Bollettino di Geofisica Teorica ed Applicata Vol. 53, n. 1, pp. 7-18; March 2012
DOI 10.4430/bgta0035

Design earthquake from site-oriented macroseismic hazard estimates

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(Received: October 9, 2010; accepted: March 8, 2011)

ABSTRACT A procedure is presented to determine design earthquakes that are compatible with seismic hazard estimates deduced in terms of macroseismic intensity from a distribution-free, site-oriented approach. Through this procedure it is possible to identify past earthquakes that were mostly responsible for the local hazard, as well as to identify representative magnitude distance pairs to be used for engineering purposes. An example applied to central Italy is discussed and reveals that a design earthquake provided by the approach described here is significantly different from that provided for the same site by the standard disaggregation analysis. This discrepancy is the effect of a different use of information available for hazard assessment at the site under study.

Key words: central Italy, intensity, seismic hazard, design earthquake.

1. Introduction

Despite an enormous increase in available instrumental data, seismic hazard assessment in many countries (in particular where strong events are relatively rare) cannot avoid using macroseismic information to characterize local seismicity. As an example, most (about 70%) of the damaging earthquakes that shook Italy (CPTI Working Group, 2004) are known from documentary sources only. Thus, para-instrumental epicentral features (magnitude, epicentral location, etc.) were determined from macroseismic information by using suitable procedures (e.g., Gasperini *et al*., 2010). Such macroseismic parameterizations are commonly considered for seismic hazard assessment based on a standard Cornell-McGuire approach (e.g., Bender and Perkins, 1987) to compute seismic hazard in terms of ground motion parameters (e.g., peak ground or spectral acceleration). In this way, the inherently, non-instrumental nature of basic information is "forced" inside a computation structure designed for instrumental data. This "forcing", of course, is not costless since uncertainty is added as a consequence of macroseismic-instrumental conversion in a way that is not accounted for in final results. Furthermore, the expected ground shaking is "reconstructed" at each site from epicentral information (source data) through the use of empirical attenuation relationships. Apparently, to use such an indirect pattern (from local macroseismic data to epicentral data, from these to seismotectonic zoning, then through attenuation relationships, back to ground motion at the site) to reconstruct local seismic hazard can be necessary in the case of very poor local seismic histories (that is the case of many sites around the world) but appears meaningless when very rich local seismic histories are available as in the case of Italy. Here, in the last few dacades, a huge amount of macroseismic information was collected to reconstruct local seismic histories at a large number of sites (e.g., Stucchi *et al.*, 2007). As an example, for 1401 out of 8101 municipal chief towns, a seismic history is available that includes at least 10 documented intensities in the last 1000 years.

This situation led some authors to provide hazard maps in terms of intensity through the use of a new numerical procedure, developed to provide probabilistic seismic hazard estimates directly from macroseismic observations (Magri *et al.*, 1994; Albarello and Mucciarelli, 2002; D'Amico and Albarello, 2003, 2008). With this last method, a full exploitation of the large and well distributed Italian data set is allowed by avoiding any forcing of available information into para-instrumental parameters and accounting for the peculiar nature of macroseismic data (ordinal, discrete, defined over a finite range). Applications of this procedure for seismic hazard assessment in Italy can be found in Azzaro *et al.* (1999, 2008), Albarello *et al.* (2002), D'Amico and Albarello (2003), Mucciarelli *et al.* (2008), Gomez-Capera *et al.* (2010). Results of these computations were also used to check hazard maps provided by the standard Cornell-McGuire procedure (Mucciarelli *et al.*, 2000, 2008) and to detect sites where significant site effects that are responsible for the local enhancement of seismic damages exist (D'Amico *et al.*, 2002; D'Amico and Albarello, 2003).

Due to the inherently macroseismic character of this approach, hazard estimates are provided in terms of intensity. This parameter can be considered important for civil protection purposes and, in particular, when risk scenarios are of concern (e.g., Bramerini *et al.*, 1995). In fact, despite the existence of modern fragility curves that allow the determination of expected damage from instrumental ground shaking data [peak ground velocity (PGA), etc.], approaches based on damage probability matrices, where damages are determined as a function of macroseismic intensity, are commonly applied at least in Italy, [see Calvi *et al.* (2006), for an extensive review]. This explains why, according to McGuire (1993), since the 1950s more than 60% of the countries worldwide (including industrialized countries such as Germany) have computed reference seismic hazard maps expressed in terms of intensity.

In spite of this, the use of hazard maps in terms of intensity appear useless when seismic design is of concern. This is an important aspect that cannot be overlooked. Modelization of seismic response relative to shallow subsoil and buildings, along with their interaction is a basic need for providing effective design and of preventing future damages. They require a definition for a "design earthquake" that must be characterized by a single magnitude, distance, and perhaps other parameters: this allows additional characteristics of the ground shaking to be modelled, such as duration, nonstationarity of motion, and critical pulses. However, hazard estimates deduced from the standard Cornell-McGuire approach considers a multitude of earthquake occurrences and ground motions, and produces an integrated description of seismic hazard representing all events (e.g., Cornell, 1968). In this frame, a procedure was proposed ("disaggregation analysis") that aims at providing a single magnitude-distance couple representative for the reference hazard level at the site of interest (McGuire, 1995; Buzzurro and Cornell, 1999; Pagani and Marcellini, 2007). An application of this technique to the Italian area is reported by Barani *et al.* (2009). It is worth noting that the "design earthquake" computed in this way is a "virtual" event generally representative (in terms of probability) of a large set of magnitude/distance combinations and thus, it could not correspond (but incidentally) to earthquakes that actually occurred in the past or expected in the future.

In the following, a procedure to retrieve a "design earthquake" from the analysis of local seismic histories carried out in the frame of the above-mentioned macroseismic "site-oriented" approach is proposed. Differently from a standard disaggregation analysis, seismic events selected in this way correspond to earthquakes that actually occurred in the past and that can be identified on the basis of the proposed procedure.

In the first part of the paper, basic aspects of the proposed methodology are briefly outlined. Then this approach, applied to a small town in central Italy, is given. The town was damaged by the strong shock of April 6, 2009 earthquake in central Italy ("L'Aquila earthquake").

2. M-D pairs from probabilistic analysis of local historical intensities

The procedure considered here for probabilistic seismic hazard computations is the one proposed earlier by Magri *et al.* (1994) and progressively improved [for most recent developments see Albarello and Mucciarelli (2002), D'Amico and Albarello (2008)]. This approach allows the definition of the reference intensity value I_{ref} at a site (i.e., the intensity value characterized by a fixed exceedance probability in the exposure time) by taking into account the local seismic history (i.e., the time series of seismic effects documented during the history at the site), epicentral macroseismic data (to integrate the local seismic history when necessary) and uncertainty concerning available intensity data and completeness of the seismic record. The use of these pieces of information, required the development of specific procedures to manage the peculiar properties of intensity data (that are ordinal, discrete and defined over a finite, non-metric scale) in the frame of a coherent probabilistic approach (see Albarello and Mucciarelli, 2002; Pasolini *et al.*, 2008). No seismicity smoothing is performed before computing hazard and no seismotectonic zonation is considered. This could represent an advantage when this information is affected by strong uncertainty as in the case of Italy.

In analogy with the Cornell-McGuire procedure, the bulk of this "site-oriented" approach is the computation of the "expected" number v of earthquakes that in a time window of dimensions equal to the exposure time have shaken the site under study with intensity larger than, or equal to, a intensity threshold I_s. This number is provided by the relationship

$$v\left(I_s\right)=\sum_{l=1}^{N} P_l\left(I_s\right) \tag{1}$$

where the N is the number of earthquakes that occurred during the time window considered and $P_l(I_s)$ is the probability that the *l-th* earthquake affected the site with an intensity not less than I_s. In fact, a probabilistic evaluation is requested to account for uncertainty relative to ill defined intensities (Magri *et al.*, 1994). This uncertainty depends on the incomplete documentation available for the effect of the event considered or, in the case of "virtual" intensities deduced from epicentral data, on uncertainty affecting attenuation of intensity with epicentral distance and intensity at the epicenter [see D'Amico and Albarello (2008) for details]. On the basis of $v(I_s)$ values, distribution-free hazard estimates can be provided by accounting for completeness of the seismic record [for details see Albarello and Mucciarelli (2002)]. Actually, for each I_s value, an exceedance probability $H_T(\geq I_s)$ is computed for any fixed exposure time T. On this basis, one can select as the reference intensity value I_{ref} as the maximum I_s value that satisfies the condition

$$H_T\left(\geq I_{ref}\right) > p \tag{2}$$

where p indicates a reference probability level.

After a suitable choice for T and p is made (e.g., 50 years and 10% as requested for most common situations in the Italian seismic code), the I_{ref} value for a given site can be computed. Then Eq. (1) can be reconsidered so as to identify earthquakes that contributed to seismic hazard at the site of concern at the I_{ref} or larger value. In fact, the role of a single *l–th* event in the determination of hazard at the intensity threshold I_s at the site under study ultimately depends on the values $P_l(I_s)$ in Eq. (1). Actually, these values can be considered as a "weight" of each single event in the local hazard at the threshold I_{ref} .

To each single event in the catalogue an epicentral location and a magnitude value were assigned (CPTI Working Group, 2004) on the basis of a formalized "robust" procedure (Gasperini and Ferrari, 2000; Gasperini *et al.*, 2010). In this way, to each $P_l(_{Iref})$ value, a magnitude/distance couple can be assigned. By ranking these couples as a function of $P_l(_{Iref})$, the most significant earthquakes (in terms of local seismic hazard) can be selected. Otherwise, the range of relevant epicentral distances (R) and magnitudes (M) can be binned (as R_i and M_j respectively) and the relevant $P_l\,(I_{ref})$ values can be summed in the corresponding cell to obtain a set of $P_{ij}\,(I_{ref})$ values. Given $Q(I_{ref})$ in the form

$$Q\left(I_{ref}\right) = \sum_j \sum_i P_{ij}\left(I_{ref}\right) \tag{3}$$

(where summation is extended to the whole set of distance and magnitude bins) that represents the overall number of earthquakes expected to have reached intensity I_{ref} at the site, the ratio

$$p_{ij}\left(I_{ref}\right) = \frac{P_{ij}\left(I_{ref}\right)}{Q\left(I_{ref}\right)} \tag{4}$$

represents the relative contribution to the local hazard of earthquakes in the *i*-th, *j*-th bin. By representing the p_{ij} values, a typical "disaggregation plot" (e.g., Bazzurro and Cornell, 1999) can be obtained and used to select a "representative" earthquake as the maximum of the table p_{ij}. It is worth noting that this maximum does not necessarily correspond to a single event, since a number of events located at similar epicentral distances and with similar magnitude could contribute.

3. Application

In the present study, I_{ref} values relative to an exposure time of 50 years and an exceedence

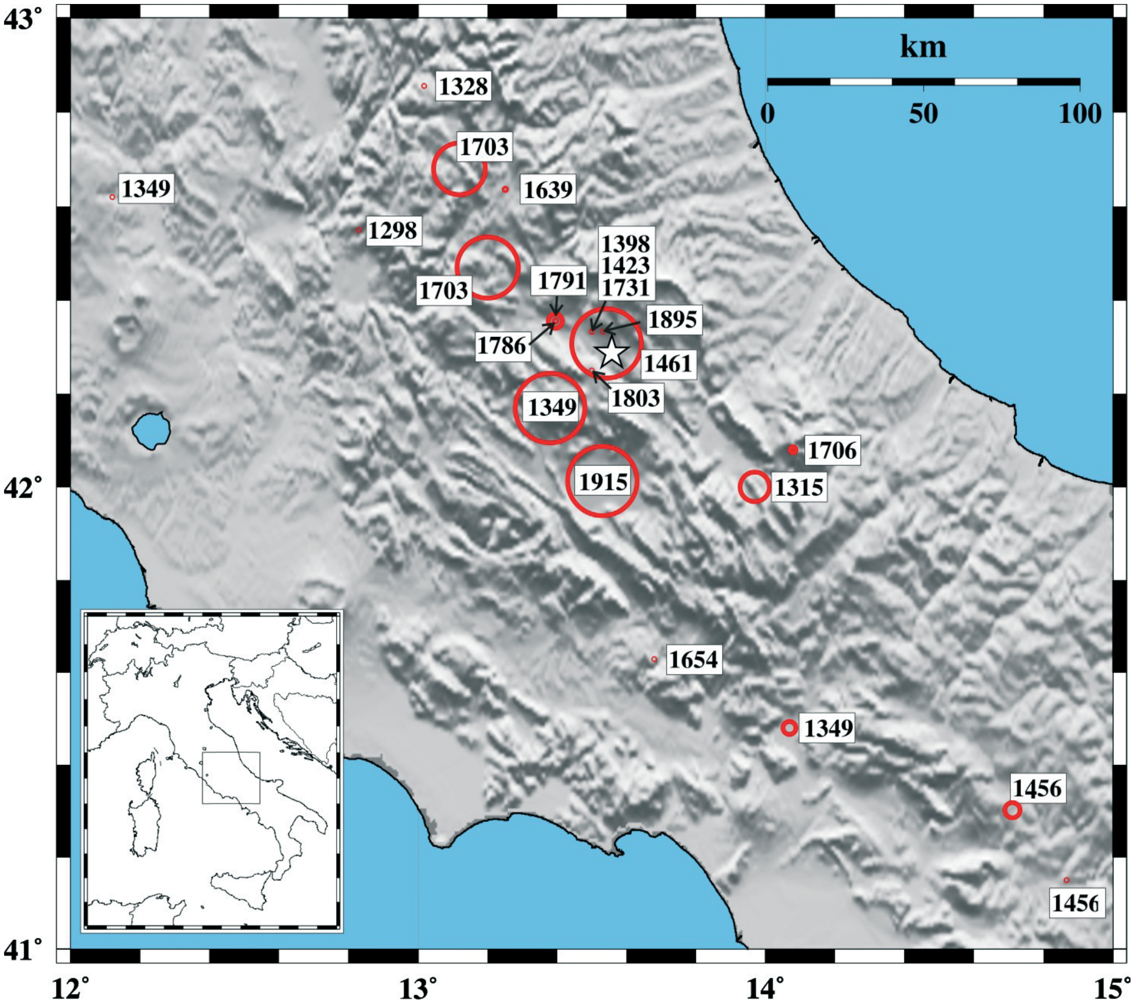

Fig. 1 - Geographical distribution of earthquakes that contribute to seismic hazard at San Demetrio ne' Vestini (indicated by the white star) at the intensity of VIII MCS (I_{ref}). Circles are centred at the epicentres of the significant events. The size of the circles is proportional to the contribution [Eq. (1)] of the relevant earthquake. Figures indicate the year of occurrence of the relevant earthquake (see Table 1).

probability of 10%, have been computed for the site of San Demetrio ne' Vestini, a small town located some tens of km SW-wards from L'Aquila in central Italy (Fig. 1).

As a first step, the reference intensity I_{ref} was computed by following the site-oriented approach described above for an exceedance probability of 10% and an exposure time of 50 years. Site seismic history used for computations have been deduced from the Macroseismic Database of Italian Earthquakes [DBM04 by Stucchi *et al.* (2007)] and from the Parametric Catalogue of Italian Earthquakes (CPTI04 Working Group, 2004). It turns out that the effects (or lack of effect) relative to 15 past seismic events have been documented at San Demetrio nè Vestini since 1762 (Table 1), with maximum recorded effects corresponding to VIII MCS in association with the 1915 central Italy earthquake. It is worth noting, however, that despite the fact that no

Table 1 - Seismic effects documented at the site of San Demetrio né Vestini (Stucchi *et al.,* 2007).

Year	**Month**	**Day**	**Intensity (MCS)**
1762	10	6	Felt
1895	11	1	Not Felt
1902	10	23	Not Felt
1915	1	13	VIII
1927	10	11	IV
1933	9	26	VI
1950	9	5	VII
1958	6	24	VI
1960	3	14	III
1961	10	31	III
1984	5	7	IV-V
1987	7	3	III
1990	5	5	Not Felt
1997	9	26	III-IV
1998	8	15	III

direct documentation was found about local damage, strong earthquakes have occurred near the site prior 1762, such as the strong 1349 and 1461 L'Aquila earthquakes both characterized by maximum intensity of the order of X MCS (CPTI04 Working Group, 2004).

Hazard computations were performed by using the numerical code SASHA (D'Amico and Albarello, 2008) that indicated an I_{ref} value of VIII MCS, in line with the maximum documented intensity.

By taking these values as reference, earthquakes with $P_l(I_{ref})$ values larger than 0 were selected for each considered site (Table 2). Relevant epicentral distances and macroseismic magnitudes (*Mw* compatible) were deduced for each of these events from the epicentral catalogue CPTI04. In Fig. 1, the results of this analysis are reported showing that a number of earthquakes contributes significantly to the hazard evaluation.

Thus, the $P_l(I_{ref})$ values were binned in classes of epicentral distances (5 km each) and magnitude (0.5 units each). The relevant $P_l(I_{ref})$ values relative to each earthquake were summed up in the relevant distance/magnitude bin and normalized [Eq. (4)] to provide a sort of "disaggregation" map. The results obtained are shown in Fig. 2. The map is multimodal as it represents the actual earthquakes. Anyway, a clear "polarization" is shown. In particular, one can see that the most important contribution to local hazard comes from relatively strong earthquakes (*Mw* in the range [6.5, 7.0[) relatively distant from the site (epicentral distance in the range [30, 40[km).

It could be interesting to compare these results with those provided for the same site by the standard disaggregation analysis (Fig. 3). This has been performed by following Barani *et al.*

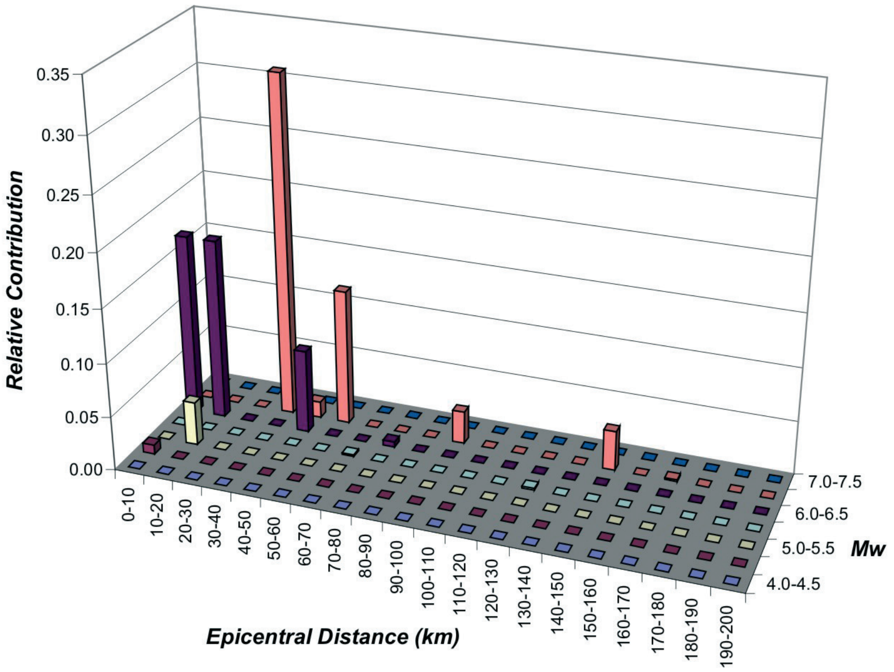

Fig. 2 - Contribution of magnitude/distance pairs to seismic hazard (for an exceedance probability of 10% and an exposure time of 50 years) at San Demetrio ne' Vestini on the basis of the site-oriented macroseismic approach (see text for details). The vertical axis reports the relative contribution to the local hazard from earthquakes characterized by the relevant magnitude-distance bin.

(2009) and indicates (see data reported in http://esse1-gis.mi.ingv.it/s1_en.php) that most prominent contributions to the local seismic hazard (relative to an exceedance probability of 10% in 50 years) comes from events in the magnitude range [4.5-5.5[with very near source (0-10 km).

Thus, a site-oriented macroseismic approach suggests a more energetic and distant design earthquake with respect to that provided by the standard approach. In this context, it could be of some interest to evaluate the impact of these different outcomes in terms of ground motion spectrum expected at the site of San Demetrio ne' Vestini. For this purpose, two magnitude/distance pairs (6.8/35 and 5.0/5) have been considered as representative of the macroseismic and standard approaches, respectively. Of course, for both macroseismic and standard approaches, other choices are actually possible and the ones above represent the magnitude-distance combinations that played the major role in the local hazard determination. The relevant pseudo spectral acceleration (PSA) and pseudo spectral velocity (PSV) curves at the site were computed by using spectral attenuation relationships provided by Sabetta and Pugliese (1996). One can see that design earthquakes deduced by the two approaches (macroseismic and standard) are characterized by strong spectral differences. In particular, expected PSA amplitudes above 1 s, appear much higher in the case of macroseismic determination while the reverse is true in the high frequency range (period below 1 s). When PSV is considered, one can see that macroseismic approach provides a much more severe scenario than the standard one in the whole range of periods of engineering interest.

Table 2 - Epicentral parameters of earthquakes contributing to the hazard estimate at the site of San Demetrio nè Vestini for the intensity threshold of VIII MCS (CPTI Working Group, 2004). For each earthquake, the date of occurrence and relevant epicentral location are given in the first 5 columns. M_w is the magnitude, Dist is the epicentral distance from the site of San Demetrio nè Vestini, I_x is the maximum MCS intensity for the relevant earthquakes and Np is the number of sites where the effects of the relevant earthquakes are documented.

Year	Month	Day	Lat (°N)	Lat (°E)	M_w	Dist (km)	I_x (MCS)	Np
1298	12	1	42.550	12.83	5.9	66	IX-X	7
1315	12	3	42.000	13.97	6.0	47	X	15
1328	12	1	42.856	13.02	6.4	77	X	13
1349	9	9	41.480	14.07	6.6	99	X	24
1349	9	9	42.620	12.12	5.9	124	VIII-IX	15
1349	9	9	42.170	13.38	6.5	20	X	22
1398	4	3	42.333	13.50	4.8	7	VI	-
1423	11	10	42.333	13.50	4.8	7	VI	-
1456	12	5	41.302	14.71	7.0	145	XI	199
1456	12	5	41.150	14.87	6.6	167	X	-
1461	11	26	42.308	13.54	6.5	3	X	10
1639	10	7	42.636	13.25	6.3	46	X	27
1654	7	23	41.630	13.68	6.2	74	X	44
1703	1	14	42.680	13.12	6.8	56	XI	196
1703	2	2	42.470	13.20	6.7	36	X	70
1706	11	3	42.080	14.08	6.6	49	X-XI	99
1731	10	15	42.333	13.50	4.8	7	VI	-
1786	7	31	42.356	13.40	5.2	15	VII	7
1791	1	0	42.356	13.40	5.4	15	VII-VIII	1
1803	4	7	42.250	13.50	4.8	6	VI	-
1895	6	30	42.333	13.53	4.8	5	VI	-
1915	1	13	42.013	13.53	7.0	31	XI	1041

This is what one can expect due to the fact that damping is less effective in the case of the near earthquake selected by following the standard approach than in the case of the relatively distant earthquake selected by the macroseismic approach. On the other hand, this last event is more energetic in the low frequency range due to its relatively large source dimension. The above differences in the spectral structure of the design earthquakes provided by the two approaches again stress the fact that focusing on the PGA value only (essentially controlled by high frequency contributions) provides a misleading image of the local hazard.

4. Discussion and conclusion

A new procedure has been described to provide design earthquake from hazard estimates

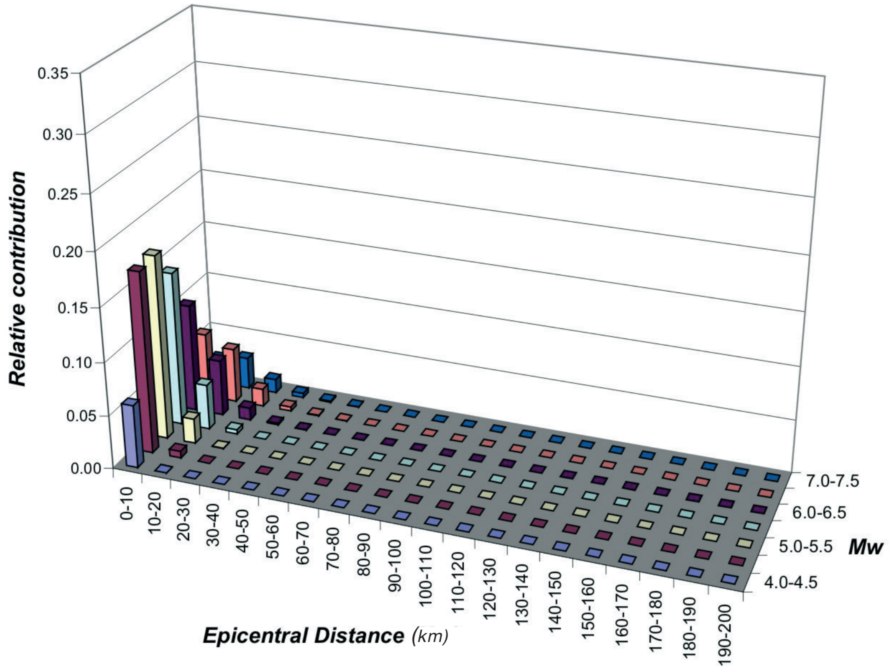

Fig. 3 - Contribution of magnitude/distance pairs to seismic hazard (for an exceedance probability of 10% and an exposure time of 50 years) at San Demetrio ne' Vestini, provided in the frame of the standard approach (http://esse1-gis.mi.ingv.it/). The vertical axis reports the relative contribution to the local hazard from earthquakes characterized by the relevant magnitude-distance bin.

carried out in terms of macroseismic intensity. The starting point is a hazard estimate deduced from the statistical analysis of local seismic history reconstructed from documentary information. No assumption is requested about distribution and geometry of seismogenic sources and on the Poissonian character of seismicity locally observed. On this basis, a search of those past seismic events that contributed mostly to the resulting hazard estimate is performed. These are characterized in terms of macroseismic magnitude and epicentral location and this allows the identification of the most significant magnitude/distance bin (the "design earthquake").

In the application example here considered, design earthquakes provided by this site-oriented macroseismic approach was compared with the one provided by a standard "disaggregation" procedure. Outcomes of these approaches are significantly different despite the fact that both approaches share the same basic assumption (stationarity of the seismogenic process), and original information (DBM04 and CPTI04 catalogues). This could depend on two important features. First of all, the macroseismic approach basically considers single earthquakes that are expected to occur again in the future. This implies that seismicity is strongly "polarized" at the epicentral location and that the contribution of single well defined events can be identified and traced-back. The standard approach, instead, considers earthquakes as "distributed" over large seismogenic structures. This implies a less "polarized" seismicity with resulting magnitude/distance pairs that does not correspond to any actual earthquake. The consequences of

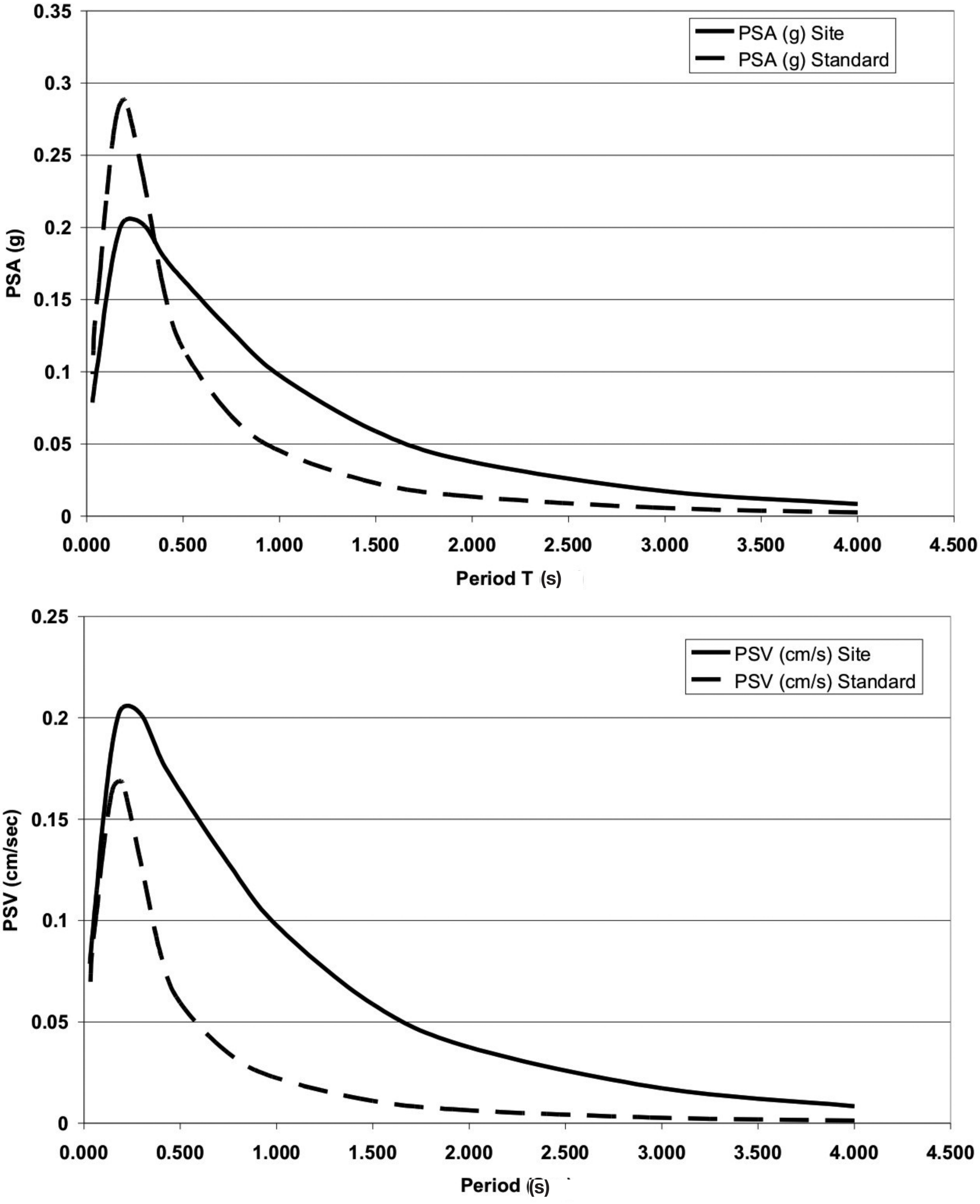

Fig. 4 - Comparison of design PSA (in the upper plot) and PSV (in the lower plot) obtained at San Demetrio ne' Vestini by the use of attenuation relationships by Sabetta and Pugliese (1996), considering the magnitude/distance pairs provided by macroseismic "site-oriented" (solid line) and standard disaggregation (dashed lines) approaches.

these differences on seismic hazard assessment were examined at some depth by Mucciarelli *et al*. (2008). This also revealed the strong sensitivity of standard approach outcomes to geometry of seismogenic zones, that can be considered as highly controversial: actually, the degree of belief one associates with standard outcomes, mostly depend on the degree of belief one associates to the relevant seismotectonic zonation. On the other hand, site-oriented approaches basically depend on the seismic history available and on the assumption that future events will mimic past occurrences without any inference about extended potential sources not activated in the historical time.

A second important difference relies on the possible role of ground motion amplification effects induced by listhostratigraphic/geomorphologic configurations. These effects are not accounted for in the standard approach, while they are inherently included in the analysis when macroseismic information is considered. This implies that design earthquakes deduced by the macroseismic approach also includes events that are important due to the local seismic response. This kind of event is instead excluded in the standard approach. This could represent an advantage for the site-oriented macroseismic approach with respect to the standard one in that possibly significant earthquakes could be "lost" when only this last procedure is considered.

Acknowledgments. Many thanks are due to Marco Mucciarelli and Alessandro Rebez for their fruitful comments that significantly contributed to improving the paper.

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