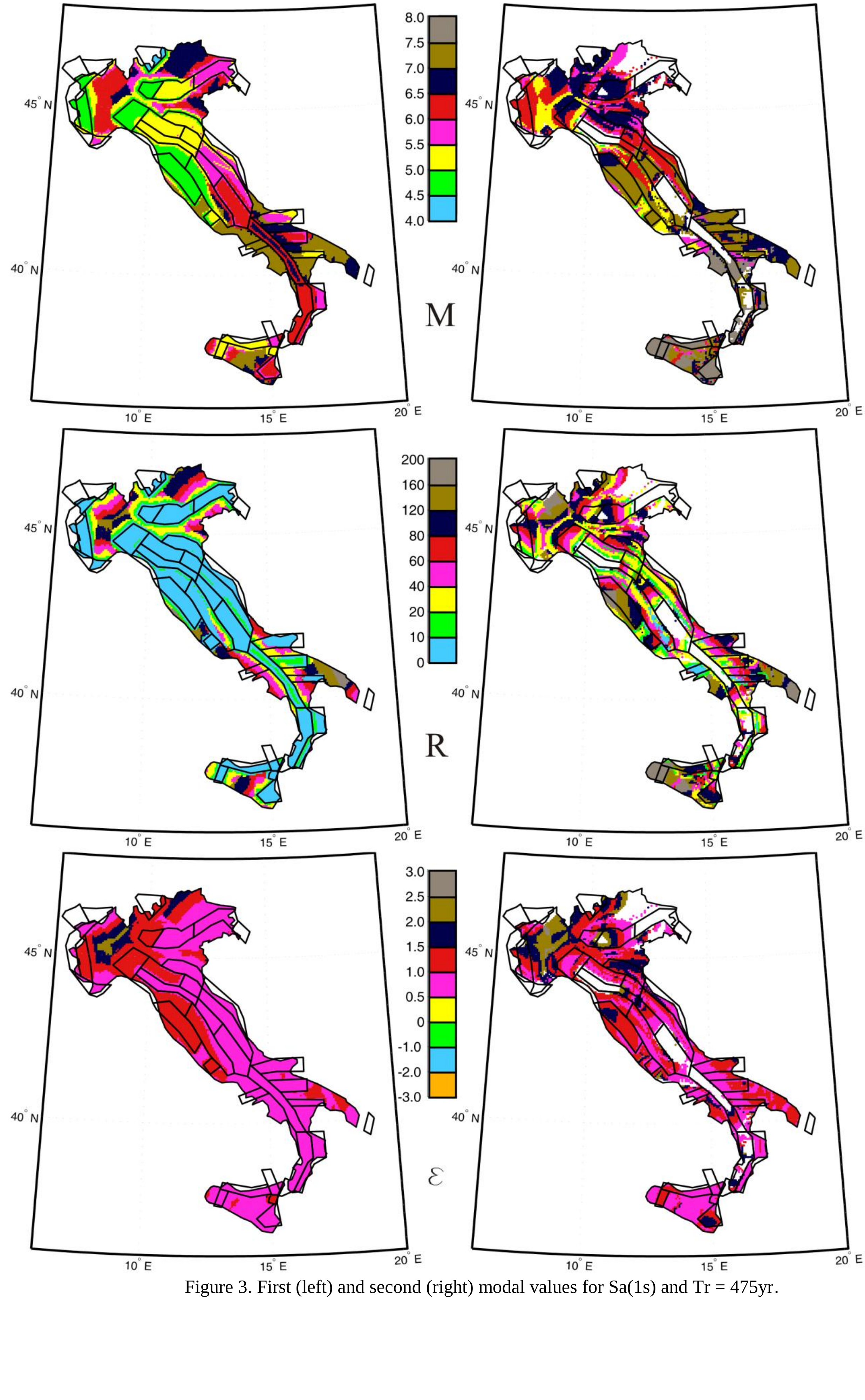

Figure 3. First (left) and second (right) modal values for Sa(1s) and Tr = 475yr.

PGA disaggregation is unimodal and characterized by one mode equal to [5.5, 4.3, 0.5] in terms of R, M and ε respectively[5]. Considering the distance value, it is clear that such DE is generated by zone 926 in which the site is enclosed.

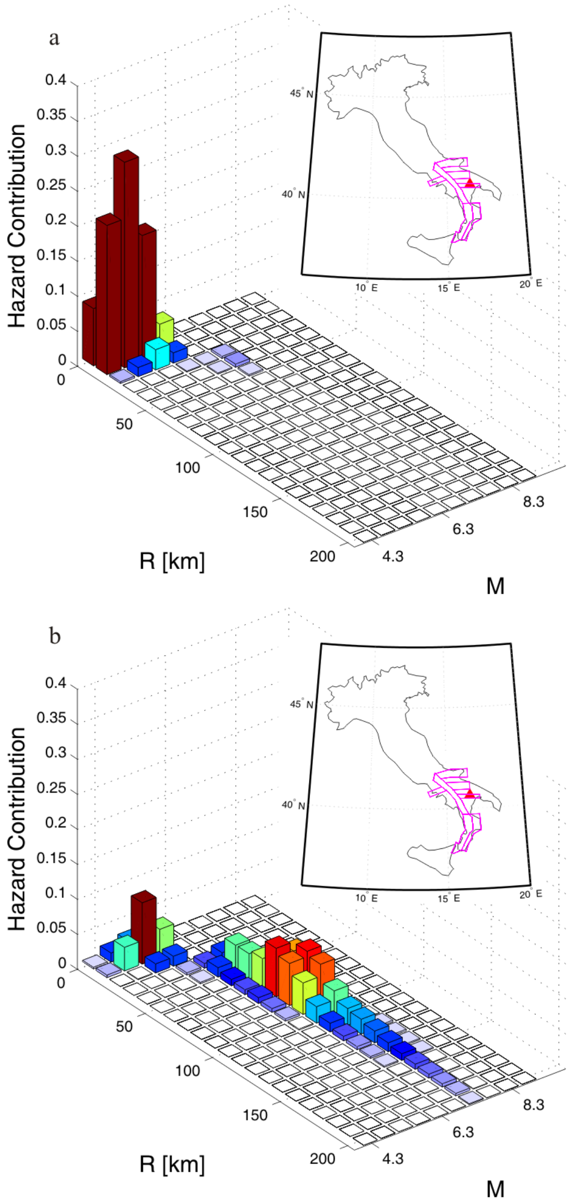

Figure 4. Disaggregation for Matera and Tr = 475yr: PGA (a) and T = 1.0s (b).

Conversely, for Sa(1sec), two very significant DEs are identified by vectors of R, M and ε equal to [89.5, 7.3, 1.0] and [7.5, 5.4, 0.5]. Similarly to the previous case, one mode derives from zone 926 and it is possible to demonstrate that the other one represents the influence of zone 927 which is more distant from the site, but is characterized by a higher M_{max} with a higher rate of earthquake occurrence.

Influence of spectral period on disaggregation results can be motivated looking at GMPE in fact, for a fixed site and return period, variations of dominating earthquakes for different spectral ordinates can only depend on the used prediction equation. In particular, it is known that high frequency waves are attenuated faster with distance and therefore it is expected that spectral ordinates associated to longer periods (1s in this case) are more affected by distant events with respect to PGA. In other words, it can be observed that distant zones with negligible (or limited) influence on PGA hazard, can show non-negligible (or increased) effects on the Sa(1s) hazard at the same site. As a consequence, design scenarios based on PGA disaggregation can be potentially misleading for moderate-to-long fundamental periods as also discussed in Convertito et al. (2009).

5 RETURN PERIOD AND DESIGN EARTHQUAKES

An interesting result, which may not be inferred directly from DEs maps is that, for the most of sites featuring more than one mode, increasing the return period of the spectral ordinate being disaggregated, the contribution of the first mode (usually the close-moderate earthquake) increases with respect to the second mode. See, for example, Palermo (13.28° E, 38.05° N), for which disaggregation results for return periods equal to 50yr and 2475yr are reported in Figure 5 referring to Sa(1s). It is apparent that hazard contribution of second DE, relevant for Tr=50yr, decreases significantly for Tr=2475yr.

The reason can be found considering an extremely simple ideal case of a site affected by two source zones: Z_1 and Z_2 generating individual (characteristic) earthquakes $\{M_1, R_1\}$ and $\{M_2, R_2\}$. Contribution to hazard (HC) of each zone is represented by Eq. (3) and Eq. (4) respectively:

$$HC_{Z_1} = \frac{\nu_{Z_1} \cdot f\left(IM > IM_0 \middle| M_1, R_1\right)}{\lambda_{IM_0}} \tag{3}$$

[5] A second modal value with a contribution to the hazard higher than the fixed threshold is identified [34.5, 7.0, 1.0] even if not clearly shown by the figure where contribution lower than $1.2 \cdot 10^{-3}$ are shown in white. Because this hazard contribution is associated to a very limited range of magnitude and distance, Matera is one of the cases in which additional conditions for identification of second DEs can be considered over-conservative comparing with the whole disaggregation distribution.

$$HC_{Z_2} = \frac{\nu_{Z_2} \cdot f\left(IM > IM_0 | M_2, R_2\right)}{\lambda_{IM_0}} \qquad (4)$$

λ_{IM_0} is a marginal probability and it doesn't depend on the considered zone; ν_z are the rates of occurrence of earthquakes for the two zones and $f\left(IM > IM_0 | m, r\right)$ depends on the GMPE.

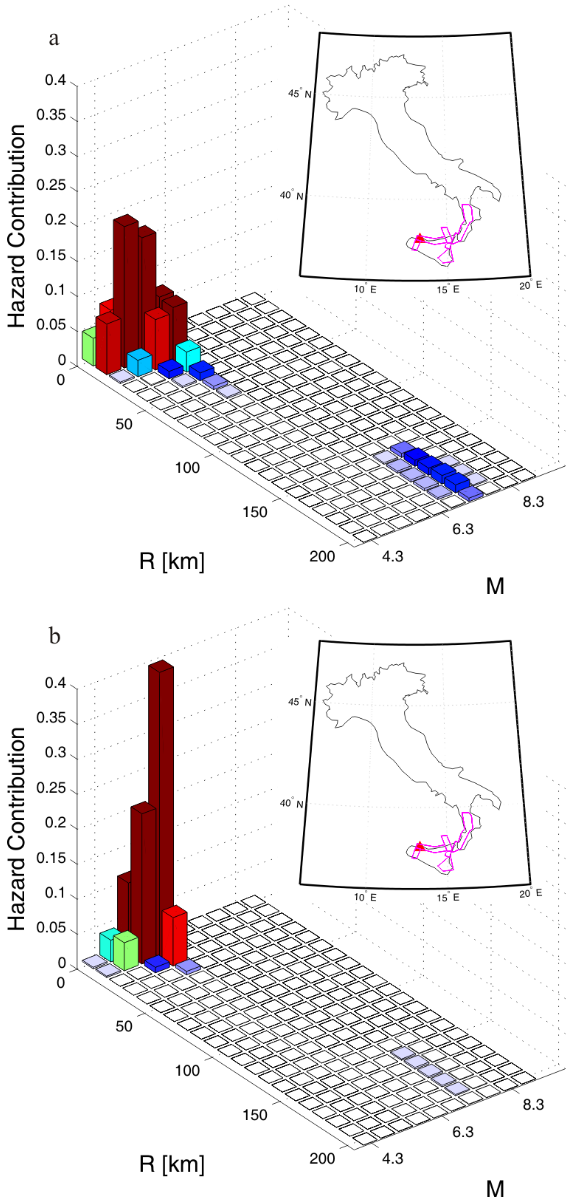

Figure 5. Disaggregation for Palermo: Sa(1sec) for Tr = 50yr (a) and 2475yr (b).

Comparison of hazard contribution of the zones can be investigated via the ratio in Eq. (5).

$$\frac{HC_{Z_1}}{HC_{Z_2}} = \frac{f\left(IM > IM_0 | M_1, R_1\right) \cdot \nu_{Z_1}}{f\left(IM > IM_0 | M_2, R_2\right) \cdot \nu_{Z_2}} \qquad (5)$$

For a given return period, the zone with the higher product of activity rate and GMPE terms provides the higher contribution to hazard. Increasing Tr, IM_0 increases and the ratio of probabilities given by GMPE determines all the relative variations of contributions.

An illustrative numerical example may be given considering the scheme of site and zones sketched in Figure 6a. Considering the Ambraseys et al. (1996) GMPE, if M_1 and M_2 are equal to 5 and 6.5 and using as R_1 and R_2 average distances of the two zones from the considered site (5km and 135km, respectively), the ratio of HC (Figure 6a) has a positive slope indicating that the contribution of Z_1 increases with the threshold (i.e., IM_0), and therefore increases as the return period is increased. The reason for that is plotted in Figure 6b. In fact, the GMPE provides a normal distribution of log(Sa) with a constant standard deviation with respect to M. It can be observed that by increasing IM_0 the exceedance probability decreases more rapidly for Z_2 with respect to Z_1, which explains the trend of Figure 6a.

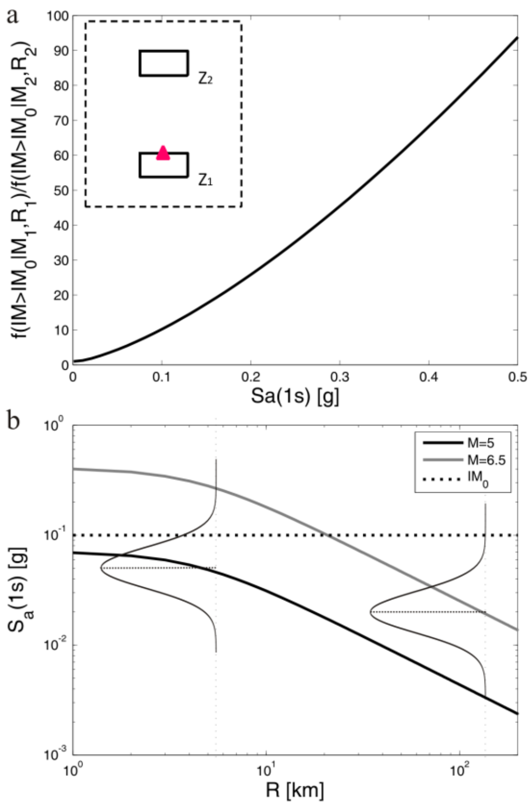

Figure 6. Ratio of CCDFs referred to Z1 and Z2 (a) and Sa(T = 1.0s) predicted by Ambraseys et al. (1996) GMPE for fixed magnitude values (b).

Finally, it is to note that an alternate case can occur: when magnitudes and distances associated to the closer zone produce average IMs lower than those due to the more distant zone. In fact, the hazard contribution that becomes negligible for higher Tr is that of the closer zone and the second scenario results of increasing importance.

Terni (12.638° E, 42.567° N) is one of these cases as depicted in Figure 7a and Figure 7b.

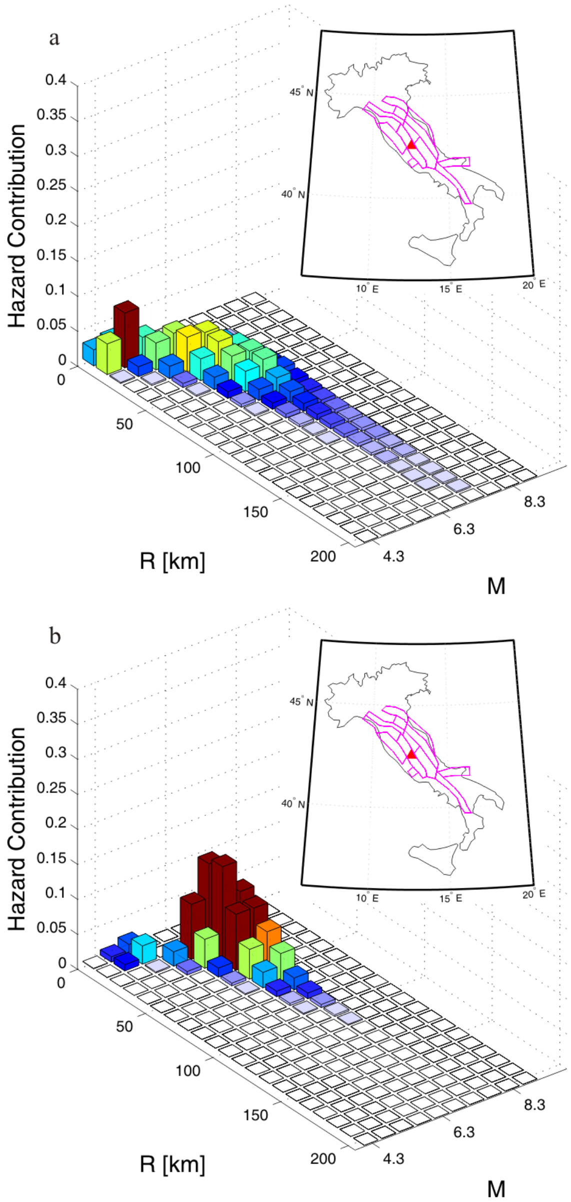

Figure 7. Disaggregation for Terni: Sa(1sec) for Tr = 50yr (a) and 2475yr (b).

6 ENGINEERING APPLICATIONS OF DESIGN EARTHQUAKES

Results of the study, in terms of M and R disaggregation distributions, have been included in REXEL, a freeware software for ground motion record selection available at http://www.reluis.it/index.php?lang=en. REXEL currently searches for suites of waveforms from two different database: European Strong motion Database, ITalian ACcelerometric Archive compatible, on average, to various types of code-based or user defined spectra (Iervolino et al., 2010a), but record selection can also be performed including some research findings relevant for seismic structural assessment. One of these is the possibility to specify the bins of magnitude and distance to whom spectrum-matching records have to belong.

Thanks to the introduction in REXEL 3.1 (beta) of the results discussed in this paper, for a chosen Italian site and return period, the software provides disaggregation PDFs related to PGA or Sa(1s) hazard at the four return periods computed herein. Therefore, the user can select the appropriate ranges of magnitude and distance in order to explicitly account for main features of the seismogenic sources driving the hazard. In this way it is possible to easily respect indications of the main European seismic codes as mentioned in Section 1.

Another direct application of the results of this study refers to *conditional hazard*. In fact, recently, earthquake engineering research demonstrated that replacing scalar spectral ordinates with vectors of IMs, may lead to an improved estimation of structural response (Bazzurro and Cornell, 2002). In fact, vectors of IMs allows to consider different characteristics of the ground motion at the same time. An example may be a vector of PGA and I_D, which is the ratio of the integral of the acceleration squared to the PGA and PGV (Eq. 6) and is a measure related with the cyclic content of ground motion.

$$I_D = \frac{1}{PGA \cdot PGV} \int_0^t a^2(t)\, dt \qquad (6)$$

In fact, acceleration-based IMs (e.g., PGA or spectral ordinates) have been shown to be important in the assessment of displacement structural response of buildings, but there are cases in which the cumulative damage potential of the earthquake is also of concern and therefore parameters as I_D may be relevant, although with a secondary role with respect to acceleration.

While computing hazard analysis for vectors of IM is demanding, an easy yet hazard-consistent way of including secondary IMs in record selection is represented by the conditional hazard concept; i.e., distributions of secondary ground motion intensity measures conditional, in a probabilistic sense, to the design hazard for the primary parameter for which an hazard map is often already available.

Conditional hazard consists of computing probabilistic distribution for the secondary IM conditional to the design value of the primary IM. This requires a measure of correlation of the two

IMs (e.g., Baker and Cornell, 2006), and design earthquakes from disaggregation of hazard for the primary IM, to be available.

In fact, assuming PGA as primary and I_D as secondary IM, it is possible to prove that, under some hypotheses respectively, the distribution of the logs of I_D conditional to the log of PGA $(\log_{10} PGA = z)$ is Gaussian with mean $(\mu_{\log_{10} I_D|\log_{10} PGA})$ and standard deviation $(\sigma_{\log_{10} I_D|\log_{10} PGA})$ which may be approximated by Eq. (7). Mean and standard deviation are a function of: (i) the average and standard deviation $(\mu_{\log_{10} I_D}; \sigma_{\log_{10} I_D})$ from the GMPE for I_D; (ii) the correlation coefficient between the logs of PGA and I_D (ρ); and (iii) the average and standard deviation $(\mu_{\log_{10} PGA|M,R}; \sigma_{\log_{10} PGA})$ from the PGA GMPE. These latter terms can be approximated substituting the whole M and R joint distribution by the first modal values or design earthquakes {M*,R*}. Thus:

$$\mu_{\log_{10} I_D|\log_{10} PGA} \approx \mu_{\log_{10} I_D|M*,R*} + \rho \cdot \sigma_{\log_{10} I_D} \frac{z - \mu_{\log_{10} PGA|M*,R*}}{\sigma_{\log_{10} PGA}}; \quad \sigma_{\log_{10} I_D|\log_{10} PGA} = \sigma_{\log_{10} I_D} \sqrt{1-\rho^2} \qquad (7)$$

With this very simple relationships and using first modal DEs discussed in this work, conditional hazard maps of I_D can be easily produced for all the Italian sites. For further details about conditional hazard the reader is referred to Iervolino et al. (2010b).

It is worth to note that using first DEs earthquakes discussed in this paper, conditional hazard (which may be virtually extended to any pair of IMs) can easily be computed for all Italian sites. An example is reported in Figure 8 where 50^{th} and 90^{th} percentiles conditional to PGA with a Tr=475yr are shown.

Conditional hazard issue has been implemented in REXEL as an additional criteria for record selection: the software provides, for each site, exceedance probability of I_D conditional to the hazard value of PGA and to the first modal values of M and R; referring to a percentile of such probability distribution users can impose an appropriate range of I_D for record selection.

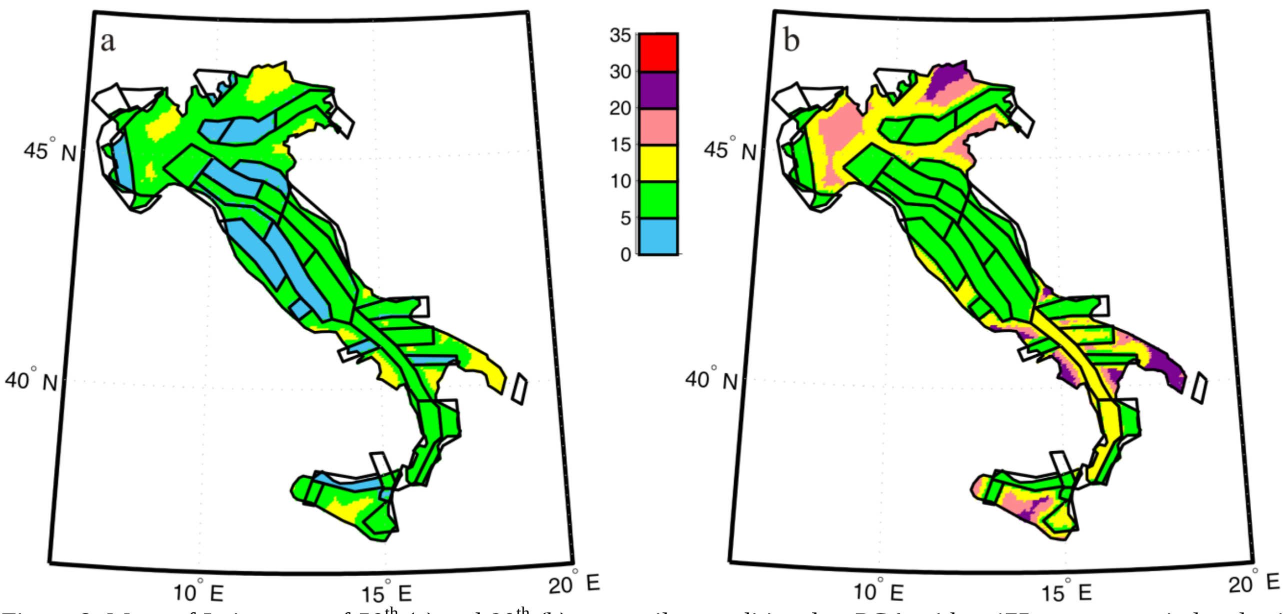

Figure 8. Maps of I_D in terms of 50^{th} (a) and 90^{th} (b) percentiles conditional to PGA with a 475yr return period and using first DEs of Figure 2.

7 CONCLUSIONS

Referring to geometric modeling of seismic source zones adopted to produce Italian hazard data to which the building code is based on, and to activity parameters from literature, design scenarios were investigated in this study focusing on practical engineering use. Two different spectral periods equal to 0s (PGA) and 1s, and four different return periods (50yr, 475yr, 975yr and 2475yr) were considered for disaggregation results.

Maps of first and second modal values of distance, magnitude and ε for Tr=475yr, were shown as an example. Moreover, extended disaggregation results for significant sites were analyzed underling and demonstrating some general findings related to the given maps: (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, (ii) the second mode accounts for the influence of the more distant zones usually with larger magnitude, (iii) moving from PGA to Sa(1s), the number of sites with at least two design earthquakes increases, and (iv) return period can produce significant changes in disaggregation results of the same site. For the latter conclusion it is show how and why, depending on combination of seismic zone parameters and their distance, increasing return period, closer or more distant DEs become predominant.

Finally a discussion on possible practical applications of the results of this study was provided. First, it was described how disaggregation distributions for all Italian sites presented in this work have been implemented in a software, REXEL, built to search for suites of spectrum matching records. Secondly, the use of design earthquakes to build hazard curves for secondary intensity measures conditional to design value of acceleration was briefly reviewed.

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