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Use of different approaches to estimate seismic hazard: the study cases of Catania and Siracusa, Italy

F. Panzera, G. Lombardo and R. Rigano

Dipartimento di Scienze Geologiche, Università di Catania, Italy

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ABSTRACT The identification of the causative faults in south-eastern Sicily (Italy) is a complicated task although the seismicity of the area has been well studied for years. For this reason a seismic hazard assessment was carried out for the Catania and Siracusa towns providing a comprehensive re-examination and re-processing of all the available seismic data. The site approach and the seismotectonic one were used and compared. The hazard assessment, using both methods, was performed following a logic-tree approach in order to consider and reduce the epistemic uncertainties. Data available in the literature, coming out from recent studies concerning the parametric earthquake catalogue and a complete database of site intensity in Italy were used. For the seismotectonic approach, two source zone models were considered for south-eastern Sicily. In the first model, the same source zone defined for the current Italian reference seismic hazard map is used; in the second model, two separate zones are considered, one includes the normal-fault structures located in the eastern part of the Hyblean area, and the other roughly corresponding to the western portion of the Hyblean front. The combined use of these approaches allowed us to obtain useful elements to define the seismic hazard in Catania and Siracusa. When the seismic history site is used, the town of Catania shows hazard values higher than the ones found for Siracusa, for each considered time interval. On the contrary, when the seismotectonic method is used, the hazard curves show a different behaviour according to the different geometry and size of the adopted source zones. The comparison between the results obtained through the two approaches is recommended since it allows us to verify the robustness of the hazard estimates performed.

Key words: seismic hazard, seismogenic sources, Sicily.

1. Forewords

Catania and Siracusa are located on the eastern coast of Sicily (southern Italy). The high level of seismicity that affects the area, together with the considerably high density of inhabitants, contribute to classifying these towns amongst those with the highest seismic risk in Italy. The potential severity of damage to which their historic-architectural patrimony could be subjected to is also not negligible. The seismic activity of the investigated area is particularly high as testified by the historical earthquakes that occurred in 1169, 1542, 1693, 1818, 1908 as well as the recent one that occurred in 1990, all having intensity ranging between the VI and XI MCS (Working Group CPTI, 2004).

The seismic hazard assessment (SHA) consists in evaluating the possible effects due to future earthquakes (and the related uncertainties) to which a study area can be subjected. It can be performed using either a deterministic (DSHA) or a probabilistic (PSHA) approach. The DSHA uses individual earthquake sources and single-valued events to establish a particular scenario that describes the hazard. Typically, a seismic source location, an earthquake of specified size and a ground motion attenuation relationship are required. However, this approach does not provide information on the occurrence probability of an earthquake parameter (acceleration, magnitude) during a finite period of time (e.g., the useful lifetime of a particular structure or facility). PSHA, being a statistical approach, needs to identify a suitable time interval having good completeness of information. On the other hand, PSHA allows us to estimate the probability when an intensity measurement (e.g., peak acceleration) could exceed a defined value during a given time (e.g., 50 years) (McGuire, 2004). It accounts for all possible combinations of magnitude-location of shocks and models describing the effects and the occurrence rate of all earthquakes that could affect an area.

Recently, the SHA in eastern Sicily has been performed by several authors (Azzaro *et al.*, 1999, 2008; Zollo *et al.*, 1999; Azzaro and Barbano, 2000; Decanini and Panza, 2000; Faccioli and Pessina, 2000; Barbano and Rigano, 2001; Barbano *et al.*, 2001; Fiorini *et al.,* 2008) who used either the DSHA or the PSHA approaches, taking into account different source areas of the major historical earthquakes that are mostly located on the Malta Hyblean fault system. In recent years, a national seismic hazard map was produced by the Working Group MPS04 (2004) and a new hypothesis was proposed for the source locations in Eastern Sicily. On the basis of the macroseismic fields, the authors thus moved the epicenters of the major earthquakes inland. The identification of the causative faults of such events is, however, still unclear and different hypotheses have been reported in literature (e.g., Argnani and Bonazzi, 2005; Gutscher *et al.*, 2006; Basili *et al.*, 2008).

The aim of the present study is to carry out a detailed probabilistic seismic hazard analysis for the towns of Catania and Siracusa using two probabilistic approaches. The results of the site method (Albarello and Mucciarelli, 2002) and the “seismotectonic” methodology (Esteva, 1967; Cornell, 1968) were compared taking also into account different seismogenic sources. Therefore, the SASHA code (D’Amico and Albarello, 2008) and the CRISIS2007 code (Ordaz *et al.*, 2007) were used to estimate seismic hazard through the above mentioned methods, respectively.

2. Seismotectonic features

The seismicity of the study area is linked to the collision between the African and European plates. Fig. 1 shows the major tectonic domains and the main active faults in eastern Sicily and the southern Calabria area.

As concerns the Calabria region, the major shocks that affected the area are located in the Crati, Savuto and Mesima basins, including the Messina Straits. Among these events, the sequences of 1783, 1905 and 1908 earthquake stand out. Details about their features, such as epicentral location, geometry and source dimensions are described by Boschi *et al.* (2000), Monaco and Tortorici (2000) and Valensise and Pantosti (2001).

In western and central Sicily, the compressional and transpressional faults are the dominant

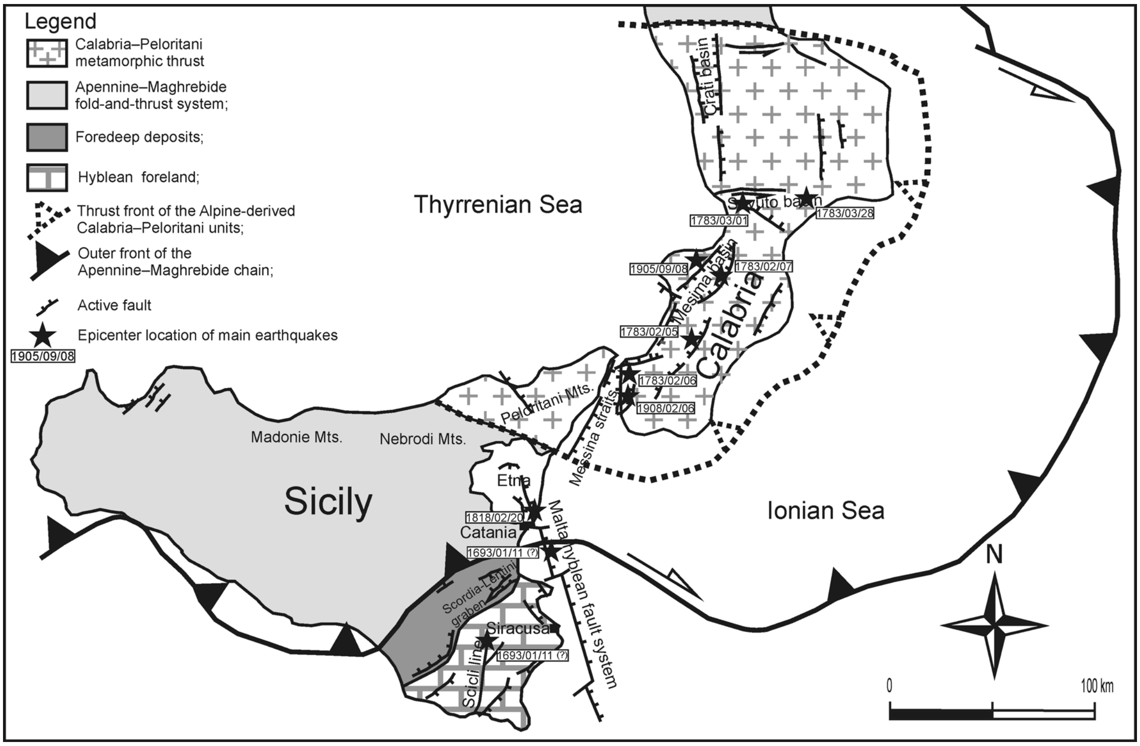

Fig. 1 - Tectonic framework of the study area with major structural domains of southern Italy (Lavecchia *et al.*, 2007, modified) and active faults identified through surface geological evidence (Galadini *et al.*, 2001, modified).

tectonic features. The Madonie-Nebrodi-Peloritani Mt. chain, that outlines northern Sicily, as well as the Tyrrhenian offshore area, are characterized by Plio-Quaternary extensional structures which are formed by N-to-NW dipping normal and normal-oblique faults, that dislocate the pre-existing compressional structures (Monaco and Tortorici, 2000; Pepe *et al.*, 2000). Eastern Sicily is delineated by the crossing of lithosphere structures that give rise to the origin of Mt. Etna and by the presence of the Malta Hyblean fault system that goes down to the Sicilian coast towards the Ionian Sea.

The definition of seismic sources in eastern Sicily is quite a debated problem due to the lack of clear evidence of surface faulting and to the few high-magnitude instrumental earthquakes. For example, the location, size and kinematics of the January 11, 1693 earthquake [M_W = 7.4; Working Group CPTI (2004)] is particularly uncertain and debated in literature. Some authors locate the source inland, whereas others locate it offshore. The inland source models are based on geologic, geomorphologic and macroseismic intensity analyses and they address either a WSW-ENE striking normal fault within the Scordia-Lentini graben (D'Addezio and Valensise, 1991; Tinti and Armigliato, 2003) or a blind NNE-SSW striking transcurrent fault, parallel to the Scicli line (Sirovich and Pettenati, 1999; Basili *et al.*, 2008). The models that adopt an offshore source are mainly based on results of seismic prospecting at sea and on tsunami modeling which suggests either the rupture of a segment of the NNW-SSE Malta fault escarpment (Piatanesi and Tinti, 1998; Azzaro and Barbano, 2000; Jacques *et al.*, 2001; Argnani and Bonazzi, 2005) or the

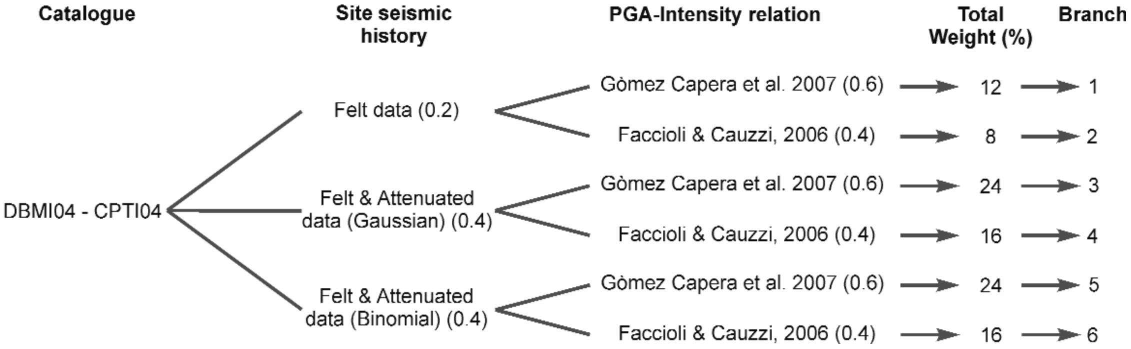

Fig. 2. - Logic tree and weighted values used in the site approach.

rupture of a locked subduction fault plane (Gutscher *et al.*, 2006). Recently, Lavecchia *et al.* (2007), have suggested associating the 1693 earthquake to the Sicilian basal thrust, to which they also link the 1818 Catania event [$M_W = 6.2$; Working Group CPTI (2004)].

In eastern Sicily, in addition to the seismicity related to these regional sized tectonic structures, there is an intense seismic activity linked to the Etna volcano. Its seismicity is characterized by low magnitude events and shallow hypocenters that produce destructive effects only at local scale.

3. Site approach

The seismic hazard estimate through the site approach was performed using the SASHA code. It was developed in order to handle the intensity data taking into account the macroseismic information of past earthquakes included in the DBMI04 (Working Group DBMI04, 2005) and used for compiling the parametric earthquake catalogue CPTI04 (Working Group CPTI, 2004). To build the seismic site histories of Catania and Siracusa, the felt data in the 217 B.C. - 2002 A.D. time interval, considering an intensity threshold of IV MCS, were taken into account.

A logic tree for the site approach (Fig. 2) was built up, taking into account all the options provided by the code to reduce the statistical uncertainties. The first elements of the logic tree are the CPTI04 and the DBMI04. Three possible site seismic histories were considered. The first kind of seismic history uses only felt data. The second one adopts felt data integrated with “virtual” intensities obtained through a Gaussian attenuation relationship (Pasolini *et al.*, 2008), and the third takes into account felt data integrated with “virtual” intensities coming out from a binomial empirical attenuation relationship (Albarello *et al.*, 2007). The above-mentioned attenuation relations were taken into account for all events having epicentral distance within 200 km from each considered site and epicentral intensity $I_0 \geq$ V-VI MCS. As regards the Etnean earthquakes, instead of using the Gaussian and binomial attenuation relationships, the attenuation model proposed by Azzaro *et al.* (2006) was adopted in order to consider the geologic setting of the volcanic area. Macroseismic intensities I_S were converted into PGA values using both the Faccioli and Cauzzi (2006) and Gómez Capera *et al.* (2007) relationships. According to the study of

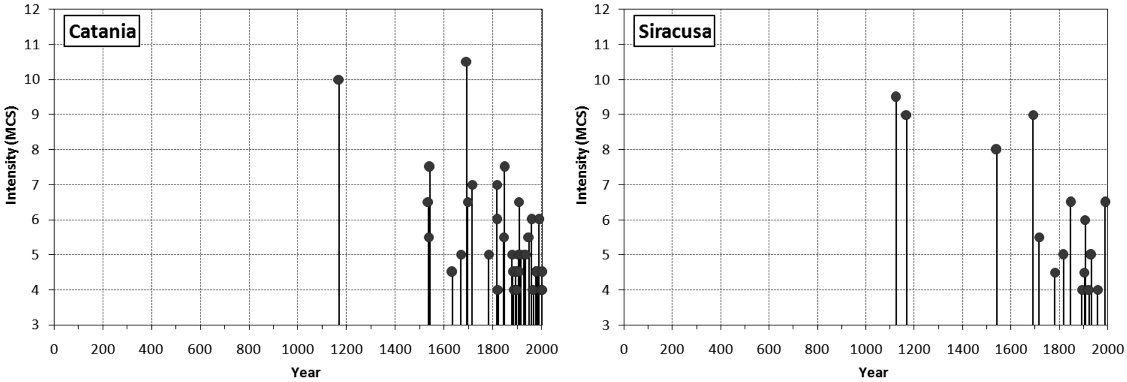

Fig. 3 - Seismic site histories for Catania and Siracusa considering only felt data (Working Group DBMI04, 2005).

Faenza and Michelini (2010), a higher weight was assigned to the PGA-intensity conversion law of Gomez Capera *et al.* (2007) with respect to Faccioli and Cauzzi (2006). This choice comes from the observation that Gomez Capera *et al.* (2007) used only Italian earthquake data and adopted the orthogonal distance regression technique, which is a more appropriate technique whenever dependent and independent variables are both affected by uncertainties. Faccioli and Cauzzi (2006) relations were obtained by integrating Italian and non-Italian earthquakes and using the least squares fitting technique.

The highest total weight in the logic tree (Fig. 2) was given to branches 3 to 6 which concern felt data with attenuated effects. Such option was preferred so as to take into account the lack of historical information (see Fig. 3) that often affects the seismic site history catalogues (Albarello *et al.*, 2007), especially at moderate to low intensity values (I = IV-V MCS).

The first step of the hazard estimation with SASHA is to build up the seismic history at each site. Moreover, before evaluating the seismic hazard, a completeness analysis has to be performed. In the site approach, the completeness of the local catalogue used for hazard computation is assessed through a statistical methodology. According to Albarello *et al.* (2001), three assumptions were adopted: a) the seismogeneic process is stationary, b) the most recent part of the catalogue is complete, c) the catalogue is statistically representative of the long-term stationary seismogenic process. At this stage, the SASHA code provides the seismic hazard for an intensity threshold and exposure time (e.g., 50 years). Resulting hazard values, computed for each intensity degree, represent the hazard curve at the studied site. A reference intensity I_{ref} is then derived from this curve corresponding to the higher intensity value that can be reached for a given exceedence probability during the considered exposure time. Finally, using the above mentioned PGA-intensity relationships, the code converts the hazard estimates from intensity to PGA providing a reference value for the last one (see D'Amico and Albarello, 2008).

4. Esteva-Cornell method

An SHA based on the Esteva-Cornell method, was performed using the open source code

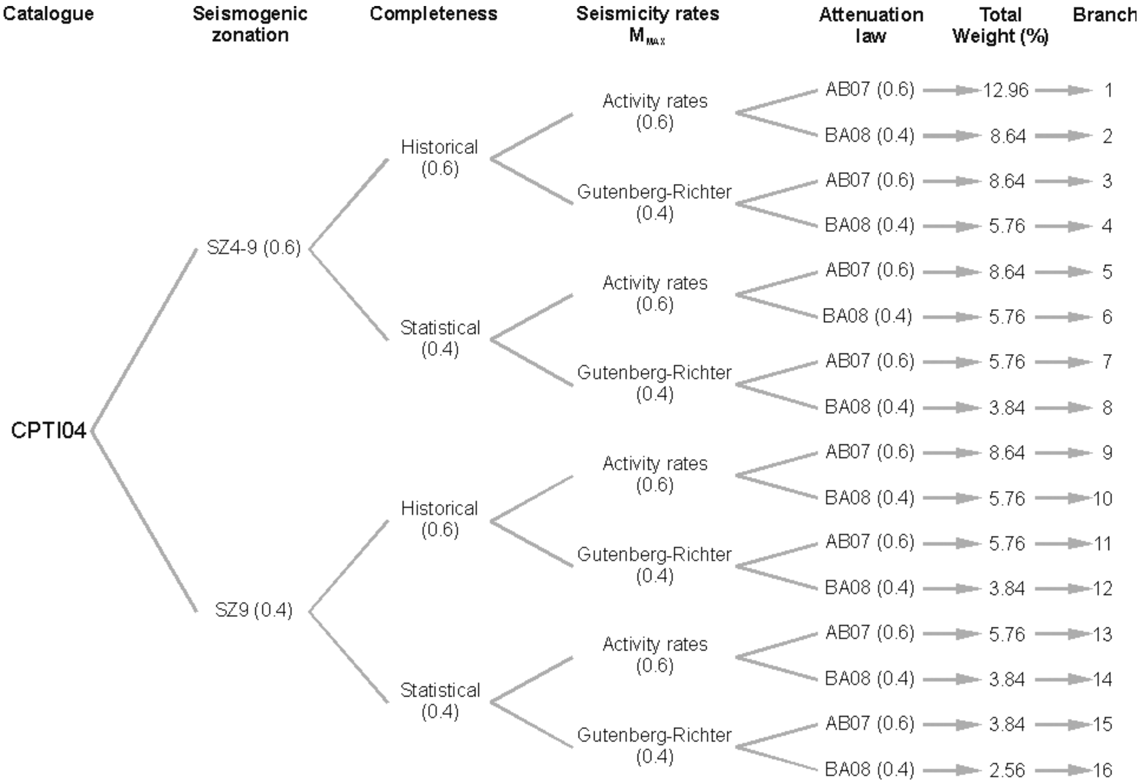

Fig. 4 - Logic tree used for the SHA through the CRISIS2007 code.

CRISIS2007. Such code requires as input data a source-zone model where the seismic rate of each considered zone and a ground motion predictive equation are described. According to current international conventions for SHA (SSHAC, 1997), a logic tree approach was followed to consider and evaluate the epistemic uncertainties that affect the hazard estimates (Fig. 4). Special care was devoted to defining alternative source-zone models to take into account the possibility of different seismogenic sources in south-eastern Sicily. This allows us to consider the uncertainties in the source location and in the fault mechanisms of the major earthquakes of the area. Two different models were therefore considered (Fig. 5). The first, based on SZ9 (Working Group MPS04, 2004; Meletti *et al.*, 2008), locates the source of the 1693 earthquake, inland. The other model (SZ4-9), which differs only locally in the definition of the seismogenic zones of south-eastern Sicily, discriminates two seismotectonic zones (78, 79) so that, according to Meletti *et al.* (2000), the possibility of the Malta escarpment being a potential source was taken into account. In the Esteva-Cornell logic tree, the highest weight was given to the branches concerning SZ4-9, since recent studies (Brancato *et al.*, 2009) demonstrate that the Malta escarpment is an active fault system that likely gave origin to the tsunami of the 1693 earthquake (Gerardi *et al.*, 2008; Visini *et al.*, 2009).

The Gutenberg-Richter *b*-value coefficients, the maximum moment magnitude (M_w) and its seismic rates (λ), as well as the seismogenic depth (H) and the faulting style (see Table 1), were

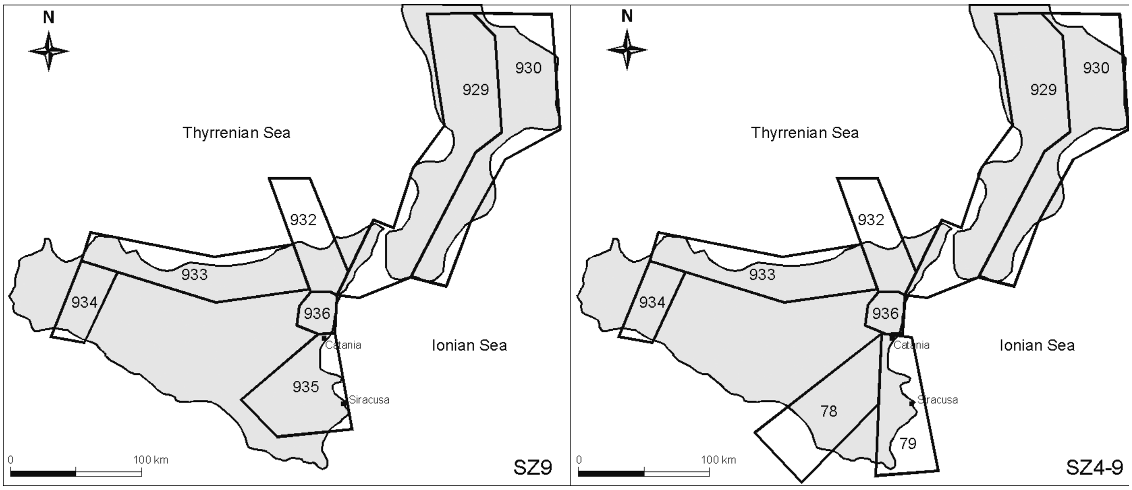

Fig. 5 - Source zone models considered for the SHA with the Esteva-Cornell method: SZ9 (from Working Group MPS04, 2004) and SZ4-9 (modified from Meletti *et al.*, 2000).

taken from the MPS04 hazard map for each of the source zones assumed in the Meletti *et al.* (2008) model. The same parameters for the SZ78 and 79 (SZ4-9 model in Fig. 5) were estimated using the CPTI04 and the same methodology proposed by the Working Group MPS04 (2004). Consequently, the activity rates (AR) were obtained by dividing the number of seismic events, of each magnitude class (twelve of 0.23 M_W with minimum magnitude equal 4.76) for the

Table 1 - Maximum magnitude ($M_{W\text{-max}}$), *b*-value, seismic rate λ, style of faulting and depth parameter (H) for each seismogenic zone (from Working Group MPS04, 2004); the same parameters obtained in the present study for SZ 78 and 79 are reported in bold.

SZ	Gutenberg-Richter					Activity Rates			Style of faulting	H (km)
	$M_{W\text{-max}}$	Historical		Statistical		$M_{W\text{-max}}$	Historical	Statistical		
		b	λ	b	λ		λ	λ		
929	7.29	-0.82	0.17	-0.79	0.17	7.29	0.17	0.17	Normal	10
930	6.60	-0.98	0.17	-0.89	0.21	6.60	0.17	0.21	Unspecified	10
932	6.14	-1.21	0.21	-1.08	0.33	6.14	0.21	0.33	Strike-slip	13
933	6.14	-1.39	0.20	-1.24	0.31	6.14	0.21	0.33	Inverse	10
934	6.14	-0.96	0.20	-0.93	0.20	6.14	0.21	0.21	Inverse	10
935	7.29	-0.72	0.12	-0.69	0.17	7.29	0.12	0.18	Strike-slip	13
936	5.45	-1.63	0.33	-1.22	0.33	5.45	0.33	0.33	Unspecified	3
78	**5.68**	**-0.92**	**0.38**	**-1.14**	**0.28**	**5.68**	**0.42**	**0.33**	**Normal**	**13**
79	**7.29**	**-0.66**	**0.10**	**-0.66**	**0.13**	**7.29**	**0.12**	**0.18**	**Normal**	**13**

completeness time. According to Working Group MPS04, two completeness time intervals, historical and statistical, were used. As concerns the parameters of Gutenberg-Richter, they were obtained by interpolating the AR values with a least square method.

Two ground-motion predictive equations were taken into account. The first relationship AB07 (Akkar and Bommer, 2007a, 2007b) uses strong-motion data sets from Europe and Middle East events. The second, BA08 (Boore and Atkinson, 2008) is defined considering earthquakes worldwide. Both equations calculate different shaking parameters (PGA, PGV, SA, SD), using the M_W, the Joyner-Boore source distance (R_{JB}), the characteristic style-of-faulting and the site class. For both attenuation models, rock ($V_{S,30} \geq 800$ m/s) and soft soil ($183 \leq V_{S,30} \leq 366$ m/s) conditions were taken into account. As regards the Etna volcano seismic zone (SZ936), no specific attenuation law was used, but both the AB07 and BA08 relationships were applied, assuming to reduce, by standard deviation, the PGA and the SA values obtained.

Italian volcanic districts are characterized by insufficient earthquake recordings for the calibration of ground motion attenuation relations. For this reason, past studies of SHA in Italy had adopted either the commonly used attenuation relations, reducing them by a fraction of the standard deviation (e.g., Slejko *et al.*, 1998), or a specific attenuation relation for the volcanic districts (Working Group MPS04, 2004) obtained through the random vibration theory (Cartwright and Lounguet-Higgins, 1956). On the Etna volcano, two classes of events are observed: a) volcano-tectonic earthquakes (VT), linked to shear fracture processes, having spectral features with dominating high frequencies, and b) long period events (LP), characterized by an enrichment of long-period (1-10 s) components of the ground motion (Milana *et al.*, 2008). However, the LP events occur more rarely than the VT which represent the largest part of the seismic events recorded at the Mt. Etna volcano. In Fig. 6, an example of acceleration spectra for VT and LP events is plotted together with the theoretical spectral acceleration obtained through AB07 and BA08 attenuation relations, considering an unspecified fault mechanism. These earthquakes were recorded at the Bronte seismic station, located on the western flank of Etna, in an A type soil category (Working Group ITACA, 2010). Especially for periods smaller than 0.1 s and greater than 0.5 s, the figure shows a fairly good agreement between the theoretical and the experimental spectral accelerations of the VT event, when the theoretical ones are reduced by a standard deviation. For long period events, there is a disagreement especially at periods greater than 1 s. Such evidence agrees with the findings of Faccioli and Rovelli (2007) and Milana *et al.* (2008) who observed that the VT earthquakes follow the same attenuation relation valid for tectonic events, whereas the LP events diverge from expected values obtained with common attenuation relations. In the light of these considerations, in the present study, we accepted to approximate the attenuation relation for the volcanic area, assuming to reduce the values of PGA and SA obtained through AB07 and BA08 relations by a standard deviation. Such assumption provides, in our opinion, quite a good solution for the Etna area, considering also that VT events are by far the more frequently recorded type of earthquakes.

Another important problem pertains to the site-to-source distance, especially for the disaggregation analysis. Disaggregation is used here to compute the contributions to the 10% exceedance probability in 50 years of horizontal PGA. In the adopted attenuation relations the distance was measured with R_{JB}, whereas the SZ definition was done referring to epicentral locations. In CRISIS2007, the attenuation relationships can be specified in terms of 4 different measures of distance such as the focal, the epicentral, the Joyner and Boore or the closest distance

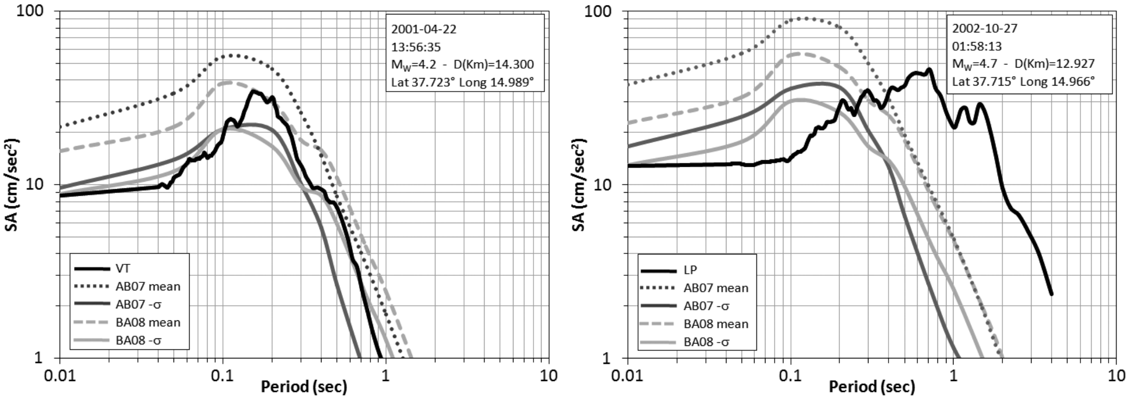

Fig. 6 - Comparison between response spectra of a VT (left panel) and an LP event (right panel) with the predicted theoretical spectral acceleration.

to rupture area (R_{RUP}). If the R_{RUP} or the R_{JB} distances are used, the CRISIS2007 code needs to know the rupture area or the rupture length, as a function of magnitude, in order to compute the required distances. The code then assumes that the relation between area/rupture length and magnitude is: $A = K_1 e^{K_2 M};\ L = K_3 e^{K_4 M}$, where A is the source area (in km^2), L is the rupture length (in km), M stands for the magnitude and K_1 , K_2, K_3 and K_4 are constants given by the user or chosen from a built-in set of constants. In this study, source area (A) and the Wells and Coppersmith (1994) constants were adopted, specifying these latter in the "source geometry" screen of the code. In such instances, CRISIS2007 will assume that the earthquake takes place in a plane defined by the source geometry, and that the rupture area will be a circle, within this plane, with an area A and a radius $\gamma = \sqrt{A / \pi}$. CRISIS2007 uses the type of distance adopted in the attenuation relationship for the hazard computation and, in addition, in the "global parameter" screen, it allows us to specify which kind of distance the users would like to adopt for the disaggregation output. According to this possibility, we choose to express the results of the disaggregation in terms of epicentral distance.

5. Results and discussions

The use of the SASHA code provided, through a set of hazard curves, the estimation of a reference intensity (I_{ref}), which expresses a threshold indicating that, for a fixed exceedance probability level (e.g., 10% in 50 years), the observed effects could be greater than, or equal to, I_{ref}. It is interesting to observe (Table 2) that smaller values of I_{ref} come out for branches 1 and 2 of the logic tree in Fig. 2 (only felt data), whereas higher values are obtained in branches 5 and 6 (felt and "virtual" data). Such results are in good agreement with the observations of Albarello *et al.* (2007), pointing out that "virtual" intensities affect the SHA especially in areas where seismic site histories are particularly poor.

The hazard curves for all branches, at exceedance probability in 50 years (Fig. 7), were obtained taking into account the site intensity (I_S) values and the corresponding PGA_{ref} provided

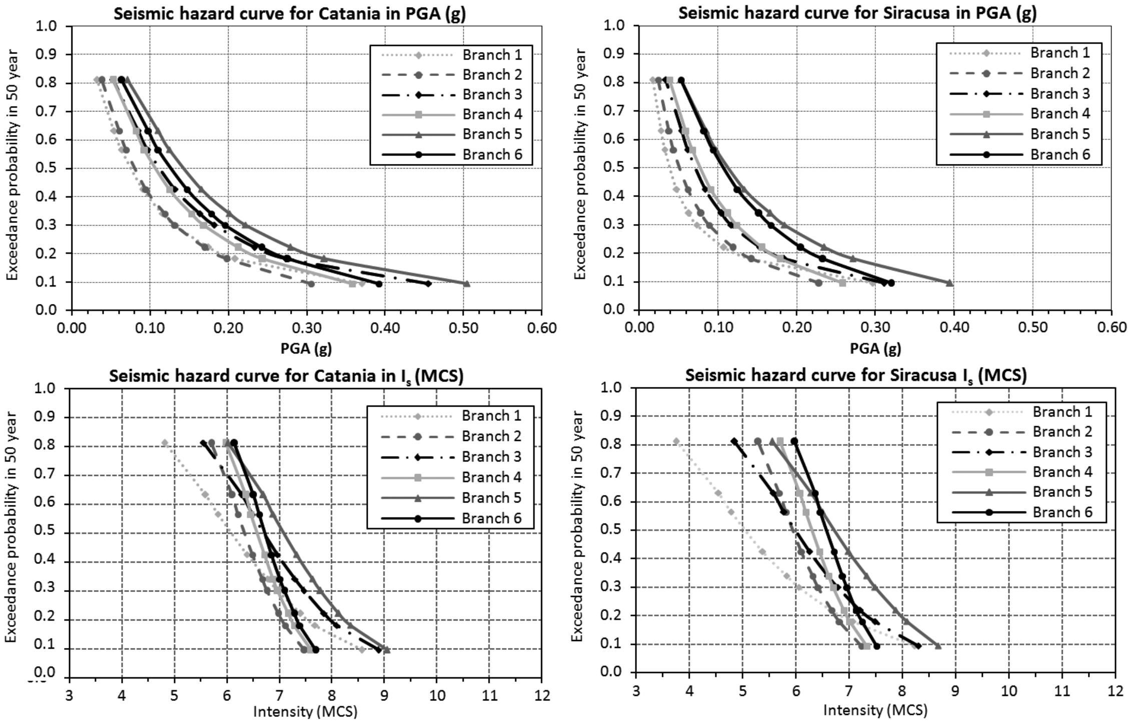

Fig. 7 - Hazard curves in $\mathrm{PGA_{ref}}$ (upper panels) and I_S (MCS) (lower panels) for each branch of the logic tree for site approach.

Table 2 - I_{ref}, obtained for nine exceedance probabilities (E.P.) in 50 years, for each branch of the logic tree for the site approach adopted for Catania and Siracusa.

Catania									
E.P.	**0.81**	**0.63**	**0.57**	**0.43**	**0.34**	**0.3**	**0.22**	**0.18**	**0.10**
Branch 1	5	6	6	6	7	7	7	7	8
Branch 2	5	6	6	6	7	7	7	7	8
Branch 3	6	6	7	7	7	7	7	8	8
Branch 4	6	6	7	7	7	7	7	8	8
Branch 5	7	7	7	7	7	7	8	8	8
Branch 6	7	7	7	7	7	7	8	8	8
Siracusa									
E.P.	**0.81**	**0.63**	**0.57**	**0.43**	**0.34**	**0.3**	**0.22**	**0.18**	**0.10**
Branch 1	4	5	5	5	6	6	6	7	8
Branch 2	4	5	5	5	6	6	6	7	8
Branch 3	5	6	6	6	6	6	7	7	8
Branch 4	5	6	6	6	6	6	7	7	8
Branch 5	6	6	7	7	7	7	7	8	8
Branch 6	6	6	7	7	7	7	7	8	8

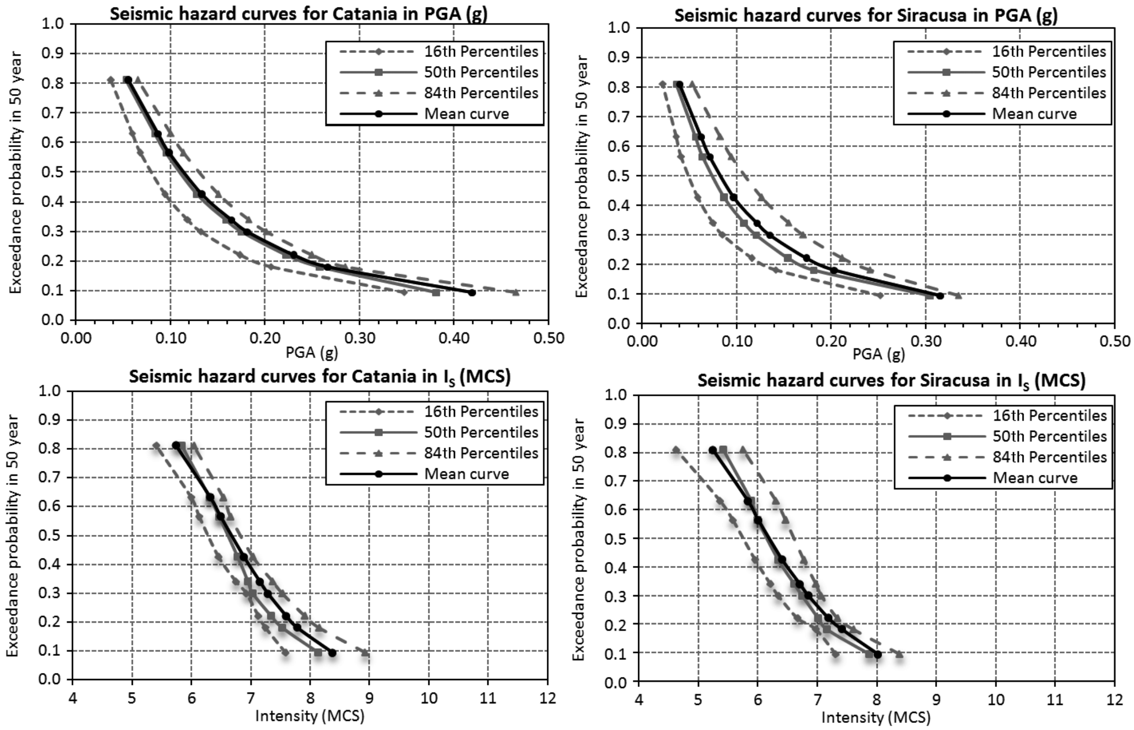

Fig. 8 - Mean, median (50th percentile), 16th and 84th percentiles hazard curves in PGA_{ref} (upper panels) and I_S (MCS) (lower panels) for Catania and Siracusa.

by the code, using the Gomez Capera *et al.* (2007) and the Faccioli and Cauzzi (2006) relationships. The highest values of PGA_{ref} and I_S were obtained when branch 5 of the logic three is followed, whereas lower values are observed for branches 1 and 2, both in Catania and Siracusa.

Table 3 summarizes the 16th, 50th, 84th percentiles and the mean values obtained by the logic tree for site approach at nine exceedance probabilities in 50 years. Fig. 8 shows the mean and the percentile hazard curves, putting in evidence the fact that both PGA_{ref} and I_S attain slightly higher values in Catania rather than in Siracusa.

Seismic hazard, using the Esteva-Cornell approach, was computed for each branch of the logic tree considering rock and soft soils (Fig. 9). In Table 4, the mean and median PGA values obtained for the whole logic tree, as well as for SZ4-9 or SZ9 are shown, together with the related uncertainty, quantified through the 16th and 84th percentiles.

The mean, median, 16th and 84th percentiles hazard curves obtained for Catania and Siracusa on rock and soft soils, that in other words represent the reference hazard estimate, are shown in Fig. 10. Inspection of the hazard curves puts in evidence small differences (±0.03 g) in PGA values. In particular, for exceedance probability smaller than 0.43 in 50 years, Catania has a slightly higher hazard than Siracusa, which, on the other hand, shows a slightly higher hazard for exceedance probability in 50 years greater than 0.43 (Fig. 10 and Table 4). Such results are, in our opinion, significantly affected by the location of the two towns with respect to the seismic

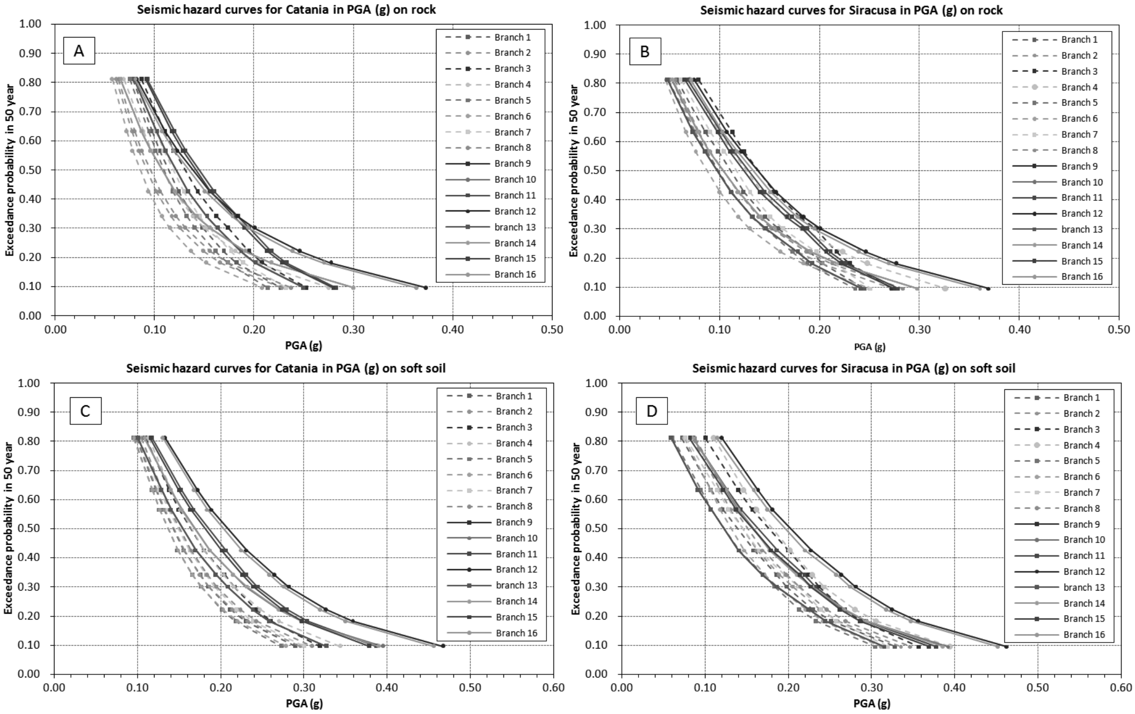

Fig. 9 - Hazard curves in PGA for each branch of the logic tree for rock (A, B) and soft soil (C, D).

Table 3 - Mean, 16th, 50th (median) and 84th percentile values of PGA and I_S (MCS) for nine exceedance probabilities (E.P.) in 50 years.

E.P.	Catania								Siracusa							
	PGA (g)				Intensity (MCS)				PGA (g)				Intensity (MCS)			
	16th	50th	84th	Mean	16th	50th	84th	Mean	16th	50th	84th	Mean	16th	50th	84th	Mean
0.10	0.35	0.38	0.46	0.42	7.6	8.1	8.9	8.4	0.25	0.30	0.33	0.32	7.3	7.9	8.4	8.0
0.18	0.21	0.26	0.28	0.27	7.2	7.5	8.2	7.8	0.14	0.18	0.24	0.20	7.0	7.2	7.6	7.4
0.22	0.17	0.22	0.25	0.23	7.1	7.3	7.9	7.6	0.12	0.15	0.21	0.17	6.7	7.0	7.3	7.2
0.30	0.13	0.18	0.20	0.18	6.9	7.0	7.5	7.3	0.09	0.12	0.17	0.13	6.3	6.7	7.1	6.9
0.34	0.12	0.16	0.18	0.16	6.8	6.9	7.4	7.2	0.08	0.11	0.15	0.12	6.2	6.6	7.0	6.7
0.43	0.09	0.13	0.15	0.13	6.5	6.8	7.0	6.9	0.06	0.09	0.13	0.10	6.0	6.3	6.8	6.4
0.57	0.07	0.09	0.11	0.10	6.1	6.5	6.7	6.5	0.04	0.06	0.09	0.07	5.6	6.0	6.5	6.0
0.63	0.06	0.08	0.10	0.09	6.0	6.3	6.5	6.3	0.04	0.06	0.08	0.06	5.4	5.9	6.3	5.8
0.81	0.04	0.05	0.07	0.06	5.4	5.8	6.0	5.8	0.02	0.04	0.05	0.04	4.6	5.4	5.8	5.2

Table 4 - Mean, 16th, 50th (median) and 84th percentile values of PGA for rock and for soft soil conditions obtained considering the whole logic tree, SZ4-9 and SZ9 seismogenic zonations.

E.P.		**CATANIA**								**SIRACUSA**							
		ROCK				**SOFT SOIL**				**ROCK**				**SOFT SOIL**			
		16th	**50th**	**84th**	**Mean**	**16th**	**50th**	**84th**	**Mean**	**16th**	**50th**	**84th**	**Mean**	**16th**	**50th**	**84th**	**Mean**
LOGIC TREE	**0.10**	0.227	0.252	0.300	0.255	0.292	0.327	0.393	0.331	0.243	0.274	0.315	0.271	0.315	0.352	0.393	0.349
	0.18	0.174	0.203	0.231	0.199	0.231	0.260	0.302	0.260	0.193	0.217	0.241	0.213	0.245	0.278	0.301	0.271
	0.22	0.158	0.187	0.216	0.182	0.213	0.240	0.277	0.239	0.178	0.191	0.221	0.194	0.225	0.254	0.275	0.248
	0.30	0.135	0.156	0.193	0.156	0.186	0.213	0.243	0.209	0.146	0.157	0.192	0.163	0.187	0.220	0.241	0.214
	0.34	0.126	0.144	0.179	0.146	0.175	0.199	0.229	0.196	0.133	0.143	0.176	0.149	0.171	0.204	0.227	0.199
	0.43	0.111	0.127	0.154	0.127	0.156	0.175	0.204	0.173	0.111	0.121	0.149	0.126	0.143	0.173	0.201	0.169
	0.57	0.091	0.107	0.122	0.105	0.132	0.145	0.166	0.145	0.086	0.095	0.116	0.098	0.112	0.137	0.160	0.132
	0.63	0.083	0.100	0.111	0.097	0.123	0.134	0.151	0.133	0.074	0.083	0.103	0.086	0.100	0.122	0.144	0.118
	0.81	0.064	0.079	0.085	0.076	0.099	0.107	0.117	0.106	0.049	0.056	0.071	0.059	0.065	0.085	0.107	0.082
SZ4-9	**0.10**	0.216	0.230	0.251	0.233	0.280	0.298	0.318	0.299	0.246	0.262	0.282	0.263	0.313	0.332	0.355	0.335
	0.18	0.167	0.178	0.202	0.182	0.221	0.236	0.258	0.237	0.189	0.208	0.229	0.209	0.243	0.259	0.285	0.261
	0.22	0.150	0.166	0.181	0.167	0.204	0.217	0.240	0.219	0.174	0.189	0.215	0.191	0.222	0.239	0.264	0.240
	0.30	0.127	0.145	0.155	0.144	0.178	0.190	0.214	0.192	0.145	0.156	0.180	0.160	0.188	0.209	0.234	0.208
	0.34	0.117	0.136	0.145	0.135	0.167	0.179	0.201	0.181	0.133	0.143	0.166	0.147	0.173	0.192	0.222	0.194
	0.43	0.102	0.119	0.129	0.119	0.149	0.159	0.178	0.161	0.112	0.121	0.141	0.125	0.148	0.163	0.196	0.167
	0.57	0.085	0.099	0.109	0.100	0.127	0.135	0.149	0.136	0.086	0.095	0.112	0.098	0.119	0.129	0.154	0.131
	0.63	0.078	0.092	0.101	0.092	0.119	0.125	0.137	0.126	0.075	0.083	0.098	0.086	0.107	0.116	0.138	0.117
	0.81	0.062	0.072	0.081	0.073	0.096	0.101	0.109	0.102	0.050	0.056	0.069	0.059	0.072	0.081	0.099	0.082
SZ9	**0.10**	0.254	0.292	0.356	0.289	0.333	0.389	0.449	0.378	0.246	0.288	0.353	0.284	0.321	0.382	0.444	0.370
	0.18	0.203	0.223	0.266	0.224	0.263	0.298	0.345	0.294	0.196	0.220	0.264	0.220	0.250	0.293	0.341	0.285
	0.22	0.187	0.202	0.236	0.204	0.242	0.272	0.315	0.269	0.180	0.199	0.236	0.199	0.229	0.267	0.312	0.260
	0.30	0.157	0.177	0.195	0.175	0.211	0.236	0.272	0.234	0.148	0.169	0.194	0.166	0.191	0.228	0.270	0.222
	0.34	0.144	0.165	0.183	0.162	0.197	0.221	0.255	0.218	0.134	0.154	0.178	0.152	0.174	0.213	0.253	0.205
	0.43	0.122	0.142	0.156	0.140	0.172	0.194	0.223	0.192	0.112	0.130	0.150	0.128	0.144	0.179	0.216	0.173
	0.57	0.098	0.115	0.128	0.114	0.142	0.159	0.182	0.157	0.086	0.100	0.117	0.098	0.111	0.140	0.171	0.134
	0.63	0.089	0.105	0.117	0.104	0.130	0.145	0.166	0.144	0.074	0.088	0.103	0.086	0.095	0.126	0.154	0.119
	0.81	0.067	0.080	0.090	0.080	0.102	0.112	0.129	0.112	0.049	0.059	0.071	0.058	0.062	0.085	0.111	0.081

zones considered. Catania is also very close to SZ936 that has a high seismicity rate at a relatively small magnitude with respect to SZ79 or SZ 935.

The choice of the source zone model for south-eastern Sicily seems to affect the hazard computation (Fig. 9 and Table 4) significantly. The trend of the Catania hazard curves, referring to the branches of SZ4-9 (see dashed lines in Fig. 9A, C), points out a lower hazard than that obtained when SZ9 is considered (see continuous lines in Figs. 9A and 9C). As matter of fact the *b*-values and the activity rates (λ) of SZ935 are slightly higher than those obtained for SZ79

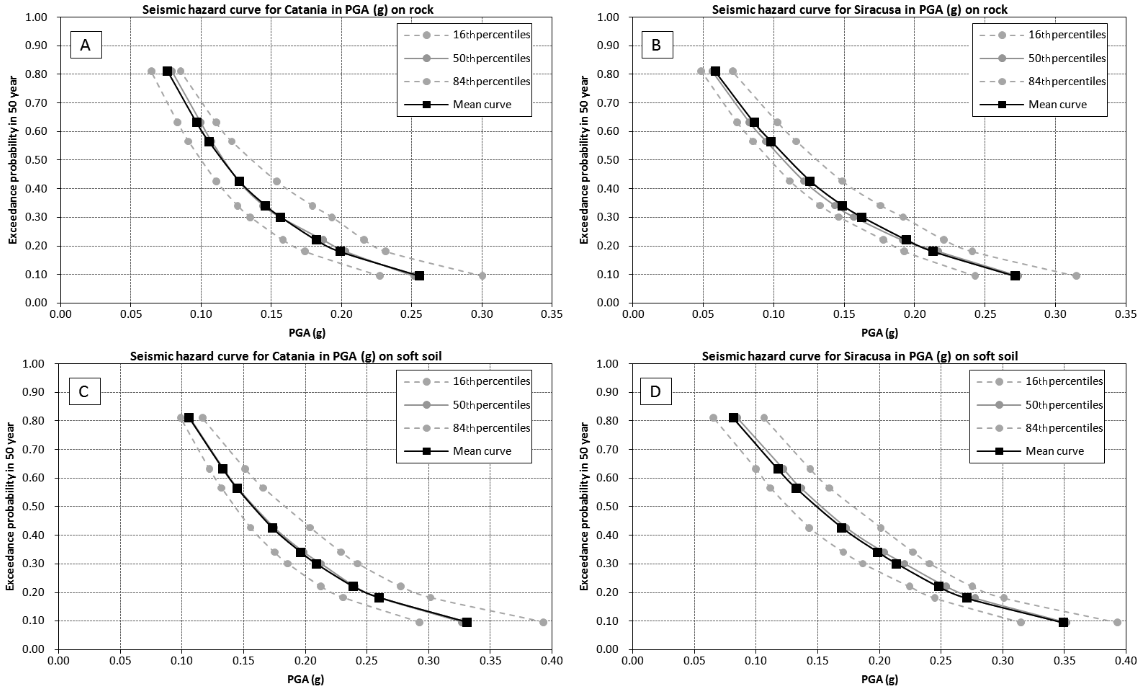

Fig. 10 - Mean, median (50th percentile), 16th and 84th percentiles hazard curves obtained for Catania and Siracusa on rock (A, B) and soft soil (C, D).

(Table 1). We opted to extend the seismogenetic zones (SZ935) to include all seismic data of the area, which provides an increase in the hazard estimates and smoothes the local differences. On the other hand, the use of small zones, with a minor seismic activity (SZ79) can imply a decrease in the hazard assessment. This is the consequence of the well known "hazard spreading effect" of the Cornell approach. The assumption of homogenous seismicity rates in a seismogenic zone tends, in actual fact to "distribute" throughout the entire zone extension, the hazard associated to the seismic activity observed in a limited portion (Del Gaudio *et al.*, 2009). Despite such considerations, the PGA values obtained by considering SZ4-9 are not very different from those obtained when SZ9 is taken into account and the differences do not exceed ±0.05 g for all considered exceedance probabilities in 50 years.

Moreover, uniform hazard response spectra in acceleration (UHRSA), assuming rock-site conditions, were computed at both the Catania and Siracusa sites for 11 spectral periods ranging between 0.05 and 2.0 s. The mean UHRSA for the whole logic tree (Figs. 11a and 11b) were obtained for return periods of 475 and 975 years. It is generally found that large magnitude events affect the long period portion (>0.5 s) of a UHRSA whereas, small magnitude events affect the short-period section of the spectrum (Tselentis *et al.*, 2010). The graphs in Figs. 11a and 11b, show a high content at the short period in UHRSA, with picks ranging between 0.1-0.3 s. This indicates that both in Catania and Siracusa, the UHRSA are influenced by a great number of earthquakes having moderate magnitude and short source-to-site distance. A comparison of the UHRSA with the ones of the Italian hazard map (Working Group MPS04, 2004) shows that the

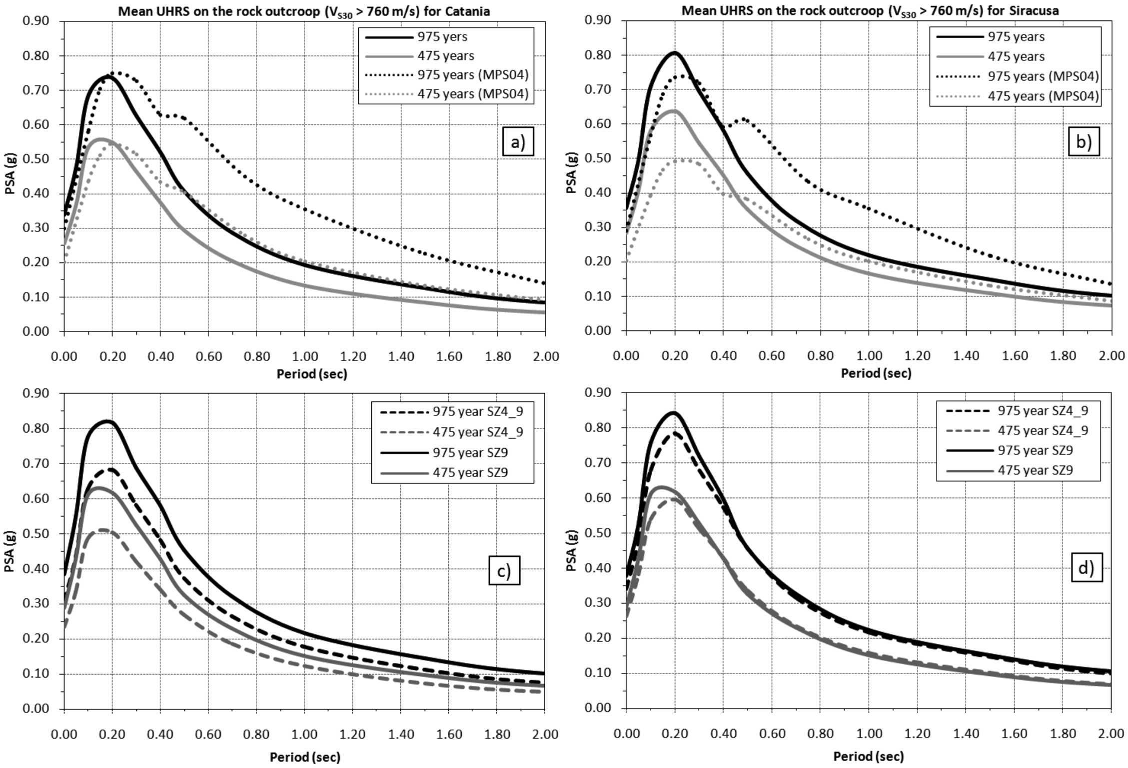

Fig. 11 - Mean UHRSA for 475- and 975-year return periods for the whole logic tree, corresponding UHRSA obtained by Working Group MPS04 (2004) (a, b) and UHRSA taking into account SZ4-9 and SZ9 separately (c, d).

response spectral accelerations for Catania are smaller than those obtained by the Working Group MPS04 (2004), at periods greater than 0.2 s (see dotted lines in Figs. 11a and 11b). The UHRSA computed for Siracusa are higher than the response spectra acceleration of Working Group MPS04 (2004) in short periods (<0.40 s). Similarly to Catania, the UHRSA of the Working Group MPS04 (2004) exhibits larger values at long periods (>0.4 s), therefore indicating a greater contribution over long periods due to larger magnitude events and to greater source-to-site distance. Such a difference, in our opinion, could be related to the fact that in the present study, only seismogenic sources located within a distance of about 300 km from south-eastern Sicily were considered. A suitable selection of the source zone models for south-eastern Sicily strongly influences the UHSRA as well. It is indeed evident (Figs. 11c and 11d) that the acceleration response spectra referring to SZ9 (full lines) always show PSA values greater than those referring to SZ4-9 (dashed lines).

The UHRSA gives an appropriate probabilistic representation of the seismic action but does not, generally, correspond to the spectrum of a specific earthquake. For this reason a disaggregation analysis of the PSHA is necessary (Bazzurro and Cornell, 1999). A two dimensional disaggregation in magnitude and epicentral distance (R_{epi}) was performed for a 475-year return time. Such procedure allows us to identify the design earthquake that characterizes the local seismic hazard. Similarly to the procedure used for obtaining the hazard curves and the response spectra, the disaggregation charts were obtained for the whole logic tree, for SZ4-9 and for SZ9 models (Figs. 12a and 12b). The dominant scenario earthquake can be defined using either the mean or the modal value of its magnitude (M) and source-to-site distance (R_{epi}) (see Table 5) coming out from the use of the different branches of the logic tree. Using the mean values, although they are simple to understand and to compute, not always represent a realistic scenario whereas, the mode corresponds to the M-R group that gives the largest contribution to the hazard and, consequently, corresponds to a more realistic source (Barani *et al.*, 2009). Inspection of the disaggregation graphs (Fig. 12) shows that, for all considered models, the major contribution to the dominant scenario is given by an earthquake having magnitude M=6.4 and R_{epi}= 22 km. Both mean and modal values obtained (see Table 5) do not show significant differences for all models unless the source-distance (R_{epi}) is taken into account. The mean values of M and R_{epi} obtained in the present study were compared with the ones calculated by the Working Group MPS04 (2004). The results obtained in this study are higher than those provided by the Working Group MPS04 (2004) both as concerns the magnitude (about 0.2 units) and the epicentral distance (about 5 km). It is, however, worth noting that, as observed by Barani *et al.* (2009), our results show that the attenuation equation used in the hazard computation strongly affects the parameters of the dominant scenario earthquake.

6. Concluding remarks

The seismic hazard assessment in south-eastern Sicily provided interesting results for the Catania and Siracusa areas permitting us, at the same time, to point out the differences deriving from the use of either the site or the seismotectonic approach.

It can be observed that the site approach generally assigns a higher hazard for all the exceedance probabilities to Catania than to Siracusa. Such findings can be interpreted as the consequence of the higher damage suffered historically by this town and its average shorter distance from the seismogenic sources of major historical earthquakes as located by Azzaro and Barbano (2000).

The Esteva-Cornell method puts in evidence the fact that the hazard estimate for the two towns strongly depends on the size and geometry of the source zones postulated for south-eastern Sicily. Such features entail a spatial distribution of the seismic rates and a sort of “spreading” of the hazard, as well as the effect that all sites located in the inner part of the SZ will show a greater hazard than those located at its boundaries. Besides, the bigger the SZs, the greater the computed average hazard (Del Gaudio *et al.*, 2009). Therefore, if we look at the location of Catania and Siracusa inside either SZ9 or SZ4-9, it is evident that in the former instance (SZ9) the town of Catania has a higher hazard rather than in the latter situation (SZ4-9) where it is located closer to the boundary of the seismogenic zone with respect to Siracusa (see Figs. 5 and 9). The “spreading effect” has also to be taken into account in order to explain the higher PGA and PSA values when SZ9 is used.

It is worth noting that the PGA values obtained through the site method are quite similar to those computed by the Esteva-Cornell one only when the soft soil conditions are taken into account, whereas major differences occur when the rock site conditions are considered (see Tabs. 3 and 4). Such differences could be a consequence of the intrinsic differences between the two

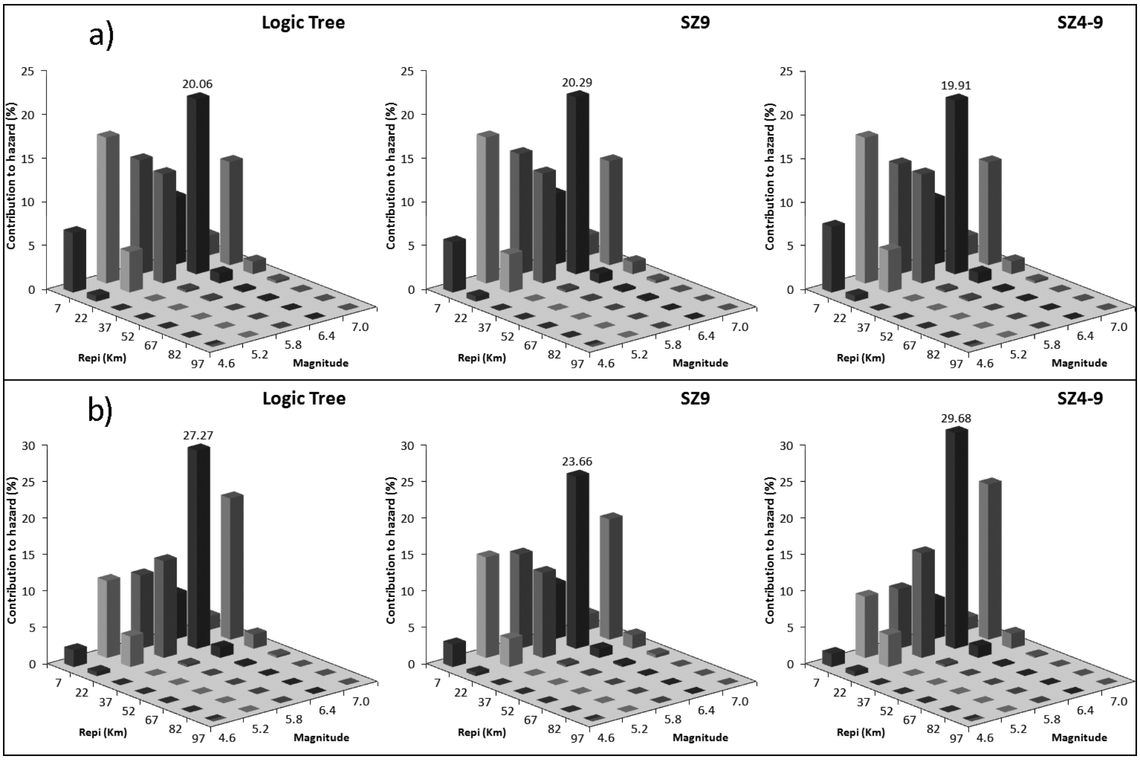

Fig. 12 - Disaggregation of the seismic hazard for Catania (a), and Siracusa (b) considering an exceedance probability of 10% in 50 years.

Table 5 - Mean and modal values of magnitude (*M*) and distance (R_{epi}), obtained by considering 10% exceedance probability, for SZ4-9, SZ9, for the complete logic tree and mean values found by the Working Group MPS04 (2004).

CATANIA															
SZ4-9				SZ9				LOGIC TREE				MPS04			
Mean		Modal		Mean		Modal		Mean		Modal		Mean		Modal	
10%				10%				10%				10%			
M	D	M	D	M	D	M	D	M	D	M	D	M	D	M	D
5.9	15.7	6.2	14.4	6.2	15.6	6.3	14.4	6.0	15.7	6.3	14.4	5.8	9.3	-	-
SIRACUSA															
SZ4-9				**SZ9**				**LOGIC TREE**				**MPS04**			
Mean		**Modal**		**Mean**		**Modal**		**Mean**		**Modal**		**Mean**		**Modal**	
10%				**10%**				**10%**				**10%**			
M	D	M	D	M	D	M	D	M	D	M	D	M	D	M	D
6.2	18.8	6.4	19.1	6.1	16.7	6.4	16.9	6.2	18.0	6.4	18.2	5.9	11.4	-	-

approaches used that make a realistic comparison rather difficult. The site approach, in particular, uses macroseismic intensity data that are intrinsically linked to the dominant soil type which, in a relatively wide area, is reasonably soft soil.

The results obtained in the present study, compared with those coming from the national hazard map (Working Group MPS04, 2004) show some differences that could be referred to the use of a different logic tree, as well as the adoption of different attenuation relations and to that of considering local (within about 300 km) seismogenic sources only.

The use of a combined approach, in the seismic hazard estimation, appears however advisable for a mutual validation of the obtained results and any choice is strictly linked to the knowledge of the local seismotectonic features.

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Corresponding author: Francesco Panzera
Dipartimento di Scienze Geologiche, Università di Catania
C.so Italia 57, Catania, Italy
Phone: +39 0957195722; fax: +39 0957195712; e-mail: panzerafrancesco@hotmail.it