Calibration and Validation of MEEP Method for Location and Magnitude Estimation of Historical Earthquakes from Intra-Carpathian Region of Romania

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Abstract. Intra-Carpathian Region of Romania experienced strong earthquakes as it is mentioned in the national and international databases, e.g. November 26, 1829 (Ms=6.4), October 10, 1834 (Ms=6.3), January 26, 1916 (Ms=6.4), July 12, 1991 (Mw=5.7). The paper focuses on calibration and validation of MEEP method (Macroseismic Estimation of Earthquake Parameters, Musson & Jimenez, 2008) to provide a homogeneous and repeatable procedure for processing intensity data points (IDPs) which may supply the location and magnitude Mw of historical earthquakes occurred in the Intra-Carpathian Region of Romania and surroundings. The MEEP method is based on 1) grid-search technique for locating the epicentres and 2) the felt area approach to estimate the magnitude. It has the advantage to be used for small and moderate events. We used two high-quality datasets of earthquakes of the 20th century for which macroseismic data points (IDPs), instrumental moment magnitude (Mw) and instrumental epicentral coordinates are available, one for calibration and the other one for validation of the method. The main parameters used through MEEP algorithm were calibrated at regional scale using high-quality instrumental data: 1) crustal attenuation Q=435 (Q at f=3 Hz, which is understood to be the limit of the human perception of seismic waves), 2) Kövesligethy’s inelastic attenuation (α = 0.0065), 3) isoseismic spacing coefficient (k = 3.1) and 4) C = 2015, a constant generally related to tectonic regime. The MEEP method was successfully tested for events occurred within extra-Carpathian regions and the Pannonian Basin.

1. Introduction

The catalogues of the earthquake are generally compilations with two major components, one historical or pre-instrumental (macroseismic) and the other one modern or instrumental. Due to the methods and techniques used to obtain and process the primary data (seismic movements and their effects on the ground surface) the earthquakes catalogues are heterogeneous especially in terms of magnitude. Along with obtaining high-quality macroseismic data and estimating the earthquake parameters by instrumental methods, conditions were created to calibrate the historical earthquakes and to ensure a good level of homogeneity of earthquakes catalogues (locations and moment magnitude, Mw). The macroseismic intensity is a measure of the earthquakes effects and their size (magnitude). The macroseismic field is simply described by epicentral or maximum intensity, intensity data points (IDPs) and their spatial distribution in a relationship with the magnitude and it can be used to parameterize historical earthquakes, assessing epicentre location, magnitude and depth. Generally,
two kinds of data and algorithms are available to this aim. In most cases, specific data are used that represents the epicentral / maximum intensity, isoseismic areas and/or perception area. These data are processed through regression techniques to convert macroseismic intensity in magnitude and to estimate the epicentres locations. The results obtained through these methods are very useful to homogenize the earthquake databases even if they can be relative and incomplete because of the low quality of primary data; e.g. single point intensity data that is not always the epicentral intensity, the isoseismic areas are uncertain or strongly affected by analyst subjectivism being collected most of the times from literature without their primary data (IDPs). For the Intra-Carpathian study region, [1] obtained recently a set of robust scientific relationships to estimate the moment magnitude, Mw, from macroseismic data using regression techniques. However, if there are available more IDPs for the same event, we can relate the macroseismic field to magnitude, seismic energy attenuation, focal depth and even site effects to estimate more realistically the hypocentre parameters (location and depth) and magnitude, including their uncertainties. Several methods have been developed to obtain focal parameters of historical earthquakes using IDPs (e.g. [2], [3] and references therein). Because of the crustal heterogeneity and its influence on seismic energy dissipation and absorption, all of these methods require regional calibration of the coefficients that define the attenuation law of macroseismic intensity as a function of epicentral/hypocentral distance.

The aim of our paper is to calibrate the MEEP (Macroseismic Estimation of Earthquake Parameters) method developed by [2] in order to complete and homogenize the Romanian earthquake catalogue (Romplus) compiled by [4] and continuously updated on www.infp.ro. We particularly refer to Intra-Carpathian Region of Romania, a region with small to moderate crustal seismicity that experienced many strong earthquakes (Mw ≥ 5.5) as it is mentioned by [4], e.g. August 4, 1444 (Mw = 6.0), November 19, 1523 (Mw = 5.9), November 26, 1829 (Mw = 6.2), January 26, 1916 (Ms = 6.4), July 12, 1991 (Mw = 5.6). MEEP method distinguishes two phases: 1) the epicentre and depth determination using a grid-search and residual minimisation technique and 2) the magnitude estimation following the felt area approach [2]. For a robust calibration of the method, we compiled two datasets of earthquakes of the 20th century for which intensity data points (IDPs), instrumental moment magnitude (Mw) and instrumental hypocentres are available. One set is used for calibration of the method and the other one is used for its validation and testing. We computed the main coefficients and parameters of the algorithm: crustal attenuation of seismic waves at f = 3.0 Hz (the limit of the human perception of seismic waves), Kovesligethy’s anelastic and isoseismal spacing coefficients, respectively. Finally, we successfully tested the method for crustal earthquakes occurred within extra-Carpathian regions and Pannonian Basin supporting thus its applicability in these regions.

### 2. Data and analysis

Intensity data points for 20 calibration and 46 validation earthquakes that we used in our study were collected from the National Institute for Earth Physics archive (NIEP - Timisoara Seismological Observatory), [17], seismological services from neighbouring countries (e.g. www.georisk.hu) and from literature (e.g. [5-16]) (see Figure 1). The macroseismic intensity of each IDP had been revised and then homogenized on EMS98 Macroseismic Scale criteria following the procedure developed and applied for the western part of Romania by [17]. All calibration earthquakes have an instrumental location, depth and magnitude Mw. Mw was computed using either spectral method, even for the earthquakes occurred at the beginning of the 20th century [18], or conversion from other instrumental magnitudes (ML, Ms, mb) using the relationships of [1] and [4]. We also used some events that have been parametrized using other modern methods to test the new parameters of MEEP algorithm.

The MEEP method was elaborated by [2] to be used in a consistent way and to produce homogeneous results across Europe. It was applied, along with other methods to compile the European SHARE-SHEEC Catalogue [16]. It appears to be stable even for small to moderate onshore and offshore events, and thus it is a good option for the study region that is characterized by a sparse small to
moderate seismicity and a specific geographic framework of cross-border regions. It is well known that in the cross-border regions the macroseismic data for historical earthquakes are often incomplete and heterogeneous because of inherent inconsistencies among different countries (e.g. lack of communications, various calendars, different kind of constructions, different macroseismic scales). The MEEP method combines several algorithms and uses IDPs with \( I > III \) EMS degrees, location and magnitudes being estimated on grid-search technique and felt area approach, respectively. The epicentre is determined by the residuals minimization approach. First, the centroid of the higher IDPs is computed as a starting point for grid search procedure that takes the Kovesligethy model to fit the IDP set:

\[
I = I_o - \left( k \log \frac{r}{r_o}\right) + k \propto \log(e - h)
\]

where \( r \) is the epicentral distance (km), \( I_o \) is intensity in the epicentre, \( h \) is the focal depth (km), \( e \) is Euler’s constant, \( k \) is a constant representing isoseismal spacing and \( \propto \) is an anelastic coefficient. The depth value is initially set to a user-provided value and then solved by optimisation at the end of the grid search. After getting the hypocentre parameters the magnitude is estimated on physical principles basis following the work of [19]. Thus, the radius of perceptibility is interpreted as measurable physical parameters such as shear-wave velocity and the dominant frequency at which weak earthquakes shaking is perceived by humans [19]:

\[
M = n \log \left( \frac{A}{\pi^2} \right) + \left( \frac{2m}{\pi^2 \omega^2} \right) \cdot A^{0.5} + C
\]

where \( n \) is geometrical spreading (considered to be 0.5), \( A \) is the felt area in km² and \( C \) is a scaling constant and:

\[
m = \frac{\pi f}{Q \beta}
\]

where \( f \) = frequency of earthquake motion at the limit of the felt area (usually \( f = 3 - 4 \) Hz), \( Q \) = the shear wave attenuation and \( \beta = \) shear wave velocity (3.5 km/s).

The depth is estimated before the magnitude calculation using the intensity radii and Kovesligethy’s approach. Given the epicentre and hypocentral distance, a joint optimisation on depth and theoretical \( I_o \) value is performed. The analyst has to set how much \( I_o \) exceeds the observed \( I_{max} \) [2]. Unfortunately, the method provides a depth value between 0 and 20 km what creates some shortcomings in the cases of deeper earthquakes, such as magnitude over- or underestimating seismotectonic erroneous interpretations.

The method allows supplying a measure of uncertainties, that although are not standard deviations, they derive from errors in the approach and it represents the lower limit of uncertainties (e.g. the location uncertainty is the distance for which the ratio of the worst RMS (root mean square) over the best one is 2 and the magnitude uncertainty is the interval for which the RMS doubles the best fit [2]).

2.1. Calibration

We determined the MEEP algorithm parameters (\( Q, \propto, k \) and \( C \)) using 829 IDPs gathered and revised for the 20 calibration earthquakes (Figure 1) that have instrumental source parameters (\( M_w = 3.4 - 5.6, h = 6 - 19.5 \) km, \( I_o = \) IV-VIII EMS degrees). The IDPs cover a wide range of intensity values (\( I_i = \) III-VIII EMS degrees).

Attenuation factor \( Q \) has been determined using broadband digital data from 305 selected local earthquakes ((\( M_w = 2.0 - 4.5, h = 1.1 - 27.1 \) km). They have been recorded between 2006 and 2016
by the 61 seismic stations (Figure 1 and Figure 2) belonging to 1) permanent network of NIEP, 2) temporary network developed within the framework of South Carpathian Project (SCP 2009 - 2011) and 3) seismological agencies from Hungary and Serbia included in the European networks (e.g., Geofon, www.gfz-potsdam.de). Anelastic attenuation \( Q(f) \) is assumed to be frequency dependent following the relation:

\[
Q = Q_0 f^n
\]  

(4)

where \( Q_0 \) is \( Q \) at \( f < 1.0 \) Hz (frequency independent), \( f \) is the frequency (in Hz) and \( n \) is a constant. We used Seisan free software package (codaq routine) to compute coda \( Q \) [20]. Single backscattered model and 30 seconds windows starting at the assumed coda waves onset at \( 2Ts \) (\( Ts \) is S wave time arrival) have been applied in our analysis. All selected seismograms were bandpass – filtered at eleven central frequencies (1.5 – 10 Hz). The acceptable threshold of the signal-noise ratio was chosen to be
S/N = 2.5. We obtained $Q_0 = 121 \pm 21$ and $n = 0.70 \pm 0.19$ with a distribution having normal fitting, unimodal but asymmetric (Figure 2-inset). The spatial distribution of $Q_0$ is presented in Figure 2. The larger values (smaller attenuation) are obtained at the stations located in the Apuseni Mountains area.

[17] computed the $\alpha$ coefficient for the western border of the study region: $\alpha = 0.0082$ in NW, $\alpha = 0.0071$ in the central-western area and $\alpha = 0.0051$ in SW, with the average value $\alpha = 0.0067 \pm 0.0012$.

In order to determine the best combination of $Q$, $\alpha$, $k$ and $C$ we used several $Q$ and $\alpha$ values (combination within standard deviation range of $Q_0$ and $n$). Applying a trial and error procedure we kept the values that fit the best observational data (minimum misfit) (Table 1). The quality of these parameters is reflected in the statistics presented in Figure 3 and Figure 4. Thus, the regression curve

| No | Q   | $\alpha$ | k   | C   | Source         |
|----|-----|----------|-----|-----|---------------|
| 1  | 435$^a$ | 0.0065  | 3.1 | 2.15 | This paper   |
| 2  | 625 | 0.0080   | 2.0 | 1.36 | [21]         |

$^a$ – $Q_3$ or Q for $f = 3.0$ Hz

Figure 2. Spatial distribution of $Q_0$. Black points are the earthquakes used to compute Q. Inset: $Q_0$ histogram
Figure 3. Magnitude Mw (left) and hypocentres residuals (right) computed for calibration earthquakes. Grey continuous line is $M_{\text{macroseismic}} = M_{\text{instrumental}}$. Regression equation $y=f(x)$ is presented along with its correlation coefficient.

between Mw instrumental and Mw macroseismic shows strong correlation coefficient, $R^2 = 0.94$ and $R^2 = 0.96$. Also, the location and depth residuals have mostly small values supporting the robustness of the regional calibrated method.

2.2. Validation

The coefficients and parameters obtained by calibration were used for determining the parameters of the validation and testing dataset. This dataset was compiled according to the same criteria as for the calibration dataset. We used 46 earthquakes (NIDP=1451, Mw = 2.9 – 6.8, Io = III 1/2 – IX EMS degrees, h = 3 - 35.5 km) with parameters obtained on instrumental basis (94%) or by [16] using other macroseismic methods (6%). They were used 1) to assess the performance of calibration by comparing the locations and magnitudes for all events with their original locations and Mw and also with locations and magnitudes computed using MEEP method but having parameters determined by [21] and 2) to test the applicability of the method in neighbouring regions as extra-Carpathian region of Romania and far to West in Pannonian Depression. The distribution of epicentres and IDPs are presented in Figure 1. The statistics of the results are shown in Figure 4 and Figure 5-left.

It is obvious the quality of the calibration method also confirmed by the high value of the correlation coefficient of the regression line Mw instrumental - Mw macroseismic ($R^2 = 0.96$) and small residuals for locations. Comparing the results of applying the MEEP method with the parameters obtained by us and those obtained by [21] for the Stable Continental Region (SCR), we found significant differences in the magnitude estimations. Thus, in the case of parameters obtained in this paper, Mw values are distributed along the Mw instrumental = Mw macroseismic regression line with small deviations ($\pm 0.5$ units of magnitude). For SCR parameters, we can note a systematic under-estimation of magnitude with up to one magnitude unit in the case of large magnitudes and also a large scatter of the estimated values in relation to the regression curve. Moreover, the efficiency of the MEEP method with SCR parameters is negative for earthquakes with Mw < 3.5.

In the case of test events located in extra-Carpathian regions (eastern Romania, Romania - Bulgaria
Figure 4. Magnitude Mw (left) and hypocentres residuals (right) computed for validation and testing earthquakes. Left: comparative distributions of Mw computed using the MEEP method with parameters obtained in our study and those computed for the Stable Continental Region (SCR) by [21]. Gray symbols are for testing events. For other symbols and equations see Figure 3.

and Romania - Hungary borders) (Figure 1), we obtained very good estimates for both, location and magnitude (Figure 4, left). Thus, for the Romanian event with ML = 5.7 (21.11.2014, h = 32 km, I_max = VI EMS degrees [6]) we calculated Mw = 5.9 and obtained a location with a difference of -4.5 km in latitude and -9.8 km in longitude. For the earthquake located in Bulgaria, with Mw = 6.8 (14.10.1892) we obtained Mw = 7.0 and a difference of 3.8 km in latitude and 5.9 km in longitude. For the earthquakes produced at Romania - Hungary border (1829, Mw = 5.6 and 1834, Mw = 6.5) we obtained locations with differences of 3.7 km, respectively 7.0 km in latitude and 0.9 km, respectively 5.0 km in longitude, and for magnitude the differences are 0.2 and respectively 0.1 units of magnitude.

We applied the method by reducing the number of IDPs for the same event in order to test its efficiency in the case of few macroseismic data. The results show that the method can be successfully used even in the case of one IDP by extending the interval in which I_o can vary until acceptable residuals for magnitude and location are obtained. The results can then be improved and stabilized by applying the relationships determined by [1] and knowing the local seismotectonics regime.

2.3. Depth estimation

We improved the depth estimation from macroseismic data using Blake’s relationship [22]:

\[ Io - I_i = k \log \left( \frac{D_i}{h} \right) \]  

where \( Io \) is epicentral intensity, \( I_i \) is the observed intensity in a particular location (IDP value), \( h \) is focal depth that will be estimated and \( k \) is a coefficient. We used \( k = 4.3 \pm 0.4 \) obtained by [5] and tested in our study on the two datasets of macroseismic data. The differences between instrumental and the macroseismic depths obtained with Blake’s method exceed 5 km only for 8% from the investigated events in comparison with 40% in the case of MEEP method (Figure 5, right). Thus, it is obvious the superiority of the Blake’s method used to estimate the depth of historical earthquakes as
Figure 5. Left: Magnitude residuals computed using MEEP method with parameters obtained in this paper and those determined by [21] for the Stable Continental Region (SCR). Right: Depth residuals computed through MEEP and Blake methods.

against MEEP method. For the test earthquakes from extra-Carpathian regions whose depths computed with the MEEP method are limited to a maximum of 20 km, we obtained, using Blake method, values comparable to instrumental values. For example, for the earthquake located in eastern part of Romania (21.11.2014, \( h = 32 \) km) we computed \( h_{\text{macroseismic}} = 39.0 \) km with a difference of 7 km beside the instrumental depth.

3. Results, discussions and conclusions

By determining the parameters and coefficients of the MEEP algorithm using high-quality macroseismic and instrumental data, we calibrated a robust scientific method that can be used in a homogeneous, transparent and repetitive manner for the reevaluation of the Romanian crustal historical earthquakes in order to complete and revise the Romplus Romanian catalog of earthquakes. To determine the depths of historical earthquakes, Blake's method was calibrated in this study as a variable alternative to the MEEP method.

The MEEP method has been validated on the basis of a dataset that meets the same conditions as those used for its calibration, the statistical indicators of the earthquake source parameters sustaining the quality of the calibration and the robustness of the method in the case of earthquakes produced in the intra-Carpathian area. We have also shown that the method can be successfully used in the reevaluation of historical crustal earthquakes produced in the eastern territories of the Carpathian-Pannonian Basin (Pannonian Depression, Intra-Carpathian Region of Romania, East European Platform, Getic Unit in Romania and Bulgaria).

We have demonstrated that the method can also be used successfully in the case of historical earthquakes for which there is a low number of IDPs or the macroseismic field is incompletely defined (e.g. in border areas with neighboring countries).

Our results draw attention to the use of the SHEEC-SHARE catalogue for completing and reviewing the Romanian earthquake catalogue. We support the idea of re-evaluating the crustal earthquake parameters in this catalogue that were obtained with the MEEP method because the parameters determined for SCR are not suitable for the territory of Romania. These parameters result in a significant underestimation of magnitude with negative impact in estimation of the seismic hazard and seismogenic potential of local sources.
Our results along with those obtained by [1] have a great importance for the homogenization process of the historical component of Romanian earthquakes catalogue, Romplus.

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