ORIGINAL RESEARCH

Correlations between macroseismic intensity estimations and ground motion measures of seismic events

Angelo Masi[1] · Leonardo Chiauzzi[2] · Giuseppe Nicodemo[1] · Vincenzo Manfredi[1] ⓘ

Abstract

Macroseismic intensity data are an important source to learn from historical earthquakes. Nevertheless, this data needs to be converted into more suitable intensity measures to be used in risk analyses, as well as in design practice. To this purpose, in this paper, correlations between macroseismic scales and ground motion parameters have been derived. Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV) and Housner Intensity (I_H) as instrumental measures, and European Macroseismic Scale (EMS-98) and Mercalli-Cancani-Sieberg (MCS) as macroseismic measures, have been considered. 179 ground-motion records belonging to 32 earthquake events occurred in Italy in the last 40 years have been selected, provided that for each record, macroseismic intensity in terms of either EMS-98 or MCS or both were also available. Statistical analyses have been carried out to derive both direct (i.e. macroseismic vs instrumental intensity) and inverse (instrumental vs macroseismic intensity) relationships. Results obtained from the proposed relationships have been analyzed and compared with some of the most prominent results available in the technical literature.

Keywords Macroseismic intensity · PGA · PGV · Housner intensity · EMS-98 scale · MCS scale

1 Introduction

The estimation of macroseismic intensity of seismic events is usually carried out worldwide in order to quantify, through observations of the effects on buildings, the environment and people, the shaking pattern and the damage extent due to earthquakes. Macroseismic intensity is still often the only observed parameter to quantify the level of ground motion severity in many towns where seismometric instruments are not available. Moreover, macroseismic intensities are the only intensity measures available for pre-instrumental historical earthquakes.

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With the advent of seismometric instruments and the availability of time-history records, many authors developed relationships between macroseismic intensity and instrumental measures in order to define the relevant values of ground motion parameters in the sites where only the macroseismic intensity was available or vice versa. In this way, the large amount of information from historical earthquakes in terms of macroseismic intensity can be converted into terms of instrumental intensity in order to define the seismic hazard of an area. Further, starting from the shake maps in terms of instrumental intensity, macroseismic results can be used for post-earthquake analyses and immediate emergency plans.

Several studies proposed relationships between different macroseismic intensity scales (e.g., Modified Mercalli Intensity, MMI; Mercalli-Cancani-Sieberg, MCS (Sieberg 1930); Medvedev–Sponheuer–Karnik, MSK (Medvedev 1977); European Macroseismic Scale, EMS (Grünthal 1993, 1998)) and ground motion parameters (e.g., Peak Ground Acceleration, PGA; Peak Ground Velocity, PGV; Arias Intensity, I_A; Housner Intensity, I_H). Other studies focused on relationships among the most adopted macroseismic intensity scales (e.g. Musson et al. 2010).

In Italy, the first relationships between instrumental parameters and macroseismic intensity scales were derived by Margottini et al. (1992). The authors defined some correlations between macroseismic intensity (i.e. MSK and MCS) and instrumental parameters (i.e. PGA and I_A) starting from a database of 56 records related to 9 Italian earthquakes occurred between 1980 and 1990. Wald et al. (1999) developed regression relationships between MMI and PGA-PGV by comparing horizontal peak ground motions to observed intensities for 8 Californian earthquakes. A large amount of data deriving from California earthquakes was considered by Worden et al. (2012) to develop reversible relationships between MMI and three ground-motion parameters, such as PGA, PGV and pseudo-spectral acceleration (PSA). The proposed relationships were defined by adopting the Total Least Squares (TLS) method, which is able to account for uncertainty in both ground motion and macroseismic values. Starting from the database of Margottini et al. (1992), updated with additional earthquake data, Faccioli and Cauzzi (2006) defined new relationships between MCS and PGA-PGV. A complete overview of the works above described was developed by Gòmez Capera et al. (2007), that also proposed a relationship between MCS intensity and PGA by adopting the Orthogonal Distance Technique (ODR). Considering the ODR technique, Faenza and Michelini (2010) determined relationships between MCS intensities and both PGA and PGV. In the literature, only a small number of relationships is defined in terms of EMS-98. Among them, Chiauzzi et al. (2012) correlated EMS-98 intensity and Housner intensity (I_H), an integral parameter able to better represent the severity of seismic events (Masi et al. 2010, 2015), considering a sample of about sixty earthquake records.

The relationships reported above are generally linear regressions in which instrumental parameters are in terms of logarithm value. The main differences among them are related to the selected database, processing of data with different regression techniques and choice of macroseismic scale to be considered. With respect to the specific macroseismic scale, Chiauzzi et al. (2012) assumed as substantially coincident EMS-98, MSK-76 and EMS-92 scales. In fact, these scales take into account, in a simplified, even though sufficiently accurate way, building vulnerability and damage distributions in assigning macroseismic intensity values. On the contrary, MCS poorly takes building vulnerability into account, even though in Faccioli and Cauzzi (2006), the equality among MSK and MCS was assumed. Concerning this matter, some authors (e.g. Codermatz et al. 2003) concluded that a substantial equality exists between MCS and the European definition of the macroseismic intensities (i.e. MSK-76, EMS-92 and EMS-98). On the contrary, other authors (e.g.,

Molin 1995) observed that, for higher intensities (i.e. VII degree), EMS and MCS scales may differ by one degree or more. Similarly, Braga et al. (1982) highlighted significant differences (up to 2 degrees) between the MSK and MCS scales during the huge damage survey of the 1980 Irpinia-Basilicata earthquake.

Regarding instrumental parameters, PGA is generally adopted in the available relationships due to its physical meaning and its large use in current seismic analyses. Nevertheless, Masi (2003; Masi et al. 2011) highlighted the poor correlation between PGA and building damage compared with integral seismic parameters such as I_H and Arias Intensity, particularly in case of non-ductile existing buildings.

In this paper, starting from the study of Chiauzzi et al. (2012), relationships between macroseismic scales and instrumental ground motion parameters, and vice versa, have been derived by considering a large database of ground motion records. Three instrumental intensity measures (i.e. PGA, PGV and I_H) and two macroseismic scales (i.e. MCS and EMS-98 scales) have been adopted in order to derive direct (i.e. macroseismic intensity *vs* instrumental parameter) and inverse relationships (i.e. instrumental parameter vs macroseismic intensity). These latter (inverse relationships) permit macroseismic data of historical earthquakes to be converted according to the scales mainly adopted in Italy (i.e. MCS) and in all European countries (i.e. EMS-98) into the three instrumental intensity measures most adopted in seismic risk analyses (i.e. PGA, PGV and I_H). On the contrary, given an instrumental value of ground motion (i.e. PGA, PGV and I_H), direct relationships can be used to derive seismic input values in empirical building damage models, such as Damage Probability Matrices (DPMs, Braga et al. 1982; Zuccaro et al. 2000; Dolce et al. 2003, 2006). It is worth noting that the available DPMs generally adopt either MSK or EMS-98 scales and, as said previously, only a small number of relationships (e.g. Chiauzzi et al. 2012) are able to generate macroseismic input for such models. As a consequence, the results of the present paper represent an important tool in order to adopt DPMs in the framework of earthquake damage scenarios.

The proposed relationships have been analyzed and compared with some of the most prominent ones available in the literature.

2 Methodology

In order to derive relationships between macroseismic and instrumental measures, a large database (179 items of data) consisting of both macroseismic data and accelerometric signals relevant to 32 seismic events has been considered. The selected events are characterized by ground motion records close to the area where macroseismic data is also available. This latter is in terms of EMS-98 and/or MCS scales, while Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV) and Housner Intensity (I_H; Housner 1952) values have been computed from ground motion records. Specifically, for each accelerometric signal, the I_H value has been calculated as the area under the pseudo-velocity spectrum, using Eq. 1:

$$I_H = \int_{0.1}^{2.5} PVS(T, \xi)\, dT \tag{1}$$

where PVS(T, ξ) is the pseudo-velocity spectrum, T is the fundamental period of vibration and ξ is the fraction of critical damping (assumed equal to 5%).

In the correlations with macroseismic data, the maximum value of PGA, PGV and I_H evaluated from the two horizontal components of the ground motion record has been considered.

Regression analyses have been performed by using the Total Least Squares (TLS) method according to the procedure by Zaiontz (2019), also reported in Appendix. This statistical method allows the relationship between an independent (X) and a dependent variable (Y) to be estimated by minimizing the sum of the squares evaluated as the orthogonal distance between observed and predicted values. Consequently, it is a more appropriate technique in problems where both independent and dependent variables are affected by uncertainty. Use of the TLS technique also allows for inverting the relationships between macroseismic and instrumental intensity so that the calculated coefficients can be used to express instrumental values as function of macroseismic intensity.

After an accurate description of the database reported at Sect. 2.1, both direct regression relationships and inverse ones are derived at Sect. 3.

2.1 Database

In the present section the database used in the regression analyses is described and discussed. It consists of 179 accelerometric signals (each including both North–South and East–West components) derived from 32 earthquakes occurred in Italy in the last forty years. Figure 1 shows the epicentral area of the selected earthquakes, while Table 9 (in "Appendix") reports the main parameters of the earthquake events.

The ground motion records are extracted from the Italian Accelerometric Archive (Working Group ITACA 2017). They were recorded by either the National Accelerometric Network (RAN) of the Italian Civil Protection Department (DPC) or the National Seismic Network operated by Istituto Nazionale di Geofisica e Vulcanologia (INGV—National Geophysics and Volcanology Institute), or other networks.

For each event, macroseismic data in terms of either EMS-98 or MCS scales or both are also available. Specifically, two subsets of data have been defined: the first contains EMS-98 data (139 records belonging to 28 earthquakes) while the second one regards MCS macroseismic intensity (157 records belonging to 27 earthquakes). For 23 earthquake events, both EMS-98 and MCS data are available.

Macroseismic intensities have been derived from two different sources: (1) from past studies available in the literature (Margottini et al. 1992; Stucchi et al. 1998; Galli et al. 2001; Azzaro et al. 2004; Chiauzzi et al. 2012), for seismic events occurred before 2002; (2) from post-earthquake surveys performed by QUEST (QUick Earthquake Survey Team by Istituto Nazionale di Geofisica e Vulcanologia, INGV), for seismic events occurred after 2002. The QUEST dataset, in particular, provides macroseismic data according to both the EMS-98 and MCS scales.

It is worth underlining that earthquake events have been selected by considering only available macroseismic intensity values referred to village in which an accelerometric station (and the corresponding signal) was also located.

The selected database is reported in Table 10 (in "Appendix").

As shown in Fig. 2a, the local magnitude values (M_l) of the considered earthquake events have an almost normal distribution, with most of the data (55%) in the range $5 \leq M_l \leq 6$. Further, magnitude value refers to stations having a distance larger than 10 km (about 73% over the entire magnitude range), as shown in Fig. 2b, where M_l *vs* distance values are plotted. To this purpose, the Joyner–Boore distance (R_{JB})
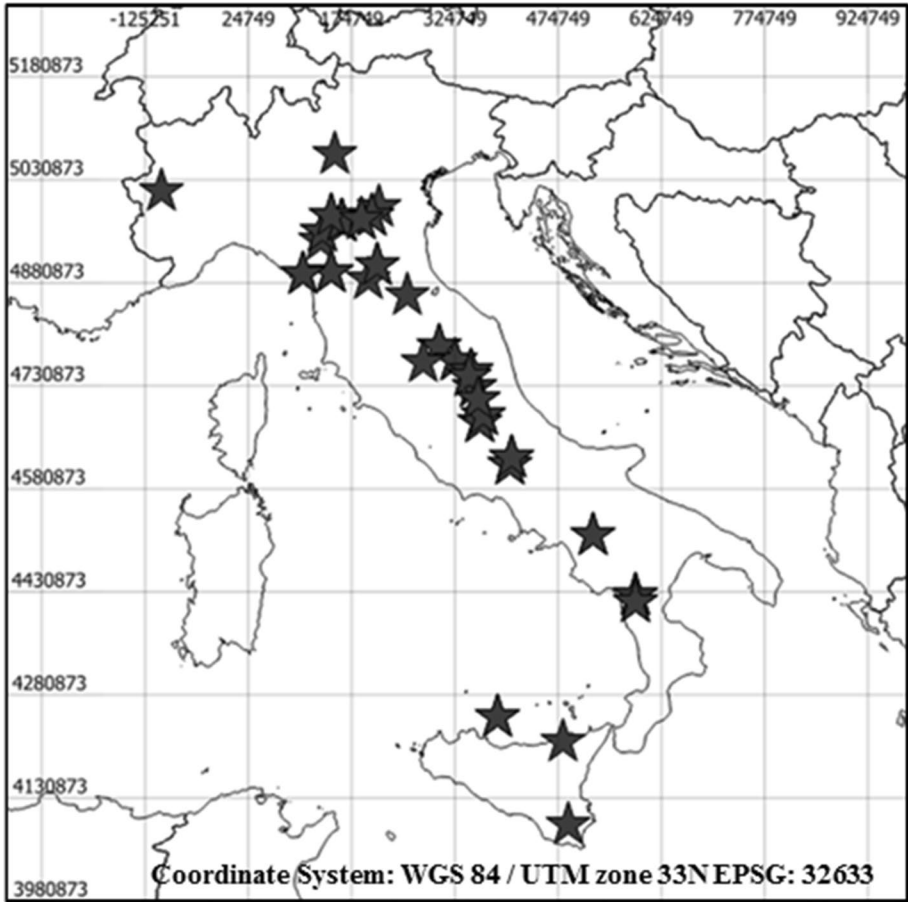
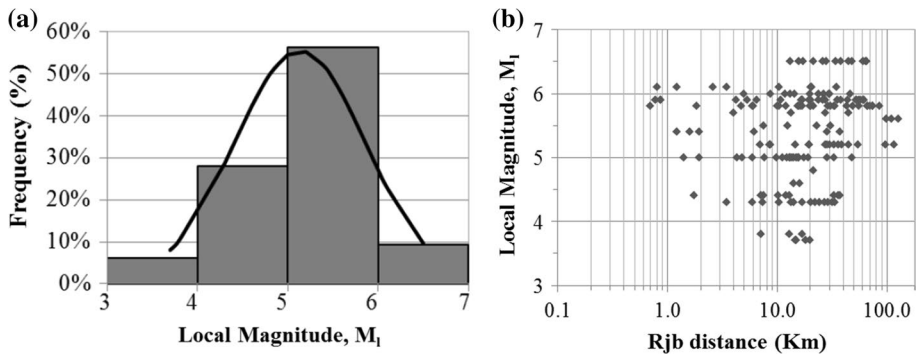**Fig. 1** Epicentral area of the selected earthquakes

Fig. 2 Histogram of the selected earthquakes grouped according to local magnitude, M_l (*on the left*) with relative normal distribution. Magnitude versus distance, considering the Joyner Boore distance, R_{JB} (*on the right*). The Rjb distance axis is in logarithmic scale

was considered. R_{JB} values were calculated through the empirically calibrated model described in Montaldo et al. (2005) and Chioccarelli et al. (2012), starting from the epicentral distance value.

Regarding the database adopted in the regression analyses, Table 1 summarizes the main statistic parameters evaluated for both instrumental (PGA, PGV and I_H) and macroseismic (MCS and EMS-98) intensities. Specifically, the mean and median values of PGA are 0.124 g and 0.063 g respectively, while they are 7.398 and 2.853 cm/s for PGV, and 0.311 m and 0.137 m in terms of I_H. Considering the samples in terms of macroseismic intensity, the mean and median values are 5.79 and 5.5 for MCS, respectively; 5.55 and 5.0 for EMS-98. Large difference between mean and median values, in particular for instrumental parameters, is found. This is mainly because instrumental parameters are lognormally distributed. Indeed, the mean and median of the sample in terms of logarithmic values are very close, that is −2.977 and −2.999 for PGA, 1.118 and 1.093 for PGV, and −2.399 and −2.255 for I_H, respectively.

Figures 3 and 4 show the mass distribution of the samples for the two subsets of data in terms of EMS-98 and MCS macroseismic intensities, respectively, and the corresponding instrumental values (in terms of PGA, PGV and I_H).

The EMS-98 data distribution (Fig. 3d) is mainly characterized by low intensities, that is 4, 5 and 6 with a percentage of 18%, 28% and 15%, respectively. Similarly, in terms of ground motion parameters, about 50% of the values has very low intensity, i.e. PGA ≤ 0.05 g (Fig. 3a), PGV ≤ 5 cm/s (Fig. 3b) and I_H ≤ 0.1 m (Fig. 3c).

Similar results can also be found for the data subset in terms of MCS intensity, with frequencies of 24%, 17% and 18% for 5, 5.5 and 6 MCS intensity, respectively (Fig. 4d). In terms of instrumental measures, lower values (i.e. PGA ≤ 0.05 g, PGV ≤ 5 cm/s and I_H ≤ 0.1 m) include about 40% (50% for PGV) of the sample.

Data related to earthquake events for which macroseismic intensities are available in both of the two considered scales (117 values) permit MCS and EMS-98 results to be compared. To this purpose, it is worth highlighting that for most of the data (about 70% of the sample, 78 values), MCS intensity is found equal to the EMS-98 one, while in about 30% of the sample (39 values), MCS intensity is higher (half or one degree) than the EMS-98 one. Figure 5a displays the linear regression function between MCS and EMS-98 intensity values (R = 0.98) while Fig. 5b shows the residual values for MCS (observed minus estimated) and the corresponding trend.

Table 1 Statistics concerning instrumental (PGA, PGV and I_H) and macroseismic (MCS and EMS-98) data

	PGA (g)	PGV (cm/s)	I_H (m)	MCS	EMS-98
Sample size	179	179	179	157	139
Mean	0.124	9.573	0.311	5.79	5.55
Median	0.063	4.163	0.137	5.5	5
Minimum	0.002	0.045	0.002	4	4
Maximum	0.878	70.306	2.529	10.5	10
Standard Deviation	0.152	10.994	0.466	1.22	1.34
25th Percentile	0.025	1.186	0.034	5	4.5
75th Percentile	0.178	11.953	0.322	6	6

Fig. 3 Distribution of strong-motion data in terms of IEMS-98 intensities (**d**) and the corresponding instrumental values PGA (**a**), PGV, (**b**) and IH (**c**)

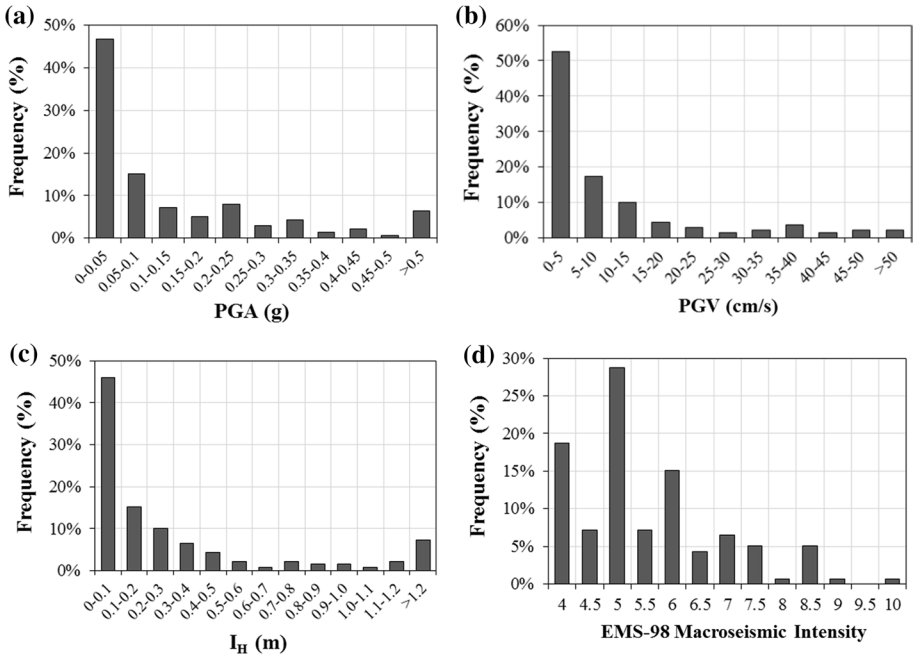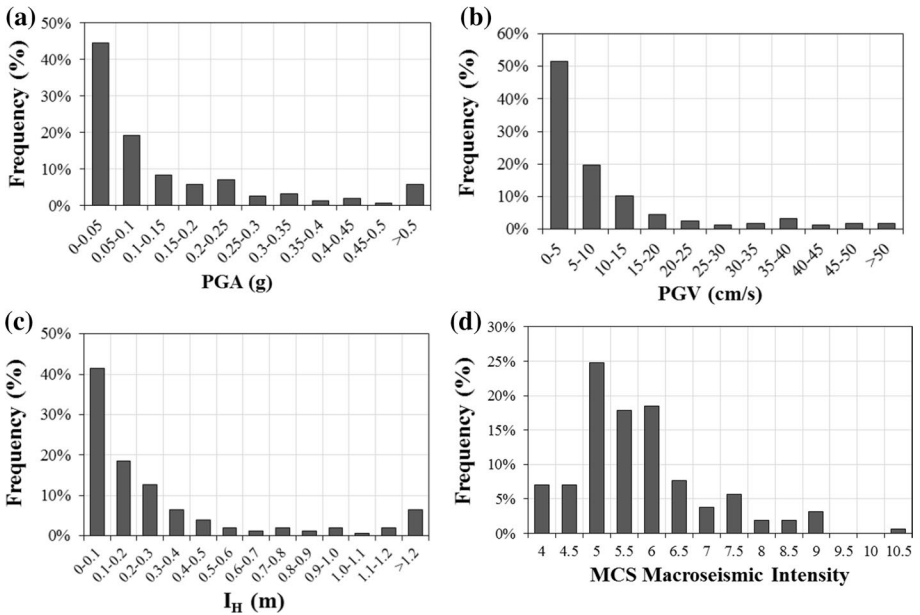**Fig. 4** Distribution of strong-motion data in terms of MCS intensities (**d**) and the corresponding instrumental values PGA (**a**), PGV, (**b**) and IH (**c**)
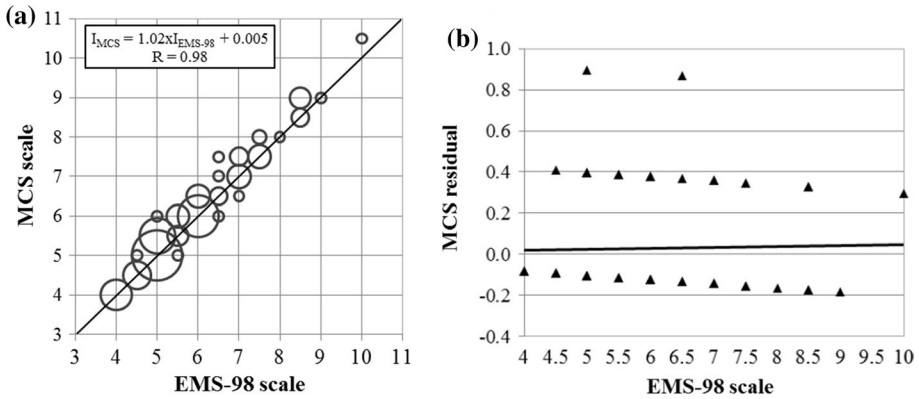
Fig. 5 a Best-fit linear regression between the MCS and EMS-98 values considering the areas in which both macroseismic values are available. The size of the circles is proportional to the number of data. **b** Residual values obtained from the considered MCS data with respect to the linear regression reported in **a**

3 Proposed relationships

Starting from the above described database, in this section statistical regressions by considering three instrumental parameters, i.e. Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV) and Housner Intensity (I_H), and two macroseismic intensity scales, i.e. EMS-98 and MCS, have been derived and analyzed. As previously said, they can be used in both direct (i.e. instrumental parameter is assumed as the independent variable and macroseismic intensity is the dependent one) and inverse direction (i.e. macroseismic intensity is assumed as the independent variable and instrumental parameter is the dependent one).

Figure 6 shows the EMS-98 macroseismic intensity values as a function of the natural logarithm of PGA (Fig. 6a), PGV (Fig. 6b) and I_H (Fig. 6c). First of all, the diagrams show that the data in terms of ground motion values are characterized by a larger variation in the range of intensities up to 6.0 EMS-98. As a matter of fact, for lower seismic intensities, building damage is generally absent and macroseismic intensities are mainly assigned on the basis of effects on people and objects. Therefore, a larger scatter of macroseismic data compared to instrumental data can be expected. On the contrary, for degrees higher than 6.0 EMS-98, building damage in terms of both distribution and severity becomes the key element in assigning of macroseismic intensity and, consequently, a lower variability can be found.

Based on the above described trend and in accordance with other studies on this topic (e.g. Faenza and Michelini 2010; Worden et al. 2012), two types of functions have been considered in order to fit the data set, i.e. single (SF) and bilinear (BF) function, as shown in Fig. 6 and reported in the following:

Single functions

$$I_{EMS-98} = 0.89 \cdot \ln(PGA) + 8.05 \tag{2}$$

$$I_{EMS-98} = 0.77 \cdot \ln(PGV) + 4.59 \tag{3}$$

$$I_{EMS-98} = 0.72 \cdot \ln(I_H) + 7.21 \tag{4}$$

Bilinear functions

$$I_{EMS-98} = 0.48 \cdot \ln(PGA) + 6.32 \quad PGA < 0.06\ g \tag{5}$$

$$I_{EMS-98} = 1.72 \cdot \ln(PGA) + 9.82 \quad PGA \geq 0.06\ g \tag{6}$$

$$I_{EMS-98} = 0.36 \cdot \ln(PGV) + 4.38 \quad PGV < 5.5\ cm/s \tag{7}$$

$$I_{EMS-98} = 1.81 \cdot \ln(PGV) + 1.90 \quad PGV \geq 5.5\ cm/s \tag{8}$$

$$I_{EMS-98} = 0.32 \cdot \ln(I_H) + 5.59 \quad I_H < 0.15\ m \tag{9}$$

$$I_{EMS-98} = 1.64 \cdot \ln(I_H) + 8.08 \quad I_H \geq 0.15 m \tag{10}$$

For all the considered instrumental parameters, the best fit is found using the bilinear function (BF), as confirmed by adopting the Akaiki Information Criterion (AIC) (Burnham and Anderson 1998). Specifically, AIC values for BFs are 657, 633 and 627, respectively for PGA, PGV and I_H relationships; the corresponding values for SFs are 660, 640 and 648. As a result, only BFs are considered in the following.

The switch point values for BFs (equal to 0.06 g, 5.5 cm/s and 0.15 m, respectively for PGA, PGV and I_H intensity measures) have been determined by sequentially adding (for R+ distribution) and removing (for R− one) a pair of data from opposite ends of PGA, PGV and I_H samples and, then, by evaluating the coefficient of correlation R. The switch point is the value at which R begins to simultaneously decrease (for R−) and increase (for R+). In
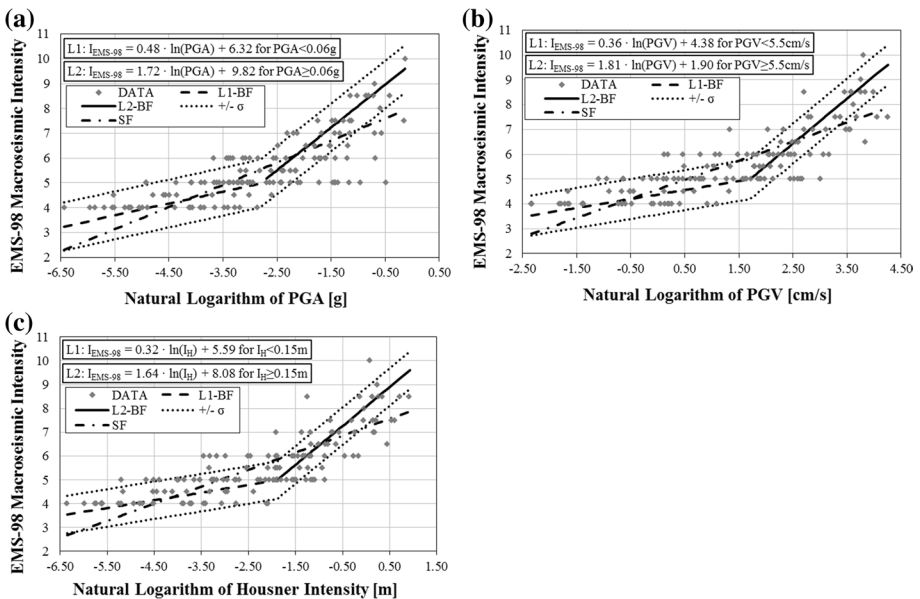

Fig. 6 EMS-98 intensities *versus* the natural logarithm of PGA (**a**), PGV (**b**) and I_H (**c**) values. Single function (SF, dash-dot line), bilinear function (BF, L1 dashed line, L2 solid line) and the associated ± one standard deviation (dotted lines) are also shown

order to detect the switch point value, an analytical procedure based on the difference between two consecutive R values (for both R+ and R− distributions) has been set up. According to the procedure, the switch point value is fixed when the above mentioned difference exceeds a given tolerance. For example, with reference to I_H parameter (Fig. 7c), at a value equal to −1.9 (in terms of natural logarithm, equal to about 0.15 m), the R− values tend to decrease (i.e. the difference with the previous R value exceeds the given tolerance) and the R+ values begin to increase as well (i.e. the difference with the previous R value exceeds the given tolerance). Consequently, for the I_H bilinear function, the switch point is equal to 0.15 m.

Figures 7 show the trends of the R values for all the considered ground motion parameters.

For each relationship, Table 2 reports the statistical results in terms of correlation coefficient R, Mean Squared Error (MSE) and standard deviation (σ) of the residuals. It is worth noting that the MSE values have been evaluated through the following expression (11):

$$MSE = \frac{1}{n} \sum_{i=1}^{n} \left(Y_i - \hat{Y}_i \right)^2 \tag{11}$$

where Y are the observed data and $\hat{Y}$ are the predicted one.

Statistical analyses show that, for I_H values greater than 0.15 m, a high correlation coefficient (R=0.76) is found, which is close to the one obtained for PGV≥5.5 cm/s (R=0.75). On the contrary, a poor correlation (R=0.56) characterizes the lower values of I_H (i.e. I_H<0.15 m), corresponding to medium-to-low values of EMS intensity. As already said, these results are expected because instrumental intensity measures such as I_H and PGV are well correlated to building damage which is generally experienced for higher values of seismic intensity (i.e. I_H>0.15 m, PGV≥5.5 cm/s). Similar
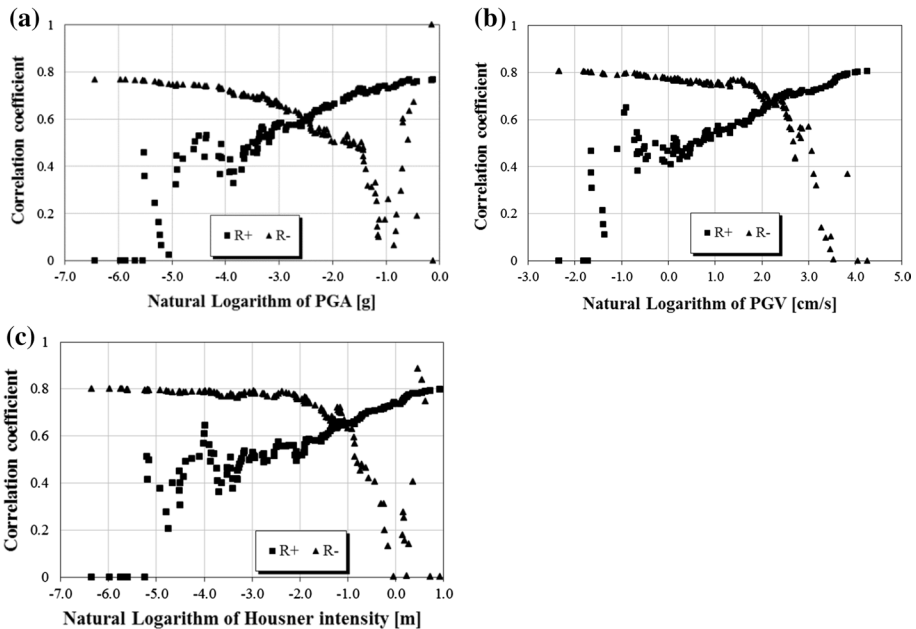

Fig. 7 Distribution of the correlation coefficients for PGA (a), PGV (b) and I_H (c) samples

Table 2 Statistical results for the proposed relationships (Eqs. 5 - 10) in terms of correlation coefficient R, Mean Squared Error (MSE) and standard deviation (σ) of the residuals

Eqs	R	MSE	σ
5	0.58	0.95	0.96
6	0.64		
7	0.59	0.65	0.81
8	0.75		
9	0.56	0.62	0.79
10	0.76		

results have been found also for PGA, where R is equal to 0.64 for PGA ≥ 0.06 g, while R = 0.58 is found for PGA < 0.06 g.

These results are also confirmed by both MSE and standard deviation values. In fact, the relationships in terms of PGA show both a greater error in the predicted values (MSE = 0.95) and a larger dispersion (σ = 0.96) than PGV and I_H, whose MSE values are equal to 0.65 and 0.62, while σ values are 0.81 and 0.79, respectively.

Considering that previous Eqs. 5–10 provide macroseismic values in a continuous form, a conversion into the discrete degrees of EMS-98 scale can be useful. To this purpose, Fig. 8 shows the results obtained from Eqs. 5–10 for intensities ranging between 4 and 9, rounded to the nearest integer value. For ease of use, the horizontal axis, corresponding to the ground motion parameters (i.e. PGA, PGV and I_H), is in base-10 logarithmic scale.

As a consequence of the strong correlation between the two macroseismic scales (MCS and EMS-98, see Fig. 5), similar trends have been found in terms of MCS, as shown in Fig. 9a, b and c, respectively for PGA, PGV and I_H intensity measures.
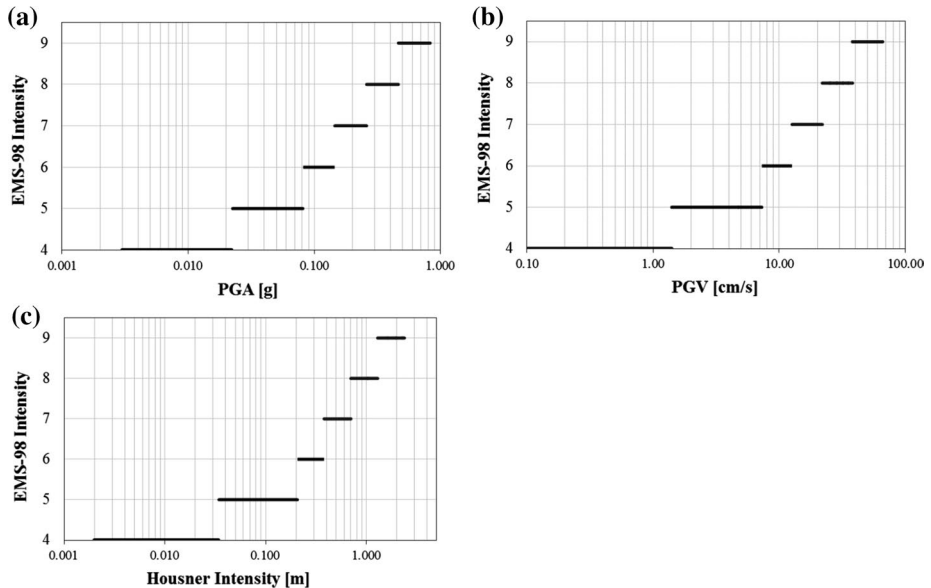
Fig. 8 Macroseismic intensity (according to the EMS-98 scale) with respect to PGA (**a**), PGV (**b**) and I_H (**c**) values. The horizontal axis is in logarithmic scale

In the same Fig. 9, both SFs and BFs are also shown and their analytical expressions are reported in the following:

Single functions

$$I_{MCS} = 0.94 \cdot \ln(PGA) + 8.36 \tag{12}$$

$$I_{MCS} = 0.87 \cdot \ln(PGV) + 4.55 \tag{13}$$

$$I_{MCS} = 0.83 \cdot \ln(I_H) + 7.50 \tag{14}$$

Bilinear functions

$$I_{MCS} = 0.51 \cdot \ln(PGA) + 6.55 \quad PGA < 0.06\ g \tag{15}$$

$$I_{MCS} = 1.81 \cdot \ln(PGA) + 10.22 \quad PGA \geq 0.06\ g \tag{16}$$

$$I_{MCS} = 0.41 \cdot \ln(PGV) + 4.53 \quad PGV < 5.5\ cm/s \tag{17}$$

$$I_{MCS} = 1.83 \cdot \ln(PGV) + 2.11 \quad PGV \geq 5.5\ cm/s \tag{18}$$

$$I_{MCS} = 0.32 \cdot \ln(I_H) + 5.73 \quad I_H < 0.15\ m \tag{19}$$

$$I_{MCS} = 1.72 \cdot \ln(I_H) + 8.38 \quad I_H \geq 0.15\ m \tag{20}$$
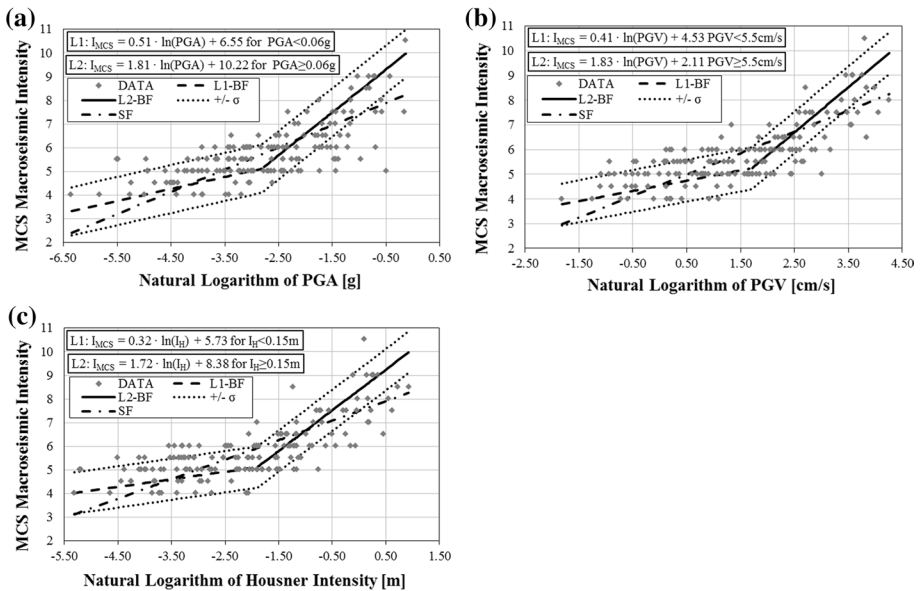
Fig. 9 MCS intensities *versus* the natural logarithm of PGA (**a**), PGV (**b**) and I_H (**c**) values. Single function (SF, dash-dot line), bilinear function (BF, L1 dashed line, L2 solid line) and the associated ± one standard deviation (dotted lines) are also shown
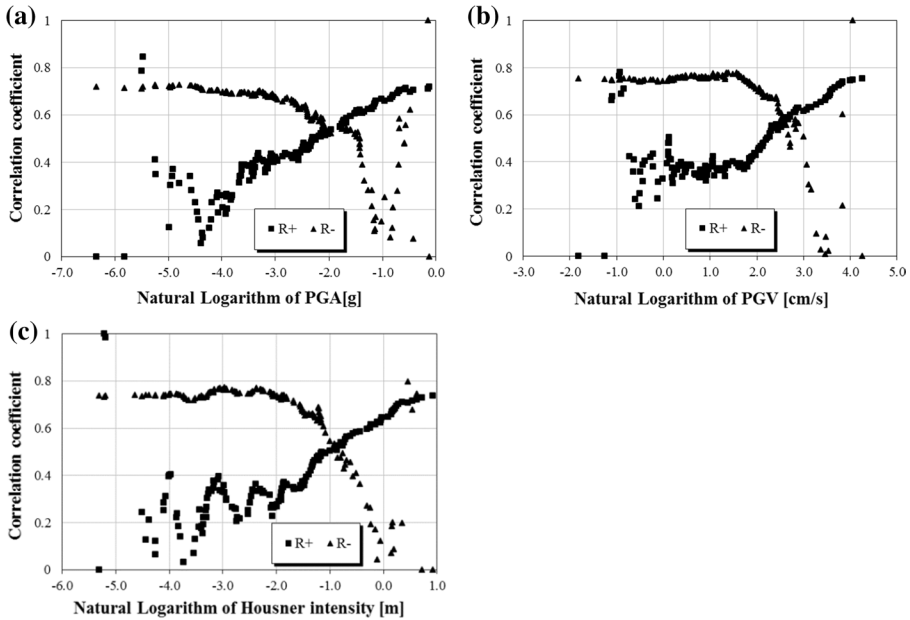
Fig. 10 Distribution of the correlation coefficients for PGA (**a**), PGV (**b**) and I_H (**c**) samples

Table 3 Statistical results for the proposed relationships (Eqs. 15–20) in terms of correlation coefficient R, Mean Squared Error (MSE) and standard deviation (σ) of the residuals

Eqs	R	MSE	σ
15	0.44	1.04	1.02
16	0.67		
17	0.38	0.71	0.85
18	0.76		
19	0.34	0.76	0.87
20	0.74		

Similarly to the relationships in terms of EMS-98, also for MCS data the best-fit is represented by the bilinear function. Specifically, AIC values for BFs are 762, 748 and 758, respectively for PGA, PGV and I_H; the corresponding values for SFs are 771, 750 and 762. As a consequence, only BFs are considered in the following.

The switch point values, equal to 0.06 g for PGA, 5.5 cm/s for PGV and 0.15 m for I_H, are coincident with those ones for the EMS-98 scale. Figure 10 shows the trend of the correlation coefficients R.

For Eqs. 15–20, Table 3 reports the statistical results in terms of correlation coefficient R, Mean Squared Error (MSE, see Eq. 8) and standard deviation (σ) of the residuals.

For the lower ranges of values of the considered instrumental parameter (i.e. PGA < 0.06 g, PGV < 5.5 cm/s and I_H < 0.15 m, also corresponding to the L1 branch of the bilinear functions), statistical analyses provide the lower R values, that are equal to 0.44, 0.38 and 0.34,

(a)

(b)

(c)
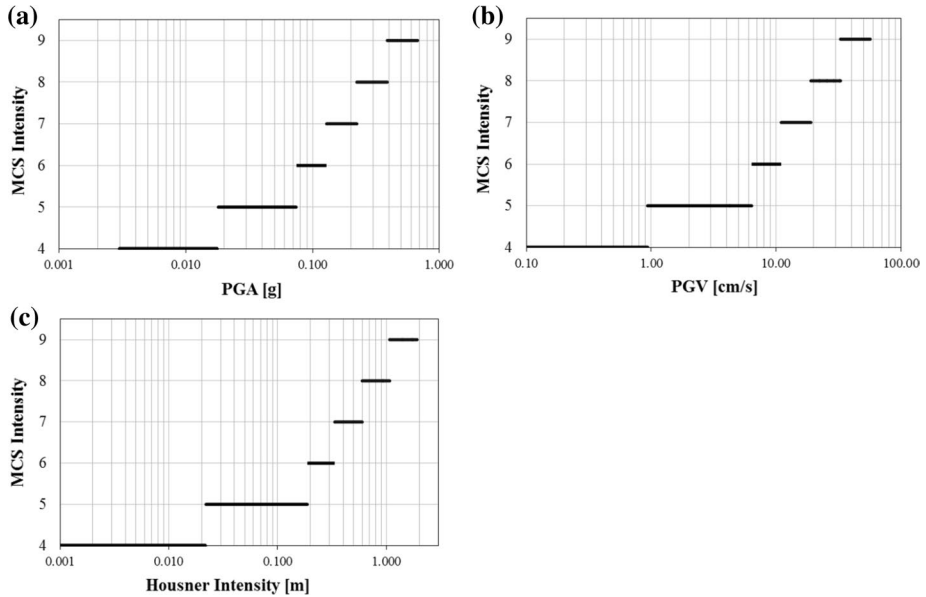
Fig. 11 Macroseismic intensity (according to the MCS scale) with respect to PGA (**a**), PGV (**b**) and Housner intensity (**c**) values. The horizontal axis is in logarithmic scale

respectively. On the contrary, higher values have been found for the L2 branch (i.e. values higher than 0.06 g for PGA, 5.5 cm/s for PGV and 0.15 m for I_H), which are 0.67, 0.76 and 0.74 for the relationships in terms of PGA, PGV and I_H, respectively.

In terms of error in the estimation and dispersion of results, the relationships relevant to PGA show the greater values of both MSE (1.04) and σ (1.02), while the lower ones are found for PGV (MSE = 0.71, σ = 0.85).

In order to provide a more useful representation of the proposed relationships, Fig. 11 shows the results obtained from Eqs. 15–20 for discrete degrees of the MCS scale, respectively for PGA (Fig. 11a), PGV (Fig. 11b) and I_H intensities (Fig. 11c). For ease of use, the horizontal axis, corresponding to the ground motion parameters (i.e. PGA, PGV and I_H), is in base-10 logarithmic scale.

As a consequence of the adopted regression method (TLS), the above described relationships can be easily inverted, i.e. using the same coefficients. In this way, known the macroseismic value as independent variable, the values of ground motion parameters (dependent variable) can be estimated, as follows:

EMS-98 intensity measure

$$PGA = e^\wedge \left(\left(I_{EMS-98} - 6.32 \right) / 0.48 \right) \quad I_{EMS-98} \leq 5 \tag{21}$$

$$PGA = e^\wedge \left(\left(I_{EMS-98} - 9.82 \right) / 1.72 \right) \quad I_{EMS-98} > 5 \tag{22}$$

$$PGV = e^\wedge \left(\left(I_{EMS-98} - 4.38 \right) / 0.36 \right) \quad I_{EMS-98} \leq 5 \tag{23}$$

$$PGV = e^\wedge\left(\left(I_{EMS-98} - 1.90\right)/1.81\right) \quad I_{EMS-98} > 5 \tag{24}$$

$$I_H = e^\wedge\left(\left(I_{EMS-98} - 5.59\right)/0.32\right) \quad I_{EMS-98} \leq 5 \tag{25}$$

$$I_H = e^\wedge\left(\left(I_{EMS-98} - 8.08\right)/1.64\right) \quad I_{EMS-98} > 5 \tag{26}$$

MCS intensity measure

$$PGA = e^\wedge\left(\left(I_{MCS} - 6.55\right)/0.51\right) \quad I_{MCS} \leq 5 \tag{27}$$

$$PGA = e^\wedge\left(\left(I_{MCS} - 10.22\right)/1.81\right) \quad I_{MCS} > 5 \tag{28}$$

$$PGV = e^\wedge\left(\left(I_{MCS} - 4.53\right)/0.41\right) \quad I_{MCS} \leq 5 \tag{29}$$

$$PGV = e^\wedge\left(\left(I_{MCS} - 2.11\right)/1.83\right) \quad I_{MCS} > 5 \tag{30}$$

$$I_H = e^\wedge\left(\left(I_{MCS} - 5.73\right)/0.32\right) \quad I_{MCS} \leq 5 \tag{31}$$

$$I_H = e^\wedge\left(\left(I_{MCS} - 8.38\right)/1.72\right) \quad I_{MCS} > 5 \tag{32}$$

The switch point values of the above reported equations have been computed by solving Eqs. 5–10 (for EMS-98) and Eqs. 15–20 (for MCS) with the relevant corner values and rounding to the nearest integer value of the corresponding macroseismic intensity scales. As a result, for all ground-motion parameters (i.e. PGA, PGV and IH) and macroseismic scales (i.e. EMS-98 and MCS), the switch point values are set equal to 5.

Table 4 summarizes the statistical results in terms Mean Squared Error (MSE, see Eq. 11) and standard deviation (σ) of the residuals.

Starting from the above reported relationships, Table 5 provides the ranges of PGA, PGV and I_H values evaluated for some EMS-98 degrees. Note that the final values of each range refer to ± half a degree of a given EMS-98 intensity. For example, the corner values of the first range in Table 5, i.e. 0.003–0.02 g in PGA, have been evaluated by solving Eqs. 21–22 with 3.5 and 4.5 EMS-98 intensities.

As for the EMS-98 inverse relationships, Table 6 provides the range values of PGA, PGV and I_H corresponding to each MCS intensity obtained from Eqs. 27 and 32. The corner values of ranges refer to ± half a degree of each MCS intensity.

Table 4 Statistical results for the proposed inverse relationships (Eqs. 21–32) in terms of Mean Squared Error (MSE) and standard deviation (σ) of the residuals

	EMS-98		MCS	
	MSE	σ	MSE	σ
PGA (g)	0.01	0.11	0.01	0.11
PGV (cm/s)	80.17	8.98	117.01	10.16
I_H (m)	0.11	0.34	0.12	0.34

Table 5 Ranges of PGA, PGV and I_H for EMS-98 intensities

EMS-98 intensity	4	5	6	7	8	9
PGA (g)	0.003–0.02	0.02–0.08	0.08–0.15	0.15–0.26	0.26–0.46	0.46–0.83
PGV (cm/s)	0.09–1.40	1.4–7.3	7.3–12.6	12.6–22.0	22.0–38.1	38.1–66.2
Housner intensity (m)	0.002–0.03	0.03–0.21	0.21–0.38	0.38–0.70	0.70–1.29	1.29–2.38

4 Analysis of the proposed relationships and comparison with other studies

In this section, the proposed relationships have been analyzed and compared with some of the most prominent ones available in the technical literature.

For the sake of clarity, Table 11 (in "Appendix") summarizes the proposed regression relationships, separately for direct (i.e. for computing macroseismic intensity given a ground motion value, first column) and inverse functions (i.e. for estimating instrumental values starting from macroseismic intensities, second column).

First of all, the direct relationships proposed for higher instrumental values (i.e. PGA ≥ 0.06 g, PGV ≥ 5.5 cm/s and $I_H \geq 0.15$ m) generally provide higher values of the correlation coefficient (R) than those obtained for lower values (PGA < 0.06 g, PGV < 5.5 cm/s and $I_H < 0.15$ m). These results are not startling because, on one hand, the considered instrumental parameter such as PGA, PGV and I_H are generally well correlated to the damage potential of seismic events and, on the other hand, macroseismic intensity assignment is affected by lower uncertainty when building damage increases. On the contrary, for low seismic intensity (e.g. PGA < 0.06 g, PGV < 5.5 cm/s and $I_H < 0.15$ m), negligible damage on buildings is generally experienced and, therefore, macroseismic intensity is mainly based on not physical effects (e.g. vibration felt by people) and/or poor information (e.g. swinging of objects). As a consequence, a larger scatter in the data distribution is expected.

Comparing the R values obtained from the direct relationships in terms of the three instrumental measures also confirms the better correlation relevant to integral parameters, such as I_H, than peak intensity ones (i.e. PGA). In fact, R values related to I_H are 0.76 and 0.74 respectively for the relationships in terms of EMS-98 and MCS. On the contrary, in terms of PGA, R values equal to 0.64 and 0.67 are found, respectively for EMS-98 and MCS. For PGV, a similar value of R with respect to I_H has been found in the relationship for EMS-98 (R = 0.75) while it shows a slightly better correlation (R = 0.76) than I_H (R = 0.74) in case of fitting with MCS data.

The above reported results are also confirmed by the other statistical operators, such as the Mean Squared Error (MSE) and the standard deviation (σ). Specifically,

Table 6 Ranges of PGA, PGV and I_H for MCS intensities

MCS intensity	4	5	6	7	8	9
PGA (g)	0.003–0.02	0.02–0.07	0.07–0.13	0.13–0.22	0.22–0.39	0.39–0.67
PGV (cm/s)	0.08–1.0	1.0–6.4	6.4–11.0	11.0–19.0	19.0–32.8	32.8–56.6
Housner intensity (m)	0.001–0.02	0.02–0.19	0.19–0.34	0.34–0.60	0.60–1.07	1.07–1.91

in the case of EMS-98, the values evaluated for I_H (MSE = 0.62, σ = 0.79) and PGV (MSE = 0.65, σ = 0.81) are lower than those referred to PGA (MSE = 0.95, σ = 0.96).

Further, for the same instrumental intensity measure (i.e. PGA, PGV and I_H), slightly higher R values have been found for the EMS-98 relationships compared to the MCS ones. In terms of MSE and standard deviation, EMS-98 relationships provide lower values with respect to MCS ones. This result can be clearly ascribed to the fact that, unlike MCS, the European scale takes into account both building vulnerability and observed damage distribution in assigning macroseismic intensities and, consequently, a better correlation to building damage is expected, especially for the higher intensity values.

Comparisons between the proposed relationships and those obtained in other studies have been carried out in order to discuss possible differences. As aforementioned, most of the available relationships in the technical literature consider PGA as instrumental measure and MCS as macroseismic scale. Therefore, in Fig. 12, the regression relationship proposed in the present study for computing MCS macroseismic intensities given PGA values has been compared with those obtained by Faccioli and Cauzzi (2006) and Faenza and Michelini (2010). Table 7 reports the relationships derived by the authors and the adopted dataset. For the sake of clarity, the information related to the proposed relationship is also reported.

As for the computed MCS intensity, the differences among the considered relationships can be grouped with respect to three ranges of values. For PGA < 0.01 g, the proposed relationship shows higher values than those obtained by Faenza and Michelini. In the range 0.02 g < PGA < 0.2 g the proposed relationship underestimates the macroseismic intensities with respect to both Faccioli and Cauzzi and Faenza and Michelini. Finally, for PGA > 0.3 g, the values obtained from the proposed relationship are greater than those obtained from the other considered relationships.

In the comparison reported in Fig. 12, it is worth noting that the Faccioli and Cauzzi relationship provides results limited to the range 0.02 g ≤ PGA ≤ 0.6 g. For the lowest value (PGA = 0.02 g), the Faccioli and Cauzzi relationship provides similar values to those
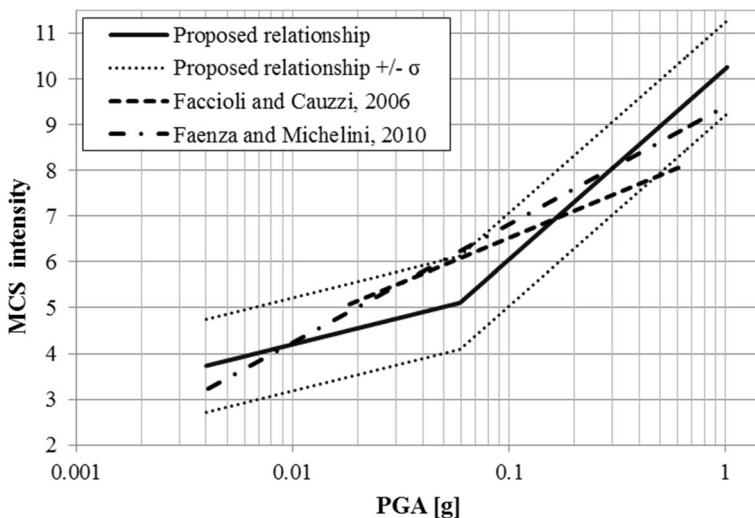
Fig. 12 Comparison between the proposed relationship between MCS intensity and PGA with the regressions of Faccioli and Cauzzi (2006) and Faenza and Michelini (2010). The PGA axes is in logarithmic scale

Table 7 Relationships considered in the comparisons

References	Direct relationships	Inverse relationships	Dataset
Margottini et al. (1992)	–	$\log(PGA) = 0.525 + 0.22 \cdot I_{MCS}$	56 PGA-MCS data points from 9 Italian earthquakes
Faccioli and Cauzzi (2006)	$I_{MCS} = 1.96 \cdot \log(PGA) + 6.54$	$\log(PGA) = -1.33 + 0.2 \cdot I_{MCS}$	75 PGA-MCS data points from 26 earthquakes
Faenza and Michelini (2010)	$I_{MCS} = 2.58 \cdot \log(PGA) + 1.68$	$\log(PGA) = -0.65 + 0.39 \cdot I_{MCS}$	266 PGA-MCS data points from 87 Italian earthquakes
Proposed	$I_{MCS} = 0.51 \cdot \ln(PGA) + 6.55 \, PGA < 0.06 \text{ g}$ $I_{MCS} = 1.81 \cdot \ln(PGA) + 10.22 \, PGA \geq 0.06 \text{g}$	$\ln(PGA) = (I_{MCS} - 6.55)/0.51 \, I_{MCS} < 5$ $\ln(PGA) = (I_{MCS} - 10.22)/1.81 \, I_{MCS} \geq 5$	157 PGA-MCS data points from 27 earthquakes

Table 8 MCS intensities provided by the considered relationship for PGA equal to 0.1 g

PGA (g)	PGA versus MCS relationships	MCS intensity
0.1	Proposed relationships	6
	Faccioli and Cauzzi (2006)	6.5
	Faenza and Michelini (2010)	7
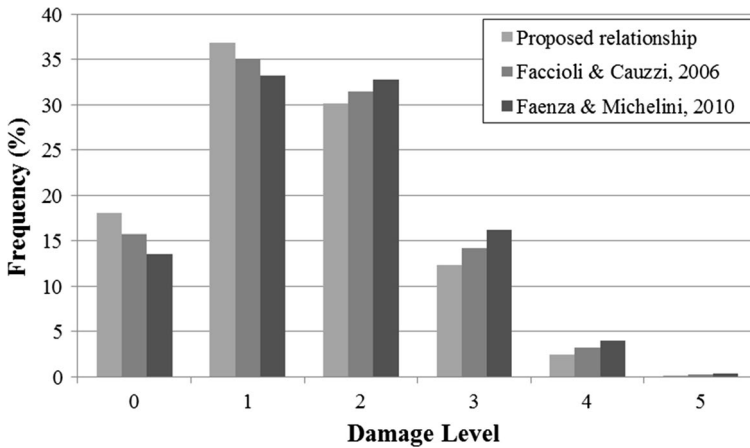
Fig. 13 Damage distribution for vulnerability class A according to DPMs defined by Zuccaro et al. (2000)

obtained by both the proposed regression and the Faenza and Michelini regression, while, for PGA values around 0.6 g, it provides lower macroseismic intensity values. Finally, the considered relationships are within the range obtained for the proposed regression ± one standard deviation.

The differences found in the comparison are mainly due to the different adopted datasets and the bilinear form of the proposed relationship, as reported in Table 7. To this regard, it is worth noting that in the database used by Faenza and Michelini the low intensity values (PGA ≤ 0.1 g) prevail differently from the database in this study. Specifically, the percentage of PGA values lower than 0.1 g is 82%, while it is 62% for that considered in this study. Furthermore, other sources of differences can be also ascribed to both the regression technique and the criteria adopted for grouping different macroseismic scales.

In order to evaluate the influences of the above described comparison in terms of predicted damage, an earthquake scenario is performed by using the DPMs defined by Zuccaro et al. (2000). As can be evaluated from Fig. 12, for PGA equal to 0.1 g, MCS intensities range from 6 (Proposed relationship) to 7 (Faenza and Michelini). All the results are reported in Table 8.

These values, meant as seismic input for vulnerability class A, provide the damage distributions reported in Fig. 13. In particular for damage grade 3, the percentage of buildings ranges from about 12.3% (Proposed relationship) to about 16.1% (Faenza and Michelini). An intermediate value (about 14.2%) can be predicted by adopting the Faccioli and Cauzzi relationship.

For the inverse relationships (i.e. PGA vs MCS), the proposed relationship has been compared with those obtained by Margottini et al. (1992), Faccioli and Cauzzi (2006) and Faenza and Michelini (2010), reported in Table 7.

Figure 14 shows the values obtained by the considered relationships for discrete MCS values ranging from 4 to 9.

Starting from a similar value estimated for $I_{MCS} = 5$, the proposed relationship provides lower values with respect to the other relationships for $I_{MCS} < 5$. On the contrary, in the range $I_{MCS} \geq 5.5$, the proposed regression provides greater values than all the considered relationships, although, for 8.5/9 MCS intensity, the Faenza and Michelini relationship provides a similar value (about 0.65 g). It is worth noting that the Margottini et al. relationship cannot be applied for intensity greater than 8 MCS.

5 Final remarks and future developments

Macroseismic data of historical earthquakes represent an essential source to improve knowledge on the seismic hazard of an area. In order to be considered in risk analyses, as well as in design practice, macroseismic intensities need to be converted into more suitable engineering parameters. In this framework, starting from a previous study carried out by some of the authors, correlations between macroseismic intensities and ground motion parameters have been derived. Peak Ground Acceleration (PGA), Peak Ground Velocity (PGV) and Housner Intensity (I_H) as instrumental measures, and European Macroseismic Scale (EMS-98) and Mercalli-Cancani-Sieberg scale (MCS) as macroseismic measures, have been considered. A large database containing 179 ground-motion records related to 32 earthquake events occurred in Italy in the last 40 years has been collected to derive reversible relationships (i.e. macroseismic vs instrumental intensity and vice versa).
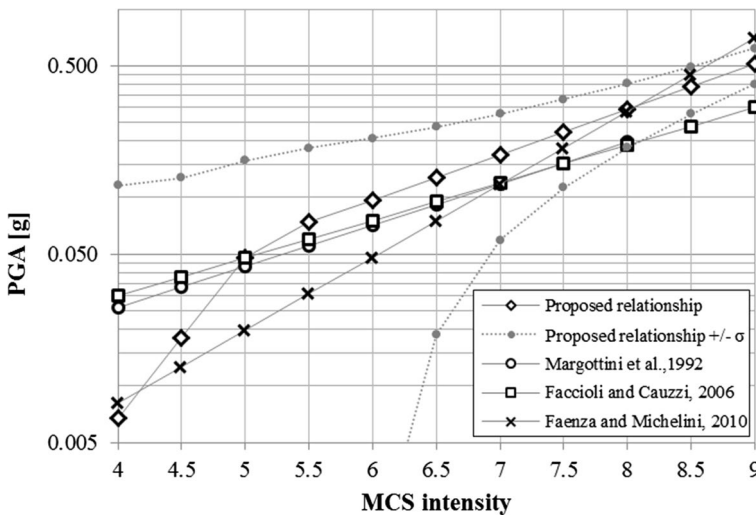
Fig. 14 Comparison between the proposed (inverse) relationship between PGA and MCS intensity with the regressions of Margottini et al. (1992), Faccioli and Cauzzi (2006) and Faenza and Michelini (2010). The PGA axes is in logarithmic scale

For both EMS-98 and MCS data, the best-fit is a bilinear function with switch point at 0.06 g, 5.5 cm/s and 0.15 m, respectively for PGA, PGV and I_H.

Statistical analysis results show that the higher correlation among instrumental and macroseismic data is generally found for the higher intensity values, for which building damage becomes the key parameter in assigning macroseismic intensity. For example, the correlation coefficient for the relationships in terms of EMS-98 scale is about 0.76 for I_H, 0.75 for PGV and 0.64 for PGA. Similar results are also found in terms of Mean Squared Error (MSE) and standard deviation (σ) of the residual. In fact, I_H and PGV show lower values for both MSE (0.62 and 0.65, respectively) and σ (0.79 and 0.81, respectively) with respect to PGA (MSE = 0.95, σ = 0.96). These results also confirm the better capability of both I_H and PGV to represent the damage potential of ground motions with respect to PGA. Similar trend are found for the regressions in terms of MCS, although the statistical analysis results are generally poorer than EMS-98.

The comparison with other relationships available in the literature shows that the proposed relationship (in terms of MCS and PGA intensity measure) generally underestimates the macroseismic values for the lower intensities, while it provides higher values than those obtained from Faenza and Michelini for the higher intensities.

The proposed relationships actually provide useful tools in performing risk analyses and studies of earthquake scenarios. With respect to other relationships available in the literature, they provide instrumental *vs* macroseismic intensity relationships, and vice versa. Peak (i.e. PGA and PGV) and integral intensity measures (i.e. I_H) as for instrumental measures, and MCS and EMS-98 scales, as for macroseismic intensity, are considered. Further, they were derived on the basis of a larger dataset compared to other studies (e.g. Margottini, Wald et al., Faccioli and Cauzzi, Chiauzzi et al.) which, nevertheless, in the future needs to be extended by considering more earthquakes occurred in other countries.

Appendix

See Tables 9, 10 and 11.

Table 9 Main parameters of the selected earthquakes

Epicentral area	Data	Latitude	Longitude	Depth (Km)	M_L	M_W
Irpinia	23/11/1980	40.76	15.31	15.0	6.5	6.9
Parma	09/11/1983	44.65	10.37	28.1	5.0	5.0
Gubbio	29/04/1984	43.21	12.57	6.0	5.2	5.6
Lazio-Abruzzo	07/05/1984	41.70	13.86	20.5	5.9	5.9
Lazio-Abruzzo	11/05/1984	41.78	13.89	12.1	5.7	5.5
Garfagnana	23/01/1985	44.14	10.57	9.4	3.8	/
L'Aquila	20/05/1985	42.23	13.32	10.0	3.7	/
Reggio Emilia	24/04/1987	44.82	10.70	5.0	4.6	/
Reggio Emilia	02/05/1987	44.81	10.72	3.1	4.6	4.7
Umbria-Marche	26/09/1997	43.03	12.86	5.7	5.8	6.0
Basilicata	09/09/1998	39.98	16.03	7.4	5.5	5.6
Palermo	06/09/2002	38.38	13.70	5.0	5.6	5.8
Forlì	26/01/2003	43.88	11.96	6.5	4.3	4.7
Appennino Bolognese	14/09/2003	44.26	11.38	8.3	5.0	5.3
Lago di Garda	24/11/2004	45.69	10.52	5.4	5.2	5.0
Mugello	01/03/2008	44.06	11.25	3.8	4.4	4.7
Emilia Romagna	23/12/2008	44.54	10.35	22.9	5.2	5.5
L'Aquila	06/04/2009	42.34	13.38	8.3	5.9	6.1
Valle del Tevere	15/12/2009	43.01	12.27	8.8	4.3	4.2
Sicilia	24/06/2011	38.06	14.78	7.3	4.4	4.5
Pianura Padana	17/07/2011	45.01	11.37	2.4	4.8	4.8
Torino	25/07/2011	45.02	7.37	11.0	4.3	4.3
Pianura Padana	25/01/2012	44.87	10.51	29.0	5.0	5.0
Emilia	20/05/2012	44.90	11.26	9.5	5.9	6.1
Emilia	29/05/2012	44.84	11.07	8.1	5.8	6.0
Pollino	26/10/2012	39.88	16.02	9.7	5.0	5.2
Fivizzano	21/06/2013	44.13	10.14	7.0	5.2	5.1
Monti Iblei	08/02/2016	37.00	14.80	6.0	4.3	4.2
Accumoli	24/08/2016	42.70	13.23	8.1	6.0	6.0
Ussita	26/10/2016	42.91	13.13	7.5	5.9	5.9
Norcia	30/10/2016	42.83	13.11	9.2	6.1	6.5
Capitignano	18/01/2017	42.53	13.28	9.1	5.4	5.5

Table 10 Macroseismic and instrumental data of the considered events

Data	Epicentral area	Station name	Village	Instrumental parameters			Macroseismic intensity	
				I_H (m)	PGA (g)	PGV (cm/s)	EMS-98	MCS
1980/11/23	Irpinia	ARN	Arienzo	0.13	0.035	3.15	6[1]	6.5[1]
		BRN	Brienza	0.43	0.218	12.68	6.5[1]	7[1]
		BSC	Bisaccia	0.78	0.096	21.44	6[1]	6.5[1]
		BVN	Bovino	0.14	0.048	6.34	5[1]	6[1]
		CLT	Calitri	1.17	0.175	29.06	7.5[1]	8[1]
		MRT	M. San Severino	0.45	0.141	13.29	6.5[1]	7.5[1]
		RNR	Rionero in vulture	0.57	0.099	15.01	7[1]	7.5[1]
		STR	Sturno	1.73	0.316	70.31	7.5[1]	8[1]
		TDG	Torre del greco	0.25	0.060	8.06	5.5[1]	6[1]
		TRR	Tricarico	0.30	0.046	6.58	5.5[1]	6[1]
		BGI	Bagnoli Irpino	1.21	0.187	34.42	7[1]	7[1]
		ALT	Auletta	0.22	0.057	6.28	6[1]	6.5[1]
		BNV	Benevento	0.42	0.046	9.29	6[1]	6[1]
1983/11/09	Parma	FRN	Fornovo di T.	0.05	0.034	1.59	6[1]	6[1]
1984/04/29	Gubbio	PTL	Pietralunga	0.21	0.178	7.96	6[1]	6[1]
		UMB	Umbertide	0.03	0.032	1.13	6[1]	6[1]
		PGL	Peglio	0.04	0.052	2.19	5[1]	5[1]
		CTC	Città di Castello	0.16	0.050	3.59	5[1]	5.5[1]
		CGL	Cagli	0.01	0.007	0.53	5[1]	5[1]
		NCR	Nocera Umbra	0.09	0.204	5.90	6[1]	6[1]
1984/05/07	Lazio-Abruzzo	ATN	Atina	0.15	0.112	3.78	7[1]	7[1]
		PNT	Pontecorvo	0.15	0.068	5.63	5[1]	5[1]
		RCC	Roccamonfina	0.15	0.044	4.40	6[1]	6[1]
		ORT	Ortucchio	0.11	0.087	4.05	5[1]	5[1]
		BRS	Barisciano	0.01	0.013	0.41	4.5[1]	4.5[1]

Table 10 (continued)

Data	Epicentral area	Station name	Village	Instrumental parameters			Macroseismic intensity	
				I_H (m)	PGA (g)	PGV (cm/s)	EMS-98	MCS
		CSV	Castelnuovo	0.07	0.028	1.82	5[1]	5[1]
		LPD1	Lama dei pel.	0.15	0.077	5.23	6[1]	6[1]
		SCF	Scafa	0.26	0.133	10.05	6[1]	6.5[1]
		PGG	Poggio Picenze	0.03	0.017	0.76	5[1]	5[1]
		RIP	Ripa Fagn.	0.04	0.017	0.99	5[1]	5[1]
1984/05/11	Lazio-Abruzzo	VLB	V. Barrea	0.24	0.201	8.48	6[1]	6.5[1]
		ATN	Atina	0.04	0.025	1.20	6[1]	6[1]
		LPD1	Lama dei pel.	0.04	0.042	1.63	5.5[1]	5.5[1]
		SCF	Scafa	0.05	0.040	1.99	5[1]	5[1]
1985/01/23	Garfagnana	VGL	Vagli paese	0.02	0.031	1.23	4[1]	4[1]
		SST	Sestola	0.02	0.031	1.18	5[1]	5[1]
		BRG	Barga	0.03	0.043	1.12	5[1]	5.5[1]
1985/05/20	L' Aquila	BRS	Barisciano	0.04	0.033	1.59	5[1]	5.5[1]
		CSV	Castelnuovo	0.02	0.050	1.17	5[1]	5[1]
		PGG	Poggio Pic.	0.04	0.050	2.21	6[1]	6[1]
		SDM	S. Dometrio V.	0.02	0.020	1.20	4[1]	4[1]
1987/04/24	Reggio Emilia	SRB	Sorbolo	0.01	0.013	0.34	5[1]	5[1]
		NVL	Novellara	0.04	0.039	2.26	5[1]	5[1]
1987/05/02	Reggio Emilia	SRB	Sorbolo	0.01	0.037	1.11	5[1]	5.5[1]
		NVL	Novellara	0.15	0.077	7.24	5[1]	5[1]
1997/09/26	Umbria-Marche	CLF	Colfiorito	0.74	0.227	17.05	7.5[2]	7.5[2]
		NCR	Nocera-Umbra	0.79	0.502	32.57	7[2]	7.5[2]
		ASS	Assisi	0.23	0.188	10.22	/	6.5[2]

Table 10 (continued)

Data	Epicentral area	Station name	Village	Instrumental parameters			Macroseismic intensity	
				I_H (m)	PGA (g)	PGV (cm/s)	EMS-98	MCS
		CSA	Camara	0.60	0.172	13.41	/	6.5[2]
		MTL	Matelica	0.27	0.116	8.35	/	6[2]
		GBP	Gubbio (GBP)	0.94	0.098	18.06	/	6[2]
		GBB	Gubbio (GBB)	0.09	0.083	2.87	/	6[2]
		BVG	Bevagna	0.31	0.079	8.95	/	6.5[2]
		PGL	Peglio	0.08	0.069	2.63	/	6[2]
		SNG	Senigallia	0.14	0.045	3.85	/	5.5[2]
		LNS	Leonessa	0.04	0.033	1.30	/	5.5[2]
		FHC	Arquata del Tronto	0.03	0.033	1.14	/	5.5[2]
		CSC	Cascia	0.05	0.022	1.39	/	5.5[2]
		CGL	Cagli	0.03	0.020	1.26	/	6[2]
		RTI	Rieti	0.10	0.019	1.80	/	5.5[2]
		PNN	Pennabilli	0.05	0.015	1.08	/	5.5[2]
		AQG	L' Aquila (AQG)	0.02	0.007	0.39	/	5.5[2]
		AQK	L' Aquila (AQK)	0.03	0.004	0.62	/	5.5[2]
		AQI	L' Aquila (AQI)	0.03	0.004	0.65	/	5.5[2]
1998/09/09	Basilicata	GRM	Grumento	0.12	0.041	2.98	4[3]	4[3]
		LRG	Lauria-Galdo	0.28	0.242	11.72	6[3]	6[3]
		LRS	Lauria San Giovanni	0.30	0.165	12.52	6[3]	6[3]
		SCL	Scalea	0.22	0.044	5.03	5[3]	5[3]
		VGG	Viggianello	0.15	0.073	3.81	5.5[3]	6[3]
2002/09/06	Palermo	CDI	Castel di Iudica	0.02	0.005	0.49	4[4]	4[04]
		CLG	Caltagirone	0.02	0.007	0.55	4[4]	4[4]

Table 10 (continued)

Data	Epicentral area	Station name	Village	Instrumental parameters			Macroseismic intensity	
				I_H (m)	PGA (g)	PGV (cm/s)	EMS-98	MCS
2003/01/26	Forlì	PTT	Patti	0.05	0.010	1.12	4.5[4]	4.5[4]
	Forlì	STS	Santa Sofia	0.04	0.095	2.46	/	6[5]
2003/09/14	Appennino Bolognese	FRE	Firenzuola	0.04	0.026	1.47	5[6]	5.5[7]
		BSZ	Borgo San Lorenzo	0.02	0.010	0.60	4.5[6]	5[6]
		FAZ	Faenza	0.02	0.008	0.60	4.5[6]	4.5[6]
		BRB	Barberino di Mugello	0.02	0.007	0.39	5[6]	5[6]
2004/11/24	Lago di Garda	GVD	Gavardo	0.06	0.073	3.29	/	5.5[7]
2008/01/03	Mugello	FRE	Firenzuola	0.06	0.048	2.90	/	4.5[8]
		BSZ	Borgo San Lorenzo	0.01	0.019	0.43	/	5[8]
		BRB	Barberino di Mugello	0.02	0.015	0.80	/	5[8]
2008/12/23	Emilia Romagna	AUL	Aulla	0.03	0.022	1.44	/	5[9]
		PNM	Pontremoli	0.02	0.015	0.67	/	5[9]
		SSU	Sassuolo	0.02	0.012	0.53	/	4.5[9]
		MDN	Modena	0.03	0.012	0.80	/	4.5[9]
		MIL	Milano	0.01	0.005	0.33	/	4.5[9]
		GNV	Genova	0.01	0.003	0.29	/	4[9]
		LSP	La Spezia	0.005	0.002	0.16	/	4[9]
2009/04/06	L' Aquila	AQV	L' Aquila (AQV)	1.32	0.657	42.66	8.5[10]	9[11]
		AQG	L' Aquila (AQG)	1.15	0.489	35.72	8.5[10]	9[11]
		AQA	L' Aquila (AQA)	0.89	0.444	31.85	8.5[10]	9[11]
		AQK	L' Aquila (AQK)	1.42	0.362	35.77	8.5[10]	9[11]
		CLN	Celano	0.22	0.090	7.04	/	5.5[11]
		AVZ	Avezzano	0.47	0.069	11.29	/	5[11]

Table 10 (continued)

Data	Epicentral area	Station name	Village	Instrumental parameters			Macroseismic intensity	
				I_H (m)	PGA (g)	PGV (cm/s)	EMS-98	MCS
		MTR	Montereale	0.15	0.063	3.54	/	5[11]
		FMG	Fiamignano	0.10	0.027	2.58	/	5.5[11]
		ANT	Antrodoco	0.10	0.026	2.47	/	5[11]
		SUL	Sulmona	0.13	0.034	3.65	/	5[11]
		CHT	Chieti	0.30	0.030	7.87	/	5[11]
2009/12/15	Valle del Tevere	PRG	Perugia	0.01	0.007	0.25	4[12]	/
2011/06/24	Sicilia	NAS	Naso	0.02	0.037	1.05	4[13]	/
		TOR	Tortorici	0.03	0.034	1.36	5[13]	/
		PTT	Patti	0.03	0.021	1.29	4[13]	/
		BCL	Barcellona P. Gotto	0.01	0.006	0.25	4[13]	/
		MZZ	Milazzo	0.00	0.004	0.18	4[13]	/
		GSM	Gioiosa Marea	0.01	0.004	0.19	4.5[13]	/
		NSA	Nicosia	0.01	0.003	0.25	4[13]	/
2011/07/17	Pianura Padana	MRN	Mirandola	0.03	0.026	0.93	4[14]	/
2011/07/25	Torino	SUS	Susa	0.00	0.057	0.52	4[15]	/
		PNR	Pinerolo	0.01	0.022	0.53	5[15]	/
		SLZ	Saluzzo	0.00	0.003	0.10	4[15]	/
2012/01/25	Pianura Padana	SRP	Sorbolo	0.15	0.117	7.02	5.5[16]	6[16]
		NVL	Novellara	0.09	0.074	3.75	4.5[16]	4.5[16]
		PAR	Parma	0.02	0.027	0.89	5[16]	5.5[16]
		BRR	Berceto	0.01	0.011	0.64	4.5[16]	4.5[16]
2012/05/20	Emilia	MRN	Mirandola	1.58	0.303	46.31	6.5[17]	6.5[17]
2012/05/29	Emilia	MRN.	Mirandola	1.86	0.857	57.49	7.5[17]	7.5[17]

Table 10 (continued)

Data	Epicentral area	Station name	Village	Instrumental parameters			Macroseismic intensity	
				I_H (m)	PGA (g)	PGV (cm/s)	EMS-98	MCS
		CNT	Cento	0.64	0.300	16.87	6[17]	6[17]
		MOG0	Moglia	0.95	0.240	26.58	7.5[17]	7.5[17]
		T0814	Carpi	0.86	0.505	23.64	6[17]	6[17]
		SAN0	San Felice sul Panaro	1.18	0.314	35.24	7[17]	7[17]
		T0818	Concordia sulla Secchia	1.25	0.280	39.25	7.5[17]	7.5[17]
		RAV0	Crevalcore	0.31	0.084	9.76	6.5[17]	6.5[17]
		SAG0	Sant' Agostino	0.27	0.081	7.73	6[17]	6[17]
		BON0	Bondeno	0.08	0.036	2.89	6[17]	6[17]
		FIN0	Finale Emilia	0.50	0.239	17.55	7[17]	7[17]
2012/10/26	Pollino	0PAP	Papasidero	0.23	0.239	11.64	5[18]	5[18]
		MRM	Mormanno	0.31	0.186	11.24	6[18]	6[18]
		0MOR	Morano Calabro	0.19	0.179	8.42	5[18]	5[18]
		VGG	Viggianello	0.17	0.126	5.17	5[18]	5[18]
		0LAI	Laino Borgo	0.13	0.116	5.95	5.5[18]	5.5[18]
		ORS	Orsomarso	0.06	0.072	2.34	5[18]	5[18]
		PRA	Praia a Mare	0.05	0.049	1.96	4.5[18]	4.5[18]
		CVL	Castrovillari	0.05	0.047	1.35	5[18]	5[18]
		LRG	Lauria	0.04	0.037	1.62	4.5[18]	4.5[18]
		SCL	Scalea	0.13	0.033	2.50	4[18]	4[18]
		SDN	San Donato di Ninea	0.03	0.020	0.89	4[18]	4[18]
		0FRA	Frascineto	0.06	0.017	1.50	4[18]	4[18]
		LTR	Latronico	0.05	0.012	1.14	4[18]	4[18]
2013/06/21	Fivizzano	FVZ	Fivizzano	0.16	0.232	6.58	5[19]	5.5[19]

Table 10 (continued)

Data	Epicentral area	Station name	Village	Instrumental parameters			Macroseismic intensity	
				I_H (m)	PGA (g)	PGV (cm/s)	EMS-98	MCS
		PZS	Piazza al Serchio	0.12	0.090	4.81	5[19]	5[19]
2016/02/08	Monti Iblei	PLZ	Palazzolo Acreide	0.01	0.025	0.51	4.5[20]	/
		NTE	Noto	0.01	0.005	0.16	4[20]	/
		ISI	Ispica	0.00	0.005	0.19	4[20]	/
		VZZ	Vizzini	0.01	0.017	0.51	4[20]	/
		SRT	Sortino	0.01	0.016	0.62	4[20]	/
		VTT	Vittoria	0.01	0.006	0.20	4[20]	/
		SCR	Santa Croce Camerina	0.00	0.003	0.10	4[20]	/
		LNT	Lentini	0.00	0.004	0.17	4[20]	/
		SRC	Siracusa	0.00	0.002	0.10	4[20]	/
2016/08/24	Accumoli	AMT	Amatrice	1.10	0.878	45.01	10[21]	10.5[22]
		RQT	Arquata del Tronto	0.29	0.424	15.03	8.5[21]	8.5[22]
		PCB	Poggio Cancelli	0.42	0.309	13.30	5[21]	/
		CSC	Cascia	0.19	0.106	5.56	/	5[22]
		MTR	Montereale	0.40	0.090	9.70	5.5[21]	6[22]
		LSS	Leonessa	0.06	0.020	2.15	5[21]	5[22]
		SNO	Sarnano	0.16	0.092	6.02	5.5[21]	5[22]
		ASP	Ascoli Piceno	0.10	0.088	2.92	5[21]	5[22]
		ANT	Antrodoco	0.14	0.022	3.18	/	5[22]
		PZI	Pizzoli	0.22	0.051	5.26	/	5[22]
		TLN	Tolentino	0.30	0.120	6.35	/	5[22]
2016/10/26	Ussita	CNE	Castel Santangelo sul Nera	0.97	0.556	37.29	8[23]	8[23]
		PRE	Preci	0.26	0.262	10.22	7[23]	6.5[23]

Table 10 (continued)

Data	Epicentral area	Station name	Village	Instrumental parameters			Macroseismic intensity	
				I_H (m)	PGA (g)	PGV (cm/s)	EMS-98	MCS
		CLO	Castelluccio	0.54	0.220	13.42	6.5[23]	6[23]
		FOC	Foligno Colfiorito	0.31	0.613	20.13	5[23]	5[23]
2016/10/30	Norcia	NOR	Norcia (NOR)	2.53	0.320	54.13	8.5[23]	8.5[23]
		NRC	Norcia (NRC)	2.05	0.447	46.14	8.5[23]	8.5[23]
		CNE	Castel Santangelo sul Nera	1.28	0.500	43.01	9[23]	9[23]
		PRE	Preci	0.48	0.324	16.31	7.5[23]	7.5[23]
		CSC	Cascia	0.37	0.165	11.95	6.5[23]	6.5[23]
		FOC	Foligno Colfiorito	0.28	0.382	12.43	5[23]	5.5[23]
		SNO	Sarnano	0.21	0.121	6.72	5[23]	5.5[23]
		TLN	Tolentino	0.31	0.120	7.62	7[23]	7[23]
2017/01/18	Capitignano	MSC	Mascioni (MSC)	0.32	0.241	13.89	5[24]	5.5[24]
		MSCT	Mascioni (MSCT)	0.34	0.253	14.45	5[24]	5.5[24]
		PCB	Poggio Cancelli	0.49	0.566	22.37	7[24]	7.5[24]
		PZI	Pizzoli	0.13	0.105	5.07	5[24]	5.5[24]
		TER	Teramo	0.08	0.090	2.50	5.5[24]	5.5[24]
		ASP	Ascoli Piceno	0.08	0.105	2.84	5.5[24]	5.5[24]

[1]Margottini et al. (1992); [2]Stucchi et al. (1998); [3]Galli et al. (2001); [4]Azzaro et al. (2004); [5]Camassi and Ercolani (2003a); [6]Camassi et al. (2003b); [7]Gruppo di Lavoro INGV (2004); [8]Camassi et al. (2008); [9]Camassi et al. (2009); [10]Tertulliani et al. (2010); [11]Galli and Camassi (2009); [12]Arcoraci et al. (2009); [13]Azzaro et al. (2011); [14]Bernardini and Ercolani (2011a); [15]Bernardini et al. (2011b); [16]Arcoraci et al. (2012a); [17]Arcoraci et al. (2012b); [18]Azzaro et al. (2012); [19]Arcoraci et al. (2013); [20]Azzaro et al. (2016); [21]Tertulliani and Azzaro (2016a); [22]Galli et al. (2016); [23]Tertulliani and Azzaro (2016b); [24]Tertulliani and Azzaro (2017)

Table 11 Correlations between instrumental parameters (PGA, PGV and I_H) and macroseismic intensity scales (MCS and EMS-98)

Direct relationships	Inverse relationships
$I_{EMS-98} = f(PGA)$	$PGA = f(I_{EMS-98})$
$I_{EMS-98} = 0.48 \cdot \ln(PGA) + 6.32$ PGA < 0.06 g	$PGA = e^{\wedge}((I_{EMS-98} - 6.32)/0.48)$ $I_{EMS-98} \leq 5$
$I_{EMS-98} = 1.72 \cdot \ln(PGA) + 9.82$ PGA $\geq$ 0.06 g	$PGA = e^{\wedge}((I_{EMS-98} - 9.82)/1.72)$ $I_{EMS-98} > 5$
$I_{MCS} = f(PGA)$	$PGA = f(I_{MCS})$
$I_{MCS} = 0.51 \cdot \ln(PGA) + 6.55$ PGA < 0.06g	$PGA = e^{\wedge}((I_{MCS} - 6.55)/0.51)$ $I_{MCS} \leq 5$
$I_{MCS} = 1.81 \cdot \ln(PGA) + 10.22$ GA $\geq$ 0.06g	$PGA = e^{\wedge}((I_{MCS} - 10.22)/1.81)$ $I_{MCS} > 5$
$I_{EMS-98} = f(PGV)$	$PGV = f(I_{EMS-98})$
$I_{EMS-98} = 0.36 \cdot \ln(PGV) + 4.38$ PGV < 5.5 cm/s	$PGV = e^{\wedge}((I_{EMS-98} - 4.38)/0.36)$ $I_{EMS-98} \leq 5$
$I_{EMS-98} = 1.81 \cdot \ln(PGV) + 1.90$ PGV $\geq$ 5.5 cm/s	$PGV = e^{\wedge}((I_{EMS-98} - 1.90)/1.81)$ $I_{EMS-98} > 5$
$I_{MCS} = f(PGV)$	$PGV = f(I_{MCS})$
$I_{MCS} = 0.41 \cdot \ln(PGV) + 4.53$ PGV < 5.5cm/s	$PGV = e^{\wedge}((I_{MCS} - 4.53)/0.41)$ $I_{MCS} \leq 5$
$I_{MCS} = 1.83 \cdot \ln(PGV) + 2.11$ PGV $\geq$ 5.5cm/s	$PGV = e^{\wedge}((I_{MCS} - 2.11)/1.83)$ $I_{MCS} > 5$
$I_{EMS-98} = f(I_H)$	$I_H = f(I_{EMS-98})$
$I_{EMS-98} = 0.32 \cdot \ln(I_H) + 5.59$ I_H < 0.15 m	$I_H = e^{\wedge}((I_{EMS-98} - 5.59)/0.32)$ $I_{EMS-98} \leq 5$
$I_{EMS-98} = 1.64 \cdot \ln(I_H) + 8.08$ I_H $\geq$ 0.15 m	$I_H = e^{\wedge}((I_{EMS-98} - 8.08)/1.64)$ $I_{EMS-98} > 5$
$I_{MCS} = f(I_H)$	$I_H = f(I_{MCS})$
$I_{MCS} = 0.32 \cdot \ln(I_H) + 5.73$ I_H < 0.15 m	$I_H = e^{\wedge}((I_{MCS} - 5.73)/0.32)$ $I_{MCS} \leq 5$
$I_{MCS} = 1.72 \cdot \ln(I_H) + 8.38$ I_H $\geq$ 0.15 m	$I_H = e^{\wedge}((I_{MCS} - 8.38)/1.72)$ $I_{MCS} > 5$

Total Least Squares (TLS) method

According to Zaiontz (2019), the goal of the TLS method is to minimize the sum of the squared Euclidean distances d^2 from the observed points y_i to the corresponding ones on the regression line (which is in the form y = a + bx), as follows:

$$min\left\{ \sum_{i=1}^{n} d_i^2 \right\}$$

that is equivalent to:

$$min\left\{ \sum_{i=1}^{n} \frac{(y_i - y_i')^2}{b^2 + 1} \right\}$$

where y_i and y_i' are the observed and the corresponding estimated data (along the vertical line), respectively, and b is given by:

$$b = \frac{w + \sqrt{w^2 + r^2}}{r}$$

where

$$w = \sum_{i=1}^{n} \left(y_i - y_m \right)^2 - \sum_{i=1}^{n} \left(x_i - x_m \right)^2$$

and

$$r = 2 \sum_{i=1}^{n} \left(x_i - x_m \right) \left(y_i - y_m \right)$$

x_m and y_m are the mean values of the x_i and y_i values, respectively. The intercept a can now be expressed as:

$$a = y_m - b x_m$$

An analogous procedure can be found also in Petráš and Bednárová (2010).

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