Italian Map of Design Earthquakes from Multimodal Disaggregation Distributions: Preliminary Results.

Eugenio Chioccarelli
Dipartimento di Ingegneria Strutturale, Università degli Studi di Napoli, Federico II, Naples, Italy.

Iunio Iervolino
Dipartimento di Ingegneria Strutturale, Università degli Studi di Napoli, Federico II, Naples, Italy.

Vincenzo Convertito
Istituto Nazionale di Geofisica e Vulcanologia (INGV), Osservatorio Vesuviano, Naples, Italy.

ABSTRACT:
Probabilistic seismic hazard analysis allows to calculate the mean annual rate of exceedance of ground motion intensity measures given the seismic sources the site of interest is subjected to. This piece of information may be used to define the design seismic action on structures. Moreover, through disaggregation of seismic hazard, it is possible to identify the earthquake giving the largest contribution to the hazard related to a specific IM value. Such an information may also be of useful to engineers in better defining the seismic treat for the structure of interest (e.g., in record selection for nonlinear seismic structural analysis). On the other hand, disaggregation results change with the spectral ordinate and return period, and more than a single event may dominate the hazard, especially if multiple sources affect the hazard at the site. In this work disaggregation for structural periods equal to 0 sec and 1.0 sec is presented for Italy, with reference to the hazard with a 475 year return period. It will be discussed how for the most of Italian sites more than a design earthquake exist, because of the modelling of seismic sources.

Keywords: Seismic Hazard, Disaggregation, Design Earthquakes, Record Selection.

1. INTRODUCTION

Given the characterization of seismic sources and once a ground motion intensity measure (IM) is chosen, probabilistic seismic hazard analysis (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 uniform hazard spectrum (UHS); i.e, the response spectrum with a constant exceedance probability for all ordinates (Reiter, 1990). Currently the UHS is, in the most advanced seismic codes, 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; CEN, 2003).
PSHA, for its integral nature, combines the contribution to the hazard from all considered sources. The event most important 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 (M), source to site distance (R) and ε (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 referred to as the earthquakes dominating the seismic hazard in a probabilistic sense, and may be used as design earthquakes; e.g., Iervolino (2008).
Analytically disaggregation result is the joint probability density function (PDF) of magnitude, distance and ε 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:

$$f\left(m,r,\varepsilon \middle| IM > IM_0\right) = \frac{\sum_{i=1}^{N} \nu_i \cdot I\left[IM > IM_0 \middle| m,r,\varepsilon\right] \cdot f_{M,R,\varepsilon}\left(m,r,\varepsilon\right)}{\sum_{i=1}^{N} E_i\left(IM > IM_0\right)} \tag{1.1}$$

where: N is the number of seismic source which affect hazard at the site of interest; ν_i is the mean annual rate of occurrence of earthquakes within each zone; $E_i\left(IM > IM_0\right)$ 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 ε, whose joint PDF is represented by $f_{M,R,\varepsilon}\left(m,r,\varepsilon\right)$. From the equation 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 ε from disaggregation (Reiter, 1990; Convertito et al., 2009).

In Italy, INGV (*Istituto Nazionale di Geofisica e Vulcanologia*) provides disaggregation, for nine return periods between 30 and 2475 year, but for the Peak Ground Acceleration (PGA) only (see http://esse1-gis.mi.ingv.it/). In this work, disaggregation of all Italian sites for structural periods equal to 0 sec (PGA) and 1.0 sec are presented. Disaggregation for these two periods are intended to help in identifying design earthquakes for the short and moderate/long period ranges of the UHS related to the life safety limit-state of ordinary constructions. Four different return periods (Tr) 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, other results shall be available by Iervolino et al. (2010a). The work can be considered as an extension of Convertito et al. (2009), which focused on a region in southern Appennines in Italy, and has some similarities to the temporally parallel work of Barani et al. (2009), although here a special attention is given to the multimodal features of the PDFs from disaggregation in order to define the design earthquakes for code-based record selection for nonlinear dynamic analysis of structures.

2. ITALIAN SEISMIC HAZARD MODEL AND MULTIPLE DESIGN EARTHQUAKES

Recent Italian seismic code (CS.LL.PP., 2008) introduced a new seismic classification of national territory, which was discretized as a grid of 10751 nodes where the seismic hazard has been computed in terms of acceleration spectral ordinates from 0 sec to 2 sec, along with PGA disaggregation as discussed. In this way, the code provides design spectra very close to the UHSs and software tools have been developed to automatically select sets of records compatible to them (Iervolino et al., 2010b). However, this may be insufficient to define design earthquakes for structures in the moderate period range. To overcome this gap, herein hazard is developed for PGA (considered as a benchmark) and spectral acceleration for T equal to 1.0 sec, and the disaggregation is computed for the whole country referring to the 475-year hazard.

Exceedance probabilities are 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 of Meletti et al. (2008), also adopted by INGV (Figure 1). Seismicity parameters of each zone are those used by Barani et al. (2009) (Table 2.1). The considered grid for Italy is the same of that from INGV and used in the Italian seismic code (CS.LL.PP., 2008). All the analyses refer to rock site conditions. According to Ambraseys et al. (1996), which is the ground motion prediction equation (GMPE) considered, magnitude is that of surface waves (M_s).

Because of seismogenic zones modelling, the hazard software assumes an 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.

Table 2.1. Characterization of seismic sources according to Barani et al. (2009). For each zone it is provided: minimum (M_{min}) and maximum magnitude (M_{max}); annual rate of earthquake occurrence above $M_{min,}$ (υ); and negative slope of Gutenberg-Richter relationship (b).

Zone	M_{min}	M_{max}	υ	b
901	4.3	5.8	0.045	1.133
902	4.3	6.1	0.103	0.935
903	4.3	5.8	0.117	1.786
904	4.3	5.5	0.050	0.939
905	4.3	6.6	0.316	0.853
906	4.3	6.6	0.135	1.092
907	4.3	5.8	0.065	1.396
908	4.3	5.5	0.140	1.408
909	4.3	5.5	0.055	0.972
910	4.3	6.4	0.085	0.788
911	4.3	5.5	0.050	1.242
912	4.3	6.1	0.091	1.004
913	4.3	5.8	0.204	1.204
914	4.3	5.8	0.183	1.093
915	4.3	6.6	0.311	1.083
916	4.3	5.5	0.089	1.503
917	4.3	6.1	0.121	0.794
918	4.3	6.4	0.217	0.840
919	4.3	6.4	0.242	0.875
920	4.3	5.5	0.317	1.676
921	4.3	5.8	0.298	1.409
922	4.3	5.2	0.090	1.436
923	4.3	7.3	0.645	0.802
924	4.3	7.0	0.192	0.945
925	4.3	7.0	0.071	0.508
926	4.3	5.8	0.061	1.017
927	4.3	7.3	0.362	0.557
928	4.3	5.8	0.054	1.056
929	4.3	7.6	0.394	0.676
930	4.3	6.6	0.146	0.715
931	4.3	7.0	0.045	0.490
932	4.3	6.1	0.118	0.847
933	4.3	6.1	0.172	1.160
934	4.3	6.1	0.043	0.778
935	4.3	7.6	0.090	0.609
936	3.7	5.2	0.448	1.219

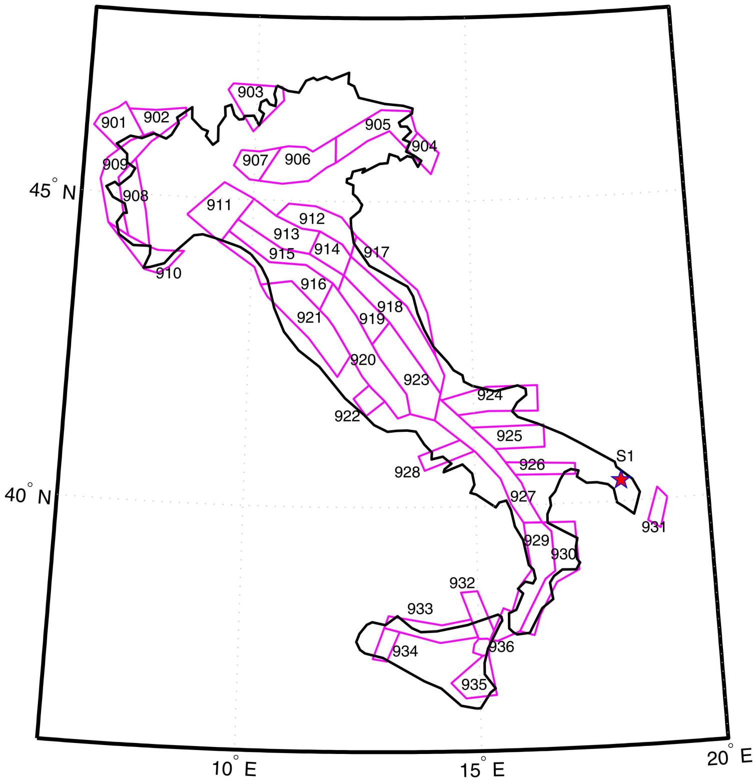

Figure 1. Seismogenetic zones for Italy according to Meletti et al. (2008).

3. ANALYSES AND RESULTS

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 ε 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 ε equal to 0.05, 1.0 and 0.5, respectively. Minimum and maximum values used for ε 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 ε 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 ε respectively.

In Figure 2 and Figure 3 modes of disaggregation distributions are shown. 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 is 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 = 1.0sec 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 sites may be useful to know not only the first mode, but also the second one, in definition of seismic action on structures.

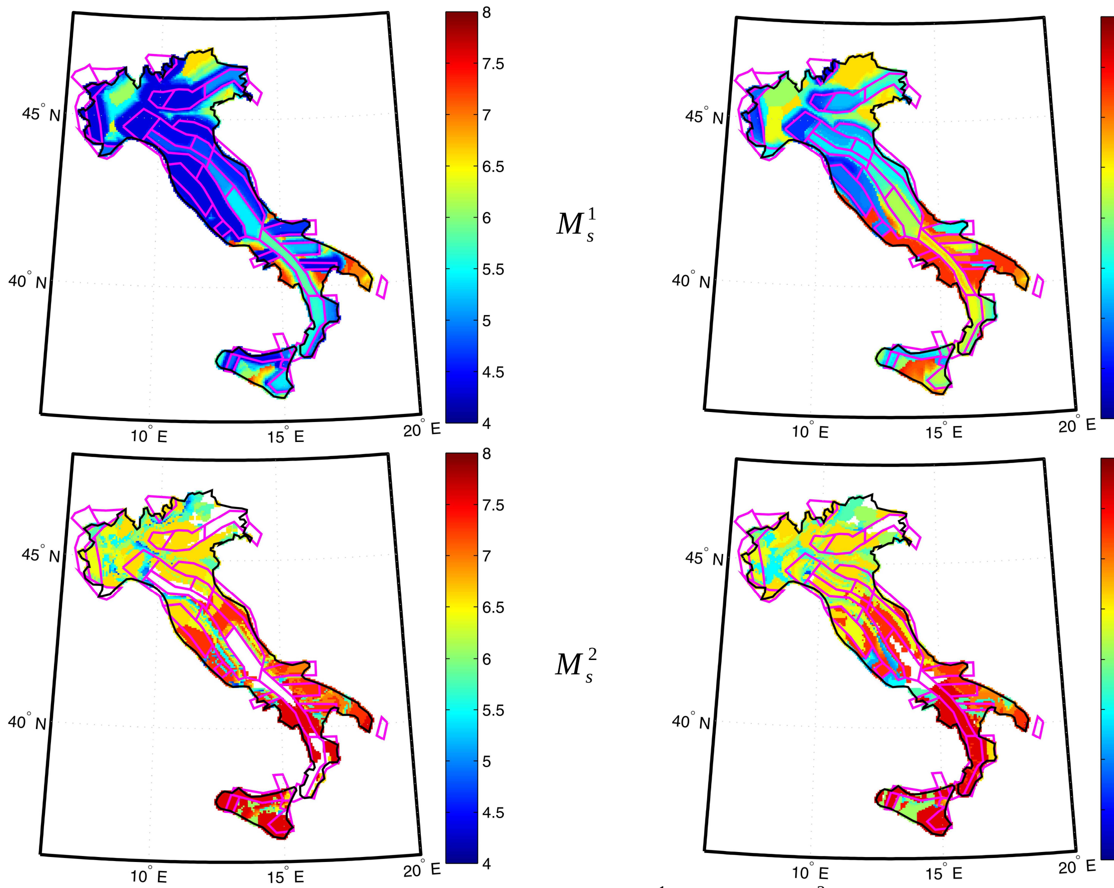

Figure 2. Map of disaggregation results represented by first (^{1}) and second (^{2}) modal values of M_s for PGA (*left*) and Sa(1.0sec) (*right*) and for Tr = 475year.

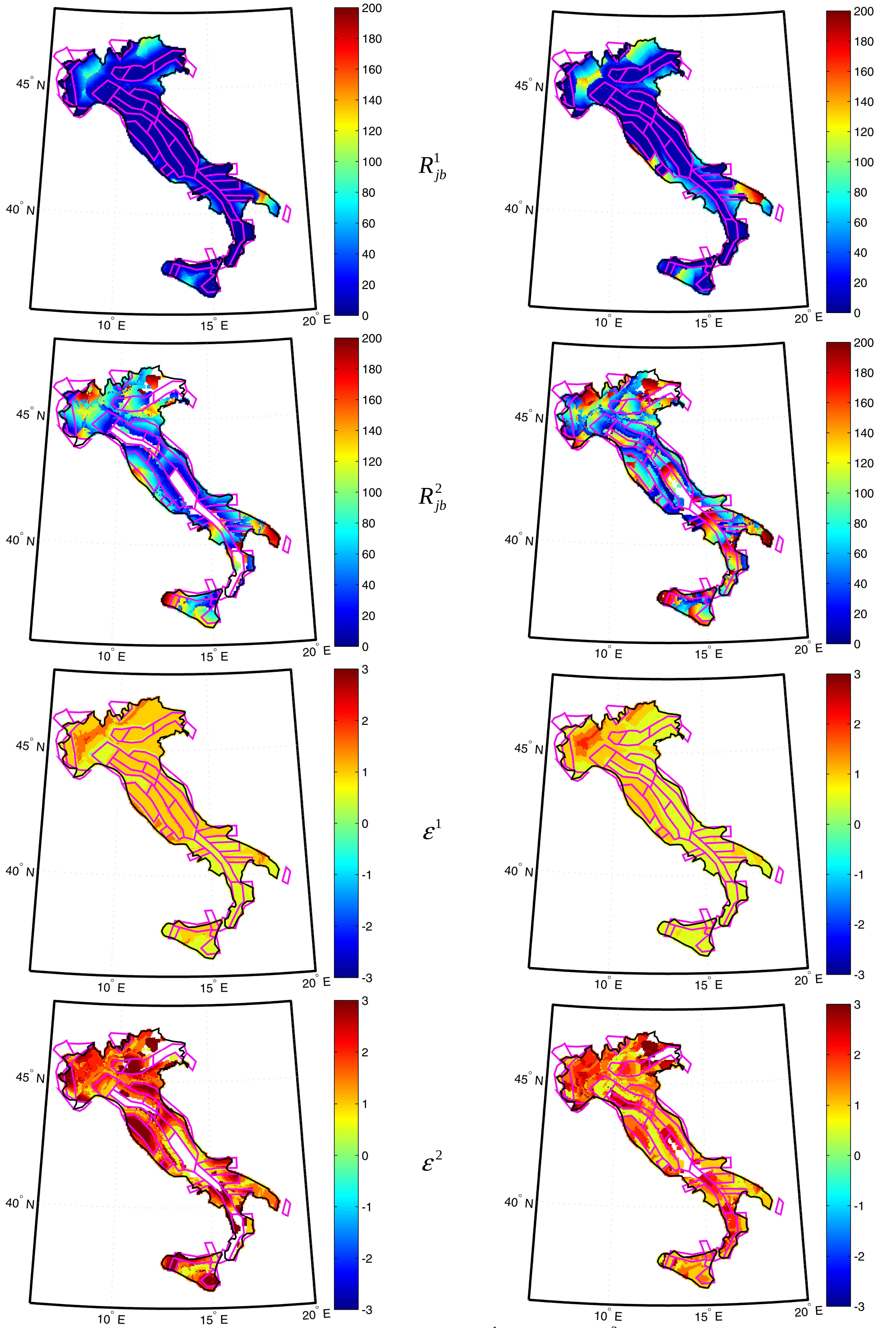

Figure 3. Map of disaggregation results represented by first (1) and second (2) modal values of R_{jb} and ε for PGA (*left*) and Sa(1.0sec) (*right*) and for Tr = 475year.

3.1. An example of multimodal disaggregation

In Convertito et al. (2009) and in Barani et al. (2009) some interesting examples of disaggregation results for individual sites have already been presented: most of those cases are characterized by two different modal values with comparable contributions. In this work the site of Lecce (S1 in Figure 1) is considered (latitude 40.338° N, longitude 18.147° E) and disaggregation results are shown for PGA and 1 sec spectral acceleration period and for Tr = 475 years. In particular the joint PDF obtained from Eqn 1.1 is represented in Figure 4 showing the marginal PDFs or R_{jb} and ε and of R_{jb} and M.
The considered site is not enclosed in any seismic source and its hazard is affected by sources 931 and 926 with a minimum distance lower than 100 km and by sources 925, 927, 929 and 930 with a minimum distance between 100 and 200 km. For the combination of the characteristics of all the sources around the site, the PGA and Sa(1.0 sec) hazards both correspond to 0.053g.

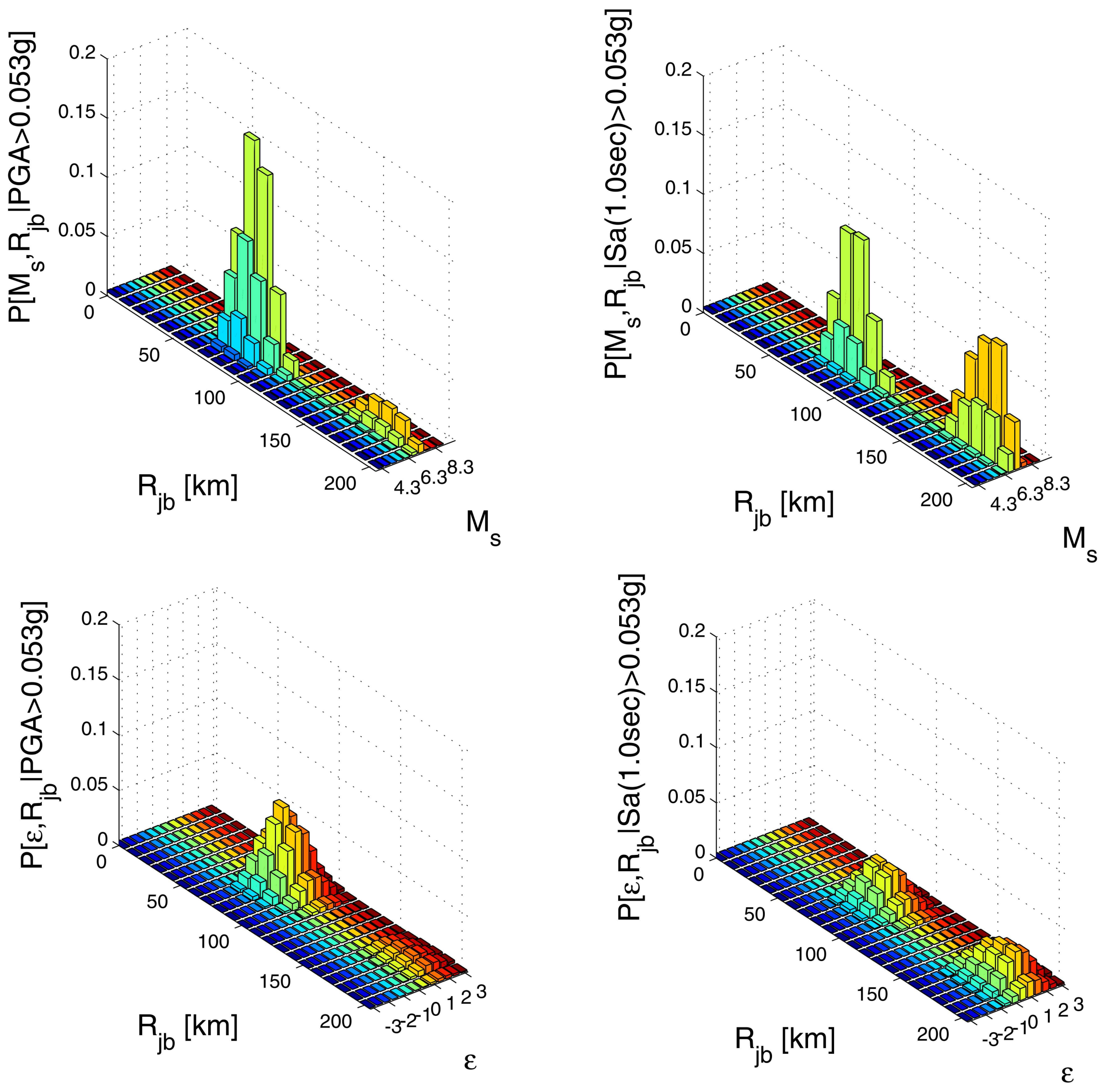

Figure 4. Disaggregation results for Lecce for PGA (*left*) and Sa(1.0sec) (*right*)

Disaggregation of PGA shows that the site is characterized by two different modal values: the first one due to R_{jb} and M_s equal to about 80 and 6.8 respectively and the second one due to R_{jb} equal to 180 and M_s equal to 7.3. Hazard contribution of the second mode is much lower.
The same modes are computed for Sa(1.0 sec) but, as expected, the increment of spectral period determines increment of hazard contribution of more distant sources and, as consequence, the second mode becomes comparable with the first one.

These results, as noted already in Convertito et al. (2009), points out that even if hazard contribution of the second mode is comparatively low (like in the case of PGA results) a characterization of design earthquakes should prudently account for it. In fact, when looking at spectral ordinates closer to the fundamental period of the most common structures, such second mode may become significant. This has engineering consequences because, for example, although given a response spectrum the displacement structural response may be not very sensitive to magnitude and distance (Iervolino and Cornell, 2005), ground motions characterized by different magnitudes and source-to-site distances can display different seismic demand, for example, in terms of cyclic structural response; see also Iervolino et al. (2010c).

4. CONCLUSIONS

Disaggregation can be considered as the more useful tool to address the definition of design earthquakes to be used in engineering practice (e.g., ground motion record selection for nonlinear dynamic analysis of structures). In this work design earthquakes from disaggregation of all Italian sites for structural periods equal to 0 and 1.0 sec was presented referring to hazard with a 475 year return period. First and second modal values are used here as synthetic identifiers of design earthquakes.
Results show that, usually, the modal value with the largest contribution to hazard corresponds to a moderate-magnitude earthquake caused by the closer source, while the influence of the more distant zones is accounted with the second mode. Moreover, because in most cases Italian sites are located inside seismogenic zones, first mode of disaggregation is characterized by a R_{jb} lower than 10 km.
For spectral acceleration at T = 1.0 sec, the contribution of more distant source is higher than in the PGA case.
Finally it is to conclude that only a few sites are characterized by a single design earthquake and this is particularly evident from disaggregation of Sa(T = 1.0) hazard, which is more representative than PGA for ordinary buildings.

ACKNOWLEDGEMENTS

Authors want to thank Dr. Simone Barani of the University of Genova (Italy) for the discussion about seismic sources parameters used in this study.

REFERENCES

Ambraseys, N.N., Simpson, K.A. and Bommer, J.J. (1996). Prediction of Horizontal Response Spectra in Europe, *Earthquake Engineering and Structural Dynamics* **25**, 371-400.
Barani, S., Spallarossa, D. and Bazzurro, P. (2009). Disaggregation of probabilistic ground motion hazard in Italy. *Bull. Seismol. Soc. Am.* **99**, 2638-2661.
CEN, European Committee for Standardisation TC250/SC8/ (2003). Eurocode 8: Design Provisions for Earthquake Resistance of Structures, Part 1.1: General rules, seismic actions and rules for buildings, *PrEN1998-1*.
Convertito, V., Iervolino, I. and Herrero, A. (2009). Importance of mapping design earthquakes: insights for the southern apennines, Italy. *Bull. Seismol. Soc. Am.* **99**, 2979-2991.
CS.LL.PP. (2008). DM 14 gennaio 2008 Norme Tecniche per le Costruzioni. *Gazzetta Ufficiale della repubblica Italiana* **29** (in Italian).
Gruppo di Lavoro (2004). Redazione della mappa di pericolosità simica prevista dall'Ordinanza PCM 3274 del 20 Marzo 2003. *Rapporto conclusivo per il Dipartimento della Protezione Civile, INGV, Milano-Roma*, aprile 2004, 65pp. (in Italian)
Iervolino I., Chioccarelli E., Convertito V. (2010a). Italian Maps of Design Earthquakes. (in preparataion)
Iervolino I., Giorgio M., Galasso C., Manfredi G. (2010c). Improving seismic action assessment: conditional design maps for secondary intensity measures. *Proc. of 14th European Conference on Earthquake Engineering*, Ohrid, Republic of Macedonia.
Iervolino, I. and Cornell, C.A. (2005). Record selection for nonlinear seismic analysis of structures, *Earthquake Spectra* **21**, 685-713.

Iervolino, I., Galasso, C., Cosenza, E. (2010b). New features of REXEL 2.61 beta, a tool for automated record selection. *Proc. of 14th European Conference on Earthquake Engineering*, Ohrid, Republic of Macedonia.

Iervolino, I., Maddaloni, G. and Cosenza, E. (2008). Eurocode 8 compliant real record sets for seismic analysis of structures, *Journal of Earthquake Engineering* **12**, 54-90.

Joyner, W.B., and Boore, D.M. (1981). Peak horizontal acceleration and velocity from strong-motion records including records from the 1979 Imperial Valley, California, earthquake. *Bull. Seismol. Soc.Am.* **71**, 2011–2038.

Meletti, C., Galadini, F., Valensise, G., Stucchi, M., Basili, R., Barba, S., Vannucci, G. and Boschi, E. (2008). A seismic source zone model for the seismic hazard assessment of the Italian territory, *Tectonophysics* **450**, 85–108.

Reiter, L. (1990). Earthquake Hazard Analysis, Issues and Insights. *Columbia University Press*: New York.