Testing and Developing the Macroseismic Intensity Attenuation Relationships for the Vrancea (Romania) Crustal Earthquakes

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Abstract. A correct seismic hazard assessment and intensity-based shake maps of a seismic zone depend on the determination of parameters that emphasize the distribution and the macroseismic intensity attenuation for that seismogenic zone. Due to the reduced number of strong ground motion records, macroseismic intensity information available for previous earthquakes which have occurred in studied area were the only source of information utilized for developing attenuation relationship for that zone. The aim of this paper is to test the existing equations published for various crustal seismic sources and develop a new macroseismic intensity attenuation law for the Vrancea crustal seismic source. The Vrancea crustal seismogenic zone had experienced moderate earthquakes in the past with magnitudes which did not exceed 5.9 [1] and macroseismic maralps had been constructed by various authors for these earthquakes representing intensity pattern and decrease of this parameter with distance on different azimuths. Some of the selected attenuation laws were tested for different values of epicentral intensity and with reference to eight directions. The input data consist of macroseismic intensities collected for 4 small and moderate earthquakes (Mw ≥ 3.9) that had occurred during the last hundred years with epicentral/maximum intensity in the range IV to VI MSK degrees. The seismic events used to verify the attenuation laws were selected based on the magnitude and number of macroseismic observations collected for each event. Using this data, attenuation relationships of macroseismic intensity with distance will be tested and modified. The deduced attenuation equation might be used for rapid intensity assessment of the potential future earthquakes occurred in this seismic zone.

1. Introduction

The macroseismic intensity obtained by the quantification of the earthquakes’ effects, continues to represent an important parameter for seismological and seismic engineering researches, and also for the Governmental institutions and insurance companies in case of natural disasters (earthquakes). The macroseismic data are, furthermore, useful for developing the predictive equations of the macroseismic intensity for certain seismic areas, and also for comparing and correlating the intensities with strong ground motion parameters (i.e. PGA, PGV, PGD) [2]. To that effect, the intensity is included in the estimation of the future earthquake effects (damages being included here), and thus, at least on general matter, in the seismic risk study. However, in the last years, the macroseismic intensity attenuation is less studied, in comparison to the attenuation of maximum ground acceleration, due to the fact that PGA is used in engineering design. Moreover, knowing the macroseismic intensity
attenuation is important for the calibration of the seismic hazard models. As already known, a correct evaluation of the seismic hazard in a specific seismic area is strictly related to a close examination of the distribution parameters and also to the macroseismic intensity attenuation, for that certain seismogenic area.

Even though the literature on the ground motion attenuation is generous, the one referring to the intensity attenuation is lessened. The discrepancy can be explained relatively simple: the increase of the studies referring to the seismic hazard, with the purpose of obtaining the coefficients used in engineering design, lead to a higher request regarding the development of better and more confident equations which expresses the attenuation of the seismic parameters of ground motion, especially for the peak ground acceleration (PGA) [3]. Nowadays, the computed seismic hazard in intensity terms is less common, but it has its own advantages. For the cases where the purpose of the studies target the large public or the insurance companies, the importance of the hazard in intensity terms is easier to be understood, from the point of view of the effects on society, compared to the values of PGA. This is also emphasized by the fact that there is no straight correlation between the distribution of PGA and the earthquakes’ damages [4]. This fact might be an extra argument for the study of ground movement in terms of macroseismic intensity. Moreover, it is very useful to be able to estimate the intensity values (IDP) for a potential earthquake or for an earthquake that just happened. In the case of a significant earthquake, the information regarding the possible effects can be prepared in advance, based on the expected distribution effects after such a strong earthquake with similar magnitudes and epicenters.

Obtaining the distribution and attenuation relations for the macroseismic intensities of the normal depth shocks, is of high importance for the seismic hazard studies in these areas, being characterized by a moderate to high seismic potential, and for this reason it represents a special interest, both from theoretical but also practical point of view, being considered an efficient instrument in a correct configuration of seismic risk scenarios for these areas. From this point of view, obtaining the attenuation relations is important, and moreover, permanent updating of these relations for a correct estimation of the ground motion parameters for future events.

Considering the upper mentioned facts, the actual study has as main objective to accomplish a complex activity regarding the testing and developing of new attenuation relations of the macroseismic intensity for future Vrancea crustal earthquakes. To that end, in order to attain the proposed goal all the crustal seismic events for which macroseismic information exists, were taken into consideration, including the period before and at the beginning of instrumental seismology, the selection being made based on the events magnitudes and on the number of IDP’s. The data used in this study consists in values of macroseismic intensities obtained by the conversion of the earthquakes effects description, considering the prescriptions of the macroseismic intensity scale used in Romania.

As mentioned above, in most cases, the attenuation relations are obtained from the accelerations (PGA) and velocities (PGV) recorded by strong motion networks, but considering the fact that in Romania the first K2 stations have been installed after 1997, and the network is still not densely enough in the studied area and surroundings, thus we are obliged to continue using the intensity parameter in these type of studies, due to the fact that it offers information on long periods of space and time. The results are significant, since the ground motion parameters to be determined in this paper will be based also on information provided by recent Vrancea earthquakes. The parameters of the empirical macroseismic intensity attenuation relations, will be used for the computation, representation and visualization in the shortest time of the Shake Map map, in order to rapidly estimate the distribution of ground motion, immediately after the occurrence of Vrancea crustal earthquakes.
2. Vrancea seismic region
The Vrancea area is a complex region from seismic point of view, located at the intersection of 3 major plates: the East European Plate, the Intra-Alpine micro-plate and the Moesian micro-plate [5]. The triple junction of this plates is Vrancea area, characterized by active geodynamic conditions. This region is one of the most active in Europe, being very well known for the strong subcrustal earthquakes occurred here, with a frequency of 3-4 destructive earthquakes per Century (i.e. November 1940 and March 1977). Besides the subcrustal earthquakes, there is also an intra-plate active seismicity. The normal depth earthquakes are related to the Earth’s crust fractures, faults which differentiate crustal blocks more or less stable. The normal depth area is directioned towards East in regard to the intermediate depth area. In this area, the earthquakes are produces at small depths (h<60 km), at magnitudes intervals smaller than intermediate earthquakes (Mmax<5.9). Nevertheless, these earthquakes can cause significant damages (high intensities) in the localities surrounding the epicenter, due to the fact that they can be strongly felt in reduced regions due to the low depth of the foci [2], [6]. The last moderate earthquake occurred in this area was the event from 22.11.2014 (Ml=5.7), being felt in the extra-Carpathian area, up to Ukraine and Republic of Moldavia, South of Bulgaria and SE of Turkey. The earthquake had strong psychological effects on humans, but the building damage was reduced. Thus, the earthquake generated minor to moderate damages, such as small cracks in walls, fall of fragments of plaster in houses, and also large and extensive cracks in the walls of a few old buildings in the localities situated in the epicentral area, but also in the Eastern part. The damages included also cracks at some chimneys and ceilings. The maximum observed intensity was VI MSK.

3. The macroseismic data set
The data necessary for testing the attenuation laws were selected depending on magnitude and the number of collected macroseismic observations. A number of 4 seismic events were included in this study, which cover both the instrumental and pre-instrumental periods. The macroseismic information used are the IDPs collected for crustal earthquakes during 1908-2014 in Vrancea area, for which a sufficient number of information is available. The dataset contains also the observed intensities for smaller crustal events (3.9 <Mw <4.5), based on the number of available observations and due to lack of other higher events, the occurrence frequency of these events being known to be reduced in the crustal area [6]. The Vrancea crustal earthquake parameters for which the macroseismic information were used in this study are presented in Table 1. The used macroseismic intensities are given on MSK scale [7]. The dataset consists of a number of 802 IDPs. Figure 1 displays the distributions of the macroseismic intensities observed at crustal earthquakes.

| No. | Date       | Time (GMT) | h (km) | Coordinates       | Mw  | In/Imax (MSK) | No. IDP |
|-----|------------|------------|--------|-------------------|-----|---------------|---------|
| 1   | 13.03.1908 | 00:40:00   | 25     | 45.5 27.9         | 4.5 | V             | 22      |
| 2   | 30.04.2004 | 09:19:36   | 17     | 45.58 27.14       | 3.9 | IV            | 16      |
| 3   | 3.10.2004  | 09:02:02   | 7.6    | 45.18 28.94       | 4.1 | VI            | 84      |
| 4   | 22.11.2014 | 19:14:17   | 39     | 45.87 27.16       | 5.4 | VI            | 680     |

In figure 2 is presented the distribution of the observed macroseismic intensities for analyzed earthquakes vs. epicentral distance, moment magnitude respectively. Figure 3 shows the number of IDPs from dataset for each degree of intensity MSK, the epicentral distances, respectively.
**Figure 1.** IDPs distribution corresponding to Vrancea crustal earthquakes

**Figure 2.** Observed intensities distribution (a) and Mw (b) vs. epicentral distance, for the set of earthquakes

**Figure 3.** Histograms of the crustal earthquakes, with: a) the distribution of the number of IDPs vs. epicentral distances; b) number of IDPs corresponding to each macroseismic intensity degree
Figure 4. The difference between the epicentral intensity and the observed intensity in each point (DI) vs hypocentral distance for the macroseismic data corresponding to Vrancea crustal earthquakes

Figure 4 presents the pairs hypocentral distance - difference between intensities (DI=Io-Iobs) for the used dataset. It is obvious that the data spreading is high and that these distributions are not uniform, offering a less clear image of the macroseismic intensity attenuation with distance.

4. Attenuation laws
The severity of the soil movement in certain point located at distance from the seismic source, represents actually the intensity of the ground motion. The intensity of the ground movement associated to an earthquake, in a certain site, is governed by multiple factors, as follows: earthquake’s magnitude, the distance between the seismic source and the site where the intensity evaluation was done (hypocentral distance), the azimuth towards the fault’s direction (the fault plane), the geological condition of the propagation environment of the seismic perturbation, the local geological conditions and the topography. Normally, the movement intensity increases with the increase of earthquake’s magnitude, and decreases with the increase of the distance, although significant fluctuations might appear due to the geological inhomogeneities. Also, the seismic intensity attenuation depends on the epicentral intensity, the epicentral distance and the focal depth. Thus, the seismic intensity attenuation phenomena is very complicated and, of course, a complex study subject. One of the first macroseismic intensity attenuation relations was proposed at the beginning of the last century by Kövesligethy [8] and assumes that the seismic energy decreases due to the geometrical spreading and the absorption of the geophysical environment. In time, numerous attenuation relations were developed for most of the seismogenic areas of the world (i.e. SUA, Canada, Japan, Europe, Iran, India, Russia, Romania etc). In this study, a consistent set of attenuation relations were tested, obtained for Romanian earthquakes by romanian scientists ([9], [10], [11]) (see Table 2), but also many attenuation relations developed by a number of foreign authors for different crustal areas in the world (i.e. [12], [13], [14], [15] etc.) (see Table 3), using intensity data from earthquakes for which existed this type of information.

Table 2. The attenuation relations developed for Romanian crustal seismic zones and used for testing

| No. | Authors | Attenuation laws |
|-----|---------|-----------------|
| Eq1 | [9]     | \ln I = \ln I_o + a_1 - b_1 \ln D |
| Eq2 |         | \ln I = \ln I_o + a_2 - c_1 \ln D |
| Eq3 |         | I = I_o + a_3 - b_2 \ln D |
| Eq4 |         | I = I_o + a_4 - b_3 \ln D |
| Eq5 | [10], [11] | I = I_o + b_4 \ln D |
| Eq6 |         | \ln I = \ln I_o + a_5 - c_2 \ln D |
| Eq7 |         | \ln I = \ln I_o - c_3 \ln D |
| Eq8 |         | \ln I = \ln I_o - b_4 \ln D |

where: D = hypocentral distance, R = epicentral distance, I_o = epicentral intensity, I = site intensity
In the previously developed attenuation relations, the isoseismal maps were used, and not directly the IDPs of the analyzed events. The shape of the isoseisms is established by the scientist, thus introducing a higher degree of subjectivity in the obtained equations. This is one of the reasons for which, nowadays, it gave up to draw the isoseists for recent events. The main advantage of using direct IDPs is that the applied procedures are explicit, thus the results are reliable. For this reason, there were selected for testing in this study only earthquakes for which there are IDPs available. The computed intensity values were compared to those observed. The parameters of the attenuation relations from equations 1-8 can be found in the upper mentioned papers. These relations were obtained as function of the azimuth of the intensity data points towards North, which were separated in sectors from 45 to 45 degrees in a clockwise direction.

### Table 3. The attenuation relations proposed for different crustal areas in the world.

| No. | Authors | Attenuation laws |
|-----|---------|------------------|
| Eq9 | [16]    | $I = -1.9438 \ln(D) + 4.1 M_w - 9.5763$ |
| Eq10| [14] (Egypt) | $I = 0.86 \cdot M_w - 3.01 \cdot \log(h) + 5.33 - 1.9 \cdot \log \left( \frac{R^2 + h^2}{h^2} \right) - 0.0035 \cdot (\sqrt{R^2 + h^2} - h)$ |
| Eq11| [14] (Italy)  | $I = 1.13 \cdot M_w - 3.09 \cdot \log(h) + 4.89 \cdot 3.83 \cdot \log \left( \frac{R^2 + h^2}{h^2} \right) - 0.00113 \cdot (\sqrt{R^2 + h^2} - h)$ |
| Eq12| [14] (Turkey) | $I = 0.58 \cdot M_w + 4.58 - 2.82 \cdot \log \left( \frac{R^2 + h^2}{h^2} \right) - 0.0002 \cdot (\sqrt{R^2 + h^2} - h)$ |
| Eq13| [17]    | $I/I_o = \exp[-(0.8999/\hbar + 0.0014)A]$ |
| Eq14| [18]    | $I = I_o + 2.87 \cdot 0.0052 \cdot R \cdot 1.15 \cdot \ln(R)$ |
| Eq15| [19]    | $I = 1.2 \cdot M_w - 0.919 \log(h) + 0.93 - 2.6 \log \left( \frac{R^2 + h^2}{h^2} \right) - 0.006(\sqrt{R^2 + h^2} - h)$ |
| Eq16| [20]    | $I = 3.95 + 0.913 \cdot M_w - 1.107 \cdot \ln \left( R_{epi}^2 + (1 + 0.813 \cdot e(M_w - 5))^2 \right)$ |
| Eq17| [15]    | $I = 2.085 + 1.428 \cdot M_w - 1.402 \cdot \ln \left( R_{epi}^2 + (2.042 \cdot e(M_w - 5) - 0.209)^2 + 0.078 \cdot \ln \left( R_{hip}/50 \right) \right)$ |
| Eq18| [21]    | $I = 1.8125 - 0.003851 \cdot R - 2.6096 \cdot \log R + 1.4206 \cdot M_w$ |
| Eq19| [22]    | $I = 1.85265 \cdot M_w - 0.0092238 \cdot R_{hip} - 3 \cdot \log R_{hip} + 0.3096$ |
| Eq20| [23]    | $I = 1.5 \cdot M_w - 3.8 \cdot \log \left( \frac{R_{epi}^2 + h^2}{h^2} \right)$ |
| Eq21| [24]    | $I = 0.898 \cdot M_w + 1.215 - 1.809 \cdot \log_{10} \left( \frac{R_{epi}^2 + h^2}{h^2} \right) - 3.447 \cdot 10^{-3} \cdot (\sqrt{R_{epi}^2 + h^2} - h)$ |
| Eq22| [8]     | $I = I_o - 3 \cdot \log(R/h) - 1.340002 \cdot (R/h)$ |
| Eq23| [12]    | $I = I_o - 1.07865 \cdot \log(R/h) + 0.00414$ |
| Eq24| [13] (h=10km) | $I = I_o - 1.07853 \cdot \ln(R/h) - 0.00414 \cdot (R/h)$ |

where: $D =$ epicentral distance, $R =$ hypocentral distance, $I_o =$ epicentral intensity, $I =$ site intensity, $M_w =$ moment magnitude, $h =$ focal depth.
Figure 5. The residuals distribution with respect to observed intensities and hypocentral distance for crustal earthquakes (802 IDP), using (Eq1) [9]

From Figure 5 it can be observed that the (Eq1)[9] underestimates the higher observed intensities, the computed intensities tend to be smaller than those observed, specially at large hypocentral distances. When applying the Eq24 [13] on the same data set, it can be noted that this one fits quite well on earthquakes with h < 10 km. The relation from Eq10 [14], applied on the same dataset, underestimates the intensity values at epicentral distances lower that 90 km (Figure 6).

Figure 6. The residuals distribution with respect to observed intensities and hypocentral distance for crustal earthquakes (802 IDP), using Eq10 [14]

Using Eq22 [8], overestimated values at large epicentral distances were obtained. However, this relation was modified for Vrancea crustal earthquakes, by determining some new values of the $a$ and $b$ parameters from the equation: $I = I_0 - a \log(R/h) - b(R-h)$. Another relation tested on Vrancea crustal earthquakes was Eq23 [12] and slightly modified in this study (Figure 7). Also, Eq1 was modified after was tested on the observed data set (Table 4 and Figure 8).

Figure 7. The residuals distribution with respect to observed intensities and hypocentral distance for crustal earthquakes (802 IDP), using modified Eq23 [12]
Figure 8. The residuals distribution with respect to observed intensities and hypocentral distance for crustal earthquakes (802 IDP), using modified Eq1 [9]

Table 4. New parameters of the attenuation law (eq. 1)

| Azimuth | a   | b   | Azimuth | a   | b   |
|---------|-----|-----|---------|-----|-----|
| 0°      | 1.06| 0.288| 180°    | 1.43| 0.4 |
| 45°     | 1   | 0.31 | 225°    | 1.5 | 0.43|
| 90°     | 1.4 | 0.39 | 270°    | 1.25| 0.37|
| 135°    | 1.45| 0.41 | 315°    | 1.2 | 0.32|

Based on the attenuation relations from Eq1 [9] (Figure 9) and Eq22 [8] (Figure 10), and modified in this study, isoseismal maps were accomplished, associated to the biggest possible earthquake (worst scenario) for the Vrancea crustal zone. The selected parameters are: the epicenter coordinates: 45.9N, 27.2E; h=25km, Io=VIII MSK, Mw=6.

Figure 9. Intensity map for a possible seismic event with Mw=6 si Io=VIII MSK (modified Eq1 [9])

Figure 10. Intensity map for a possible seismic event with Mw=6 si Io=VIII MSK (modified Eq22 [8])

Using the same modified attenuation relations ([9] (Figure 11a) and [8] (Figure 11b)) intensity maps were accomplished, associated to a similar earthquake to the one from 2014. The selected parameters: the epicenter coordinates: 45.48N, 26.95E; h=40km, Io=VI MSK, Mw=5.4.
Figure 11. Intensity maps associated to an earthquake similar to the one from November 2014: a) Eq1 [9] and b) Eq22 [8] modified

5. Conclusions
This paper has sought to make an analysis regarding the quantitatively comparing between the observed and predicted macroseismic intensity for Vrancea crustal earthquakes. It was decided to accomplish the analysis for this type of earthquakes for some reasons: (i) the number of available IDP from Vrancea crustal earthquakes has increased from the time when some relations were obtained for this region; (ii) many IDP collected from a moderate (Mw 5.4) crustal earthquake that occurred in 2014 improved the distribution with respect to intensity and distance; and (iii) a number of new attenuation laws for crustal earthquakes have been published and, hence, can be compared to the observations.

In this study, 24 macroseismic intensity attenuation relations were verified on the Vrancea crustal earthquake dataset. The data used for testing the relations consists in a reduced number of small and moderate earthquakes (3.9< Mw <5.4) for which 802 IDP exists. The best relations gave quite small differences between the observed and computed data, for 90% of the intensity points, the errors being between -1.5 and +1.5 degrees. From all the tested relations, the one obtained by Pantea [8] for the Vrancea crustal earthquake fits better the observed intensities. This relation was proposed for 8 azimuths, with different parameters on each azimuth. It was found that most of the relations developed for other crustal zones tested perform poorly, which is mainly due to a larger variability in the observed macroseismic intensity, although a few relations derived using IDP from various zones provide reasonably good values. These relations with the best fit, meaning the Eq1 [9], Eq22 [8] and Eq23 [12], were slightly modified, through obtaining new values for their parameters.

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