Attenuation of Macroseismic Intensity for Crustal Romanian Earthquakes: Calibrating the Bakun-Wentworth's Method

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Abstract. The purpose of the present study is to elaborate a new model of the macroseismic intensity attenuation using all observed intensities data for the crustal earthquakes in Romania and then, based on this relationship, to calibrate the Bakun-Wentworth method, one of the modern methods most used to estimate the parameters of the historical earthquakes (localization, moment magnitude - Mw). The study is based on 14 calibrating earthquakes (4.5 ≤ Mw ≤ 5.7, 811 IDPs, II ≤ I ≤ VIII⁰ EMS) and 7 validation earthquakes (3.5 ≤ Mw ≤ 5.4, 215 IDPs, II ≤ I ≤ VIII⁰ EMS) produced mainly in western part of Romania and for which the reported macroseismic intensities were revised in a homogeneous manner and their locations and moment magnitudes were instrumentally determined. The method was tested using earthquakes produced in neighbouring regions, expanding its application space for earthquakes produced, for example, in the extra-Carpathian areas and Pannonian Depression. The comparative analysis with the results obtained with other methods confirms the high performance and the scientific rigour of the new attenuation relationship and of the Bakun-Wentworth method and their effective applicability for testing and validation of the results obtained in the process of the Romanian earthquakes catalogue revision.

1. Introduction
Earthquake catalogues represent the most important product of seismology being of fundamental importance in seismotectonic studies, recent crustal deformation and seismic hazard. They invariably have two components, a historical one with parameters of estimated source based on macroseismic data and a modern one, built on instrumental data. The homogenization of earthquake catalogues depending on the magnitude and locations of the recorded seismic events was and is one of the main concerns of seismologists with the aim to obtaining high quality databases and covering time periods longer, comparable to the return periods of strong earthquakes that define hazard and seismic risk. This homogenization process first involves the calibration of historical earthquakes produced before the year 1900. In the last decades, several modern methods of setting up historical earthquakes have developed and applied. among them, the most used being the methods Boxer [1], Meep [2] and Bakun-Wentworth [3,4]. These methods require the development of models for attenuation of macroseismic intensity using.
high quality macroseismic data obtained for earthquakes whose source parameters (moment magnitude, localization, focal depth) were computed based on instrumental data.

Figure 1. Earthquakes epicenters used for calibration (red dots), validation blue triangle) and testing (brown diamond) and associated IDPs distribution.

The seismic hazard on Romanian territory is due to the crustal and intermediate depth earthquakes occurred in the Vrancea area. Historical crustal earthquakes produced in Romania prior to 1980, studied mainly on the basis of the macroseismic data, and which are the subject of our study, are grouped at the contact between the Pannonian Depression and the Carpathian Orogen, in the central area of the Southern Carpathians and in the Foreland of the Eastern Carpathians, in the immediate vicinity of the Vrancea area. Sporadically, such earthquakes are noted in the Transylvanian Basin and at the contact between the orogenic structures and the Eastern-European and Moesian Platforms (Figure 1). The maximum observed intensity is Imax = IX° EMS and it was noted in the case of Mw = 6.4 earthquake, produced on October 15, 1834, north of Oradea, at the border between Romania and Hungary, [5]. The most recent revision of the parameters of the Romanian historical crustal earthquakes was made within the international project Share [6] and [7, 8]. However, the parameters obtained by [6] must be revised because they were obtained on the basis of regional calibrated relationships without considering the strong influence of local attenuation factors as shown [9, 10]. On the other hand, [7] only revised earthquakes in the West and South-West of Romania. Recently, [9, 10] have calibrated instrumentaly, using a large number of reference earthquakes and observation data 1) direct conversion relationships of epicentre intensity or isoseismic areas at the moment magnitude, Mw and 2) Meep's method [2], one of the most effective methods of setting up historical earthquakes based on macroseismic data (epicentre intensity, Io, intensities data points, IDPs) and instrumentals (coefficient of crustal attenuation, Q, locations, focal depth, moment magnitude, Mw, attenuation relationships). The revision of the Romplus earthquake catalog [11] is currently underway in two NIEP projects, for the crustal earthquakes applying the results from [9, 10, 12].
In this paper, we have proposed to calibrate the Bakun and Wentworth Method (BWM from now on), using an attenuation of macroseismic intensity model determined for the tectonic and structural conditions of Romania. This method uses all available intensity data (intensity data points, IDPs), rather than the subjective isoseismal lines to determine epicenter locations, equivalent moment magnitude and the associated uncertainties and it that have been applied in many other regions (e.g. [13] and references therein). Once calibrated, the BWM can be used as an alternative method for reviewing the parameters of the Romanian historical crustal earthquakes and / or as a method of validating the results obtained with other methods. It has the advantage that the results obtained are functions of probability which sustain the analyst's intervention to optimize the final solution, the most credible in a wider geoinformational context given by the knowledge of the active geological structures, the crustal deformations and the historical and recent seismicity. Moreover, its applicability is tested for a small number of observation data or an incomplete azimuth covering with macroseismic observation data, especially in adjacent areas but with similar geotectonic peculiarities (e.g. Pannonian Depression zone or the Moesian Platform depressions and surrounding areas).

2. Data and analysis

In order to ensure a homogeneous dataset, we selected the calibration and validation earthquakes produced after the year 1900, including all available IDPs (IPD ≥ M0 EMS) from the databases developed by [7, 8, 9, 10], based on the studies developed by [14-27] and references therein. The dataset has been completed with information from the literature or some international agencies databases (e.g. www. isc.uk). Instrumental data for calibration and validation historical earthquakes are those obtained by [12].

The BWM allows the analysis of the macroseismic intensities collected for an earthquake on the basis of which the location of the source as a macroseismic epicenter or intensity centre, IC is determined and the macroseismic magnitude or magnitude of the intensity, MI, equivalent to the moment magnitude Mw (Mw estimated or MwI) is estimated. In the first step of the procedure the attenuation model, that expresses the relationship between the values of individual intensity (IDPs), the moment magnitude and the hypocentral distance between each IDP and the instrumental epicenter. The relationship that defines this model is presented typically in the following form:

\[ I_{ij} = C_0 + C_1 M_{Wj} + C_2 D_{ihj} + C_3 \log D_{ihj} \]  

(1)

where \( M_{Wj} \) is the instrumental moment magnitude of the earthquake \( j \) ( \( j = 1 \ldots n \) earthquakes), \( I_{ij} \) is the observed intensity value for an earthquake \( j \) in the point \( i \), and \( D_{ihj} \) is the hypocentral distance, in km, of the location \( i \) (event \( j \)) and \( D_0 = \sqrt{D_i^2 + h^2} \) for each IDP (\( D_i \) is the epicentral distance, \( h \) is the focal depth). The coefficients \( C_0 \) and \( C_1 \) highlight the link between magnitude and intensities \( I \), \( C_2 \) describes intrinsic attenuation or absorption and \( C_3 \) the geometric one. By inverting the model, we determine the magnitude of \( MI_{ij} \) in each observation point and for each earthquake \( j \), as follows:

\[ MI_{ij} = \frac{1}{C_1} [I_{ij} - C_0 - C_3 D_{ihj} - C_2 \log D_{ihj}] \]  

(2)

Applying this method requires the computing of the attenuation relationship coefficients using calibration and validation earthquakes for which: 1) there are very good quality macroseismic observations (IDPs), revised in a homogeneous manner on the same intensity scale (here European Macroseismic Scale, EMS98) azimuthally distributed as completely as possible around the epicenter, 2) IDPs cover a wide range of intensities, 3) moment magnitude, Mw is well constrained instrumental and 4) locations and focal depths are robust, based on instrumental data. In the second step of the BMW procedure, the location and magnitude of each earthquake \( j \) are estimated by calculating \( MI_{ij} \) in hypothetical epicenters \( x_i \) arranged in a grid-type network, the \( MI \) magnitude of each earthquake being the average of \( MI_{ij} \) magnitudes. Then, we compute the average root mean square rms(M^2_i) for each
hypothesised Ii-epicentre pair using a weights system defined according to the distance [3]. For each earthquake the rms(Mi) outlines the epicenter area, [3] associating the values of these contours with probabilistic confidence levels of 50%, 67%, 80%, 90% and 95% statistically equivalent to rms(Mi) variations of not more than \( \pm 1 \sigma \), respectively \( \pm 2 \sigma \) (\( \sigma \) = standard deviation). The intensity center (IC) for the \( j \) earthquake is the hypothetical epicenter \( x_k \) for which the rms(Mi) is minimal, it represents more the centroid moment than the epicenter [28] and can be realistically adjusted within the level of confidence in which is depending on the tectonic characteristics. The IC selection is optimized by the bootstrap procedure. The earthquake magnitude \( M_w \) is equal to the magnitude of the IC intensity center with quantified uncertainty according to the level of statistical confidence and the number of IDPs (details in [3,4]).

3. Results and discussions

3.1. The attenuation model

To calibrate the relationship (1) we used the mean values of the hypocentral distances obtained from 14 calibration earthquakes with instrumental constraint source parameters (1038 IDPs, 4.8 \( \leq M_w \leq 5.7 \), \( I_i = \text{II-VIII} \) EMS). The results, validated and tested with the observations of 408 IDPs obtained from 12 validation earthquakes (4.0 \( \leq M_w \leq 6.4 \), \( I_i = \text{II-VIII} \) EMS) of which, 416 IDPs from 3 test earthquakes (5.7 \( \leq M_w \leq 6.4 \), \( I_i = \text{II-VIII} \) EMS) (Figure 1). The attenuation model determined on the basis of calibration earthquakes is defined by the relationship:

\[
I_i = 1.940 (\pm 1.04) + 1.961 (\pm 0.17)Mw + 0.004(\pm 0.003)D_{ih} - 4.576logD_{ih}
\]  

(3)

with \( R^2 = 0.927, \sigma = 0.385 \). The magnitude calculated in points \( i \) will be:

\[
M_{it} = [I_i - (1.940 + 0.004D_{ih} - 4.576logD_{ih})]/1.961
\]  

(4)

To obtain an unaltered calibration of incomplete data at low intensities we only use values \( I_i > I_{\text{min}} + 1 \) or \( I_i > I_{\text{min}} + 1.5 \). The relationship obtained for modeling the attenuation is represented graphically, for exemplification, using 3 reference events (Figure 2), three validation events (Figure 3) and three test events (Figure 4). We notice in Figures 2 and 3 that our attenuation model is robust, with a very good fit between the observation data (\( I_i \)) and those estimated by relation (3) regardless of the number of IDPs and the earthquake magnitude. Also, as noted by [7], the IDPs azimuth does not significantly affect the estimated intensities values, the residues being equal to zero and the regression mean slope of the between residues \( I_i \) and azimuth, calculated for the reference and validation earthquakes has very low values \( (0.00034 \pm 0.00099) \) (e.g. Figure 2, bottom). However, there can be noticed differences between the observed intensities and those estimated with the relation (3) at low values of the intensities due to the very small number of observations which negatively influence the calculated average values of the hypocentral distances (e.g. Figure 3b - events of 23.11.2006, \( M_w = 4.5 \) and 16.01.1916, \( M_w = 6.4 \); Figure 4b - events of 15.08.1985, \( M_w = 5.3 \) and 21.11.2014, \( M_w = 5.7 \)). The regression line slope, slightly different to zero, from the residual graph \( I_i \) versus the hypocentral distance (Figure 4c) shows that local effects, source directivity and/or misalignment of the observed intensities (observer's subjectivity, land conditions with unpopulated or slightly populated areas) may be the main causes of variance of residues by distance. The regression coefficient roughly equal to zero and the positive \( I_i \); residues for \( D_{ih} > 75 \) km support the idea of overshooting of the intensities due to local effects, the more so as the attenuation model we have obtained has been shown above to be very robust. There is a high degree of correlation between the observed values intensities and magnitudes and those computed with relations (3) and (4), respectively \( R^2 = 0.7 \) and \( R^2 = 0.9 \), the deviations from the \( I_{\text{ESTIM}} = I_{\text{OBS}} \) and \( M_{w_{\text{estimated}}} = M_{w_{\text{instrumental}}} \) curves being very small, respectively \( \sigma_{I_{\text{M}}} = 0.5 \) degrees of intensity at extreme intensity values and \( \sigma_{M_{w_{\text{M}}} = 0.15 \) magnitude units at small magnitude values (Figure 3d).
The analysis of three test earthquakes located and felt on large areas of the Pannonian Depression and the extra-Carpathian Area (Focsani and Getica Depressions and the East European and Moesian Platforms) shows the compatibility of the attenuation model with the morphostructural conditions specific to these regions (Figure 4) and thus the applicability of relations (3) and (4) for reviewing the historical earthquakes produced and recorded in these territories is argued. We have also successfully tested the applicability of the relationship for magnitude estimation in case of a low number of IDP (N = 14, earthquake on 29.11.1988, Mw = 4.2, Io = V° EMS). The relationship (4) can be used together with the relationships developed by [10] and if we have a single point of observation, if it is located in the epicentre area of a strong earthquake (observation associated with a aftershock) or in an area with recent known tectonics and seismicity (clusters, focal mechanisms).

**Figure 2.** Examples of three calibration earthquakes used to develop the attenuation model. a) The IDPs distributions for earthquakes from 02.04.1901, Mw= 5.3 (IDPs from [18] and [7]), 12.07.1991, Mw=5.6 and 02.12.1991, Mw=5.5 ([7]); red stars are instrumental epicenters. b) Intensity vs hypocentral distance plots and attenuation curve for the three events (black dashed lines). c) Ii residuals vs azimuth of IDPs.
Figure 3. Examples of three validation earthquakes. **a**) the IDPs distributions and the attenuation curves for the validation earthquakes on 29.11.1988, Mw=4.2 (IDPs from [7], 23.11.2006, Mw=4.5 (IDPs from [26], Mw after [19], and 02.12.1991, Mw=5.5 (after [7]); red stars are instrumental epicenters. **b**) Intensity vs hypocentral distance scatter plots and attenuation curve for the three events (black dashed lines). **c**) Ii residuals vs Mw, hypocentral distance and observed intensities; red lines are least-squares linear fits; black dashed lines are regressions for Dh>75 km. **d**) Ii and average MwI estimated with the relationships (3) and (4) for the calibration and validation earthquakes compared with those observed and instrumental ones, respectively.
3.2. Location and magnitude $M_{W_I}$ estimation

With the attenuation model (3), we followed the BWM procedure to determine the locations (IC) and their corresponding magnitudes ($M_{W_I}$) for the calibration and validation earthquakes, to verify the method capability to obtaining source parameters comparable to the instrumental ones. We used the method for a test earthquake to check its applicability in surrounding regions, with similar (depressions, thinning crust) or different (platforms) morpho-structural peculiarities. For this, we used the computing program applied by the Neries project partners [30]. In Table 1 and Figure 5 are presented the results of the method application to a calibration (02.04.1901, $Io = VII^0_{OSMS}$, $M_{W_I} = 5.3$), calibration (29.11.1988, $Io = VI^0_{OSMS}$, $M_{W_I} = 4.2$) and test (Oct 14, 1892, $Io = VIII^0_{OSMS}$, $M_{W_I} = 6.5$) earthquakes.

It can be observed that all IC locations, both, instrumental and macroseismic, determined with the MEEP method of [2], recently calibrated by [10], are in the confidence zone of 50%, at very low distances between them. The moment magnitudes are also comparable (Table 1) which proves the scientific rigor of the new attenuation model, reflecting also the validity and credibility of the results obtained in this study. In the case of strong earthquakes ($M_{W_I} > 5.0$) it can be noted an apparent elongation of the confidence intervals of residues in a direction parallel to the active tectonic as possible effect of the source directivity, the obvious effect in the epicentral area where the stronger movements are generated by sliding on the fault near the centroid moment [28]. To determine the foci depth, the Blake method, instrumentally calibrated, will be used [10].

Figure 4. Examples of test earthquakes. a) IDPs distributions and attenuation curves for test earthquakes 14.10.1892, $M_{W_I}=6.5$ $Io=VIII^0_{OSMS}$, 4.2 (IDPs from [27], $M_{W_I}$ after [6]), 15.08.1985, $M_{W_I}=5.3$ (IDPs from [17, $M_{W_I}$ after [29]) and 21.11.2014, $Io=VI^0_{OSMS}$, $M_{W_I}=5.5$ (after [15]). b) Intensity vs hypocentral distance scatter plots and attenuation curve (black dashed lines) for the three events.
Table 1. The results of BWM application for test earthquakes represented in Figure 5.

|             | Instrumental data location | Mw      | Meep location | Meep Mw  | BWM location | BWM Mw  |
|-------------|----------------------------|---------|---------------|----------|--------------|---------|
| 02.04.1901  | 45.513/20.638              | 5.3     | 45.482/20.640 | 5.5 ± 0.1 | 45.590/20.700 | 5.39 ± 0.03<sup>a</sup> |
| 29.11.1988  | 45.675/21.585              | 4.2     | 45.660/21.579 | 4.2 ± 0.4 | 45.625/21.580 | 4.3 ± 0.1<sup>b</sup> |
| 14.10.1892<sup>*</sup> | -                          | -       | 43.714/26.845 | 7.3 ± 0.1 | 43.669/27.024 | 6.6 ± 0.4<sup>a</sup> |

<sup>a</sup> average Mw<sub>I</sub> using all IDPs; <sup>b</sup> range of magnitude following the confidence parameters criteria [Bakun1999];<br> <sup>*</sup> magnitude after [31] is between 6.0 and 7.0.

Figure 5. BWM application: location and Mw<sub>I</sub> determination for calibration (02.04.1901), validation (29.11.1988) and test (14.10.1892) earthquakes and comparing results with instrumental and macroseismic data obtained with the Meep calibrated method [10]. Tectonic after [32].

4. Conclusions
We calibrated instrumental, using high-quality data, the attenuation relationship of macroseismic intensity with distance and moment magnitude for the Romanian crustal earthquakes. The relationship was validated based on a data set that fulfilled the same quality conditions as calibration. The method was used to test the Bakun-Wentworth method of historical earthquakes parameterization using macroseismic data. Our results show that the method can be used in a transparent, homogenous and
repetitive manner for the historical earthquakes re-evaluation, produced throughout the Carpathian - Panonic Basin, including wider, neighbouring, extra-Carpathian regions, being a viable, rigorous scientific alternative for the MEEP method used to revise the Romanian earthquake catalogue. The attenuation relationship can also be used only for magnitude estimation of the historical earthquakes for which there is a small number of macroseismic data being thus, useful and efficient for validating the results obtained with simple conversion relationships between intensity and magnitude, this new relationship introducing the characteristics of the crustal attenuation between the foci and the observation point.

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