Bollettino di Geofisica Teorica ed Applicata Vol. 53, n. 1, pp. 19-36; March 2012
DOI 10.4430/bgta0036

Probabilistic seismic hazard assessment in the high-risk area of south-eastern Sicily (Italy)

V. D'Amico, C. Meletti and F. Martinelli

Istituto Nazionale di Geofisica e Vulcanologia, Pisa, Italy

(Received: October 12, 2010; accepted: March 14, 2011)

ABSTRACT A probabilistic seismic hazard analysis was carried out for the SE sector of Sicily, an area characterized by the highest levels of seismic hazard in Italy and by high exposure, both in terms of cultural heritage and of critical industrial facilities. Compared to the Italian reference hazard map (MPS04), this study is based on the most updated information about regional seismic sources and ground-motion attenuation. Epistemic uncertainties associated with the input elements of the computational model were taken into account following a logic-tree approach. Special care was devoted to defining the regional source zone model by considering four alternative models that share the zones defining the boundary conditions of the study area but differ in the seismotectonic characterization of SE Sicily. Seismic hazard was assessed in terms of PGA, PGV, spectral acceleration and displacement on rock for four return periods (30, 50, 475, 975 years). A disaggregation analysis was then performed for some sites of interest. Results confirm the high hazard of the area, with expected values of PGA (at 10% probability of exceedance in 50 years) slightly higher than the reference MPS04 map. Strong differences emerge instead between the acceleration uniform hazard spectra of this study and the reference ones for the longest return periods.

Key words: probabilistic seismic hazard, SE Sicily, Italy.

1. Introduction

The history of modern probabilistic seismic hazard analysis (PSHA) in Italy is in close correlation with the evolution of seismic provisions and, particularly, of seismic zoning. In 2002, the San Giuliano di Puglia earthquake (the collapse of a school and the subsequent death of 27, 6-year-old pupils) revealed the inadequacy of the Italian seismic zoning enforced in 1984, on the basis of an elaboration (CNR-PFG, 1980) that combined a probabilistic seismic hazard assessment, the maximum observed intensities and a risk indicator. Thus, in order to update the seismic zoning, the National Civil Protection Department requested a new hazard map (in terms of PGA) which was then released in 2004 [MPS04: MPS Working Group (2004), Stucchi *et al.* (2011)], based on updated earthquake catalogue [CPTI04: CPTI Working Group (2004)] and seismic source zone model (Meletti *et al.*, 2008), and on a set of ground-motion attenuation relationships derived from Italian and European data (Ambraseys *et al.*, 1996; Sabetta and Pugliese, 1996; Malagnini *et al.*, 2000, 2002; Akinci *et al.*, 2004; Morasca *et al.*, 2006). The MPS04 map was then adopted as the reference seismic hazard map for Italy in 2006 (Prime

Minister's Ordinance 3519/2006, Official Gazette n. 108, May 11, 2006) and it is still the reference document for Regional administrations that intend to update the seismic zoning fixed in 2003 for the whole of Italy (Prime Minister's Ordinance 3274/2003, Official Gazette n. 105, May 8, 2003). In 2009, a new building code [NTC08: NTC (2008)] was finally adopted, where the site-dependent design spectra come from the acceleration uniform hazard spectra computed following the same hazard model of MPS04 (Montaldo *et al*., 2007; Stucchi *et al*., 2011).

In this paper, we present the results of a PSHA study carried out for the south-eastern sector of Sicily, approximately corresponding to the Siracusa district territory, to the south of Catania (Fig. 1a).

This is one of the areas of Italy with highest seismic hazard in the reference MPS04 map, with expected PGA values (at 10% exceedance probability in 50 years) on rock reaching 0.278 g (Fig. 1b). In fact, as shown in Fig. 1a, strong past seismicity occurred in this region, including three earthquakes above magnitude 6 (CPTI Working Group, 2004), that is the events of 1169 and 1542 (M_w 6.6 and 6.62, respectively) and the largest earthquake historically known in Italy, i.e., the M_w 7.41 event of January 11, 1693, which caused extensive damage and even total destruction (intensity up to XI MCS) of several localities (Boschi *et al*., 1997; Boschi and Guidoboni, 2001). Though consensus about the regional seismotectonic setting exists (e.g., Azzaro and Barbano, 2000), the debate is still open about the causative fault of the 1693 earthquake.

In the past, it was common opinion to consider the Malta Escarpment responsible for this event: it is an important offshore extensional structure, well-known in the literature (e.g., Grasso, 1993), with evidence of recent activity. According to some interpretations, it is considered a first order structural element, probably the limit between the African plate and the Adria microplate (Meletti *et al*., 2000). Among others, Azzaro and Barbano (2000) suggest the association of the 1693 event to the Malta Escarpment.

More recently, however, new data and interpretations propose an inland source for this earthquake: Sirovich and Pettenati (2001), on the basis of the inversion of macroseismic observations, suggest a blind strike-slip structure parallel to the well-known Scicli line; Basili *et al*. (2008), according to new evidence from geological field analyses, propose a compressional fault (Mt. Lauro), that is shorter than the Malta Escarpment but long enough to release strong earthquakes.

The seismic risk of the study area is then enhanced by the fact that this region is characterized by a high level of exposure, both in terms of cultural heritage (e.g., the city of Siracusa with the ancient nucleus Ortigia, the baroque Cathedral of Noto) and critical industrial facilities, mostly located in the coastal area of Priolo Gargallo, which hosts a huge number of petrochemical and refinery plants. For these reasons, in this study, we performed a multi-parameter PSHA that is more detailed than the reference MPS04 hazard model, paying particular attention to characterizing the regional source model and relevant uncertainty. Specific analyses of seismic hazard for this area were also carried out in the past (Decanini and Panza, 2000), but based on deterministic scenarios.

Compared with the reference seismic hazard model, the present analysis provides hazard estimates for several shaking parameters (PGA, PGV, spectral acceleration and displacement) and takes into account the most updated information about the regional seismic sources (both area and fault sources) and ground-motion attenuation models, while it shares the earthquake

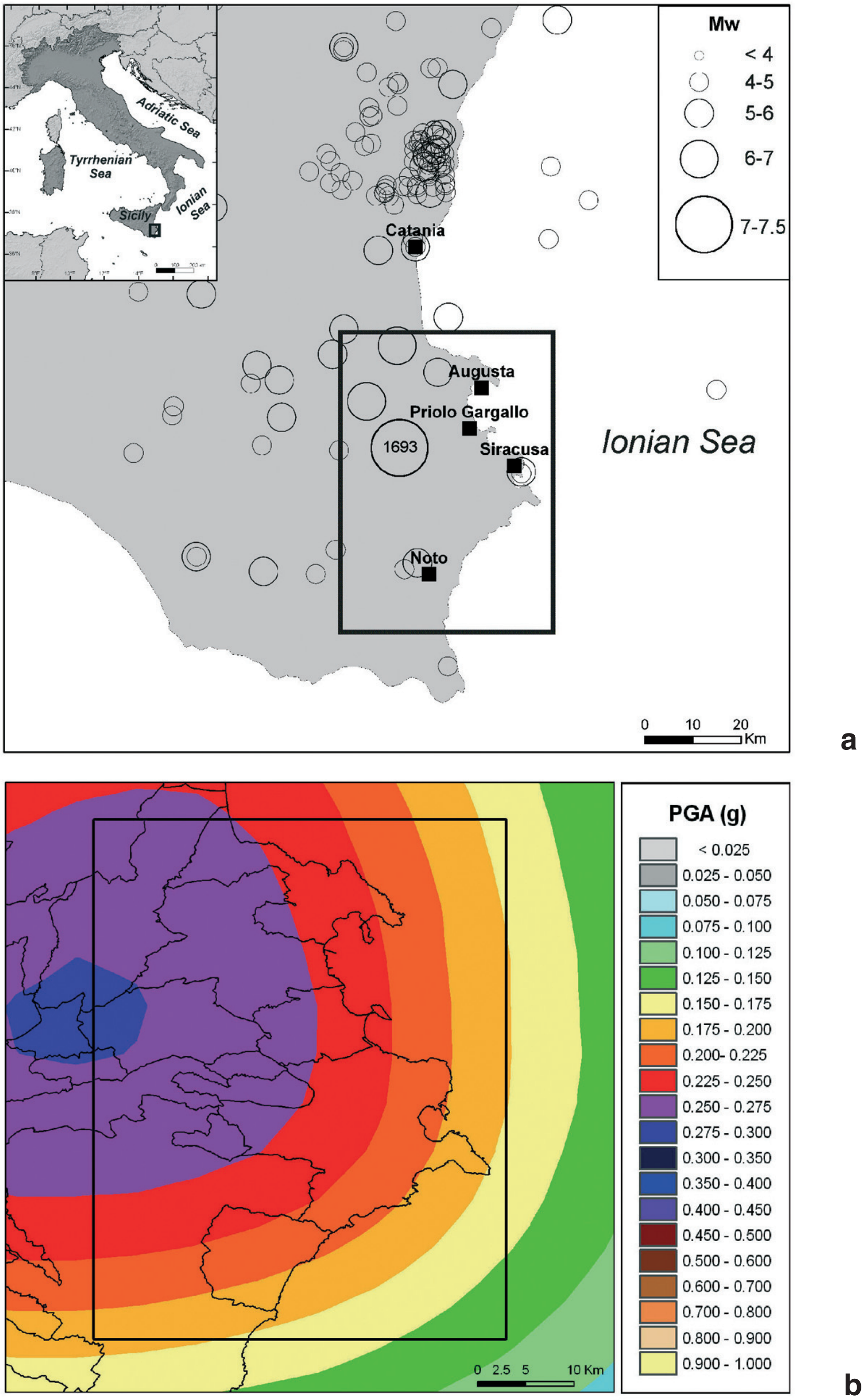


Fig. 1 - a) Seismicity in south-eastern Sicily from 217 B.C. to 2002 [from CPTI04 catalogue: CPTI Working Group (2004)]. b) Values of PGA (in g) with 10% exceedance probability in 50 years in the reference national seismic hazard map [MPS04: MPS Working Group (2004)]. The study area (box) and municipal boundaries are shown.

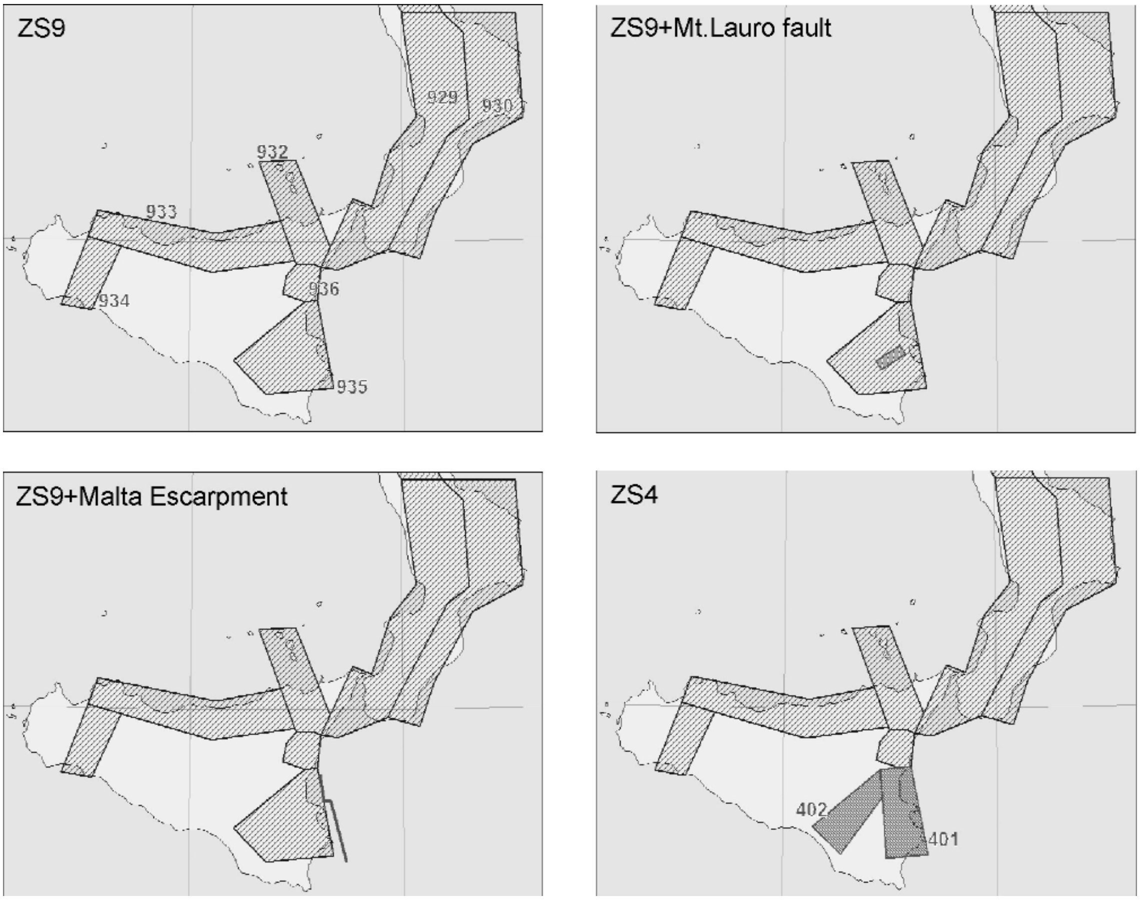


Fig. 2 - The four seismic source zone models considered in this study. Model 1: ZS9 (Meletti *et al*., 2008); model 2: ZS9 + Mt. Lauro fault; model 3: ZS9 + Malta Escarpment fault; model 4: ZS4 (derived from Meletti *et al*., 2000).

catalogue CPTI04 and related completeness time-intervals (MPS Working Group, 2004) with MPS04. According to international practice in PSHA (Kulkarni *et al*., 1984; Coppersmith and Youngs, 1986; SSHAC, 1997), a logic-tree approach was then followed to capture the epistemic uncertainty associated with the input elements of the computational model.

2. Seismic hazard analysis

Computations were performed by using the new 2008 version of CRISIS, an Open Source code developed by Ordaz *et al*. (1999) and recently significantly upgraded in the frame of the Italian research project INGV-DPC S2 (agreement 2007-2009), funded by the National Civil Protection Department. CRISIS is essentially based on the standard Cornell approach (Cornell, 1968) to PSHA and allows two types of seismicity models, both associated to Poissonian occurrences, but based on different magnitude-frequency relations: truncated Gutenberg-Richter and characteristic-earthquake models (Kiremidjian and Anagnos, 1984). In the new version of the

Table 1 - Parameters of the Gutenberg-Richter model (λ=exceedance rate of threshold magnitude M_0, b and s.d._b=b-value and relevant standard deviation), M_0 and M_{max} values for each source zone of ZS9 and ZS4 models (935 BG corresponds to the background zone 935 of the two models including fault sources). The predominant style-of-faulting of each zone is also listed (N=normal, R=reverse, S=strike-slip, U=undetermined).

		Historical completeness			**Statistical completeness**				
ZS9	**style-fault**	**λ**	**b**	**s.d._b**	**λ**	**b**	**s.d._b**	**M_0**	**Mmax**
929	N	0.394	-0.816	0.041	0.313	-0.793	0.037	4.64	7.29
930	U	0.146	-0.979	0.042	0.106	-0.892	0.051	4.64	6.60
932	S	0.118	-1.214	0.118	0.105	-1.082	0.116	4.64	6.14
933	R	0.166	-1.389	0.100	0.159	-1.244	0.089	4.64	6.14
934	R	0.043	-0.964	0.149	0.039	-0.933	0.138	4.64	6.14
935	S	0.089	-0.724	0.046	0.097	-0.693	0.075	4.64	7.41
936	U	0.425	-1.631	0.046	0.352	-1.224	0.060	4.18	5.45
935 BG	S	0.087	-0.900	0.093	0.095	-0.986	0.078	4.64	6.60
ZS4	**style-fault**	**λ**	**b**	**s.d._b**	**λ**	**b**	**s.d._b**	**M_0**	**Mmax**
401	N	0.090	-0.764	0.052	0.116	-0.750	0.081	4.64	7.41
402	R	0.023	-0.795	0.144	0.022	-0.894	0.000	4.64	6.14

program, also non-Poissonian occurrences are admitted in the form of non-parametric models, thus allowing to take into account even very complex time-dependent earthquake recurrences. In this study, only the Poissonian occurrence was considered, assuming the Gutenberg-Richter model in case of area sources and the characteristic behaviour for fault sources.

The input elements required for the analysis are: a seismic source zone model with each zone characterized in terms of seismicity rates, an earthquake catalogue with relevant completeness time-intervals, a ground-motion predictive equation as function of source energy and distance. Alternative models were considered for the above elements in the frame of a logic-tree approach in order to explore the role of epistemic uncertainties on seismic hazard estimates.

Table 2 - Main features of the three ground-motion predictive models considered in this study (M_w=moment magnitude; R_{jb}=Joyner-Boore distance; R_{hyp}=hypocentral distance).

GMPM	**Area**	**Ground motion parameter**	**Spectral periods (s)**	**Magnitude range (M_w)**	**Source distance**	**Distance range (km)**
Akkar & Bommer (2010)	Europe, Mediterranean, Middle East	PGA (cm/s^2) PGV(cm/s) PSA (cm/s^2)	0.05 - 3	5 - 7.6	R_{jb}	< 100
Boore & Atkinson (2008)	World (PEER NGA)	PGA (g) PGV(cm/s) PSA (g)	0.01 - 10	5 - 8	R_{jb}	< 200
Cauzzi & Faccioli (2008)	World	PGA (m/s^2) SD (cm)	0.05 - 20	5 - 7.2	R_{hyp}	< 150

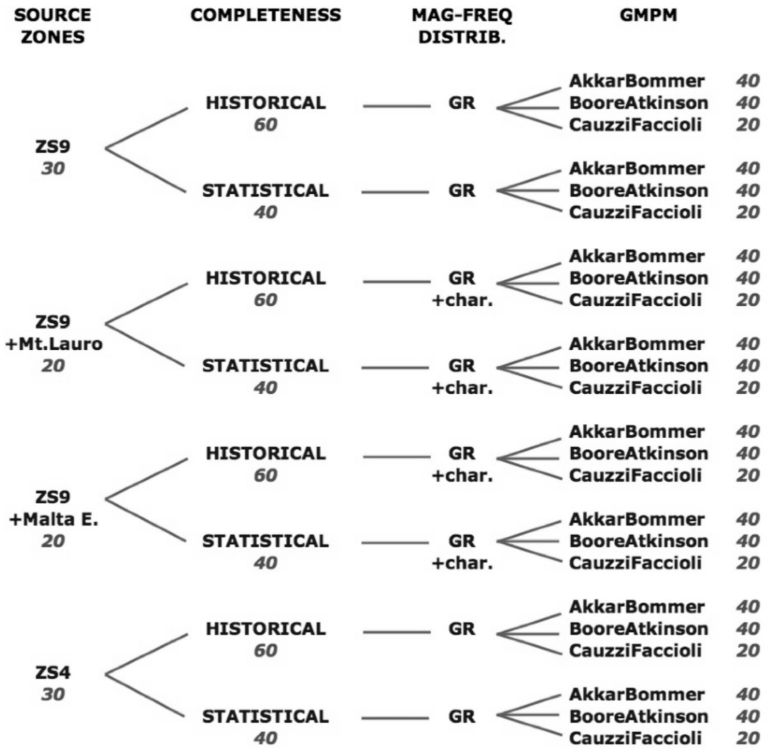


Fig. 3 - Logic tree showing the alternative options considered in the analysis (italics indicate the weight values in percentage assigned to each option).

2.1. Input elements

Special care was devoted to defining the regional seismic source zone model by taking into account different hypotheses. In particular, four alternative models were considered (Fig. 2), which share the zones defining the boundary conditions of the study area [i.e., zones 929, 930, 932, 933, 934, 936 of the ZS9 model by Meletti *et al*. (2008), developed for the MPS04 hazard map], but differ in the seismotectonic characterization of SE Sicily:

1) ZS9: the same source zone used for the reference MPS04 map (i.e., zone 935) which covers the whole study area was adopted,
2) ZS9+Mt. Lauro fault: zone 935 of model 1) was retained but, according to the DISS 3 database of seismogenic faults (Basili *et al*., 2008), the 1693 earthquake was related to the Mt. Lauro compressional fault. The dimensions of this structure reported in DISS could produce a lower magnitude than the one assigned to this event in the CPTI04 catalogue on the basis of a macroseismic approach [namely Boxer method, by Gasperini *et al*. (1999)], that is M_w 6.6 instead of 7.41. According to DISS, however, a smaller earthquake in a compressional environment should be able to justify the damage observed during the 1693 event.
3) ZS9+Malta Escarpment fault zone: as model 2), but the 1693 earthquake was attributed to the larger Malta Escarpment offshore extensional structure (e.g., Azzaro and Barbano, 2000). Unlike the Mt. Lauro fault, the dimensions of this structure are compatible with the large

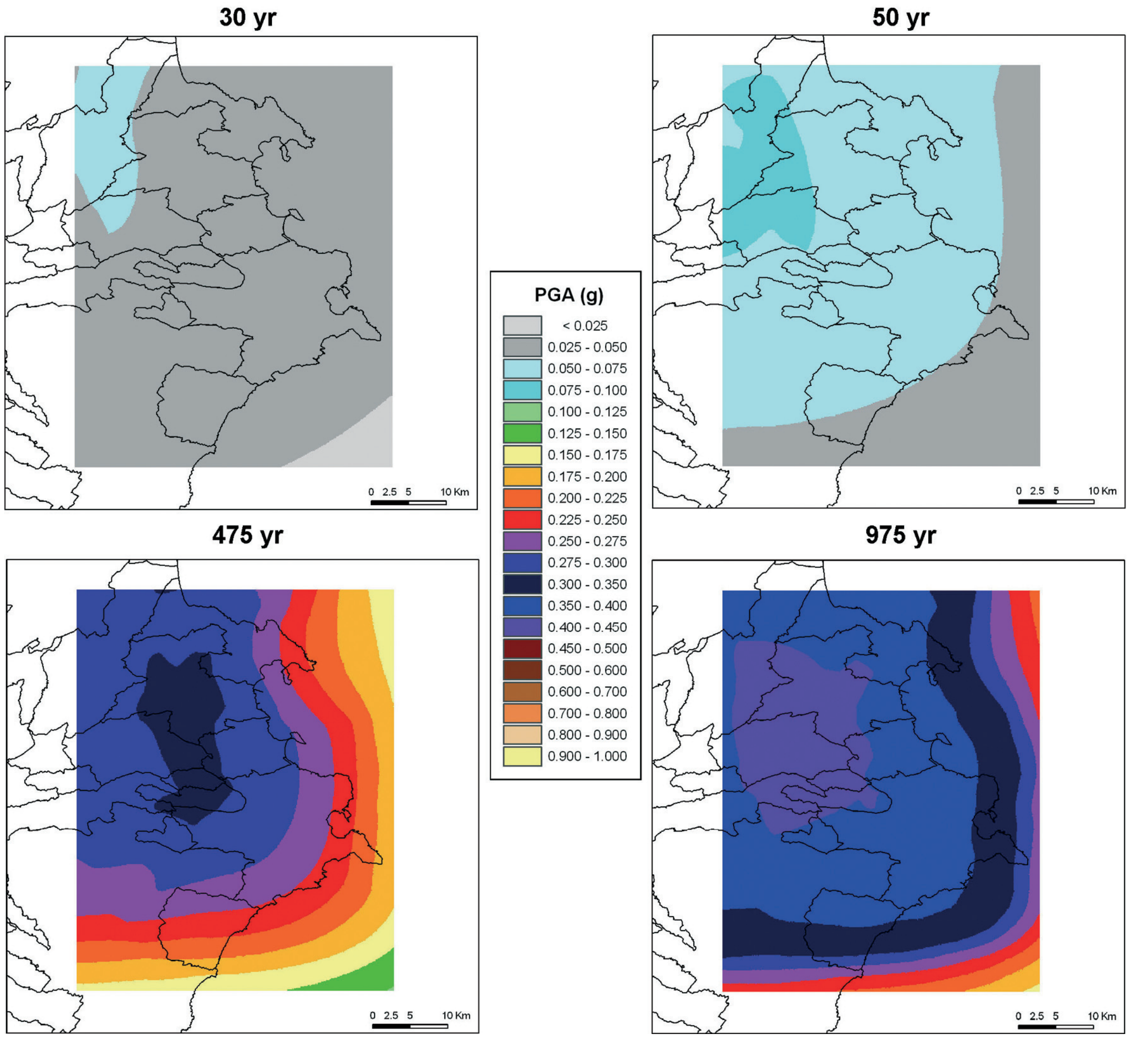


Fig. 4 - Expected PGA values (in g) for 30, 50, 475 and 975-year return periods (i.e., at exceedance probability of 81%, 63%, 10% and 5%, respectively, in 50 years).

magnitude (M_w 7.41) assigned to this event from macroseismic data. Moreover, evidence of a tsunami generated by the 1693 earthquake (Gerardi *et al.*, 2008) inclines to make one think of an offshore source rather than an inland one, as suggested instead by Tinti *et al.* (2001). This hypothesis is also supported by the offshore location of the epicentre, that results from an algorithm for epicentral determination based on macroseismic data (Bakun and Wentworth, 1997) which is alternative to the Boxer method adopted for the CPTI04 catalogue.

4) ZS4: two source zones that derive from the ZS4 seismotectonic model (Meletti *et al.*, 2000) were considered: the former (401), lying along the Ionian coast, is responsible for the largest, mainly normal-fault earthquakes of the area (including the event of January 1693), and the latter (402), corresponding to the compressional Iblean front, is characterized by minor seismicity.

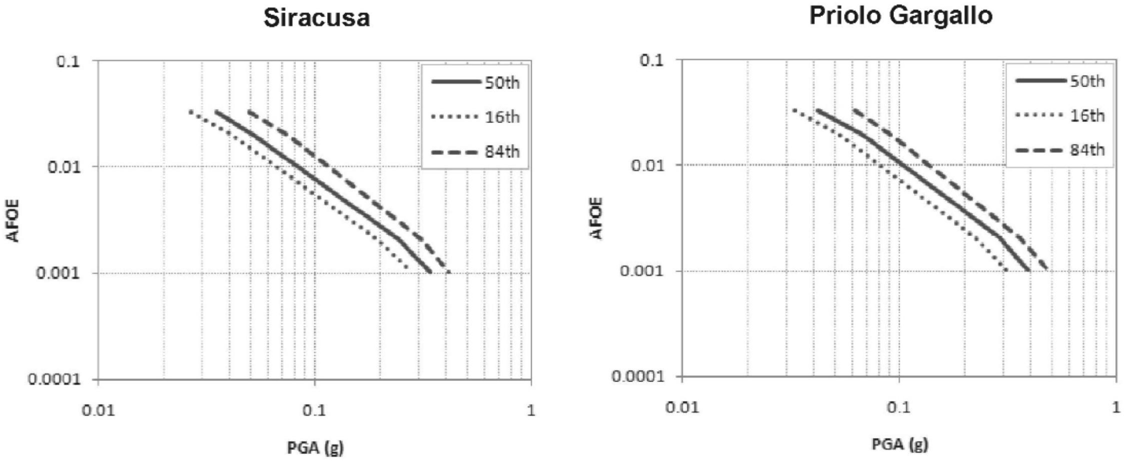


Fig. 5 - Median, 16th- and 84th-percentile hazard curves (annual frequency of exceedance, AFOE, vs. PGA) for the sites of Siracusa and Priolo Gargallo.

The fault sources adopted in this study in models 2) and 3) are those that, in our opinion, are based on stronger evidence. As stated above, a characteristic behaviour was assumed for these faults, with characteristic magnitude corresponding to the one assessed for the 1693 earthquake (i.e., M_w 6.6 for Mt. Lauro fault and 7.41 for Malta Escarpment). The remaining seismicity (with magnitude lower than the characteristic one) was attributed instead to the background zone 935, whose seismicity rates were recomputed with respect to the original ones used for MPS04 and, thus, in model 1).

The seismicity of area sources was characterized from the CPTI04 catalogue (CPTI Working Group, 2004), which lists the damaging events that occurred in Italy from 217 B.C. to 2002, by considering only its complete portions for different magnitude ranges. To this purpose, the two alternative sets of completeness time-intervals defined for MPS04 [for details, see MPS Working Group (2004)] were adopted: one assessed from historical considerations, according to Stucchi *et al*. (2004), and one from statistical analysis, following the methodology by Albarello *et al*. (2001). The differences between the two approaches can be summarized as follows: the historical approach looks outside the catalogue, while the statistical one looks inside it. In the first case, as for a modern seismic network, the historians determine if and when the possible sources of information were active and, in such a way, they define (in a procedure not yet standardized) the period when the catalogue can be considered complete. On the contrary, the statistical approach looks only at the information reported in the catalogue by assuming that the time-windows where seismicity is stationary are complete. Then, for each zone, the earthquake rates were determined in the assumption that a truncated Gutenberg-Richter relationship holds, through a least-squares fit of annual rates computed in each magnitude bin, with maximum magnitude fixed to the largest value observed (historically and geologically) in the past or assuming a precautionary value of M_w 6.14 (as in MPS04) for those zones where the observed value is below this threshold (i.e., zones 932,

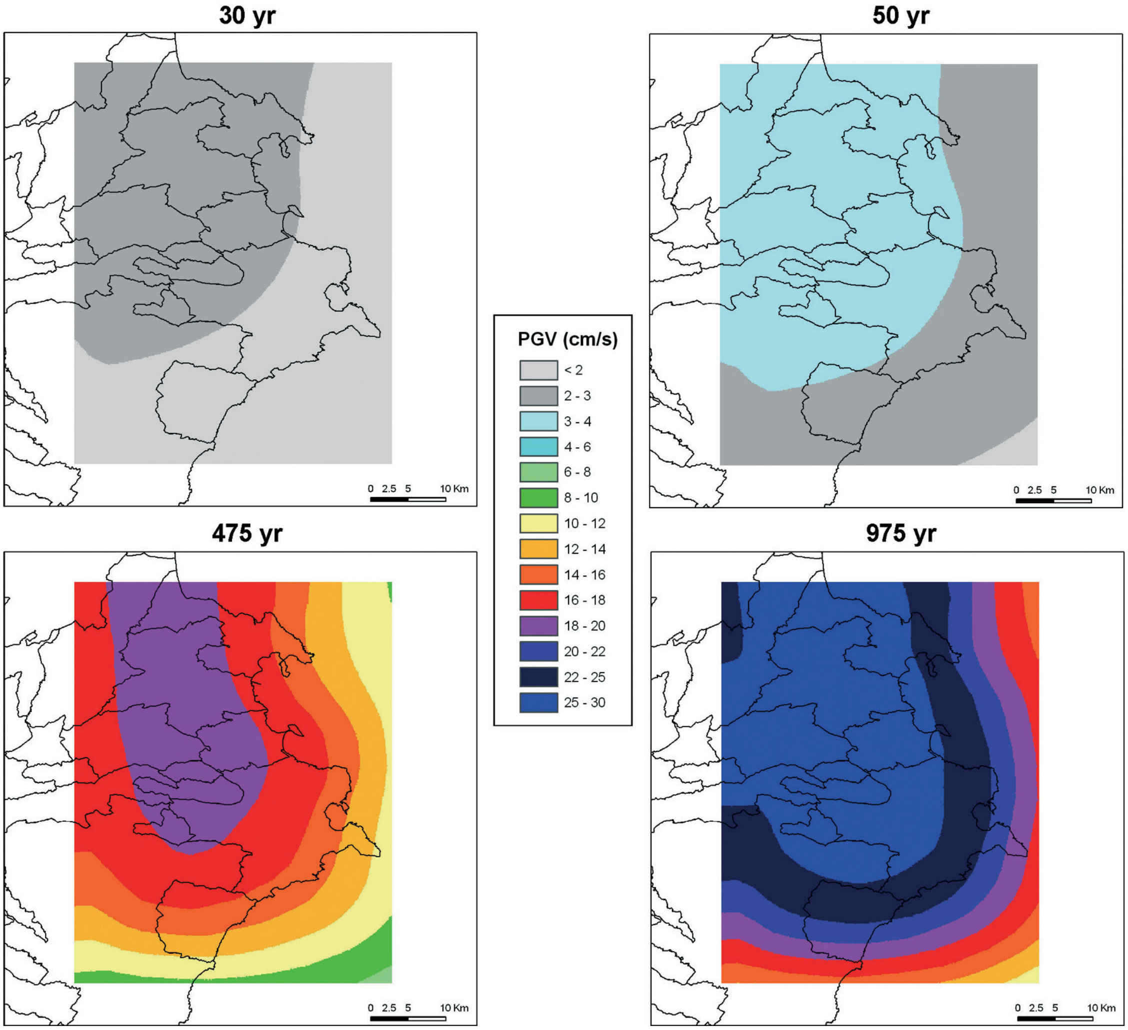


Fig. 6 - Expected PGV values (in cm/s) for 30, 50, 475 and 975-year return periods (i.e., at exceedance probability of 81%, 63%, 10% and 5%, respectively, in 50 years).

933, 934, 402). Table 1 lists the seismicity parameters of the area sources.

As concerns ground-motion predictive models (GMPMs), three recent studies were considered: Akkar and Bommer (2010), Boore and Atkinson (2008), Cauzzi and Faccioli (2008). These models derive from different strong-motion data sets and predict several shaking parameters: peak values of ground acceleration and velocity (PGA, PGV) and pseudo-acceleration or displacement (PSA or SD) elastic response spectra for different ranges of spectral periods (Table 2). All models use moment magnitude and source distance (Joyner-Boore distance for the first two models, focal distance for the latter) as explanatory variables together with style-of-faulting classes.

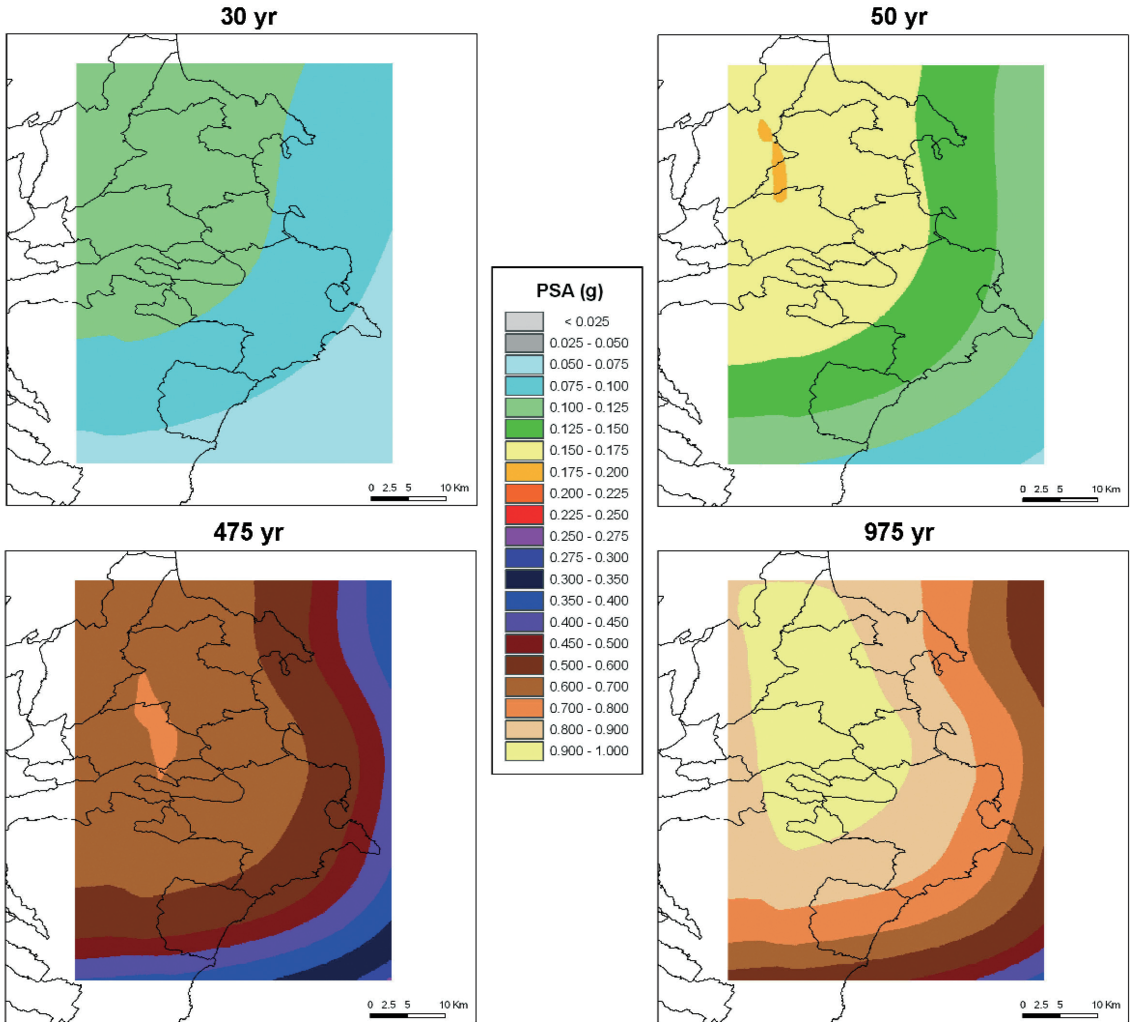
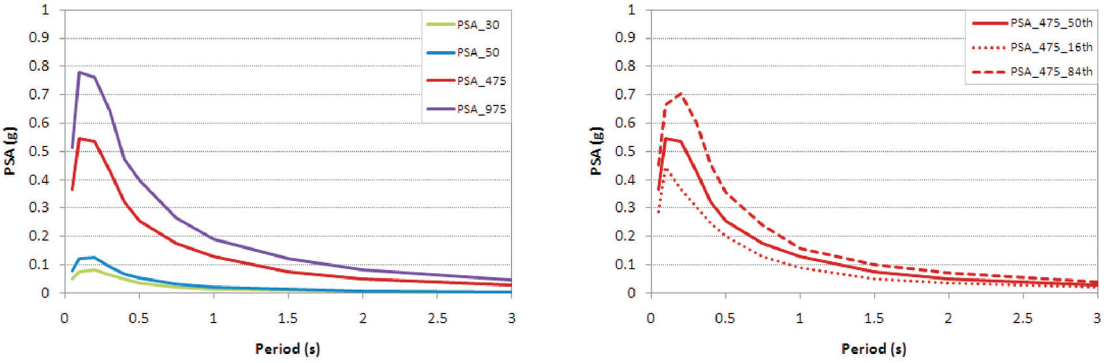


Fig. 7 - Expected acceleration values (in g), for 0.2 s period, for 30, 50, 475 and 975-year return periods (i.e., at exceedance probability of 81%, 63%, 10% and 5%, respectively, in 50 years).

The above alternative input elements were combined into a logic tree (Fig. 3) made of 24 branches (16 in the case of PGV estimates, since only two GMPMs could be used), each one characterized by a weight representing the reliability of the relevant choice. In particular, more weight was given to the two area source models, since their use in PSHA (both in Italy and worldwide) is more consolidated and common with respect to fault sources. For the two sets of completeness time-intervals, the weights adopted for MPS04 were retained. Concerning the GMPMs, a lower weight was attributed to the Cauzzi and Faccioli (2008) model only because, to date, it has been used less extensively than the other two. An estimate of hazard was then derived for each branch and the median (considering the weight assigned to every branch) was taken as the reference value.

Siracusa



Priolo Gargallo

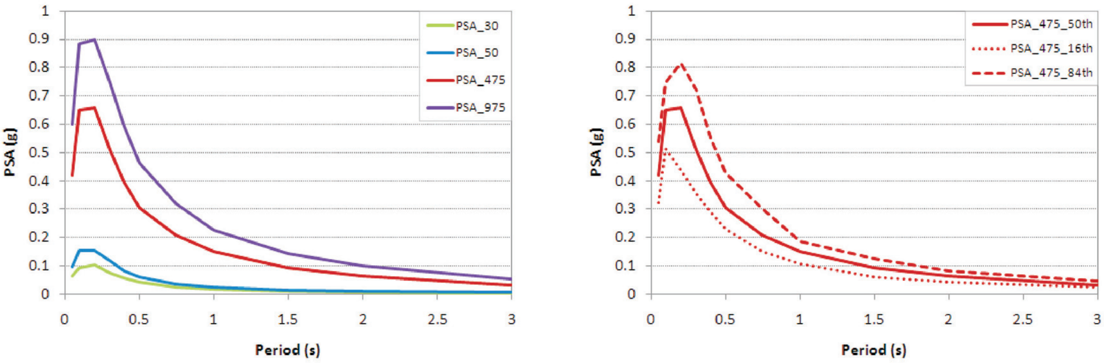


Fig. 8 - Uniform hazard spectra in acceleration (in g) for Siracusa and Priolo Gargallo. Left: median spectra for 30, 50, 475 and 975-year return periods; right: median, 16th- and 84th-percentile spectra for the 475-year return period.

2.2. Results

Seismic hazard was computed on rock-site conditions, on a grid with node distance of 2 km covering the study area, for the four return periods required by the NTC08 building code (i.e., 30, 50, 475, 975 years) in terms of PGA, PGV and spectral acceleration and displacement.

Maps in Fig. 4 show the computed PGA values for the four return periods considered (i.e., with probability of exceedance of 81%, 63%, 10% and 5% in 50 years). The expected values for 475 and 975 years range between 0.123-0.307 g and 0.168-0.414 g, respectively. Fig. 5 displays the PGA hazard curves (median estimates along with relevant uncertainty, quantified as the difference between 84th and 16th percentiles) computed at two of the most important sites of the area: the city of Siracusa and the industrial site of Priolo Gargallo.

The distribution of expected PGV values for the same return periods is shown in Fig. 6: they range between 7.3-19.1 cm/s and 10.8-27.7 cm/s, respectively for 475 and 975 years.

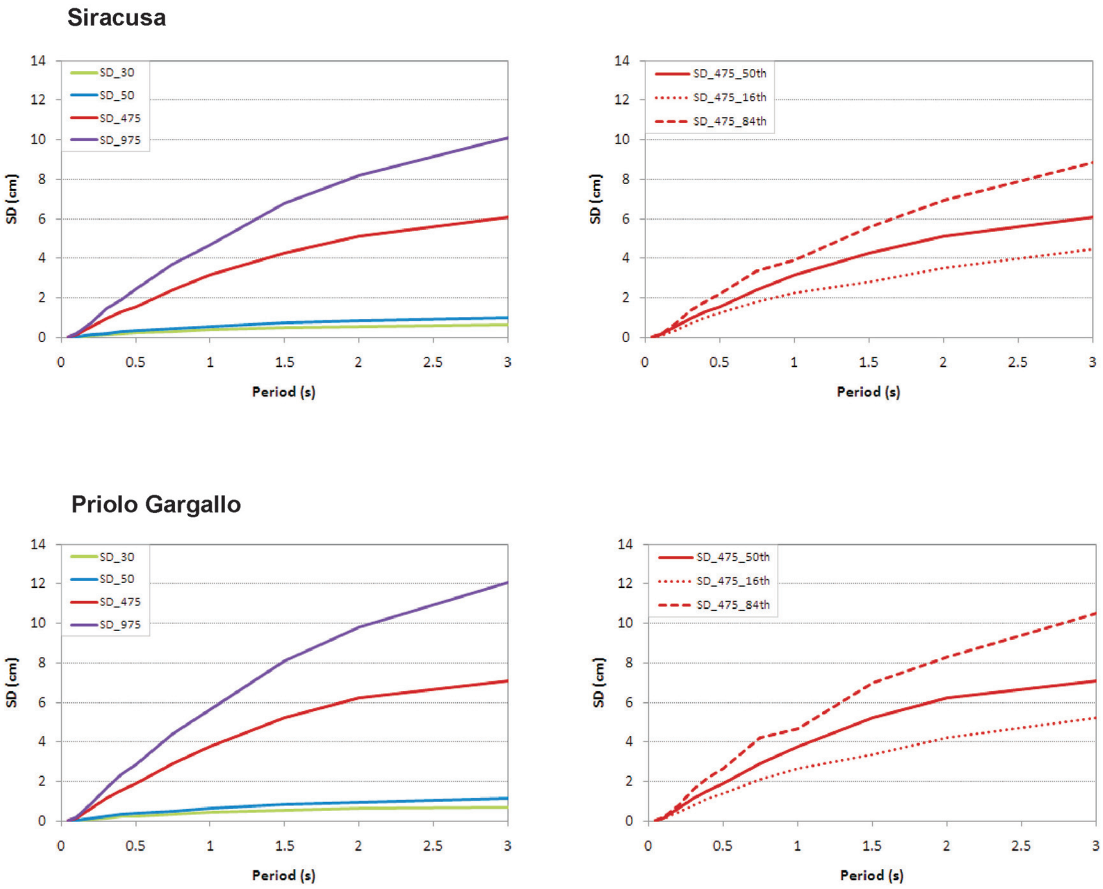


Fig. 9 - Uniform hazard spectra in displacement (in cm) for Siracusa and Priolo Gargallo. Left: median spectra for 30, 50, 475 and 975-year return periods; right: median, 16th- and 84th-percentile spectra for the 475-year return period.

Then, uniform hazard spectra in terms of acceleration and displacement were computed for 11 spectral periods in the range 0.05-3 s, that is the range covered by the three considered attenuation models. Fig. 7 shows the distribution of acceleration values with probability of exceedance of 81%, 63%, 10% and 5% in 50 years for the spectral period of 0.2 s, where the absolute highest values (up to 0.704 g and 0.962 g for 475 and 975 years, respectively) are reached.

Figs. 8 and 9 display the acceleration and displacement uniform hazard spectra for Siracusa and Priolo Gargallo. The large uncertainty on the median hazard estimate is worth noting: in fact, for the 475-year return period, the 84th-percentile curve nearly reaches the median spectrum computed for the longest return period.

In order to understand which one of the input elements is the main responsible for this large uncertainty in the hazard estimate (also evident from Fig. 5), we analysed the results from some individual branches of the logic tree. In particular, the effect of alternative source zone models

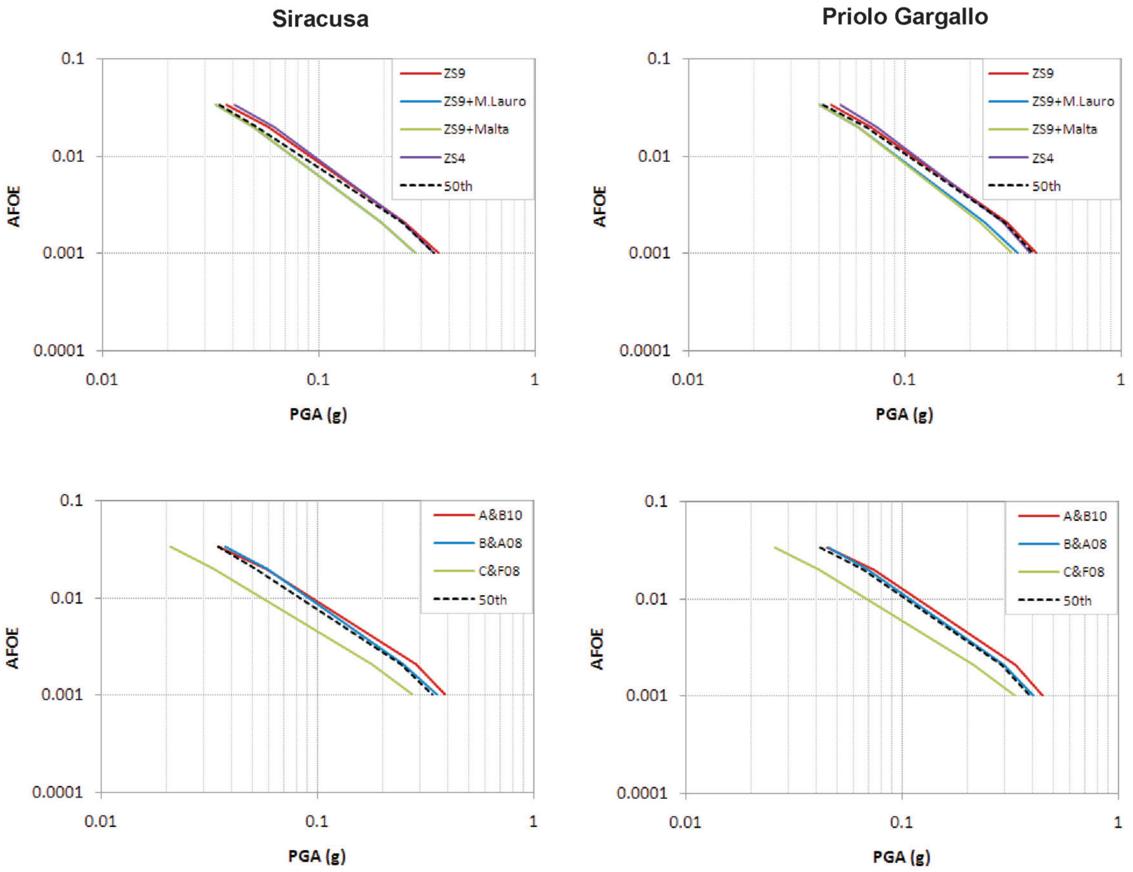


Fig. 10 - PGA hazard curves resulting from individual branches of the logic tree. Top: changing the source zone model, for the same choices on completeness time-intervals and GMPM (i.e., historical completeness and Boore and Atkinson's equation); bottom: changing the GMPM, for the same choices on completeness time-intervals and source zone model (i.e., historical completeness and ZS9 model).

and GMPMs was explored, since these are the two elements known to have the largest impact on seismic hazard. Fig. 10 compares the PGA hazard curves computed at the two selected sites by changing the source zone model (top panels), for the same choices on completeness time-intervals and GMPM [i.e., historical completeness and Boore and Atkinson's (2008) equation], and by changing the GMPM (bottom panels), for the same choices on completeness time-intervals and source zone model (i.e., historical completeness and ZS9 model). As shown in the figure, the two curves obtained from the area source models (ZS9 and ZS4) display a clearly distinct trend from the ones derived by the two models which include fault sources. However, the large variability in the hazard estimate seems to be mainly attributable to the effect of different GMPMs and, particularly, to Cauzzi and Faccioli's (2008) predictive equation which leads to very different results compared to the other two models.

A disaggregation analysis was then performed for PGA at some sites of interest in order to

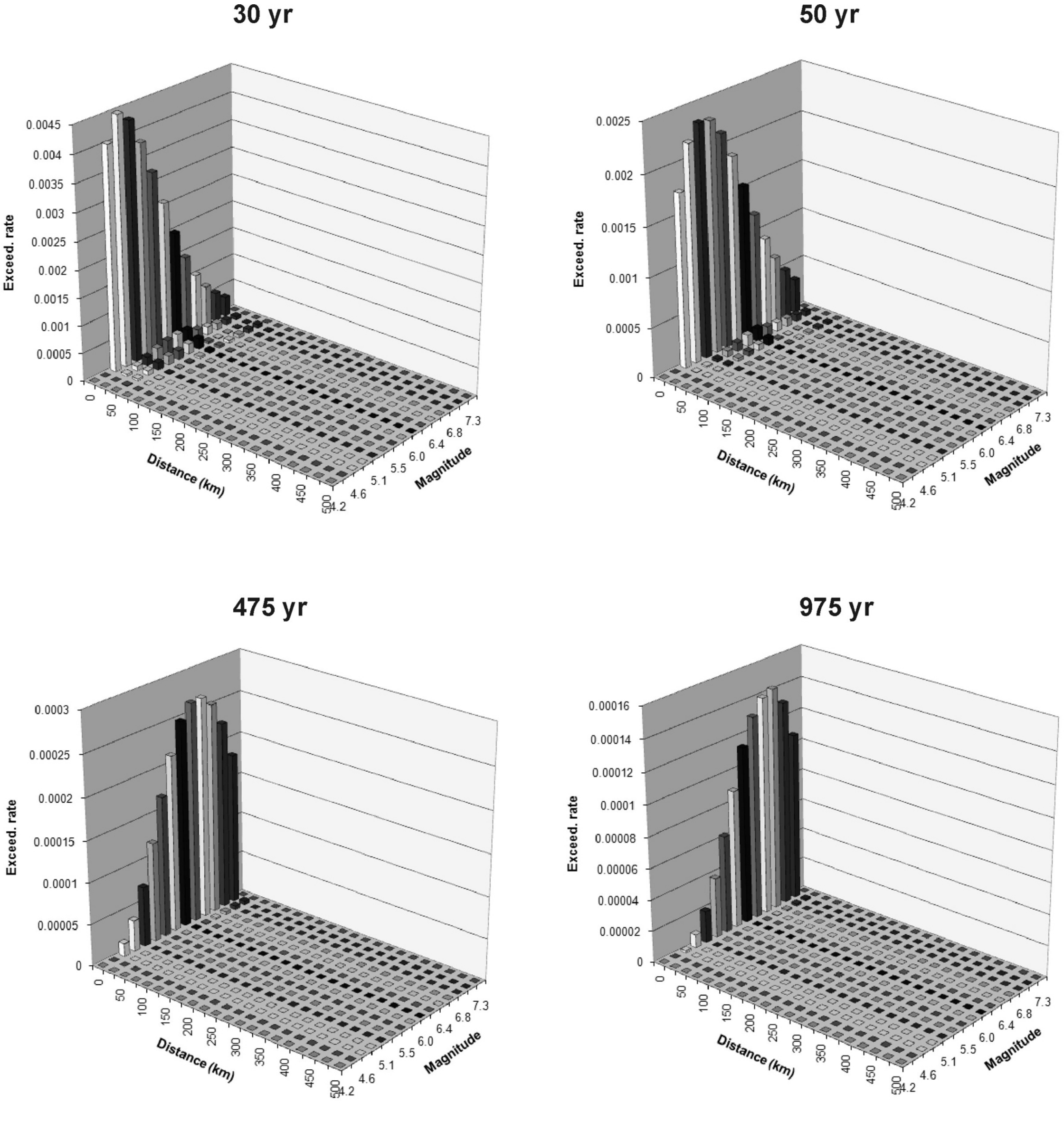


Fig. 11 - Disaggregation analysis of PGA hazard for the site of Priolo Gargallo.

determine at what extent the different possible sources (i.e., combinations of magnitude-distance) contribute to the hazard of a site. For this purpose, the analysis was carried out for the branch of the logic tree which provides the hazard values closest to the median hazard estimate, that is the branch corresponding to ZS4 source zone model, historical completeness, Boore and Atkinson's (2008) attenuation predictive equation. Disaggregation results for the Priolo Gargallo site are shown in Fig. 11: as expected, because the study area is located inside a source zone and very

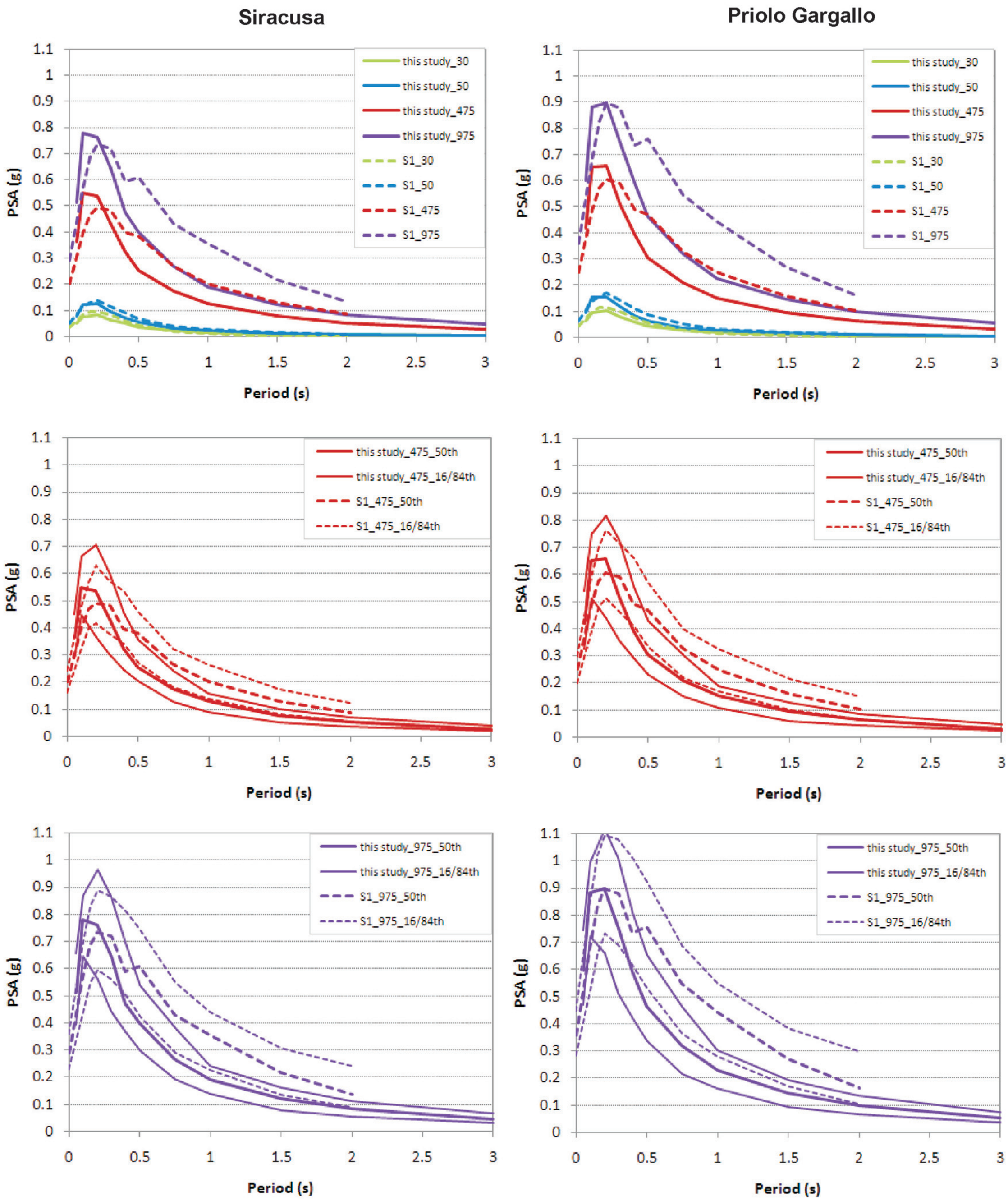


Fig. 12 - Comparison between the acceleration uniform hazard spectra computed in this study (solid lines) and the reference S1 spectra (dashed lines) for Siracusa and Priolo Gargallo. Top panels: median spectra computed for the four return periods considered; middle and bottom panels: median, 16th, and 84th percentile spectra for 475 and 975-year return periods, respectively.

close to the considered faults, the hazard is dominated by near sources (distance <25 km) with magnitude getting higher with increasing return period.

3. Discussion and conclusions

The results of this study confirm the very high level of seismic hazard in the area of SE Sicily. In fact, considering the expected PGA at 10% probability of exceedance in 50 years (475-year return period), nearly the whole inland area is characterized by values higher than 0.25 g, thus falling into seismic zone 1, as established by the Prime Minister's Ordinance 3274/2003.

Compared with the national reference seismic hazard map (MPS04), the spatial pattern of expected PGA values for the 475-year return period looks rather similar but the estimated values are slightly higher (compare Fig. 4 bottom left with Fig. 1b), reaching a maximum of 0.307 g vs. 0.278 g of MPS04. Comparable values of PGA result instead for the longest return period (975 years), with a maximum of 0.414 g vs. 0.403 g.

On the contrary, strong differences emerge between the acceleration uniform hazard spectra derived in this study and the reference ones (i.e., the spectra computed following the same computational scheme of MPS04 in the frame of the INGV-DPC 2005-2007 S1 project, http://esse1.mi.ingv.it/) used to define the seismic-design load according to the present NTC08 building code. Fig. 12 (top panels) compares the two families of acceleration spectra (median estimates) for the four considered return periods at the two selected sites of Siracusa and Priolo Gargallo. Though maximum values are similar (major differences for 475 years), for the two longest return periods, the median spectral shapes appear deeply different. In fact, the spectra of this study display a plateau (portion of maximum acceleration values) shifted towards the left (shorter periods) and a much faster decay with period than the reference S1 spectra. The effect of the different decay is particularly strong for periods higher than about 0.5 s, with a nearly complete overlap between the S1 475-year spectrum and the present 975-year curve. However, due to the large uncertainty affecting both the reference and the present hazard estimates, the two families of spectra do not result significantly different, though their dissimilar decay with period makes the present median curves above 0.4 s nearly coincident with (or even lower than) the S1 16th-percentile spectra (see Fig. 12, middle and bottom panels).

Major innovations with respect to the reference hazard estimates concern the regional source zone model (four models including also fault sources instead of one with area sources only), the use of most recent GMPMs and the adopted computation program [CRISIS instead of SEISRISK III by Bender and Perkins (1987)]. Though further investigations are needed to clearly identify which one of these new elements is the major responsible for the strong differences observed between the two families of uniform hazard spectra, we believe that a key role is played by the new set of GMPMs. In fact, while three out of the four source zone models considered here are to some extent related to the ZS9 model used for MPS04, the set of GMPMs is completely different from the one used for the reference hazard estimates. On the other hand, it is well-known that GMPMs (and relevant aleatory variability) represent one of the most crucial input elements in PSHA (e.g., Bommer and Abrahamson, 2006).

REFERENCES

Akinci A., Mueller C., Malagnini L. and Lombardi A.M.; 2004: *Seismic hazard estimate in the Alps and Apennines (Italy) using smoothed historical seismicity and regionalized predictive ground-motion relationships.* Boll. Geof. Teor. Appl., **45**, 285–304.

Akkar S. and Bommer J.J.; 2010: *Empirical equations for the prediction of PGA, PGV, and spectral accelerations in Europe, the Mediterranean region, and the Middle East*. Seismol. Res. Lett., **81**, 195-206.

Albarello D., Camassi R. and Rebez A.; 2001: *Detection of space and time heterogeneity in the completeness of a seismic catalog by a statistical approach: an application to the Italian area.* Bull. Seismol. Soc. Am., **91**, 1694-1703.

Ambraseys N.N., Simpson K.A. and Bommer J.J.; 1996: *Prediction of horizontal response spectra in Europe.* Earthquake Eng. Struct. Dyn., **25**, 371-400.

Azzaro R. and Barbano M.S.; 2000: *Analysis of seismicity of Southeastern Sicily: a proposed tectonic interpretation.* Ann. Geofis., **43**, 171-188.

Bakun W.H. and Wentworth C.M.; 1997: *Estimating earthquake location and magnitude from seismic intensity data.* Bull. Seismol. Soc. Am., **87**, 1502-1521.

Basili R., Valensise G., Vannoli P., Burrato P., Fracassi U., Mariano S., Tiberti M. and Boschi E.; 2008: *The Database of Individual Seismogenic Sources (DISS), version 3: Summarizing 20 years of research on Italy's earthquake geology.* Tectonophysics, **453**, 20-43.

Bender B. and Perkins D.; 1987: *SEISRISK III: A Computer Program for Seismic Hazard Estimation.* U.S. Geological Survey Bulletin 1772, 48 pp.

Bommer J.J. and Abrahamson N.A.; 2006: *Why do modern probabilistic seismic hazard analyses often lead to increased hazard estimates?* Bull. Seismol. Soc. Am., **96**, 1967-1977.

Boore D.M. and Atkinson G.M.; 2008: *Ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped PSA at spectral periods between 0.1 s and 10.0 s.* Earthquake Spectra, **24,** 99-138.

Boschi E. and Guidoboni E.; 2001: *Catania, terremoti e lave: dal mondo antico alla fine del Novecento.* INGV-SGA, Editrice Compositori, Bologna, 414 pp.

Boschi E., Guidoboni E., Ferrari G., Valensise G. and Gasperini P. (eds); 1997: *Catalogo dei forti terremoti in Italia dal 461 a.C. al 1980, vol. 2.* ING-SGA, Bologna, 644 pp.

Cauzzi C. and Faccioli E.; 2008: *Broadband (0.05 to 20 s) prediction of displacement response spectra based on worldwide digital records.* J. Seismol., **12**, 453-475.

CNR-PFG; 1980: *Proposta di riclassificazione sismica del territorio nazionale.* Pubbl. 361, ESA Editrice, Roma, 83 pp.

Coppersmith K.J. and Youngs R.R.; 1986: *Capturing uncertainty in probabilistic seismic hazard assessments within intraplate environments.* In: Proceedings of the Third U.S. National Conference on Earthquake Engineering, August 24-28, 1986, Charleston, SC, Earthquake Engineering Research Institute, Berkeley, CA, Vol. I, pp. 301-312.

Cornell C.A.; 1968: *Engineering seismic risk analysis.* Bull. Seismol. Soc. Am., **58**, 1583-1606.

CPTI Working Group; 2004: *Catalogo Parametrico dei Terremoti Italiani, version 2004 (CPTI04).* INGV, Milano, http://emidius.mi.ingv.it/CPTI04/.

Decanini L. and Panza G.F. (eds); 2000: *Scenari di pericolosità sismica ad Augusta, Siracusa e Noto.* CNR - Gruppo Nazionale per la Difesa dai Terremoti, Roma, 200 pp.

Gasperini P., Bernardini F., Valensise G. and Boschi E.; 1999: *Defining seismogenic sources from historical earthquake felt reports.* Bull. Seismol. Soc. Am., **89**, 94-110.

Gerardi F., Barbano M.S., De Martini P.M. and Pantosti D.; 2008: *Discrimination of tsunami sources (earthquake versus landslide) on the basis of historical data in Eastern Sicily and Southern Calabria.* Bull. Seismol. Soc. Am., **98**, 2795–2805.

Grasso M.; 1993: *Pleistocene structures along the Ionian side of the Hyblean Plateau (SE Sicily): implications for the tectonic evolution of the Malta escarpment.* In: Max M.D. and Colantoni P. (eds), Geological Development of the Sicilian-Tunisian Platform, Proceedings International Symposium Marine Science, Urbino, Italy, November 4-6, 1992, pp. 49-54.

Kiremidjian A.S. and Anagnos T.; 1984: *Stochastic slip-predictable model for earthquake occurrences.* Bull. Seismol.

Soc. Am., **74**, 739-755.

Kulkarni R.B., Youngs R.R. and Coppersmith K.J.; 1984: *Assessment of the confidence intervals for results of seismic hazard analysis.* In: Proceedings, 8th World Conference of Earthquake Engineering, San Francisco, Vol. 1, pp. 263-270.

Malagnini L., Akinci A., Herrmann R.B., Pino N.A. and Scognamiglio L.; 2002: *Characteristics of the ground motion in Northeastern Italy.* Bull. Seismol. Soc. Am., **92**, 2186–2204.

Malagnini L., Herrmann R.B. and DiBona M.; 2000: *Ground-motion scaling in the Apennines (Italy).* Bull. Seismol. Soc. Am., **90**, 1062–1081.

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.

Meletti C., Patacca E. and Scandone P.; 2000: *Construction of a seismotectonic model: the case of Italy.* Pure Appl. Geophys., **157**, 11-35.

Montaldo V., Meletti C., Martinelli F., Stucchi M. and Locati M.; 2007: *On-line seismic hazard data for the new Italian building code.* J. Earthquake Eng., **11**, 119-132.

Morasca P., Malagnini L., Akinci A., Spallarossa D. and Herrmann R.B.; 2006: *Ground-motion scaling in the western Alps.* J. Seismol., **10**, 315–333.

MPS Working Group; 2004: *Redazione della mappa di pericolosità sismica prevista dall'Ordinanza PCM del 20 marzo 2003 n.3274 All. 1.* Rapporto conclusivo per il Dipartimento della Protezione Civile, Istituto Nazionale di Geofisica e Vulcanologia, Milano-Roma, April 2004, 65 pp. + 5 appendices, http://zonesismiche.mi.ingv.it/.

NTC; 2008*: Norme Tecniche per le Costruzioni.* D.M. 14 Gennaio 2008.

Ordaz M., Aguilar A. and Arboleda J.; 1999: *CRISIS99: Program for computing seismic hazard.* Version 1.07, Mexico.

Sabetta F. and Pugliese A.; 1996: *Estimation of response spectra and simulation of nonstationary earthquake ground motions*. Bull. Seismol. Soc. Am., **86**, 337-352.

Sirovich L. and Pettenati F.; 2001: *Test of source-parameter inversion of the intensities of a 54,000-death shock of the seventeenth century in Southeast Sicily.* Bull. Seismol. Soc. Am., **91**, 792–811.

SSHAC (Senior Seismic Hazard Analysis Committee); 1997: *Recommendations for probabilistic seismic hazard analysis: guidance on uncertainties and use of experts*. Report NUREG-CR-6372, in 2 volumes, Washington D.C., U.S. Nuclear Regulatory Commission.

Stucchi M., Albini P., Mirto C. and Rebez A.; 2004: *Assessing the completeness of Italian historical earthquake data.* Ann. Geophys., **47**, 659-673.

Stucchi M., Meletti C., Montaldo V., Crowley H., Calvi G.M. and Boschi E.; 2011: *Seismic hazard assessment (2003-2009) for the Italian building code.* Bull. Seismol. Soc. Am., **101**, 1885-1911.

Tinti S., Armigliato A. and Bortolucci E.; 2001: *Contribution of tsunami data analysis to constrain the seismic source: the case of the 1693 eastern Sicily earthquake.* J. Seismol., **5**, 41-61.

Corresponding author: Vera D'Amico
Istituto Nazionale di Geofisica e Vulcanologia
Via della Faggiola 32, 56126 Pisa (Italy)
Phone: +39 050 8311967; fax: +39 050 8311942; e-mail: vera.damico@pi.ingv.it