Calibration of Crustal Historical Earthquakes from Intra-Carpathian Region of Romania

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Abstract. The main task of the presented study is to elaborate a set of relations of mutual conversion macroseismic intensity - magnitude, necessary for the calibration of the historical crustal earthquakes produced in the Intra-Carpathian region of Romania, as a prerequisite for homogenization of the parametric catalogue of Romanian earthquakes. To achieve the goal, we selected a set of earthquakes for which we have quality macroseismic data and the Mw moment magnitude obtained instrumentally. These seismic events were used to determine the relations between the Mw and the peak/epicentral intensity, the isoseist surface area for I=3, I=4 and I=5: Mw = f (Imax / Io), Mw = f (Imax / Io, h), Mw = f (A3, A4; A5). We investigated several variants of such relationships and combinations, taking into account that the macroseismic data necessary for the re-evaluation of historical earthquakes in the investigated region are available in several forms. Thus, a number of investigations provided various information resulted after revising initial historical data: 1) Intensity data point (IDP) assimilated or not with the epicentre intensity after analysis of the correlation level with recent seismicity data and / or active tectonics / seismotectonics, 2) Sets of intensities obtained in several localities (IDPs) with variable values having maxims that can be considered equal to epicentral intensity (Io), 3) Sets of intensities obtained in several localities (IDPs) but without obvious maximum values, assimilable with the epicentral intensity, 4) maps with isoseismals, 5) Information on the areas in which the investigated earthquake was felt or the area of perceptiveness (e.g. I = 3 EMS during the day and I = 4 EMS at night) or the surfaces corresponding to a certain degree of well-defined intensity. The obtained relationships were validated using a set of earthquakes with instrumental source parameters (localization, depth, Mw). These relationships lead to redundant results meaningful in the process of estimating the quality and credibility of the primary data used (e.g. IDPs, isoseismals) and in the correct determination of Mw.

1. Introduction

Parametric catalogues of earthquakes represent one of the most important products of the Seismology. These are compilations that have two different components depending on the methods and techniques of observation, recording and processing of the primary data that ensure the estimation of focal parameters of the recorded earthquakes. So there is a historical macroseismic component and an instrumental one. The first component is unique, its focal parameters being determined solely from data obtained through direct observation on the effects of earthquakes they produced on people, environment and engineering construction (macroseismic data). The second component has its focal parameters computed on instrumental and sometimes macroseismic data basis. The instrumental
component of Romanian Parametric Earthquakes Catalogue, Romplus by [1] has two parts. The first one is between 1879 and 1990 and is characterized by macroseismic focal parameters during the first decades of the period and instrumental focal parameters after the 1930's [2]. Part two begins after 1990, along with installing the digital stations [1 and 2]. Since magnitude is a key factor in any analysis which is based on data of earthquakes and seismicity catalogues must ensure a high level of homogeneity in terms of this parameter. Being estimated by methods, algorithms and techniques which are very different, from the macroseismic to those instrumental ones, modern relationships are needed for magnitude homogenization. This can be done efficiently using a calibrated set of instrumental data for moment magnitude, Mw and combinations of relational parameters such as maximum observed intensity or intensity in the epicentre, different degree of isoseismal area, perception area. We prefer the moment magnitude Mw because it can be a real measure of the earthquakes being derived from seismic moment Mo as a physical parameter of the seismic source in the focal volume [3].

The main task of the presented study is to elaborate a set of relations of mutual conversion macroseismic intensity-magnitude, necessary for the macroseismic magnitude calibration of the historical crustal earthquakes produced in the Intra-Carpathian region of Romania, as a prerequisite for homogenization of the parametric catalogue of Romanian earthquakes. To achieve the goal, we selected a set of earthquakes for which we have quality macroseismic data and the Mw moment magnitude obtained instrumentally (calibration events). These seismic events were used to determine the coefficients of the Mw=f(Imax/Io), Mw=f(Imax/Io, h), Mw=f(A3, A4; A5) relations, between the Mw and the epicentral intensity, the isoseist area with intensity I=3, respectively I=4 and I=5 degree on European Macroseismic Scale, (EMS). We have determined several variants and combinations of their relationships as the macroseismic data, necessary for the re-evaluation of historical earthquakes in the investigated region, are available in several forms: 1) Intensity data point (IDP) assimilated or not with the epicentre intensity after analysis of the correlation level with recent seismicity data and/or active tectonics and seismotectonic features, 2) Sets of intensities obtained in several localities (IDPs) with variable values having maxims that can be considered equal to epicentral intensity (Io), 3) Sets of intensities obtained in several localities (IDPs) but without obvious maximum values, to be assimilated with the epicentral intensity, 4) maps with isoseistes, 5) Information on the areas in which the investigated earthquake was felt or the area of perceptiveness (e.g. I=3 EMS during the day and I=4 EMS at night) or the surfaces corresponding to a certain degree of well-defined intensity. The obtained relationships were validated using a set of earthquakes with instrumental source parameters (localization, depth, Mw). Then, they were tested on crustal modern earthquakes occurred in other neighbouring regions.

2. Data and methods

The macroseismic data used in the paper were collected from the NIEP archive (Timisoara Seismological Observatory) and from the literature (e.g. [4-9]). These refer to earthquakes with focal parameters obtained from instrumental data (location, depth, Mw). Two sets of data were selected, one for calibration of the macroseismic data conversion relationships at Mw (h=3-20 km, Mw=3.0-5.7, Io=3.5-8 EMS) and one for checking and validating the results (h=3-40 km, Mw=2.9-6.8, Io=3.5-9 EMS). Both of them have a well distributed macroseismic field. Several earthquakes occurred in neighboring regions have also been used to test the applicability of relationships obtained for earthquakes produced in cross-border areas. Selected data sets are shown in figure 1.

In order to determine the conversion relationships, it was taken into account that macroseismic data collected from historical documents or taken from the literature are presented in various forms. Thus, there are intensity data obtained: 1) in a single location (Ii or IDP-intensity data point), 2) in several locations, and there are clues related to maximal or epicentral intensity (Io). On the other hand, there are situations when there is information about the surface on which the earthquake was felt or rays of
the isoseismals of certain degree of intensity, and sometimes the focal depths is known or can be determined.

Conversion relationships of macroseismic data to Mw have been developed so that all these data can be used with maximum use regardless of their presentation form.

**Figure 1.** Map of Romania and neighbouring areas. Dashed black line delineates the study region. Epicentres of calibration and test earthquakes are shown as red circle-white squares and blue diamonds, respectively

### 2.1. Calibration

#### 2.1.1. Macroseismic intensity method (MIM)

The method uses relations like \( Mw = f(\frac{Io}{Imax}) \) in which Io is the epicenter intensity, and Imax is the maximum observed intensity and does not always correspond to Io. This method is the most common in the compilation of earthquake catalogs. More elaborate forms also introduce focal depth if it was determined on the basis of high quality and resolution data (great number of ID, very good azimuthal covering, instrumental attenuation characteristics, etc.). We applied the technique of orthogonal regression and the minimization of the residual squares on a data set consisting of 35 standard calibration earthquakes and obtained the following relations:

\[
Mw = 0.53Io(±0.03) + 1.2(±0.20)\log h + 0.11(±0.26) \quad N=35, R^2=0.930 \quad (1)
\]

\[
Mw = 0.004(±0.03)Io^2 + 0.56(±0.38)Io + 0.96(±1.16) \quad N=35, R^2=0.872 \quad (2)
\]

\[
Mw = 0.61(±0.004)Io + 0.82(±0.26) \quad N=35, R^2=0.870 \quad (3)
\]
2.1.2. Isoseismal areas method (IAM)

The method uses relations like $M_w = f \left( \frac{R_i}{A_i} \right)$, where $R_i$ is the isoseist radius of the degree of intensity "i" and $A_i$ is the surface area corresponding to a degree of intensity "i" (the area closed by the isoseist of degree "i").
Figure 3. Calibration earthquakes. Left: estimated magnitude Mw. Red line is the best fitting of the data; dashed green lines are the 95% prediction interval of regressions. Middle: histogram and fitted normal probability density function (red line) of the magnitude residuals, Mw (O-C); σMw = equivalent error of magnitude. Right: example of the performance of IAM method for the events of calibration dataset (estimated magnitudes are compared with instrumentally determined magnitudes Mw); red line is one-to-one relation, Mw instrumental = Mw estimated. From top to bottom the graphics correspond to the equations 4, 5 and 6. In each panel, the left figure, middle histogram and the right figure belong together.

Often, only the area of surface where the earthquake was felt or area of perceptiveness or a combination between the isoseist area and epicenter intensity is used. Although the isoseists drawing is not standardized and is influenced by the analyst's subjectivity, the method is more robust as the isoseists mediate and incorporate a large number of observations, the macroseismic field irregularities due to the local effects and the source directivity, the anisotropy of the macroseismic attenuation, the dispersion of the observation points due to the demographic configuration of the investigated area. We obtained the following relationships that could be used to Mw conversion of this kind of macroseismic data:
\[ M_w = 1.294(\pm 0.378) + 0.787(\pm 0.082)\log A_3 \quad N=18, \quad R^2=0.850 \quad (4) \]

\[ M_w = 1.583 (\pm 0.294) + 0.801 (\pm 0.072)\log A_4 \quad N=21, \quad R^2=0.848 \quad (5) \]

\[ M_w = 1.855 (\pm 0.219) + 0.846 (\pm 0.062)\log A_5 \quad N=23, \quad R^2=0.890 \quad (6) \]

where A3, A4 and A5 are the surface areas to a degree of intensity 3, 4 and 5 on EMS scale, \( R^2 \) is the correlation coefficient and N, the number of data.

The statistical parameters of the regressions are displayed in figure 2 and figure 3. It can be noted that the 95% prediction band comprises all events, except for an insignificant number. The correlation coefficients are strong (\( R^2 > 0.85 \)), characteristic for pattern from which they will depart very few exceptions. The deviations are small in average (peak values of residuals, “rms” histograms are between -0.3 and 0.3), with the highest values (up to ±0.4-0.5) for a few events with \( M_w < 4.0 \).

2.2 Validation

We used 45 events to test and validate the new relationships obtained in this work. In figure 4 are presented some diagrams showing the correlation between \( M_w \) instrumental and \( M_w \) computed and their residuals (\( M_w (O - C) \)). Only 9 earthquakes have enough good quality macroseismic data to test and validate the relations 4, 5 and 6, respectively (Figure 4, bottom). Some of them are located in other nearby regions (e.g. Pannonian Depression, South Carpathians, Bulgaria, extra-Carpathian region; see Figure 1). The correlation coefficients are strong (\( R^2 > 0.84 \)), characteristic for pattern from which they will depart very few exceptions. The deviations are larger than those in the case of calibration events. It can be noted more peak values of residuals histograms that range from -0.5 up to 0.3. Finally, all statistical parameters support that these new relationships can be used successfully in the study region and those in their neighbourhood.

3. Results and discussions

We applied two methods to develop a set of available relations useful to convert macroseismic data to moment magnitude, \( M_w \): 1) Macroseismic intensity method that uses intensity data points, IDPs (MIM) and 2) Isoseismal areas method based on surfaces areas covered by isoseists of different intensity degrees measured on European Macroseismic Scale (IAM).

The relationships have been obtained by orthogonal regression analysis using a high quality instrumental and macroseismic data (35 calibration events and 45 testing and validation events). We preferred this technique because it assumes more realistic that all parameters (Io, Ai, M and h) have errors and so the results are more easily analysed critically. Moreover, the relationships are reversible.

Our relationships could be considered valuable and scientifically robust because 1) the data sets comprise a minimum of 20 entries; 2) the correlation between the parameters is greater than 85 % and 3) equivalent errors of magnitude are smaller than 0.5 magnitude units (the limit of precision which the practitioner knows well).

From the analysis of the results (Figures 2, 3 and 4) we have seen that the assessment of the moment magnitude, \( M_w \) is very good in almost cases and for the whole magnitude, depth and intensity range. However, we can note that some relationships (equations number 1, 2 and 3) slightly underestimate \( M_w \) for larger magnitudes and conversely they slightly overestimate \( M_w \) for smaller magnitudes (up to ±0.3 magnitude units). In the case of relationships 4, 5 and 6 these deviations have maximum values of ±0.5-0.6 magnitude units.
Figure 4. Validation and test earthquakes. Top: estimated magnitudes (eq. 1, 2 and 3) for a set of 45 validation events with instrumental Mw. Red lines are one-to-one relation, Mw instrumental=Mw estimated. $R^2$ is the correlation coefficient. Middle: histogram of the magnitude residuals, Mw (O-C); $\sigma_{Mw}$ = equivalent magnitude errors. Bottom: estimated magnitudes using eq. 4, 5 and 6 for 9 validation and test earthquakes.
The values of the most significant statistical parameters range mostly between acceptable to very good values, e.g., \(-0.5 \leq \text{rms} \leq 0.5\) and \(R^2 = 0.85 - 0.95\) for the correlation coefficient, respectively (average rms is the equivalent error of magnitude). These values and the 95% prediction interval of regressions show that extremely few data deviate from the average and also support the high degree of confidence in the estimates made by the new relationships. The range of validity of equations number 1 to 6 is \(2.9 \leq M \leq 6.8\).

The relationships we obtained in this paper are strong and unique firstly by their instrumental and high quality macroseismic support. Then, by applying orthogonal regression we have a simultaneous visualization of all input data errors in what is available to estimate seismic hazard. Used together, these relationships lead to redundant results, but nonetheless are valuable in assessing the quality and credibility of macroseismic data used for calibration of historical earthquake (e.g., IDs, isoseistes). Therefore, they ensure correct estimation of the moment magnitude \(M_w\) from macroseismic data.

4. Conclusions
We have developed a set of empirical relationships, robust from a mathematical point of view, to allow the estimation of historical earthquakes moment magnitude, \(M_w\) on different types of macroseismic data basis. The significance criterion (e.g., correlation coefficient \(R^2 > 0.85\)) supports the high quality intensity-\(M_w\) conversions and thus the efficiency and reliability of applying them in estimating the magnitude from macroseismic data. Considering the equivalent error \(\sigma_{M_w} = 0.14 - 0.36\) it is also obvious that our relationships are a new generation that fit very well the data.

The conversion results for earthquakes outside the region studied are very good, too (figure 4, bottom). Thus, our new relationships can be also used in a broader territory, particularly in cross-border areas of Romania where many significant earthquakes occurred [1, 6, 9].

They will constitute an analytical tool to successfully homogenization of the Romanian Parametric Earthquakes Catalogue, Romplus (compiled by [1] and updated continuously, on www.infp.ro), as the necessary condition to mitigate the differences between its instrumental and macroseismic components regarding of the magnitude. Through homogenization based on our relationships the Romanian catalogue for crustal earthquakes will be complete and consistent for a much longer time back in history. Furthermore, by applying our relationships will be possible to estimate uncertainty of the computed magnitude. This facility offers a valuable statistical basis for interpretation of the results obtained from studies based on this catalogue.

Acknowledgment(s)
This paper was carried out within Nucleu, Program no.1635, supported by ANCSI, Project PN 16 35 01 05. Data used in the present study were provided by the National Institute for Earth Physics (Romania) and processed within the National Data Centre in Magurele. We are grateful to Ms. E. Toro (retired seismologist) for the rich material provided macroseismic data for developing this work.

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