



## SEISMIC HAZARD MAP FOR THE ITALIAN TERRITORY USING MACROSEISMIC DATA

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### Abstract

A seismic hazard map, in terms of macroseismic intensity, is proposed for the Italian continental territory and Sicily, which has a 10% probability of exceedance in 50 years. The methodology used here was first proposed by Cornell (1968), which requires information about the location and seismicity rates within each of the defined seismogenic zones, as well as an attenuation model. In particular, it is proposed an original macroseismic intensity attenuation model derived from the Italian macroseismic database DBMI04. The seismic hazard map, obtained in terms of intensity, was subsequently transformed into PGA by means of a linear relation between intensity and PGA, in order to compare it with the national seismic hazard map MPS04.

**Key words:** Probabilistic seismic hazard, macroseismic data, seismogenic zonation, intensity attenuation, Italy

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### Resumen

Se propone un mapa de amenaza sísmica, en términos de intensidad macrosísmica con un 10% de probabilidad de excedencia en 50 años, para Italia continental y Sicilia. La metodología usada fue propuesta originalmente por Cornell (1968), la cual requiere información acerca de la localización y tasas de sismicidad dentro de cada una de las zonas sismogénicas definidas, como también del modelo de atenuación. En particular se propone un modelo nuevo de atenuación de la intensidad macrosísmica desarrollado a partir de la base de datos macrosísmica italiana DBMI04. El mapa de amenaza sísmica obtenido fue transformado en PGA usando relaciones lineales entre la intensidad y PGA para luego compararlo con el mapa nacional de amenaza sísmica MPS04.

**Palabras clave:** Riesgo sísmico probabilístico, datos macrosísmicos, zonación simogénica, atenuación de intensidad, Italia.

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### 1. Introduction

Seismic hazard is generally assessed in terms of peak ground acceleration (*PGA*) for deriving engineering design parameters for new buildings. However, the short time interval covered by the

instrumental records can be a problem in regions where the earthquake cycle is rather slow and seismicity not very frequent. In terms of seismic hazard assessment, this can affect the evaluation of seismicity rates in the data sample, because they may not be representative of seismogenic

processes. The low density of recording stations determines, in some parts of the world, a limited availability of the strong motion data needed to study the attenuation. It is clear that in these cases the macroseismic data are very important as they may represent the only available data.

Macroseismic intensity is defined by Grünthal (1998) as a classification of the severity of the ground shaking on the basis of observed effects in a limited area. As a consequence of this definition, the macroseismic intensity is a parameter that could be used to evaluate expected ground shaking.

In Italy, as in other countries, most of the earthquake catalogue data are derived mainly from macroseismic studies (Gruppo di Lavoro CPTI, 2004). The historical research has contributed to the knowledge of the historical seismicity dating back 1000 years (Stucchi *et al.*, 1991; Albini *et al.*, 2004); the earthquakes occurred before the 20th century and many consecutive events are only qualified with macroseismic intensity data. In the last years in Italy, a number of macroseismic databases have been proposed (Monachesi and Stucchi, 1997; Boschi *et al.*, 2000; Gruppo di Lavoro DBMI, 2005). This wealth of data permits to assess the seismic hazard in terms of macroseismic intensity.

A seismic hazard assessment, based on historical earthquakes concerning the local history of seismic effects (site approach), has been proposed by Albarello *et al.* (2002), Albarello and Mucciarelli (2002), Mucciarelli *et al.* (2000), Kijko *et al.* (2001, 2003); Monachesi *et al.* (1994), Gaull and Kelsey (1999) and Basili *et al.* (1990).

Slejko *et al.* (1998) elaborated a map of seismic hazard of Italy, in terms of macroseismic intensity, using the standard probabilistic approach (Cornell, 1968), the NT 4.1 earthquake catalogue (Camasi and Stucchi, 1996), the seismogenic zonation published by Scandone (1997), and two intensity attenuation models (Grandori *et al.*, 1987; Berardi *et al.*, 1993) without introducing the standard deviation.

This paper presents a new seismic hazard map of Italy mainland and Sicily derived by using updated data, a new derived intensity attenuation model, and the Cornell methodology as implemented in the SeisRisk III code (Bender and Perkins, 1987).

Table 1 describes the input elements used to evaluate the seismic hazard. The first three elements were taken from the national seismic hazard map released in 2004 (Gruppo di Lavoro MPS, 2004); in particular, the CPTI04 earthquake catalogue (Gruppo di Lavoro CPTI, 2004), the ZS9 seismogenic zonation (Figure. 1), and the historical (CO-04.2) and statistical (CO-04.4) completeness time intervals. The other two elements (e.g., seismicity rates in terms of epicentral intensity ( $I_0$ ) and intensity attenuation models) have been computed by Gómez (2006).

This author presents an original macroseismic intensity attenuation model derived from the most recent Italian DBMI04 macroseismic database (Gruppo di Lavoro DBMI, 2005) that includes different relationships, which are developed in section 2.

In section 3, a logic tree approach is used to explore some possible alternatives of epistemic character regarding the catalogue completeness, seismicity rates, and the attenuation models.

In the same section, it is described the modification introduced in SeisRisk III (Bender and Perkins, 1987) to compute hazard in terms of macroseismic intensity. The obtained intensity values have been transformed to *PGA* by using specific empirical relationships developed for Italy (Margottini *et al.* 1992; Faccioli and Cauzzi, 2006).

## 2. Intensity attenuation models

### 2.1. State-of-the-art

Macroseismic intensity attenuation is described by Musson and Cecic (2002) as the rate of decay of shaking with distance from the epicentre. The literature provides a number of empirical relationships that model the intensity decay in varied regions of the world as a function of

epicentral or hypocentral distance.

The first model was proposed by Kövesligethy (1906) at the beginning of the last century and assumes that the energy of seismic waves declines due to geometrical spreading and absorption of the geophysical media. Mathematically, the attenuation of intensity is written as the difference between epicentral and site intensity. Where ( $D$ ) is a function of epicentral distance in km, ( $h$ ) is the focal depth in km, and ( $\alpha$ ) is a free parameter.

In Blake (1941), the Kövesligethy relationship is simplified eliminating the linear term (absorption coefficient) but letting the coefficient of the logarithm (geometrical coefficient) as a free parameter ( $b$ ). Following Blake (1941), other authors such as Howell and Schultz (1975), Chandra *et al.* (1979), Ambraseys (1985), and Dowrick (1992) proposed attenuation intensity models as special cases of the Kövesligethy relationship introducing additional simplifications.

Table 2 illustrates some of the studies proposed in literature; for further references see: Neumann (1954), Ergin (1969), Grandori *et al.* (1991), Peruzza (2000), Gómez and Salcedo (2002), Castro *et al.* (2002), ECOS (2002), Fäh *et al.* (2003), Carletti and Gasperini (2003), Albarello and D'Amico (2005), Azzaro *et al.* (2006).

The macroseismic intensity attenuation models proposed in the literature are either logarithmic or non-logarithmic (linear, polynomial).

The logarithmic models are derived assuming empirically that the macroseismic intensity is proportional to the logarithm or to a power of the seismic energy density (Howell and Schultz, 1975). The limitation of these models is that the correlation with macroseismic data is not good. For instance, the Kövesligethy relationship cannot be used to estimate the coefficients of geometric spreading and absorption, and at the same time estimate focal depth ( $h$ ) (Ambraseys, 1985). In Italy, this type of model has been proposed, among others, by Albarello and D'Amico (2004). Their relation describes the intensity decay as a function of the epicentral

intensity and hypocentral distance using four free parameters.

Non-logarithmic models result from a statistical approach that allows finding the best fit of the macroseismic data. Two main studies could be mentioned for Italy: Berardi *et al.* (1993) and Gasperini (2001). The first proposed a simple attenuation model called the Cubic Root Attenuation Model (CRAM) with two free parameters, and the latter proposed a bilinear attenuation model (Table 2) with three free parameters.

The CRAM functional model (Berardi *et al.*, 1993) has been chosen in the present study to model the attenuation of Italian macroseismic intensity data:

$$\Delta I = \alpha + \beta D^{1/3} \quad (1)$$

It assumes that the intensity decay, expressed by the difference between epicentral and site intensity, is proportional to the cubic root of the epicentral distance ( $D$ ), without dependence on the earthquakes focal depth. The CRAM is as fairly simple model as it uses only two free parameters. However, it provides a better fit of the macroseismic data compared to other models such as the logarithmic and square root (Berardi *et al.*, 1993).

## 2.2. Macroseismic data set

The Italian macroseismic database DBMI04 (Gruppo di Lavoro DBMI, 2005) has been considered in the present study. DBMI04 contains about 60,000 intensity data points (IDP), in MCS scale, related to 1042 earthquakes occurred from 217B.C. to 2002.

In order to derive an intensity attenuation to be used in Probabilistic Seismic Hazard Analysis (PSHA), a careful selection of the macroseismic data was carried out considering diverse criteria. Table 3 describes 13 criteria to filter the intensity records not to be used. First, the macroseismic observations of the Etna volcanic zone (ZS936 seismicogenic zone of ZS9) are eliminated because the propagation of the seismic energy in this zone is different than other tectonic zones (Del Pezzo

**Table 1.** Elements used to evaluate seismic hazard in terms of macro-seismic intensity. The elements with \* are proposed in Gruppo di Lavoro MPS (2004), while those with \*\* are proposed in Gómez (2006).

Input element	Used in this study
Earthquake Catalogue	CPTI04 *
Seismogenic Zonation	ZS9 *
Completeness of the earthquake catalogue	Historical completeness time intervals (CO-04.2) * Statistical completeness time intervals (CO-04.4) *
Seismicity rates	Activity rates (AR) in epicentral intensity classes ( $I_0$ )**  Gutenberg-Richter rates (GR) in epicentral intensity ( $I$ )**
Ground motion attenuation relationship	Macroseismic attenuation relationship as a function of epicentral distance **

**Table 2.** Examples of attenuation intensity relationships referenced in literature. All relationships are logarithmic, except Berardi *et al.* (1993) and Gasperini (2001).  
 $I_0$  = epicentral intensity,  $R$  = hypocentral distance (km),  $D$  = epicentral distance (km);  $ML$  = local magnitude;  $h$  = depth of focus (km),  $M$  = magnitude;  $b, d, \alpha$ , are constants.

Author	Attenuation relationship
Kövesligethy (1906)	$I_0 - I_i = 3 \text{Log}(D/h) + 3 \alpha \text{Log}(e) (D_i - h)$
Blake (1941)	$I_0 - I = b \text{Log}(D/h)$
Howell and Schultz (1975)	$\text{Ln}(I/I_0) = 0.364 - 0.130 \text{Ln}R - 0.0019 R$
Gupta and Nuttli (1976)	$I(D) = I_0 + 3.7 - 2.7 \text{Log}D - 0.0011D$
Chandra <i>et al.</i> (1979)	$D \geq 20 \text{ km}$ $I(D) = I_0 + 6.453 - 4.960 \text{Log}(D+20) - 0.00121D$
Sbar and DuBois (1984)	$I = I_0 + 3.2 - 1.5 \text{Ln}D - 0.0015D$
Ambraseys (1985)	$I_0 - I = -0.22 + 0.0024 (R-h) + 2.85 \text{Log}(R/h)$
Greenhalgh <i>et al.</i> (1989)	$I = I_0 e^{-0.032R/2} / R$
Dugue (1989)	$I_0 - I = 0.2 \text{Ln}(D-d) + 0.04(D-d), d > 10$
Dowrick (1992)	$I = 2.18 + 1.41M - 1.18 \text{Ln}R - 0.0044R$
Berardi <i>et al.</i> (1993)	$I_0 - I = -0.729 + 1.122 \sqrt[3]{D_i}$
Zsiros (1996)	$I_0 - I = 3 \text{Log}(\frac{D}{h}) + 3(0.0161) \text{Log}(e)(D-h)$
Gasperini (2001)	$ I_0 - I  = \begin{cases} 0.445 + 0.059R & (R \leq 45 \text{ km}) \\ 0.445 + 0.059 * 45 + 0.0207(R - 45) & (R > 45 \text{ km}) \end{cases}$
Albarelllo and D'Amico (2004)	$I = 3.6 - 0.003R - 0.98 \text{Ln}R + 0.705I_0$
Musson (2005)	$I = 3.31 + 1.28ML - 1.22 \text{Ln}R$

**Table 3.** Criteria for selecting the intensity data points (IDP) to be used in a statistical analysis of the intensity attenuation of the Italian territory. The total number of selected IDP is 20,873, related to 212 earthquakes occurred from 1279 to 2002.

#	Data eliminated	Reason																				
1	Earthquakes of the Etna volcanic zone (ZS936).	The volcanic zone is excluded because the energy propagation is different from the other zones.																				
2	Earthquakes with epicentral intensity $I_s < 7$ .	The present study is focused on strong earthquakes.																				
3	Earthquakes with number of IDP ( $N_{IDP}$ ) $\leq 12$ .	Earthquakes with few IDP could bias the regression analysis.																				
4	Particular earthquakes, for example the 1117, 1456, 1753 and 1914 events.	These earthquakes are not well known, the literature describes them as deep earthquakes.																				
5	Offshore earthquakes.	These events could bias the regression analysis because the distribution of IDP is inhomogeneous.																				
6	Earthquakes in border regions (as a consequence, the seismogenic zones ZS903 and ZS904 are rejected).	These earthquakes are not well known.																				
7	Earthquakes that does not match the earthquakes catalogue completeness criteria.	To be coherent with the earthquakes used to assess the seismicity rates in PSHA																				
8	Earthquakes with epicenters outside the seismogenic zones of ZS9.	This study is focused on events inside of seismogenic zones of ZS9.																				
9	Special cases (SC) (DBMI04, 2005) with code: TE (Territory), SS (small settlement), SB (solitary building).	The statistical nature of intensity is not met.																				
10	Data for which intensity has not been assessed.	These data are not easy to use in statistical study in attenuation.																				
11	IDP with $I_s < 3$ ( $I_s$ =felt intensities)	The present study is focused on strong intensities.																				
12	Data with epicentral distance less than 1 km.	Earthquakes with few IDP could bias the regression analysis.																				
13	IDP rejected according to the following distance criterion.  For every $I_0$ is determined the local distance for $I_s=4$ , called $Dist_{I_{s4}}$ , using the relationship of Albarello e D'Amico (2004); for every $I_0$ , IDP with $D \geq Dist_{I_{s4}}$ are rejected.	<table border="1"> <thead> <tr> <th>I0 class</th> <th>Dist_Is4</th> </tr> </thead> <tbody> <tr> <td>11.0</td> <td>453.5</td> </tr> <tr> <td>10.5</td> <td>387.4</td> </tr> <tr> <td>10.0</td> <td>326.1</td> </tr> <tr> <td>9.5</td> <td>270.2</td> </tr> <tr> <td>9.0</td> <td>220.0</td> </tr> <tr> <td>8.5</td> <td>176.0</td> </tr> <tr> <td>8.0</td> <td>138.0</td> </tr> <tr> <td>7.5</td> <td>106.0</td> </tr> <tr> <td>7.0</td> <td>80.0</td> </tr> </tbody> </table>	I0 class	Dist_Is4	11.0	453.5	10.5	387.4	10.0	326.1	9.5	270.2	9.0	220.0	8.5	176.0	8.0	138.0	7.5	106.0	7.0	80.0
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Seismic hazard map for the Italian territory using macroseismic data

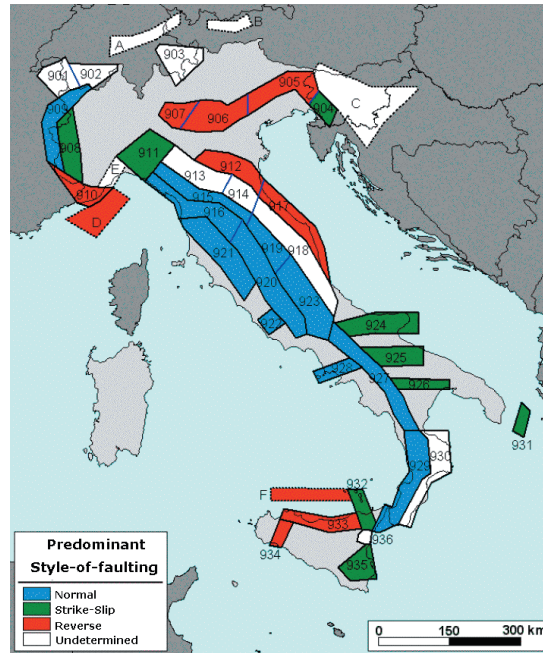


Figure. 1. ZS9 Seismogenic zonation proposed by Gruppo di lavoro MPS (<http://zonesismiche.mi.ingv.it/documenti/App2.pdf>, 2004).

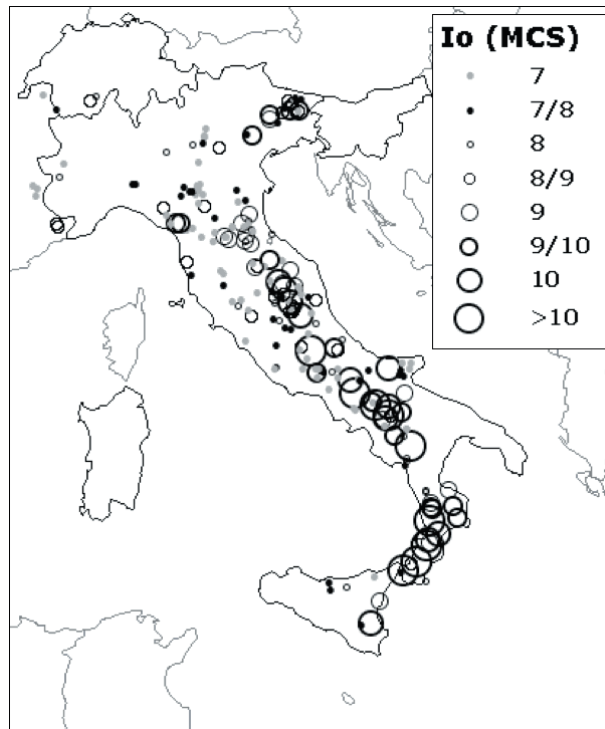
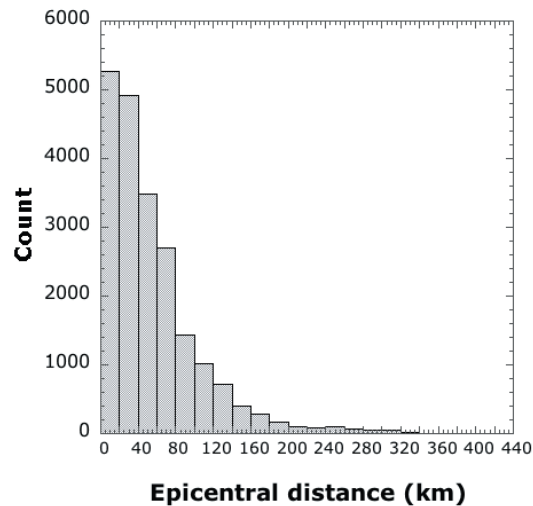


Figure. 2. Epicentral distribution of the earthquakes selected (macroseismic intensity attenuation; 212 events).



**Figure 3.** Frequency distribution of the site intensities ( $I_s$ ) as a function of epicentral distance.

*et al.*, 1987; Ciccotti *et al.*, 2000). Other filters are used to remove earthquakes characterised by epicentral intensity  $I_0 < 7$ , site intensity  $I_s < 3$ , number of macroseismic observation  $N_{IDP} < 13$  and epicentres outside of ZS9.

The IDP of earthquakes that are not well known have also been disregarded. For instance, the 1456 and 1914 earthquakes are described (Meletti *et al.*, 1988; Meloni *et al.*, 1988) as deep events, which are not easy to use in a statistical study of the macroseismic intensity attenuation because they are distributed over a very large area.

Another criterion is based on the distance: for every  $I_0$  the local distance for  $I_s=4$ , called  $Dist_{I_{s4}}$ , is determined using the relationship of Albarello and D'Amico (2004); for every  $I_0$ , IDP with  $D \geq Dist_{I_{s4}}$  are rejected.

After applying the 13 criteria (Table 3), the intensity database is reduced to 20,873 IDP related to 212 earthquakes that occurred from 1279 to 2002. Figure 2 shows the epicentral distribution of the 212 selected earthquakes.

The distribution of the selected IDP for each epicentral intensity class and for each site intensity class are shown in tables 4a and 4b respectively. The largest number of IDP belongs to the  $I_0$  7MCS class and the  $I_s$  5 MCS class.

Figure 3 shows the frequency distribution of the intensities as a function of epicentral distance, which indicates that the majority of IDP are

located within 100km from the epicentre.

The IDP of the volcanic areas are divided into two datasets:

- The first corresponds to the ZS921 (Etruria), ZS922 (Colli Albani) and ZS928 (Ischia-Vesuvio) seismogenic zones;
- The second corresponds to the ZS936 (Etna) seismogenic zone.

From these two datasets, a selection of macroseismic data was used considering the criteria described in table 5, resulting in a subset of 716 IDP for Ertruria, Colli Albani and Ischia-Vesuvio and 1328 IDP related to 54 earthquakes for the Etna zone (ZS936).

### 2.3. Development of macroseismic intensity attenuation models

According to Bommer *et al.* (2003), the combination of seismic source characterisation, including rupture mechanism and ground-motion prediction equations that explicitly account for style-of-faulting, should produce refined estimates of the seismic hazard. The most recent seismic source zone model of Italy, called ZS9 (Gruppo di Lavoro MPS, 2004), includes for each zone an average depth of the seismogenic layer, and an indication of the predominant faulting style (Figure. 1). This information was used to assess the seismic hazard of Italy with regional attenuation relationships, and with the

**Table. 4a.** Distribution of IDP for each  $I_0$  (epicentral intensity) class.

$I_0$ Class (MCS)	IDP Number
11	2385
10/11	899
10	2351
9/10	2259
9	1547
8/9	3606
8	2190
7/8	2021
7	3615
<b>Total</b>	<b>20.873</b>

**Table. 4b.** Distribution of IDP for each  $I_s$  (site intensity) class.

$I_s$ Class (MCS)	IDP Number
11	52
10/11	95
10	223
9/10	198
9	560
8/9	672
8	1545
7/8	1416
7	2560
6/7	1730
6	2412
5/6	1011
5	2886
4/5	1348
4	2475
3/4	608
3	1082
<b>Total</b>	<b>20.873</b>

Bommer *et al.* (2003) style-of-faulting scaling factors.

In analogy with the *PGA* attenuation relationships, and using the information provided by ZS9, Gómez (2006) derived a set of macroseismic intensity attenuation relationships, called Cub05-Reg., from the 20,873 IDP described in the previous section. The set includes:

1. A valid relationship for the entire Italian territory (CUB05-General);
2. A relationship for areas with predominant normal style-of-faulting (PFM-Normal);
3. A relationship for areas with predominant strike-slip and reverse-style-of-faulting (PFM-Strike-Slip+Reverse);
4. A relationship for the Etna volcanic zone (ZS936).

Table 6 summarizes the values of the parameters of equation 1 obtained for each attenuation

relation and their relative standard deviation. The macroseismic data have been fitted by the least squares method using the KaleidaGraph software (Synergy Software, 2005)

Independent attenuation relationships for areas with reverse and strike-slip style faulting respectively were also derived, but they have been disregarded because the data sample is not statistically significant (Gómez, 2006). Similarly, attenuation relations for the ZS921, ZS922 and ZS928 volcanic areas have been rejected because they are not significantly different from CUB05-General.

Figure 4a shows a plot of the intensity decay ( $\Delta I = I_0 - I$ ) as a function of epicentral distance (blue curve), along with the 20,873 IDP (small grey points) used to obtain this relationship (CUB05-General) with a standard deviation of  $\pm 0.94$ . Figure 4b shows the  $\Delta I$ -residuals (observed-computed) as a function of the epicentral distance grouped in 5 km classes for



**Table. 5.** Data from DBMI04 (Gruppo di Lavoro DBMI, 2005) not used to fit the attenuation intensity model for the volcanic areas. The total number of selected IDP are 716 for Etruria (ZS921), Colli Albani (ZS922) and Ischia-Vesuvio (ZS928), and 1328 IDP for the Etna zone (ZS936).

#	Data eliminated	Reason
1	Special cases (SC) (DBMI04, 2005) with code: TE (Territory), SS (small settlement), SB (solitary building).	The statistical nature of intensity is not met.
2	Data for which intensity has not been assessed.	These data are not easy to use in statistical study in attenuation.
3	IDP with $I_s < 3$ ( $I_s$ =site intensities).	The present study is focused on high intensities.
4	IDP with $D > 40$ km for ZS936 (Etna).	Records outside seismogenic zones
5	IDP with $D > 90$ km for ZS921, ZS922 e ZS928.	Records outside seismogenic zones

**Table. 6.** Parameters of the attenuation relationships and their standard deviations.

#	Characteristic of the regression equation	$N_{IDP}$	$\alpha$	$\beta$	Standard deviation $\sigma$
1	CUB05-General	20.873	-1,3096	1,1833	0,94
2	Predominant Focal Mechanism Normal	13.393	-1,3518	1,2263	0,88
3	Predominant Focal Mechanism Reverse + Strike-Slip	5.020	-0,8904	1,0197	1,00
4	ZS936 (Etna)	1.328	-0.4860	1,4066	1,15

the CUB05-General relationship.

The intensity attenuation model for predominant normal faulting (PFM-Normal) obtained from 11,393 IDP is shown in figure 5a, while the distribution of the  $\Delta I$ -residuals as a function of epicentral distance is shown in figure 5b.

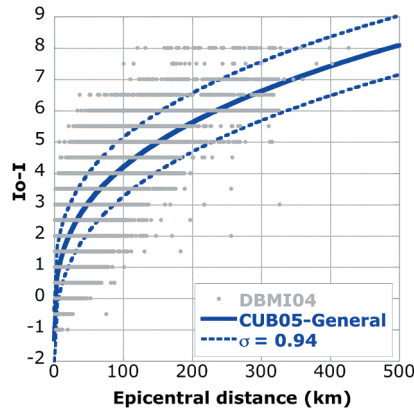
The distribution of  $\Delta I$  residuals for CUB05-General and PFM-Normal models are very similar (Figure 4b and Figure 5b) and show moderate oscillations from 5 to 150 km, meaning that the computed intensities can be considered as a good estimate of the observed intensities. For epicentral distances greater than 150 km, the attenuation models do not provide a good estimate of the intensity observations. In both attenuation models, the standard error given by the 95 % confidence intervals increases for distances greater than 330 km.

Figure 6a shows the intensity attenuation relation for both reverse and strike-slip faulting (5,020 IDP) while in Figure 6b are plotted the  $\Delta I$ -residuals. In the distance range of 5 to 80

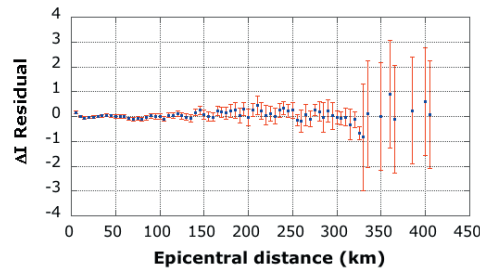
km, the intensity decay calculated with the attenuation relationships overestimates the observed intensities; after 80 km the model tends to underestimate the intensity value decay.

The attenuation relationship for the Etna seismogenic zone is presented in figure 7a and the distribution of  $\Delta I$ -residuals in figure 7b, which shows a slight increase of the standard error of 10 km of epicentral distance.

Figure 8 shows that the frequency distributions of the  $\Delta I$ -residuals (observed-computed) obtained from the four relationships described so far (CUB05-General, PFM-Normal, PFM-Reverse and Strike-Slip, Etna) are Gaussian curves (normal distribution). This follows naturally from the fact that intensity equations are written as  $f(I)=I$  and not  $f(I)=Ln I$  (Musson, 2005). Each Gaussian curve in figure 8 has a standard deviation (Tab. 6) that can be used to model the uncertainty of the ground shaking in hazard studies.



**Figure. 4a.** Intensity attenuation model CUB05-General (solid blue line) obtained from 20873 selected macroseismic data (grey points) (Gruppo di Lavoro DBMI, 2005).



**Figure. 4b.** Distribution of the residuals relative to CUB05-General as a function of the epicentral distance grouped in intervals of 5 km. The 95 % confidence intervals are shown as error bars.

Figure 9 compares the four attenuation models obtained in this study (Tab. 6). Using this, it could be concluded:

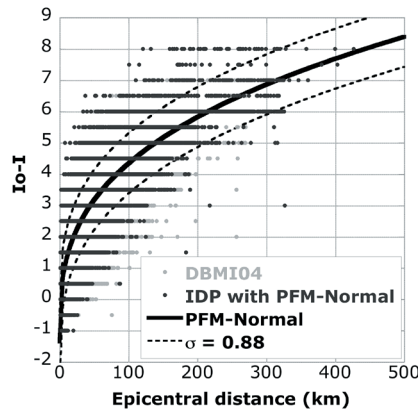
1. the Etna relationship shows the highest intensity attenuation, consistently with its peculiar geologic setting;
2. Within the first 30 km of distance, there is not much difference between CUB05-General and PFM-Normal models. After 30km the PFM-Normal model shows that the attenuation is slightly greater than the CUB05-General model;
3. The PFM-Reverse and Strike-Slip model is very similar to CUB05-General within the first 20km, after this distance the attenuation is slightly lower than the CUB05-General.

empirically observed data from strong ground motion. However, the classification adopted, based on style-of-faulting, carries implicitly a regionalization: the normal faulting style is found, in fact, along the Apennines, while the reverse faulting style is found in NE Italy and Southern Italy in the Apulian area.

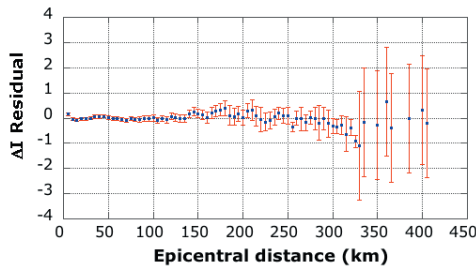
Recent studies by Malagnini *et al.* (2000; 2002) show that these areas are characterized by different geometric and anelastic attenuation that leads to a faster decay of the ground motion in central and southern Apennines compared with North and Eastern Italy. The results in figure 9 can be attributed both to the effect of the regionalization and to the style-of-faulting, but it is impossible at this stage to discriminate between them.

At a given epicentral distance, PFM-Normal predicts is lower compared with the CUB05-General, whereas PFM-Strike-Slip and Reverse predicts higher values. This is similar to

Compared to the models proposed by Albarello and D'Amico (2004), Gasperini (2001) and Berardi *et al.* (1993), the CUB05-General model decreases less rapidly within the first 90 km of



**Figure. 5a.** Intensity attenuation model (solid black line) obtained from 13393 selected macroseismic data for areas with predominant normal faulting style (sky-blue points) (Gruppo di Lavoro DBMI, 2005).



**Figure. 5b.** Distribution of the residuals relative to PFM-Normal as a function of the epicentral distance grouped in intervals of 5 km. The 95% confidence intervals are shown as error bars.

epicentral distance (Figure 10).

For distances greater than 90 km, the attenuation of the CUB05-General is greater than Albarello and D’Amico model, but decreases less rapidly than Gasperini (2001) and Berardi *et al.* (1993) model. For epicentral distances equal to zero, the value of  $\Delta I$  in CUB05-General tends asymptotically to zero.

### 3. Macroseismic intensity hazard assessment

#### 3.1. Methodology

Most seismic hazard software (Bender and Perkins, 1987; Ordaz *et al.*, 2003) is designed to work with *PGA* or spectral acceleration such as residuals following a normal logarithmic distribution (Sabetta and Pugliese, 1987; Ambraseys *et al.*, 1996; Boore *et al.*, 1997).

When computing seismic hazard using macroseismic intensity, it is important to remember that the residuals of the intensity

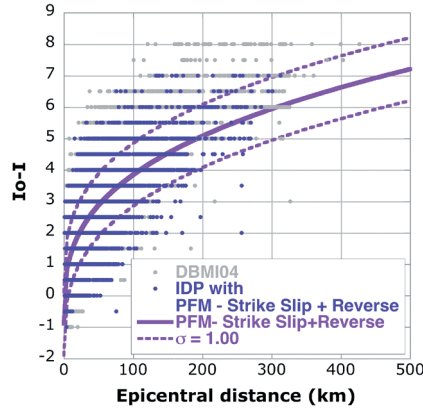
attenuation models follow a normal distribution (see section 2.3; Albarello and D’Amico, 2004; Musson, 2005).

In the present study, the program SeisRisk III (Bender and Perkins, 1987) has been modified in order to evaluate the seismic hazard by implementing a normal distribution scatter and a scale factor equal to 12.0 (Gómez and Sudati, 2005).

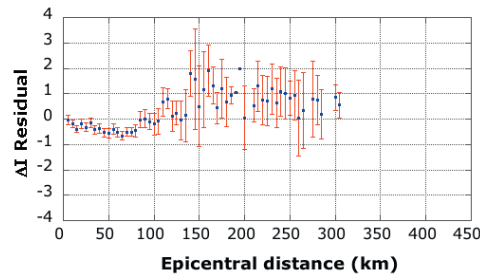
The seismic hazard map, in terms of macroseismic intensity, has been evaluated using the same methodology used by Gruppo di Lavoro MPS (2004) to compute the national seismic hazard of Italy.

Some alternatives of epistemic character have been explored using a logic tree approach:

- a) Earthquake catalogue completeness time-intervals determined using either the historical (CO-04.2) or statistical (CO-04.4) approach (Gruppo di lavoro



**Figure. 6a.** Intensity attenuation model (solid purple line) obtained from 5020 selected macroseismic data for areas with predominant style of Strike-Slip and Reverse (orange points) faulting (Gruppo di Lavoro DBMI, 2005).



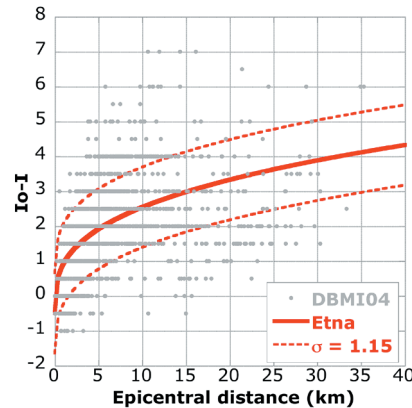
**Figure. 6b.** Distribution of the residuals relative to PFM-Strike-Slip and Reverse as a function of the epicentral distance grouped in 5km intervals. The 95% confidence intervals are shown as error bars.

- MPS, 2004);
  - b) Criteria to assess  $I_0$ max as the maximum epicentral intensity for each seismogenic zone of ZS9;
  - c) Criteria to compute the seismic rates: activity rates (AR) and Gutenberg-Richter rates (GR);
  - d) Two groups of intensity attenuation relationships. The first group uses the relationships obtained in Gómez (2006) (Cub05-Reg.) with standard deviation. The second group uses the relationship proposed by Albarello and D’Amico (2004) for all seismogenic zones of ZS9, except the Etna volcanic zone (ZS936), which uses the relationship proposed by Azzaro *et al.* (2006); the standard deviation of the attenuation models are respectively 1.25 and 0.82.
- 1) The historical completeness CO-04.2 and the statistical completeness CO-04.4 have assigned weights of 60% and 40% respectively;
  - 2) The set of individual seismicity rates (activity rates, AR) (60%) are weighted more than the Gutenberg-Richter rates (GR-rates) and the set of  $I_{max2}$  (40%);
  - 3) The weight of the regional attenuation relationship (Cub05-Reg) is greater (67%) than Albarello and D’Amico (2004), and Azzaro *et al.* (2006) relationships (33%).

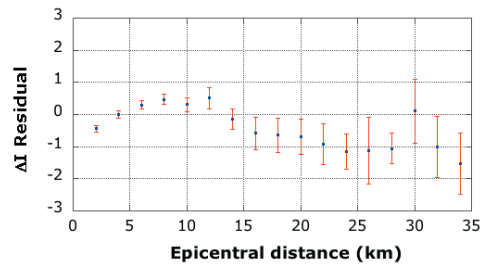
**3.2. Map of  $I_{max}$  (10%/50 years; 475-year return period)**

The values of  $I_{max}$ , with a 10% probability of exceedance within a 50-year exposure time, were computed applying the logic tree methodology (Figure 11). Results are given as:

Figure 11 shows the logic tree and the weighting scheme:



**Figure. 7a.** Intensity attenuation model (solid red line) obtained from 1328 selected macroseismic data for the Etna volcanic area (ZS936) (Gruppo di Lavoro DBMI, 2005).



**Figure. 7b.** Distribution of the residuals relative to Etna volcanic area (ZS936) as a function of the epicentral distance grouped in intervals of 2 km. The 95% confidence intervals are shown as error bars.

- Distribution of median (50th percentile) of the 8 branches of the logic tree (Figure 12);
- Distribution of 84th percentile (Figure 13);
- Distribution of 16th percentile (Figure 14).

In figure 12, the maximum intensity value is IX, observed in Central and Southern Italy.

The minimum value in the Italian peninsula is equal to 6. The values of the distribution of 84th and 16th percentile are not very different (Figure 13 and Figure 14), as they range between 6 and 9 in the first case, and between 6 and 8/9 in the remaining cases.

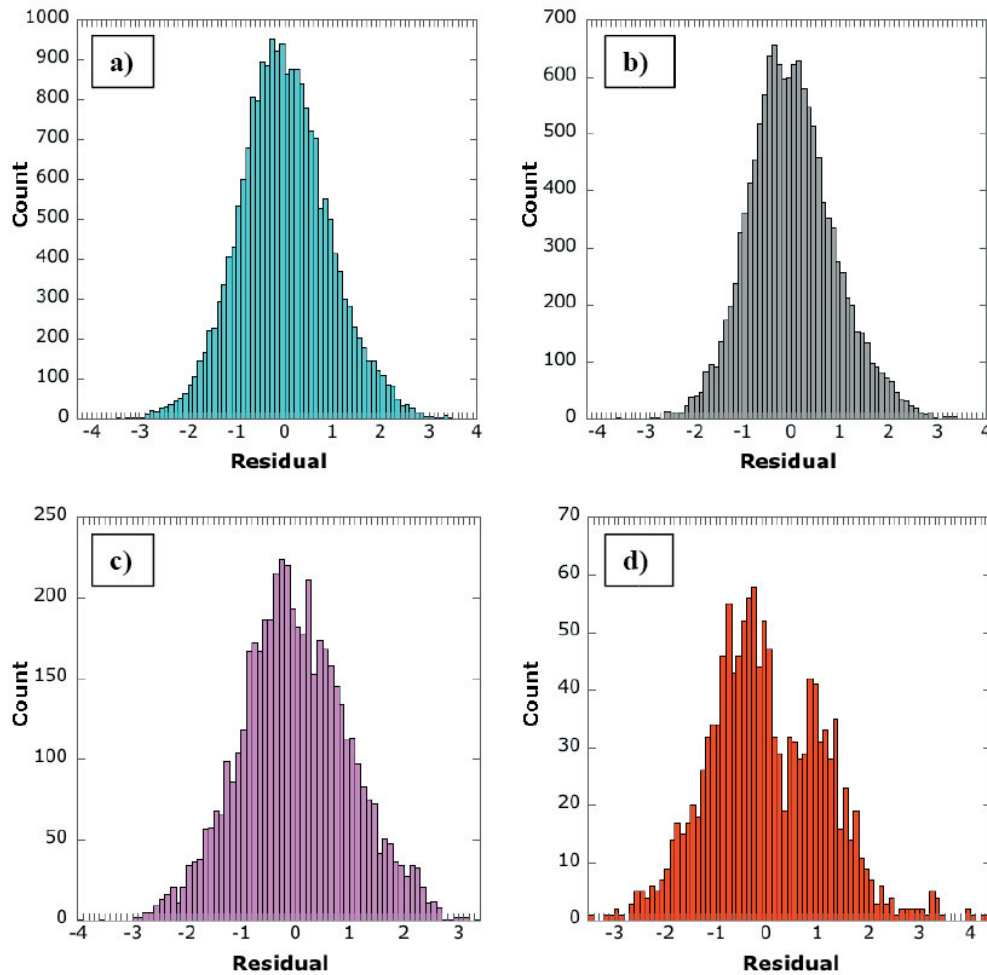
The difference between the value of the 84th percentile and the median (e.g., the maximum uncertainty on the seismic hazard assessment) can be as high as 0.5. Such moderate difference between the percentiles can be due to the small number of branches (only 8) used in the logic

tree, or it may be related to the discrete nature of the intensity data. In this case, adding more branches to the logic tree may not introduce enough variability to determine an increase (or decrease) of the intensity level at a given site.

### 3.3. Comparison between the maps in *PGA* (MPS 2004) and *Imax* (10%/50years)

Empirical relationships between macroseismic intensity and *PGA* are useful for comparing maps such as the one of figure 12 with seismic hazard assessment in *PGA*. A few studies deal with the relationships between macroseismic intensity and *PGA* and the majority has been published for the western USA (Neuman, 1954; Gutenberg and Richter, 1956; Trifunac and Brady, 1975; Murphy and O'Brien, 1977; Wald *et al.*, 1999; Boatwright *et al.*, 2001). In Italy, relationships between the macroseismic data and *PGA* records have been proposed among others by Margottini *et al.* (1992), Panza *et al.* (1997; 1999; 2001) and by Faccioli and Cauzzi (2006). Some relationships published in literature are shown in

Seismic hazard map for the Italian territory using macroseismic data



**Figure. 8.** Frequency distribution of the residuals ( $\Delta I$  observed - computed) obtained from the intensity attenuation models: a) CUB05-General; b) PFM-Normal; c) PFM-Strike-Slip+Reverse; d) ZS936 (Etna).

figure 15 as the mean values of the correlation.

The seismic hazard map in terms of intensity shown in figure 12, which represents the  $I_{max}$  with probability of exceedance 10% within a 50-year exposure time, has been converted in  $PGA$  values using the relationships of Margottini *et al.* (1992) (local intensity) and Faccioli and Cauzzi (2006).

Figure 17 shows the converted seismic hazard map representing the weighted mean of the two empirical relationships used according to the scheme proposed in figure 16. Faccioli and Cauzzi (2006) receives a higher weight (67%) compared with the 33% of Margottini *et al.* (1992), because the dataset used in that study is more recent.

The maximum value is equal to 0.34 g for a site located in Southern Italy. Figure 18 shows the seismic hazard map in  $PGA$  (10%/50 years) proposed by Gruppo di Lavoro MPS (2004), where the maximum value is equal to 0.28 g.

Figure 19 shows the difference between the maps shown in figures 17 and 18:

- The positive values (red shades) indicate areas where the values of the converted map are greater than those of the seismic hazard map MPS04 (Gruppo di Lavoro MPS, 2004);
- On the contrary, the negative values (blue shades) indicate areas where MPS04 values are greater than those

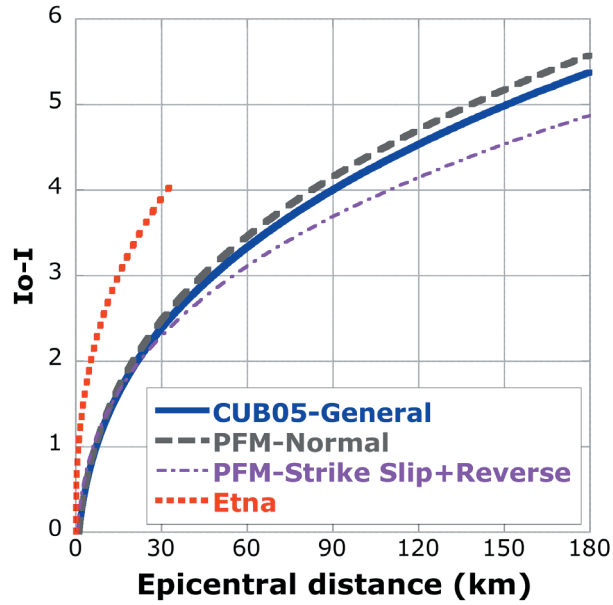


Figure. 9. Intensity attenuation models obtained in this study.

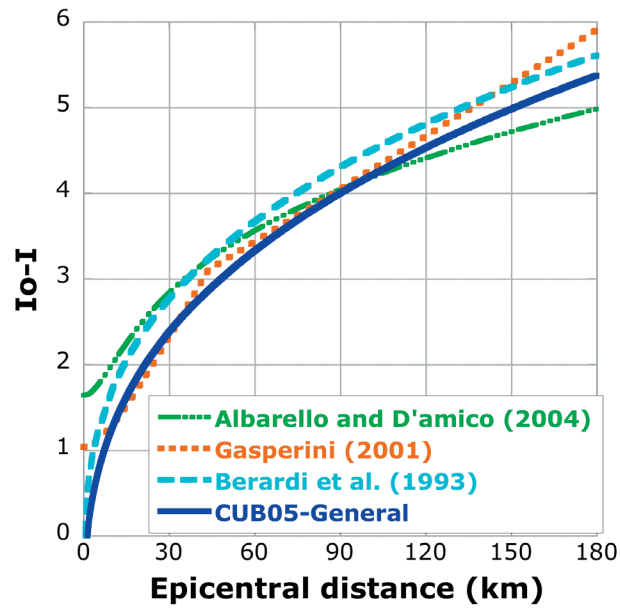


Figure. 10. CUB05-General intensity attenuation model compared with those obtained by different studies in Italy.

Seismic hazard map for the Italian territory using macroseismic data

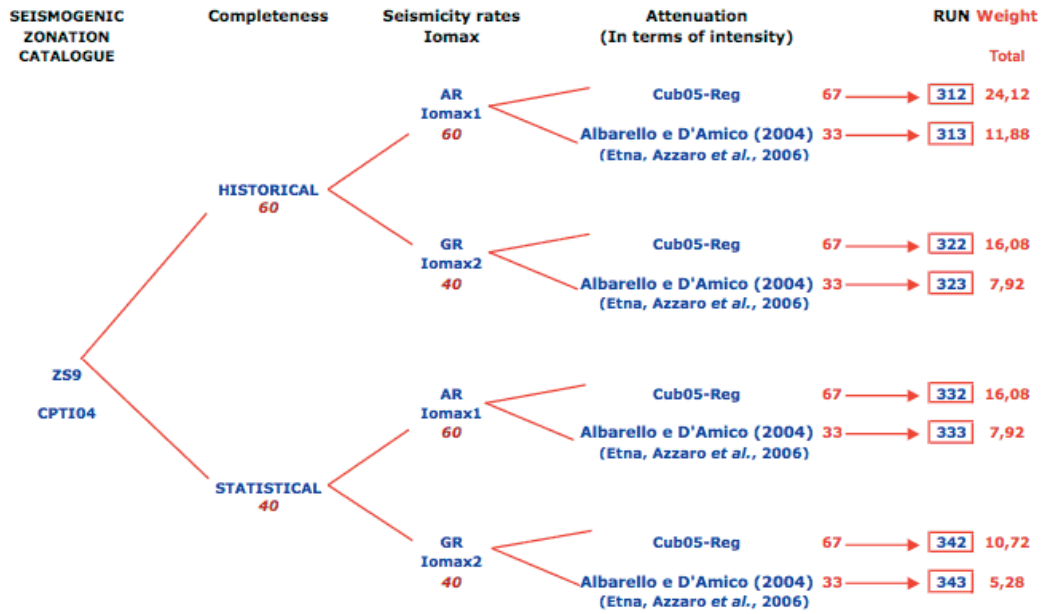


Figure. 11. Logic tree and weighted values used for seismic hazard calculation in macroseismic intensity.

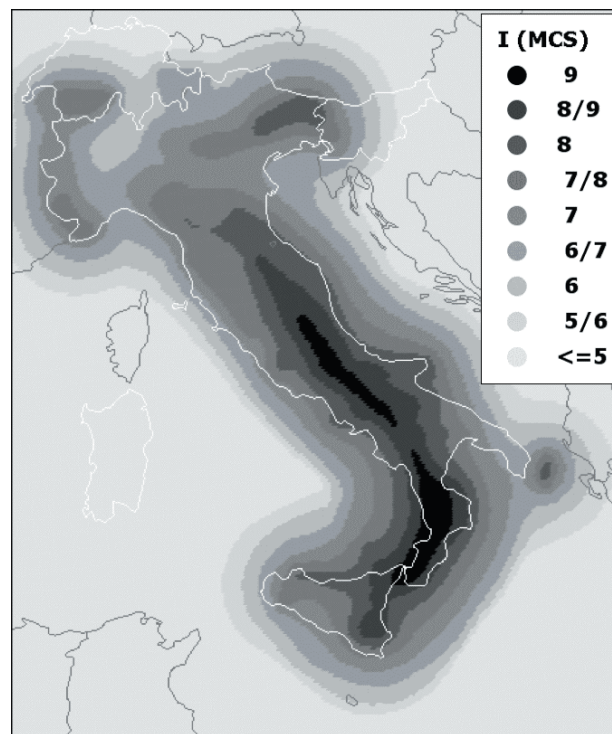
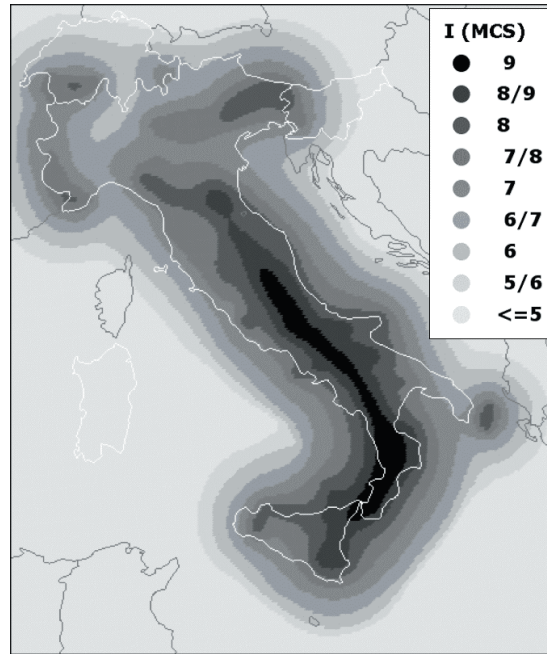
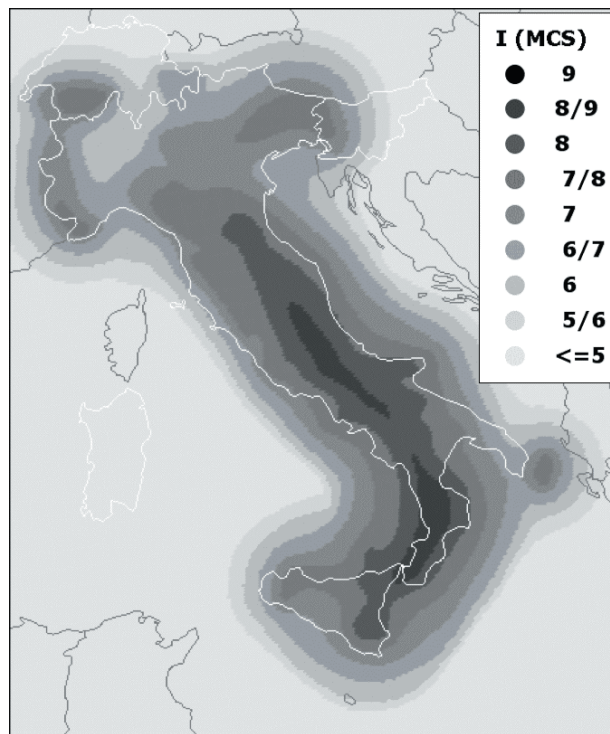


Figure. 12. Seismic hazard map in terms of macroseismic intensity (Imax with a probability of exceedance 10% within a 50-year exposure time) for the continental Italian territory and Sicily. The standard deviation in the intensity attenuation model has been accounted for.





**Figure. 13.** Map of the distribution of the 84th percentile (Imax with a probability of exceedance 10% within a 50-year exposure time) related to the map in figure 12.



**Figure. 14.** Map of distribution of the 16th percentile (Imax with a probability of exceedance 10% within a 50-year exposure time) related to the map in figure 12.

Seismic hazard map for the Italian territory using macroseismic data

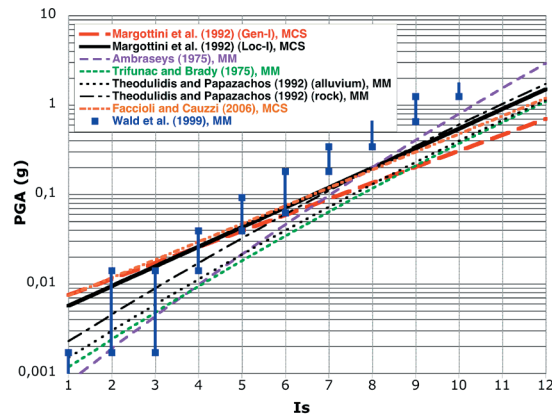


Figure. 15. Comparison of some macroseismic intensity/PGA relationships published in literature.



Figure. 16. Weighted values used to convert the Imax distribution in PGA.

of the seismic hazard map converted in *PGA* from *Imax*.

The smaller differences between the two maps are located in the interval  $-0.010g$  to  $0.010g$  (white zones).

The areas located outside the seismogenic zones of ZS9 (Figure 19) show greater (up to  $0.075$ ) *PGA* values in the “converted map” than in MPS04. It can be observed that for an epicentral distance greater than 100 km, the macroseismic intensity decays less rapidly than *PGA*, thus providing higher ground motion values.

In Central and Southern Italy, the average *PGA* values obtained from *Imax* are  $0.025g$  greater than the values of MPS04. However, the intensity is a measure of ground shaking, independent of site conditions, while the seismic hazard map MPS04 has been derived specifically for hard ground.

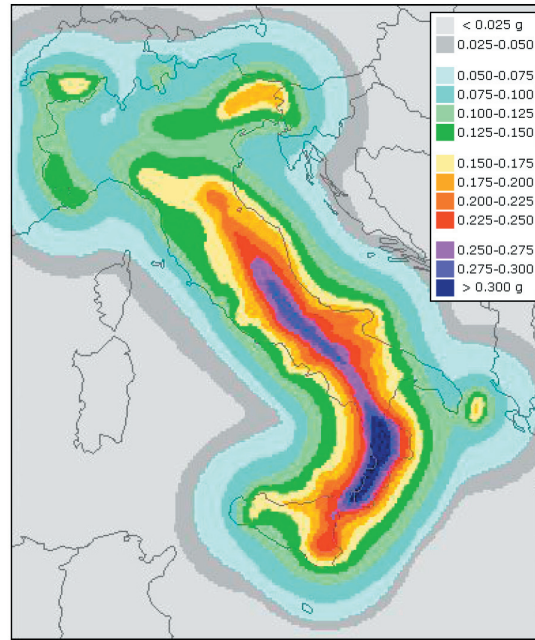
Negative values (up to  $0.075g$ ) in North-East Italy, Northern Apennines and Eastern Sicily can be related to the use of regional empirical ground-motion attenuation relations in MPS04.

#### 4. Conclusions

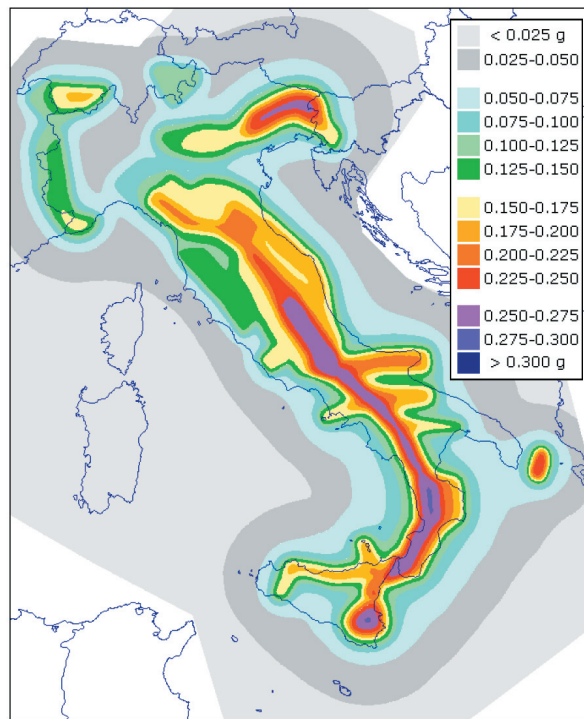
Macroseismic data has been used in this study to gain a better knowledge of the macroseismic intensity attenuation and seismic hazard of Italy.

New macroseismic intensity attenuation relationships of regional character for the Italian territory are proposed using the most recent Italian DBMI04 macroseismic database. These includes a valid relationship for the whole Italian territory, a set of relations that account the predominant style-of-faulting (normal, reverse and strike-slip), and a relationship for the Etna volcanic zone (these relationships are shown in Table 6, and are called Cub05-Reg).

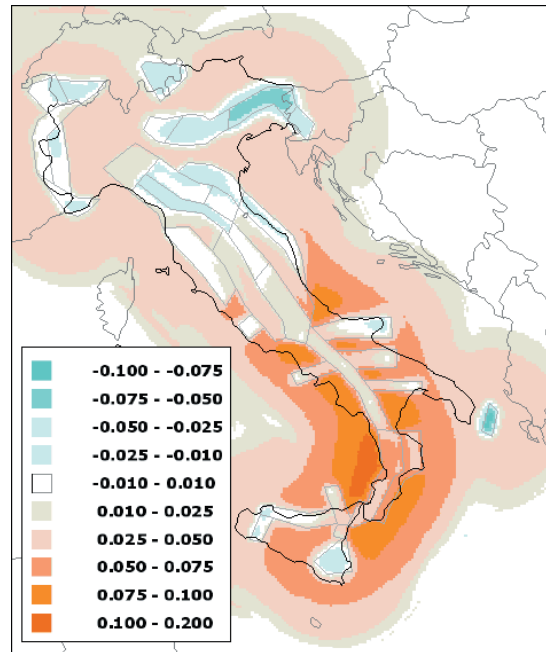
Eight years after Slejko *et al.*, (1998), a new seismic hazard map, with 10% probability of exceedance in 50 years in terms of macroseismic intensity, is proposed for continental Italy and Sicily (Figure 12). The calculation of the seismic hazard has taken into account uncertainties of epistemic and random character. This is a regular practice in probabilistic seismic hazard assessment in terms of peak ground acceleration. The hazard map has been deduced by applying the Cornell methodology, and updated input



**Figure. 17.** Seismic hazard map in terms of intensity converted in PGA values using the relationships of Margottini et al. (1992) and Faccioli and Cauzzi (2006) according to the scheme proposed in figure 16. The maximum value is equal to 0.34 g.



**Figure. 18.** Seismic hazard map in PGA (10%/50 years) proposed by Gruppo di Lavoro MPS (<http://zonesismiche.mi.ingv.it>, 2004 ). The maximum value is equal to 0.28 g.



**Figure. 19.** Areas located outside the seismogenic zones of ZS9 with higher PGA values

elements such as:

- CPTI04 Earthquake catalogue (Gruppo di Lavoro CPTI, 2004);
- ZS9 Seismogenic zonation (Gruppo di Lavoro MPS, 2004);
- Historical and statistical completeness time intervals (Gruppo di Lavoro MPS, 2004);
- Two sets of macroseismic intensity attenuation models: a regional (Cub05-Reg) and a national (Albarelo and D'Amico, 2004; Azzaro *et al.*, 2006) were used for the ZS936 seismogenic zone (Etna zone).

The computer code adopted to calculate the seismic hazard was SeisRisk III (Bender and Perkins, 1987), which has been modified to be used with macroseismic intensity data (e.g., allowing a normal distribution instead of a normal logarithmic distribution of the residuals).

The seismic hazard map proposed concurs with the results obtained by Gruppo di Lavoro MPS (2004).

In fact, the differences between the two maps lies within the range of the uncertainties associated

to the hazard evaluation.

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