ESTIMATION OF MACROSEISMIC INTENSITY – NEW ATTENUATION AND INTENSITY VS. GROUND MOTION RELATIONS FOR DIFFERENT PARTS OF EUROPE

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ABSTRACT :

Seismic hazard studies, as well as earthquake early warning systems, are usually focused on estimating the distribution of ground shaking associated with earthquake activity in a given region. Usually, ground shaking levels are presented in terms of peak ground acceleration (PGA), peak ground velocity (PGV) or other recorded parameters. One major drawback of such studies is the very limited strong motion dataset available in many regions even of high seismicity. Furthermore, there is hardly any direct correlation between the distribution of e.g. PGA and damage. To overcome such limitations we study strong ground motion in terms of macroseismic intensity. This makes it possible to include also historical earthquakes in an analysis by using comprehensive intensity point datasets and has the advantage of the results being directly related to the observed earthquake damages. As part of the EC project SAFER (Seismic eArly warning For EuRope), we study the attenuation of macroseismic intensities and derive relations between intensity and recorded ground motion values. Results will be presented for the Marmara Sea area (Turkey), the Naples area (Italy) and the Vrancea area (Romania). We consider a physically constrained attenuation model and account for the finite fault dimensions of large earthquakes in the regressions. Data from several earthquakes are joined, and for the case of Romania, anisotropy in the macroseismic field is accounted for in the derived attenuation model. Relations between intensity and recorded ground motions are based on available strong motion data and the effect of applying different weighting schemes is tested. Results indicate that our regression model provides a reliable estimate of macroseismic intensities for the studied regions, which can be implemented e.g. in seismic hazard analyses or with the USGS ShakeMap software for rapid estimation of the ground motion distribution after a large earthquake.

KEYWORDS: Macroseismic intensity, Attenuation, Seismic Hazard, Vrancea, Marmara Sea, Campania

1. INTRODUCTION

When generating shake maps with the purpose of earthquake early warning, an essential parameter is the attenuation of seismic waves in the area of interest. Such ground motion attenuation models are also of crucial importance for seismic hazard assessments. Attenuation relations are traditionally given in terms of recorded ground motion parameters, e.g. PGA, based on strong motion data. When studying the damage potential of large earthquakes, such PGA based relations have two drawbacks. First, the availability of recordings is limited and therefore one is often forced to apply attenuation relations based on recordings from different areas with similar tectonics. Second, there is no straightforward way to associate the recorded ground motions with damage which is a complex function of ground motion level, duration, local site conditions and building vulnerability.

As an alternative, to overcome these problems, ground motion attenuation is expressed in terms of macroseismic intensity. Intensities have the major advantage of much better availability, as data are dependent on the availability of people and a built environment rather than instrumentation and therefore can be sampled closer and as far back in time as historical records allow. Furthermore, the macroseismic intensity is assigned based on the observed ground shaking/damage and thereby it can be directly related to the damage potential of future earthquakes. Another advantage is that intensity data are easy understandable by non-seismologists and easy convertible by risk management teams.

In the present study we derive attenuation relations for macroseismic intensity for three focus areas of the EC project SAFER: The Marmara Sea region, NW Turkey, the Vrancea region, Romania and the Campania region in southern Italy. Furthermore, relations between macroseismic intensity and recorded ground motion in terms of peak ground acceleration (PGA) and peak ground velocity (PGV) are derived.

In the Marmara Sea region, especially the city of Istanbul is under a significant seismic hazard and potential seismic risk due to the likely rupture of a 100-150-km-long segment of the North Anatolian Fault just south of the city, within the lifetime of the present city environment. The capacity of the North Anatolian Fault for generating large earthquakes was latest manifested by the occurrence of the M=7.4 1999 Izmit earthquake. This event caused damage over an extended region around the rupturing fault and lead to the loss of more than 19000 lives.

The seismic hazard in Romania is dominated by the repeated occurrence of intermediate depth earthquakes in the Vrancea region. These earthquakes are confined to a very limited region of ca. 30 x 70 x 130 km with magnitudes reaching up to 7.5, and are expected to be associated with a partly detached slab under the Carpathian mountain belt. During the last 60 years, four major earthquakes have affected the region (1940, 1977, 1986 and 1990), the 1977 event causing severe damage, mainly in Bucharest, and killing ca. 1500 people (Wenzel et al., 2002). A peculiar characteristic of the Vrancea earthquakes is the distribution of ground shaking due to the events, which is not symmetric around the rupturing fault plane. There is a shift of the maximum intensities relative to the epicenter and the isoseismal lines are extended further in the NE-SW direction than in the NW-SE direction indicating stronger attenuation perpendicular to the Carpathian bend than in the parallel direction. This effect has important implications for the seismic hazard due to the Vrancea earthquakes, especially for the city of Bucharest which is in the direction of low attenuation.

The Campania region is highly exposed to the seismic risk related to the high seismicity with moderate to large magnitude earthquakes in the Appenninic belt. Most recently, the destructive 1980 M=6.9 Irpinia earthquake caused more than 3000 causalities, and widespread serious damage to buildings and infrastructure throughout the whole region, underlining the crucial importance of seismic hazard and risk assessment in the region. One measure in this direction is the implementation of an earthquake early warning system for the city of Naples which has a population reaching 2 millions.

There exist attenuation relations for macroseismic intensities for the three studied areas, which have been derived from datasets of varying quality and follow different functional relations. Most relations have been derived under a point-source approximation and not all functional forms have a physical basis. A full listing of available relations is too comprehensive for the current report. For the Marmara Sea region, Erdik and Eren (1983) and Erdik et al. (1985) have presented relations which are valid for the entire North Anatolian Fault. For the Vrancea region, different approaches have been followed to include the anisotropy of attenuation. Most studies have derived several relations valid for different azimuths or different zones of similar attenuation characteristics. Common for the available relations for the Vrancea region is that they are complicated to implement for the user. Relevant for the Campania region, several previous studies have focused on the issue of macroseismic intensity attenuation in Italy. Whereas all authors acknowledge that regional variations are present in the attenuation pattern in Italy, most of these relations are generally valid for the entire Italian region.

Relations between recorded ground motion and intensity have previously been derived both based on global datasets and for limited regions. Most of these relations give ground motion as a function of intensity and cannot be inverted in a straightforward way. However, some of the more recent publications focus on deriving intensity as a function of recorded ground motion (e.g. Atkinson and Sonley, 2000; Kaka and Atkinson, 2004; Faccioli and Cauzzi, 2006; Atkinson and Kaka, 2007) and can serve as a reference for this study.

In this study we derive local intensity attenuation and conversion relations for the three regions. The attenuation models take into account the finite extent of the fault plane and represent site intensities as a function of fault distance, event depth and moment magnitude. It is aimed at deriving simple, physically based relations which are easy to implement for the user. For the Vrancea region, the anisotropic intensity attenuation is accounted for. We base our relations on available macroseismic information for previous earthquakes in the regions.

2. METHODOLOGY

We derive attenuation relations based on the attenuation model of Sørensen et al. (in review) which is a physically based relation with the following form:

$$I = cM_W + d\log(h) + e - a\log\sqrt{\frac{R^2+h^2}{h^2}} - b\left(\sqrt{R^2+h^2} - h\right) \tag{2.1}$$

The first three terms represent the epicentral intensity as a function of moment magnitude (M_w) and hypocenter depth (h), the fourth and fifth terms represent geometrical spreading (having its main effect at short distances) and energy absorption (most significant at larger distances), respectively. In order to account for the finite dimensions of the fault, R was defined as the Joyner-Boore distance, i.e. the shortest distance to the surface projection of the fault plane. For each specific region, this model may be modified to fit the attenuation characteristics of the region, as will be described in the results section.

Input data for the regression is a collection of intensity data points (IDP) describing the intensity at a given location. To avoid bias due to variation in the number of observations for different intensity classes, a weighting scheme has been applied where each intensity class (integer intensity level) has been assigned the same weight in the regression, regardless of the number of observations within the class. Therefore, the determination of the regression parameters a, b, …, e leads to the weighted least squares problem

$$\min_x \left\| W^{-1}(I - Ax) \right\| \tag{2.2}$$

where $I=(I_i)$, i=1,…,n, is a vector of n IDP, A is an (n×5) design matrix, W is an (n×n) weighting matrix with only diagonal entries, and x=(c, d, e, -a, -b) is the parameter vector to be estimated. The values of the diagonal elements of W are chosen in such a way that (1) they are equal for all data in one intensity class and (2) the sum of squared inverse weights is equal for all intensity classes (classes are identically weighted).

For the peak ground motion vs. intensity (PGMI) relations, we follow the approach generally agreed on in the literature and search for linear relations between log(PGA) or log(PGV) and intensity. Due to the limited number of data available, we keep the relations as simple as possible and do not include terms dependent on distance and magnitude which would not be well constrained by the current dataset. We thereby seek relations of the form (where PGM is either PGA or PGV):

$$I = a\log(PGM) + b \tag{2.3}$$

A general property of datasets relating peak ground motion and intensity is a great spread in the observed data, which is also present in our dataset. Such variation may lead to poor estimates of the highest and lowest intensities as the intermediate intensities, where most data are available, have a much greater weight in the regression. To overcome such problems some authors (e.g. Atkinson and Sonley, 2000) perform the regressions on the mean values of log(PGM). We choose to study this issue in more detail and derive four relations for each ground motion parameter based on 1) the raw data entering the regression with equal weight, 2) a weighted regression where each intensity class is given the same weight in the regression, 3) a regression on the average values of PGM for each intensity level (average is calculated before taking the logarithm) and 4) a regression on the average value of log(PGM). All four approaches can be justified and in this respect, such analysis gives us information about the uncertainties related to the properties of the dataset.

3. DATA

We have collected datasets of macroseismic intensity for the three study areas based on various sources. A general problem when working with macroseismic intensity data is that intensities are assigned relative to various scales and with, in certain cases, a considerable amount of personal judgment. The personal judgment has generally a much greater impact on the assigned intensity than the use of the different 12-degrees scales (Musson et al., 2006). It is attempted to overcome this problem with the introduction of the European Macroseismic Scale (EMS-98, Grünthal, 1998), which provides detailed guidelines for the assignment of macroseismic intensities taking into account building vulnerability. The EMS-98 scale has been in use since it was first introduced as an update to the MSK-64 scale in 1993. The EMS-98 was developed to avoid at all costs that conversions between MSK-64 and MM intensities have to be applied. In this study, we follow Musson et al. (2006) and can therefore assume that the three intensity scales are consistent in the here used intensity range.

3.1. Marmara Sea region

The macroseismic intensity data available for the Marmara Sea region consist of a number of isoseismal maps for selected large earthquakes. Most of these are collected by Eydogan et al. (1991) in terms of Modified Mercalli Intensity (MMI), covering the time interval 1900-1988. In addition, an isoseismal map for the 1999 Izmit earthquake is available from Özmen (2000). We include data for earthquakes in the Marmara Sea region (26-31E, 39.5-41.5N), for which a minimum of four intensity levels are available as isoseismal contours, in total 7 events in the time period 1912-1999.

In order to perform the regression for attenuation of macroseismic intensity, the isoseismal maps were digitized. Following digitization, it has been chosen to convert the isoseismal lines into IDP by covering the map area by a fine grid (2 km grid spacing). Each grid point was assigned the intensity value of the contour containing the point. Grid points outside the intensity contours of the isoseismal map were not included in the study. The final dataset consists of 124311 IDP covering the intensity range 5-10, the magnitude range M_w=5.9-7.4 and a distance range of 0-335 km. These values represent also the limitations of the derived attenuation relation as it cannot be assumed that simple extrapolation outside these bounds will be successful.

For the PGMI relation we use ground motion parameters extracted from the European Strong-Motion Database (ESD). Combined strong-motion and intensity information is available for the 1983 Biga earthquake and the 1999 Izmit earthquake. In total, we have 32 PGA-I pairs and 31 PGV-I pairs for earthquakes in the Marmara Sea region.

3.2. Vrancea region

For the Vrancea region, the attenuation relation has been derived from a dataset covering the latest five large earthquakes with macroseismic data available in the region. For each earthquake, macroseismic intensity maps provided by the University of Karlsruhe (K.-P. Bonjer, personal communication, 2007) have been digitized, in total 4058 intensity data points are available for the five earthquakes. The final dataset covers the region between 20.5-30.7°E and 41.7-48.4°N. The studied events have magnitudes in the range M_w=6.4-7.7 and depths in the range h=79-150 km. IDPs are at distances R=0-500 km from the surface projection of the fault planes.

Ground motion information has been taken either from the ESD or from stations run by the National Institute for Earth Physics (NIEP) in Bucharest and the University of Karlsruhe as part of the Collaborative Research Center (CRC) 461 "Strong Earthquakes: A Challenge for Geoscience and Civil Engineering" (http://www-sfb461.physik.uni-karlsruhe.de/). For the latter, most PGA and PGV readings have been provided by NIEP (B. Grecu, personal communication, May 2007) and for a few remaining stations, the peak acceleration values have been read directly from the recorded waveforms. Our combined dataset for the Vrancea region consists of 46 PGA-I pairs and 30 PGV-I pairs.

3.3. Campania region

As input to our analysis for the Campania region, we have extracted macroseismic intensity data from the DBMI04 database (Stucchi et al., 2007). As our main focus is on the city of Naples, we have included only events which are felt here with I=6 or more and have a minimum of 30 IDP. Only events occurring in the

Appenninic belt or at shorter distance to Naples are included to avoid influence of different tectonic environments. These criteria lead to the selection of 9 earthquakes. When extracting data from the DBMI04 database, only IDPs which have been assigned a numerical intensity value have been included, leaving out events classified as, for example, "felt". Points which have been assigned an intensity value covering two intensity classes (e.g. 7-8) were given the intermediate half-integer value (e.g. 7-8 was given the value 7.5 etc). It should be noted here, that this practice is generally not recommendable (see e.g. Grünthal (1998) for details), but we find it necessary as intensities must be entered as numerical values in the regression and excluding the 'double-intensity' points would lead to a significant reduction of the dataset. The final dataset consists of 2945 IDP covering the intensity range 3-11 at distances of 0-660 km for earthquakes in the magnitude range M_w=6.3-7.0 at depths between h=6.3-15.6 km.

In the Campania region, the only earthquake with both recordings and macroseismic information available is the 1980 Irpinia event. For this event, information about PGA and PGV has been extracted from the ESD. In total we have 21 PGA-I and PGV-I pairs for the Irpinia earthquake.

4. RESULTS

4.1. Attenuation relations

In the following, the obtained attenuation relations which are based on Eqn. 2.1 and modified to fit the attenuation characteristics of each individual region are presented. Examples of the ability of each relation to fit the observed data are presented in Figure 1.

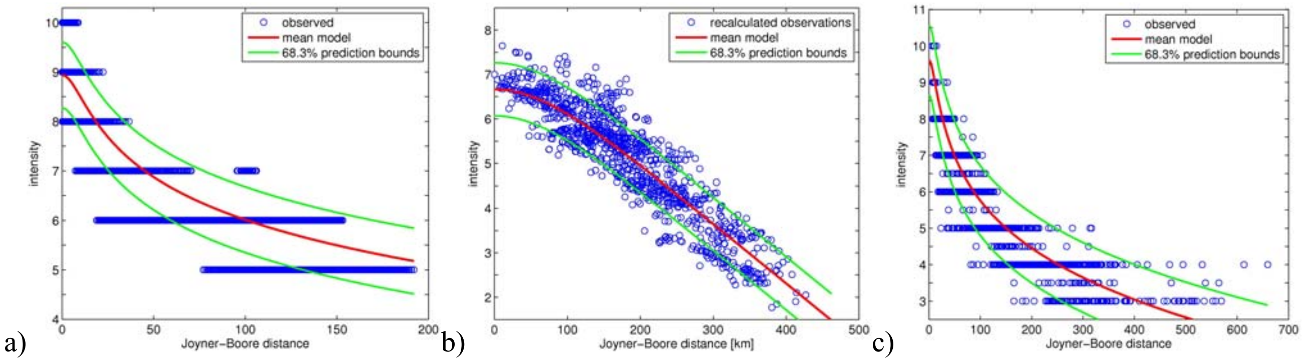

Figure 1 Comparison of observed intensities to the attenuation relations derived in this study and their 68.3% prediction bounds for a) the 1999 Izmit earthquake (Marmara Sea region), b) the 1986 Vrancea earthquake (here the observations have been corrected for the site term) and c) the 1980 Irpinia earthquake (Campania region)

4.1.1 Marmara Sea region

For the Marmara Sea region, the depth variation among the individual events is small, and as the event depths are furthermore associated with significant uncertainty, it was chosen to exclude the d·log(h)-expression in the source term from the regression model to keep the problem as simple as possible. This in practice means that an average depth effect on the epicentral intensity is included in the constant term e.

The following attenuation relation for macroseismic intensity in the Marmara Sea region was obtained with a regression error σ=0.651:

$$I = 0.58M_W + 4.58 - 2.82\log\sqrt{\frac{R^2+h^2}{h^2}} - 0.0002\left(\sqrt{R^2+h^2} - h\right). \qquad (4.1)$$

4.1.2 Vrancea region

The anisotropic intensity distribution poses challenges in the establishment of an attenuation relation for the Vrancea region. In order to account for the anisotropy in a way which is easy for the user to implement, we include a site-correction term in the attenuation relation. Including the correction term, we obtain the following relation:

$$I = 2.06M_W - 5.88\log(h) + 4.58 - 1.84\log\sqrt{\frac{R^2+h^2}{h^2}} - 0.012\left(\sqrt{R^2+h^2} - h\right) + 0.14M_W dI\ . \quad (4.2)$$

Here, the site correction fucnction dI is a spatial function of longitude λ and latitude θ, combining five anisotropic two-dimensional Gaussian-distributed functions:

$$dI(\lambda,\theta) = \sum_{j=1}^{5} p_{6,j} \exp\left(-\left[p_{3,j}(\lambda - p_{1,j})^2 + 2p_{5,j}(\lambda - p_{1,j})(\theta - p_{2,j}) + p_{4,j}(\theta - p_{2,j})^2\right]\right). \quad (4.3)$$

The coefficients $p_{i,j}$ are listed in Table 4.1.

Table 4.1 Parameters for site correction function (Eqn. 4.3)

	j=1	j=2	j=3	j=4	j=5
i=1	25.057	23.097	26.007	30.000	27.099
i=2	46.636	44.449	43.049	45.068	45.639
i=3	0.273	0.234	0.227	0.469	0.543
i=4	0.564	1.348	0.685	1.856	0.618
i=5	0.180	0.466	-0.038	-0.899	-0.486
i=6	-1.602	1.989	-1.917	1.029	1.157

Applying this relation, a new intensity estimate can be made with an error of 0.6 intensity units. As it is illustrated in Figure 2, the shape of the intensity distribution is well reproduced by the relation.

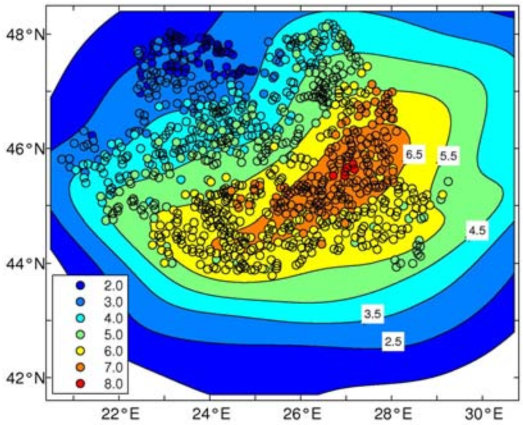

Figure 2 Map view comparison of observed intensities from the 1986 Vrancea earthquake (circles) to intensities predicted using Eqn. 4.2 (contours).

4.1.3 Campania region

For the Campania region, the following relation lead to the best fit of the observed intensities:

$$I_S = 1.13M_W - 3.09\log(h) + 4.89 - 3.83\log\sqrt{\frac{R^2+h^2}{h^2}} - 1.13\cdot 10^{-3}\left(\sqrt{R^2+h^2} - h\right). \quad (4.4)$$

The mean regression error for the relation is 0.955, which is also approximately the expected error in a new intensity estimate using the relation. This uncertainty reflects to a great extent the large spread in the input data. As it can be seen in Figure 1, the average trend of the data is well fit.

4.2. PGM vs. intensity relations

The PGMI relations obtained with different weighting schemes for the three regions of interest, including mean regression errors, are listed in Table 4.2 and presented in Figure 3.

In Figure 3 we see that the different weighting schemes lead to significantly different relations between peak ground motion and intensity. The mean regression errors are generally lower for the regressions based on average values, which is as expected as these regressions are performed for fewer data points, and outliers may cancel each other due to the averaging. The weighted regression solutions seem to represent an average of the derived solutions and the 68% prediction bounds have been included for these relations. All other relations fall within these prediction bounds which again illustrates that the variation between the different relations is a measure of the limitations in our dataset. Based on our relations we can predict the intensity with an uncertainty of ca. one intensity unit in all three studied regions.

Table 2 PGMI relations for the three regions of interest. MRE: mean regression error

Region	Weighting	PGA relation	MRE	PGV relation	MRE
Marmara Sea	Raw data	I=3.20·log(PGA)+6.33	0.8062	I=3.23·log(PGV)+9.37	0.8267
	Weighted data	I=3.62·log(PGA)+6.51	0.8062	I=4.00·log(PGV)+10.18	0.8267
	Average	I=4.52·log(PGA)+6.38	0.4469	I=5.14·log(PGV)+11.08	0.7068
	Log average	I=4.29·log(PGA)+6.51	0.4859	I=5.04·log(PGV)+11.15	0.6245
Vrancea	Raw data	I=1.76·log(PGA)+6.56	0.6726	I=2.10·log(PGV)+8.42	0.5359
	Weighted data	I=2.76·log(PGA)+6.63	0.6726	I=2.33·log(PGV)+8.58	0.5359
	Average	I=4.48·log(PGA)+6.55	0.3572	I=2.84·log(PGV)+8.93	0.3587
	Log average	I=4.24·log(PGA)+6.70	0.3748	I=2.77·log(PGV)+8.97	0.3398
Campania	Raw data	I=1.07·log(PGA)+6.40	0.7259	I=0.97·log(PGV)+7.29	0.7087
	Weighted data	I=1.35·log(PGA)+6.43	0.7259	I=1.26·log(PGV)+7.62	0.7087
	Average	I=2:39·log(PGA)+6.45	0.5802	I=2.31·log(PGV)+8.57	0.4562
	Log average	I=1:98·log(PGA)+6:51	0.7318	I=2.02·log(PGV)+8.44	0.5977

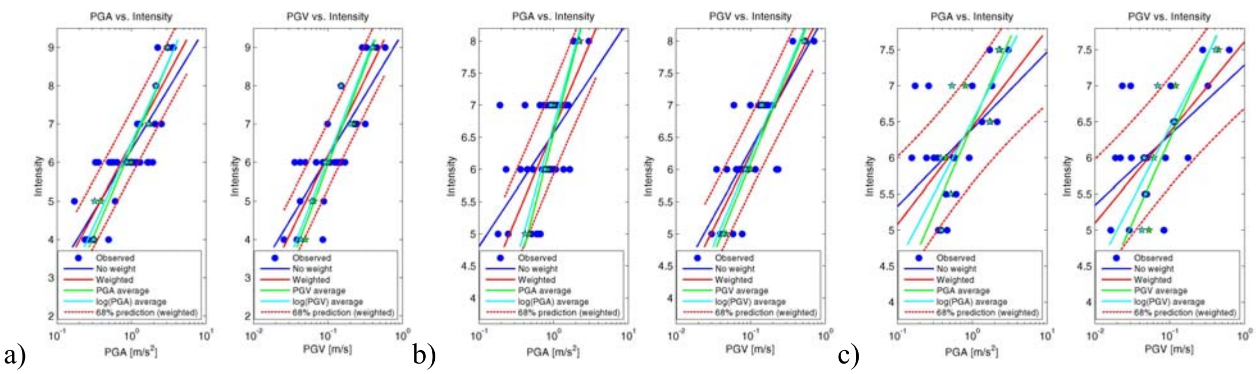

Figure 3 PGMI relations derived applying different weighting schemes for a) the Marmara Sea region, b) the Vrancea region and c) the Campania region.

5. CONCLUSIONS

In the present study we have derived attenuation relations for macroseismic intensity and relations between peak ground motions and intensity for three European regions of high seismicity; the Marmara Sea region, the Vrancea region and the Campania region. The available datasets and variations in tectonic setting and attenuation properties have required the application of different functional relations for the attenuation.

The derived attenuation relations are based on physical considerations and it has been aimed at deriving relations which are as easy to implement for the user as possible. The uncertainties related to intensity predictions from the derived relations are of the order of one intensity level. This uncertainty reflects the large spread which is generally characteristic of macroseismic intensity observations due to their independence of local geological conditions and the significant amount of subjective judgement involved in assigning the intensities. Their main strengths of easy accessibility, long reporting history and direct relation to damage, however, proves the strong advantages of using intensity estimates as a measure of severity of earthquake shaking.

We find that the derived relations provide an important supplement to the existing relations for the three studies regions due to their regional character, physical basis and user friendly representations.

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