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Seismic hazard estimate in the Alps and Apennines (Italy) using smoothed historical seismicity and regionalized predictive ground-motion relationships

A. AKINCI[1], C. MUELLER[2], L. MALAGNINI[1] and A.M. LOMBARDI[1]

[1] *Istituto Nazionale di Geofisica e Vulcanologia, Rome, Italy*
[2] *U. S. Geological Survey, Denver, CO, USA*

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Abstract - The aim of this study is to conduct a new probabilistic seismic hazard assessment for central and northern Italy, using the most recently developed predictive relationships for ground motion, along with updated seismic catalogs. Seismic hazard is evaluated over three regions (western Alps, eastern Alps, and Apennines) using a new methodology that follows the procedure originally described by Frankel (1995). The approach of using spatially-smoothed historical seismicity is different from the one used previously by Slejko et al. (1998) and Romeo et al. (2000) for Italy, in which source zones were drawn around the seismicity and the tectonic provinces. We analyze the declustered historical seismicity, compute the rate of earthquakes on a grid, and smooth these rates to account for uncertainty in the spatial distribution of future earthquakes. In our study, the smoothed seismicity is obtained by counting the number of earthquakes with magnitude greater than 4 (accounting for completeness variations) in each cell of a grid with spacing 0.1° in latitude and 0.1° in longitude. We incorporate new regionalized predictive ground-motion relationships into the hazard calculation, and compare results with alternative models derived by Ambraseys et al. (1996) and Sabetta and Pugliese (1996). We generate maps of peak ground acceleration with 10% probability of exceedance in 50 years (475-year return period) for a rock site condition. These are not intended to be the final seismic hazard maps for the regions; instead, we wish to present the usage of a new methodology for Italy, and examine the effect of the new attenuation relationships on the hazard. We estimate the seismic hazard from the historical seismicity only, and not from faults with recurrence rates obtained from geologic data (this will be taken into account in

Corresponding author: A. Akinci, Istituto Nazionale di Geofisica e Vulcanologia, Via di Vigna Mucata 605, 00143 Rome, Italy. Phone: +39 0651860403, fax: +39 0651860507; e-mail: akinci@ingv.it

future work). The maps obtained in this study are based on the assumption that the process of earthquake occurrence is inherently Poissonian, so that the probabilistic ground motions are time-independent.

1. Introduction

Italy is one of the most seismically active Mediterranean regions, where a long history of earthquakes has strongly influenced the development of earthquake-resistant structural design. During the last century, Italy has frequently experienced strong shaking induced by earthquakes: catalogs contain about 100 events with magnitude 5.0 or greater, and about ten of these exceed magnitude 6.0. During the 20th century alone, more than 120,000 people were killed by earthquakes in Italy (Valensise and Pantosti, 2001): including more than 80,000 by the 1908 Messina earthquake (M_w = 7.0, Calabria-Sicily Strait), about 33,000 by 1915 Fucino (M_w = 6.7, central Apennines), about 3,000 by 1980 Irpinia (M_s = 6.9, southern Apennines), and about 1,000 by 1976 Friuli (M_w = 6.5, eastern Alps). From studies of these and other events abundant information exists related to seismic hazard assessment, including catalogs of large and moderate historical earthquakes (e.g. Boschi et al., 1995, 1997), and predictions of maximum expected macroseismic intensity and ground motions (Faccioli, 1979; Gruppo di Lavoro Scuotibilità, 1979; Giorgetti et al., 1980; Petrini, 1980; Petrini et al., 1981, 1987).

In 1996 the current probabilistic seismic hazard maps for Italy were officially delivered to the Civil Protection Department, which financed the project, and to the Ministry of Public Works, for consideration in legislation. The hazard assessment was conducted using the Cornell (1968) probabilistic approach by applying the Seisrisk III (Bender and Perkins, 1987) code [for details about the calculations, see Slejko et al. (1998), and further analysis in Albarello et al. (2000)]. In that project, a seismo-tectonic model for the whole territory was defined by 80 seismogenic zones (Model PS4), each with a homogeneous distribution of seismicity, based on a structural-kinematic analysis of Italy (Meletti et al., 2000). A new earthquake catalogue, NT4.1 (Camassi and Stucchi, 1997), was used for computing the hazard maps. The hazard parameters were calculated using the attenuation relations derived by Ambraseys et al. (1996; hereafter AMB96), and Sabetta and Pugliese (1987, 1996; hereafter SP96).

In this study, we apply the smoothed-historical-seismicity method (Frankel, 1995), an alternative to the approach that was used previously for the hazard calculation in Italy, in which area source zones were drawn around seismic or tectonic provinces. One advantage of the smoothed-seismicity method is to avoid choosing zone boundaries that are sometimes poorly controlled by data and drawn by subjectively merging geological and seismological information. The delimitation and parametric characterization of small zones can be responsible for introducing uncertainties into the hazard evaluation. For example, many zones in the PS4 model contain a small number of earthquakes with magnitude > 4.0 (22 zones with total number of earthquakes around 10), and it is therefore difficult to accurately characterize the level of seismic activity. In its purest form, the smoothed-seismicity method simply assumes that patterns of historical earthquakes predict future activity, but it can easily be supplemented by tectonic - or geodetic - based zones or other model elements if there is reason to suspect that seismicity catalogs are insufficient.

Even though in the approach by Frankel (1995) no seismicity source zones are needed, some model parameters can be taken as homogeneous throughout regional sub-zones. Our study region is subdivided into three broad zones mainly on the basis of the different rupture mechanism (Montone et al., 1999, 2003), geological homogeneity (Vai, 2001), and the catalog characteristics/completeness (Camassi et al., 2002), of the region: western Alps, eastern Alps, and Apennines.

Note that we do not assume a constant rate of earthquake generation in each zone; on the contrary, we consider seismicity where it has taken place historically. Therefore, we use regionalized predictive ground-motion relationships obtained for the Apennines by Malagnini et al. (2000), for the eastern Alps by Malagnini et al. (2002), and for the western Alps by Morasca et al. (2003). These authors used data from the background seismicity, and demonstrated the great importance of large amounts of observations in ground motion scaling analyses, and how the attenuation parameters vary significantly on a regional scale. In this study, we also show the differences between the new regionalized ground motion relationships and those derived by AMB96 and SP96, calculated from strong motion data collected in different tectonic and geological environments of the Mediterranean region.

We generate maps of peak ground acceleration (PGA) with 10% probabilities of exceedance in fifty years in three zones, western Alps, eastern Alps, and Apennines, using three different attenuation relationships. Since we do not introduce faults into the model, our results show variability due only to the characteristics of the seismicity and ground motion.

2. Tectonic-geologic setting and destructive earthquake

Different kinematic styles exist in Italy as a result of the complex geodynamic processes that have conditioned the build-up of the two main tectonic structures: the Alps and the Apennines. The land is mostly mountainous except for the large, triangular Po River plain that divides the Alps from the Apennines which form the backbone of the peninsula.

The Alps are a mountain chain originated by the convergence of the African and European plates after consumption of the interposed Jurassic Tethys Ocean (Fig. 1). The portion of the African plate involved in the collision is usually called the Adriatic microplate or Adria (Dercourt et al., 1986). The Alps are composed of two folded chains, with opposite orogenic polarity, separated by the Insubric lineament, a major E-W-trending tectonic element. The North-alpine chains are built by a pile of nappes in a sandwich-like structure, where the intermediate oceanic units are enclosed between the underlying European units and overlying African units (Dal Piaz, 1995). Large and thick portions of the crystalline basement of both continental margins are involved in the structures, such as the Helvetic massifs in the western Alps and lower Austroalpine nappes in the eastern Alps. The structure of the southern Alps is a south-verging thrust belt involving the Permian to Tertiary cover and, partly, the underlying Hercynian crystalline basement (Castellarin, 2001).

The Apennines can be divided transversally (Dainelli, 1975) into an inner (Tyrrhenian) zone, a main range, and an outer (Adriatic or/and Ionian zone). The outer zone is for the most part rather uniform throughout the peninsula. From north to south, the Apennines, main range, can be subdivided into three parts (Vai, 2001).

1) E-NE verging fold-thrust belt and the mainly sandy-clayey arcuate, northern Apennines, including Liguria, northern Tuscany, Emilia and Romagna, are characterized by relatively low elevations. There is evidence of progressive outward migration of the divide from Pliocene to the Pleistocene by diachronous uplift of the more external belts. This is consistent with the outward migration of both the compressional and extensional deformation fronts.

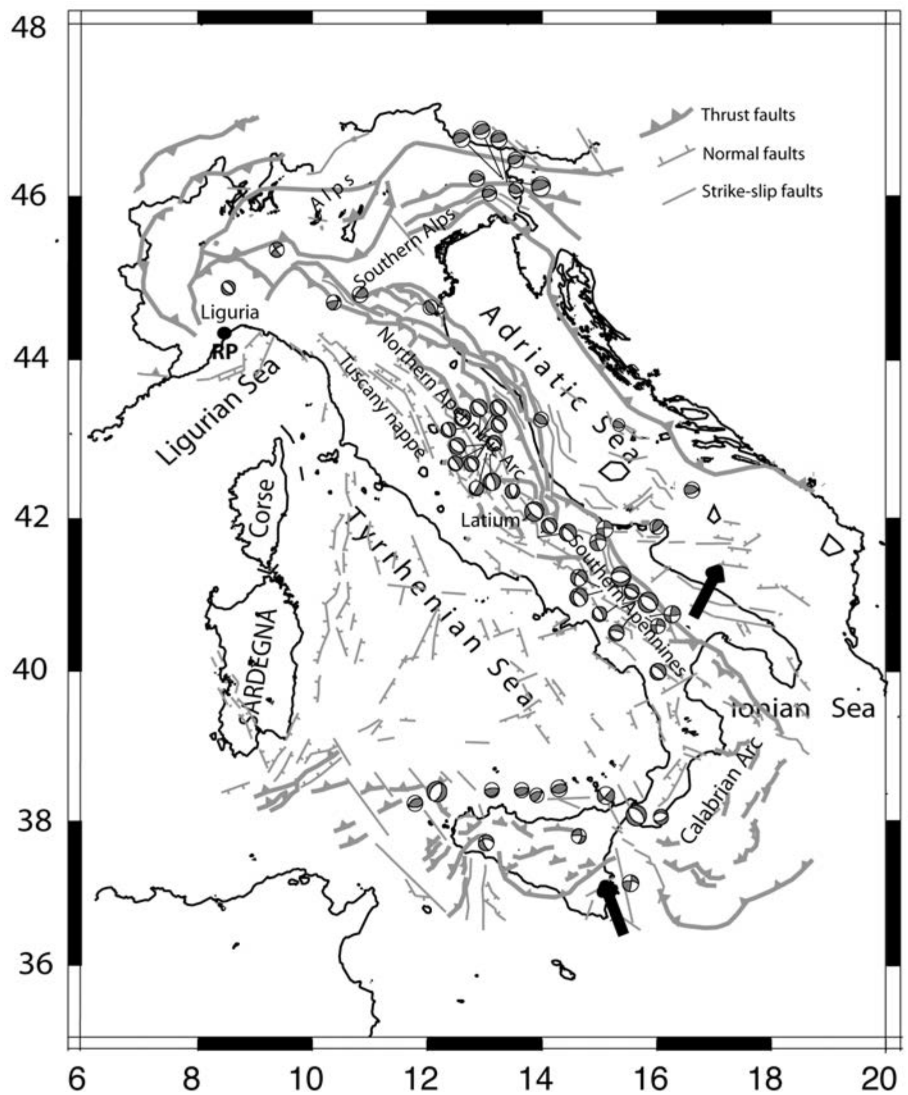


Fig. 1 - Tectonic setting of Italy with main tectonic lineaments. Arrows indicate the slip vectors derived from VLBI observations at the Matera-Adria and Noto-Africa stations. RP represents the rotation pole of the system (from Meletti et al., 2000). Earthquake focal mechanisms of selected events with magnitude higher than 5.0 in the period of 1900-2001 are taken from Montone et al. (2003).

2) The thrust belt, mainly calcareous central Apennines, including southernmost Tuscany, Latium, Umbria, Marche and Abruzzi, reach higher altitudes, up to the 2914 m of Gran Sasso Mt Corno. Volcanism has been active in the inner western part associated with NW-SE trending linear extensional basins.

3) The mainly clayey-marly-sandy, southern Apennines are nearly as high as the central Apennines, up to the 3340 m of Mt Etna. They are characterized by steep and complex cross-sections related to the extensive duplex tectonic style and strike-slip faulting. The axial part of the southern Apennines (in Calabria and eastern Sicily) has undergone recent rapid uplift indicated by coastal Quaternary marine deposits at elevations higher than 1000 m. The inner, western part of the southern Apennines arc has active inland and offshore volcanism, including Mt Vesuvius, Phlegrean Fields, Mt Etna and Stromboli, Volcano and other Aeolian islands. Pleistocene and older volcanism has occurred across Sardinia, throughout the southern Tyrrhenian Sea and in inland parts of the Apennines.

As indicated in Fig. 2, the largest earthquakes (magnitude > 6.0) affect the main range of the Apennines, the Calabria area, and the central-eastern Alps. The most striking geological and geomorphologic evidence of recent fault activity characterizes these sectors. The seismic activity in the southwestern Alps is related to the Ligurian Sea structure; the 23 February 1887, magnitude-6.3 earthquake was the greatest seismic event in the area in the last thousand years (Ferrari, 1991). The Friuli Alps (eastern Alps) have experienced the greatest shortening, and are characterized by a stronger seismicity (Carulli et al., 1990; Bressan et al., 1998). The most important historical earthquake of the region, the M_w = 6.5 Friuli earthquake, occurred on 6 May 1976. The most important historical earthquake in the northern Apennines occurred in 1920 in Garfagnana with magnitude M_s ~ 6.3. However, northeastward slow extension, ~ 0.3 mm/yr, is obtained in the northern Apennines from the seismic moment tensor of historical earthquakes by Selvaggi (1998). In the southern Apennines, where the extension rate is 1.6 mm/yr (Selvaggi, 1998), the tensional tectonics are responsible for important normal-faulting earthquakes (up to magnitude ~ 7.0). The Fucino earthquake of 13 January 1915 was the largest historical event in the region with a magnitude M_s = 6.9 (Ward and Valensise, 1989). Even though the southern Apennines and Calabria, are not objective of this study, it is important to point out that the most destructive earthquakes, such as the 28 December 1908, Messina Straits earthquake, M_w = 7.1 and 23 November 1980, Irpinia earthquake, M_s = 6.9, occurred in this region.

3. Hazard calculations

The approach of this paper is based on that used for the contiguous United States by Frankel et al. (1996), for Alaska by Wesson et al. (1999) and for Hawaii by Klein et al. (2001). The methodology follows the basic approach of Cornell (1968), in which exceedance rates for different levels of ground motion are calculated from magnitude-dependent earthquake rates and regional attenuation curves. This approach uses models based on gridded historical seismicity that has been spatially-smoothed to different length scales, an alternative to the traditional approach in which source zones are drawn around the seismicity or around tectonic provinces.

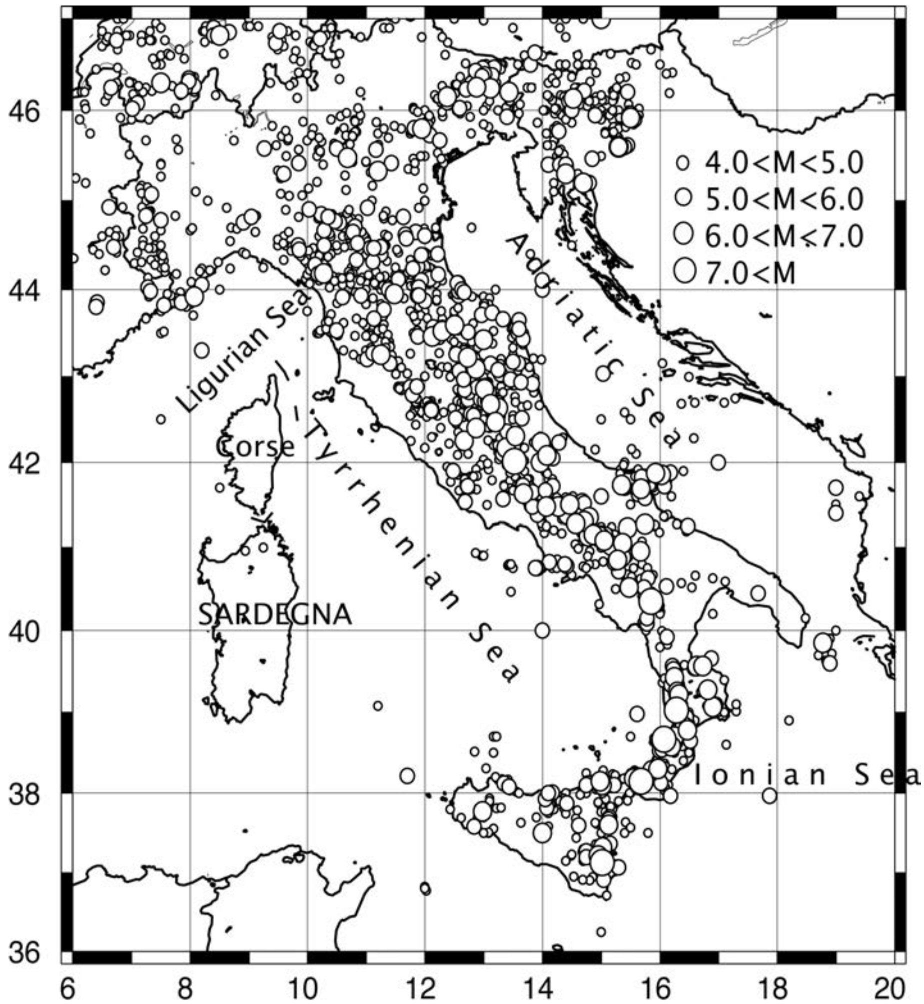


Fig. 2 - Location of earthquakes in the CPTI catalog (Gruppo di Lavoro CPTI, 1999) from 271 BC to 1992 AD, $M > 4.0$.

The procedures and codes used to construct the hazard maps are available at the website of the USGS National Seismic Hazard Mapping Project (http://geohazard.cr.usgs.gov/eq/).

With respect to the different crustal properties and tectonic features of the regions, as well as the completeness of the seismic catalog given by Camassi et al. (2002), the study region is divided into three macro zones. Each of these macro zones is characterized by its respective value of the parameters *b*-value, maximum magnitude, M_{max}, and the attenuation relationships (Fig. 3).

In order to calculate the hazard in each zone, the area under study is divided into cells 0.1° in latitude by 0.1° in longitude (roughly 10x10 km), and in each cell the earthquakes in several magnitude-time completeness groups are counted to obtain the *a*-value distribution over the study area (Weichert, 1980). The *a*-value specifies the seismicity rate in an exponential (Gutenberg and Richter, 1949) frequency-magnitude distribution, $\log N = a\text{-}bM$, where N is the

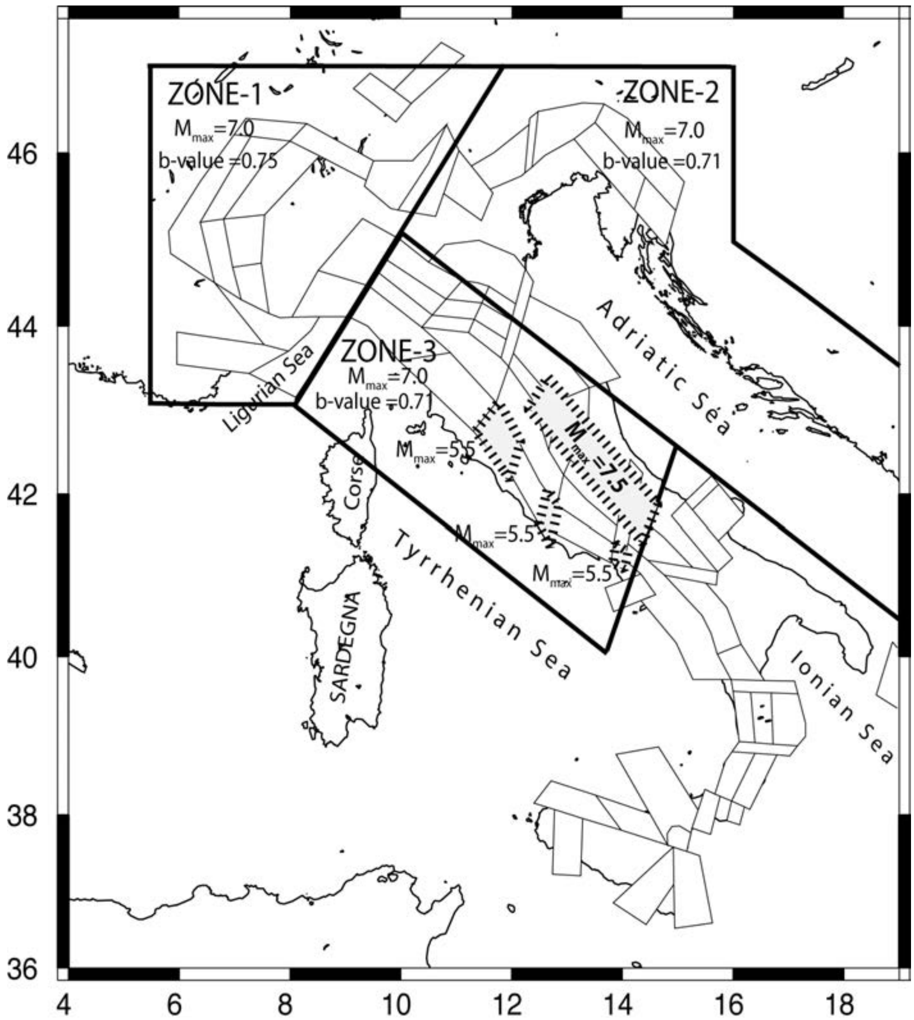


Fig. 3 - Regionalization used for seismicity parameters and attenuation relationships; it has been obtained over three regions, concerning the tectonic and geological structure (Meletti et al., 2000; Montone et al., 2003) together with the PS4 model (80 seismogenic zones). The maximum magnitude is assigned as 7.0 for the western Alps, eastern Alps, and Apennines. It is increased to 7.5 in a zone along the central Apennines and decreased to 5.5 in volcanic regions. The *b*-value is determined separately and assumed to be uniform in each zone: 0.75 in western Alps, 0.71 in eastern Alps, and 0.72 in Apennines.

number of events with magnitude equal to, or greater than, M, and b is the slope of the distribution that describes the relative frequency of small and large magnitudes.

We use the declustered catalog CPTI [Catalogo Parametrico dei Terremoti Italiani; Gruppo di Lavoro CPTI (1999)], which contains 2480 records of earthquakes exceeding intensity degree V-VI MCS in the time window 217 BC-1992 AD (Fig. 2). The periods of stationarity/ completeness of the CPTI catalog were identified for different magnitude ranges in five zones by Camassi et al. (2002). Table 1 shows the completeness of the catalog for three zones in terms of variability in the beginning of completeness times for magnitude ranges. The catalog is freely available for scientific purposes at the INGV web site (http://emidius.mi.ingv.it/CPTI/home.html). The CPTI

Table 1 - Catalog completeness times for magnitude ranges in each zone from Camassi et al. (2002).

ZONE-1					
Magnitude range	4.15-4.45	4.45-4.75	4.75-6.25	> 6.25	
Years (AD)	1875	1875-1840	1840-1550	1550-1300	
ZONE-2					
Magnitude range	4.15-4.45	4.45-4.75	4.75-5.35	5.35-6.25	> 6.25
Years (AD)	1875	1875-1840	1840-1550	1550-1250	1250-1100
ZONE-3					
Magnitude range	4.15-4.45	4.45-5.35	5.35-6.25	> 6.25	
Years (AD)	1870	1870-1500	1500-1220	1220-1100	

catalog was designed for seismic hazard purposes, and a homogeneous magnitude value was assigned to each event. Four types of magnitudes, given as M_e, M_m, M_s, and M_a are available: M_e is the macroseismic equivalent magnitude computed by Gasperini and Ferrari (1995, 1997); M_m is the macroseismic magnitude, computed from the epicentral intensity I_o and by the relation M_s - / I_o proposed by Rebez and Stucchi (1996); M_s is the instrumental magnitude reported in database NT4.1. Even though various types of magnitudes are available for each earthquake, a single type of magnitude is not available for all. Therefore, a homogeneous magnitude, M_a, was calculated by a weighted average of the previously mentioned magnitudes. In our study, we use M_a magnitude for the hazard calculations since it is similar to M_w for magnitudes greater than 5.5 (Stucchi M., personal communication).

In this study *b*-values are assumed to be uniform in each macro zone, and are computed from the declustered catalog using the maximum likelihood method: 0.75 in the western Alps, 0.71 in the eastern Alps, and 0.72 in the Apennines. The estimation of *b* and its uncertainty is important in seismic hazard studies. Two methods are commonly used: the least-squares (or weighted least-squares) method (Guttorp, 1987) and the maximum-likelihood method (Weichert, 1980). The reliability of these methods depends upon many elements: the sample size, the errors in data, the choice of binning magnitudes, and the difference between the threshold magnitude and the maximum possible magnitude considered for the region examined. However, the maximum-likelihood method is generally considered statistically more efficient and less dependent upon the few events observed in high magnitude bands (Bender, 1983).

Gridded values of 10^a (earthquakes/cell/year) are computed and smoothed spatially by a two-dimensional Gaussian function with a correlation distance of 25 km in three zones since we use the different completeness time and attenuation relationships for each zone (Fig. 4). This optimal correlation distance for Italy was obtained by Console and Murru (2001) using a trial-and-error procedure.

Finally, the annual rate of exceeding a specified ground motion at a site is calculated from a double summation over distance and magnitude, using suitable ground motion relationships and uncertainties. In this study, three different attenuation relationships AMB96, SP96, and the appropriate regional one are used for hazard calculations in each zone, weighted as 0.25, 0.25, and 0.5 through a logic tree, and using a maximum source-site distance of 150 km. We use a minimum magnitude of 5.0 for the hazard calculations, based on the common observation that earthquakes with magnitude less than about 5 are generally unlikely to cause significant damage. We use a maximum magnitude of 7.0 with two exceptions: M_{max} = 7.5 in a zone along the central Apennines, and M_{max} = 5.5 in several volcanic regions (Fig. 3). Since the Apennines' axis has a history of several large earthquakes of magnitude M around 7, we think that M_{max} = 7.5 is the appropriate choice for the narrow zone indicated in Fig. 3, and represents the scenario where more than a single fault segment go off at the same time. About the smaller M_{max} for the volcanic regions, M 5.5 is a choice taken over a similar argument, since $M \sim 5$ is the largest historical magnitude in the catalog for the Alban Hills.

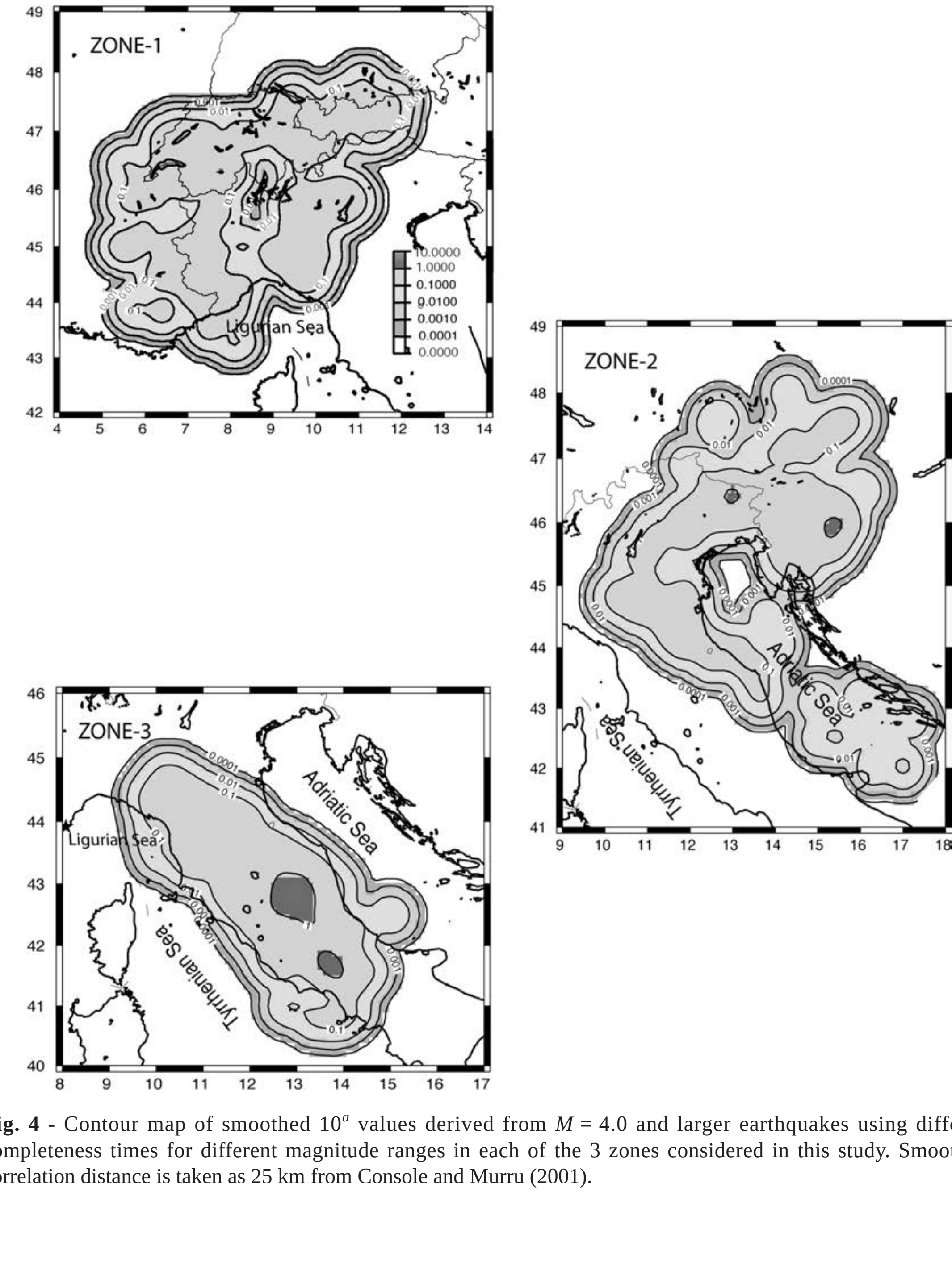


Fig. 4 - Contour map of smoothed 10^a values derived from M = 4.0 and larger earthquakes using different completeness times for different magnitude ranges in each of the 3 zones considered in this study. Smoothing correlation distance is taken as 25 km from Console and Murru (2001).

3.1. The new predictive relationships for the ground motion

Previously, attenuation relationships were developed by Ambraseys (1995) and Ambraseys et al. (1996) for the Mediterranean regions and by Sabetta and Pugliese (1987, 1996) for Italy through regressions of strong-motion data. The AMB96 relationships were defined on the basis of the European strong motion data bank and calibrated on 422 triaxial records generated by 157 earthquakes in Europe and adjacent regions. The SP96 relationships were calibrated on 95 strong motion records for 17 Italian earthquakes.

Recent studies have shown that the ground motion levels can be quite different in zones of different tectonic regimes, such as extensional and compressional (Atkinson and Boore, 1995; Atkinson and Silva, 1997; Boore et al., 1997; Campell, 1997; Sadigh et al., 1997; Spudich et al., 1999). As mentioned previously, from a tectonic point of view Italy has different and complex tectonic structures from north to south: (I) Alpine compression zone, (II) northern Apennine arc, (III) Calabrian arc, and (IV) Sicily (Boriani et al., 1989). These zones are associated with different tectonic and geologic units, factors that influence the wave propagation/attenuation within the region. Therefore it is important to use attenuation relationships derived from these main tectonic regions.

Where strong-motion data are sparse or totally lacking to derive attenuation functions, seismograms from background seismicity can be used together with other procedures to obtain useful attenuation functions. For example, from existing networks in the eastern Alps Malagnini et al. (2002) used 17,238 recordings from 1753 earthquakes, in the western Alps Morasca et al. (2003) analyzed 6000 records from 446 earthquakes, and in the Apennines Malagnini et al. (2000) used 7500 seismograms from 957 regional earthquakes. In each region the data were used to parameterize source-spectral models (Brune, 1970, 1971), regional attenuation functions, and empirical functions of the dispersion-induced ground-motion duration. Then random vibration theory was used to predict the absolute levels of ground shaking, following Boore's (1996) implementation of the stochastic ground motion model (Boore's SMSIM codes).

Fig. 5a shows a comparison between the attenuation relations by Malagnini et al. (2002) for the eastern Alps, Malagnini et al. (2000) for the Apennine, and Morasca et al. (2003) for the western Alps with AMB96 and SP96. The predicted peak horizontal accelerations of AMB96 and SP96 are very similar to Malagnini et al. (2000, 2002) and Morasca et al. (2003) predictions in the distance range, 20-200 km in the Apennines and western Alps, while they are lower in the eastern Alps between 0-70 km distance ranges and higher beyond 70 km.

Regional differences in the attenuation of seismic waves are apparent when comparing the areas of the different tectonic regimes. A recently deformed region, the Apennines, has a strong attenuation, $Q(f) = 130f^{0.1}$ (Malagnini et al., 2000), caused by the presence of fractures and fluids in the crust. Attenuation is lower in more stable crust, like the African foreland and the Adria micro-plate, which includes the Friuli region (eastern Alps), $Q(f) = 260f^{0.55}$ (Malagnini et al., 2002). The western Alps, where crystalline basement is shallower, has also a low-attenuation crust, $Q(f) = 310f^{0.2}$ (Morasca et al., 2003).

Another difference in the ground motions comes from the geometrical spreading coefficient used for the ground-motion estimates. The existing predictive relationships for the Italian and

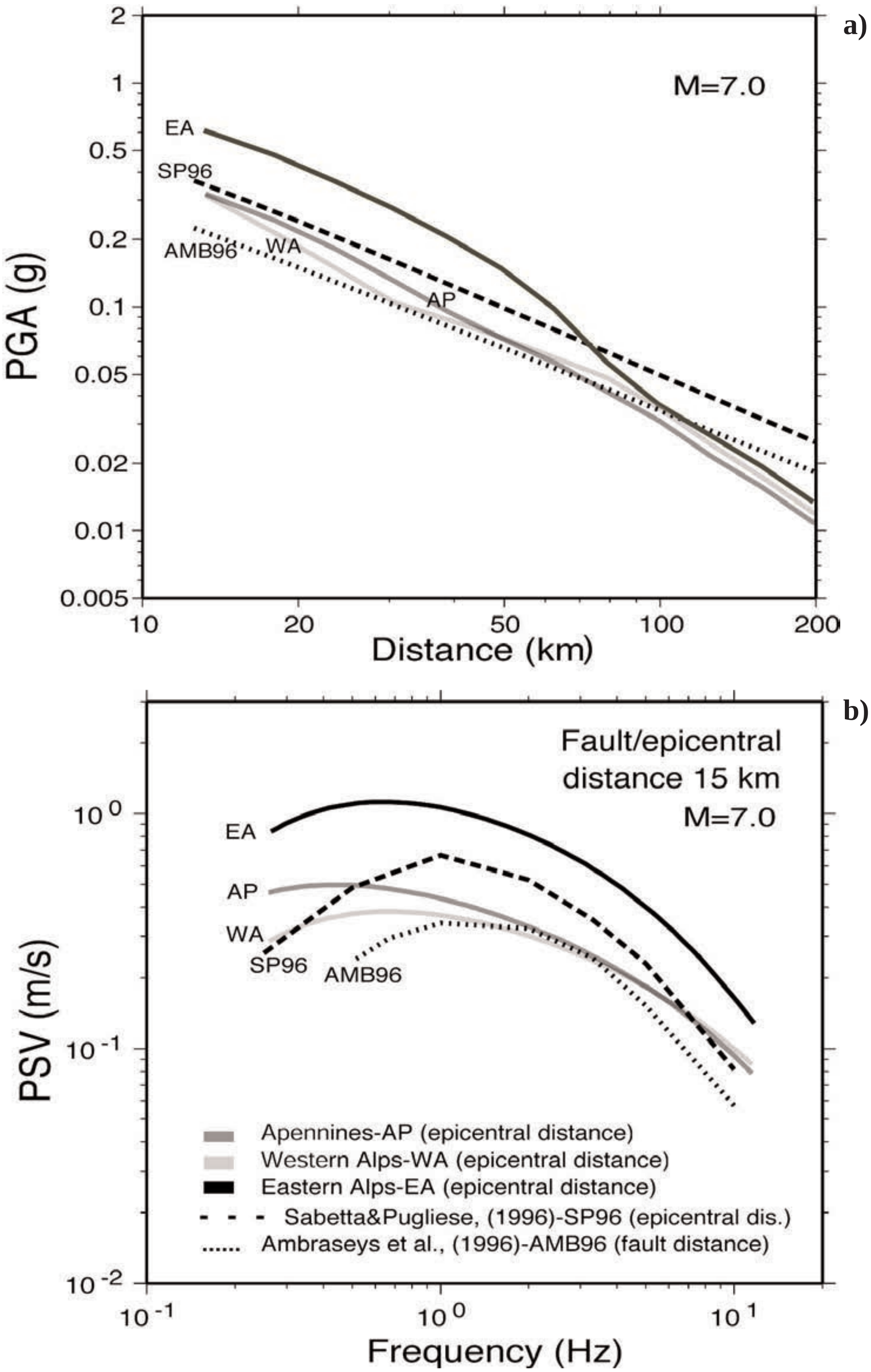


Fig. 5 - Estimation of PGA and response spectra (5% damping, at a 15 km epicentral distance) computed for M = 7.0 earthquake at hard rock site. Results based on the attenuation and excitation parameters obtained by Malagnini et al. (2000, 2002) and Morasca et al. (2003) (solid lines), are compared with the results of the empirical strong-motion regressions by Sabetta and Pugliese (1996, dashed curves) and Ambraseys et al. (1996) (dotted curves).

European regions, AMB96 and SP96, were obtained by fixing the geometrical spreading to $1/r$, because the poor distance distribution of the observations did not allow more detailed analysis. On the other hand, Malagnini et al. (2000, 2002) and Morasca et al. (2003) used very large data sets and investigated the crustal propagation in the studied regions in detail. The geometrical spreading exponent describes the wave-front geometry, which strongly depends on the velocity structure of the propagation medium (Aki and Richards, 1980). It is clear that if we fix the geometrical spreading function to, $1/r$, we hypothesize a spherical wave front, and hence, implicitly, a uniform crust, while an independent estimate of geometrical spreading takes into account possible heterogeneities and strong layering. To model the absolute level of ground shaking, we estimated the stress parameters of the largest events to be $\Delta\sigma = 50$ MPa in the western Alps, $\Delta\sigma = 60$ Mpa in the eastern Alps and $\Delta\sigma = 20$ MPa in the Apennines.

We note the advantages of using response spectra to characterize the ground motion, and compare the peak spectral velocity, PSV (m/s) (for 5% damping), computed using the excitation/attenuation models proposed by Malagnini et al. (2000, 2002) and Morasca et al. (2003) with response spectra obtained by AMB96 and SP96 for a magnitude 7.0 earthquake for a rock site at a 15 km distance. Fig. 5b presents the computed response spectra using high-frequency ground motion model parameters and the available relationships of AMB96 and SP96. Comparisons are made in terms of epicentral distance for Malagnini et al. (2000, 2002), Morasca et al. (2003), and SP96, and of fault distance for AMB96.

In this study, the regionalized predictive relationships for the ground motions are prepared in the form of tables for a set of moment magnitudes and hypocentral distances. Similarly, separate tables for the various ground-motion parameters such as peak acceleration and response with 5% critical damping, were prepared for the probabilistic hazard calculations.

4. Results

In our study, the hazard calculations are based on the Cornell (1968) method and a smoothed seismicity approach. Three different attenuation relationships AMB96, SP96, and the appropriate regional one are used for hazard calculations in each zone, and weighted as 0.25, 0.25 and 0.5 through a logic tree. The results obtained are maps of horizontal PGA with 10% probability of exceedance in 50 years (return period of 475 years). The maps, after this logic tree procedure, show high probabilistic accelerations in the central Apennines and the Friuli region (eastern Alps), around 0.28 g. The lowest PGA is observed in the western Alps, around 0.10 g (Figs. 6b, 7b, 8b). The probabilistic ground motions presented in the maps take into account the aleatory uncertainty of the attenuation relationships. The effect of the different attenuation relationships on the ground motion is quite clear in Figs. 6a, 7a, 8a. The SP96 and AMB96 relationships give PGA around 0.16 g in the Tuscan-Ligurian Apennines, 0.15 g in the western Alps, and 0.10 g in the Maritime Alps, while Morasca et al. (2003) predict ~ 0.20 g, 0.10 g and 0.08 g, respectively (see Figs. 6a and b). In the eastern Alps AMB96 and SP96 predict PGA around 0.24 g, while a value of 0.32 g is predicted by the Malagnini et al. (2002) relationship in the same region. It is important to point out that the complete set of accelerometric waveforms recorded in Friuli during the sequence of 1976-77 are included in the regressions by Malagnini et al. (2002). For the northern Apennines, SP96 and AMB96 give the same PGA, 0.20 g, while 0.24 g is obtained from Malagnini et al. (2000). In the central Apennines PGA of 0.24 g, 0.28 g and 0.32 g are obtained by using the relationships from Malagnini et al. (2000), AMB96 and SP96, respectively (Figs. 8a and 8b).

Since several important parameters used for the hazard calculations are obtained independently from different approaches, it is important to test the sensitivity of the results to

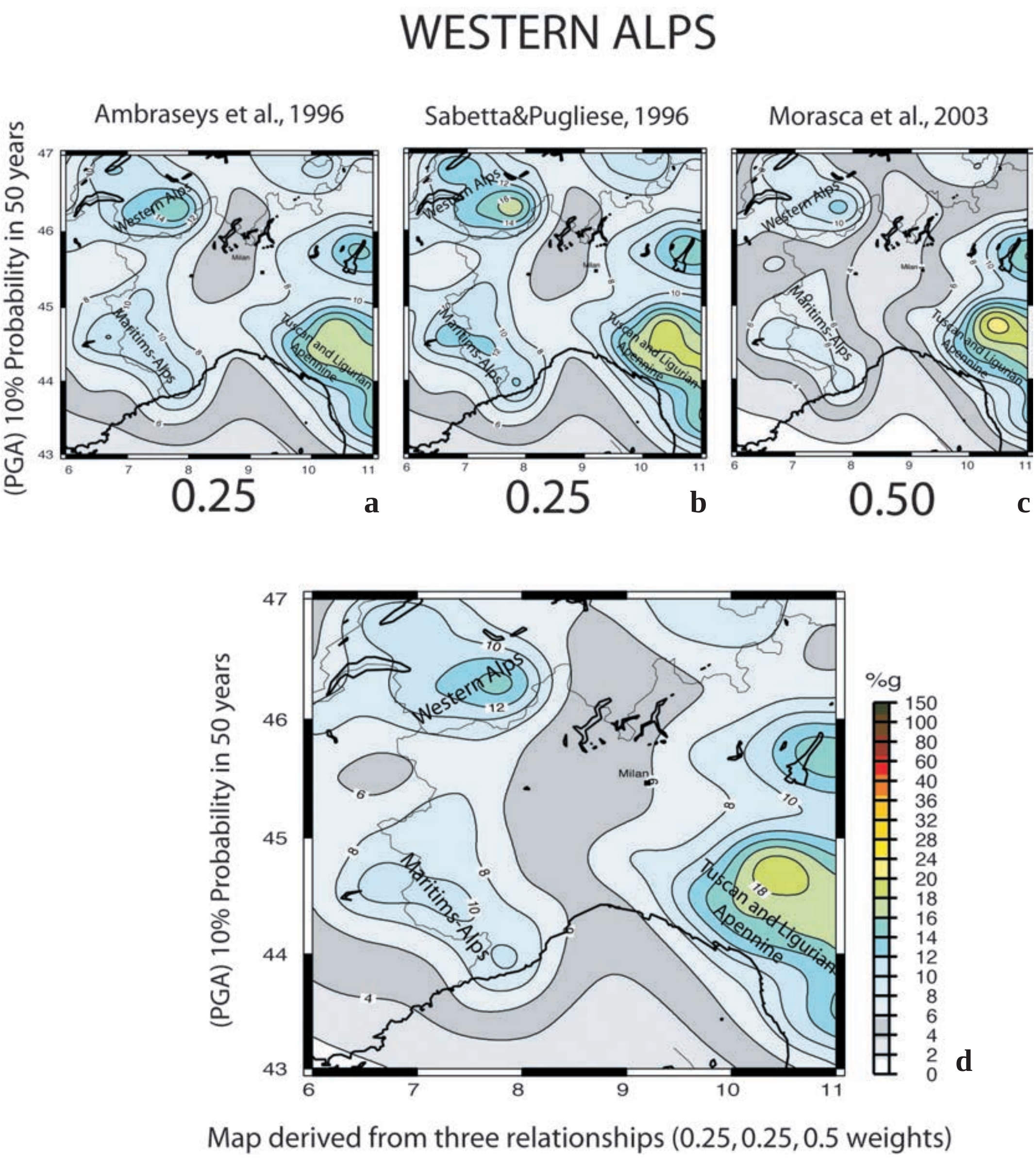


Fig. 6 - Maps of probabilistic PGA (10% probability of exceedence in 50 years) derived from smoothed historical seismicity for the western Alps. Three different attenuation relationships [AMB96, SP96, and Morasca et al. (2003)] are used for hazard calculations in each zone and then weighted as 0.25, 0.25 and 0.5 through a logic tree.

their uncertainties. Our results show that reasonable changes in the *b*-value and maximum magnitude have fairly small effects on hazard. Fig. 9a shows hazard curves for Rome; the probabilistic PGAs were calculated using a *b*-value of 0.72, which is obtained in the Apennines, and 0.82, and M_{max} values of 6.5 and 7.0. Fig. 9b shows a similar comparison between different attenuation relationships used to calculate the ground acceleration at two points, Rome and Gemona. This figure shows that attenuation relationships have a much higher impact on the hazard assessment than the *b*-value and M_{max}.

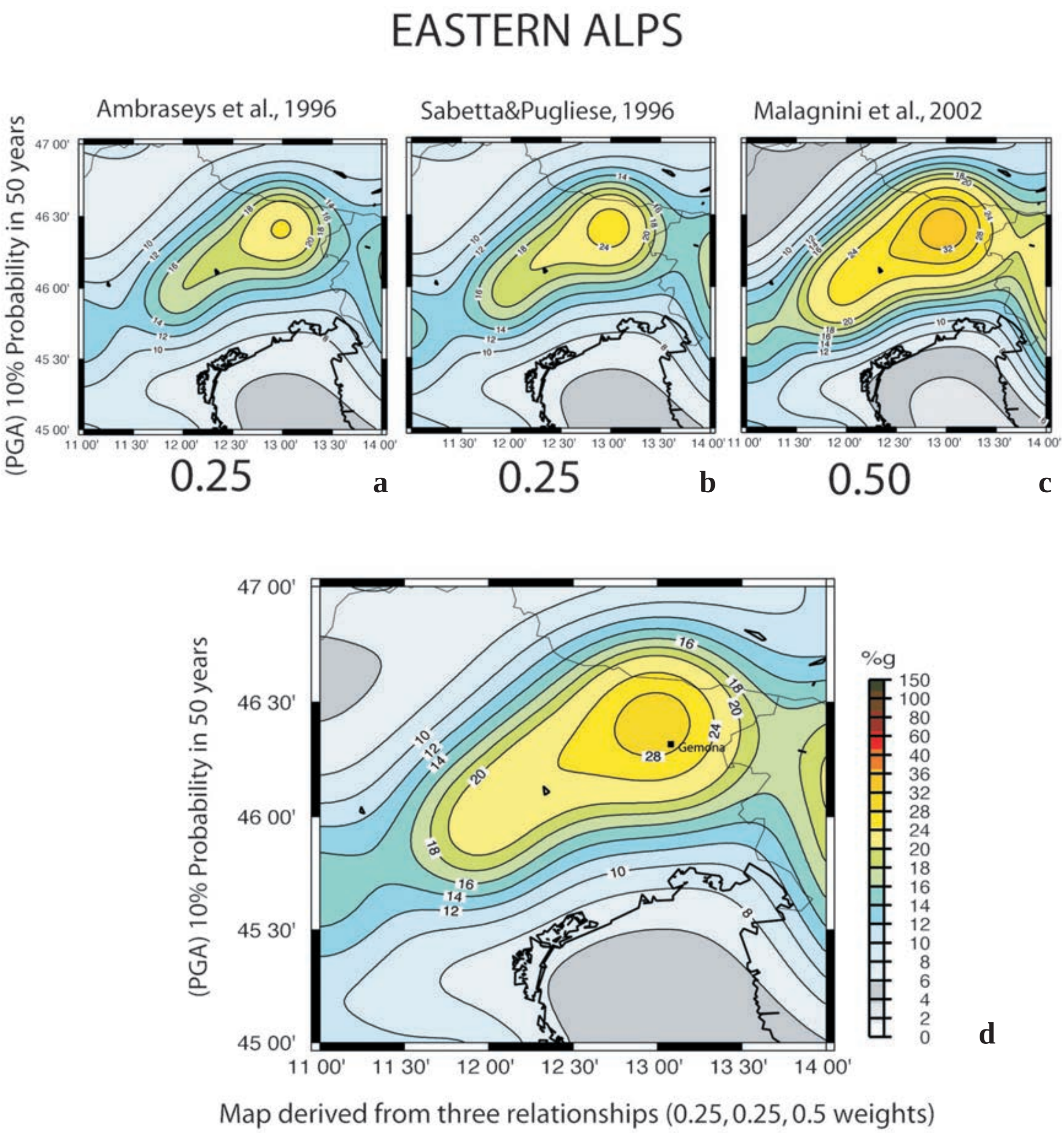


Fig. 7 - Maps of probabilistic PGA (10% probability of exceedence in 50 years) derived from smoothed historical seismicity for the eastern Alps. Three different attenuation relationships [AMB96, SP96, and Malagnini et al. (2002)] are used for hazard calculations in each zone and then weighted as 0.25, 0.25 and 0.5 through a logic tree.

5. Discussion and conclusions

In this study, the PGA maps with 10% probability of exceedance in 50 years were derived from gridded values of historical seismic activity. The areas of large probabilistic ground motions clearly coincide with zones with a large number of events with magnitude 4.0 and larger. Large events on known faults are not included explicitly in the hazard model (these results will be presented in the future). Therefore, results presented in this paper should not be

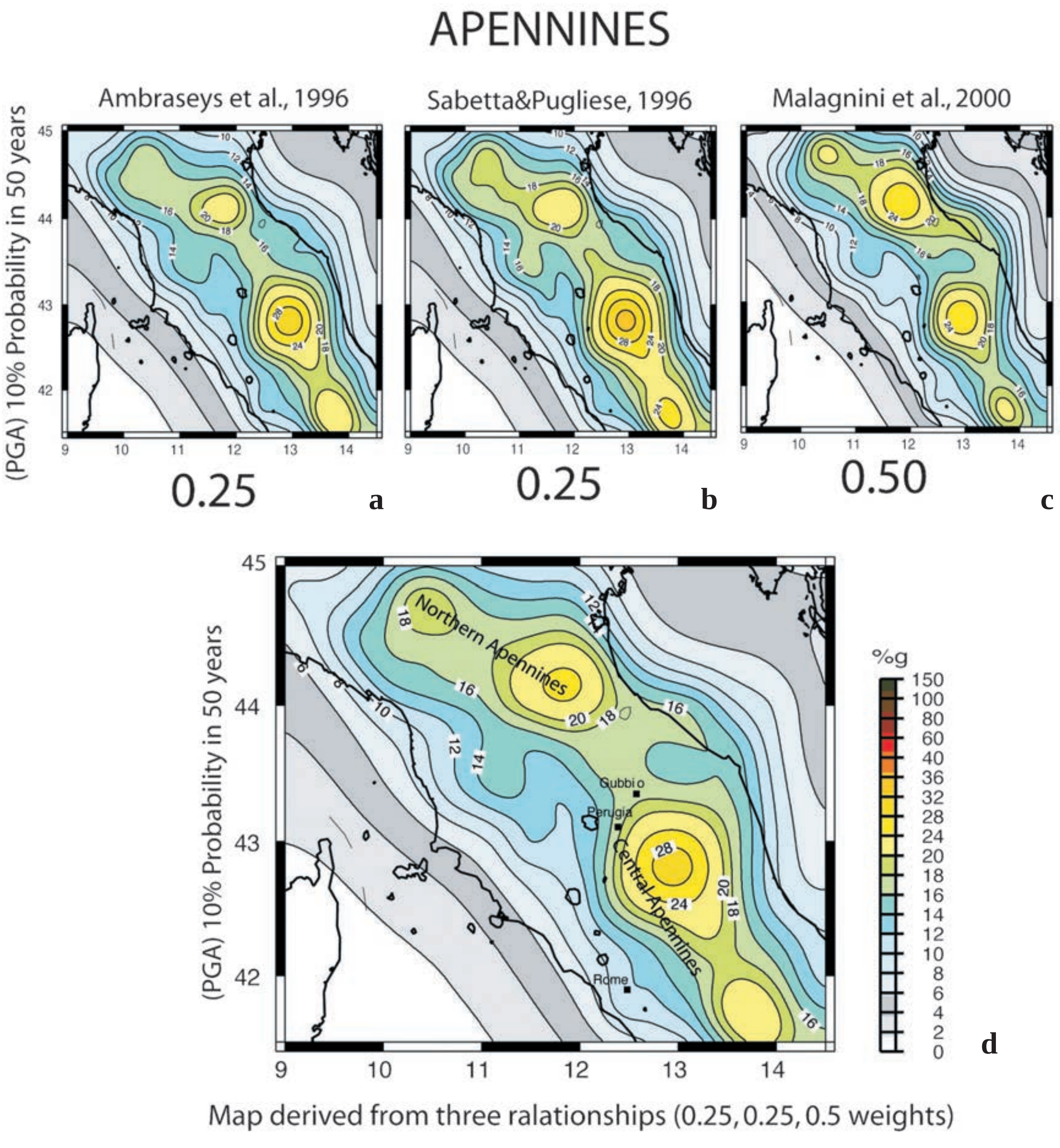
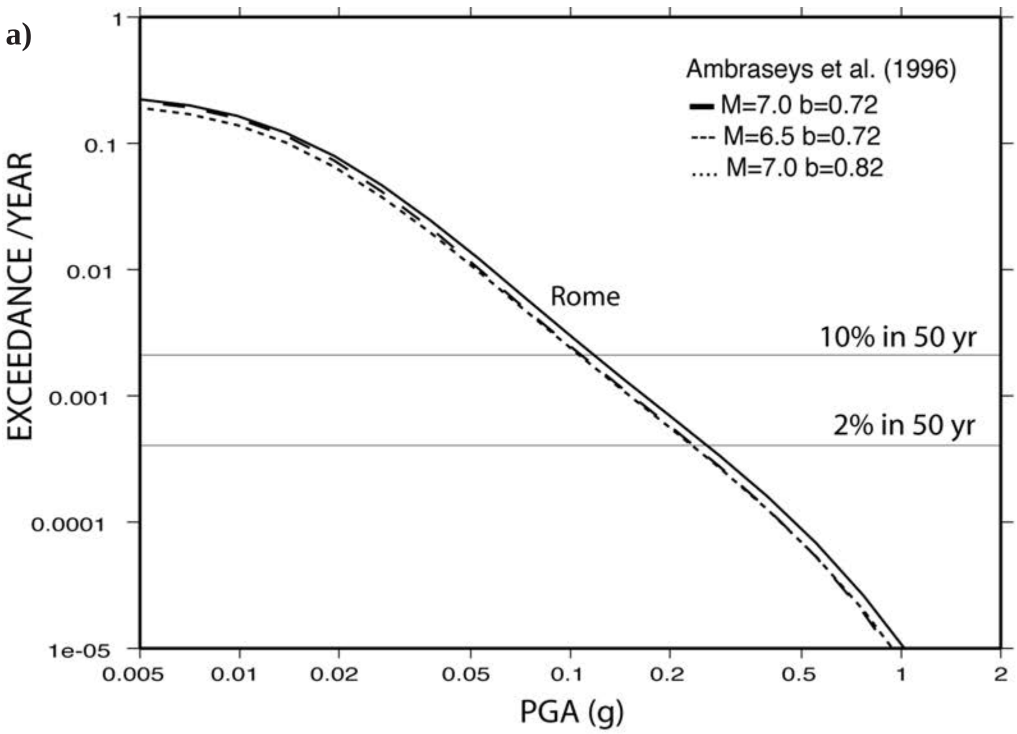


Fig. 8 - Maps of probabilistic PGA (10% probability of exceedence in 50 years) derived from smoothed historical seismicity for the Apennines. Three different attenuation relationships [AMB96, SP96, and Malagnini et al. (2000)] are used for hazard calculations in each zone and then weighted as 0.25, 0.25 and 0.5 through a logic tree.

a)



b)

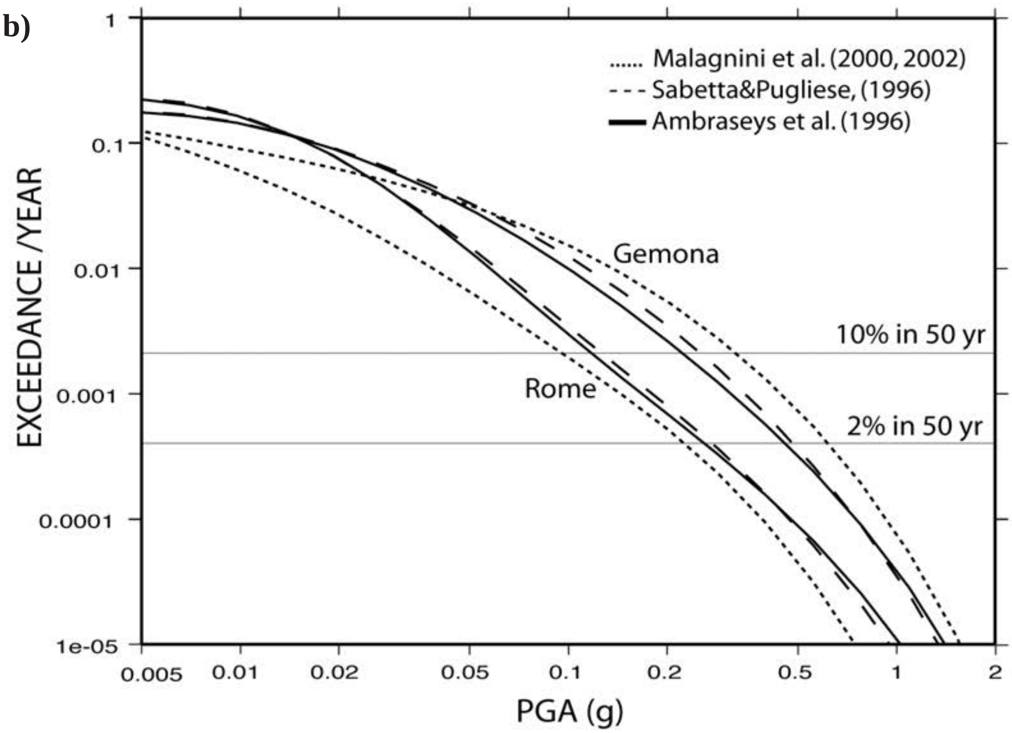


Fig. 9 - Hazard curves (annual frequency of exceedance vs. PGA) showing the sensitivity for parameters *b*-value, M_{max} and attenuation relationships on the hazard estimates: a) hazard curves for Rome using b = 0.72 and 0.82 and M_{max} = 6.5 and 7.0; b) hazard curves for Rome and Gemona comparing different attenuation relationships.

taken as final. Peruzza and Pace (2002) showed the effect of the modeling faults and difficulty of their characterization in the central Apennines. Their results show the significant changes in the hazard with the addition of faults.

Our results show that the smoothed seismicity approach gives reasonable regionalized results without the need of introducing seismogenic zones, some of which may have a small number of earthquakes and, hence, low statistical representation. In other words, where earthquake data sets for individual seismic sources are incomplete, source zones should be enlarged and additional seismological and geological data should be gathered to allow non-statistical determination of seismic source parameters.

We introduce new predictive ground motion relationships obtained for areas in different tectonic regimes. These relationships take into account properties of the source excitation and of the crustal structure, and their effect on wave propagation in the studied regions. The differences in wave propagation can thus be easily linked with the geologic and tectonic settings of the areas and play a key role in hazard studies. This work is also part of a larger effort, supported by the Istituto Nazionale di Geofisica e Vulcanologia of Rome (INGV) for obtaining new attenuation relationships for Italy and the Mediterranean region. The ultimate goal of the project is to produce modern probabilistic hazard maps at the Italian and Mediterranean scales, based on the use of predictive relationships estimated regionally.

In order to make better use of the data obtained in this study and the methodology of the logic tree in seismic hazard evaluation, it is necessary to carry out a sensitivity analysis of the results according to the variability of the different parameters, which have been introduced. This will be presented in detail in a future study.

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