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Correlation between macroseismic intensities and seismic ground motion parameters

Giuliano Francesco Panza (1) (2), **Renato Cazzaro** (1) and **Franco Vaccari** (1) (3)
(1) *Dipartimento di Scienze della Terra, Università di Trieste, Italy*
(2) *International Centre for Theoretical Physics, SAND Group, Trieste, Italy*
(3) *CNR-Gruppo Nazionale per la Difesa dai Terremoti, Roma, Italy*

Abstract
We propose correlation relations between the macrosesimic intensity felt in Italy and displacement, velocity, acceleration, design ground acceleration obtained from synthetic seismograms modelling the ground motion generated by past seismicity. The results are in good agreement with empirical relations given by other authors and compare quite well with the few observations available in the Italian territory.

Key words *intensity – acceleration – velocity – displacement – Italy*

1. Introduction

In engineering design many parameters have been introduced to evaluate the resistance of buildings and structures to ground shaking. Intensity expresses the effects of earthquakes on buildings. It is a very common estimate of earthquake size and for historical events it is the only information available. Intensity is a semiempirical measure and when observed at large scale and over a large number of points has a quite regular pattern, that may be controlled by the radiation properties of the seismic source (Panza *et al.*, 1991).

Mailing address: Prof. Giuliano Francesco Panza, Dipartimento di Scienze della Terra, Università di Trieste, Via E. Weiss 4, 34127 Trieste, Italy; e-mail: panza@geosun0.univ.trieste.it

Correlation relations between intensity and acceleration or velocity (seldom displacement) are used for the design of earthquake-resistant structures.

The simplest measure of acceleration is the Peak Ground Acceleration (PGA), *i.e.* the maximum acceleration measured on the accelerogram, consequently PGA neither gives information on earthquake duration or on the dominant frequency of seismic motion. To partly bypass this drawback, the determination of alternative quantities has been proposed: Root Mean Square Acceleration, Arias Intensity (Arias, 1974), Significant Acceleration (Bolt and Abrahamson, 1982) and Destructiveness Potential Factor (Araya and Saragoni, 1984).

The ground velocity is often considered to be more representative than acceleration itself (Ambraseys, 1974), since velocity is related to the energy flux from ground to buildings, and more recently attention has been paid to ground displacement in connection with seismic isolation (*e.g.*, Panza *et al.*, 1996).

2. Ground motion models

We look for correlation relations between the maximum macroseismic intensity, I, felt in Italy and Displacement (D), Velocity (V), Acceleration (A) and Design Ground Acceleration (DGA), computed on the basis of the available seismotectonic and structural models, using the deterministic procedure developed at the Department of Earth Sciences of the University of Trieste in the framework of national and international research programs (Costa *et al.*, 1993; Panza *et al.*, 1996).

To compute the synthetic seismograms that are at the base of the deterministic procedure, the structural models containing the source and the observation points are defined, as well as the characteristics of the seismic sources. On the basis of its geological charateristics, the Italian territory can be divided into sixteen polygons, and a flat, layered structural model, described by layer thickness, density, P- and S-wave velocities, and attenuation is associated with each polygon.

To limit the spatial distribution of sources, fifty seven seismogenic areas, as defined by Gruppo Nazionale per la Difesa dai Terremoti (GNDT) on the basis of seismological data and seismotectonic observations (Scandone *et al.*, 1990), are used. For the definition of the source mechanisms representative of each seismogenic area, more than three hundred fault-plane solutions, distributed over the whole territory, have been grouped into a data base, that contains a standard definition of the focal mechanisms, both as a function of strike, dip and rake of the nodal planes and as a function of the direction of compressional, tensional and null axes.

For the definition of seismicity, an earthquake catalogue has been prepared, merging the data from the NT3.1 catalogue (Stucchi *et al.*, 1995) for the period 1000-1979, with the data from ING (1980-1991) bulletins, for the period 1980-1991. To derive the distribution of the maximum observed magnitude over the entire territory, the image of the seismicity given by the earthquake catalogue is smoothed. For this purpose, the area is divided into cells, and each cell is assigned the magnitude value of the most energetic event that occurred within it. In order to take into account source dimensions, for events with $M_i > 6.75$, we use a centered smoothing window, with a radius of 0.2°, and only the cells falling within a seismogenic area are retained; a double-couple point source, corresponding to the magnitude M_i, is placed at the centre of each cell. The orientation of the double-couple associated with each source is automatically obtained from the data base of the fault-plane solutions.

Once the structures and the sources are specified, a grid 0.2° by 0.2° covering the whole territory, is defined and complete synthetic seismograms are computed in each node of the grid, with an upper frequency limit of 1 Hz, by the modal summation technique (Panza, 1985, Florsch *et al.*, 1991). The radial and transversal components of signals are rotated to obtain NS and EW components. Among all NS components at every node we choose the component with the greatest peak value and we define the period T_{NS} where the spectrum amplitude is maximum. For the EW components we do the same. Between these two components we choose the one with the greatest peak value (D in cm, V in cm/s, A in g - gravity acceleration) and we retain the information about longitude, latitude of the observation point, the two periods T_{NS} and T_{EW}, the magnitude and focal mechanism of the event responsible for the selected signal. We name T_{CMAX} the period of the dominant component. As expected, for displacements the maxima are concentrated around long periods, for accelerations around 1 s (the lower period used in the computation of the synthetic seismograms) and for velocities we have an intermediate situation (fig. 1). Mean and standard deviation of T_{CMAX} are: 8.3 ± 0.2 s for D, 4.9 ± 0.2 s for V and 1.3 ± 0.02 s for A.

We can extend our modelling to higher frequencies by using design response spectra, for instance Eurocode 8 (EC8). The regional structural models used (Costa *et al.*, 1993) are all of type A, as defined in EC8, therefore we can immediately determine DGA and the Maximum Spectral Value (MSV) using the EC8 parameters for soil A. DGA and MSV are spectral values and they are not directly related to PGA,

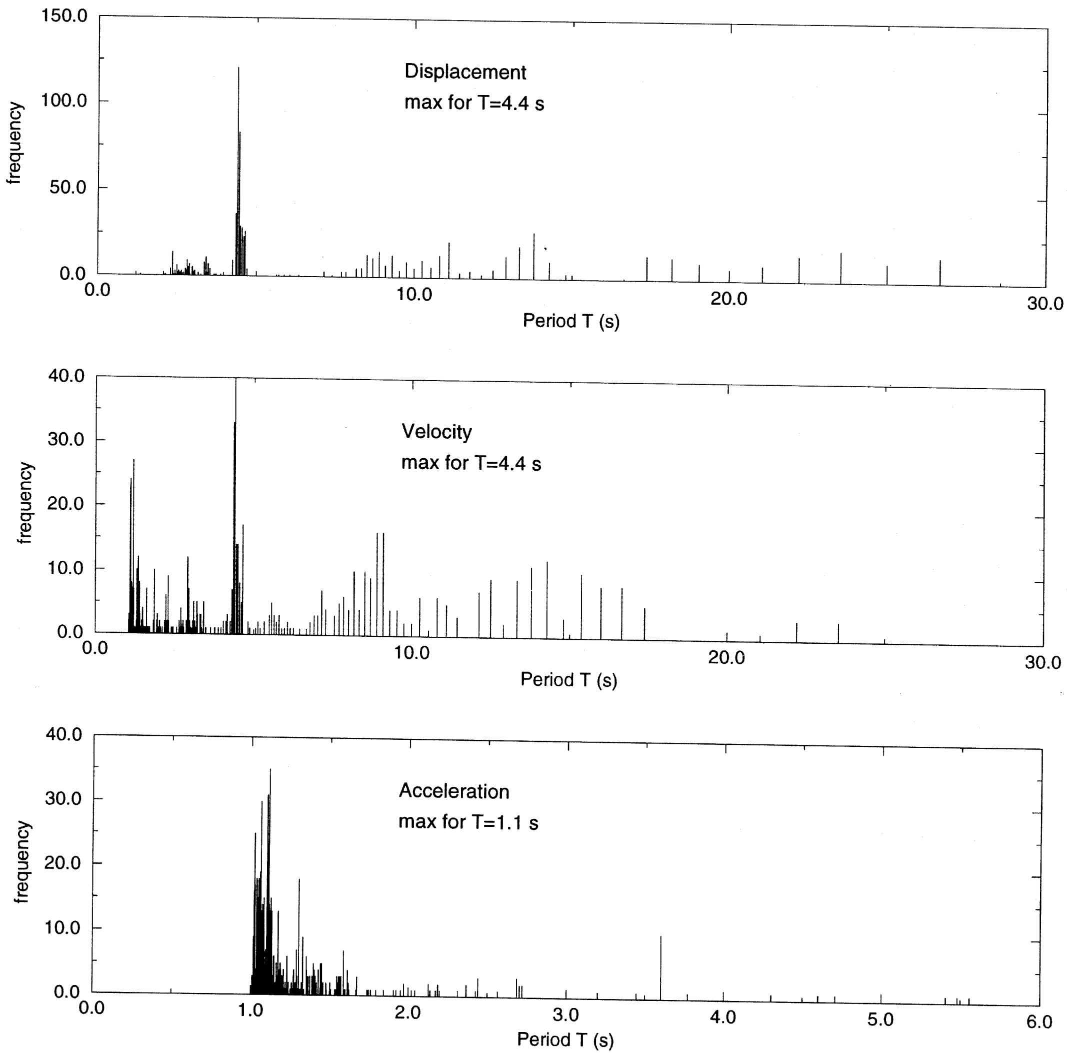

Fig. 1. T_{CMAX} distribution for displacement, velocity and acceleration.

which is a quantity estimated in the time domain, but in practice it is reasonable to compare MSV with PGA (*e.g.*, Marmureanu *et al.*, 1995).

The results of the deterministic modelling of ground motion, which makes up for the lack of a large database of experimental data, are in good agreement with the few available experimental data (Nunziata *et al.*, 1995; Panza *et al.*, 1996).

3. Intensity data

We used two sources for intensity data. The first is a map of maximum macroseismic intensity felt in Italy, made by Istituto Nazionale di Geofisica (ING intensity) (Boschi *et al.*, 1995), where I ranges between the V and the XI grade of MCS scale, the intensity value V including values below V. The second source is a set of maximum intensity felt in every municipal land, compiled jointly by ING, SSN and GNDT (ISG intensity) (Molin *et al.*, 1996). In this set VI $\leq I \leq$ X and grade VI includes values below VI, while grade X includes values above X.

4. Regressions

4.1. *Regression independent of distance*

Peak values and I are poorly correlated and their scatter is considerable (Ambraseys, 1974; Decanini *et al.*, 1995). Indeed, if we apply the correlation hypothesis:

$$\log(y) = b_0 + b_1 I \tag{4.1}$$

(where y is a peak value of D, V, A or DGA) to the whole set of data, we should reject (4.1), because the hypothesis is statistically significant. Equation (4.1) is statistically acceptable if average data, determined for every value of I, are used. Mean values of D, V, A, DGA and MSV *versus* ING intensity are reported in tables I and II (ING data), and *versus* ISG intensity in tables III and IV (ISG data).

From intensity VI to intensity IX the ISG mean values are lower than ING mean values, while, for intensity X, the ISG mean value is greater than ING one. This trend variation can be explained by the fact that, at intensity X, ISG also includes $I >$ X. For completeness, tables II and IV give MSV, the level of the flat part of the design spectra. In our case we considered EC8, for which, for soil type A, MSV is 2.5 times DGA and ranges between 2.5 and 10 Hz.

A measure of the agreement between the values obtained from our modelling and the experimental values is given by the mean values obtained from the global data given by Ambraseys (1974) and the PGA values of the records of Tolmezzo (Friuli earthquake, 1976) and Sturno (Irpinia earthquake, 1980), given in tables V and VI, respectively.

The values in table V are almost three times larger than MSV given in table II and IV, and

Table II. Mean values of DGA and MSV *versus* ING intensity (ING data).

I	(DGA $\pm\sigma$) (g)	MSV (g)
V	$(5.0 \pm 0.6) \times 10^{-3}$	12.5×10^{-3}
VI	$(9.5 \pm 1.3) \times 10^{-3}$	23.8×10^{-3}
VII	$(14.1 \pm 1.1) \times 10^{-3}$	35.3×10^{-3}
VIII	$(27.9 \pm 1.8) \times 10^{-3}$	69.8×10^{-3}
IX	$(66.4 \pm 5.6) \times 10^{-3}$	166.0×10^{-3}
X	$(134.9 \pm 13.9) \times 10^{-3}$	337.3×10^{-3}
XI	$(127.4 \pm 22.0) \times 10^{-3}$	318.5×10^{-3}

Table I. Mean values of displacement, velocity, acceleration and DGA *versus* ING intensity (ING data).

I	($D \pm \sigma$) (cm)	($V \pm \sigma$) (cm/s)	($A \pm \sigma$) (g)
V	0.10 ± 0.01	0.32 ± 0.03	$(1.4 \pm 0.1) \times 10^{-3}$
VI	0.4 ± 0.1	0.8 ± 0.2	$(3.0 \pm 0.5) \times 10^{-3}$
VII	0.7 ± 0.1	1.2 ± 0.1	$(4.3 \pm 0.4) \times 10^{-3}$
VIII	1.6 ± 0.1	2.5 ± 0.2	$(9.3 \pm 0.7) \times 10^{-3}$
IX	3.3 ± 0.3	6.3 ± 0.6	$(23.8 \pm 2.2) \times 10^{-3}$
X	6.2 ± 0.5	13.6 ± 1.5	$(50.7 \pm 5.8) \times 10^{-3}$
XI	6.1 ± 1.2	13.4 ± 2.7	$(51.2 \pm 10.8) \times 10^{-3}$

Table III. Mean values of displacement, velocity, acceleration and DGA *versus* ISG intensity (ISG data).

I	$(D \pm \sigma)$ (cm)	$(V \pm \sigma)$ (cm/s)	$(A \pm \sigma)$ (g)
VI	(0.25 ± 0.08)	(0.6 ± 0.1)	$(2.1 \pm 0.3) \times 10^{-3}$
VII	(0.6 ± 0.1)	(1.0 ± 0.1)	$(3.5 \pm 0.4) \times 10^{-3}$
VIII	(1.4 ± 0.1)	(2.1 ± 0.1)	$(7.7 \pm 0.5) \times 10^{-3}$
IX	(3.2 ± 0.2)	(5.6 ± 0.4)	$(20.4 \pm 1.5) \times 10^{-3}$
X	(6.2 ± 0.4)	(13.4 ± 1.1)	$(50.9 \pm 4.2) \times 10^{-3}$

this fact is not unexpected, since for the same intensity, acceleration values recorded in Italy are lower than the values recorded in California (Cancani, 1904; Richter, 1959), as reported by Boschi *et al.*, (1969). The PGA from the Tolmezzo record is about five times larger than the MSV values reported in tables II and IV, but the frequency content of the accelerogram is strongly shifted towards high frequencies (1.9-3.8 Hz). The PGA of Sturno exceeds the MSV values in tables II and IV by about 40%. The modelled values obtained using EC8 are lower than experimental data, and this supports the proposal of Pugliese *et al.* (1997) to use for Italy a design spectrum different from EC8, with the ratio between MSV and DGA equal to 2.75.

The application of (4.1) to the data of tables I-IV gives the results reported in tables VII and VIII. Here, and in all the following computations, χ^2 is determined assigning to the value obtained from the regression coefficients, an error of 2σ. Figures 2 and 3 summarize the results of the regressions and the distribution of the mean values. For each intensity data set (ING and ISG) the slopes of (4.1) are, within the errors, comparable between themselves, but the slopes obtained with ING data are smaller than the slopes obtained with ISG data. Figures 4, 5 and 6 compare our log-linear relations with some earlier results, obtained considering local and global data: the slope of the regression of DGA (ISG) is very similar to the one given by Cancani (1904) for PGA.

Table IV. Mean values of DGA and MSV *versus* ISG intensity (ISG data).

I	(DGA $\pm \sigma$) (g)	MSV (g)
VI	$(7.7 \pm 1.2) \times 10^{-3}$	19.3×10^{-3}
VII	$(11.9 \pm 1.2) \times 10^{-3}$	29.8×10^{-3}
VIII	$(23.8 \pm 1.5) \times 10^{-3}$	59.5×10^{-3}
IX	$(59.8 \pm 4.1) \times 10^{-3}$	149.5×10^{-3}
X	$(130.2 \pm 9.9) \times 10^{-3}$	325.5×10^{-3}

Table V. Mean values obtained from the global data given by Ambraseys (1974).

I	$A \pm \sigma$ (g)
V	$(35.3 \pm 8.0) \times 10^{-3}$
VI	$(54.9 \pm 12.7) \times 10^{-3}$
VII	$(134.9 \pm 26.4) \times 10^{-3}$
VIII	$(206.6 \pm 51.7) \times 10^{-3}$

Table VI. PGA recorded in Tolmezzo (Friuli earthquake, 1976) and Sturno (Irpinia earthquake, 1980).

Tolmezzo		Sturno	
I	PGA (g)	I	PGA (g)
VIII	360×10^{-3}	IX	220×10^{-3}

Table VII. Results of regression (4.1) for ING data.

D	V	A	DGA
$b_0 = -2.3 \pm 0.3$	$b_0 = -1.9 \pm 0.2$	$b_0 = -4.3 \pm 0.2$	$b_0 = -3.6 \pm 0.2$
$b_1 = 0.30 \pm 0.03$	$b_1 = 0.29 \pm 0.02$	$b_1 = 0.28 \pm 0.02$	$b_1 = 0.26 \pm 0.02$
$\chi_5^2 = 3.7$	$\chi_5^2 = 4.1$	$\chi_5^2 = 4.6$	$\chi_5^2 = 4.5$

Table VIII. Results of regression (4.1) for ISG data.

D	V	A	DGA
$b_0 = -2.7 \pm 0.1$	$b_0 = -2.4 \pm 0.2$	$b_0 = -4.9 \pm 0.2$	$b_0 = -4.1 \pm 0.2$
$b_1 = 0.35 \pm 0.01$	$b_1 = 0.35 \pm 0.02$	$b_1 = 0.35 \pm 0.02$	$b_1 = 0.32 \pm 0.02$
$\chi_3^2 = 1.8$	$\chi_3^2 = 2.2$	$\chi_3^2 = 2.2$	$\chi_3^2 = 2.0$

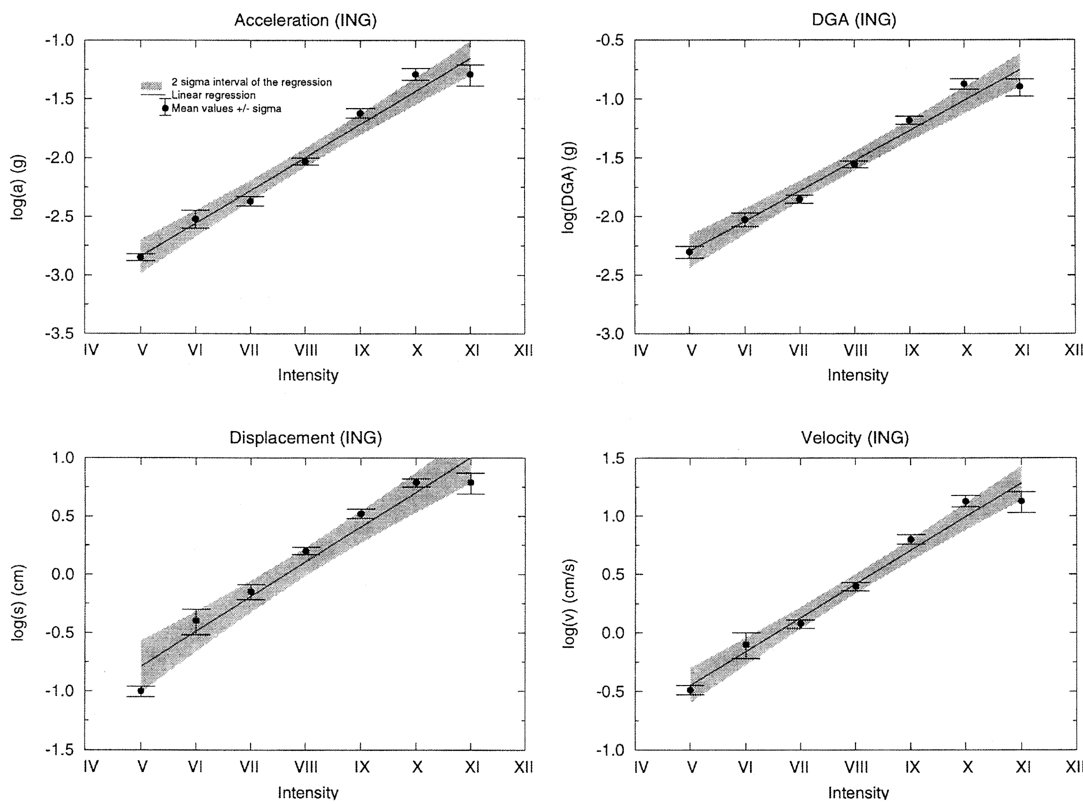

Fig. 2. Distribution of ING means and regression curves.

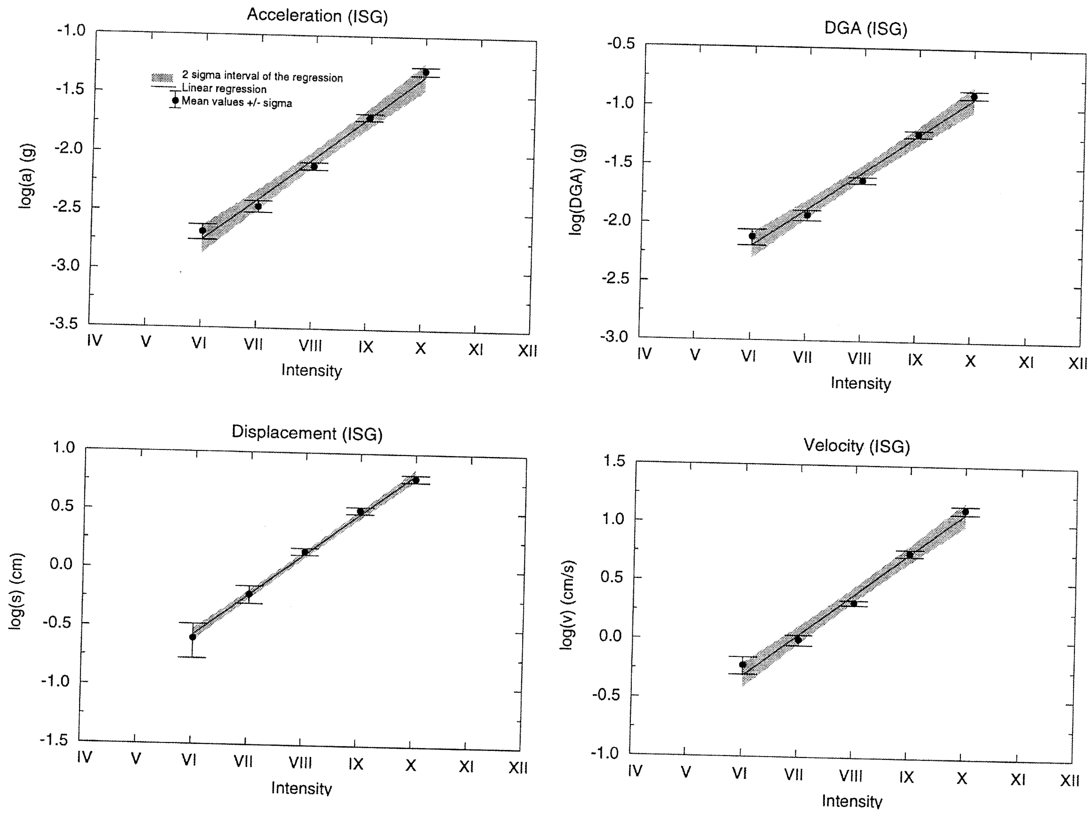

Fig. 3. Distribution of ISG means and regression curves.

4.2. *Regression dependent on distance*

At a fixed intensity, means of peak values of D, V and A, in general, decrease with epicentral distance. Decanini *et al.*, (1995) show an example of 9 events with I = VII, for which the mean of PGA for $R \leq 50$ km is almost 110 cm/s^2, while for $50 < R < 80$ km the mean PGA is 42 cm/s^2.

Following Decanini *et al.* (1995) we introduce the regression law for peak values:

$$\log (y) = b_0 + b_1 I + b_2 \log (R) \qquad (4.2)$$

where $R = \sqrt{D^2 + h^2}$ with D indicating the epicentral distance and h the focal depth.

As a consequence of the space discretization step we used in the computation of the synthetic signals, the peak values, as a function of R, can be easily grouped into ten intervals, and then averaged for a fixed intensity.

Tables IX and X contain the results of our regression for D, V and DGA. The results for V and DGA are quite close to the one given by Decanini *et al.*, (1995), and a remarkable agreement with the observations in South East Sicily and Irpinia (Decanini *et al.*, 1995) is obtained when considering MSV and V (figs. 7 and 8). We show only the results we obtained with ING data, since the results obtained with ISG data are very similar. In these figures we have plotted observations as solid circles and our modelled values as open squares. The solid

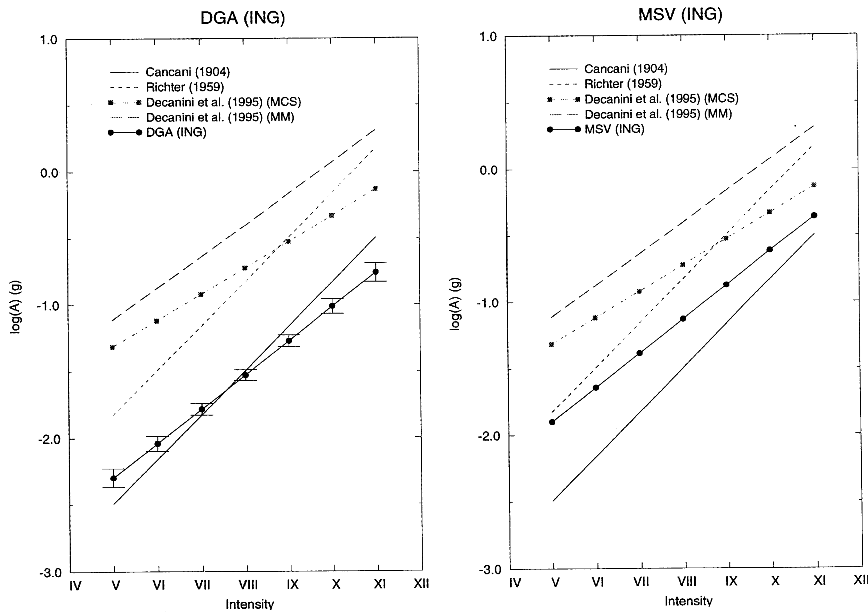

Fig. 4. Experimental curves and estimated values (± σ) of DGA (left), MSV (right). Results of Decanini *et al.* (1995), Cancani (1904), Richter (1959) are drawn for comparison.

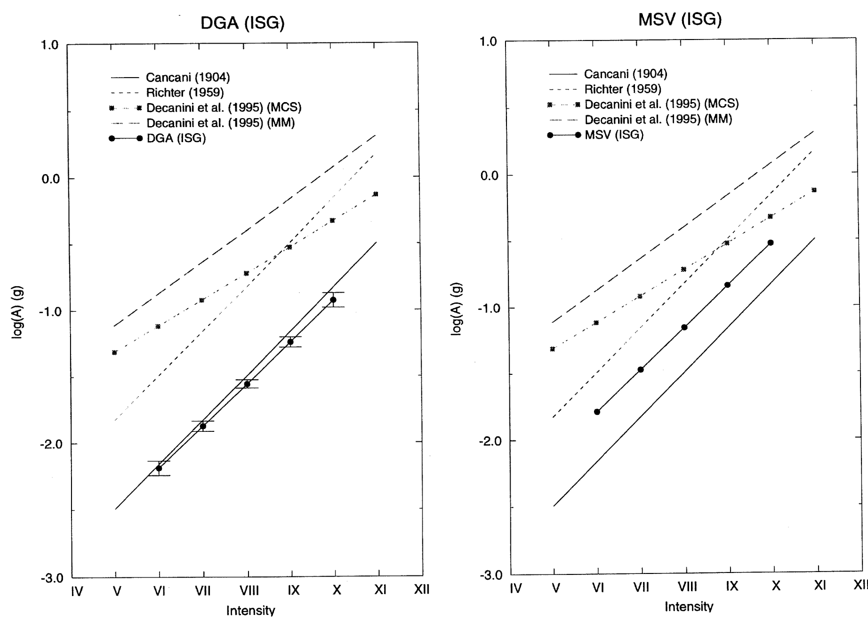

Fig. 5. Experimental curves and estimated values (± σ) DGA (left), MSV (right). Results of Decanini *et al.* (1995), Cancani (1904), Richter (1959) are drawn for comparison.

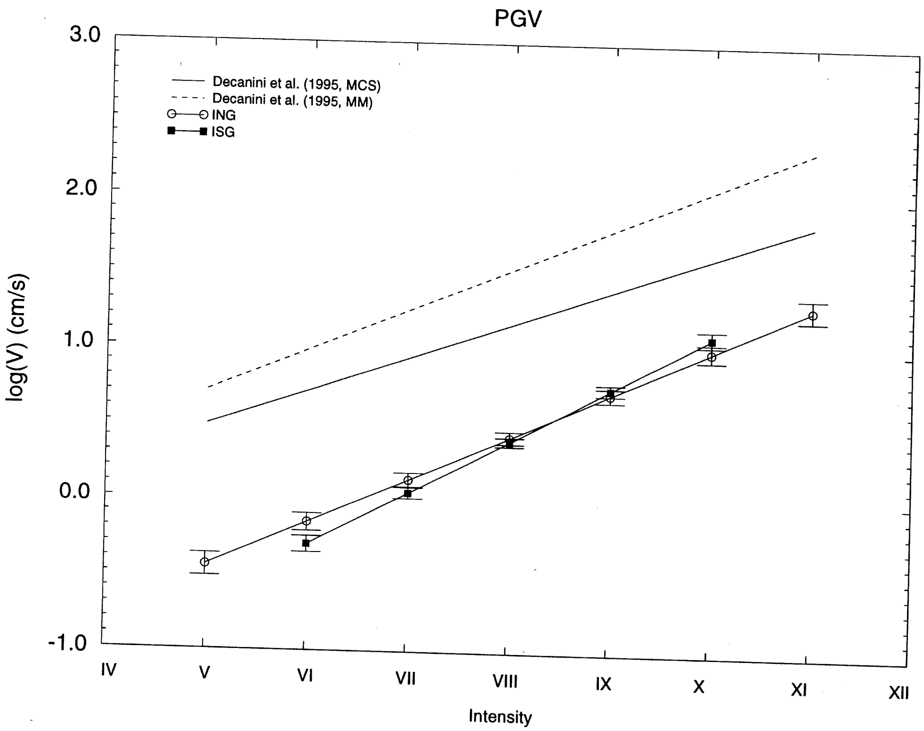

Fig. 6. Regression of PGV obtained in Decanini *et al.* (1995) and regression lines for ING and ISG data.

Table IX. Results of regression (4.2) for ING data.

D	V	DGA
$b_0 = 0.390 \pm 0.583$	$b_0 = 1.24 \pm 0.73$	$b_0 = -0.707 \pm 0.795$
$b_1 = 0.063 \pm 0.048$	$b_1 = 0.102 \pm 0.057$	$b_1 = 0.075 \pm 0.063$
$b_2 = -0.176 \pm 0.185$	$b_2 = -0.836 \pm 0.201$	$b_2 = -0.702 \pm 0.219$
$\chi^2_{22} = 50.5$	$\chi^2_{19} = 38.0$	$\chi^2_{18} = 34.3$

Table X. Results of regression (4.2) for ISG data.

D	V	DGA
$b_0 = 0.85 \pm 1.09$	$b_0 = 0.917 \pm 0.797$	$b_0 = -1.46 \pm 0.76$
$b_1 = 0.013 \pm 0.087$	$b_1 = 0.078 \pm 0.075$	$b_1 = 0.102 \pm 0.072$
$b_2 = -0.124 \pm 0.236$	$b_2 = -0.376 \pm 0.209$	$b_2 = -0.383 \pm 0.179$
$\chi^2_{12} = 18.0$	$\chi^2_{16} = 24.0$	$\chi^2_{16} = 25.7$

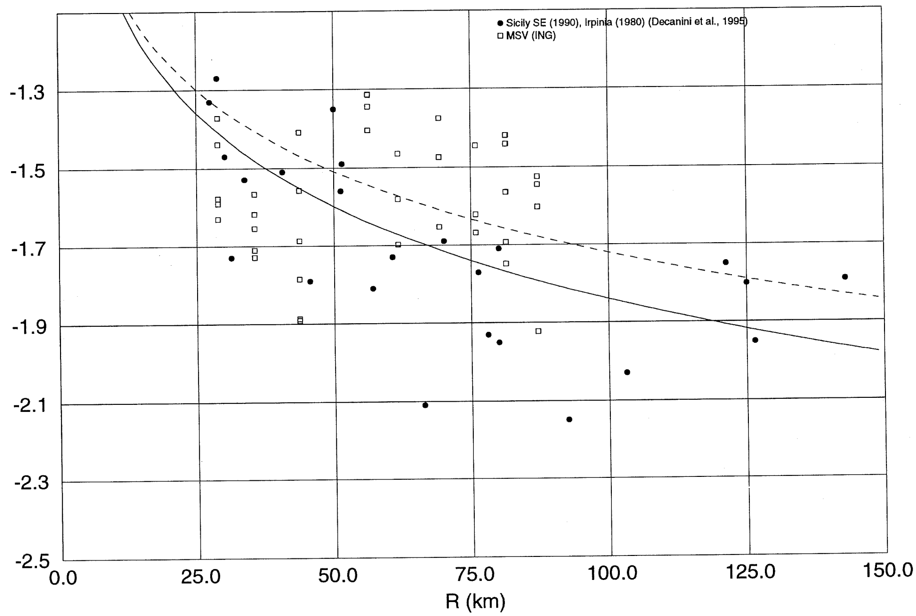

Fig. 7. Variation with hypocentral distance, R, of PGA (full circles) and MSV (open squares), normalized with I. Solid line represents $a(1) = -0.24\text{-}0.8 \log (R)$, and dashed line $a(2) = -0.31\text{-}0.7 \log (R)$.

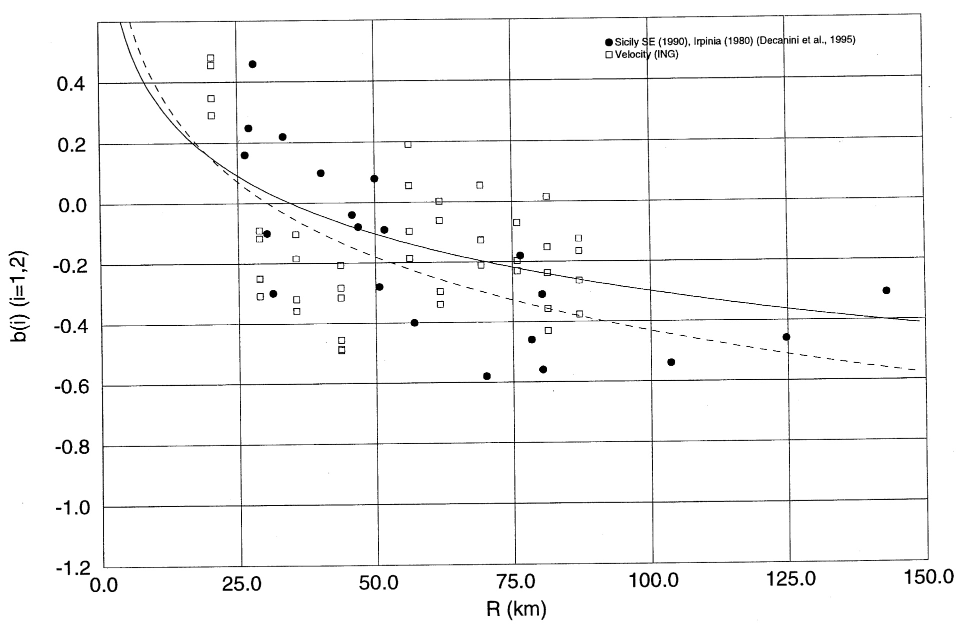

Fig. 8. Variation with hypocentral distance, R, of PGV (full circles) and V (open squares), normalized with I. Solid line represents $b(1) = 1.00\text{-}0.65 \log (R)$, and dashed line $b(2) = 1.24\text{-}0.836 \log (R)$.

and dashed lines are the regression for the observations and for our modeled values, respectively. Figure 7 plots $a(1) = \log(\mathrm{PGA})-0.07I$ and $a(2) = \log(\mathrm{MSV})-0.075I$ (single points); $a(1) = -0.24-0.8\log(R)$ and $a(2) = -0.31-0.7\log(R)$ (regression lines), and fig. 8 plots $b(1) = \log(\mathrm{PGV})-0.15I$ and $b(2) = \log(V)-0.102I$ (single points); $b(1) = 1.00-0.65\log(R)$ and $b(2) = 1.24-0.836\ \log(R)$ (regression lines).

The χ^2 test, applied to the modelled values, indicates that hypothesis (4.2) is statistically significant. The same is true for the experimental data plotted in figs. 7 and 8. The common feature shared by our modelled data and observations, is a positive jump at about 50 km of distance. If eq. (4.2) is applied separately to the data on the two sides of the discontinuity at about 50 km, the χ^2 test indicates that, in this case, hypothesis (4.2) is not statistically significant.

5. Conclusions

We have derived correlation relations between displacement, velocity, acceleration, DGA and intensity. The relations are valid on the whole Italian territory and the modelled data are in good agreement with the few available observations. Therefore, should it be required, the methodology may be directly applied to obtain regionalized relations. The χ^2 tests indicate that hypothesis (4.1) is not statistically significant when the values of D, V, A and DGA, corresponding to the same intensity, are grouped and then averaged.

The availability of relations between ground motion parameters and macroseismic intensity, valid for a specific region is quite important, since the use of relations based on information collected on a global scale may introduce quite unsatisfactory biases (Trifunac, 1992).

The analysis of the effect of distance, hypothesis (4.2), supplies additional evidence of the agreement between our modelled data and the observations made in Irpinia and SE Sicily, and points to the existence of a critical distance of about 50 km, whose physical meaning warrants further investigations.

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