

Italian intensity hazard maps: a comparison of results from different methodologies

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Abstract - Most of the seismic hazard studies of the Italian territory developed over the last decade make use of the standard Probabilistic Seismic Hazard Analysis (PSHA), based on the well known methodology proposed by Cornell (standard approach). Recent studies on this methodology check the weight and the importance on the final results of the choices made in the computational method and introduce different procedures for the evaluation of the uncertainties. In this paper, hazard estimates for Italian municipalities, provided by an improved version of the standard methodology, have been compared with those obtained through a new procedure based on a different approach. Basic aspects of this approach (site approach) are the extensive use of intensity data, extracted from documentary sources available at the investigated localities and a more complete and coherent treatment of the different sources of uncertainty involved in seismic hazard evaluations. The site approach maps, which have to be considered as equivalent and alternative to those obtained with standard PSHA, show significant differences from the latter ones. These differences appear in no way systematic and homogeneous as previous studies showed. Hazard estimates obtained from the site approach are generally more spatially heterogeneous than those computed by the standard approach. Furthermore, site estimates are generally higher than standard ones in low seismicity areas and where local information about effects of past earthquakes is relatively poor. Standard estimates, instead, are higher in high seismicity areas and, also, where better information exists about the local seismic history.

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1. Introduction

Seismic hazard assessment (SHA) consists in the comparative evaluation of several possible hypotheses about the level of Earth shaking expected within a fixed time interval (exposure time). As far as seismic risk mitigation and post-earthquake emergency planning are concerned, the direct use of macroseismic intensity, as a parameter of Earth shaking, may be more interesting than instrumental parameters (peak ground acceleration, etc.), as it is more immediate and representative of damage scenarios expected at individual municipalities.

Probability (as expression of the degree of belief) associated to the hypothesis that at least one event with intensity at least equal to I_s will occur at the site during the time span Δt (exposure time) is expressed through the hazard function. This function is generally defined on the basis of statistical analysis of past seismicity and by imposing suitable tectonic constraints. Through this function, it is possible to fix a reasonable upper bound to the intensity expected at the site s during the exposure time. This reference intensity (RI hereafter) generally depends on the adopted level of “conservatism” (Reiter, 1990). As an example, in the case of the Italian seismic code, the RI is the intensity characterised by a probability not lower than 10% to be overcome at the site of interest during an exposure time of 50 years.

At the end of the 90's, as a result of the efforts of a large part of the Italian scientific community, coordinated in the frame of the GNDT project, new seismic hazard maps of the Italian territory were produced (Slejko et al., 1998) by using a “standard” approach (Bender and Perkins, 1987). Basic information for this product was the seismotectonic zonation proposed by Meletti et al. (2000), the parametric catalog of the Italian seismicity (Camassi and Stucchi, 1996) and the attenuation rules provided by Peruzza (2000).

Since that one, another seismic hazard map has been produced (Albarello et al., 2000), on the basis of the same methodological approach, by taking into account the revision of the epicentral catalog (Working Group Parametric Catalog of Italian Earthquakes, 1999). A further improvement of these estimates also concerns the implementation of a new procedure in the computational code to estimate the catalog's completeness and related uncertainty (Albarello et al., 1995, 2001).

Despite these improvements, the application of the standard procedure to SHA in Italy is characterised by a number of pitfalls. The first one concerns the fact that uncertainty on intensity values deduced at the site from attenuation relationships has been systematically discarded. This bias could be responsible for significant underestimates of seismic hazard. In fact, it is well known (e.g. McGuire, 1993) that the under-evaluation of uncertainty directly reflects in hazard underestimates. This bias is also enhanced by the strong sensitivity of hazard estimates to attenuation rules (Romeo and Pugliese, 2000) and by the fact that uncertainty about epicentral intensities of past earthquakes is not considered at all. A further possible source of biases is also related to the statistical modelling of intensity as a continuous random variate. To discard the finite and discrete character of intensity implies any “rounding” rule which could introduce some degree of arbitrariness in the final RI estimates.

A more general problem in the standard approach concerns the fact that this methodology, mostly oriented towards the statistical characterisation of seismogenic sources, does not allow

the full exploitation of the large amount of data on local effects of past earthquakes actually available in Italy (see, e.g. Boschi et al., 1997; Monachesi and Stucchi, 1997).

A different approach to SHA was proposed (Mucciarelli et al., 1992; Magri et al., 1994; Gallipoli et al., 1998) a few years ago to overcome these problems and to better exploit the available information. Fundamental aspects of this approach (hereafter the “site” approach) are the extensive use of intensity data extracted from documentary sources available at the investigated localities, the more complete and coherent treatment of the different sources of uncertainty involved in seismic hazard evaluations and the characterisation of local seismicity by using a distribution-free statistical approach. More recently, the site approach has been improved by also incorporating the management of uncertainties concerning local catalog completeness (Albarelo and Mucciarelli, 2002) and by including a more reliable parameterisation of the probabilistic intensity attenuation law (D’Amico and Albarelo, 2003).

From one point of view, the site approach could appear weaker since it discards important information supplied by geological and seismotectonic studies which could allow to constrain possible seismogenic structures also where historical data about past seismicity are lacking or insufficient. However, the question could arise if it is better to consider this information, whose intrinsic uncertainty cannot be easily assessed and managed, at least as concerns the Italian seismotectonic situation, or to disregard it completely by taking advantage of the extension of the documentary heritage about past seismic effects which has been made available in Italy over the last years. On the other hand, the site approach could appear stronger in that it allows to take into account local conditions (implied in the considered local intensities) with respect to a standard approach which relies completely on source information only.

Apparently, it becomes quite difficult to define “a priori” criteria to judge one approach better than another. A better insight into this problem can be gained by comparing resulting hazard maps. A first attempt at comparing results of earlier versions of site and standard approaches obtained at 600 Italian sites was provided by Mucciarelli et al. (2000). This comparison showed that the two methodologies give quite different results. In general, estimates from the site approach are higher and more spatially heterogeneous than those provided by the standard methodology. D’Amico and Albarelo (2003) obtained similar results in the comparison of RI estimates provided by the revised version of the site approach in the Garfagnana-Lunigiana area (northern Italy) with standard estimates for the same area provided by Slejko et al. (1998). A sensitivity analysis carried out in that study has shown that, at least for the considered area, discrepancies observed between the two estimates could be mostly attributed to a different management of input data and related uncertainties (e.g., relative to the catalog completeness level and to intensity evaluations for old earthquakes whose effects at the site are unknown or ill-documented). A significant but minor role should also be attributed to the uniform spanning of seismicity over wide seismogenic areas performed in the standard approach.

In order to provide a more comprehensive comparison of site and standard estimates of seismic hazard, on behalf of the National Seismic Survey, the most recent implementation of the site approach has been used to compute RI values at all the Italian municipalities (8100 sites). These results have been compared with those deduced for the same set of localities by using an improved version of the standard approach.

2. Database and computational details

Epicentral information used for the standard approach has been deduced from the CPTI catalog of Italian mainshocks that occurred from 1000 up to 1990 (Working Group Parametric Catalog of Italian Earthquakes, 1999). Local seismic histories to be used in the site approach have been reconstructed on the basis of the about 51000 local intensity values which constitute the background of the CPTI records. This macroseismic data set is a combination of information coming from existing databases (Boschi et al., 1997; Monachesi and Stucchi, 1997; macroseismic bulletins of the National Institute of Geophysics and Volcanology). These data concern most main municipalities of Italy (Fig. 1). In particular, about 30% of the localities

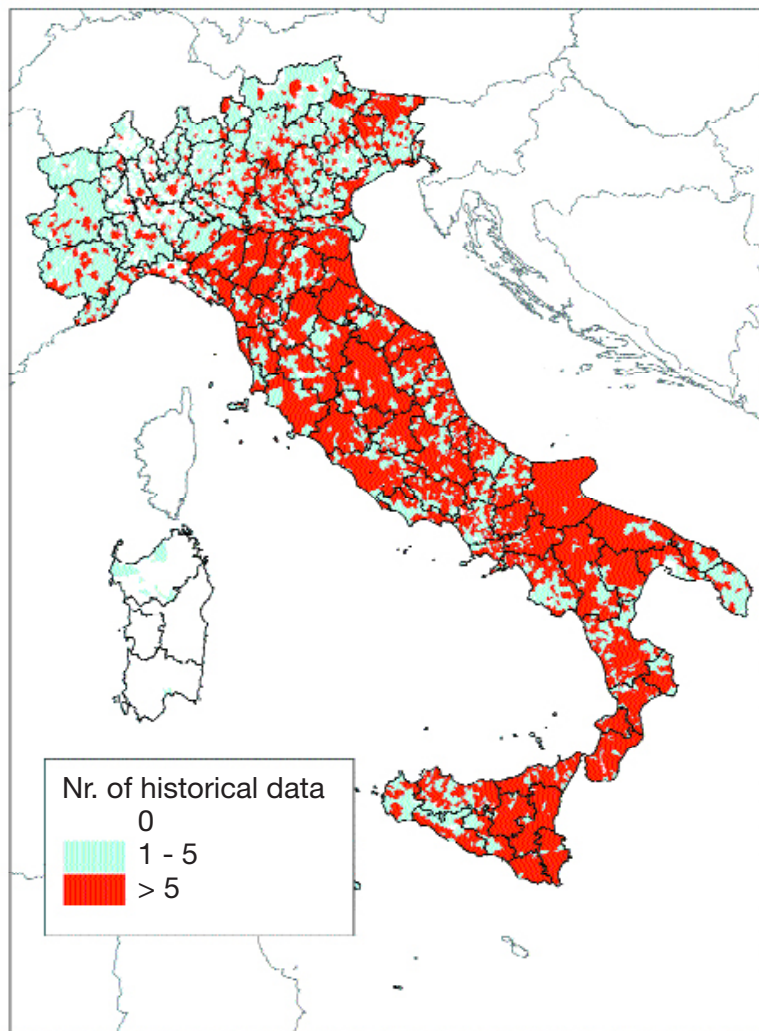


Fig. 1 - Macroseismic information available at Italian municipalities about local effects of past earthquakes. Seismic effects documented only at the main town of each municipality have been considered (40310 data). In order to improve the readability of the map, the number of felt intensities at each site has been divided into three classes (0, 1-5, > 5 respectively) each identified by a colour. This has been attributed to the whole municipal territory including the relevant main town.

is characterised by a relatively “rich” seismic history (more than 5 documented intensities are available) while for more than 50% of them at least a “poor” seismic history (1-5 documented intensities) is available. For the remaining 20% of the localities, no information exists about the local effects of past earthquakes. In general, most localities with “poor” or no seismic history are concentrated in Sardinia and north-western Italy, while relatively “rich” seismic histories are available in central and southern Italy and in eastern Sicily. As expected, “richest” seismic histories are concentrated in areas characterised by higher seismicity rates.

Methodological details concerning the application of the standard approach considered here are reported in the Appendix. The most important improvement, with respect to the previous applications (Slejko et al., 1998; Albarello et al., 2000), concerns the management of uncertainty involved in the estimate of intensity at the site from epicentral data via attenuation relationships. Since this information had been discarded in previous applications, one could expect that a new estimate would be higher than those provided before.

A complete description of the procedures underlying the site approach applied for SHA is provided in Albarello and Mucciarelli (2002). Only two aspects of its application in the present case deserve some consideration. The first one is relative to the assessment of uncertainty to be attributed to each felt intensity. In the lack of more direct information, it has been assumed that “intermediate” intensity estimates are representative of uncertain situations. In these cases, equal probability has been attributed to the hypotheses that the actual felt intensity was one of the two contiguous integer intensity values.

The second aspect concerns the role of epicentral data in site estimates. In the following, it will be assumed that the lack of local information about a known earthquake cannot be interpreted as an actual lack of seismic effects. This assumption could be in some cases too conservative. It is well known, in fact, that minor effects tend to be under-represented in documentary sources. However, in absence of direct documentation, major effects cannot be excluded and this could result in an overestimate of potential effects deduced from epicentral data and attenuation relationships. Anyway, in these cases, the available seismic history has been integrated with a probabilistic estimate of local effects carried out by the use of the logistic relationship provided by D’Amico and Albarello (2003). Only events with epicentral distances not greater than 300 km have been considered to evaluate their possible contribution to the local seismic history.

3. Comparison of RI estimates in the main Italian municipalities

Figs. 2 and 3 show the RI values computed, respectively, by using the standard and the site approaches. In both cases, RI has been computed for the main town of each municipality but, in order to make the map as readable as possible, this value has been attributed to the whole territory included in the relevant municipality. In order to make comparable RI estimates from standard and site approaches, seismic histories used in the latter have been compiled by taking into account effects felt at the main town only. Other seismic effects documented at minor localities inside the municipal territory have been discarded.

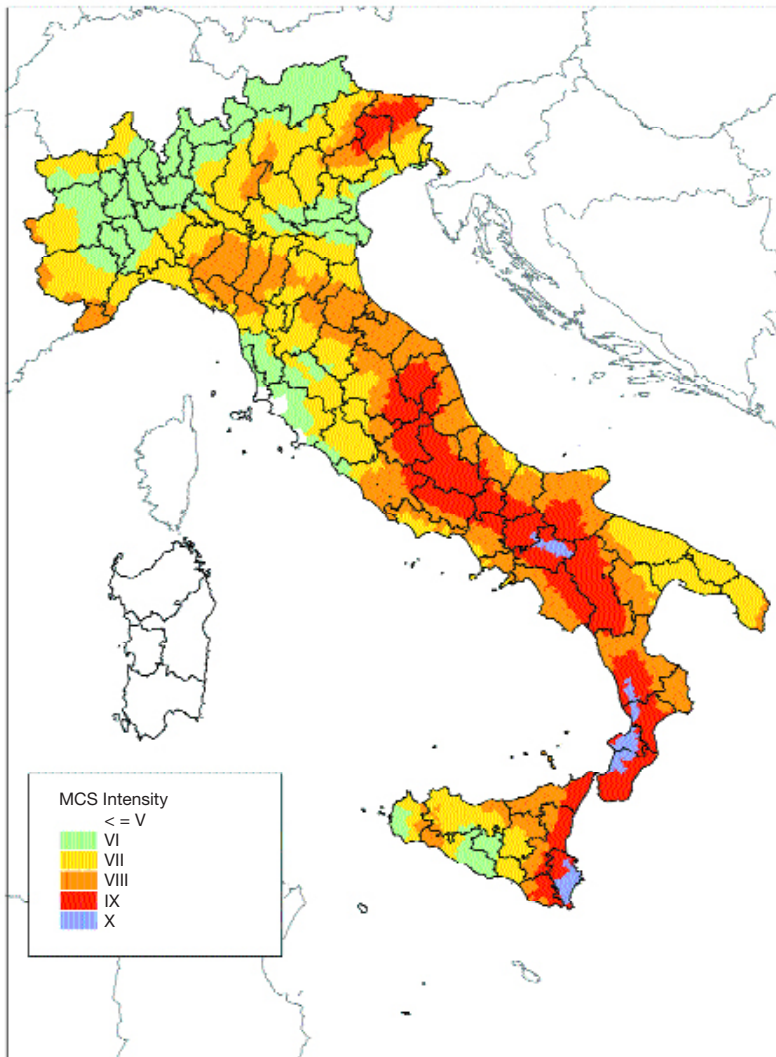


Fig. 2 - RIs (MCS scale) at Italian municipalities computed by using the standard approach. Each value corresponds to the maximum intensity value characterised by a probability of exceedance not lower than 10% within a 50-year exposure time. Only reference intensities at least equal to VI MCS have been considered. Intensity estimates resulting from the computations have been rounded to the nearest integer.

As expected, RI estimates in Fig. 2 are generally higher than those obtained from previous applications of the standard approach (Slejko et al., 1998; Albarello et al., 2000). In particular, in the new estimates, areas with RI less than VI MCS disappear, but the case of Sardinia, and RI values generally show an increase of the order of one degree. These are the effects of considering uncertainties on attenuated intensities which had been discarded previously instead. Since this fact has significantly increased hazard values, the basic role played by attenuation relationships (and by associated uncertainties) in hazard estimates provided by the standard approach appears evident (see also Romeo and Pugliese, 2000).

The comparison between the maps in Figs. 2 and 3 shows that, in case of site estimates, the number of localities with RI equal to VII expands dramatically all over Italy (areas with RI

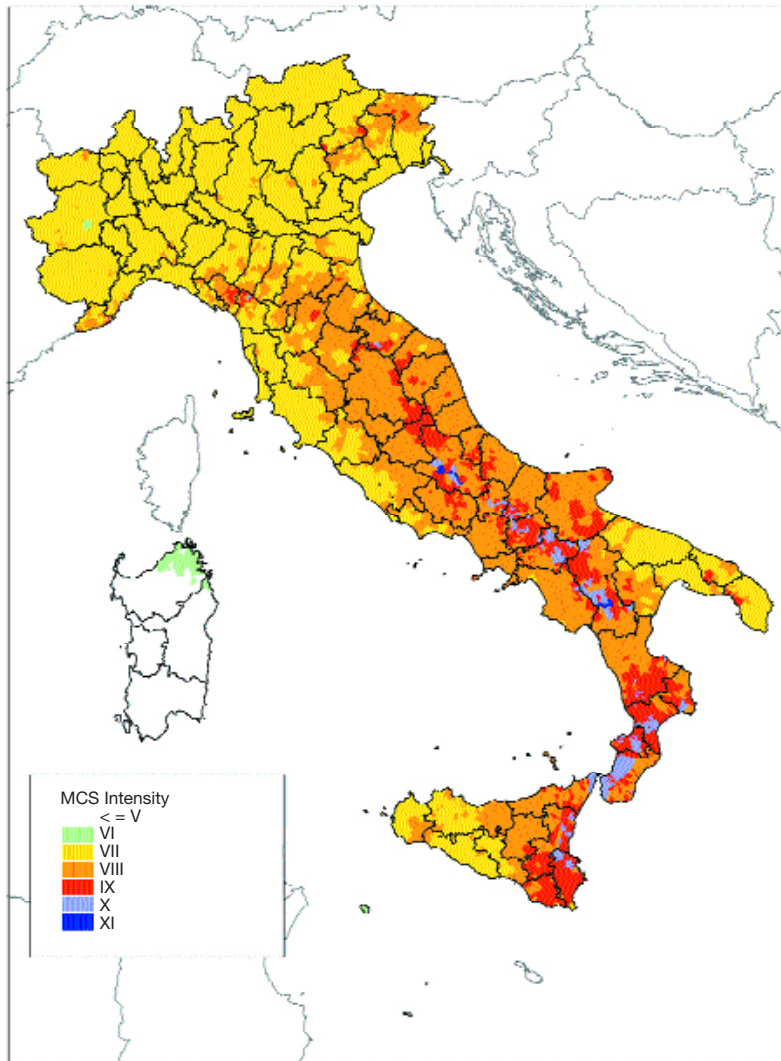


Fig. 3 - RIs (MCS) for Italian municipalities computed by using the site approach. Each value corresponds to the maximum intensity value characterised by a probability of exceedance not lower than 10% within a 50-year exposure time. Only RIs at least equal to VI MCS only have been considered.

equal to VI MCS nearly disappear from the map). As concerns larger RI values, instead, the situation becomes less homogeneous: in peninsular Italy and in Sicily, the area with RI equal to VIII MCS expands while it diminishes in the northern Apennines and eastern Alps. In the site estimates, areas with $RI \geq IX$ MCS are significantly reduced and sometimes concentrated, locally, whereas RI values reach degree XI MCS which is never present in the standard estimates. In some cases, the most dangerous sites are displaced and more sparsely distributed with respect to those identified by the standard technique.

In order to make discrepancies between RI estimates provided by the two approaches more evident, the relevant differences for each municipality are displayed in Fig. 4. Site estimates are more conservative in the western and central parts of the Alpine belt, in the easternmost part of

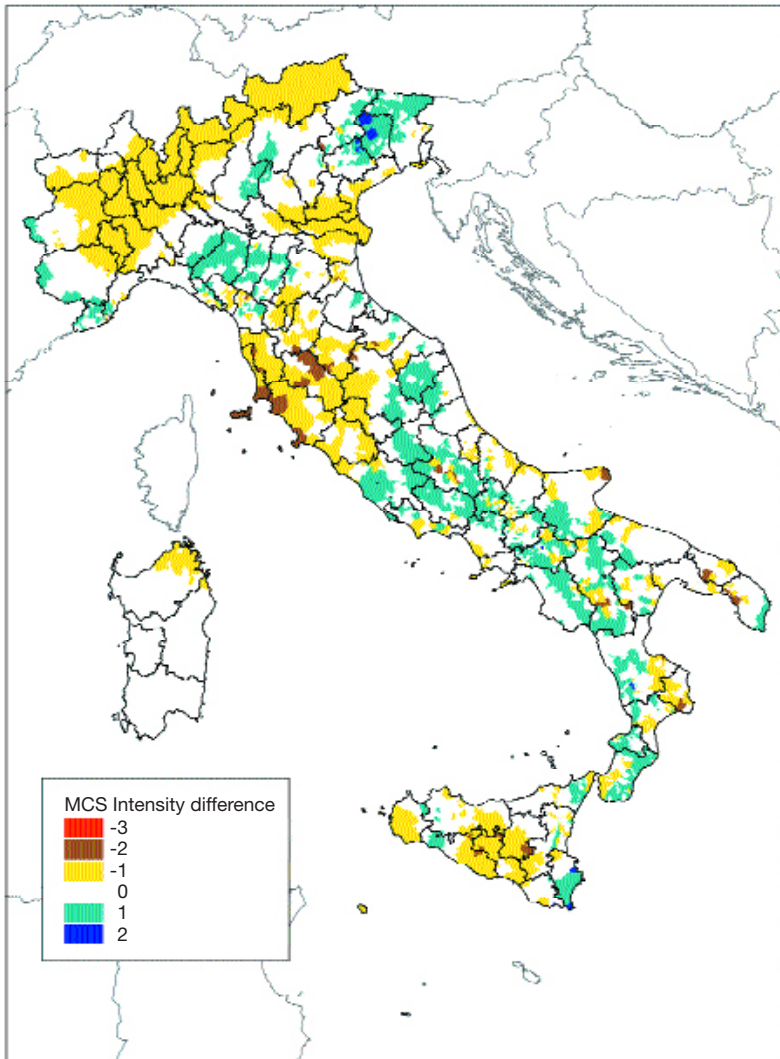


Fig. 4 - Map of differences ($RI_{STANDARD} - RI_{SITE}$) between RIs (MCS) provided by standard and site approaches respectively displayed in Figs. 2 and 3. Negative values indicate that estimates resulting from the standard methodology are lower than those deduced from the site approach, while positive values indicate that standard estimates are more conservative. When both methodologies provide reference intensities below VI MCS, differences between the two estimates have been assumed equal to zero.

the Po plain, along the Tyrrhenian coast of Tuscany, the Ionian coast of Calabria and in central Sicily. The contrary is true in the eastern Alps, most of the central and southern Apennines and along the Tyrrhenian coast of Calabria.

A further insight into the discrepancies observed between the results of the two methodologies can be gained by comparing differences reported in Fig. 4 with the space distribution of felt intensities (Fig. 1). In fact, it appears evident that areas where standard estimates of RI are lower than those from the site method are generally characterised by very poor, or poor, local seismic histories (see, e.g., Alpine margin and eastern Po plain to the north, and central Sicily to the south: the exception is western Tuscany). These areas are also

characterised by relatively low values of standard RI estimates (see Fig. 2). The comparison of the maps in Figs. 2 and 4 also shows that site estimates of RI are generally lower than those from the standard approach in sites where this last methodology provides high RI values. These qualitative considerations are corroborated by a correlation analysis carried out considering both usual and rank correlation coefficients (e.g., Kendall, 1955). This analysis identifies significant ($P < 0.05$) positive correlation between the RI differences in Fig. 4 and the number of available felt intensities (Fig. 1) as well as standard RI values (Fig. 2).

4. Discussion and conclusions

Seismic hazard maps deduced by means of the standard and the site approaches (Figs. 2 and 3, respectively) for Italian municipalities are significantly different. This conclusion is in line with previous results (Mucciarelli et al., 2000; D'Amico and Albarello, 2003). However, the present analysis shows that these differences appear in no way systematic and homogeneous as they were in previous works.

Since geological information plays a minor role in the application of the standard approach for Italy and macroseismic data pervade the Italian seismic catalog (only less than 1/3 of the entries can be actually considered of instrumental origin), both approaches share the same basic information. This fact also concerns attenuation relationships since the same macroseismic database has been used to parameterise both the attenuation laws used in the standard approach (Peruzza, 2000) and the probabilistic "attenuation" considered in the site approach (D'Amico and Albarello, 2003). Thus, reasons for the observed discrepancies can only be justified in terms of the different methodological aspects and strategies adopted in the two approaches for the management of input data and related uncertainties.

Both approaches share the same basic assumption that seismicity can be considered a stationary process. However, beyond this similarity, profound differences for the examined procedures exist in the management of basic information and relevant uncertainties.

A major methodological difference between the two approaches concerns the fundamental role attributed, in the case of the standard method, to seismogenic zones which, instead, are not considered in the site approach. In particular, the hypothesis underlying the standard approach that each seismogenic area is characterised by a uniform distribution of seismic potential produces a uniform spanning of seismicity over relatively wide regions and, consequently, a more homogeneous regional pattern of RI values and the lowering of these latter in actual epicentral areas.

Furthermore, the basic role played, in the framework of the site approach, by intensity data available at each considered locality causes a greater lateral heterogeneity of RI estimates due to the possible presence of local geostructural effects (e.g., D'Amico et al., 2002; Gallipoli et al., 2002). In this regard, site estimates could turn out to be more reliable than those from the standard procedure.

A further important difference between the two approaches concerns the evaluation of uncertainties affecting input data. It is well known, in fact, that when these uncertainties are

considered, apparent seismicity rates are increased (see, e.g., McGuire, 1993; D'Amico and Albarello, 2003). This could explain why RI estimates provided by the standard approach here considered are generally higher than those computed through previous versions of the standard method, where uncertainty associated to attenuated intensities had been disregarded (Slejko et al., 1998; Albarello et al., 2000).

The analysis of differences between hazard estimates computed through standard and site approaches respectively has pointed out the existence of a significant positive correlation between these differences and both the number of available local intensity data and standard RI values. In particular, at the municipalities located inside lower seismicity areas and characterised by very poor seismic histories (this is particularly the case of northern Italy), site hazard estimates are higher than standard ones. This occurs since we assumed that the lack of direct information about local effects of a known past earthquake cannot safely allow us to exclude the occurrence of low-probability severe effects suggested by probabilistic attenuation rules. Anyway, the fact that at these localities site estimates of RI are more "conservative" than those provided by the standard approach does not mean that these latter should be considered more reliable. In fact, a conclusive judgment about the relative reliability of the considered methodologies could only be obtained by developing approaches devoted to the validation of hazard estimates by a quantitative comparison with seismicity observed during a control period. This kind of analysis has been rarely attempted in the past (e.g. McGuire, 1979; McGuire and Barnhard, 1981; Kagan and Jackson, 2000; Petersen et al., 2000) and should deserve much more attention from the community of Earth scientists in the future.

Appendix

The standard methodology is based on a procedure introduced by Cornell (1968) and that, in a more sophisticated implementation (Bender and Perkins, 1987), has been recently adopted as an international standard (see, e.g., Giardini and Basham, 1993). In this approach, the hazard probability function is expressed in the form

$$H(\Delta t, I_s) = 1 - e^{-\lambda(I_s)\Delta t} \quad (1)$$

where $H(\Delta t, I_s)$ is the probability that at least one event with intensity not lower than I_s will occur at the site s during the exposure time Δt . This function only depends on one parameter λ which represents the seismicity rate at the site and is provided by the following relationship

$$\lambda(I_s) = \sum_{z=1}^N v_z \int_{A_z} \int_{I_0}^{I_{\max}} P_z(I \geq I_s | r, I_0) g_z(r | I_0) f_z(I_0) dI_0 dr \quad (2)$$

where the summation is extended to the total number N of considered seismic sources and the double integration is performed over the areas A_z of each seismic source and over the intensity values above a minimum threshold I_0 .

The parameter v_z is the number of earthquakes above the epicentral intensity threshold I_0 computed for unit area and by using data from the available epicentral catalog. In order to take into account uncertainty on the extension of the complete part of the parametric catalog of events in the z -th source, the following relationship has been used to compute $v_z(I_0)$

$$v_z(I_0) = \sum_{j=1}^L c_z(I_0, \Delta T_j) \frac{n_z(I_0, \Delta T_j)}{\Delta T_j} \quad (3)$$

where $c_z(I_0, \Delta T_j)$ is the probability density function representative of the degree of belief in the hypothesis that the catalog covering the time span ΔT_j for the z -th zone is representative of actual seismicity over the epicentral intensity threshold I_0 (it is “complete” for that intensity threshold), $n_z(I_0, \Delta T_j)$ is the number of events with epicentral intensity not less than I_0 occurred in the z -th seismic source during ΔT_j , and the summation is extended over the total number L of possible choices of the catalog duration; the probability function $c_z(I_0, \Delta T_j)$ has been computed for each seismic source by following the approach proposed by Albarello et al. (2001) and by Albarello and Mucciarelli (2002). In the considered application, c_z has been evaluated by taking into account all the events falling within 200 km from the barycentre of the seismic zone considered.

The probability density function $f_z(I_0)$ represents the probability that an earthquake with epicentral intensity I_0 is generated for unit area and unit time in the z -th seismogenic zone; the function $f_z(I_0)$ has been computed as

$$f_z(I_0) = \frac{v_z(I_0 + 1) - v_z(I_0)}{v_z(I_0)}, \quad (4)$$

where $v_z(I_0)$ is computed from Eq. (3).

The probability density function $g_z(r|I_0)$ represents the probability that an earthquake of epicentral intensity I_0 occurs in the z -th zone at a distance r from the site under study; in practice, $g_z(r|I_0)$ represents the seismic activity rate within the z -th zone; in the application here considered, g_z has been assumed to be uniform within each seismic source.

The distribution $P(I \geq I_s | r, I_0)$ represents the probability that at the site s the effects of an earthquake with epicentral intensity I_0 localised at a distance r from s will be characterised by an intensity at least equal to I_s . In the specific application here considered, the probability function P has been assumed to be

$$P(I \geq I_s | r, I_0) = N(\bar{I}, \sigma^2), \quad (5)$$

where N is the Gaussian distribution and

$$\bar{I} = I_0 - \frac{1}{\ln\psi} \ln \left[1 + \frac{\psi - 1}{\psi_0} \left(\frac{r}{r_0} \right) \right], \quad (6)$$

(Grandori et al., 1987); the parameters ψ , ψ_0 and r_0 of Eq. (6) have been determined for each seismic source by Peruzza (2000); for some of these sources, where available data were not sufficient for a reliable parameterisation of Eq. (5), the form

$$\bar{I} = I_0 - 0.769 + 1.015 r^{1/3}, \quad (7)$$

has been adopted for the average. In all, 58 different attenuation laws have been used. The value of σ in Eq. (5) has been tentatively assumed equal to 0.9 for all the considered attenuation relationships (Peruzza, 2000). In all the cases when epicentral distance was greater than 400 km, $P(I \geq I_s | r, I_0)$ has been assumed equal to zero.

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