ANNALS OF GEOPHYSICS, 65, 6, SE640, 2022; doi:10.4401/ag-8863
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The assessment of earthquake hazard in Italy: a review

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Article history: received June 9, 2022; accepted October 23, 2022

Abstract

We present a review of the assessment of earthquake hazard in Italy, with special reference to the relationships between hazard models and building codes. After early attempts at hazard assessment in the 19th century, the 28 December 1908, Messina Straits earthquake prompted the inception of the first national seismic legislation, passed in early 1909. Nevertheless, the official building code started to be based on a truly scientific background only after 1980, when the catastrophic Irpinia (southern Italy) earthquake forced the qualified authority to accept a science-based assessment (statistics on the earthquake catalogue data) to support the implementation of the new national seismic zonation. Later on, between 1985 and 2000, the two basic components of seismic hazard assessment, namely the earthquake record and the distribution of earthquake sources, were greatly developed through investigations carried out by the Gruppo Nazionale Difesa dai Terremoti and by the Istituto Nazionale di Geofisica. Along with the improvement of basic data, the Italian seismological community started developing a new hazard model (PS4), based on the concept of *seismotectonic probabilism*, aimed at supplying the Italian Government with a solid reference frame for updating the seismic zonation and building code. Nevertheless, this goal was achieved only two decades later: on 31 October 2002 a moderate-size earthquake caused the death of 27 children and a teacher in a collapsed school of southern Italy, forcing the qualified authority to take a major step of modernization for the second time in 22 years. The entire Italian territory, including areas of rare and sparse seismicity, was subdivided into four seismic zones, mainly on the basis of PS4 results. In 2004, the Italian seismological community developed MPS04, a fully updated hazard model that was initially conceived only in view of updating the seismic zonation. In 2007, MPS04 was extended to provide design spectra for a new building code, which was finally adopted in 2009, following the disastrous L'Aquila (central Italy) earthquake. The experience of the European project for seismic hazard assessment named SHARE, completed in 2013, represented a step forward and put the basis for a new project, termed MPS19, designed specifically to provide a sound basis for updating the Italian building code.

Keywords: Seismogenic faults; Earthquake catalogues; Seismic hazard; Building code; Italy

1. Introduction

Italy locates in a highly active and tectonically complex area of the central Mediterranean, and is particularly vulnerable to earthquakes due to the density of its population and to the characteristics of its building stock. Although earthquake magnitudes never exceeded M_w 7.5, a potentially catastrophic M_w 6+ earthquake occurs every 12 years, on average (Guidoboni et al., 2018; Rovida et al., 2022). Even moderate or small events (M_w<5) may cause significant damage (up to intensity VIII of the Mercalli-Cancani-Sieberg scale, hereinafter MCS) and major upheaval, particularly in the volcanic areas of Tuscany, Latium, Campania, and Sicily, where most of the seismicity occurs at a depth of 1-5 km. As shown in Figure 1, much of the Italian territory suffered damaging effects (MCS intensity VI and larger) at least once in the past thousand years, and roughly one third of it suffered heavy damage (VIII and larger).

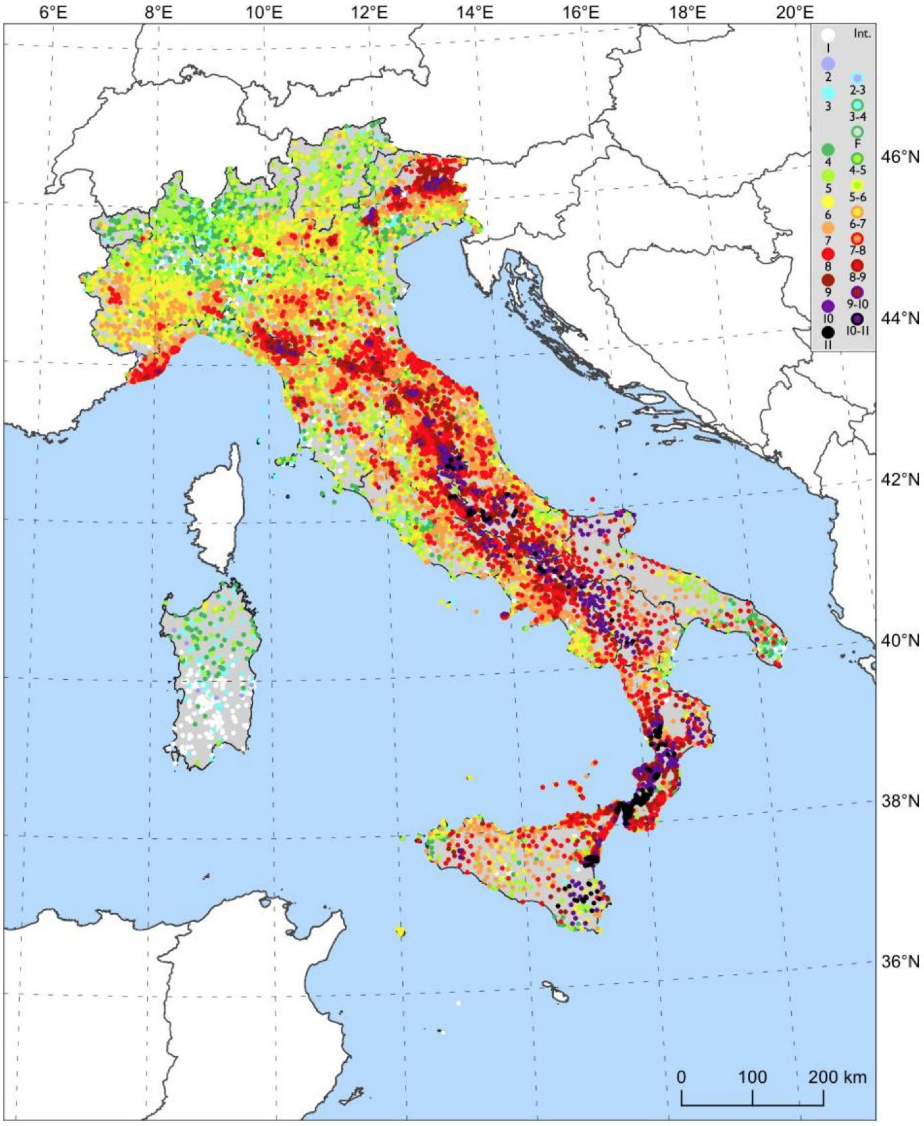


Figure 1. Maximum earthquake effects in terms of macroseismic intensity (MCS scale) in the past 1,000 years (from the DBMI15 database [Locati et al., 2021].

Italy is also a country of ancient civilization, and due to its frequent seismicity it has been also the cradle of seismic risk mitigation measures. The first earthquake-resistant building in history was designed by Neapolitan architect Pirro Ligorio (Naples 1513-Ferrara 1583) after he was hired by the northern Italian Estense family, following the rather unexpected yet highly damaging Ferrara (northern Italy) earthquake of 16 November 1570 (estimated M_w 5.5).

In more recent times the Italian governments devised progressively more stringent building codes – among the first to be enforced in the world – but these provisions were often found insufficient and subsequently updated, learning from experience.

Following the great 28 December 1908, Messina Straits earthquake (M_w 7.1), in 1909 the Italian Government emanated a *corpus* of anti-seismic rules that are generally considered the first attempt worldwide to mitigate seismic risk by an official state law. The new rules set firm standards for the anti-seismic design of new buildings; more or less along the same lines of what had been done earlier, following the catastrophic earthquakes that hit the Benevento area (southern Italy) in 1688, the whole of central and southern Calabria in 1783, and the Ischia volcanic island off the coast of Naples in 1883. Unlike these previous efforts, however, the 1909 rules also established seismic zones, that is, outlined the areas where it was compulsory to build according to seismic provisions, as to prevent damage from future earthquakes in addition to providing rules and standards for the rebirth of the damaged cities.

Regrettably, after 1909 the new seismic zones were established only after a significant earthquake, and only in the areas which had suffered the largest damage. This practice was meant to ease the flow of reconstruction funding, more than to protect the buildings in known earthquake-prone areas from the effects of future events. Figure 2 shows two examples of the complicated and fragmentary nature of the procedure followed to establish the seismic zones: not only at the national scale but even in smaller districts, where adjacent – and presumably similarly hazardous – municipalities ended up being classified even 50 years apart. To make things worse, some municipalities obtained to be permanently taken out of the seismic design zonation for building code recommendations (hereinafter simply *seismic zonation*), i.e. to return to the status of *unclassified*: the request was made on the grounds that the seismic code imposed a burden that would ultimately slow down the urban development, especially in areas where the tourism industry was growing fast.

The slow and limited progress in the expansion of the seismic zones was not due to the quality of the available seismological information, but rather to the opposition of important bodies of the Central Government, and specifically of the Ministry of Public Works. Pressured by the need to ease the development of large housing projects, many administrations chose the easiest way to reduce the costs implied by earthquake-resistant design. This policy

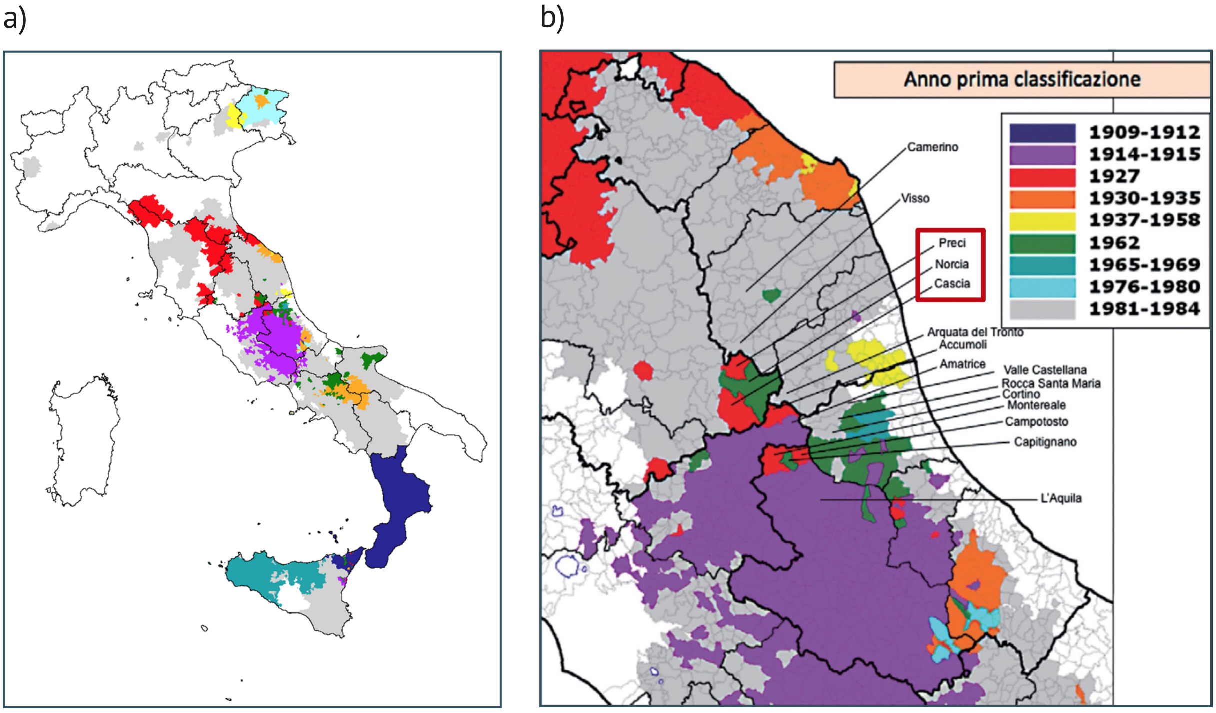


Figure 2. Year of first entry of each municipality into a seismic zone: a) in Italy until 1984 (from Meletti et al. [2014a]); b) in a portion of central Italy (from Stucchi et al. [2017]). Notice that the two images share the same color-coding. It is relatively easy to identify the footprint of the area of largest damage caused by main earthquakes of the period 1908-1976: for instance, the purple shading indicates municipalities that entered the classsification following the great 1915, Avezzano earthquake (M_w 6.8).

generated a safety deficit which ultimately translated into a much larger physical and social vulnerability of the concerned communities.

In the 1970s, alongside an important scientific effort driven by the agencies in charge of assessing the safety of prospective nuclear power plant (NPP) sites, part of the scientific community involved in research on earthquake hazard and risk committed itself to a major goal: expanding the seismic zones to include all earthquake-prone areas countrywide, so as to improve the global safety of the population.

In this paper we review the initiatives, the data, the methods and the advancements that accompanied the construction of seismic hazard models specifically aimed at supporting the seismic zonation and the enforcement of building codes countrywide. We anticipate that our review will concern only the definition of the design-base hazard levels, without taking into consideration the very large literature on local ground shaking amplification phenomena and microzonation studies.

2. Before 1990: early attempts at assessing seismic hazard

Starting in the second half of the 19th century, the availability of large amounts of good quality historical earthquake data, already stored in a number of detailed earthquake compilations [a meticulous summary can be found in Camassi, 2004], allowed the compilation of detailed seismicity maps. In their turn, these elaborations served as a basis for identifying the most earthquake-prone areas and, in some cases, for attempting some simple statistical interpretations (Figure 3).

Figure 3. The 'Abbozzo di Carta Sismica della Italia' ('Draft of a Seismic Map of Italy'), compiled in 1886 by early Italian geologist Torquato Taramelli (1845-1922), subdivided the Italian seismogenic areas based on the number of earthquake occurrences per century, starting with the year 1300. It is perhaps the oldest ancestor of the current probabilistic seismic hazard maps [Taramelli, 1886].

Meanwhile, historical information supplied important clues to understanding the source characteristics of the main Italian earthquakes of the 20th century [Valensise et al., 2020], albeit in a pre-instrumental perspective. Japanese scientist Fusakichi Omori, for instance, supplied crucial observations for constraining the location of the 1908, Messina Straits earthquake (Omori, 1909), whereas the Italian engineer Emilio Oddone provided undisputable evidence for the location and source characteristics of the great 13 January 1915, Avezzano (central Italy) earthquake [Oddone, 1915].

In the late 1960s various workers started performing statistical evaluations, following a concept introduced in the late 1950s by Soviet scientist Riznichenko [1959]; seismic activity was seen as being determined by the number of earthquakes occurring in a given energy interval within an assigned time and space unit. The method was applied to the Apennines seismicity by Riznichenko et al. [1969].

The practice of seismic hazard assessment (SHA) received a great impulse from the 6 May and 15 September 1976, Friuli earthquakes (M_W 6.4 and 5.9, respectively). Soon after, Amato et al. [1976] proposed a first approach at mapping seismic hazard, calculating expected intensity levels with a return period of 1,000 years (Figure 4).

Later on, a study of the same area by Faccioli [1979] considered five large seismic zones. The exercise was based on the original approach by Cornell [1968], and relied on maximum magnitudes and activity rates derived from Ambraseys [1976] and on two ground motion prediction equations (GMPEs) based on the accelerograms written by the 1976 Friuli earthquake. The results were given in terms of horizontal peak ground acceleration (PGA) with a return period of 50 and 500 years (an example of the output for the 50 years return period is shown in Figure 5a). Giorgetti et al. [1980] performed a similar study, relying only partially on the Cornell [1968] approach. They computed the expected shaking in terms of macroseismic intensity from the frequency-intensity distributions observed at each site, without introducing probability distributions (an example of the output for the 50 years return period

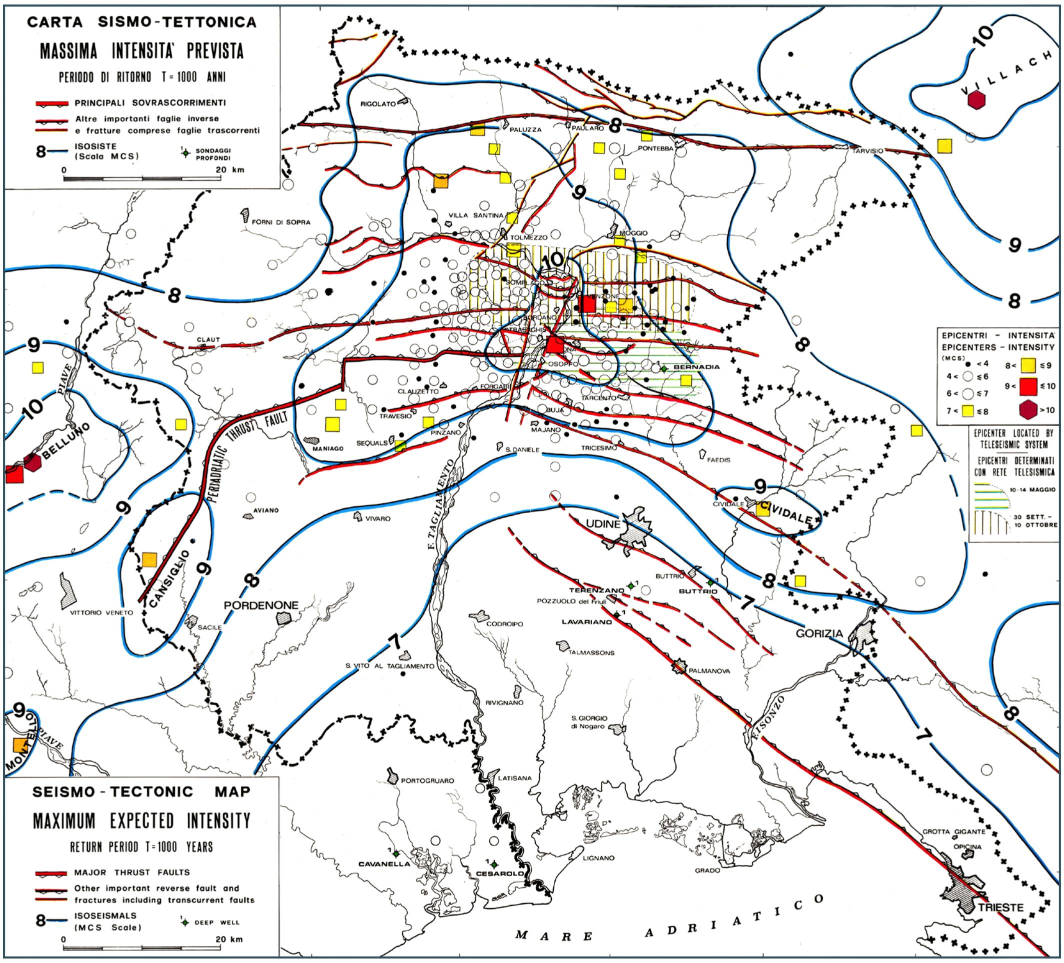


Figure 4. Seismic hazard map of Friuli superimposed on a seismotectonic map, showing the expected intensity levels for a return period of 1,000 years [Amato et al., 1976].

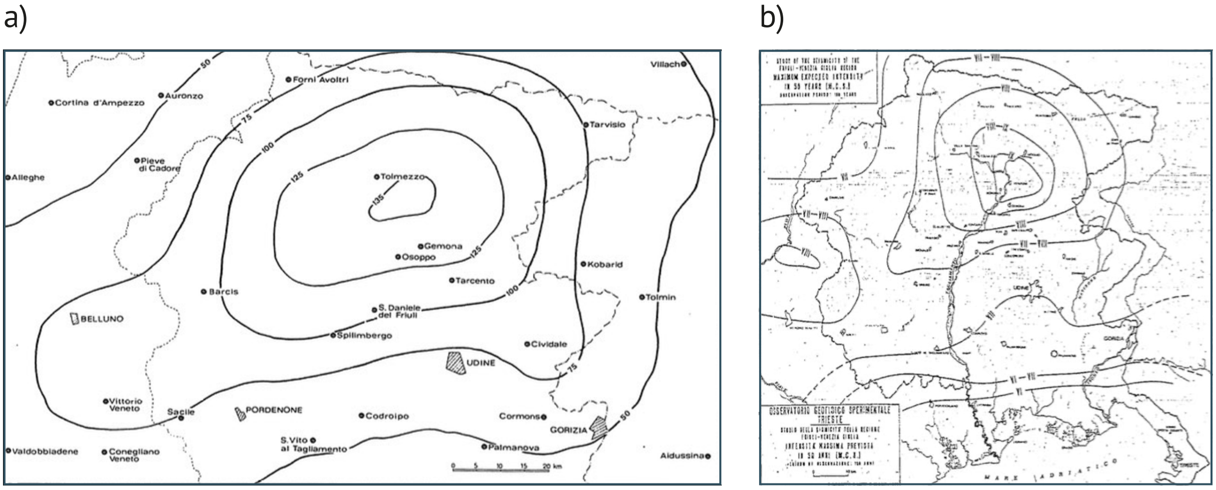


Figure 5. Expected shaking level in 50 years for Friuli (NE Italy): a) PGA [Faccioli, 1979]; b) macroseismic intensity [Giorgetti et al., 1980].

is shown in Figure 5b). Both studies were considered in the planning of the reconstruction of the Friuli villages destroyed by the earthquake.

In the early 1970s, following the inception of Italy's national nuclear program, ENEL (Ente Nazionale per l'Energia Elettrica), the National Electricity Agency, and CNEN (Comitato Nazionale per l'Energia Nucleare), the National Nuclear Safety Committee, started developing multidisciplinary studies aimed at identifying and characterizing a set of potential NPP sites countrywide. Such studies, extended to the whole Italian territory, covered many aspects of seismic hazard including accelerometric recordings, earthquake catalogues [Carrozzo et al., 1972], geodynamic

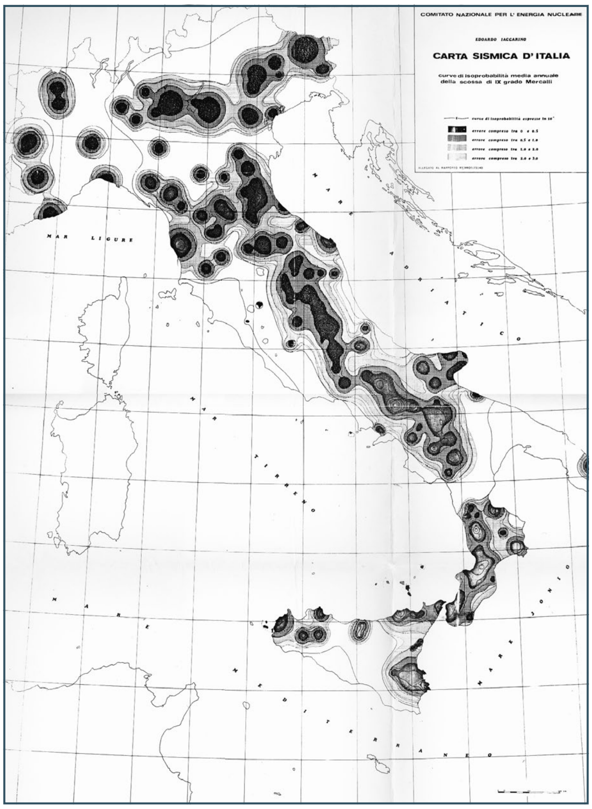


Figure 6. Seismic map of Italy, showing the probability of intensity IX shaking countrywide. The map was elaborated by Iaccarino [1973, 1976] in the framework of the studies performed by CNEN for the identification and characterization of potential nuclear sites.

models, intensity attenuation relations, statistical hazard and risk assessment procedures [e.g. Iaccarino, 1973, 1976; see also Figure 6]. They also supplied basic materials for further investigations.

One of the main objectives of the Progetto Finalizzato Geodinamica (PFG, Finalized Geodynamics Project), a research initiative launched by Italy's Consiglio Nazionale delle Ricerche (CNR) that was operational from 1976 to 1981, was to increase the number of municipalities included in the seismic zones, adding all positively earthquake-prone areas that had not been hit by a large earthquake since 1909. Completing this task was necessary to comply with the 1974 version of building code, which for the first time allowed the seismic zones to broadened based on scientific criteria. The basic information needed to identify and characterize the earthquake-prone areas was supplied by PFG's Structural Model of Italy, a national-scale compilation [Bigi et al., 1983], and later on by the Synthetic Structural-Kinematic Map of Italy [Bigi et al., 1989]; two elaborations that were assembled by a large group of geologists, representing the whole of the Italian academia, and were loaded with lots of data on the recent tectonic evolution of the country and its surrounding seas. Later, other workers developed more specifically hazard-oriented seismotectonic models, such as those by De Vivo et al. [1979], Mantovani and Boschi [1983], and Gasparini et al. [1985].

Meanwhile, based on the lessons learned from the UNDP/UNESCO project 'Seismicity of the Balkan Region (1970-1976)', PFG launched a working group termed Shakeability, with the goal of developing statistical elaborations in terms of macroseismic intensity. The resulting model (Figure 7a), published by Petrini et al. [1980, 1981] on the basis of the hazard results obtained by the Gruppo di Lavoro Scuotibilità [1979], applied the Gumbel statistics on the site intensities computed from the epicentral parameters of the earthquake catalogue developed by CNEN [Carrozzo et al., 1972]. More specifically, for each site, or municipality, the classification procedure relied on the following three parameters:

- the largest macroseismic intensity observed at the site, starting from the year 1000 A.D. (see Figure 1);
- the expected intensity at the given site for a return period of 500 years (see Figure 7a);

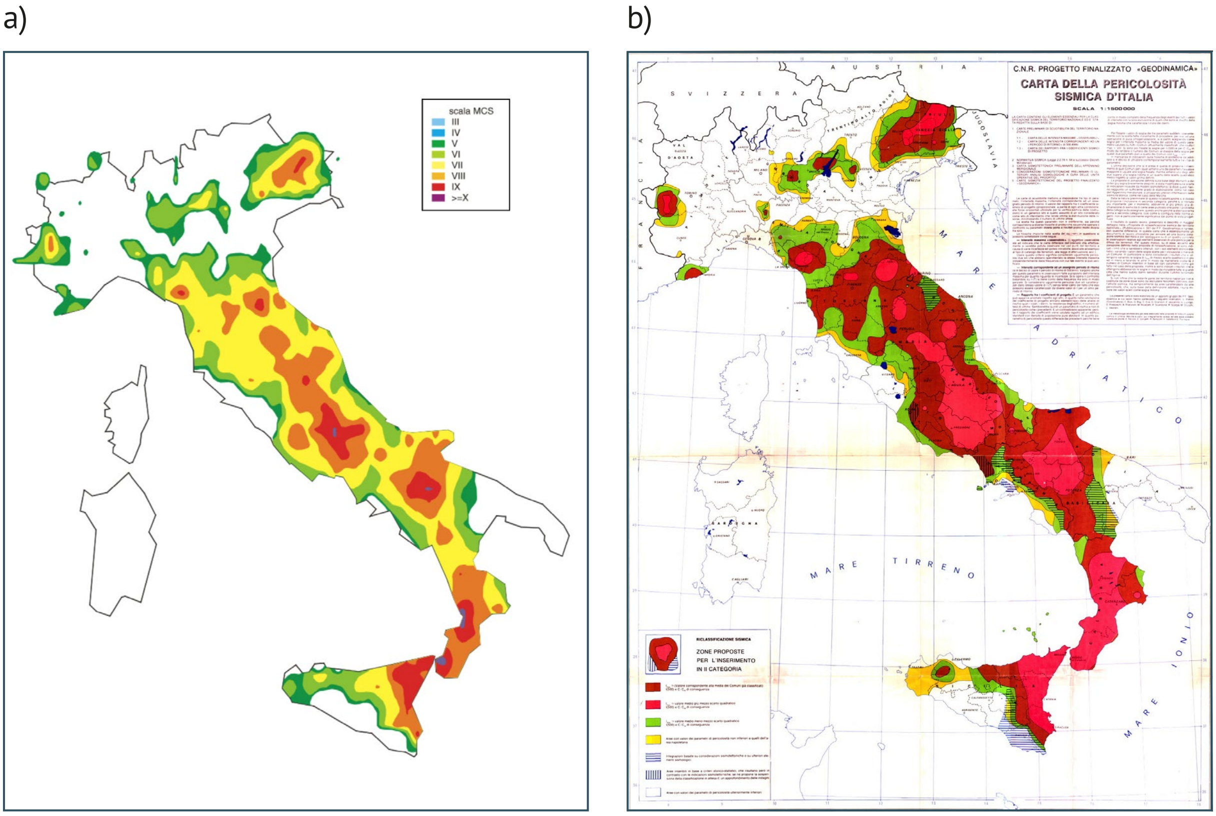


Figure 7. Seismic hazard maps of Italy: a) expected earthquake intensities (MCS scale) for a return period of 500 years (redrawn from Gruppo di Lavoro Scuotibilità [1979]): intensity IX and X areas are shown in red and purple, whereas light green indicates intensity VI; b) seismic hazard map obtained as combination of three parameters [Petrini et al., 1980, 1981].

- an expressly designed *coefficient of cost minimization* (C/C_{rif}), defined as the ratio between the seismic coefficient C assigned to the same site by the new seismic regulations and that attributed to a reference site.

Admittedly, the goal of choosing this ratio was to minimize the number of expected casualties by carefully partitioning the total expenditure planned by the central government for risk mitigation measures.

After the 19 September 1979, Norcia earthquake (M_w 5.8), and following a relevant request by the Italian Government, PFG scientists developed a combination the three parameters adopted by Petrini et al. [1980, 1981], integrated with seismotectonic considerations, to broaden the existing seismic zones: a much needed step, given the sparseness of the areas identified as hazardous simply based on the historical record, yielding the typical 'bull's eye' aspect of the hazard maps of the time (Figure 6).

Soon after the catastrophic 23 November 1980, Irpinia earthquake (M_s 6.9), this elaboration was extended to the whole national territory and compiled in terms of areas to be included into the seismic zonation [Figure 7b; Petrini et al., 1980, 1981]. Although the elaboration was referred to as a 'seismic hazard map', it was not a probabilistic elaboration as we would call it today, but rather the output of the application of statistical elaborations to the procedure for assessing which municipalities should be included in the seismic zones, performed for the benefit of the Italian Government.

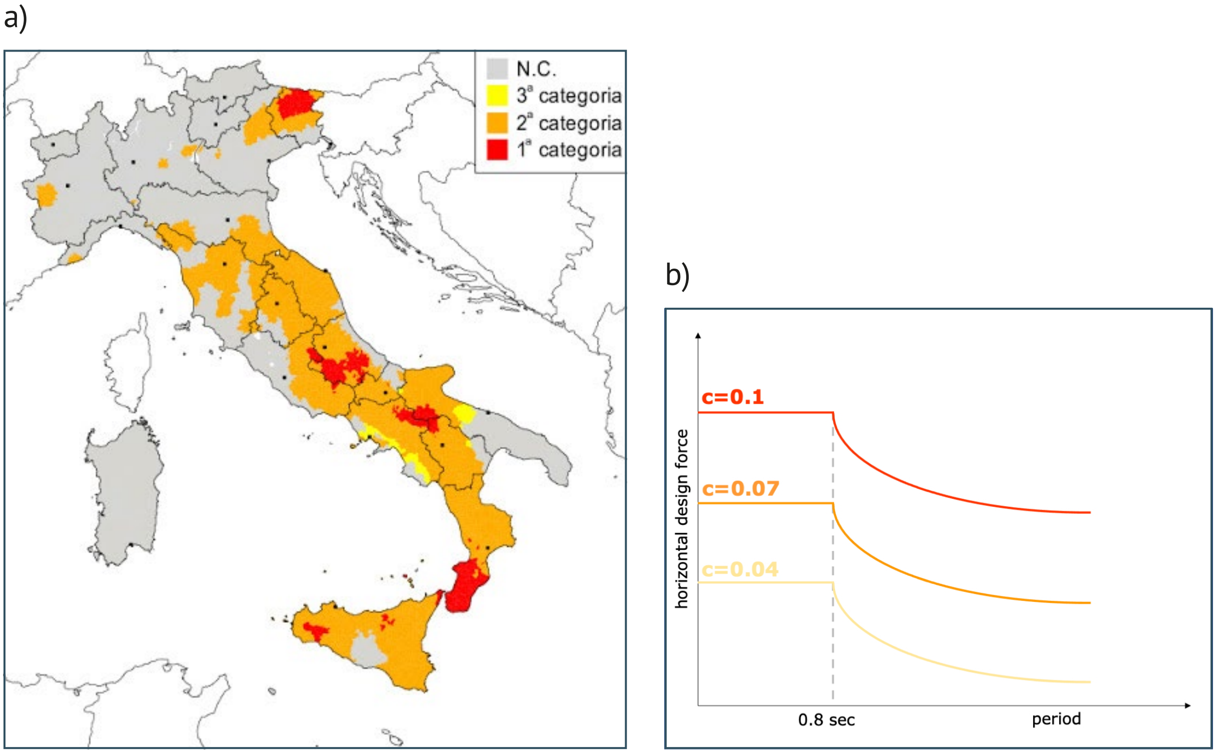


Figure 8. The 1984 Italian building code: a) municipalities included in one of three seismic zones; the grey area includes only unclassified (N.C.) municipalities; b) design spectra associated with each of the three zones (from Meletti et al. [2014a]).

Based on the previously adopted procedure, the Ministry for Public Works first allowed the seismic zones to be extended to all municipalities damaged by the 1980 earthquake. Up to 1980 the zonation was based on two hazard levels, established based on the extent of earthquake damage suffered by each municipality due to previous earthquakes. A third zone was established for Naples and surrounding areas on the basis of the large vulnerability of their building stock, but only in 1984 did the remaining municipalities indicated by Petrini et al. [1981] enter the national seismic zonation. This was a major step forward, although only 40% of the about 8,000 Italian municipalities were finally included in one of the three seismic zones. The whole process is summarized in Petrini et al. [1986]. Figure 8a shows the distribution of the seismic zones, each of which was assigned a design spectrum, partly derived from a limited set of international earthquake recordings (Figure 8b).

The basic materials used by PFG scientists for this elaboration were published later on. The earthquake catalogue was published in 1985 [Postpischl, 1985a]; it consisted of an optimization of the ENEL working catalogue which, in its turn, was constructed by collating and homogenizing the first parametric catalogues compiled in the 1970s, such as the catalogue by Carrozzo et al. [1972]. The PFG catalogue was accompanied by an Atlas [Postpischl, 1985b], providing detailed studies for about 80 major earthquakes. These events were described by isoseismal maps drawn using about 6,300 macroseismic data points; part of these studies were compiled with the help of historians, many of whom, from then on, collaborated steadily with seismologists, creating a rather large and quite unique community of *historical seismologists*.

3. Earthquake source characterization in a seismic hazard assessment perspective

The initiatives taken in the framework of the rising nuclear industry continued over the first part of the 1980s. In 1986 the Chernobyl nuclear accident changed the public attitude towards nuclear power, in Italy as much as elsewhere. The disaster prompted a swift response by the Italian Government: in a referendum held in 1987 the Italians voted to phase out nuclear energy, and all operating plants started being decommissioned. The research initiatives in the area of earthquake hazard were taken over and developed in the frame of more general seismic hazard-oriented projects, mainly run by the Gruppo Nazionale per la Difesa dai Terremoti (GNDT, National Group for the Defense Against Earthquakes) and, even more broadly, of projects run by Istituto Nazionale di Geofisica (ING; renamed Istituto Nazionale di Geofisica e Vulcanologia, INGV, in the year 2000) to promote the assessment of seismicity and the investigation of seismogenic sources.

Two fundamental components of any SHA effort, both of which required a large amount of field investigations, were developed by the Italian seismological community: the creation of a reliable record of historical and early instrumental earthquakes, and the construction of a model of seismogenic sources. Both of these initiatives were primarily designed to serve as a basis for describing the characteristics of the earthquake sources affecting the Italian territory and its surrounding countries and seas.

3.1 The rebirth of Historical Seismology studies in Italy

The compilation of earthquake catalogues started very early in many European countries, and particularly in Italy. In fact, the record of Italian historical seismicity is probably one of the most extensive worldwide, as it draws from a huge, extremely valuable and unique documentary heritage. Its inception is conventionally set around the end of the 17th century [Bonito, 1691], but the Italian earthquake history may rely on sources from the Middle Ages and even from the Antiquity, the latter often complemented by epigraphic and archaeological sources. In the late 1800s, Italian Earth scientists proposed empirical scales for classifying the intensity of earthquake effects objectively, thus turning Historical Seismology into a quantitative science over a century ago, to the point that, in 1901, Antonio Baratta [1901] published a catalogue including nearly 1,400 Italian earthquakes that occurred between the 1st century A.D. and 1898. A comprehensive overview of these activities can be found in Guidoboni and Stucchi [1993], Camassi [2004], and Guidoboni et al. [2019].

It should be stressed that in Italy, historical earthquake data are really crucial, due to the combination of two fundamental reasons. The first is that Italian earthquakes are damaging but also relatively rare, as they are generated by faults whose slip rate is usually smaller than 1 mm/yr, implying that the typical recurrence interval for a repeat of the very same earthquake is in the order of at least a millennium. A longer and densely populated earthquake catalogue hence guarantees that even the rarest events are somewhat represented in the available record. The second is that the identification of Italy's large seismogenic faults is especially complex, due to the youthfulness of the current tectonic regime and to the superposition of the effects of subsequent tectonic events [Valensise and Pantosti, 2001a]. Once again, the availability of a long and rich earthquake record guarantees that there will be an independent way of (a) knowing where the main seismogenic faults are to be found, and conversely (b) assessing whether a clearly expressed fault is still active in the current tectonic regime.

We already mentioned the efforts initiated by CNEN, then continued in the frame of the CNEN-ENEL Committee and finally summarized by PFG. Later, the first project of extensive historical investigations was carried out in

1983-1987 in the frame of an ENEL-sponsored feasibility study for selecting suitable NPP sites. It dealt with several thousand earthquakes and involved a number of academically trained historians, who became the core for the next generation studies.

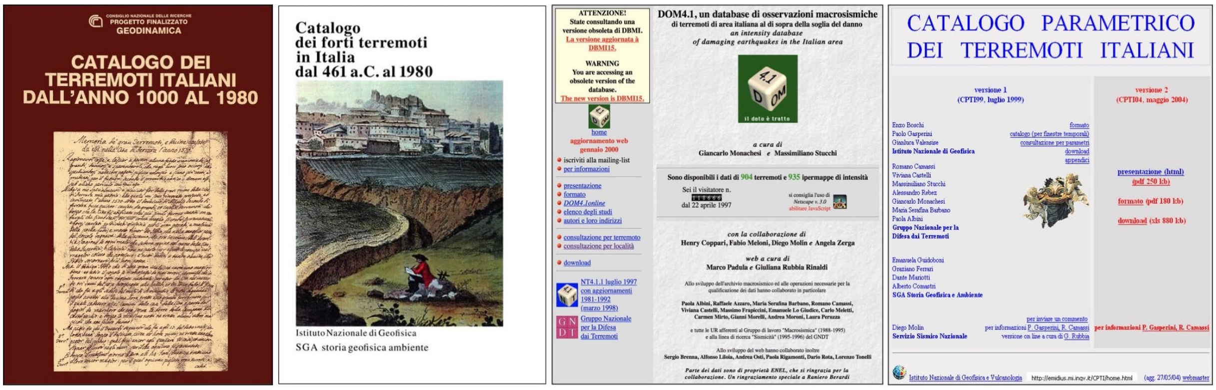
Starting in 1988, ING took the lead and the sponsorship of this project, setting the revision of the strongest Italian earthquakes (macroseismic intensity VIII-IX and above) as one of its primary goals. The main outcomes of this endeavour were a collection of studies on Mediterranean earthquakes before 1000 A.D. [Guidoboni, 1989; Guidoboni et al., 1994], and the first edition of the Catalogue of Strong Italian Earthquakes [CFTI: Boschi et al., 1995: Figure 9], a modern database distributed on a CD-ROM providing studies on 346 major Italian earthquakes. The second edition [Boschi et al., 1997] provided data concerning a total of 559 earthquakes (including some updates on the 1995 issue), whereas the third edition [Boschi et al., 2000] supplied studies for 50 additional earthquakes, mostly located in the Apennines, and several updates of studies included in the previous issues. This compilation was, then, extended with the same criteria to the Mediterranean area [Guidoboni et al., 2007] and later updated [Guidoboni et al., 2018; http://storing.ingv.it/cfti/cfti5/#].

While the above project was mainly devoted to the strongest and damaging earthquakes, in 1986 a GNDT working group started a project for updating the whole Italian catalogue (Figure 9). A preliminary version of this catalogue, to be used specifically for SHA(recall the the Cornell [1968] PSHA approach, adopted by GNDT, requires that the earthquakes follow a Poisson distribution; hence all foreshocks and aftershocks were removed from the catalogue), was delivered in 1993 [Stucchi and GNDT Macroseismic Working Group, 1993]. The consolidated catalogue appeared in 1997 (in 1998 also on-line, with the code NT4.1), along with its full reference database, termed Database of Macroseismic Observations, or DOM [Monachesi and Stucchi, 1997; http://emidius.mi.ingv.it/DOM/]. DOM featured more than 36,000 data points relating to about 1,000 damaging Italian earthquakes, and included earthquake studies performed both by members of the GNDT working group and by other investigators; it was the first on-line macroseismic database in Europe, although not the first worldwide [Rubbia, 2004].

Another important outcome of this long phase of investigations was the ‘Carta delle massime intensità macrosismiche osservate nei comuni italiani’ (Map of the maximum earthquake intensity observed in the Italian municipalities; Figure 10), published by Molin et al. [1996].

In 1999, part of the CFTI database joined the DOM database, giving birth to a *consensus* parametric catalogue called ‘Catalogo Parametrico dei Terremoti Italiani’ [CPTI, Parametric Catalog of the Italian Earthquakes: CPTI Working Group, 1999].

Following the inception of INGV in the year 2000, the new institution took the lead of collecting, homogenizing and making available through the Internet the results of the new macroseismic studies which were being made available by individual investigators, research groups and institutions. The first release of the DBMI (Database Macrosismico Italiano), an advanced version of the DOM 4.1, was made available in 2004 and later published



PFG Catalogue CFTI (on CD-ROM) DOM 4.1 (on web) CPTI Catalogue

Figure 9. Front page of the PFG [Postpischl, 1985a], CFTI [Boschi et al., 1995], DOM [Monachesi and Stucchi, 1997], and CPTI [CPTI Working Group, 1999] catalogues/databases. The PFG [Postpischl, 1985a] and CPTI [CPTI Working Group, 1999] catalogues were published as printed volumes and computer files. The CFTI catalogue [Boschi et al., 1995, 1997, 2000] was initially published as a CD-ROM, and since 2007 [Guidoboni et al., 2018] as a Web-GIS. DOM 4.1 was the first macroseismic database to be published on-line in Europe.

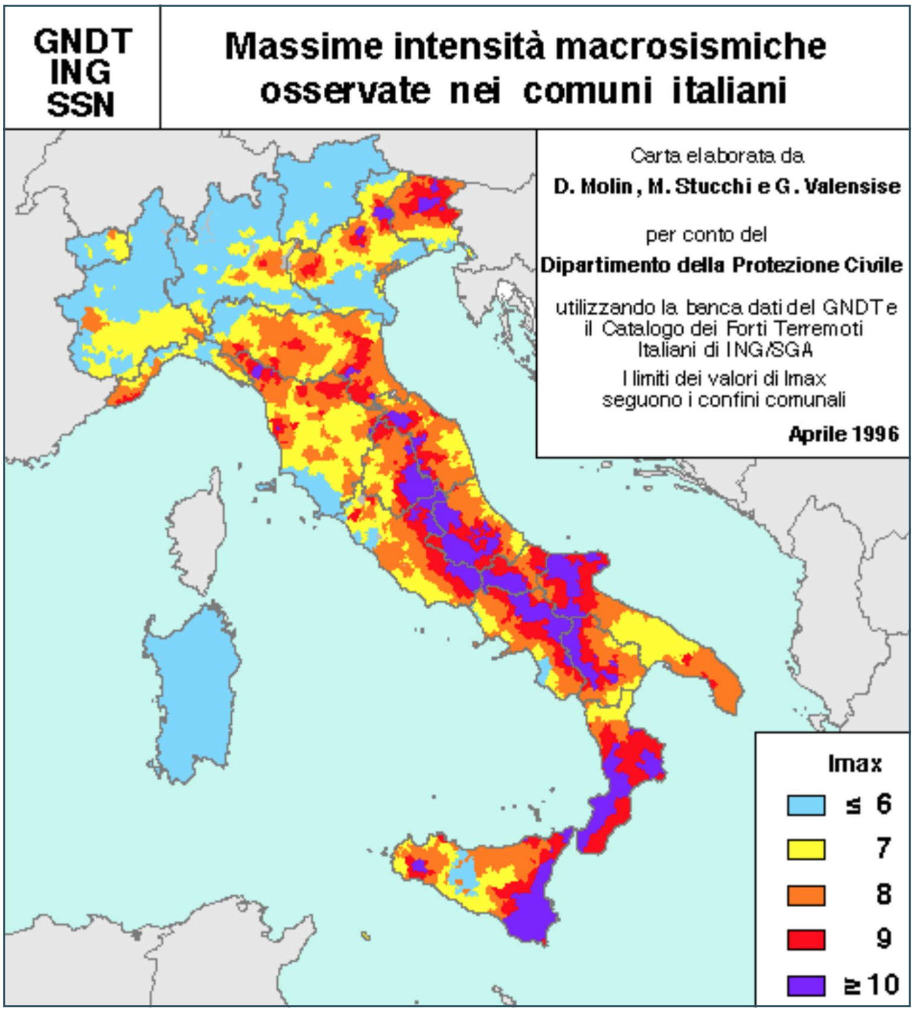


Figure 10. Map of the maximum earthquake intensity observed in the Italian municipalities [Molin et al., 1996].

[Stucchi et al., 2007] along with a new version of the catalogue itself (CPTI04: CPTI Working Group [2004]). Both the database and the catalogue were updated several times in the following years, until very recently [Locati et al., 2011, 2016, 2021, 2022; Rovida et al., 2011, 2016, 2019, 2020, 2022].

The availability of orderly sets of earthquake intensities stimulated the development of computer codes designed to determine objectively all earthquake parameters [Bakun and Wentworth, 1997; Gasperini et al., 1999]. The latter code, termed *Boxer*, included a simplified determination of the surface projection of the earthquake causative fault, that is to say, an equivalent seismogenic source defined through its strike and length, respectively obtained from the elongation of the intensity pattern and from the inferred magnitude [see Valensise et al., 2020, for an overview of these methods]. These procedures allowed seismologists to make a step forward and move beyond any personal or expert judgement.

Taking advantage of the Italian experience, INGV led the compilation of the 1000-1900 time-window of the European Earthquake Catalog SHEEC [Stucchi et al., 2013], putting together and homogenizing the macroseismic data points available throughout Europe [available through AHEAD: https://www.emidius.eu/AHEAD/: see also Locati et al., 2014] and determining earthquake parameters primarily using *Boxer* but also the method set forth by Bakun and Wentworth [1997], following a proper calibration [Gómez Capera et al., 2015].

3.2 Earthquake sources: area source delineation and characterization

Until the late 1980s, in most European countries the main contribution of the geological community to SHA generally included the identification of a set of Quaternary or Neotectonic faults and the preparation of fault maps, generally at regional or even national scale. Italy made no exception to this rule. In the 1980s the Italian Earth Science community elaborated major national compilations of fault distribution and active tectonics. This massive effort formed the basis for many and diverse applications in the Earth Sciences; due to their scale, however, these compilations could not be of immediate use for improving seismic hazard estimates through the identification of individual seismogenic faults and the assessment of their slip rate.

For all of these reasons, the early modern seismic hazard models were based on area sources belonging to a *seismic source zonation,* i.e. a model obtained by drawing a number of polygons over a seismically active territory [Cornell, 1968; Bender and Perkins, 1987]. Each polygon had a potentially irregular geometry, reflecting the complexity of major tectonic trends, and was meant to encompass an area within which seismicity could be considered homogeneously distributed in space. These models relied only marginally on the identification of actual faults or fault lines, in recognition of the limited knowledge available in most countries on their actual distribution.

The first official Italian model built following these rules was termed ZS4 (Figure 11), completed in 1993 and intended as a basis for the hazard model PS4 [Meletti et al., 2000]. ZS4 was indeed quite innovative, as it was drawn based on a kinematic evolutionary approach [Patacca et al., 1990; Scandone et al., 1992; Cinque et al., 1993], rather than just following the neotectonic structural features and earthquake patterns available at the time. Its 80 zones outlined a few mega-trends striking parallel to the Alps and to the Apennines, crossed by a number of transverse transfer zones. Based on their expected kinematic behavior, they were subdivided into compressional, extensional, or volcanic.

ZS4 was very popular amongst SHA practitioners and seismotectonic experts, and remained such until the year 2000, when the knowledge on active faulting in the Italian territory that had been accumulated during the 1990s was finally organized and presented in a number of comprehensive papers and databases [e.g. Galadini et al., 2000,

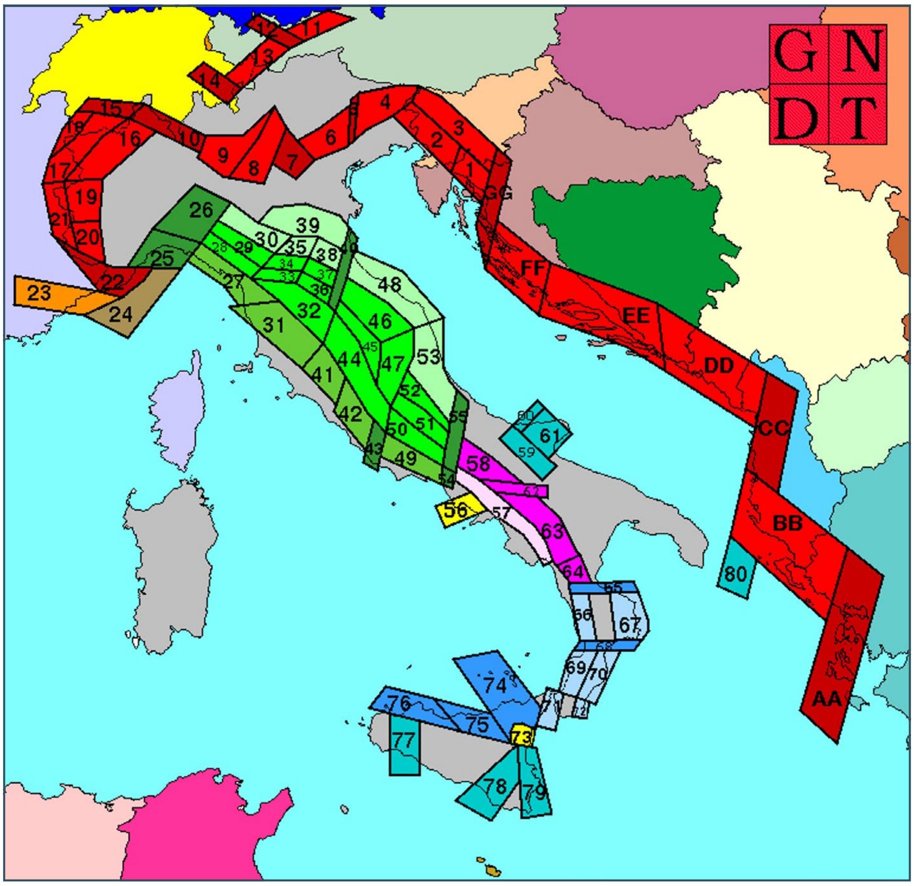


Figure 11. The ZS4 seismic source zonation model used for the PS4 project, described by Slejko et al. [1999] and Meletti et al. [2000]. It included the entire Italian peninsula but was also extended to the neighboring countries, and particularly to Slovenia, Croatia, Albania, and parts of Greece in the frame of the Global Seismic Hazard Assessment Program (GSHAP).

2001; Meletti et al., 2000; Valensise and Pantosti, 2000, 2001a, 2001b]. At that time the boundaries of many zones were seen to be crossed by positively identified seismogenic faults. Even larger inconsistencies arose from the new data available on various areas of peninsular Italy.

The availability of a wealth of new and homogeneously collected data on seismogenic processes stressed even further the need for replacing ZS4 with an updated seismic source model. The need for devising an updated SHA

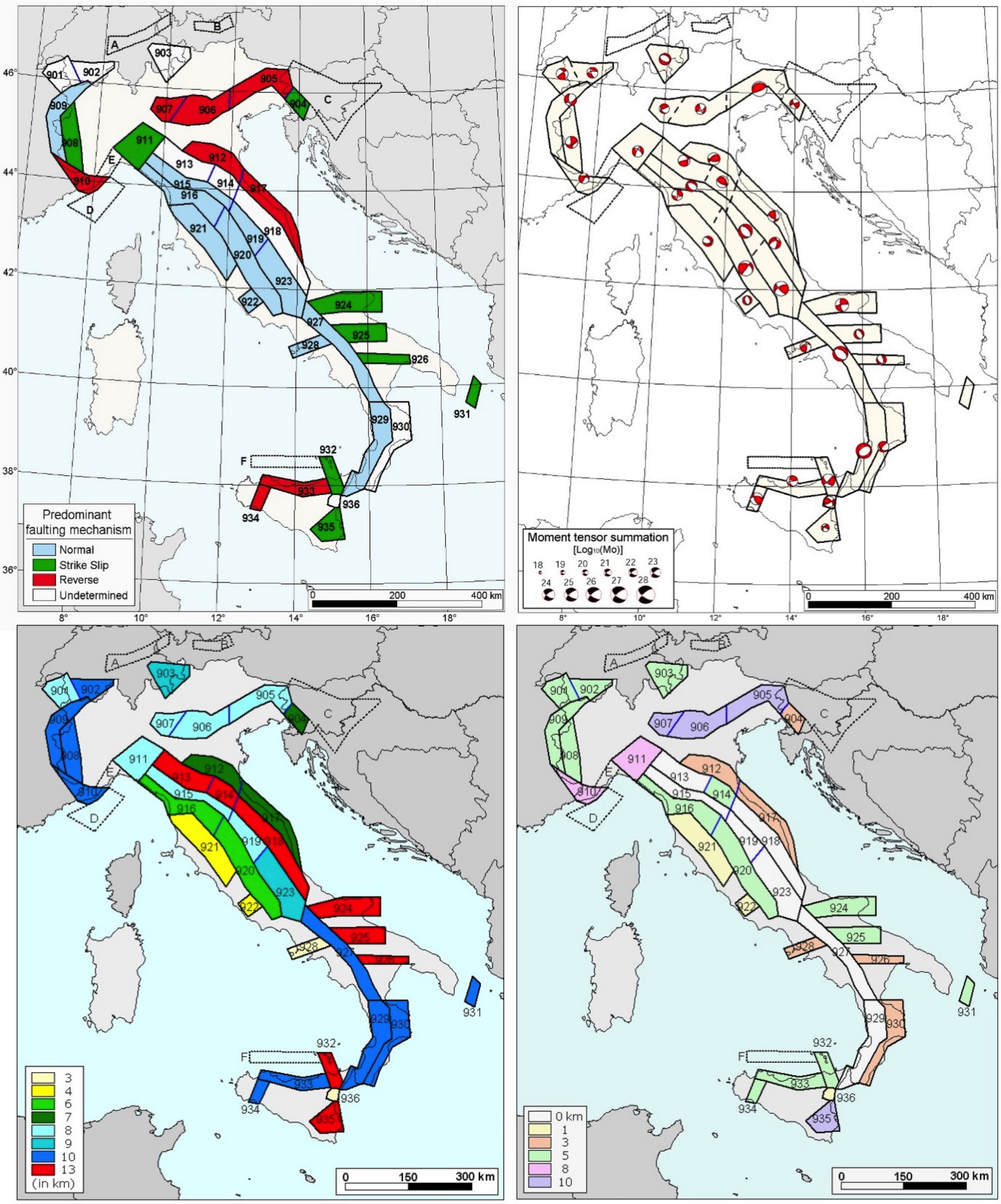


Figure 12. The ZS9 zonation model [Meletti et al., 2008]: distribution of the source zones and relevant parameters. Upper panels: predominant faulting mechanism (left) and cumulative moment tensor obtained from Kostrov's formula (right). Lower panels: effective depth (left) and classes of uncertainty associated with the location of the zone boundaries (right).

scheme became inevitable after the tragic collapse of a school caused by the 31 October 2002, M_W 5.8, Molise earthquake [Maffei and Bazzurro, 2004], which made the scientific community aware of the number and importance of unknown seismogenic faults crossing the Italian territory.

The updated model, termed ZS9 [Meletti et al., 2008] was designed to be consistent with the general background delineated by the geodynamic model proposed by Meletti et al. [2000], but incorporated all recent advances in the understanding of the active tectonics of the Italian peninsula and on the distribution of seismogenic sources delineated in the Database of Italy's Seismogenic Sources (DISS) and other active fault compilations at national and regional scale (Figure 12).

ZS9 also benefited from the results of the investigations carried out in the previous ten years on many significant earthquakes, some of which had rather unexpected seismotectonic characteristics and, more importantly, fell outside the seismic source zones defined in ZS4.

ZS9 included 42 zones, nearly 50% of those featured in ZS4, and was designed also to address a number of outstanding issues not considered in previous efforts, which included (see Figure 12):

- estimating reliable seismicity rates from the limited earthquake samples that are typical of small zones;
- supplying an estimate of the average seismogenic depth for each zone, to be used with regionalized attenuation relationships calculated with respect to hypocentral distance;
- providing an estimate of the predominant focal mechanism of each zone, to be used with the attenuation coefficients calculated as a function of the rupture mechanism by Bommer et al. [2003]; and
- avoiding abrupt and unrealistic changes in the estimated hazard across the boundaries with France, Switzerland, Austria, Slovenia, and Croatia.

3.3 Earthquake sources: active fault and seismogenic source models

Soon after the publication of the Structural Model of Italy [Bigi et al., 1983], various independent groups started investigating the catastrophic, yet geologically obscure, 23 November 1980, Irpinia earthquake (M_S 6.9), one of the largest Italian earthquakes of the 20th century [e.g. Westaway and Jackson, 1984; Pantosti and Valensise, 1990]. Meanwhile, Serva et al. [1986] conducted a detailed investigation of surface ruptures generated by the 13 January 1915, Avezzano earthquake (M_W 6.8), while Ward and Valensise [1989] confirmed the normal faulting kinematics and the extent of the earthquake rupture using historical geodetic leveling observations. Also the 28 December 1908, Messina Straits earthquake (M_W 7.1) was investigated using leveling observations [Mulargia and Boschi, 1983; Capuano et al., 1988]. The results of those studies, the positive identification of a limited number of surface breaks, the development of a simplified fault segmentation model for the most active portion of southern Italy [Pantosti and Valensise, 1989], and the excavation of the first trenches across a historical fault rupture [Pantosti et al., 1993] marked the onset of Paleoseismology in Italy.

The late 1990s and early 2000s were marked by the development of GIS-based fault catalogues and fault databases: extensive compilations at national or regional scale that aimed to blend conventional tectonic and fault information with paleoseismological results and, in some cases, with historical and instrumental earthquake data [Galadini et al., 2000, 2001; Michetti et al., 2000; Valensise and Pantosti, 2000, 2001b]. During the same years, however, several earthquakes generated by blind faults showed that fault compilations based on near-fault geological observations are necessarily incomplete; therefore as much as 60-70% of the potential earthquake sources in Italy, and nearly 100% of those occurring offshore, were bound to be missed.

The earliest attempt to document information on seismogenic sources is the DISS [Valensise and Pantosti, 2000]. Its fundamental goal was to blend seismogenic sources identified by a variety of geological and geophysical data with sources based purely on instrumental and macroseismic data (Figure 13). Meanwhile, GNDT developed a database of active faults [Galadini et al. 2000, 2001; Meletti et al., 2000]: this effort used geologic evidence to map and characterize a large number of active faults, but did not attempt to provide a segmentation model. ITHACA [Michetti et al., 2000], another database prepared by scientists with ANPA (Agenzia Nazionale Protezione Ambiente; later APAT, then ISPRA), was also essentially geology-based and focused specifically on capable faults, i.e. faults that are expressed at the surface, and on the associated potential hazard for infrastructures and critical facilities.

The rationale of the DISS database (Figure 14), which has been progressively updated over two decades [Basili et al., 2008; DISS Working Group, 2021], relied on two principles: (a) given the complexity of Italian geology and tectonics, the investigation of seismogenic sources should begin from the areas that have been hit

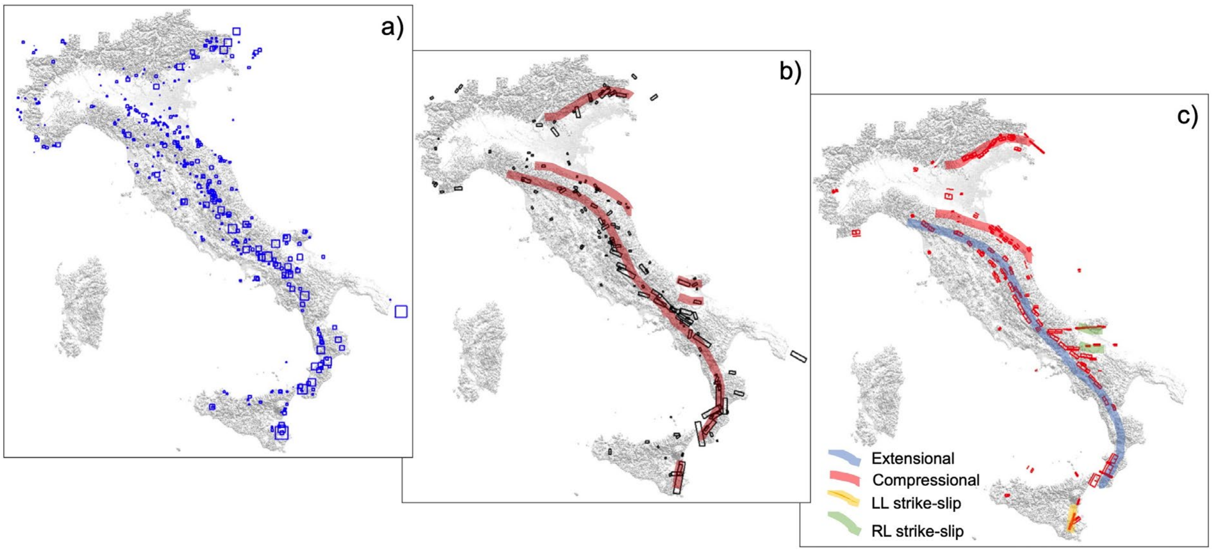


Figure 13. Main steps leading to the elaboration of the first version of the DISS [from Valensise et al., 2020]: a) representation of historical seismicity known at the time; b) intensity-based seismogenic sources obtained from the seismicity shown in a) using the Boxer code, and main tectonic trends they revealed; c) geological-geophysical seismogenic sources.

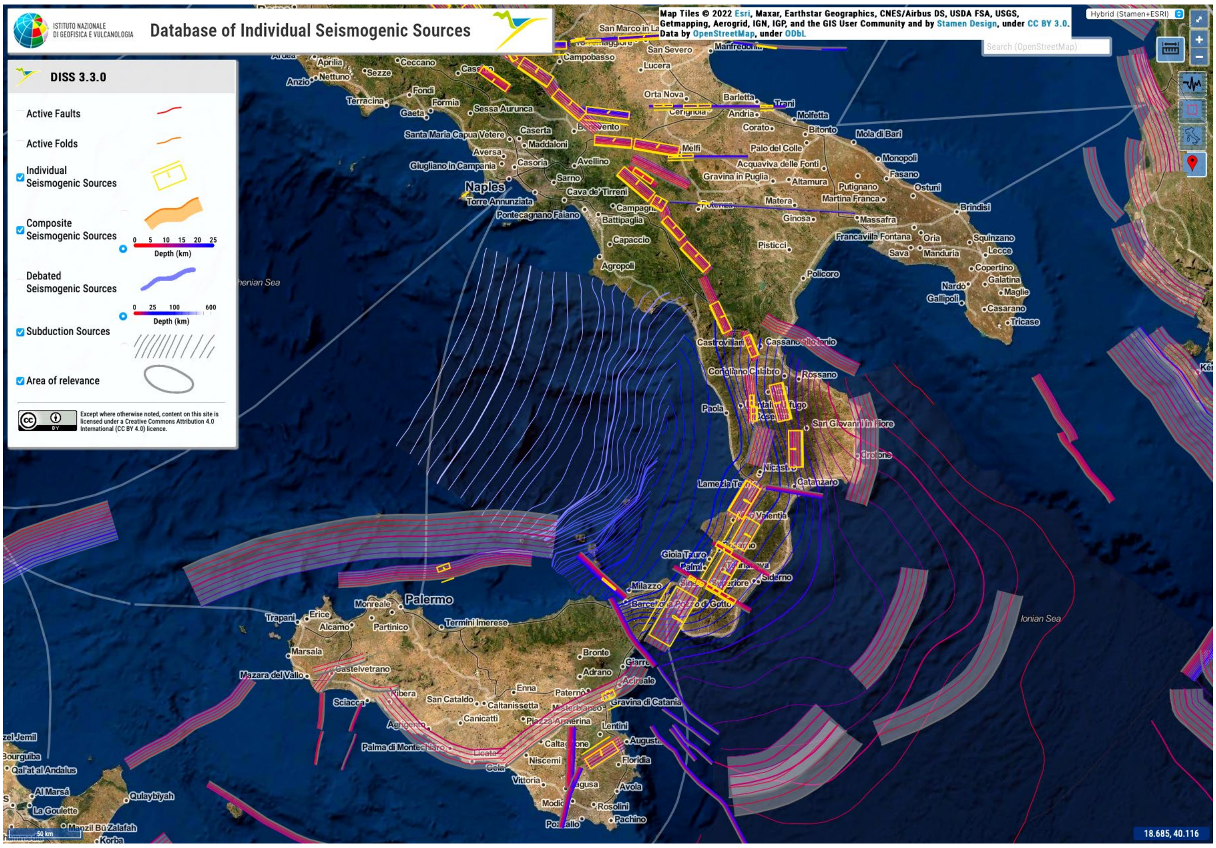


Figure 14. The latest version of the DISS [v. 3.3.0: https://diss.ingv.it] was specifically developed to serve as input for the MPS19 seismic hazard model [Meletti et al., 2021]. Over the years the original information derived from historical information has been greatly extended based on a large body of geological and tectonic evidence. DISS 3.3.0 features 132 ISSs, 197 CSSs, 4 Subduction Zones, and 38 Debated Sources, along with~990 equivalent pages of documentation and over 4,000 bibliographic entries.

by an instrumental, or recent historical, earthquake, and only later should it be expanded to presumed active but seismically silent areas; and (b) only earthquakes of magnitude 5.5 and larger provide evidence for the highest-hierarchy level of active crustal deformation, reducing and summarizing the geological complexity created by the interplay of secondary tectonic processes, local stress fields and strictly surficial processes. These relatively large earthquakes account for the evolution of the youngest geological deposits and processes and of landscape features at the scale of large crustal faults (10-50 km), allowing major seismogenic faults to be identified even if they lack a primary surface expression.

The need for compiling information on potential seismogenic sources, rather than simply on generic active faults, also rests on the consideration that a significant crustal earthquake generates three independent categories of effects: (a) strong ground shaking, that is transient but affects the largest area (roughly, fault size × 10); (b) surface deformation, that is permanent and affects a rather large area (roughly, fault size × 2), causing limited damage; and (c) surface rupture, that is permanent and affects a limited area (shorter than fault length and usually tens of meters-wide), but may produce significant damage or collapse even in earthquake-resistant buildings, infrastructures and critical facilities. The fundamental purpose of any SHA is to predict the location, magnitude and spatial extent of some or all of these undesirable earthquake effects.

DISS was conceived and developed to allow an effective separation of these effects through its key-elements: the Individual Seismogenic Source (ISS), that was meant to represent the causative fault of a specific-size, nearly-characteristic earthquake, either historical or expected; and the Composite Seismogenic Source (CSS), a more loosely constrained, unsegmented fault system capable of generating earthquakes of variable size. As such, the ISSs are suitable for calculating deterministic hazard scenarios, whereas the CSSs have been used as an independent branch in various probabilistic SHA programs, and particularly for the elaboration of the new MPS19 national seismic hazard model [Meletti et al., 2021]. More specifically, current PSHA approaches – at least in Europe – consider CSSs as capable of generating earthquakes of different size, following a specific MFD; conversely, the ISSs, which are defined as capable of generating only large and hence extremely rare events, are generally not considered by such approaches.

Over time, the results obtained by GNDT were largely incorporated in the DISS database, which in 2011 was used as a basis for developing the European Database of Seismogenic Faults (https://edsf13.ingv.it/) in the framework of the EC-funded project SHARE. The ITHACA database (http://sgi2.isprambiente.it/ithacaweb/viewer/) has been further developed to serve as a basis for microzonation surface faulting hazard assessment studies; an ongoing project run by DPC will eventually make the DISS and ITHACA databeses mutually and fully interoperable (https://diss.ingv.it/ithdiss/).

3.4 Earthquake sources: the ensemble model

The most recent step in the SHA of Italy is represented by the recently published MPS19 model [Meletti et al., 2021], which will eventually replace MPS04. Unlike all previous models, this initiative involved a very large community formed by about 100 researchers from a number of different institutions, working side by side for nearly three years. This model merges the previous models based, respectively, on zones and faults introducing also additional ingredients. More precisely, MPS19 utilizes the best data and practices among all those described in the previous three subsections, plus a wealth of geodetic, seismological, seismotectonic, surface and subsurface geological data (Figure 15), only part of which were used in the previous efforts described in this paper.

The main characteristic of MPS19 is the adoption of several independent earthquake rupture forecast (ERF) models based on different data and approaches. This innovative choice was made possible by the circumstances delineated above, which make the MPS19 exercise certainly unique in Europe, and very advanced with respect to the best practices adopted worldwide.

The decision to involve multiple scientists, groups and approaches was made in recognition of the inherently subjective nature of traditional source models, based on legitimate operating decisions by their authors and, therefore, compiled following non-standard and non-reproducible procedures. The project coordinators asked several research groups to elaborate their own independent ERF models, so as to explore the inherent and inevitable epistemic uncertainty characterizing this important input element of any probabilistic SHA (PSHA) effort. The 11 proposed ERFs include five elaborations based on area sources and two based on an updated version of the DISS, complemented by two standard zoneless smoothed seismicity models, and by two purely GPS-based elaborations.

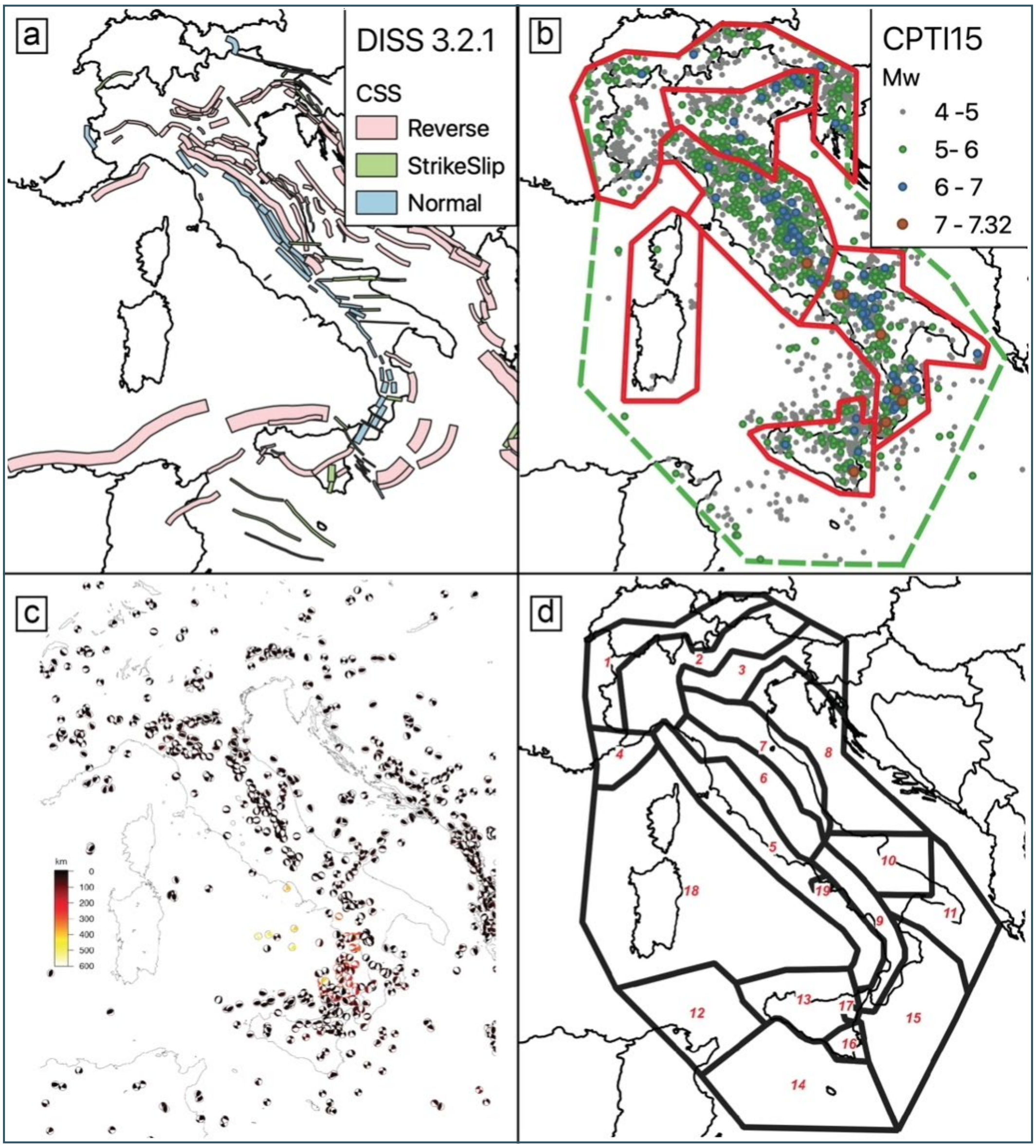


Figure 15. Individual data sets used to construct the ERF models for MPS19: (a) CSSs from DISS 3.2.1, colored according to their kinematics; (b) CPTI15 [Rovida et al., 2020] earthquake catalogue (the green dashed polygon indicates its area of relevance: red polygons are areas of homogeneous completeness); (c) focal mechanisms; (d) tectonic domains are used to the compute Mmax, the dominant seismogenic depth and the depth distribution [Visini et al., 2021].

The 11 ERFs were weighted by an elicitation procedure and by consistency tests. The elicitation procedure aimed at investigating if an ERF may be considered valid from a group of experts. Consistency tests were performed to evaluate whether the average rate and uncertainty obtained for each ERF describes satisfactorily the spatial distribution of seismicity and the total number of events in the last centuries. The final weight given to each ERF is a combination of the elicitation and the consistency weights.

The characteristics of all seismicity models adopted for MPS19 are described in detail in Visini et al. [2021], along with their output. The results of this exercise are based on a few basic principles and observations:

- in the areas where the information available on earthquakes and faults is more robust all the approaches appear to be rather consistent with each other;
- on the contrary, in all areas that are not clearly illuminated by the available data, the spread among models increases, even if each area source model is fully consistent with the historical observations selected for a sanity check.

4. The GMPEs in the italian seismic hazard models

Similarly to the knowledge on the characterization of seismic sources, also the available information on earthquake ground shaking has increased dramatically over the past 30 years, due to the improvement of accelerometric networks. Therefore, the number of ground motions relationships available in the literature also increased. With respect to older works, the most recent models benefited from the availability of recordings for a larger number of relatively earthquakes (Figure 16), and the continuous growth of the networks increased the chances of the instruments being located very close to the earthquake causative fault or directly above it [Valensise et al., 2021].

As the adoption of the GMPEs is a major source of uncertainty in any seismic hazard assessment scheme, several Italian workers preferred to use stable, peer reviewed relations rather than developing new models for Italy, even if such new models could rely on substantially larger and more reliable datasets than those available in the literature.

The epistemic uncertainty of GMPEs is generally assessed by selecting several models and then combining their predictions with a logic tree approach. In most Italian SHA efforts the selection takes into account the general characteristics of the models and the distribution of the data they are based on, both geographically and in terms of magnitude range of the recorded earthquakes.

For the outputs in terms of PGA the PS4 project [Slejko et al., 1998] adopted the Sabetta and Pugliese [1987] and the Ambraseys [1995] relationships, respectively based on Italian and on European recordings.

The MPS04 project [Stucchi et al., 2011] adopted three sets of relationships: an updated versions of the original Sabetta and Pugliese and Ambraseys equations [Sabetta and Pugliese, 1996; Ambraseys et al., 1996], plus a model derived from the papers by Malagnini and coworkers, who derived their regionalized relationships from Italian strong- and weak-motion observations [Malagnini et al., 2000, 2002; Morasca et al., 2002]. All the relationships were adapted for use with hypocentral distance and then converted into tables containing discretized pairs of magnitude and distance, as required by the SEISRISK III code [Bender and Perkins, 1987].

The authors of the MPS19 project [Meletti et al., 2021] identified three GMPEs for active crustal regions, following a thorough analysis of all models available in the literature and after testing their performance against the actual

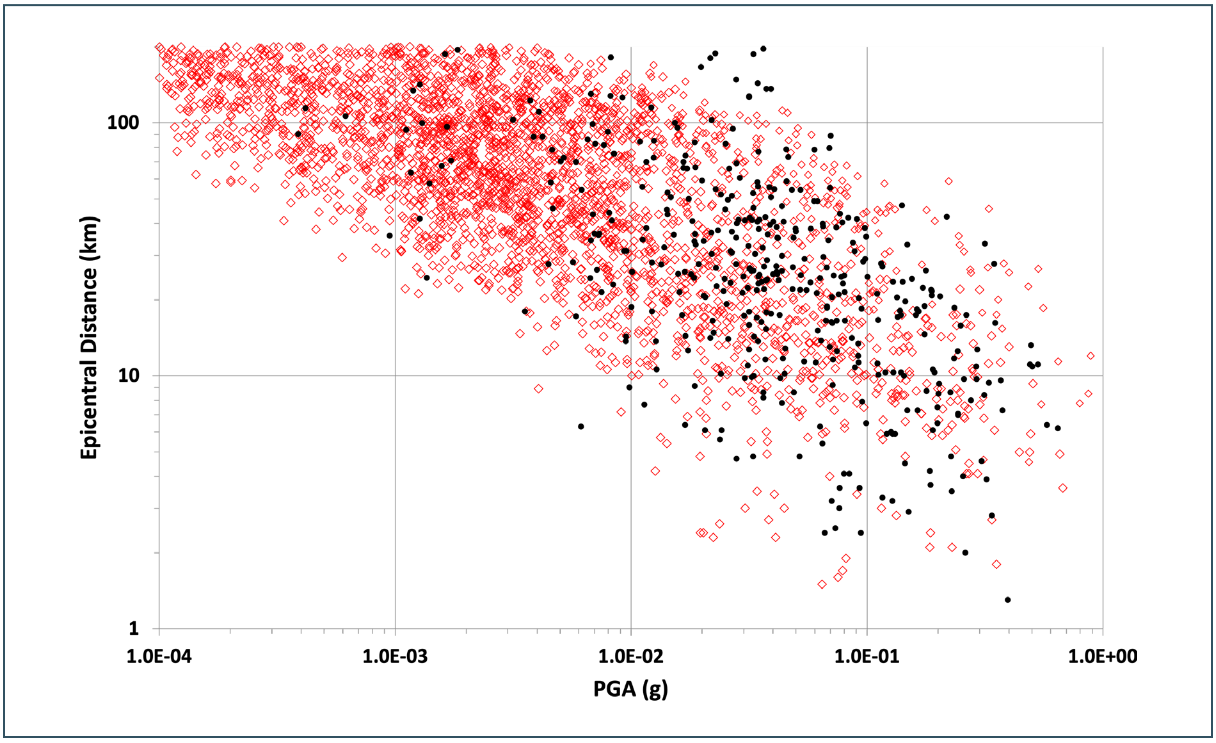


Figure 16. Accelerometric recordings in the Italian ITACA database [http://itaca.mi.ingv.it/ItacaNet_31/]: recordings in the time window 1976-2004 (when MPS04 was released) are shown in black; recordings in the time window 2005-2016 (when MPS19 project started), are shown in red.

observations, as described in Lanzano et al. [2020]. The selected models are those by Bindi et al. [2011], based on Italian accelerometric recordings and using the Joyner-Boore distance; Bindi et al. [2014], based on European data and using hypocentral distance; Cauzzi et al., [2015], based on worldwide data and using the rupture distance. This choice allowed Meletti and coworkers to take into account both the fluctuations arising from the use of different datasets and those related to the adopted distance metric.

Figure 17 shows the comparison between the models adopted in MPS04 and MPS19 (the relationships adopted in PS4 are very similar to the new versions used in MPS04; the model by Malagnini and coauthors is not shown since it is not available in parametric form). On the one hand, the plots clearly show the different behavior with distance of the older models with respect to the more recent ones; on the other hand their aleatory uncertainties (i.e. the standard deviation of the GMPEs) are larger in the models adopted in MPS19; as a result, the new models predict larger shaking, especially for large magnitude earthquakes.

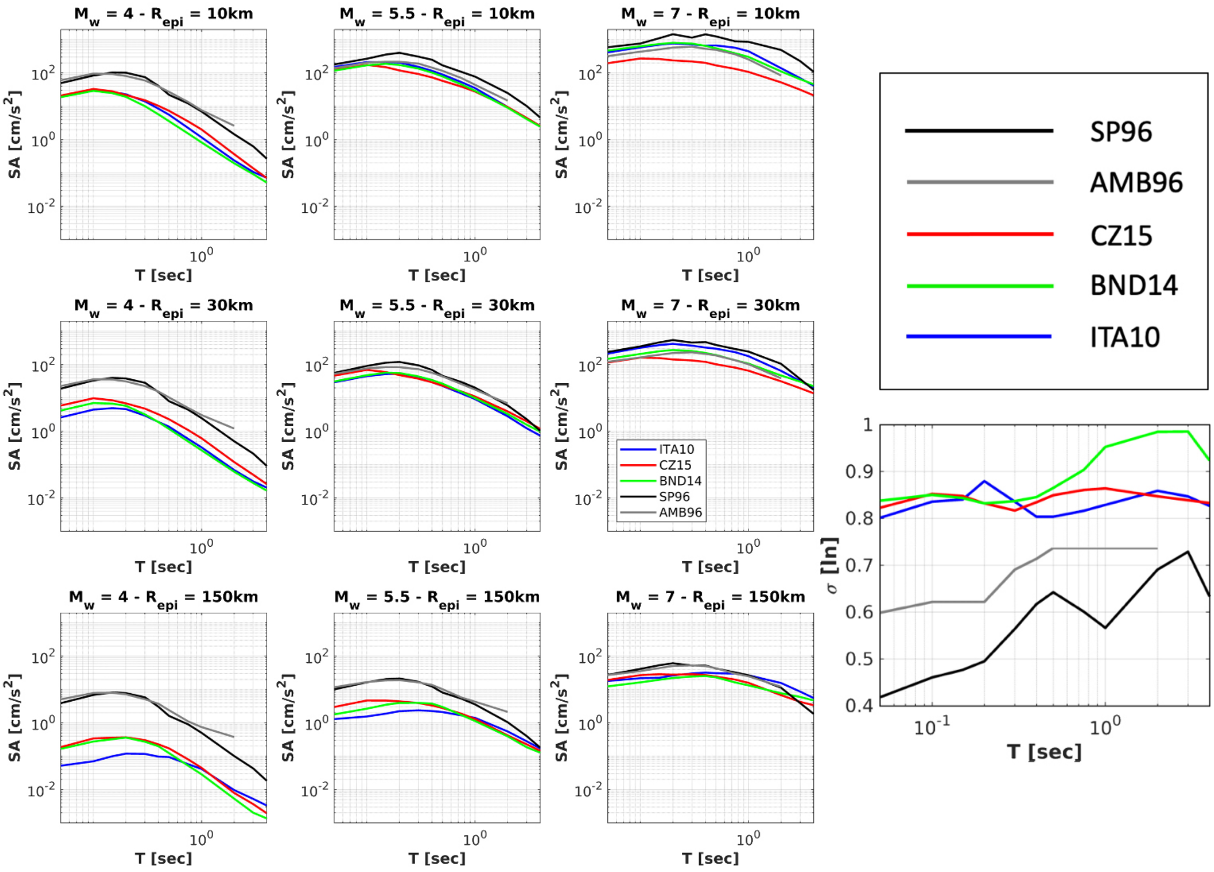


Figure 17. Comparison between GMPEs adopted in MPS04 for different magnitudes and distancesand GMPEs adopted in MPS19. Key to the codes: AMB96 [Ambraseys et al., 1996]; SP96 [Sabetta and Pugliese, 1996]; ITA10 [Bindi et al., 2011]; BND14 [Bindi et al., 2014]; CZ15 [Cauzzi et al., 2015]. The left panels show the trellis plot for normal faulting and for soil class A. The right panel shows the sigma for different periods. Elaboration by Giovanni Lanzano [2022, personal communication].

5. Hazard assessment in view of the building code

After the pioneering PSHA study developed by the PFG community in the late 1970s [Gruppo di Lavoro Scuotibilità, 1979] and summarized in the seismic hazard map based on the Gumbel approach (see Figure 7a), new emphasis was given to SHA starting in the second decade of the 1980s by GNDT, and later on by INGV. In the following we will briefly describe the main steps in the history of Italy's SHA.

5.1 The GNDT probabilistic seismic hazard model PS4 (1991-1996)

The hazard model named PS4 was constructed following the approach often referred to as *seismotectonic probabilism* [Muir-Wood, 1993], and developed in a homogeneous fashion based on all the recommendations of the adopted methodology [Cornell, 1968], resulting in a set of maps in terms of PGA and macroseismic intensity [Slejko et al., 1998]. Although PGA is considered a fundamental seismic hazard parameter in current building codes, macroseismic intensity was also considered, for two main reasons: (a) at the end of the 1990s, seismic hazard was expressed exclusively in terms of intensity in over 60% of the countries worldwide [McGuire, 1993]; and (b) the macroseismic information available for Italy is extremely rich, spanning nearly 10 centuries of earthquakes occurring close to important cultural centers and to monuments, churches, and other landmarks that in many cases still exist today.

The input was based on a standard seismotectonic zonation and parametric catalogue (ZS4 and NT4.1, respectively: see Section 3). For each zone the seismicity rate was obtained considering completeness periods for every magnitude class identified by a mixed historical/statistical analysis on the earthquake record, supported by a test on stationarity [Albarello et al., 1995] conducted on four sub-catalogues (northern, central and southern Italy, plus Sicily).

The seismicity rates were calculated using the ‘higher not highest’ original procedure, which explores the earthquake productivity in different time periods before choosing the most severe rate in agreement with the completeness periods (see Slejko et al. [1998], for further details). While the seismicity rates were used directly, i.e. without fitting them with a Gutenberg-Richter (G-R) model, the maximum magnitude (M_{max}) for each zone was obtained by extrapolating the G-R fit by 0.3 magnitude units when the associated recurrence interval fell in the range 1,000-3,000 years, which is a much longer interval than the time window covered by the adopted NT4.1 catalog.

Two GMPEs were used for obtaining two independent PGA maps: one calibrated on Italian data exclusively [Sabetta and Pugliese, 1987], and one of European validity [Ambraseys, 1995]. The former set of equations contains two parameters accounting for the specific setting of the recording site (rock, shallow alluvium, or deep alluvium), whereas the latter applies to average site conditions. For the volcanic zones, the ground motion calculated by the GMPEs was reduced by one or by a half standard deviation to account for the strong attenuation in the ground motion.

In constructing the map expressed with macroseismic intensity, for about 70% of the sites the authors used individual characteristic GMPEs, which, following the formulation proposed by Grandori et al. [1987], were calibrated

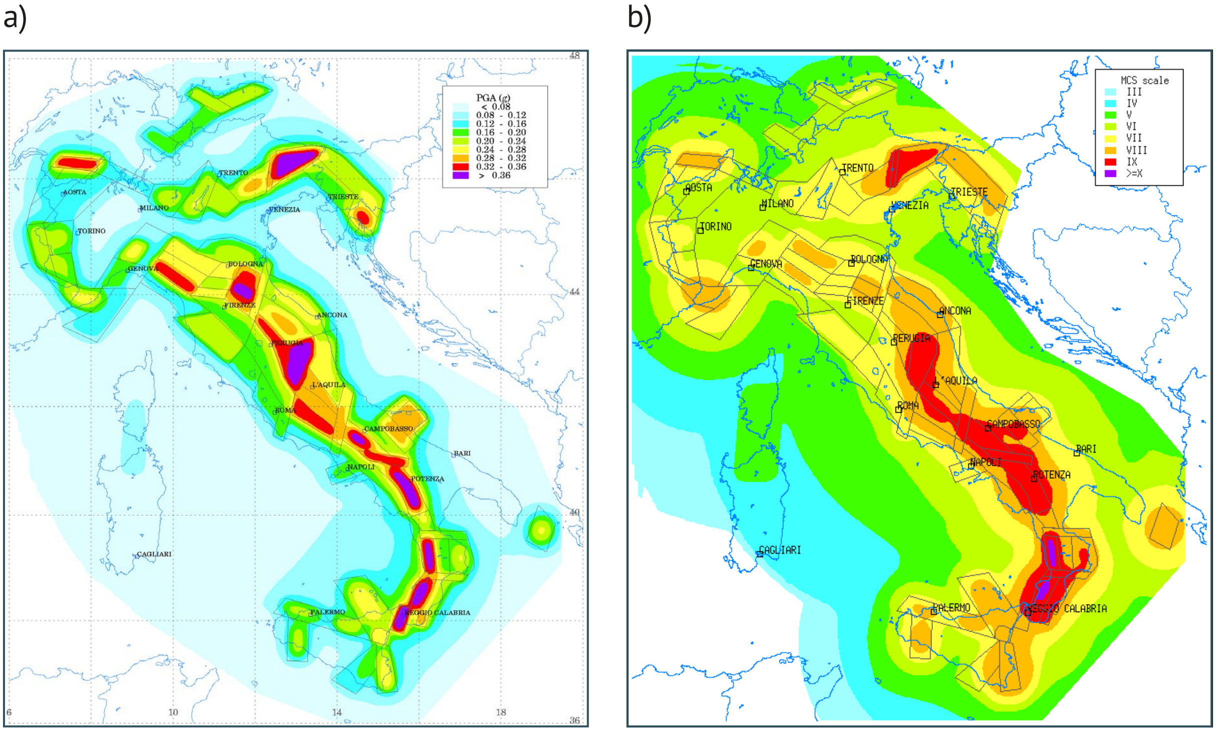


Figure 18. PS4 maps for a 475-year return period [from Slejko et al., 1998]: a) horizontal PGA (in g) obtained using the GMPEs of Ambraseys [1995], with standard deviation; b) map expressed in macroseismic intensity, obtained using different GMPEs (no standard deviation is considered).

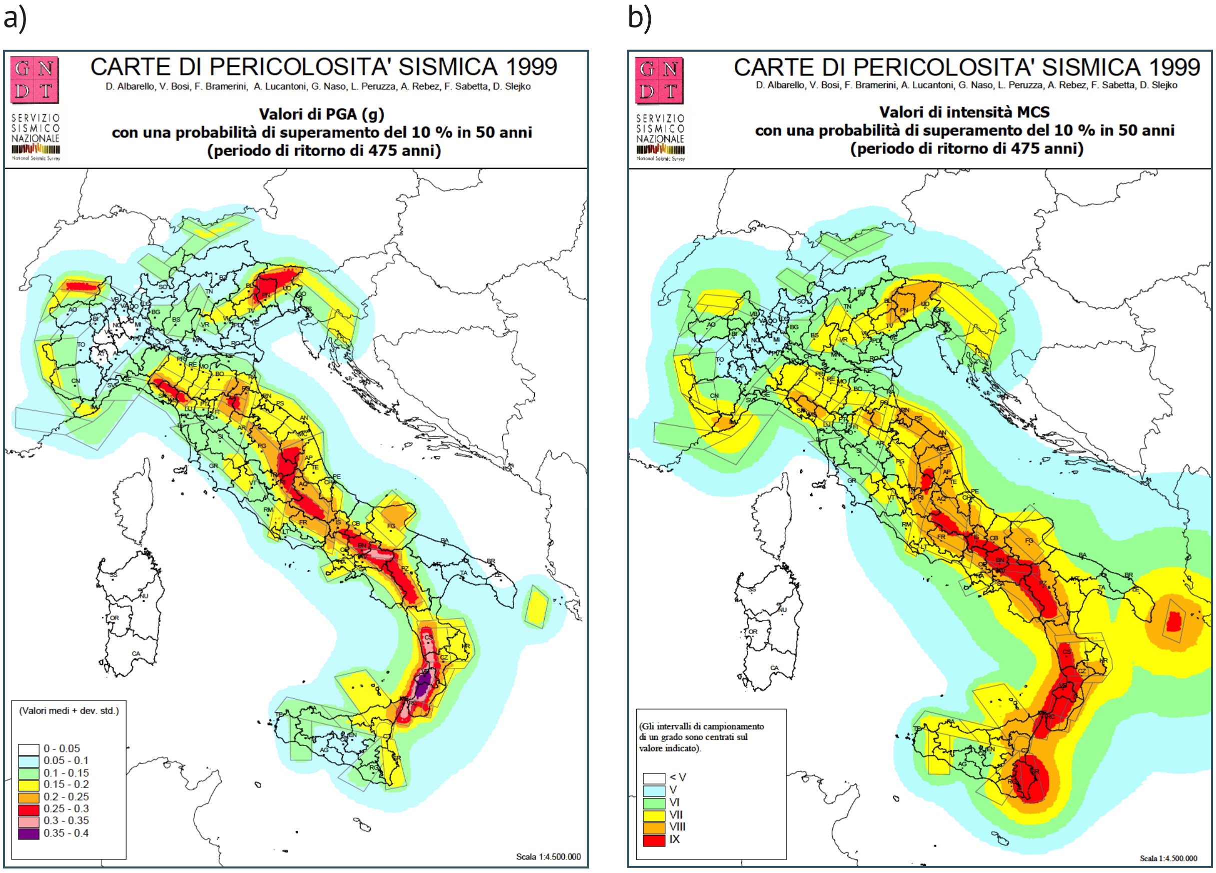


Figure 19. GNDT-SSN joint seismic hazard map for a 475-yr return period [from Albarello et al., 2000]: a) PGA; b) intensity.

for the strongest earthquake of each zone [Peruzza, 2000]. In the remainder of the zones, the computations relied on a relation proposed by Berardi et al. [1994] and calibrated on NT4.1 data.

The computations were made using the code SEISRISK III [Bender and Perkins, 1987] for an area source setting. The code returned a suite of PGA maps for return periods of 100 and 475 years, using the GMPEs supplied by Ambraseys [1995] taking or not taking into consideration the standard deviation (Figure 18a). As a matter of fact, the latter hazard maps could not be considered fully probabilistic, but were produced to make them comparable with the most popular maps of that period. A further PGA map for a 475-year return period was obtained using the GMPEs supplied by Sabetta and Pugliese [1987], including the standard deviations. The resulting map was then compared with that based on the attenuation model by Ambraseys [1995], and showed lower predicted values. The computations included also a map expressed in terms of macroseismic intensity for a 475-year return period (Figure 18b). As NT4.1 supplied an intensity value for each event, the same procedure used for the PGA map was applied also to the intensity, without introducing a maximum intensity for the zones and without considering the standard deviation for the GMPEs. Spectral hazard maps [Rebez et al., 1999] were produced as well, based on the same input data together with some sensitivity analyses [Rebez and Slejko, 2000].

It is worth recalling that the PS4 estimates were incorporated into the wider PSHA for the Adriatic region [Slejko et al., 1999], thus contributing to the compilation of the worldwide seismic hazard map produced by the Global Seismic Hazard Assessment Project (GSHAP: Giardini et al. [1999]).

Almost simultaneously with the end of the PS4 project, a seismic hazard map for Italy was proposed by scientists of the Italian National Seismic Service (SSN: Romeo and Pugliese [2000]). The procedure used to construct the SSN map was somehow similar to that followed for PS4, as it relied on the same seismogenic zonation ZS4 and on the same earthquake catalogue NT4.1; but it was different for what concerns the estimation of catalogue completeness, the computation of activity rates (obtained by a G-R fitting for each individual zone), the estimation of M_{max} for each zone (taken equal to the maximum observed value), and the adopted GMPEs (Sabetta and Pugliese, [1996], for PGA, and Blake [1941], for intensity).

5.2 The GNDT-SSN-ING 1998 proposal for a new classification (1997-2002)

Between 1984 and 1997 there had been no official request for the elaboration of an update of the national seismic classification; as a result, for this entire period there were no seismic provisions over more than two thirds of the country. After the 1997 Colfiorito earthquake, the former President of PFG and of Gruppo Nazionale di Vulcanologia (GNV), Franco Barberi, who at the time was State Secretary for the Civil Protection, prompted the elaboration of a new joint map (Figure 19) referred to as 'GNDT-SSN joint seismic hazard map' [Albarello et al., 2000]. This request stemmed from the availability of two seismic hazard maps, similar in structure but different in some computational details. The main innovations brought forward by the new joint map with respect to the previously available models consisted in the adoption of a new GMPE for the volcanic zones and of a GMPE obtained by evenly averaging the GMPEs proposed by Ambraseys et al. [1996] and by Sabetta and Pugliese [1996] for all other areas.

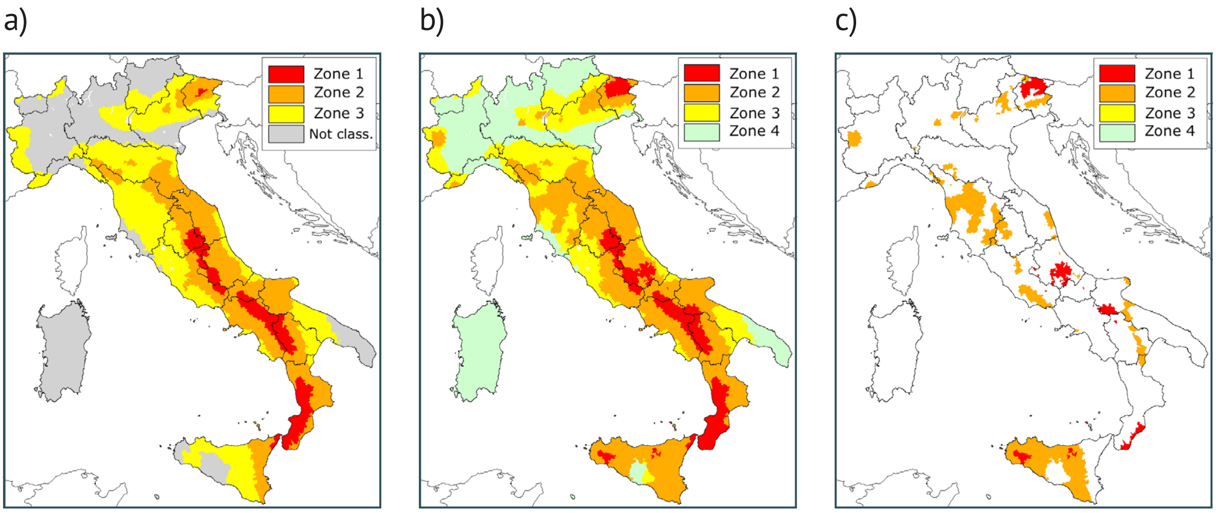


Figure 20. Distribution of seismic zones [from Meletti et al., 2014a]: a) according to the 1998 proposal; b) according to the PMO 3274; c) municipalities that retained a higher class with respect to that shown in panel a).

A working group formed by GNDT, SSN and ING combined the new joint map (Figure 20), merging a Housner intensity distribution computed *ad hoc* with a distribution of maximum observed intensities published by Molin et al. [1996], and released its final proposal in 1998 [Gavarini et al., 1999]. Unfortunately, the proposal was found unpalatable both by Italy's Central Government, which is in charge of developing hazard models at the scale of the entire country, and by the regional administrations (hereinafter referred to as Regions), which are ultimately responsible for assigning each municipality to a seismic zone. Implementing the 1998 proposal would have doubled the number of municipalities to be included in the seismic zones, which was seen as *problematic*; hence, the seismic zonation remained untouched, i.e. no change was made to the 1984 building code (Figure 8).

The ZS4 zonation was later further expanded to the Adriatic Sea and to the Croatian-Albanian-Greek inland areas, and the related hazard parameters were used by the GSHAP program for constructing a seismic hazard map of the Mediterranean region through the EU project SESAME, developed in the frame of the activities of the European Seismological Commission [Jimenez et al., 2001].

5.3 The MPS04 seismic hazard model and the implementation of the NTC08 (2003-2008)

The 31 October 2002, Molise earthquake (M_W 5.8), which killed 27 children and one teacher in the collapse of their school, occurred in an area that had never been included in the official seismic zonation, but would have been classified according to the 1998 proposal described above. In the aftermath of the earthquake, under the pressure of the public opinion and of the concerned seismological and engineering communities, the Italian Government established a new working group, which less than two months later released a totally new building code (Prime

Minister Ordinance of 20 March 2003, hereinafter PMO 3274) inspired by the Eurocode 8 [CEN, 2004]. Using the 1998 proposal as a basis (Figure 20a), the working group devised a new seismic zonation scheme (Figure 20b) based on a simple principle: the municipalities for which the proposal envisioned a higher hazard level than that currently assigned were transferred to the new zone, but those that should have been moved to a lower level retained their original assignment. Although the scheme was regarded as preliminary, the most significant change it caused was the dismissal of the 'non seismic' status: in other words, in 2003 the whole Italian territory was finally subdivided into four zones, each one characterized by a specific design spectrum associated. Later, most Regions adopted the scheme proposed by the Government, with limited changes, as explicitly permitted by PMO 3274.

As mentioned earlier, the seismic zonation was considered preliminary, and the Regions had the responsibility to update it as needed. Nevertheless, in order to guide the process and allow individual Regions to proceed according to homogeneous views, the PMO 3274 explicitly envisaged that a new, state-of-the-art, PGA seismic hazard map be prepared to serve as a countrywide reference. The operational scheme reflected the structure of the building code, which was based on four design spectra (Table 1).

Zone	Threshold PGA (g) with 10% exceedance probability in 50 years	AnchorING 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

Table 1. Definition of the seismic zones as a function of the PGA values expressed by the seismic hazard map for a 475-year return period, according to PMO 3274.

To accomplish this task INGV established a working group, which included several INGV scientists along with other Italian investigators. As the allotted time was just one year, the working group decided to use (a) a standard PSHA scheme, where the seismicity is uniformly distributed in each seismic zone, (b) an earthquake recurrence model following a Poissonian distribution, and (c) all the most updated seismological and geological information. The computations were all performed using the computer code SEISRISK III [Bender and Perkins, 1987]. Further details are found in MPS Working Group [2004], Montaldo et al. [2005], and Stucchi et al. [2011].

After a preliminary assessment in the fall of 2003, the review panel established by the Civil Protection Department (hereinafter DPC) required the introduction of a logic-tree approach, in order to account for known sources of epistemic uncertainty, as done for all the most advanced PSHA programs of the time [e.g. Frankel et al., 2002; Giardini et al., 2004]. Given the limited time available, it was agreed that only one logic tree branch would be used for the earthquake source model, and only one for the earthquake catalog. As shown in Figure 21, the working group decided to explore independently the epistemic uncertainty related to the completeness of the earthquake catalogue (using two branches: 'mainly historical' and 'mainly statistical'); the assessment of the seismicity rates and Mmax (using two branches representing activity rates and the M_{max} observed inferred from the earthquake catalogue and from geological evidence, plus G-R rates and M_{max} from conservative assumptions); and the GMPEs (using one independent branch for each of the four most common equations of the time; see Section 4 for further details).

The required map (MPS04) was released in 2004 and made available through a dedicated website (http://zonesismiche.mi.ingv.it), that has since remained operational. Further than the median values of the 16 branches, the uncertainty of the seismic hazard estimates was assessed in terms of the 16th and 84th percentiles (Figure 22).

In the frame of the same endeavor, the seismic hazard was estimated also in terms of macroseismic intensity with a 10% probability of exceedance in 50 years [Gómez Capera et al., 2010], based on empirical intensity attenuation

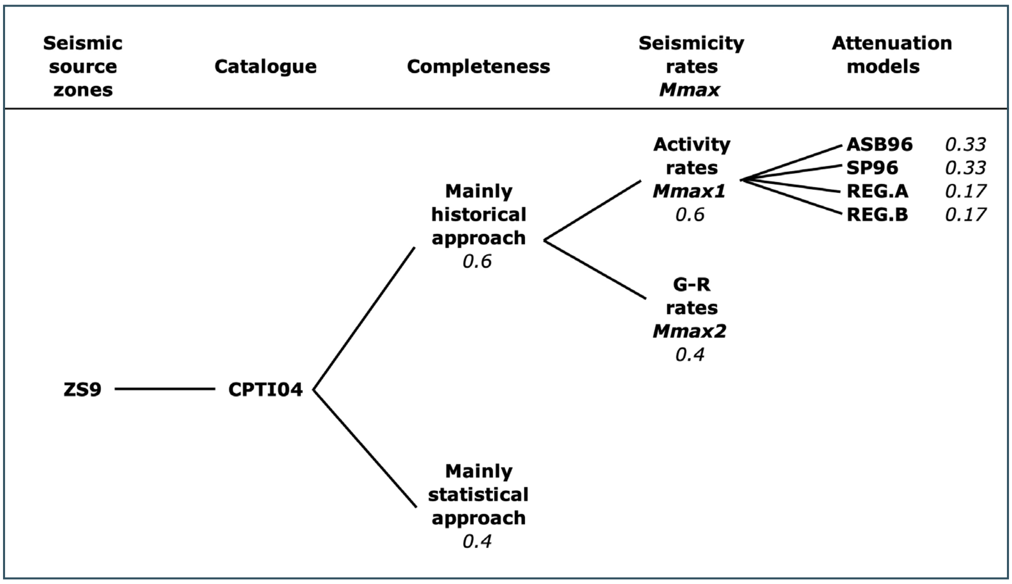


Figure 21. The logic tree scheme adopted in MPS04. The branching included two alternative estimates of catalogue completeness, two for alternative ways of estimating the seismicity rates and the M_{max}, and four GMPEs, totalling 16 branches [from Stucchi et al. 2011, redrawn].

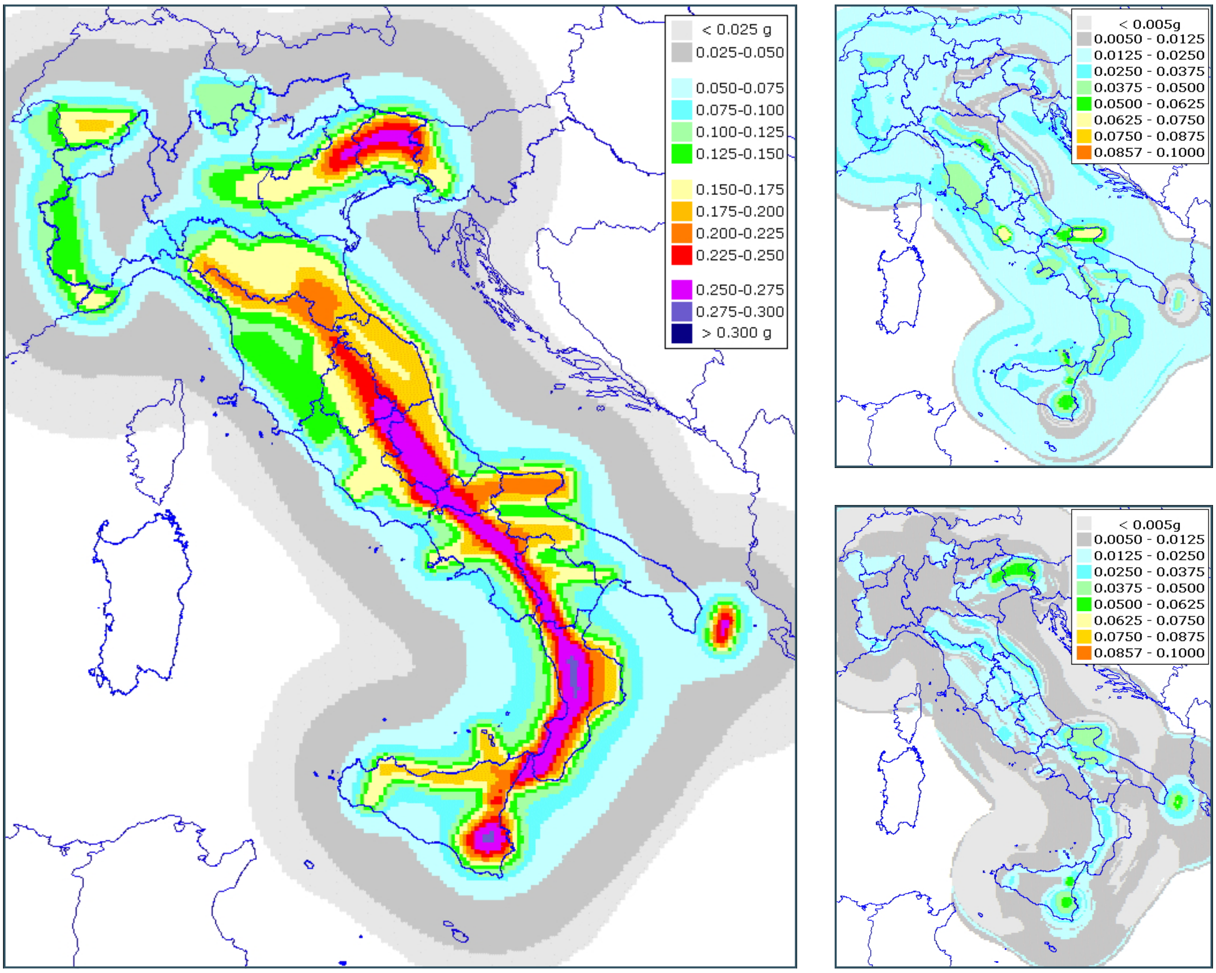


Figure 22. MPS04 model (from MPS Working Group [2004]): median PGA with 10% probability of exceedance in 50 years (left); difference between the median value and the 16th percentile (upper right); difference between the median value and the 84th percentile (lower right).

relationships that were specifically determined for this task [Gómez Capera et al., 2007]. The elaboration served primarily as a benchmark for testing the robustness of the PGA models.

Although the map was later adopted by the Government as an official national reference (Prime Minister Ordinance of 28 April 2006, hereafter PMO 3519), it was virtually never used for its initial goal, due to at least two main reasons. First of all, many Regions were not willing to reassign the seismic zone of their municipalities, while others preferred to get their own regional-scale SHA (the new ordinance allowed for it); and secondly, in some areas the new map did not propose significant changes. It is worth mentioning that, while PMO 3274 proposed an update of the reference hazard map to be performed every 5 years, the PMO 3519 unexpectedly dropped this provision.

In 2005 the DPC requested the above elaboration to be expanded to include (a) the assessment of PGA, calculated for different probabilities of exceedance in 50 years, and (b) the calculation of spectral accelerations for various spectral periods and exceedance probabilities. This task was accomplished between 2005 and 2007 in the frame of a joint INGV-DPC project [Montaldo et al., 2007]. Using the very same input described above, INGV scientists determined values of the following parameters for over 11,000 nodes of a regular grid covering the Italian territory with a spacing of 0.05° (about 5 km):

- PGA values for nine probabilities of exceedance in 50 years (2%, 5%, 10%, 22%, 30%, 39%, 50%, 63%, and 81%); and
- spectral accelerations for the 10 periods that are common to all of the adopted attenuation models (0.10, 0.15, 0.2, 0.3, 0.4, 0.5, 0.75, 1.0, 1.5, and 2.0 seconds), for all nine probabilities of exceedance.

The procedure involved the calculation of 99 (90 plus the original 9) parameters for each grid point. This final step turned MPS04 into the official new seismic hazard model of Italy. A dedicated web-GIS application was developed to make this huge amount of data available for dissemination to the concerned communities [Martinelli and Meletti, 2008; http://esse1.mi.ingv.it/]. In a simple and fast way, the user may obtain hazard curves and uniform hazard spectra (UHSs) for the specific location of interest.

Limit states	Probability of exceedance in the reference period	
Serviceability Limit States	Operativity Limit State	81%
	Damage Limit State	63%
Ultimate Limit States	Safeguard of Life Limit State	10%
	Collapse Limit State	5%

Table 2. Exceedance probabilities in relation to the four limit states considered in the NTC (2008).

Meanwhile, the building code provided by PMO 3274 was not universally welcomed by Italian engineers; therefore, between 2005 and 2007, a new committee was appointed to update it. The committee devised four limit states (Table 2) and decided that, rather than using the four design spectra, one for each seismic zone, it would have been appropriate to rely on a more detailed input, if available.

The design spectra [Montaldo et al., 2007; Stucchi et al., 2011] were adopted for the new building code, called Norme Tecniche per le Costruzioni (Technical Norms for Buildings [NTC, 2008]), published with a Decree of The Ministry of Infrastructures on 14 January 2008. The above mentioned web-GIS became – and still is – the official national source of the parameters needed for antiseismic design. The NTC [2008] design spectra were immediately greeted by most engineers (Figure 23) and were officially adopted a few months after the 2009 L'Aquila earthquake. Therefore, the official seismic zonation and its four spectra became useless for building purposes, and survived for minor provisions, mostly of an administrative nature. No further commitment appeared from the building code side.

Finally, in 2015 the DPC called for the compilation of an updated seismic model of Italy. Meanwhile, ten years later after the publication of the NTC [2008], the new NTC [2018] confirmed the structure of the code and adopted the same input spectra.

5.4 The new European seimic hazard model ESHM13 (2009-2014)

The 2013 European Seismic Hazard Model (ESHM13) delivered by the EU SHARE project is the first regional and community-based effort that was completed since the conclusion of the GSHAP program [Giardini et al., 1999] and of the European SESAME project [Jimenez et al., 2001]. The model extended to the western part of Turkey, thus integrating with a parallel and simultaneous effort, the EMME project (Earthquake Model for the Middle-East: Giardini et al., [2016]; http://hazard.efehr.org/en/Documentation/specific-hazard-models/middle-east/overview/). It was built upon homogeneous data sets and rigorous assumptions that were uniformly applied to avoid creating singularities at national borders.

ESHM13 [Wössner et al., 2015] delivered a complete set of harmonized seismic hazard results with the associated uncertainties, ideally to serve as reference for updating seismic regulations at national and regional scale in Europe. Notice also that the ESHM13 has been the first continental-scale model computed using the OpenQuake engine [Pagani et al., 2014]; all data sets, products, and results are provided through the web platform of EFEHR, the European Facilities for Earthquake Hazard and Risk [Haslinger et al., 2022; http://www.efehr.org/start/].

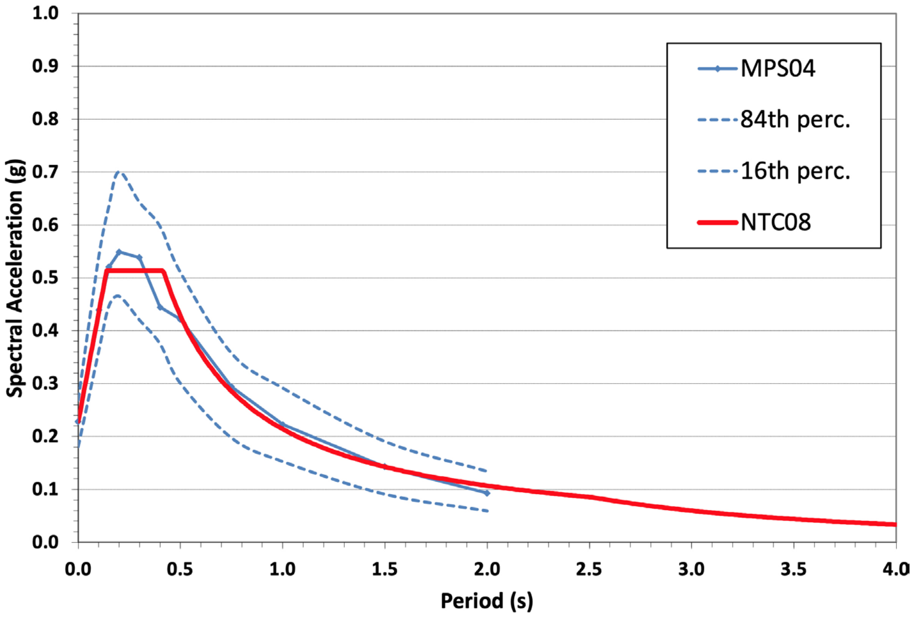


Figure 23. Definition of design spectra in the national building codes [NTC, 2008] from the UHSs released alongside the MPS04 model.

The Italian seismological community had an important role in the SHARE project: its participation was an opportunity for extending to the European continent the ideas, the methods and the best practices developed for Italy's PSHA. One could say that SHARE represented the basis also for a new season of PSHA in Italy, and particularly for the implementation of MPS19.

Meletti et al. [2014b] compared the results supplied by ESHM13 in terms of either UHS or PGA with 10% exceedance probability in 50 years with the same results provided by MSP04 (Figure 24). The comparison shows that the main differences arise from the GMPEs adopted for ESHM13, which are based on a larger number of reliable recordings than their older counterparts used for MPS04. More specifically, the new GMPEs show larger accelerations for shorter periods and smaller accelerations for longer periods with respect to the equations adopted in MPS04.

The 2020 European Seismic Hazard Model (ESHM20) was developed within the EU SERA project. It revisited the ESHM13 [Wössner et al., 2015] to identify all the input datasets (earthquake catalogues, active faults databases, GMPEs) and the components that could be further improved or updated. Its compilers interacted with the Eurocode 8 committee to share the correct information and outputs of ESHM20 in view of the update and revision of the code [Danciu et al., 2021].

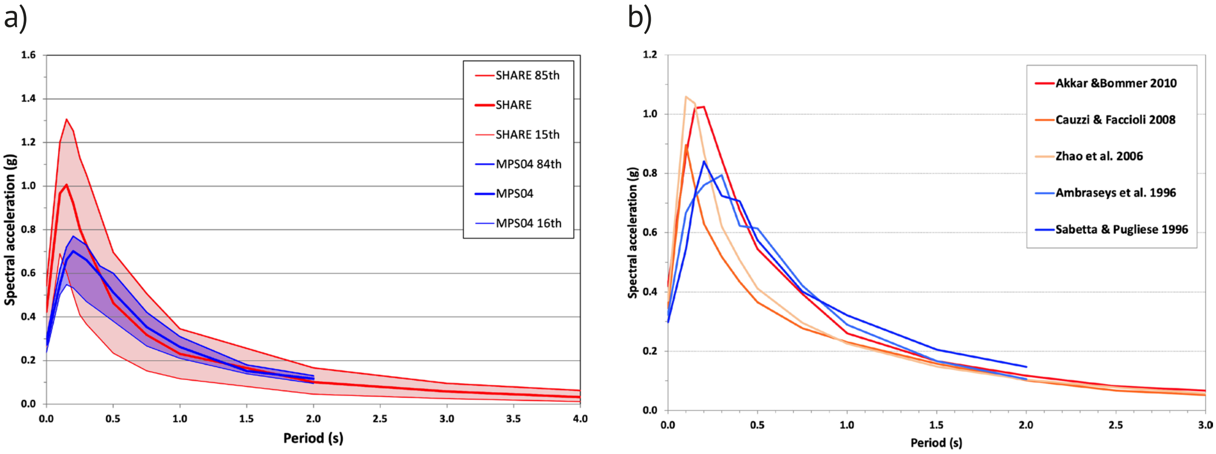


Figure 24. Comparison between UHSs in MPS04 and ESHM13 for the city of Cosenza [from Meletti et al., 2014b]: a) median values and percentiles; b) same input elements but different GMPEs (warm colors for the GMPEs adopted in ESHM13, cold color for the GMPEs adopted in MPS04).

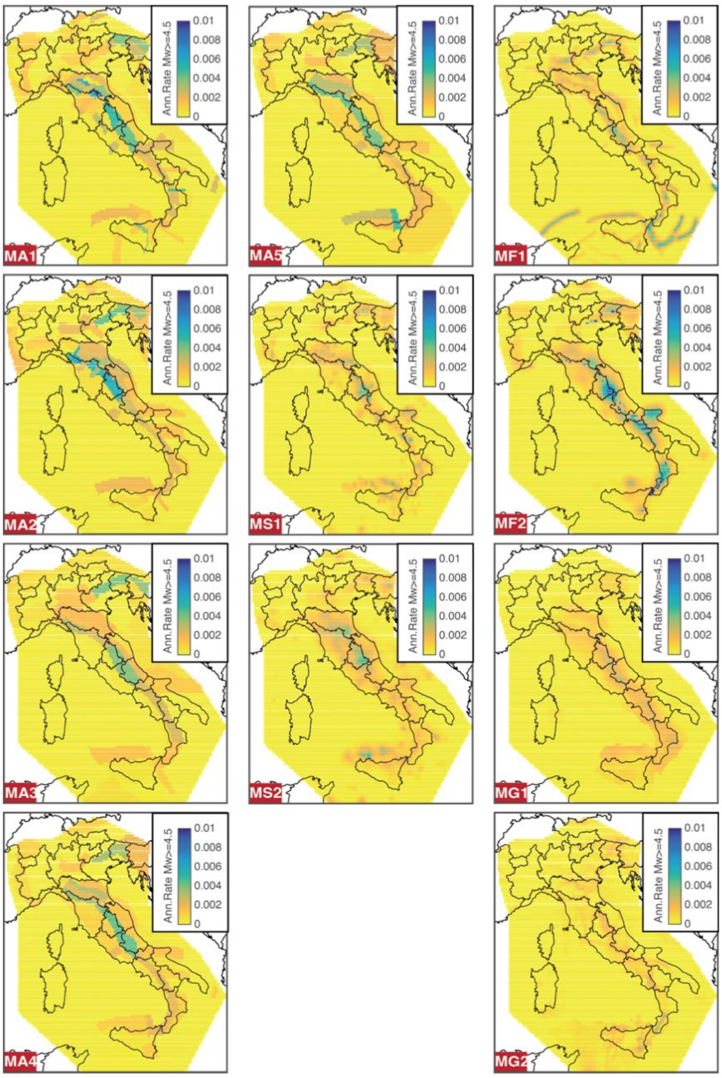


Figure 25. Seismicity rates (Mw ≥ 4.5) for the 11 ERF models adopted in the MPS19 model [from Visini et al., 2021]. MA1-MA5, area source models; MF1-MF2, fault-based models; MS1-MS2, smoothed seismicity models; MG1-MG2, GPS-based models.

5.5 The MPS19 seismic hazard model (2015-present)

The MPS19 project started with the aim of checking if the data and approaches used SHA that have become available since 2004 would obtain a significantly improved version of the reference model (MPS04). The DPC requested INGV to build a new model based on data and approaches that are state-of-the-art at global level. The newly available data included an extended and updated fault database, an updated earthquake catalogue, new seismological and geodetic observations, new GMPEs and more: a unique collection of datasets, most of which are supplied with the associated uncertainties. Another specific request concerned the possibility to test any single seismicity model and GMPE against the actual observations, and that the results of these tests be used to determine the weight of each seismicity model in the logic tree.

As discussed in Section 3, MPS19 considers 11 new alternative earthquake rate models at national scale, all delivered by independent research groups; these nationwide models are complemented by two regional and sub-regional models, respectively for the Calabrian Arc subduction zone and for the Mt. Etna volcanic area. The 11 models have been selected with the aim to explore the uncertainty implied in the earthquake rate models, as each of them is based on different data and on a different approach (Figure 25).

The earthquake rate models were grouped according to the dominant typology of the earthquake/strain sources: areas (five models), faults (two models), smoothed seismicity (two models), strains from GPS velocities (two models). Among them, two innovative categories of models do not rely at all on the earthquake catalogue, and are hence totally independent of the observed earthquake record: one is based on faults, the other one is based on geodetic data. Each model includes its own epistemic uncertainty through dedicated logic-trees, so as to obtain 94 final earthquake rate models. All proposed models were used for constructing the final elaboration, since they all passed the adopted statistical tests.

The models were then associated with a logic tree including three GMPEs (see Section 4), selected among the equations that showed the best performance when tested against the accelerometric data available for Italy [Lanzano et al. 2020]. This decision acknowledges a specific request by DPC and explores the epistemic uncertainty on the estimated ground shaking. As for MPS04, the finalization of the hazard model has gone through a successful participatory review process by an evaluation committee established by DPC itself [Meletti et al., 2021].

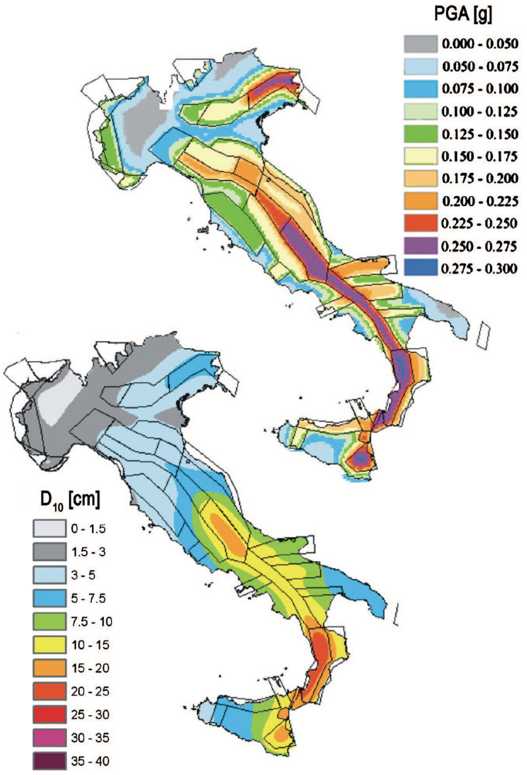


Figure 26. Comparison between MPS04 (maximum horizontal component of PGA with 10% of probability of exceedance) and long-period spectral displacement estimates [Faccioli and Villani, 2009].

5.6 Alternative views and models

This work summarized the results of several projects based on standard PSHA; nevertheless, for the sake of completeness, we want to briefly touch upon studies made for assessing PSHA in terms of displacements, following the idea of adopting the displacement-based design approach [Priestley et al., 2008] partly implemented by Eurocode 8 [CEN, 2004]. Faccioli and Villani [2009] reported the results of a project funded by DPC in 2005-2007. They used an approach similar to that adopted for MPS04, the same earthquake catalogue and the same ZS9 zonation model, but developed *ad hoc* GMPEs for displacement [Cauzzi and Faccioli, 2008]. They also published an interesting comparison of their estimates with those proposed by MPS04 (Figure 26). Although their work was not yet found mature for the Italian building code, their results are especially interesting for critical infrastructures characterized by a long oscillation period, such as long suspended bridges.

Another area of further elaboration is time-dependent PSHA. The Italian scientific community explored this topic starting with the pioneering work of Peruzza et al. [1997], followed by the MISHA project [Peruzza, 1999; Peruzza and Pace, 2002] and by the works of Akinci et al. [2009], Slejko et al. [2009] and others. Although time-dependent models have so far not been requested for the building code, other projects are underway so that the Italian scientific community will be ready in case this expertise will be needed.

It is worth mentioning the studies developed for investigating the effects introduced in the expected ground motions by the declustering process. The results obtained by Taroni and Akinci [2021] in the frame of a PSHA study for Italy confirmed that adopting a complete catalogue still returns ground motions following a Poissonian distribution, and showed that using a complete catalogue results in a quite regular and definitely significant increase of 0.1 g, in the calculated PGAs for a 475-year return period.

Reporting on the advancements of the NeoDeterministic SHA (NDSHA) is more complicated. As recalled by Panza and Bela [2020], the method was proposed at the end of the 20th century [Panza et al., 2012] on the grounds that it *"… supplies a much more scientifically-based solution to the problems of reliably characterizing earthquake hazards …"*. In the introduction to their paper, Panza and Bela [2020] strongly criticize conventional PSHA, and propose a number of analyses which, according to them, would prove the approach unsatisfactory and responsible for scientific failures and even casualties. This paper comes after a stream of comparisons between observed and predicted PGAs which extended internationally; for example, the 2001 Tohoku earthquake was used by some workers (e.g. Stein et al. [2012]; see also the reply by Frankel [2013]) to contend that the whole probabilistic approach is fallacious and should hence be replaced by NDSHA (e.g. Wyss et al. [2012]).

The analysis of the criticism against PSHA is outside the scopes of this paper; the same holds for the analysis of NDSHA which, incidentally, does not appeal much to the vast majority of the Italian engineering community. NDSHA constructs shaking scenarios by modelling the ground motion though synthetic time-series generated

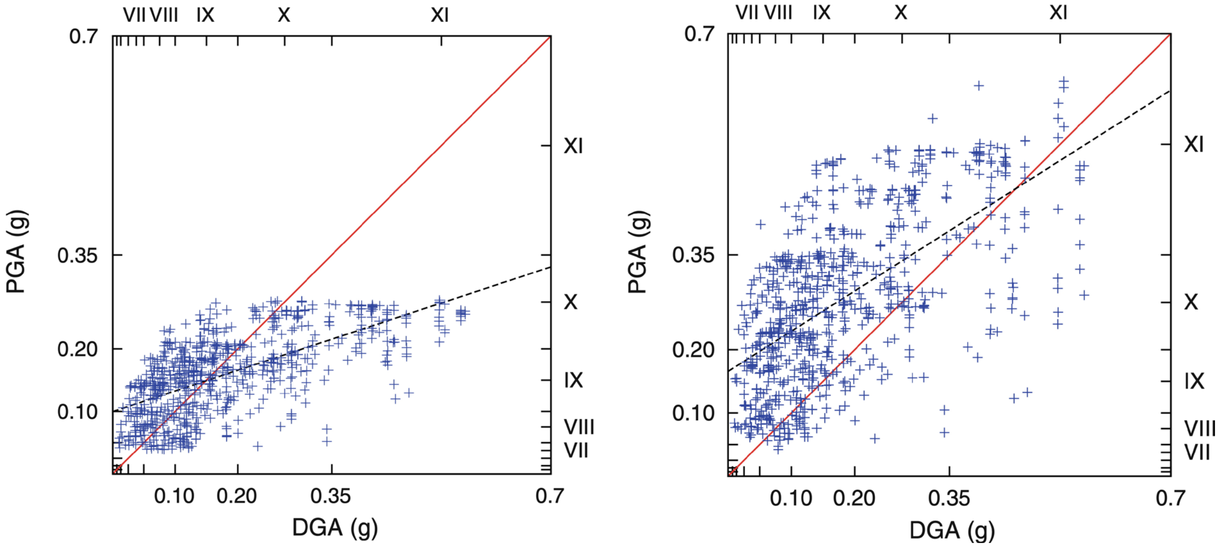


Figure 27. Comparison between NDSHA (X-axis) and MPS04 estimates (Y-axis), respectively for a 10% (left) and 2% (right) probability of exceedance in 50 years (from Zuccolo et al. [2011], modified).

by seismogenic sources (defined by magnitude and location), and describes the hazard as the envelope of ground shaking at the site, i.e. the maximum estimate among all those obtained from all scenario earthquakes. Hence, there is no statistical distribution describing earthquake occurrence and, consequently, no probabilities are associated with the expected ground motion. NDSHA models are easy to test, and a single earthquake may lead to the rejection of a model (this does not happen with a probabilistic approach; see Iervolino [2013]). As all approaches may undergo validation against real data, it should be recalled that the NDSHA estimates by Zuccolo et al. [2011] failed to predict the ground motion recorded close to Norcia during the 2016 seismic sequence in central Italy.

For Italy the NDSHA approach supplies values that are lower than those given by the PSHA (with 10% of probability in 50 years) in low-seismicity areas [Zuccolo et al., 2011], higher in areas where large earthquakes occurred in the past and in areas identified (by the authors of NDSHA) as prone to large earthquakes, and lower again in low-seismicity areas; this trend, however, is drastically overturned when considering the estimates for the 2% probability of exceedance, which corresponds to a return interval of 2,475 years (Figure 27).

6. Conclusions

In this paper we have mostly referred to scientific elaborations devoted to provide support to the development of the Italian building code. We are aware that there exist a large number of studies and papers dealing with seismic hazard, many of which were not mentioned here. This does not imply that we do not consider them useful; simply, a complete review would have required a much longer article and might have resulted hard to follow for the reader.

This paper accounts for an important part of a 40 year-long scientific and civil struggle (from the end of the 1970s to present) to increase the seismic safety of Italian buildings. The first two decades were dedicated to extending the official seismic zonation and related building code to all of Italy, whereas the past two decades were dedicated to improving the building code itself, with reference to the various seismic characteristics of the territory.

This task was accomplished with the contribution of a large number of researchers, who helped to increase the understanding of the earthquake sources and the characteristics of the energy release, to characterize the ground motion attenuation and to develop more and more sophisticated approaches to compute PSHA. In fact, PSHA has moved from the simple statistical treatment of the earthquake data performed in the late 1970s, to the more sound *seismotectonic probabilism* approach of the 1990s, to the recent ensemble models where all the geological and geophysical knowledge contributes to the ground motion estimates, and where the uncertainties involved in the process are taken into account and quantified.

Further than the quality of scientific investigation, most of the PSHA projects described above had also a practical success, as they directly contributed to updating the country's seismic provisions (Table 3).

PFG	Official seismic zonation, enforced from 1981 to 2003
PS4 (with SSN)	Official seismic zonation, enforced from 2003 to 2009
MPS04	Input for the seismic zonation, from 2006 on, and input for the design spectra of the building code, from 2009 on

Table 3. Summary of the models that contributed to official Italia seismic zonation.

While the ESHM13 model was not conceived for an immediate use, due to the different stand of the European countries with respect to the earthquake-safety policies and to the adoption of the Eurocode 8 [CEN, 2004], the implementation of MPS19, that was conceived as new national reference frame, is still under negotiation (as of December 2022). Decision makers in Italy are rather slow and, unfortunately, decisions in this field are often triggered by disasters. As a matter of fact, the criticism against PSHA seems to have left the engineering community indifferent; the recent NTC [2018] have adopted the aforementioned NTC [2008] design spectra based on MPS04 without even considering the idea of using a lower probability of exceedance level, or considering the uncertainties associated with the available UHSs. As a matter of fact, several countries (including U.S.A. and Canada) have chosen a more conservative exceedance probability of 2% for their reference national seismic hazard maps. Moreover, as the UHSs calculated considering more than one GMPE still carry significant uncertainties, we maintain that adding the standard deviation to the mean value would make for a useful safety valve.

In conclusion, we believe that the Italian seismological community has done its best to contribute to the national earthquake safety; this community is willing to continue investigating and improving the assessment of seismic hazard, as soon as new data and ideas become available.

Acknowledgements. We are grateful to several scientists who contributed to the development of SHA studies in Italy, and shared with us their valuable insight and experience across over forty years of research activity. Their names, their roles and their accomplishments are detailed mostly in Sections 2 and 3 of the manuscript. We also wish to thank two anonymous reviewers, who appreciated our work and provided valuable insight for improving it even further. One of them stated that our work should be a "…'*must read*' paper for anyone who wants to venture into this field in Italy", which made us especially proud and grateful.

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