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Seismic Hazard Assessment (2003–2009) for the Italian Building Code

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Abstract This paper describes the probabilistic assessment of seismic hazard (PSHA) of Italy in view of the building codes from 2003 to 2009. A code was issued in 2003 as a Prime Minister Ordinance, requiring that a PSHA for updating the seismic zoning would be performed in one year, in terms of horizontal peak ground acceleration (PGA) with 10% probability of exceedance in 50 years on hard ground. For the first time in Italy, a working group, established by the Istituto Nazionale di Geofisica e Vulcanologia, adopted a logic-tree approach to model the epistemic uncertainty in the completeness of the earthquake catalog, the assessment of the seismicity rates and M_{max}, and the ground-motion prediction equations. The seismic hazard has been computed over a grid of more than 16,000 points for the median value (fiftieth percentile) and the eighty-fourth and sixteenth percentiles of the 16 branches of the logic tree. Using the same input model, PGA values and spectral accelerations for 10 spectral periods were computed for nine different probabilities of exceedance in 50 years. This wealth of data made it possible to base the design spectra of a new building code on point hazard data instead of being related to just four zones. The 2009 M_w 6.3 L'Aquila earthquake has led many to attempt to test the reliability of this study. In this paper, we analyze suggestions coming from that event and conclude that significant changes to the design spectra are not to be recommended based just on evidence from the L'Aquila earthquake.

Introduction

The first seismic provisions in Italy were issued in 1909 after the great Messina Straits earthquake, starting a long tradition of countermeasures that were taken after damage had occurred rather than as precautions to prevent damage; after each destructive or damaging event took place, the definition of seismic zones was expanded to include the damaged areas, as is well summarized by De Marco *et al.*, 1999.

The modern era began in 1974 when the building code was updated to reflect the new ideas and findings of the developing seismology and earthquake engineering sciences. However, the relationship between the seismic zoning of the territory and the expected ground shaking remained rather weak. As a matter of fact, the 1974 seismic zoning was still based on previous damage from earthquakes, with some minor adjustments. As a consequence of the 1980 Irpinia–Basilicata earthquake, a new zoning was enforced in 1984, based on a study by Consiglio Nazionale delle Ricerche–Progetto Finalizzato Geodinamica (CNR-PFG; 1980) that combined three elements: (1) a probabilistic seismic hazard assessment (PSHA) performed in 1977; (2) the maximum observed intensities obtained from isoseismal maps of earthquakes that had occurred in the past 800 years; and (3) a risk indicator. In 1999 an *ad hoc* committee proposed a new zoning (Proposta di Riclassificazione del Territorio Nazionale; Gruppo di Lavoro, 1999) that combined: (1) a PSHA (Albarello *et al.*, 2000); (2) maximum observed intensities obtained from earthquake data of the past 800 years (Molin *et al.*, 1996); and (3) Housner intensity values. Nevertheless, this proposal was not adopted, and the 1984 zoning did not change until 2003.

In the aftermath of the 2002 M_w 5.9 San Giuliano di Puglia (southern Italy) earthquake, a new EC8-based building code was established (Prime Minister Ordinance, hereafter 3274/2003 PMO, Italian Official Gazette n. 105 of 08/05/2003). The new code intended four design spectra to be used in four seismic zones (the previous code had only three zones), which were to be assigned on the basis of a modern seismic hazard parameter (horizontal peak ground acceleration, PGA, on hard ground with a 10% probability of exceedance in 50 years) according to Table 1.

The way Table 1 was conceived led to a significant change in seismic design in Italy: for the first time, the seismic zoning covered the entire country, meaning that earthquake hazard needs to be taken into account everywhere, although the design levels are to be anchored to low acceleration

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Table 1
Definition of the Seismic Zones and Related Design Parameters, According to 3274/2003 PMO

Zone	Threshold PGA with 10% Exceedance Probability in 50 Years (*g*)	Anchor Acceleration of the Elastic Design Spectrum (*g*)
1	0.25	0.35
2	0.15	0.25
3	0.05	0.15
4	<0.05	0.05

values in many areas. On the other hand, according to the previous code, two-thirds of the territory did not belong to any seismic zone; those areas were often, wrongly, interpreted as nonseismic, thereby allowing a huge deficit of seismic design to accumulate throughout the years, with buildings being built without the necessary seismic detailing in order to avoid brittle collapse mechanisms from forming.

The application of Table 1 required a national distribution of the horizontal PGA on hard ground with a 10% probability of exceedance in 50 years. As an emergency solution the 3274/2003 PMO adopted the zoning supplied by the Proposta di Riclassificazione del Territorio Nazionale (Gruppo di Lavoro, 1999), which had gathered sufficient consensus at the time. However, this was zonation, not a true PSHA; therefore, the 3274/2003 PMO also required a new PSHA, complying with specific requirements, to be released within one year. Such a PSHA was compiled by a working group established by the Istituto Nazionale di Geofisica e Vulcanologia (INGV); a board, including European expert seismologists and earthquake engineers, was appointed to review the process.

The scope of this paper is to explain the approach followed by this PSHA and to offer insight into the logical process that led to some of our choices. The paper also describes the compilation of the new seismic hazard database that inspired the new Italian building code. Finally, a brief analysis of the seismic input to the code is made in light of the 2009 L'Aquila earthquake; the first destructive earthquake after the release of the new building code.

The INGV PSHA Project

State-of-the-Art in 2003

The first Cornell–McGuire type PSHA was performed in Italy in 1996 (Slejko *et al.*, 1998), based on a seismic source zone model (ZS4; Meletti *et al.*, 2000) and an earthquake catalog (NT4.1; Camassi and Stucchi, 1997), specifically designed for seismic hazard analysis. The ground-motion prediction equation by Ambraseys (1995), valid for Europe, was adopted. The computer code SEISRISK III (Bender and Perkins, 1987) was used; the results were given in terms of PGA and macroseismic intensity with a 10% of probability of exceedance in 50 years.

A few years later, a working group produced the so-called consensus map (Albarello *et al.*, 2000) to serve as a basis for updating the seismic zoning (the Proposta di Riclassificazione del Territorio Nazionale; Gruppo di Lavoro, 1999). The main difference with respect to the Slejko *et al.* (1998) map was the introduction of two equally weighted ground-motion prediction equations: Ambraseys *et al.* (1996, valid for Europe) and Sabetta and Pugliese (1996, valid for Italy). Romeo and Pugliese (2000) computed PSHA using a catalog that merged the NT4.1 catalog with instrumental earthquakes above M 4.6 from the Istituto Nazionale di Geofisica catalog 1981–1996. They chose the Sabetta and Pugliese (1996) relationship to compute peak ground acceleration, peak ground velocity, and spectral ordinates with a 10% probability of exceedance in 50 years.

The conventional probabilistic methodology and the data used by Slejko *et al.* (1998) were also used within the Global Seismic Hazard Assessment Program (GSHAP Giardini, 1999) to compute seismic hazard for the Adriatic region (Adria test area, Slejko *et al.*, 1999). The main difference was that GSHAP used just the Ambraseys *et al.* (1996) ground-motion prediction equation.

The site effects assessment using ambient excitations (SESAME) project (Jiménez *et al.*, 2001) performed seismic hazard assessment of the Mediterranean area using a unified seismic source model. The input data used in the assessment were the same as in the GSHAP model, but the source zone model ZS4 was modified in the border regions to be compatible with the source zones of the neighboring countries.

In 2003 these studies could not be considered up-to-date. The source zone model had turned out to be inconsistent with the most recent geological interpretations, such as the Database of Individual Seismogenic Sources (DISS 2.0, Valensise and Pantosti, 2001). The Catalogo Parametrico dei Terremoti Italiani CPTI99 earthquake catalog (Gruppo di Lavoro CPTI, 1999) and its predecessor NT4.1 (Camassi and Stucchi, 1997) did not contain the results of the historical investigation performed after 1997. The ground-motion prediction equations were in some cases not compatible with the magnitudes given by the earthquake catalogs. A new PSHA, based on updated data, was thus necessary.

The Approach

To accomplish the task of compiling a PSHA matching the 3274/2003 PMO requirements within one year, the INGV working group decided: (1) to follow a conventional PSHA scheme, in which the seismicity is uniformly distributed in each seismic source zone and the earthquake recurrence model follows a Poissonian distribution; (2) to use new input data, such as a new source zone model and a new earthquake catalog with new completeness time-intervals; and (3) to use the computer code SEISRISK III (Bender and Perkins, 1987).

The rationale for following a conventional PSHA scheme and using a commonly adopted software is that they had been (and still are) used in a number of similar projects in Italy; therefore, their limits and advantages are well known, and they allow a comparison with previous seismic hazard estimates that were performed with the aim of improving the seismic zoning.

It also has to be considered that Italy is a country where earthquakes exceeding M_w 7.5 have never been reported; on the other hand, M_w 6 events happen every 12 years, on average, and moderate or even small events ($M_w < 5$) can cause significant damage. If we select the intensity data points (IDPs) of the earthquakes after 1950 from the Italian Database of Macroseismic Intensities (DBMI04, Stucchi *et al.*, 2007), we find that about 51 well-documented earthquakes with $M_w < 5$ have caused damage (Mercalli–Cancani–Sieberg intensity ranges of $8 \geq I_{MCS} \geq 5$–6; Fig. 1), compared to about 59 earthquakes with $M_w \geq 5$ in the same time window. The damage is located in areas that, in the last 60 years, were both covered (such as the Apenninic areas) and not covered (such as most of northern Italy) by building codes. This suggests that any seismic hazard analysis aiming at risk assessment in Italy must not ignore low-energy events.

After a preliminary assessment in the fall of 2003 and the subsequent review, we decided to use a logic-tree approach to account for some sources of epistemic uncertainty, as in the most advanced examples at the time (amongst many others, Frankel *et al.*, 2002, for the United States of America, and Giardini *et al.*, 2004, for Switzerland). It was agreed that only one branch would be used for the earthquake source model and only one branch for the Catalogo Parametrico dei Terremoti Italiani earthquake catalog; the two selected items, ZS9 (Meletti *et al.*, 2008) and CPTI04 (Gruppo di Lavoro CPTI, 2004) have been compiled in strict relation to each other. Possible alternatives to ZS9 and CPTI04 are discussed in the next section (The Seismic Source Characterization).

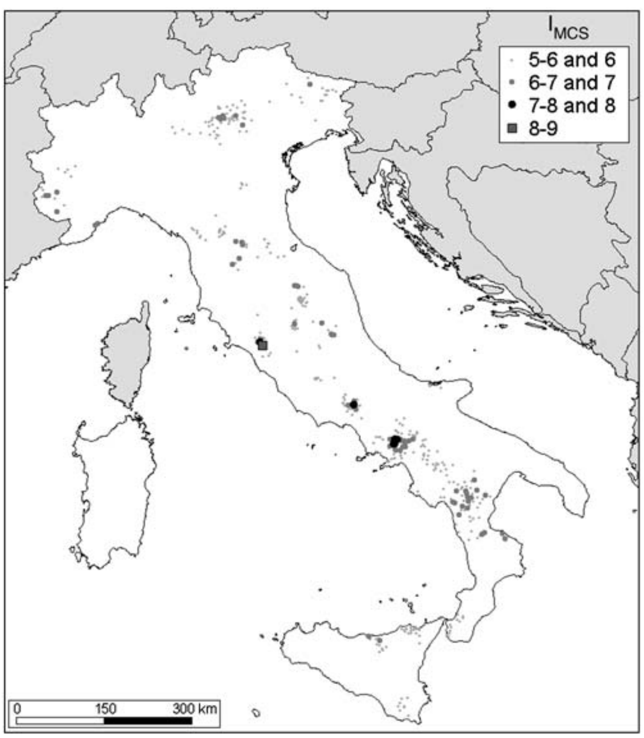

Figure 1. Damaged localities ($I_{MCS} \geq 5$–6) for well-documented $M_w < 5.0$ earthquakes after 1950.

As diagrammed in Figure 2, we then decided to explore the epistemic uncertainty related to the completeness of the earthquake catalog (two branches: mainly historical and mainly statistical); the assessment of the seismicity rates and M_{max} (two branches representing (1) activity rates and M_{max} observed from the catalog and from geological evidence and (2) Gutenberg–Richter (G-R) rates and M_{max} from conservative assumptions); and the ground-motion prediction equations (GMPEs: four branches).

We will discuss the input elements that correspond to the branches of the logic tree, with special reference to the seismic source characterization. The seismic source zone model (ZS9; Meletti *et al.*, 2008) and the ground-motion characterization (Montaldo *et al.*, 2005) have already been described in detail in the cited papers and will only be briefly summarized.

The Seismic Source Characterization

The Earthquake Source Model

The earthquake source zone model ZS9 (Meletti *et al.*, 2008) divides the Italian territory into 36 seismic source zones, covering the most seismically active areas of the country (Fig. 3). Three zones, 922, 928, and 936 are of volcanic nature, requiring *ad hoc* characterization, and are described in the following sections. Six more zones, mostly located in neighboring countries or offshore, have been designed (Fig. 3, indicated with letters), but their contribution to the seismic hazard in mainland Italy has been found to be negligible. The same holds for the background areas. There are no gaps between adjacent zones. ZS9 covers 56% of the

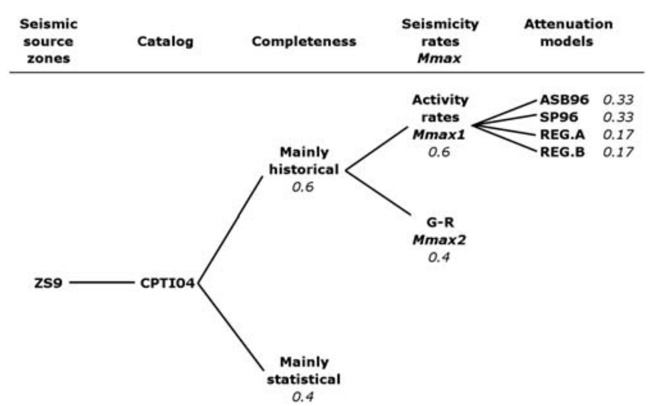

Figure 2. The logic-tree scheme adopted in this study. Numbers in italics represent weights: ZS9, Italian source zone model (Meletti *et al.*, 2008); CPTI04, Catalogo Parametrico dei Terremoti Italiani CPTI04 catalog (Gruppo di Lavoro CPTI, 2004); G-R, Gutenberg–Richter rates; ASB96 (Ambraseys *et al.*, 1996); SP96 (Sabetta and Pugliese, 1996); REG.A and REG.B, two combinations of the regionalized GMPEs (for details, see section Ground-Motion Characterization).

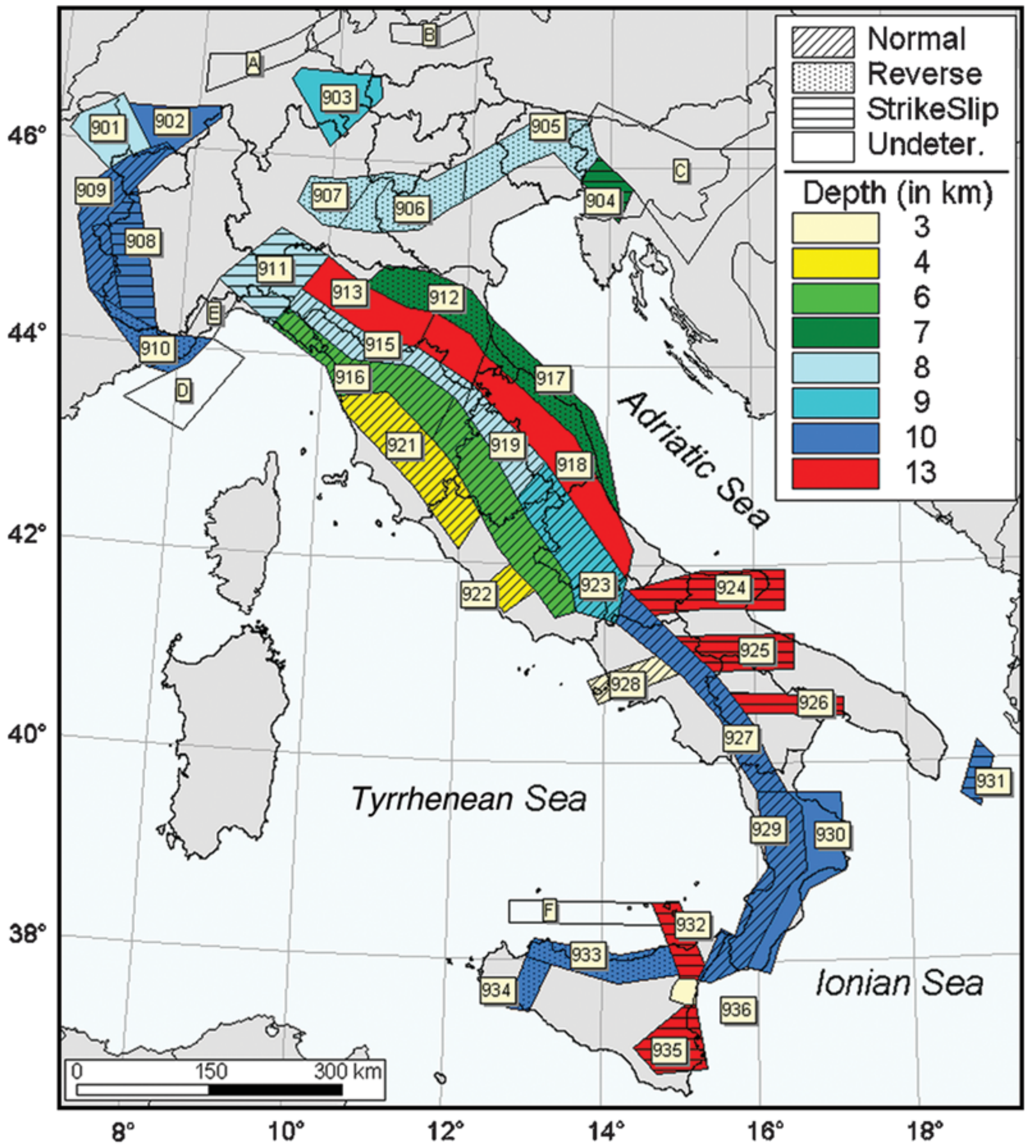

Figure 3. ZS9 source zone model (redrawn from Meletti *et al.*, 2008). The numbers in the boxes identify the earthquake source zones; the colors refer to the mean seismogenic depth (in km); the superimposed shadings refer to the predominant focal mechanism. The source zones with letters were not used in the assessment.

territory: the areas not covered by zones are considered as background. For a few areas, like Sardinia and most of the minor islands, *ad hoc* solutions have been adopted (see the Seismic Hazard Computation and Application section).

ZS9 derives from the previous ZS4 model (Meletti *et al.*, 2000) through a process that upgraded the design of the zones according to the available geological and seismological information. The ZS9 model is consistent with (1) the most recent active tectonic studies available in 2003; (2) the SESAME source zones (Jiménez *et al.*, 2001) in the border regions; and (3) the Italian earthquake catalog CPTI04 (Gruppo di Lavoro CPTI, 2004).

ZS9 model contains several parameters describing the characteristics of the source zones that are useful for the fine tuning of the PSHA and particularly for the application of ground-motion predictive relationships, such as the estimate of the main seismogenic layer (in terms of mean depth of the main earthquakes), the predominant focal mechanism (the most probable rupture mechanism for the main earthquakes), and the uncertainty of the boundaries. A summary table is available in Meletti *et al.* (2008); the way they are used for the application of ground-motion predictive relationships is described in the Ground-Motion Characterization section.

It has been argued that one source model does not account for all epistemic uncertainties. In principle, at least three alternatives could have been used: (1) the smoothed seismicity approach (Frankel, 1995), (2) a seismic source model different from ZS9, or (3) the seismogenic sources from the Database of Individual Seismogenic Sources (DISS version 2.0, or DISS 2.0; Valensise and Pantosti, 2001).

For alternative (1), the smoothed seismicity approach (Frankel, 1995) has been developed to prevent the subjectivity involved in the design of source zones. It is based on the use of the earthquake catalog and relies upon the assumption that future earthquakes will occur where past seismicity is located. We believe that this assumption is not valid in Italy because geological data indicate that the average recurrence time for large earthquakes is sometimes significantly longer than the time window covered by the earthquake catalog. Therefore, many important earthquakes may be missing.

For alternative (2), it has been suggested that the old ZS4 zonation should be used instead of ZS9; the idea was disregarded because ZS9 represented an evolution of ZS4 and was conceived in strict relationship with the CPTI04 catalog, described in the Earthquake Catalog section. For alternative (3), the direct use of seismogenic sources provided by DISS 2.0 was not believed to be viable at that time because the mapping of the seismogenic sources was—and still is—incomplete and affected by large uncertainties. The so-called composite seismogenic areas, newly introduced in the recent version of the DISS database (Basili *et al.*, 2008), could provide an interesting alternative to be explored in future Italian seismic hazard assessments.

In conclusion, the adopted strategy was a compromise between various views concerning geometry and the seismogenic role of each seismic source zone and to combine geologic evidence with cautionary considerations with the aim of defining a consensus model. Therefore, the final geometry of some zones does not correspond to a single fault system but to a more conservative combination of large earthquakes and seismogenic faults. As an example, in source zone 935 (eastern Sicily), the identification of the causative fault of one of the largest earthquakes of Italian seismic history (11 January 1693) is still a subject of debate within the scientific community; the proposed shape represents a compromise of varied opinions (see discussion in Meletti *et al.*, 2008). In a similar way, zone 933 contains some historical events that could, in principle, be assigned to the F zone; the decision was to keep the actual location and magnitude as provided by the catalog as a sort of conservative inland mirror of possibly more distant, albeit larger, earthquakes (Meletti *et al.*, 2008). Such earthquakes are therefore added to zone 933, which in turn represents a conservative model closer to settlements and infrastructures.

Earthquake Catalog

The CPTI04 catalog (Gruppo di Lavoro CPTI, 2004) was prepared especially for this project; it is strictly correlated with ZS9, as the location of the main events, together with the position of the main seismogenic faults, have contributed to the design of ZS9. CPTI04 represents an updated version of CPTI99 (Gruppo di Lavoro CPTI, 1999) in which the time window 1981–1992 has been recompiled, the time window 1993–2002 has been compiled for the first time, and values of M_w and M_S have been determined homogeneously for all events (Gasperini *et al.*, 2004).

For the compilations of time windows 1981–1992 and 1993–2002, both macroseismic and instrumental data have been considered. When available, macroseismic determinations have been preferred in order to be more consistent with the historical earthquakes. For magnitudes, values have been completely reassessed from CPTI99, after calibrating new empirical relations among M_w, M_S, m_b, and M_L, using a dataset of instrumental magnitudes and scalar seismic moments of Italian earthquakes obtained from varied sources (Ambraseys, 1990; Margottini *et al.*, 1993; Gasperini, 2002; Pondrelli *et al.*, 2002; and from the Global (formerly Harvard) CMT and the National Earthquake Information Center (NEIC)–Preliminary Determination of Epicenters (see Data and Resources section). In a similar way, M_w and related uncertainty have been assessed from the M_S-equivalent values of CPTI99 for all historical events.

The definition of the magnitude bins is a crucial, technical aspect with direct consequences for the determination of the seismic rates: it has to accommodate the data sample features with the technical requirements of the adopted software for PSHA. Moreover, it must avoid having too narrow bins because a consistent portion of M_w values come from I_o conversion and, therefore, are not uniformly distributed.

The software adopted for this study (SEISRISK III, Bender and Perkins, 1987) accepts as input the seismicity rates for up to 12 equally spaced magnitude bins. Figure 4 shows the occurrence of events for each M_w value. Some classes are very populated (M_w 4.83, 5.03, and 5.17, among others) because the relevant values are derived by epicentral intensities (I_o 6, 6–7, 7 MCS) of historical earthquakes. The most suitable way to avoid anomalous distributions in the bins was to adopt M_w intervals equal to 0.23, positioning the first bin center at 4.76 (Fig. 4). These bins identify the magnitude classes adopted in all the following elaborations.

In order to properly consider the specific characteristics of the volcanic source zones, we adopted M_w 4.3 as the lower threshold for those source zones, that is, two bins lower than for the other zones.

Catalog Completeness

PSHA is commonly computed from seismicity rates (see Maximum Magnitude) determined from a portion of the catalog that, in order to have those rates representative of a true seismicity pattern, is considered not to be influenced by gaps in the dataset. The assessment of the completeness of the catalog is, therefore, a key issue in PSHA, particularly for the preinstrumental portion of the catalogs. Current approaches are mostly based on the assumption that seismicity is stationary over a large area (i.e., on the assumption that the seismicity sample provided by a reasonably long time window is representative of the even longer one desirable for PSHA).

The way areas are selected is also important: they often coincide with countries, although a country may encompass

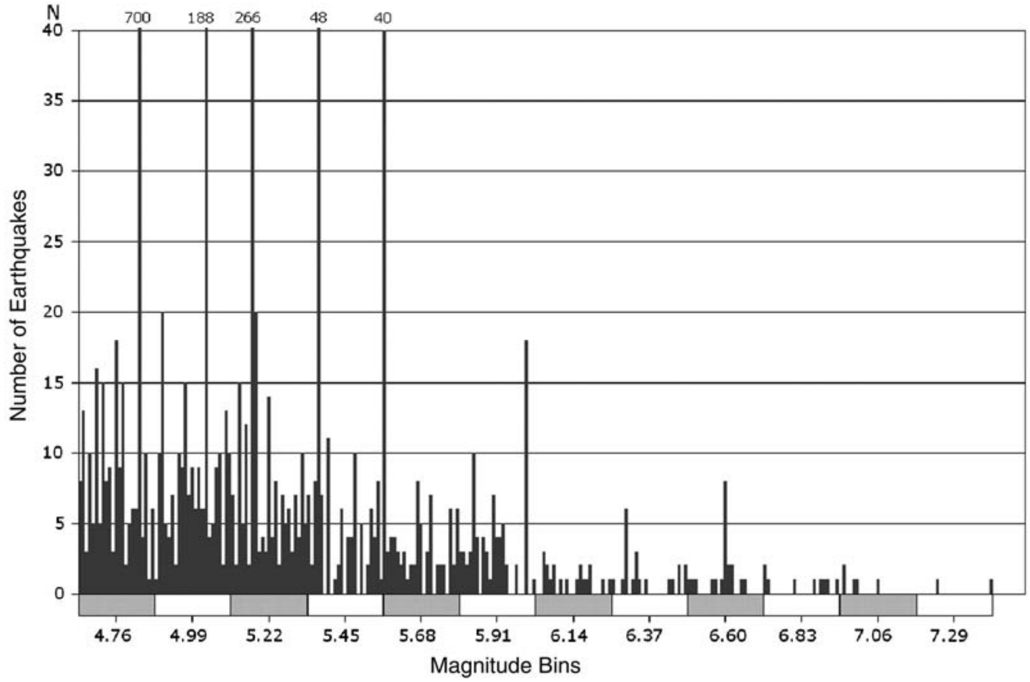

Figure 4. Number of earthquakes in CPTI04 catalog per 0.01 magnitude value. The lower bar with gray and white sectors represents the 0.23-unit-wide magnitude bins adopted in this study.

different seismic regions. As an example, Figure 5 shows that the temporal pattern of earthquakes $M_w \geq 6$ in CPTI04 differs in northern, central, and southern Italy (including Sicily). In terms of the occurrence of strong earthquakes, the seismicity in the south is higher but practically unknown before 1450; the seismicity of the north and the center shows less variation with time. Choosing 1600 as the start of the complete window for all of Italy, as in Figure 5c, may lead to inconsistencies; therefore, we prefer to assess it on a regional basis.

In addition, current methods use statistical procedures to assess catalog completeness; that is, they look inside the available data and their pattern. On the other hand, the reasons why an event is inserted into a catalog depend on whether someone wrote about it, whether such historical records have been preserved, and whether they have been later found and well interpreted. In other words, the factors affecting the number of earthquakes that may have escaped our catalogs are to be found outside the earthquake data themselves, an analogy to what happens in a seismic network where the technical notes on installation, working problems, and so on give us information on the time period during which the station was properly working. We have no means to estimate how many events of M_w 4 may have escaped our historical records, say in northern Italy from the year 1000 to 1400. However, for earthquakes of destructive capacity (in Italy with $M_w \geq 5.8$), the impact of which severely affects a region for many years, we can use considerations regarding the production, preservation, and investigation of historical sources to assess, for instance, whether in a given time window we do not find events because they most probably did not happen (instead of merely being overlooked because our time history is not complete). Today, a simple and ready-to-use historical approach to completeness assessment is not available; however, some considerations and attempts are known (Agnew, 1991; Gouin, 2001; Musson *et al.*, 2001; Swiss Seismological Service, 2002; etc.).

In this research we assess completeness, adopting two alternative methods (corresponding to two branches of the logic tree in Fig. 2) that are defined as "mainly historical" and "mainly statistical."

The basic concept for the first method is to use the historical sources of selected localities as recording systems, the analysis of which may cast light on which time windows can be considered complete for earthquake records of varying size. The methodological background is found in Stucchi *et al.* (2004).

The result of this analysis provides the completeness starting year for a given intensity I at the investigated place; this result can be interpreted as the completeness starting year for an event with its epicenter at the same place, epicentral intensity $I_o = I$, and M_w derived from I_o. The method used in the second branch is based on the exploration of the seismicity pattern around one place, using a varied sampling radius (generally 50–200 km). The output is given in terms of the starting year of the completeness for a given M_w located at that place. The method, described by Albarello *et al.* (2001), also supplies an uncertainty estimate.

While the second method can be applied at any place, the first one requires complex and unrewarding historical investigation of each recording place. If the historical sources describe other facts and the life of the place does not seem perturbed (as it usually is when an earthquake strikes), one

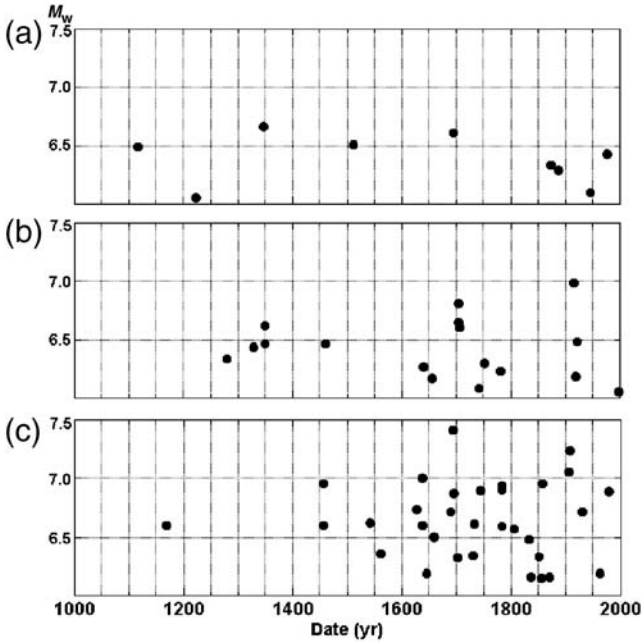

Figure 5. Time distribution of the events with $M_w \geq 6$ in the three regions of study: (a) northern Italy; (b) central Italy; and (c) southern Italy.

Figure 6. Localities where the completeness was assessed according to historical considerations (stars; lettered abbreviations indicate location names) and the statistical approach (dots). Macrozones for extrapolation are shown in color (gray, Alps; dark orange, Po Plain; light orange, central Italy; blue, southern Italy; green, Sicily).

also has to go through the historical records of the time windows where no events are listed in the catalog to be sure, from indirect evidence, that no earthquake effect actually happened. This can be inferred from the fact that the historical sources describe other facts and the life of the place does not seem perturbed as usually happens when an earthquake strikes.

In all, the historical assessment was available for only 18 localities, while the statistical assessment was performed for about 30 locations (Fig. 6). It was therefore necessary to extrapolate the available results to the source zones, using expert considerations. The extrapolation was made with reference to five composite zones considered homogeneous from the point of view of historical tradition.

The historical assessments and the results of the extrapolation are shown in Figure 7 for the M_w class 5.68 ± 0.115; the statistical ones, for the same M_w class, are given in Figure 8. In both figures, the earthquakes in that magnitude bin for each source zone are also shown.

The whole set of completeness starting year (historical approach) for all source zones and M_w bins is presented in Table 2. Figure 9 presents a comparison of the average completeness starting years obtained with the two approaches in the five macrozones of Figure 6.

Maximum Magnitude

Contrary to low-seismicity areas, in many source zones of Italy, M_{max} is well-constrained by available historical and geological knowledge that we consider to be close to complete information. For this reason, we preferred to use observed data with respect to magnitudes derived from statistical approaches and handle the uncertainty of observed magnitude by defining two sets of maximum magnitudes, called $M_{w\,max\,1}$ and $M_{w\,max\,2}$, for each source zone.

In the first set ($M_{w\,max\,1}$), the maximum magnitude has been defined as the maximum between the magnitude bin to which the maximum historical earthquake belongs and the magnitude bin of the earthquake associated with an individual seismogenic source from the database of seismogenic sources (DISS, Valensise and Pantosti, 2001). The second set ($M_{w\,max\,2}$) is similar to $M_{w\,max\,1}$, except a more conservative assumption was adopted; in this case, the maximum magnitude should be at least M_w 6.14 ± 0.115 all over the territory, except in the volcanic areas.

Figure 10 shows the adopted $M_{w\,max\,1}$ and $M_{w\,max\,2}$ values in each source zone, in comparison with the maximum M_w values from the catalog and geological data. The geological value is higher than the catalog value in three zones: 907, 912, and 917. If the $M_{w\,max}$ was close to the upper limit of a bin, for cautionary considerations it was increased to the upper bin limit; in such a way there has been a slight increase for about 20% of the zones. The source zones in which M_w values have been increased with respect to the observed values and the relevant increases are shown in Figure 11.

Seismicity Rates

SEISRISK III (Bender and Perkins, 1987) accepts seismicity rates up to 12 magnitude bins as input for the

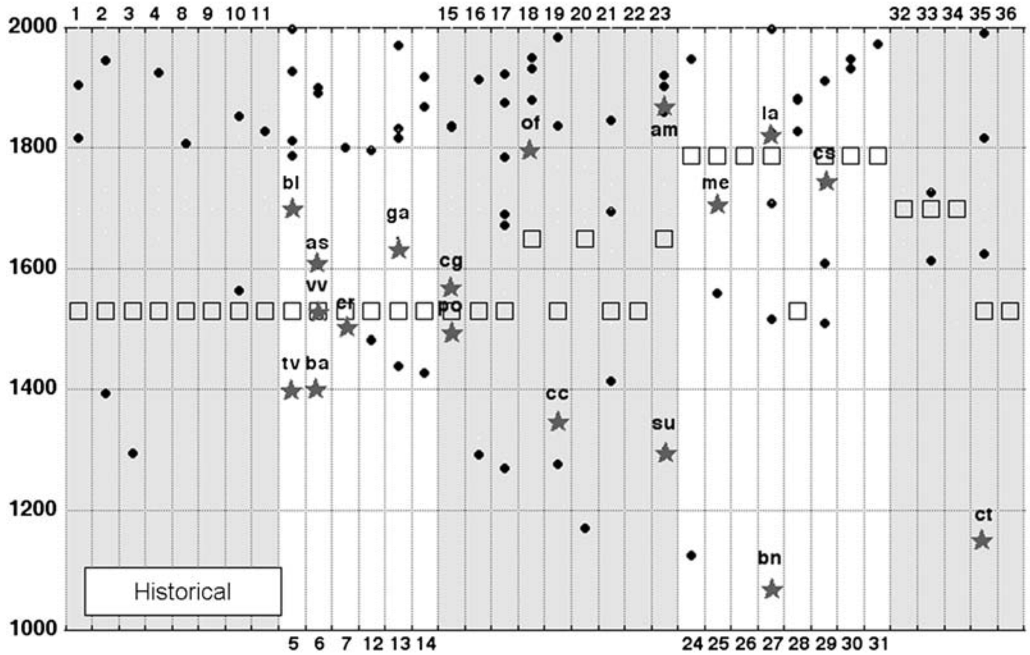

Figure 7. Starting year of the historical completeness assessment of events in the M_w 5.68 bin for the sample localities (stars) and for the source zone (open squares). Black dots represent the earthquakes in the M_w bin. Source zones are grouped according the macrozones of Figure 6; letters are location names as defined in Figure 6.

computation. Our first choice, corresponding to one branch in the logic tree, are the so-called activity rates (AR), which are the rates in each magnitude bin as estimated independently from the number of earthquakes in the complete portion of the catalog. ARs have been determined independently for each source zone. The other branch in the logic tree corresponds to a standard G-R distribution (Gutenberg and Richter, 1944). Similarly to the AR case, the G-R seismicity rates are computed independently in each source zone.

The scientific debate about the assessment of the b-value is in progress, and opinions about b-values that are fixed and equal to 1 (Kagan, 2002) are faced with evidence of a

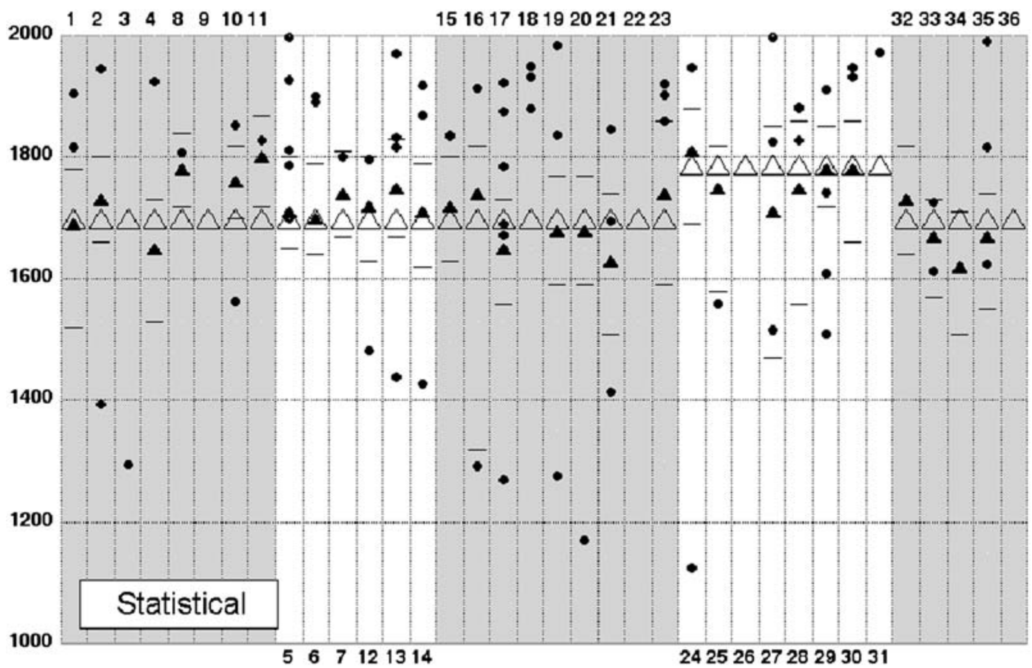

Figure 8. Starting year of the statistical completeness assessment of events in the M_w 5.68 bin for the sample localities (black triangles, with uncertainty represented by bars) and for the source zones (open triangles). Black dots represent the earthquakes in the M_w bin. Source zones are grouped according to the macrozones of Figure 6.

Table 2
Completeness Starting Year (Historical Approach) for All Source Zones and M_w Bins

	M_w Bins											
Source Zone	7.29	7.06	6.83	6.60	6.37	6.14	5.91	5.68	5.45	5.22	4.99	4.76
Alps												
901	1300	1300	1300	1300	1300	1300	1530	1530	1700	1700	1871	1871
902	1300	1300	1300	1300	1300	1300	1530	1530	1700	1700	1871	1871
903	1300	1300	1300	1300	1300	1300	1530	1530	1700	1700	1871	1871
904	1300	1300	1300	1300	1300	1300	1530	1530	1700	1700	1871	1871
908	1300	1300	1300	1300	1300	1300	1530	1530	1700	1700	1871	1871
909	1300	1300	1300	1300	1300	1300	1530	1530	1700	1700	1871	1871
910	1300	1300	1300	1300	1300	1300	1530	1530	1700	1700	1871	1871
911	1300	1300	1300	1300	1300	1300	1530	1530	1700	1700	1871	1871
Po Plain												
905	1100	1100	1100	1100	1100	1300	1300	1530	1530	1530	1836	1836
906	1100	1100	1100	1100	1100	1300	1300	1530	1530	1530	1836	1836
907	1100	1100	1100	1100	1100	1300	1300	1530	1530	1530	1836	1836
912	1100	1100	1100	1100	1100	1300	1300	1530	1530	1530	1836	1836
913	1100	1100	1100	1100	1100	1300	1300	1530	1530	1530	1836	1836
914	1100	1100	1100	1100	1100	1300	1300	1530	1530	1530	1836	1836
Central Italy												
915	1300	1300	1300	1300	1300	1300	1530	1530	1650	1650	1871	1871
916	1200	1200	1200	1200	1200	1300	1300	1530	1530	1530	1871	1871
917	1200	1200	1200	1200	1200	1530	1530	1530	1650	1650	1836	1836
918	1300	1300	1300	1300	1300	1530	1530	1650	1650	1650	1871	1871
919	1200	1200	1200	1200	1200	1300	1300	1530	1530	1530	1871	1871
920	1200	1200	1200	1200	1300	1300	1300	1650	1650	1650	1871	1871
921	1200	1200	1200	1200	1200	1300	1300	1530	1530	1530	1871	1871
922	1200	1200	1200	1200	1200	1300	1300	1530	1530	1530	1871	1871
923	1300	1300	1300	1300	1300	1530	1530	1650	1650	1650	1871	1871
Southern Italy												
924	1400	1400	1400	1400	1400	1530	1530	1787	1787	1787	1871	1871
925	1400	1400	1400	1400	1400	1530	1530	1787	1787	1787	1871	1871
926	1400	1400	1400	1400	1400	1530	1530	1787	1787	1787	1871	1871
927	1400	1400	1400	1400	1530	1530	1530	1787	1787	1787	1895	1895
928	1300	1300	1300	1300	1300	1300	1530	1530	1787	1787	1871	1871
929	1400	1400	1400	1400	1530	1530	1787	1787	1787	1787	1895	1895
930	1400	1400	1400	1400	1530	1530	1787	1787	1787	1787	1895	1895
931	1530	1530	1530	1530	1530	1530	1787	1787	1787	1950	1950	1950
Sicily												
932	1300	1300	1300	1300	1300	1530	1530	1700	1700	1700	1895	1895
933	1300	1300	1300	1300	1300	1530	1530	1700	1700	1700	1871	1871
934	1300	1300	1300	1300	1300	1530	1530	1700	1700	1700	1895	1895
935	1150	1150	1150	1150	1150	1530	1530	1530	1700	1700	1871	1871
936	1150	1150	1150	1150	1150	1530	1530	1530	1700	1700	1871	1871

spatiotemporal variation of b-values (among others, Lomnitz-Adler, 1992; Pacheco *et al.* 1992; Shanker and Sharma, 1998). The choice of allowing the b-value to vary from region to region has been adopted after considering the evidence supplied by the catalog data. Source zones are characterized by different geological and seismological behavior, the seismicity being considered homogeneous within the source boundaries but different from neighboring zones. It is hence admissible that the b-value varies among the zones, as this reflects different seismological behaviors; for instance, source zones in southern Italy are generally characterized by lower than unity b-values, which account for a relatively large number of strong events with respect to the smaller ones. On the contrary, source zones in the north, or more general in areas of low seismicity, show b-values greater than one. Volcanic source zones, which are very small territories surrounding the volcanic edifice, represent the extreme case, with b-values around 2, which is not unusual in these particular zones.

The lowest M_w bin, centered around M_w 4.76, in many cases shows a higher number of events with respect to what the G-R distribution would suggest. This is probably due to the fact that this M_w value corresponds to $I_o = 6$; such value was often assigned as a conservative assessment of scant information in former Italian catalogs, mostly compiled in the frame of nuclear power plant projects, upon which the

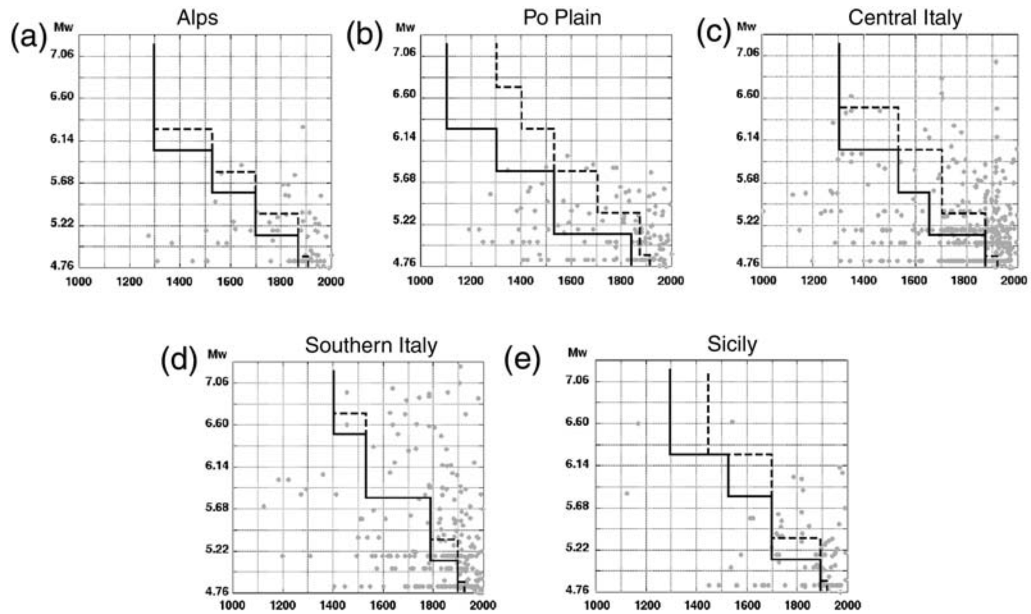

Figure 9. Average completeness starting years of the historical (solid line) and statistical (dashed line) approach for varied M_ws in the five macrozones of Figure 6. Gray dots represent earthquakes.

CPTI04 is still partly based. The recent reappraisal of the Italian historical data was mostly devoted to large and moderate events; therefore, many $I_o = 6$ events survive in the CPTI04. A recent study on small-sized events (Molin *et al.*, 2008) will feed the next CPTI version.

We computed the b-values using a least-squares fit of the AR values instead of a maximum likelihood method because it allowed us to reduce the impact of this unusually high number of small earthquakes and therefore to obtain a better estimate of the actual seismicity rates. For completeness reasons, our G-R relations have been truncated at a minimum magnitude of M_w 4.76 ± 0.115 and at maximum magnitude that varies depending on the source zone, as discussed previously in this section. Figure 12 show some cases related to the mainly historical completeness assessment.

In order to keep the G-R branches balanced with the AR branches, the a-values have been fixed to be equal to the cumulative number of events in the source zone, which is equal to the corresponding a-values of the AR branches. In such a way, we assume that the total number of events is always the same. The only exception is source zone 927, for which the difference between the fitted a-value and the one from the AR branch was very large (Fig. 12); in this case, we selected the fitted a-value.

The rates assigned to M_{max} derive from either the catalog or DISS 2.0 data, when available, or they are computed from the G-R distribution.

A Sanity Check

In order to test the reliability of the computed seismicity rates with respect to the observed ones, we compare the cumulative number of events inside the source zones per magnitude bin of (1) the CPTI04 earthquake catalog with

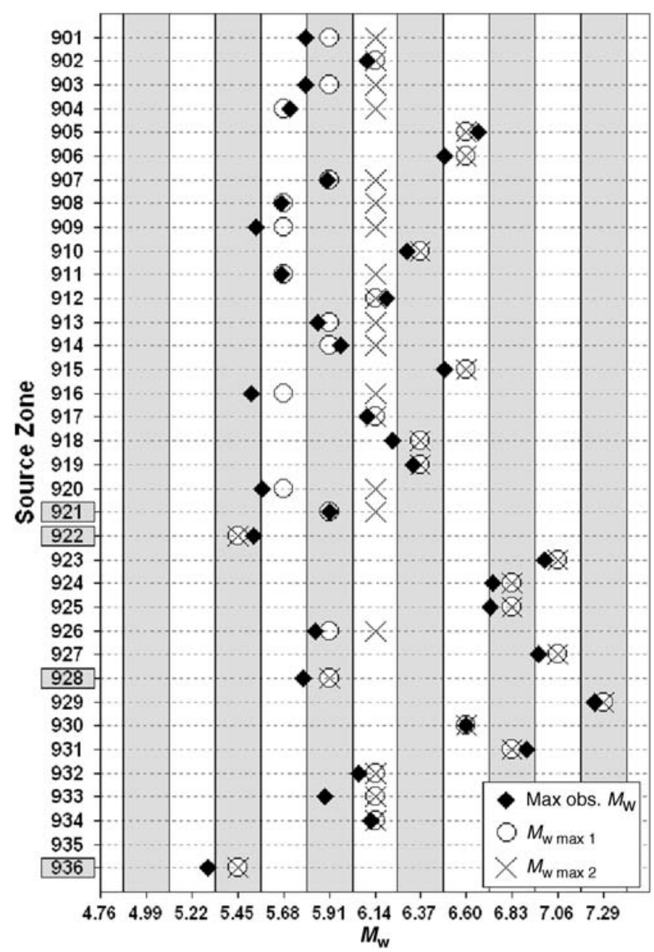

Figure 10. Maximum magnitude values adopted for each source zone, compared with the observed $M_{w\,max}$. Volcanic source zones are identified by gray rectangles around their numbers.

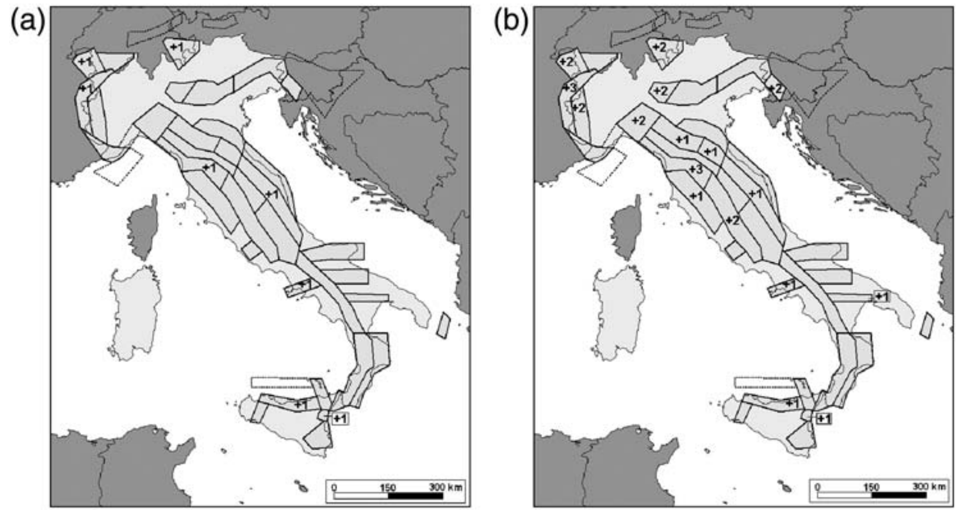

Figure 11. Number of M_w bins (1 bin = 0.23 unit) added with respect to the maximum observed magnitude: (a) $M_{max\,1}$ and (b) $M_{max\,2}$.

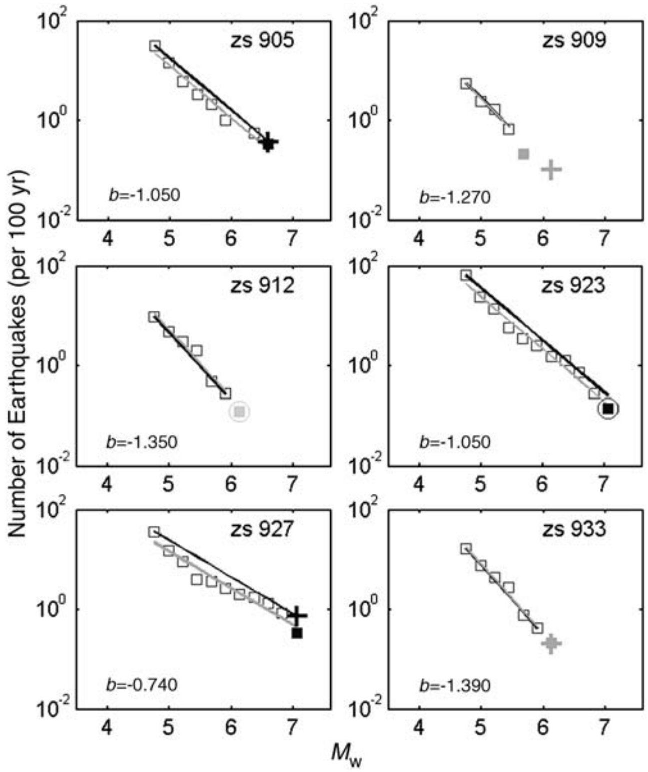

Figure 12. Comparison between activity rates (AR, open squares), G-R rates (gray lines, obtained by fit), and G-R rates anchored to total number of events (black lines) for some seismic source zones, computed using the historical completeness. The *b*-value is also reported for each source zone; zone numbers are included in the top right of each graph. In the AR branches, the adopted rates for M_{max} are estimated from the catalog (black square), from geologic information (light gray squares, in zs 912), and from imposed M_{max} (dark gray squares). In the G-R branches, the adopted rates for M_{max} are estimated from the G-R distribution in the case of the observed M_{max} (black cross), from the G-R distribution in the case of imposed M_{max} (gray cross), and from the AR branches when geological data are available (light gray circle, in zs 912) or in case the G-R distribution foresees too high of a rate (black circle).

$M_w \geq 4.76$, which contains a little more than 1500 earthquakes over 1000 years, (2) the seismicity model obtained by projecting the AR rates obtained from historical completeness over 1000 years, and (3) the seismicity model obtained by projecting the G-R rates obtained from historical completeness over 1000 years (Fig. 13). The AR and G-R seismicity models provide far more events than CPTI04 does; this could be explained by the fact that the rates are determined over a presumed complete period and, therefore, account for the presumed missing events in the incomplete part of the catalog. However, if we compare the number of events in the M_w bins $\geq$6.15 in 1000 years, we obtain 64 for CPTI04, 102 for the AR model, and 149 for the G-R model. As a consequence, the missing earthquakes should be 38 (102 − 64) in the AR case (which is more than 50% of the CPTI04 content) or 85 (149 − 64) in the G-R case (about 120% of it). These numbers appear high: according to historical considerations, we do not believe that the catalog can be incomplete for such a large number of destructive events. Looking in detail, the 38 and the 85 presumed missing events are not regularly distributed among the source zones (Fig. 14): they show a high concentration in four source zones (905, 923, 927, and 929), which sum up to 24 (AR model, 63%) and 45 (G-R model, 52%) missing events, respectively. In these zones, both seismicity models seem strongly determined by the recent activity. Although the rates may appear overestimated with respect to a time window of 1000 years, they may represent a possible evidence of seismicity clustering and, therefore, better represent the recent and future seismic activity. In addition, most of the gaps between the AR and G-R models in the source zones 905, 923, 929, and 935 (Fig. 14) are explained by the choice of keeping the G-R models balanced with the AR ones.

It is worth noting that the same comparison, performed on the seismicity models obtained from the statistical completeness, show the same features, although the gaps among the catalog and the seismicity models are slightly larger.

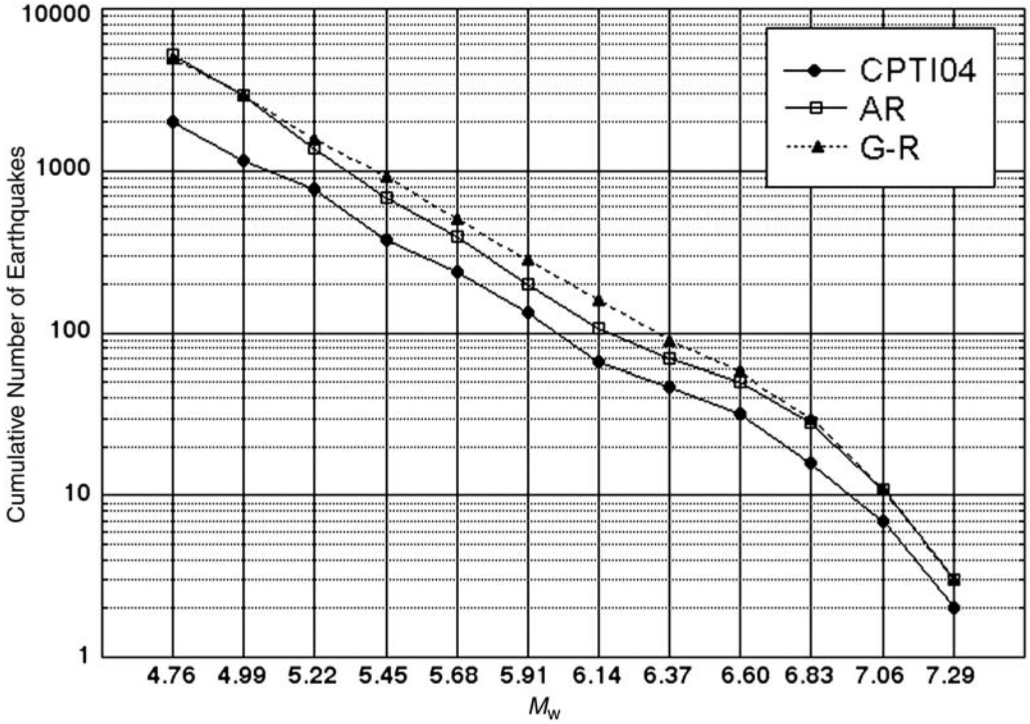

Figure 13. Comparison between the cumulative number of earthquakes inside the source zones per magnitude bin from the CPTI04 catalog (solid line, black dots), with the cumulative numbers obtained by extrapolating the seismicity rates AR (solid, thin line, empty squares) and G-R rates (dashed line, black triangles) for a 1000-year interval.

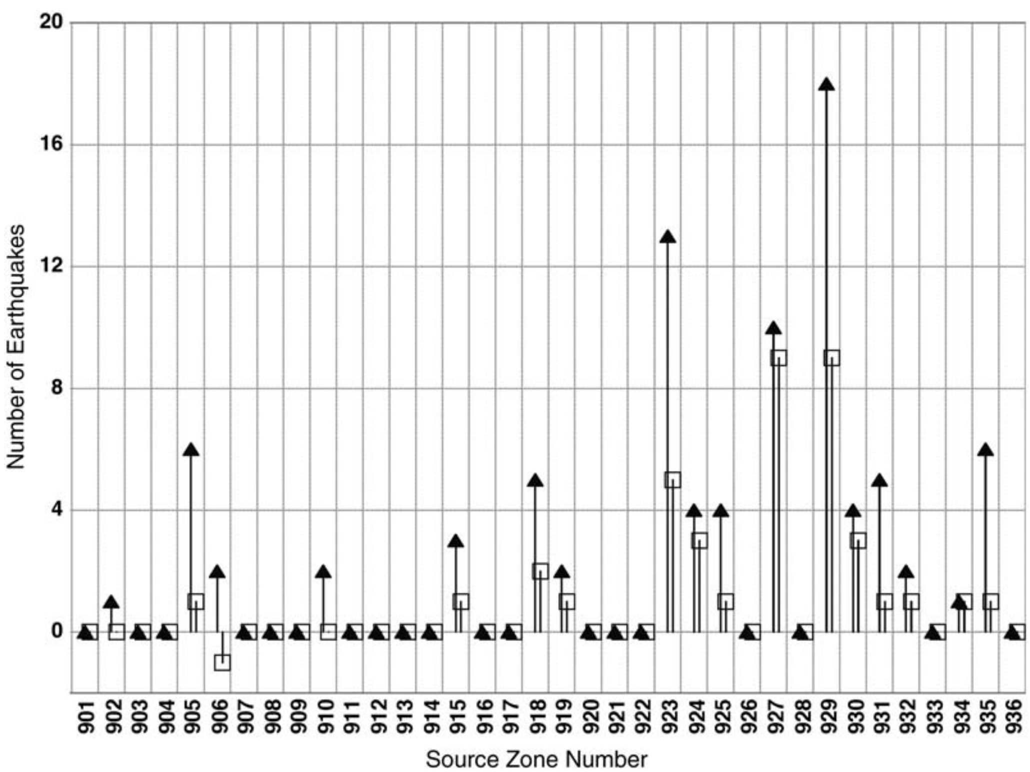

Figure 14. Distribution of the presumed missing events with $M_w \geq 6$ in each source zone, according to the AR model (open squares) and to the G-R model (black triangles).

Table 3
Correction Factors for Different Style of Faulting

Model	Reverse	Normal	Strike-Slip
Ambraseys *et al.*, 1996	1.13	0.88	0.93
Sabetta and Pugliese, 1996	1.15	0.89	0.94

Adopted from Bommer *et al.* (2003). The columns report the factors to be applied to the earthquakes for different types of faulting.

Ground-Motion Characterization

The main point of this section has been the best possible use of the available attenuation models and the attempt of using regionally determined models to capture possible regional differences in ground motion.

Two sets of ground-motion prediction equations have been selected: strong-motion based relationships (i.e., Ambraseys *et al.*, 1996; Sabetta and Pugliese, 1996) and strong- and weak-motion-based relationships derived from Malagnini *et al.* (2000, 2002), Morasca *et al.* (2002), De Natale *et al.* (1988), and Patanè *et al.* (1994; 1997). For a more detailed description of the models and their implementation in this PSHA, the reader is referred to Montaldo *et al.* (2005).

Two of the most significant improvements introduced for the first group of attenuation relationships were the correction of the Joyner and Boore (1981) distance to epicentral distance for the Ambraseys *et al.* (1996) relation and the style-of-faulting adjustments applied to both Ambraseys *et al.* (1996) and Sabetta and Pugliese (1996) relations.

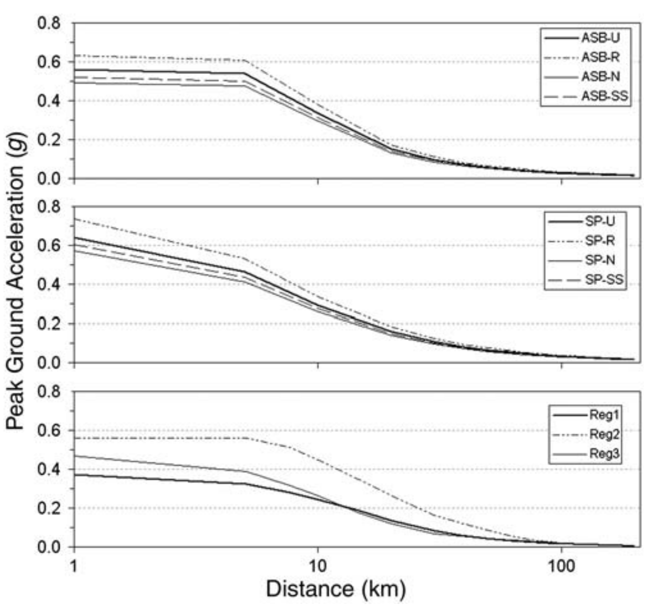

Figure 15. Comparison between different GMPEs adopted in this study: ASB, Ambraseys *et al.* (1996); SP, Sabetta and Pugliese (1996); Reg1, Reg2, and Reg3, regional models 1, 2, and 3, respectively. Focal mechanisms: U, unspecified; R, reverse; N, normal; and SS, strike slip. All relations are compared for M 6.5 and PGA; they are converted to Joyner–Boore distance (ASB and SP) and to epicentral distance (Reg1, Reg2, Reg3).

Following Scherbaum *et al.* (2004), the relation by Ambraseys *et al.* (1996) has been adjusted to use epicentral distances. This relation is defined in terms of the Joyner and Boore (1981) distance, which is calculated from the surface projection of the fault for earthquakes with $M_S \geq 6.0$ and the epicentral distance for less energetic events. A conversion between the distance from the fault (R_{JB}) and the epicentral distance (R_{EPI}) was developed for earthquakes of $M_S \geq 6.0$ using European data (see Montaldo *et al.*, 2005, for details). The conversion is

$$R_{JB} = -3.5525 + 0.8845 \cdot R_{EPI} \qquad (R^2 = 0.95).$$

Style-of-faulting correction factors proposed by Bommer *et al.* (2003; see Table 3) were also applied to strong-motion based relationships (Fig. 15).

The possibility of using models that have been determined on a regional basis from strong- and weak-motion recordings was investigated. These relations are derived from large datasets and have the advantage of characterizing ground-motion attenuation in areas with limited or no strong-motion recordings. The scaling laws proposed by Malagnini *et al.* (2000; 2002) and Morasca *et al.* (2002) are calibrated against data from three large regions: the western Alps (region 1), eastern Alps (region 2), and central-northern Apennines (region 3). With the exception of the Malagnini *et al.* (2002) study, which includes strong motions from the 1976 Friuli earthquake, the other two relations are derived solely from weak motions.

Prior to their use in PSHA, strong- and weak-motion-based relations were carefully verified against available strong ground-motion records from the same areas or areas with analogous predominant style-of-faulting. Montaldo *et al.* (2005) show that the comparison is satisfactory for all models and that the regional attenuation models account for changes in the observed attenuation characteristics as magnitude and distance vary. They also show that generally the predicted peak horizontal acceleration obtained from the regional relations at different magnitude levels is comparable to that obtained by the Ambraseys *et al.* (1996) relation.

Because the regional ground-motion models were not defined in all areas, the attenuation models were extended to other areas with similar crustal characteristics, giving rise to two alternative logic-tree branches. The first branch (REG.A in Fig. 2) follows the suggestions by Akinci *et al.* (2004): the southern Apennine and Calabrian arc were associated with the western Alps; northern Sicily with the Apennine; and the Apulian platform; and eastern Sicily with the eastern Alps. In the second branch (REG.B in Fig. 2), the Apulian platform and the southern Apennine were associated with the central-northern Apennine. The two branches also differ with respect to the adopted depth: branch A uses $h = 10$ km for all source zones except the volcanic ones, in which $h = 4$ km; branch B uses varied depths provided by Meletti *et al.* (2008).

In both cases, the scaling laws proposed by De Natale *et al.* (1988) and Patanè *et al.* (1994; 1997) were used in volcanic areas, assuming different stress-drop values.

Seismic Hazard Computation and Application

Computation

Table 4 summarizes the main parameters of the source zones, as derived from the section The Seismic Source Characterization, to be used for the computation.

The weights applied to the branches of the logic tree (Fig. 3) were assessed as follows. A larger weight (0.6) was assigned to the historical completeness assessment with respect to the statistical one (0.4) because we rely more on the historical considerations and on the basis of the test described in the section A Sanity Check. A larger weight (0.6) was assigned to the AR seismic rates and $M_{\max 1}$ values with respect to the G-R ones in connection with $M_{\max 2}$ (0.4), also on the basis of the test described in the section A Sanity Check. The three GMPEs were given the same weight (0.333); the two branches of the regional models were given 0.5 each (see Montaldo *et al.*, 2005).

The next question raised was whether we should use the mean (as supported by McGuire *et al.*, 2005) or some fractile, namely the median (as supported by Abrahamson and Bommer, 2005) hazard. Eventually, the advisors suggested we use the median, primarily because it was common opinion that the weights were a measure of our confidence in the various models that should be reflected in the hazard map to some extent. As the hazard dataset was prepared for application purposes, we also wanted to avoid the known instability of the mean hazard curve.

According to the 3274/2003 PMO, the PSHA was compiled in terms of PGA classes of $0.025g$; input data and procedures were made available through a dedicated web site (Gruppo di Lavoro MPS, 2004). The distribution of the median value is shown in Figure 16.

The uncertainty of the seismic hazard estimates has been assessed in terms of the sixteenth and eighty-fourth percentiles. Figure 17a,b show the differences between the eighty-fourth and fiftieth percentile values (the differences range between $0.005g$ and $0.063g$) and the differences between the eighty-fourth and sixteenth percentile values. The largest differences are found in the source zones where the Friuli model by Malagnini *et al.* (2002) has been adopted.

Background Seismicity and Treatment of Seismic Hazard for Italian Islands

In this elaboration, no background seismicity was processed. This is because the source zones include most of the seismicity, although we assume that earthquakes with M_w up to 5 can occur everywhere in Italy (Meletti *et al.*, 2008) and, therefore, also outside the source zones but with very low frequency. A test that was made in order to evaluate how a background area might contribute to the total seismic hazard revealed that such contribution was negligible.

For some areas far away from the source zones, namely Sardinia and most of the minor islands, tectonic and seismological information are not available. Therefore, it has not been possible to adopt the same methodology applied to mainland Italy and Sicily to these areas, and they have been treated individually with an *ad hoc* analysis. For some islands, such as Tuscan Archipelago, Pontine, Egadi, and the Tremiti Islands, the obtained PGA values have been considered consistent with the available information. For Sardinia, Pelagie Islands, and Pantelleria (which are characterized by a very low seismicity), a default PGA value equal to $0.05g$ has been suggested; for some of the Eolian Islands (offshore of northern Sicily, namely Ustica, Alicudi, Filicudi, Panarea, and the Stromboli Islands), a specific assessment based on a simplified logic tree has been performed (Fig. 18).

New versus Old: How Much Has the Seismic Hazard Changed?

As mentioned in the Introduction of this paper, one of the reasons for choosing the approach and the software used in this study was to allow comparison with previous assessments. It should be recalled that most previous studies are available only as maps representing the PGA with a 10% probability of exceedance in 50 years on rock or generic soil conditions (Slejko *et al.*, 1998) and typically represent the seismic hazard using different PGA bins. Figure 19 shows the comparison at seven major towns between the PGA values having a 10% probability of exceedance in 50 years, as obtained by varied studies. The values by Slejko *et al.* (1998), Slejko *et al.* (1999) and Romeo and Pugliese (2000) come from the original maps, where the values of PGA are expressed as intervals: the error bars are the interval of the relevant classes. The values from Albarello *et al.* (2000) and this study are represented as gray diamonds and black squares, respectively; they are the actual values at each site.

With the exception of this study, all the studies presented in this comparison are based on the seismogenic model ZS4 (Meletti *et al.*, 2000); the works by Slejko *et al.* (1998, 1999) were based on the NT4 catalog (Camassi and Stucchi, 1997); and works by Romeo and Pugliese (2000) and Albarello *et al.* (2000) were based on the CPTI99 catalog (Gruppo di Lavoro CPTI, 1999). As a general trend, this study supplies lower ground-motion values compared to the previous ones, particularly with respect to Slejko *et al.* (1998 and 1999), while they seem more in agreement with the results supplied by Albarello *et al.* (2000) and Romeo and Pugliese (2000). One of the explanations can be found in the overall reduction of the number and size of the earthquakes in CPTI04 with respect to the previous catalogs, due to the elimination of false events and resizing of M_w estimates, and in the general expansion of the completeness time intervals, which allowed us to consider longer quiescence intervals as part of the complete time window. These two elements have a much

Table 4
Parameters of Seismic Source Zones

	Source Zone	Predominant Focal Mechanism*	CPTI04/DISS 2.0 $M_{w\,max}$†	$M_{w\,max\,1}$‡	$M_{w\,max\,2}$‡	b-Value with Historical Completeness	b-Value with Statistical Completeness	Depth Hyp. A§	Att. REG.A§	Depth Hyp. B§	Att. REG.B§
901	Savoia	Undet.	5.79	5.91	6.14	−1.18	−1.26	10	1	8	1
902	Vallese	Undet.	6.10	6.14	6.14	−1.26	−1.05	10	1	10	1
903	Grigioni–Valtellina	Undet.	5.79	5.91	6.14	−1.26	−1.05	10	1	9	1
904	Trieste–Monte Nevoso	Strike slip	5.71	5.68	6.14	−1.12	−1.32	10	2	7	2
905	Friuli–Veneto Orientale	Reverse	6.66	6.60	6.60	−1.06	−1.12	10	2	8	2
906	Garda–Veronese	Reverse	6.49	6.60	6.60	−1.14	−1.70	10	2	8	2
907	Bergamasco	Reverse	5.90	5.91	6.14	−1.71	−1.48	10	1	8	1
908	Piemonte	Strike slip	5.67	5.68	6.14	−1.91	−1.67	10	1	10	1
909	Alpi Occidentali	Normal	5.54	5.68	6.14	−1.27	−1.38	10	1	10	1
910	Nizza–Sanremo	Reverse	6.29	6.37	6.37	−1.12	−1.06	10	1	10	1
911	Tortona–Bobbio	Strike slip	5.67	5.68	6.14	−1.47	−1.33	10	1	8	1
912	Dorsale Ferrarese	Reverse	6.29	6.14	6.14	−1.35	−1.32	10	2	7	2
913	Appennino Emiliano-Romagnolo	Undet.	5.85	5.91	6.14	−1.80	−1.53	10	3	13	3
914	Forlivese	Undet.	5.97	5.91	6.14	−1.33	−1.23	10	3	13	3
915	Garfagnana–Mugello	Normal	6.49	6.60	6.60	−1.34	−1.36	10	3	8	3
916	Versilia–Chianti	Normal	5.52	5.68	6.14	−1.96	−1.58	10	3	6	3
917	Rimini–Ancona	Reverse	6.10	6.14	6.14	−1.04	−1.01	10	2	7	2
918	Medio-Marchigiana/Abruzzese	Undet.	6.23	6.37	6.37	−1.10	−1.11	10	3	13	3
919	Appennino Umbro	Normal	6.33	6.37	6.37	−1.22	−1.39	10	3	8	3
920	Val di Chiana–Ciociaria	Normal	5.57	5.68	6.14	−1.96	−1.58	10	3	6	3
921	Etruria	Normal	5.91	5.91	6.14	−2.00	−2.01	4	4	4	4
922	Colli Albani	Normal	5.53	5.45	5.45	−2.00	−2.01	4	4	4	4
923	Appennino Abruzzese	Normal	6.99	7.06	7.06	−1.05	−1.09	10	3	9	3
924	Molise–Gargano	Strike slip	6.73	6.83	6.83	−1.04	−1.06	10	2	13	3
925	Ofanto	Strike slip	6.72	6.83	6.83	−0.67	−0.75	10	2	13	3
926	Basento	Strike slip	5.84	5.91	6.14	−1.28	−1.38	10	2	13	3
927	Sannio–Irpinia–Basilicata	Normal	6.96	7.06	7.06	−0.74	−0.72	10	1	10	3
928	Ischia–Vesuvio	Normal	5.78	5.91	5.91	−1.04	−0.66	4	4	3	4
929	Calabria Tirrenica	Normal	7.24	7.29	7.29	−0.82	−0.79	10	1	10	1
930	Calabria Ionica	Undet.	6.60	6.60	6.60	−0.98	−0.89	10	1	10	1
931	Canale d'Otranto	Strike slip	6.90	6.83	6.83	−0.63	−0.63	10	2	10	3
932	Eolie–Patti	Strike slip	6.06	6.14	6.14	−1.21	−1.08	10	3	13	3
933	Sicilia Settentrionale	Reverse	5.89	6.14	6.14	−1.39	−1.24	10	3	10	3
934	Belice	Reverse	6.12	6.14	6.14	−0.96	−0.93	10	3	10	3
935	Iblei	Strike slip	7.41	7.29	7.29	−0.72	−0.69	10	2	13	2
936	Etna	Undet.	5.30	5.45	5.45	−1.63	−1.22	4	4	3	4

*Undet., undetermined focal mechanism.

†Maximum experienced magnitude from catalog or DISS database.

‡Adopted maximum magnitude according to criterion 1 ($M_{w\,max\,1}$) or criterion 2 ($M_{w\,max\,2}$).

§Depth Hyp. A, mean depth associated with the REG. A branches of the logic tree; Att. REG.A, the attribution to a macroregion for GMPEs in the REG.A branches; Depth Hyp. B, the mean depth associated with the REG.B branches; Att. REG.B, the attribution to a macroregion for GMPEs in the REG.B branches.

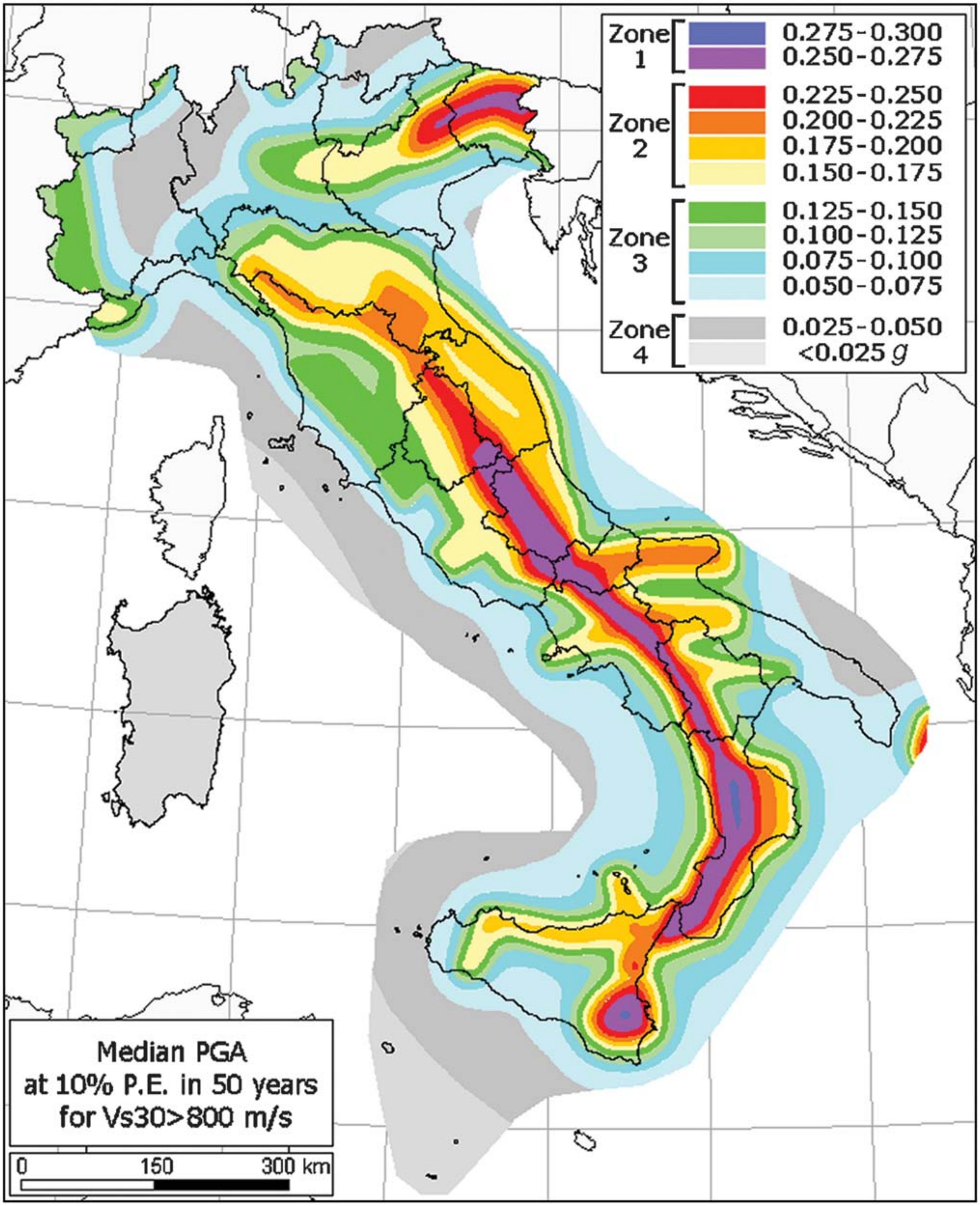

Figure 16. The seismic hazard map showing the PGA distribution with 10% probability of exceedance in 50 years, computed on hard ground ($V_{S30} > 800$ m/s).

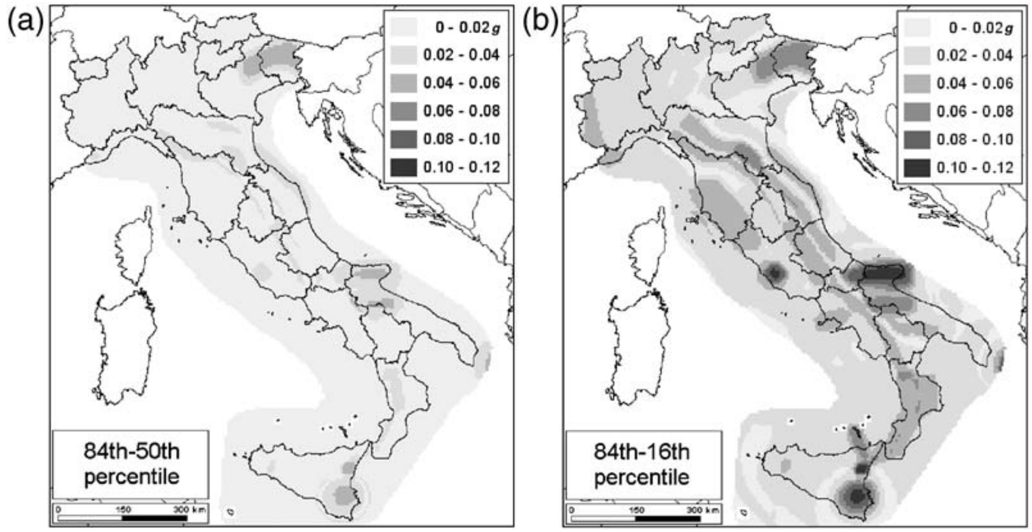

Figure 17. Absolute differences between (a) the eighty-fourth percentile and fiftieth percentile values and (b) the eighty-fourth percentile and sixteenth percentile values.

higher effect on the hazard than that produced by the changes in ground-motion predictive equations.

The Application to Seismic Zoning

The result of this PSHA has been approved by the board of reviewers and by the Commissione Grandi Rischi (Committee for Great Risks) of the Department of Civil Protection. According to 3274/2003 PMO, areas with PGAs falling into classes 1 and 2 (0–0.05g) had to be assigned to seismic zone 4; classes 3, 4, 5, and 6 (0.05–0.15g) to zone 3; classes 7, 8, 9, and 10 (0.15–0.25g) to zone 2; and classes 11 and 12 (0.25–0.30g) to zone 1. The application of the building code was not mandatory for zone 4. Table 5 summarizes the number of changes induced for nearly 8100 Italian municipalities. The most striking evidence is the increase of the number of municipalities in zone 3 and the decrease in zone 4, which happens in the low seismicity areas, mainly in the north. The changes in the most hazardous zones (1 and 2) are negligible.

The result of this study was acknowledged in 2006 as the official seismic hazard reference model of Italy (Prime Minister Ordinance 3519/2006, Italian Official Gazette n. 108 of 11/05/2006), to be used to update the assignment of the municipalities to one of the four seismic zones (if the Regional Governments find it opportune).

A New and More Detailed Description of the Seismic Hazard

Expanding the Seismic Hazard Dataset

Because the building code of 3274/2003 PMO also required the design and assessment of buildings to several

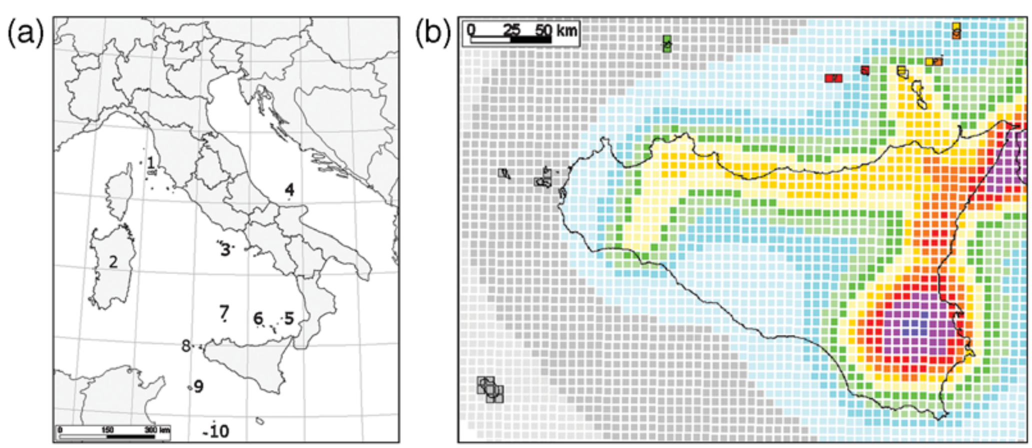

Figure 18. (a) Islands where special considerations have been adopted in order to assess seismic hazard with different approaches with respect to mainland Italy and Sicily: 1, Tuscan Archipelago; 2, Sardinia; 3, Pontian Islands; 4, Tremiti Islands; 5, Stromboli and Panarea; 6, Alicudi and Filicudi; 7, Ustica; 8, Egadi Islands; 9, Pantelleria; and 10, Pelagian Islands. (b) Enlarged view of Sicily and the surrounding islands, where pixels with borders have values determined with the peculiar analyses described in the text. The color legend is the same as that of Figure 16.

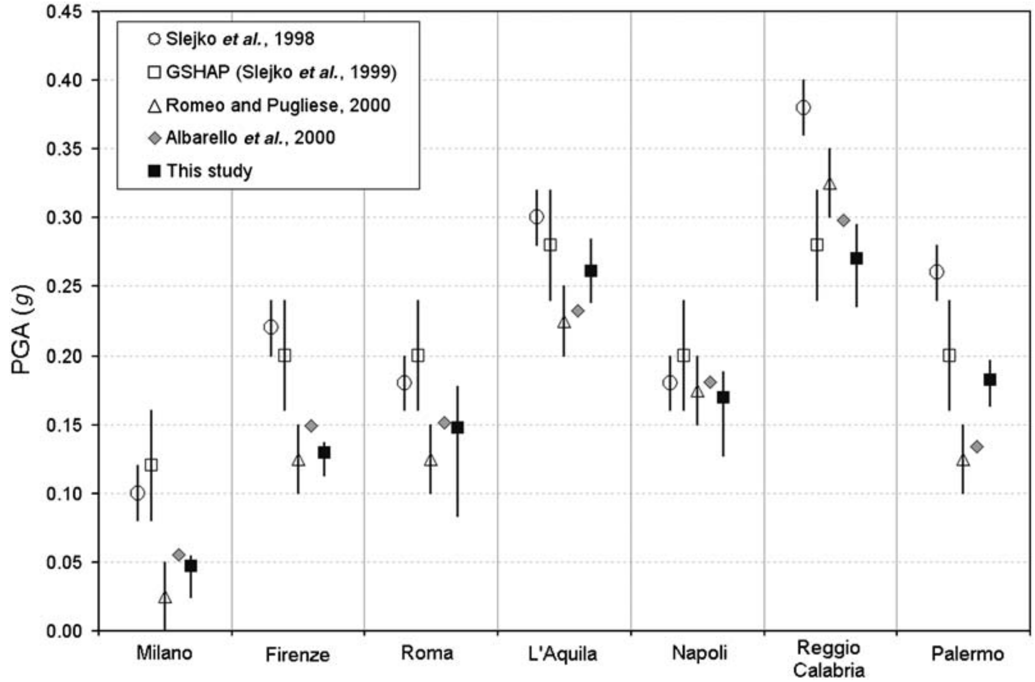

Figure 19. Comparison between PGA values at seven selected cities, with 10% probability of exceedance in 50 years, as estimated by different studies. For this study, the symbol is the median value, and the error bars correspond to the sixteenth and eighty-fourth percentiles.

limited states related to their performance (damage limitation, significant damage, and near collapse) under different levels of seismic action, the need arose for a number of return periods to be provided from the seismic hazard assessment.

Therefore, the Dipartimento della Protezione Civile (DPC) suggested the elaboration to be expanded to the assessment of (1) PGA, calculated for several probabilities of exceedance in 50 years, and (2) spectral accelerations for varied spectral periods and exceedance probabilities. This task was accomplished between 2005 and 2007 in the frame of an INGV-DPC project (S1 project, see Data and Resources section; Meletti, 2007). By using the same input described previously (earthquake recurrence model, ground-motion prediction equations, logic tree, etc.), the values of the following parameters have been determined for more than 16,000 points of a regular grid of 5 km: (1) PGA values for nine probabilities of exceedance in 50 years (2%, 5%, 10%, 22%, 30%, 39%, 50%, 63%, and 81%); and (2) spectral accelerations for the 10 periods common to every attenuation model used (0.10, 0.15, 0.2, 0.3, 0.4, 0.5, 0.75, 1.0, 1.5, and 2 seconds), for all the nine probabilities of exceedance.

The values of 99 (90 plus the original 9) parameters have been computed for each grid point. This bulk of data represents the seismic hazard database of Italy. To make this huge amount of data available for dissemination, a dedicated web-GIS application has been developed (Fig. 20; Martinelli and Meletti, 2008; see Data and Resources section). In a simple and fast way, the user may obtain hazard curves (Fig. 21) and uniform hazard spectra for the location of interest.

The S1 project web site is now the reference site for seismic hazard in Italy and is accessed by a large number of professionals and public agencies; the monthly mean number of accesses exceeds 40,000.

In addition, in the frame of the S1 project, the seismic hazard in terms of macroseismic intensity with a 10% probability of exceedance in 50 years was assessed to serve as a comparison (Gómez Capera *et al.*, 2010). (New empirical intensity attenuation relationships were determined for this purpose; Gómez Capera *et al.*, 2007.)

A disaggregation of the PGA values for all nine probabilities of exceedance in terms of mean and modal values of M, R, and ε was also attempted by Spallarossa and Barani (2007). However, such computation does not represent the disaggregation of this study because the procedure we adopted is not compatible with the use of the median. For this reason, the S1 project suggested to disaggregate a proxy (i.e., one of the 16 branches of the logic tree that better approximates the median, the differences being less than

Table 5

Number of Municipalities Assigned to Each of the Four Zones According to 3274/2003 PMO, as Compared to the Results of a Straightforward Application of This Study

Seismic Zone	Number of Municipalities (3274/2003 PMO)	Number of Municipalities (This Study)	Differences
1	716	568	−148
2	2323	2295	−28
3	1633	3569	+1936
4	3430	1670	−1760

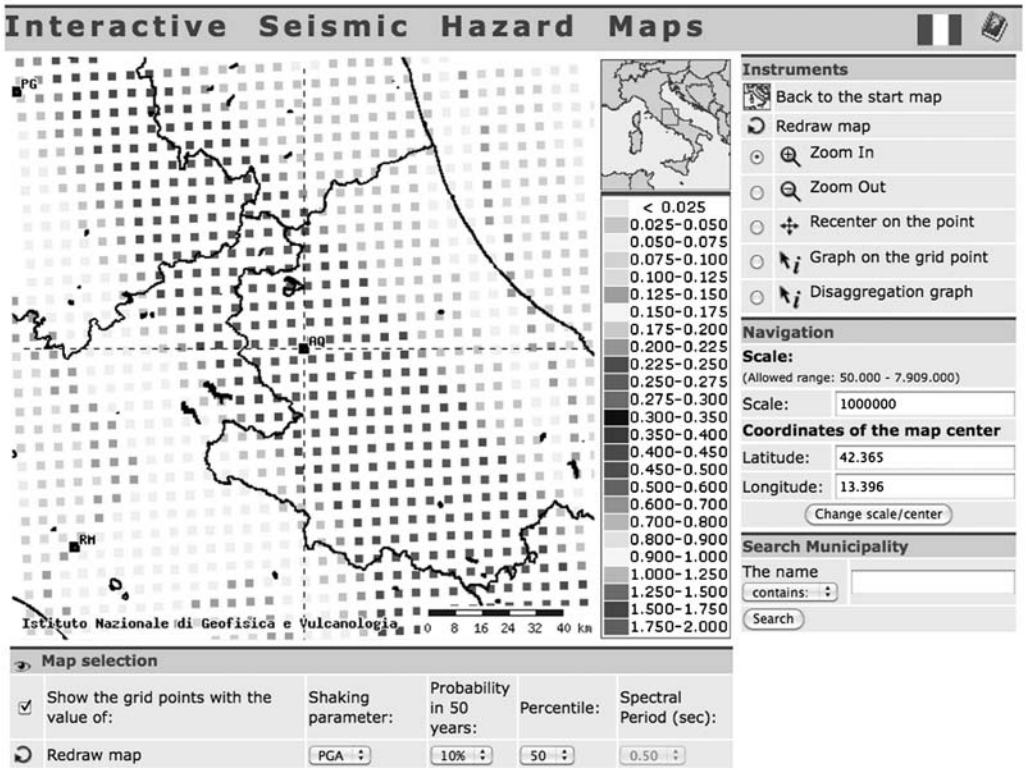

Figure 20. Homepage of the webGIS application for the dissemination of seismic hazard of Italy (see Data and Resources section).

0.04%). This proxy was intended to be branch 921, obtained by using historical completeness, AR rates, $M_{\max 1}$ values, and Ambraseys *et al.*, 1996 as the attenuation model). Contrary to what has been reported by Spallarossa and Barani (2007), in Barani *et al.* (2009) it appears that a different input was used in the disaggregation (their procedure does not foresee the use of AR rates); this determines nonnegligible differences (greater than $0.06g$ in more than 20% of the territory) with respect to this study and also to branch 921.

It is further noted that, for engineering purposes (e.g., for selection of accelerograms), disaggregation of PGA may be insufficient and should ideally be carried out at the period of vibration of the structure of interest (e.g., Convertito *et al.*, 2009).

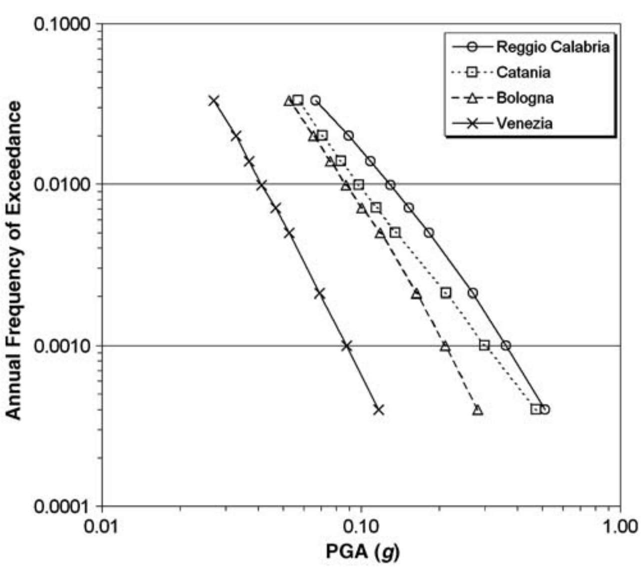

Figure 21. Comparison of hazard curves for four cities with different seismic hazard levels; each city (listed from zone 1 to 4 in the legend) is representative of a different seismic zone.

The New Requests of the Building Code

As with all major changes, the application of the 2003 building code met with difficulties from public administrations, professionals, and even scientists, with respect to both the code itself and the zoning. As for the previous version, the code adopted four standard design spectra anchored to the four upper PGA values (0.05, 0.15, 0.25, and $0.35g$; Table 1; Fig. 22) corresponding to each of the four seismic zones. This implied that the same, upper PGA value was to be used as an anchor value in all locations inside one zone, in spite of their true PGA values; the gap is often remarkable (Figs. 22 and 23). The results of this study reach $0.28g$ as an upper bound, and the eighty-fourth percentile rarely overcomes $0.30g$. Some engineers then suggested that the upper PGA anchor value ($0.35g$) could be reduced. Furthermore, this study supplied a well-graded PGA dataset, therefore suggesting that a finer grading could be adopted with respect to the four zones.

In 2007 the wealth of data available from the S1 hazard dataset was considered by a committee appointed to update the building code and related zoning. The committee decided

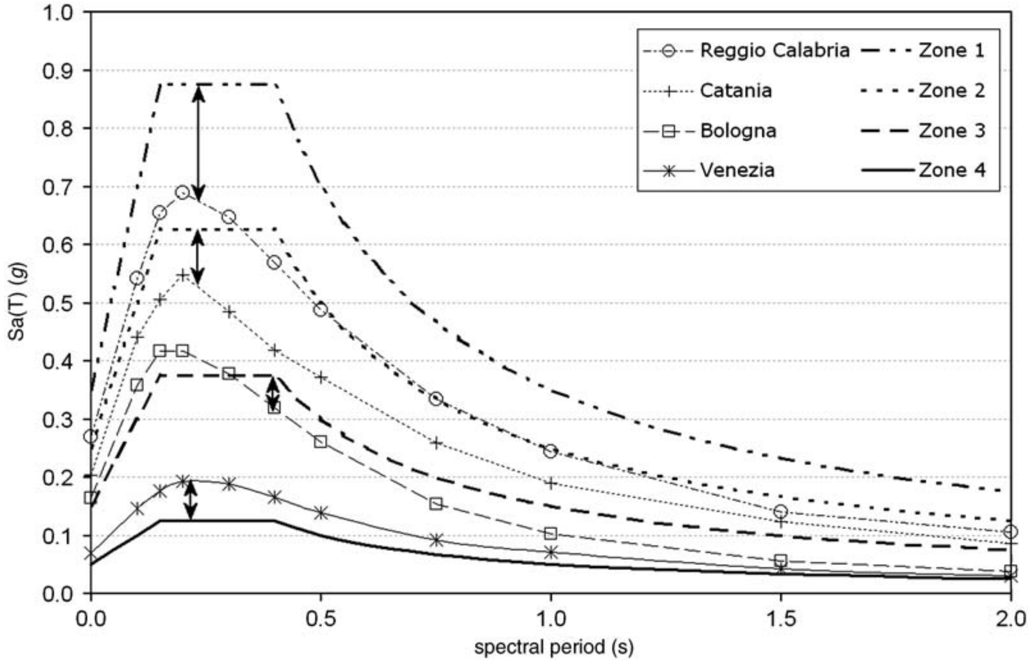

Figure 22. Comparison between the design spectra of the four seismic zones according to 274/2003 PMO and the calculated UHS at four cities, representative of the four zones. The double-headed arrows connect the UHS and the corresponding design spectrum for each city.

to proceed to a site-dependent design spectrum, instead of a zone-dependent one, as in the previous code. The new building code (NTC08; Norme Tecniche per le Costruzioni, 2008) defines the design spectrum at each site of a grid of about 11,000 points, covering the whole territory; it thus varies with return period and location. The spectral shape of NTC08 is based on three parameters for each return period: PGA, as derived from the S1 project, and two additional parameters that allow the spectral shape to more closely fit the uniform hazard spectrum (UHS), that is the corner period (T_c) and the spectral amplification factor (F_0) (Fig. 24).

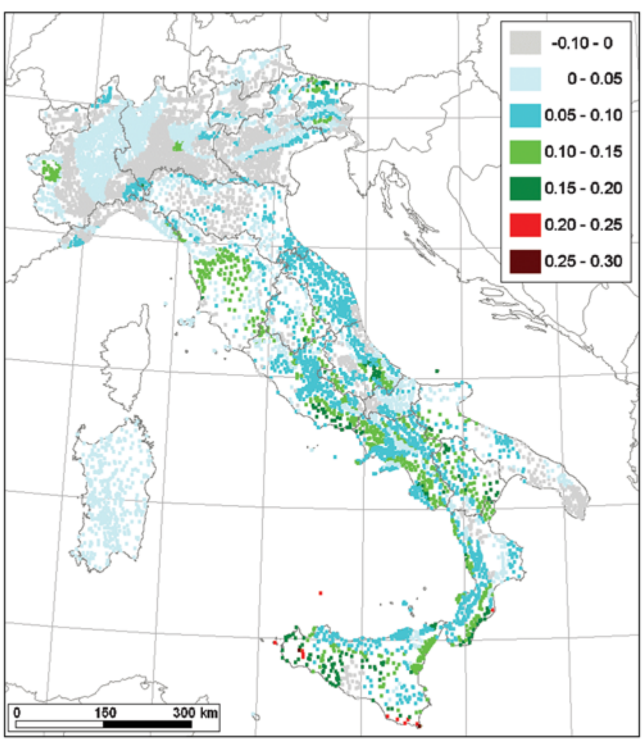

Figure 23. Differences between the anchor PGA values of 3274/2003 PMO and the PGA values provided by this study.

The advantage of the NTC08 approach for building code spectra is that the designed buildings should all have a similar level of risk, regardless of their location or period of vibration; the disadvantage is that the site-dependent approach of the code no longer includes the additional level of conservatism that was included with the previous, zone-dependent approach.

If we take the municipality of L'Aquila as an example, Figure 25 shows the comparison between the design spectra provided by the 2003 building code for seismic zones 1 and 2 and the one expected for L'Aquila according to the S1 project and NTC08. It is clear from such a comparison that the 2003 design spectrum for zone 2, to which L'Aquila belongs, is in good agreement with the one proposed by the S1 hazard dataset.

After a waiting period in which the use of either the old or the new building code was allowed, the full adoption of the new code started in July 2009, according to an urgent provision by the Italian Government (Decree n.39/2009, 28/04/2009) that was triggered by the 6 April 2009 L'Aquila earthquake.

The 2009 L'Aquila Earthquake

The numerous recordings of the 2009 L'Aquila M_w 6.3 earthquake have led to a number of comparisons being made

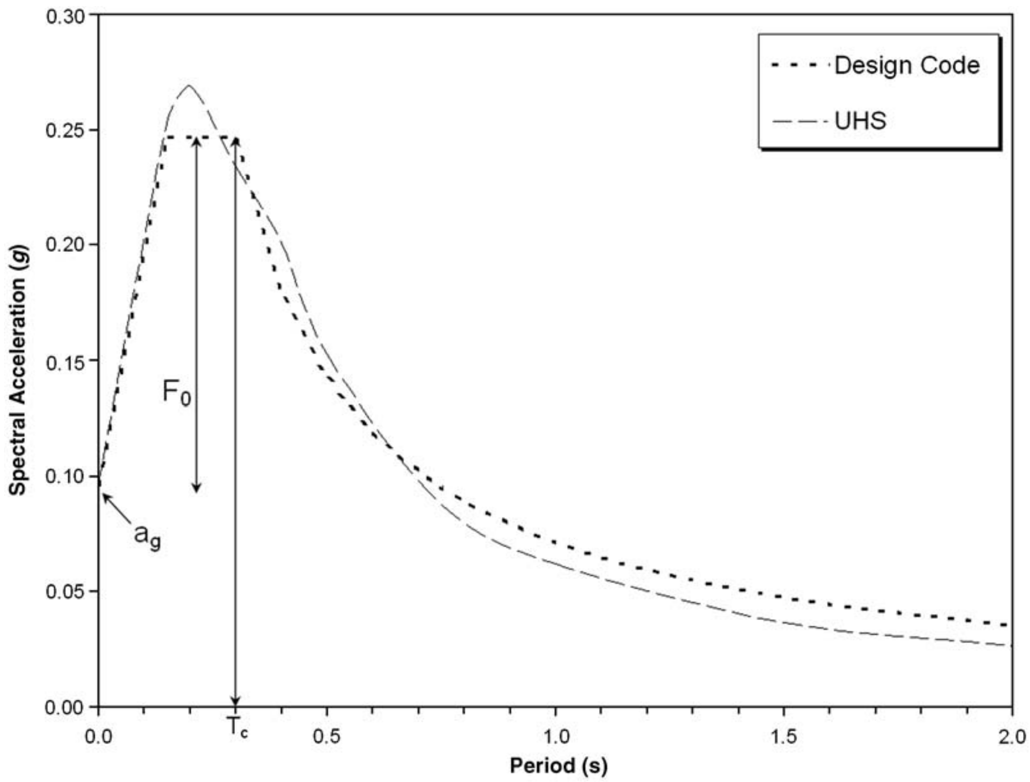

Figure 24. Schematic representation of design code spectra obtained from UHS and the parameters that define it.

between the recorded spectra and the spectra found in NTC08. The input for such comparisons was supplied by the high PGA values (up to 0.66*g*) recorded very close to the causative fault (Ameri *et al.*, 2009). Actually, such values are far above the PGA values supplied by this study, especially at low periods of vibration. According to some authors,

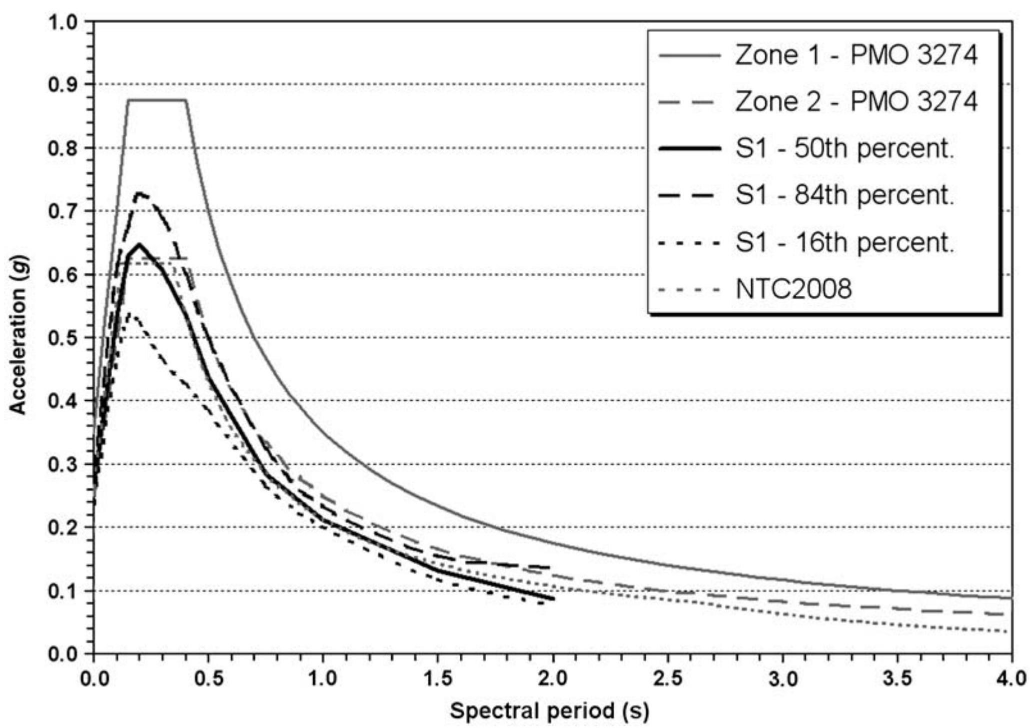

Figure 25. Comparison between the design spectra provided by the 2003 building code for seismic zones 1 and 2 and the one expected for L'Aquila, according to the S1 project and NTC (2008). All spectra refer to hard ground.

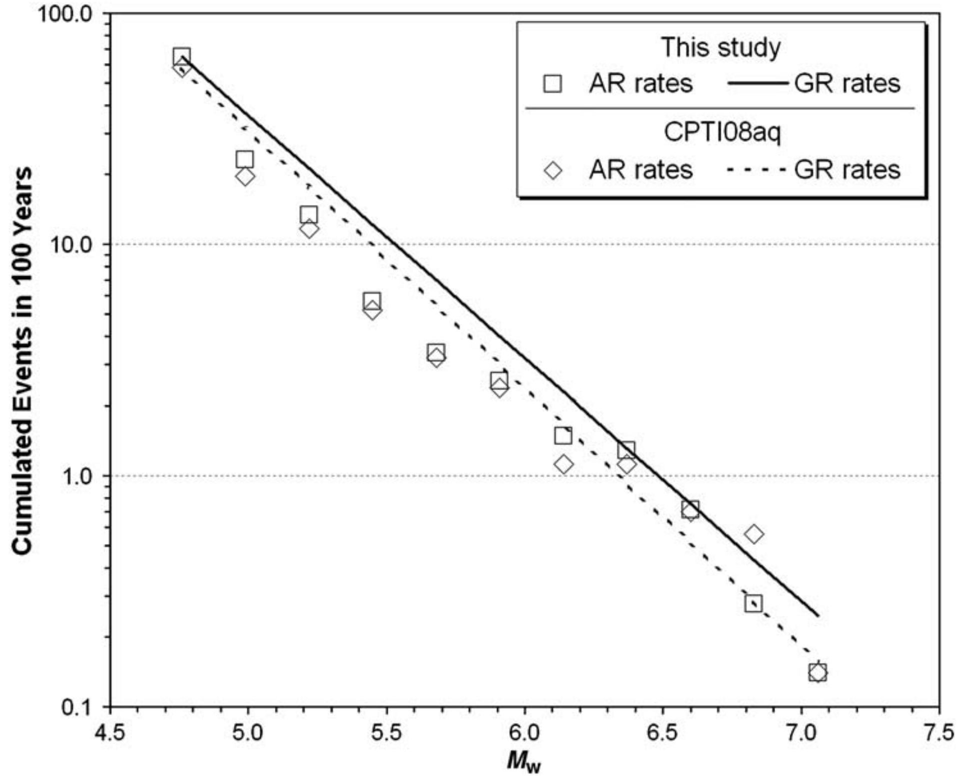

Figure 26. Seismicity rates in terms of AR and G-R rates used for ZS923 in this study compared with the rates resulting from the adoption of the CPTI08aq catalog (Rovida *et al.*, 2009).

the reasons should be found in inadequacies of the earthquake recurrence model, the GMPE, or the characteristics of the spectra. We are convinced that such comparisons are not well grounded and, assuming that it is for a 475-year return period, that the only meaningful test of a PSHA is to ask whether (over a 50-year period) more than 10% of the national territory experienced ground accelerations higher than those mapped. Even then, it can be demonstrated that to make this test robust would require several consecutive 50-year periods of observation, in the same way that we need much longer than 475 years of acceleration recordings to validate the hazard estimate at a single location (Beauval *et al.*, 2008).

On the other hand, the L'Aquila event was one of the most recorded seismic events in the history in Italy, and the wealth of information that was obtained from these recordings cannot but improve our understanding of earthquakes in Italy. It seems therefore useful to investigate whether, following the L'Aquila earthquake, our increased knowledge would in any way cause us to change the way in which the hazard in the area is described and hence the seismic actions prescribed for design by NTC08.

Earthquake Recurrence Model

The earthquake parameters of M_w 6.3, normal fault mechanism, and hypocentral depth 9.5 km (see Data and Resources section) are compatible with those of source zone 923 of the ZS9 seismogenic model (Meletti *et al.*, 2008). We have performed a test to evaluate the influence of seismicity rates on the seismic hazard of the area: to this purpose, the PSHA has been redone for seismic source zone 923 after reassessing the seismicity rates (Fig. 26) by adding the 6 April 2009 event to the CPTI04 catalog and using the new catalog CPTI08aq (Rovida *et al.*, 2009) compiled for the investigations on the area.

Results of this test show that the peak acceleration expected at L'Aquila with a 10% probability of exceedance in 50 years increases little more than 1%, thus is below the uncertainty of this study (9%), which is defined as the difference between the median value and the sixteenth or eighty-fourth percentile. The main conclusions are that the seismicity model used for the seismic hazard of the L'Aquila region (in terms of catalogs, completeness, and seismicity rates) would not be subject to change based on our increased knowledge following the L'Aquila earthquake.

Ground-Motion Prediction Equations

Many Italian seismologists and engineers claim that current design spectra are inadequate due to shortcomings in the earthquake recurrence model; however, the topic of GMPEs has shown the largest progress and change since 2003 and is thus an area upon which more attention should be paid. In fact, the recent near-field recordings of the L'Aquila earthquake have been shown to supply good constraints to many of the current GMPEs. A series of new models specifically for Italy are available, including Frisenda *et al.* (2005), Bragato and Slejko (2005), Massa *et al.* (2008), and Bindi *et al.* (2009); in addition, there are new European equations by Ambraseys *et al.* (2005) and Akkar and Bommer (2007, 2010). Finally, there are the Next Generation Attenuation equations, which have been demonstrated to be applicable to Europe by Stafford *et al.* (2008). An overview of European ground-motion prediction equations and their possible application to Eurocode 8 has been published by Bommer *et al.* (2010). All such GMPEs can introduce variations in the spectra ordinates: nevertheless, comparisons of the GMPEs used in the Italian seismic hazard study and the recorded ground motions at varying distance from the epicenter have shown that the near-field description of the spectra ordinates was well captured by the implemented GMPEs (e.g., Crowley *et al.*, 2010).

Spectra Comparison

We do not believe that comparisons between design code spectra and recorded ground motions are meaningful and that they can be used to validate (or otherwise) the spectra. This is due to a number of reasons, namely: (1) the probabilistic nature of design code spectra, which are based on uniform hazard spectra; (2) the fact that it is hard to associate a unique return period to the very different accelerations recorded during the L'Aquila earthquake; (3) the knowledge that the Italian hazard study assumes source zones that intrinsically do not allow comparison with an event that occurred on a specific fault; and (4) the uniform hazard spectrum envelopes spectra of different events, and thus different ordinates of the UHS might be due to different earthquake sources. All of these reasons reinforce the fact that design spectra cannot be meaningfully compared with a single spectrum of L'Aquila.

Nevertheless a number of researchers have made comparisons between the NTC08 code spectra and recordings from L'Aquila (e.g., Ameri *et al.*, 2009; Paolucci, 2009; Masi *et al.*, 2011; Masi and Chiauzzi, 2009; Iervolino *et al.*, 2010; Crowley *et al.*, 2010). We believe that the main findings of these studies reaffirm the preceding discussion that code spectra and single site spectra cannot be compared. Furthermore, the recordings considered in these comparisons were near source, and it is well known that such ground motions may show effects related to the source-to-site geometry (e.g., Somerville *et al.*, 1997), which may not be accounted for properly by this nor any other standard PSHA study that does not take into account individual faults (which includes the majority of PSHA studies carried out for design codes). Some studies have tried to investigate if these near-source effects occurred in L'Aquila (e.g., Chioccarelli and Iervolino, 2010) to raise the attention within the engineering community that such issues are not currently covered by international design codes.

Conclusion

The recent complex probabilistic assessment of seismic hazard of Italy from the perspective of the building code started as a consequence of the 2002 S. Giuliano di Puglia earthquake (M_w 5.9), which triggered a complete change of the former 1974 building code, following mainly the procedures within Eurocode 8 (2004). A new code was published in 2003, requiring a hazard assessment for seismic zoning purposes to be performed within 1 year, in terms of horizontal peak ground acceleration on hard ground with a 10% probability of exceedance in 50 years. Such a PSHA has been performed by a working group established by INGV: this elaboration, addressed and reviewed by an international board of reviewers, adopted a logic-tree approach for the first time in Italy to explore the variability of the completeness of the earthquake catalog (two branches: mainly historical and mainly statistical), the assessment of the seismicity rates and M_{max} (two branches: activity rates and G-R rates), and the ground-motion prediction equations (GMPEs, four branches). As for the earthquake source model and the earthquake catalog, both compiled for this project, no alternatives were found to be available.

Seismic hazard was computed over a grid of more than 16,000 points as the median value (fiftieth percentile) of 16 branches; the values of the eighty-fourth and sixteenth percentiles were also computed. The PSHA has then been improved, making use of the same input elements, to compute PGA values for nine probabilities of exceedance in 50 years and spectral accelerations for 10 spectral periods considered for all the nine probabilities of exceedance. All data are available through a dedicated web site. This wealth of data suggested that the design spectra could be based on point hazard data instead of being related to just four zones. Between 2007 and 2008, a new building code, NTC08, was prepared and published; the shape of the design spectra is based on the hazard dataset described in this paper.

However, the new building code was only enforced after the 6 April 2009 M_w 6.3 L'Aquila earthquake, which has led some investigators to perform tests of the reliability of the results of this study. We have analyzed such tests and have made our own. Our conclusion is that significant changes to the NTC8 spectra would not be recommended on the evidence of the L'Aquila earthquake.

We feel that the hazard description supplied by this study helps cast a new light on the seismic risk distribution in Italy. The attention of most seismologists, engineers and public administrators is usually captured by the highest seismic hazard areas, where the seismic code has been in force for a long time and, in our opinion, safety problems are mainly related to the appropriateness of the code provisions and to their actual implementation in practice. On the other hand, we believe that a large amount of risk is also hidden in those areas (much of zone 3 and 4) where no seismic building code was applied before 2003.

As for the future, a significant improvement could come from the new data and views available to date. The seismicity database (parametric catalog CPTI, macroseismic database DBMI) and the knowledge of active faults and seismogenic sources (Basili *et al.*, 2008) have improved. The impact of the new data on the estimated earthquake recurrence parameters and maximum magnitudes can be evaluated through sensitivity studies. New ground-motion models are available for Italy and Europe, as mentioned in Ground-Motion Prediction Equations.

New computational codes are also now available. Because of the increased capability of new processors and to a large cluster of them, it was possible to develop more and more complex and powerful codes so that now it is possible to obtain detailed and refined elaboration in a short time. Codes such as OpenSHA or CRISIS 2008 (see Data and Resources section) allowed us to adopt several and complex seismicity models (the newest GMPEs) to model three-dimensional seismic source zones and many other new features.

In addition, we believe that the L'Aquila earthquake has raised the issues of the influence of near-field effects on response spectra and whether these should be accounted for in design code spectra. Furthermore, we wonder if the possibility of including the epistemic uncertainty in the seismic hazard into the code (perhaps through an explanation of this uncertainty so that the engineer may decide which percentile to use in a design; Abrahamson and Bommer, 2006) could be explored for future updates to the code. We also believe that the recent hazard assessments in terms of displacement (e.g., Faccioli and Villani, 2009) should be considered and improved so as to supply an even more detailed hazard description that could be of use for future design codes.

Data and Resources

Data from the Gruppo di Lavoro MPS (2004) can be found at http://zonesismiche.mi.ingv.it (last accessed January 2011).

Data from the Project S1, funded by the National Civil Protection Department and the Istituto Nazionale di Geofisica e Vulcanologia (INGV—DPC Project S1), are available at http://esse1.mi.ingv.it, last accessed January 2011. The seismic hazard database of Italy is available as a dedicated webGIS application (Martinelli and Meletti, 2008, and is available at http://esse1-gis.mi.ingv.it/s1_en.php (last accessed May 2011).

Data from the Catalogo Parametrico dei Terremoti Italiani (Gruppo di Lavoro CPTI, 1999, and Gruppo di Lavoro CPTI, 2004) are available at http://emidius.mi.ingv.it/CPTI99 and http://emidius.mi.ingv.it/CPTI04 (last accessed May 2011).

Data from the Global Centroid Moment Tensor (CMT) Project are available at www.globalcmt.org/CMTsearch.html (last accessed May 2011).

Data from the National Earthquake Information Center–Preliminary Determination of Epicenter catalog are available at http://earthquake.usgs.gov/earthquakes/eqarchives/epic/ (last accessed May 2011).

Data from Stucchi *et al.* (2007) are also available at http://emidius.mi.ingv.it/DBMI04 (last accessed January 2011). Digital data of each event, clickable maps, and seismic histories of each site can be downloaded from this web site. The updated version DBMI10 will be released on this same web site.

The computer code SEISRISK III (Bender and Perkins, 1987) was used to calculate PGA and macroseismic intensity with a 10% of probability of exceedance in 50 years. Additional codes for seismic hazard assessment are OpenSHA (http://www.opensha.org; last accessed May 2011) or CRISIS 2008, by Universidad Nacional Autónoma de México (http://nuovoprogettoesse2.polimi.it; last accessed May 2011).

Earthquake parameters used in the earthquake recurrence model are from http://portale.ingv.it/primo-piano/archivio-primo-piano/notizie-2009/terremoto-6-aprile/meccanismi-focali (last accessed May 2011).

Acknowledgments

This study summarizes the results of a long-term investigation that had as its main goal the supply of scientific data for improving the seismic safety of Italian buildings. It therefore profited from the contribution and experience of many scientists and public officers who shared that goal with us, including many working groups and authors of some referenced papers, who participated with us in committees, that allowed this study to be finalized.

We are pleased to acknowledge the valuable contribution of the advisors, namely D. Giardini, F. Barberi, M. Garcia Fernandez, P. Pinto, D. Slejko, and J. Bommer (who also kindly contributed by reviewing a first draft of this paper), and the valuable comments and support we received from R. Pinho. We also want to acknowledge the constant support by the officers of Department of Civil Protection and, mostly, by the former Head, G. Bertolaso and former Deputy Head, V. Spaziante; the latter succeeded in bridging the gap between science and legal issues, allowing our results to be used for improving public safety.

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