Macroseismic Intensity Estimation from Instrumental Ground Motion Recordings in the Case of Small and Moderate Vrancea Subcrustal Earthquakes

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Abstract. Romania is one of the most seismic-prone countries in Europe due to the periodically occurrence of strong intermediate-depth earthquakes in Vrancea seismogenic zone. The Vrancea area is located beneath the South-Eastern Carpathian Arc bend, at the contact between the East - European plate and the Intra-Alpine and Moesian sub-plates. An intense seismic activity is recorded in the mantle, within a narrow, almost vertical descending volume between 60 and 180 km depth. Earthquakes with magnitudes larger than 5.0 (Mw) and macroseismic effects exceeding V MSK degrees on extended populated area occur in Vrancea seismic zone, with a return period of around 2 years. Besides the extended scientific studies, the near real time estimation of the macroseismic intensity recently became mandatory for the insurance companies to cover some of the losses and damages that earthquakes might cause to houses, belongings, and other buildings. The first approach to obtain intensity values was to develop an online environment for collecting people feedback regarding the effects of earthquakes and for the automatic approximation of the intensity. The automatic intensity estimation code from the online feedback proposed by [1], [2] and adopted by [3] for the Romanian earthquakes was improved and used for this study. Additionally, there were used prediction equations to obtain intensity values from the epicentral intensity, and epicentral and hypocentral distances. Besides the estimation of macroseismic intensities from online people feedback and from attenuation relations, equations for conversion of peak ground acceleration in macroseismic intensity were also required for a rapid evaluation of ground motion effects. In order to avoid the increase of the prediction uncertainties, the data must be selected in such a way that they represent the parameters’ rank for which the prediction will be accomplished and the selected data must be representative for the investigated regions and seismic source. In this paper were developed conversion methods from PGA to macroseismic intensity for moderate intermediate depths earthquakes with 4.5<Mw<6.0. All the studies were realised in the case of Vrancea recent (2014-2019) moderate intermediate depth earthquakes, felt on the extra-Carpathian region.

1. Introduction
In the last decade, many efforts were done to predict the macroseismic intensity in case of felt Vrancea earthquakes [4], [5], [6], [7] and additionally an online environment was developed for the automatic approximation of the intensity from peoples’ feedback [3]. Because “seismic intensity scale is
established based on the effects of seismic actions on humans and environment, on buildings and land crust”, the macroseismic intensity can be obtained from the response of the population to some specific questions that gives us opportunity to calculate the size of the seismic event in a given area [8]. The Intensity Scale is a measure that has been used from historical times, before first seismograph and the interrogation method of population is used on a global level and is the only way to find clear information from all areas. The online macroseismic questionnaire has been made in conformity with Romanian STAS [9], and follows strictly the descriptions of macroseismic intensity scale. The automate processing method is based on [10] and has been adapted for intermediate depth earthquakes. Population must be aware that this is no constrain, there are just a few minutes of volunteering for a more accurate map of intensity.

Besides the extended scientific studies, the near real time estimation of the macroseismic intensity recently became mandatory for the insurance companies to cover some of the losses and damages that earthquakes might cause to houses, belongings, and other structures. Due to the insurance companies’ requests, the macroseismic questionnaires method was doubled by the seismic intensity determination using instrumental data, as recommended in the Romanian Seismic Intensity Scale Standard (STAS 3684-71 [9]).

In our opinion, the questionnaire method is more useful, because acceleration/velocity/displacements values can be obtained only in seismic station sites and not from around the country, but the conversion method must not be neglected. In Romania, for instance the National Seismic Network has 147 accelerometers and 226 SP and BB seismometers functioning in 170 different locations (Figure 1), but there are 320 cities, 2900 towns and more than 13000 villages. Even if the ground motion parameters could provide a reliable intensity value, this is not enough to assure a good coverage of the country.

Figure 1. The National Romanian Seismic Network and the studied moderate intermediate depth Vrancea earthquakes

2. Macroseismic and seismic recordings database

All macroseismic responses for earthquakes that have occurred since 2014, after the November 2014, Marasesti crustal earthquake have been downloaded from the online system and IDPs’ were processed. During this period, there were 86 intermediate and crustal Romanian earthquakes [13], [14], with magnitudes 3.5<Mw<6, 46 of them inside Vrancea seismogenic zone, at intermediate depth, with almost 10,000 macroseismic responses.
The evolution in time of the responses is presented in Figure 2 and Table 1. It is seen that the interest of the people for involvement in the activity of collecting the macroseismic data has increased after 2016 when a strategic function was implemented in the application, i.e. the automat assignment of the macroseismic intensity in the respondent's location, and also the possibility of distributing the information on facebook. In this way an exponential distribution of the questionnaire link is made and the number of those who complete it increases.

![Answered questionnaires/earthquake](image)

**Figure 2.** Time distribution of earthquakes with macroseismic responses

**Table 1.** Time distribution of earthquakes with macroseismic responses

| Year | Answers | Mmax |
|------|---------|------|
| 2014 | 205     | 5.4  |
| 2015 | 460     | 4.3  |
| 2016 | 1413    | 5.6  |
| 2017 | 2797    | 5    |
| 2018 | 5070    | 5.8  |
| Total | 9945 | 5.8  |

For the present study were selected only the earthquakes that occurred in Vrancea seismogenic zone, at depth larger than 60Km. The total number of answers was 9945. Only nine earthquakes had more than 100 answers to the macroseismic questionaires, i.e a total number of 7445, from which 3048 intensity data points (IDPs’) were obtained (Table 2 and Figure 1). For these earthquakes, the information gathered online was processed by unifying the city name format and identifying the coordinates and calculating the intensity value associated with each locality, and then the macroseismic data obtained were mapped, thus making the macroseismic maps from Figures 3- 10.

**Table 2.** Earthquakes with 4.5<Mw<6 occurred in Vrancea intermediate depth seismogenic zone in the last 5 years

| Nr. crt | Date/Hour (GMT) | Lat.° N | Long.° E | h (km) | Mw | M<sub>L</sub> | I<sub>L</sub> (MSK) | I<sub>max</sub> | PGA max cm/s<sup>2</sup> | Nr. IDPs | Nr. PGAs |
|--------|----------------|---------|----------|--------|----|------------|----------------|--------------|----------------|----------|----------|
| Eq1    | 23.09.2016/23:11 | 45.7148 | 26.6181  | 92     | 5.5| 5.8        | VI             | VI           | 122.22          | 425      | 33       |
| Eq2    | 27.12.2016/23:20 | 45.7139 | 26.5987  | 96.9   | 5.6| 5.8        | VI             | VI           | 43.31           | 197      | 20       |
| Eq3    | 08.02.2017/15:08 | 45.4874 | 26.2849  | 123.2  | 4.8| 5          | V              | VI           | 9.69            | 623      | 19       |
| Eq4    | 19.05.2017/20:02 | 45.7228 | 26.7547  | 121.6  | 4.5| 4.7        | IV             | VI           | 4.93            | 239      | 90       |
| Eq5    | 01.08.2017/10:27 | 45.5357 | 26.4389  | 104.3  | 4.3| 4.7        | IV             | VI           | 6.13            | 107      | 89       |
| Eq6    | 02.08.2017/23:32 | 45.5286 | 26.4106  | 131    | 4.6| 5          | V              | VI           | 15.88           | 209      | 20       |
| Eq7    | 14.03.2018/10:24 | 45.6757 | 26.5877  | 136.9  | 4.2| 4.6        | IV             | VI           | 3.69            | 170      | 93       |
| Eq8    | 25.04.2018/17:15 | 45.6066 | 26.4319  | 147.6  | 4.1| 4.5        | III            | V            | 11.88           | 213      | 87       |
| Eq9    | 28.10.2018/00:38 | 45.6079 | 26.4068  | 147.8  | 5.5| 5.8        | VI             | VI©         | 67.69           | 865      | 50       |
| Total  |                  |         |          |        |    |            |                |              | 3048            | 501      |          |
In Figures 2-10 are presented the intensities and PGA’s for earthquakes Eq1, Eq2 and Eq9, all of them with $I_{\text{max}}>\text{IV}$.

**Figure 3.** IDP’s and PGA’s for Eq1 (Mw=5.5)

**Figure 4.** IDP’s and PGA’s for Eq2 (Mw=5.6)

**Figure 5.** IDP’s and PGA’s for Eq4 (Mw=4.5)
Figure 6. IDP’s and PGA’s for Eq5 (Mw=4.3)

Figure 7. IDP’s and PGA’s for Eq6 (Mw=4.6)

Figure 8. IDP’s and PGA’s for Eq7 (Mw=4.2)
The largest acceleration (122 cm/s\(^2\)) was recorded in Barlad, Vaslui county, Romania, at 89 km epicentral distance from Mw 5.5 September 24, 2016 earthquake (Eq1), and the largest reported MSK intensity was VI½ (Eq1, 2 and 9). Most of the maximum PGAs' from Table 1 were recorded in Barlad.

3. Conversion relations from peak ground acceleration to intensity values. Results and discussions

In this study, the conversion procedure from instrumental recordings (peak ground acceleration – PGA) to intensities is computed for moderate intermediate depths earthquakes with 4.5<Mw<6, from Table 1 and Figure 1, occurred on Vrancea zone, and felt on the extra-Carpathian area. We have obtained more than 250 pairs of PGA-IDP that have been used to compute the conversion relations, requested by the insurance companies in order to be able to honor the existing insurance policies. Unfortunately, in more than 100 localities were we had instrumental recordings, there have been reported only 44 macroseismic intensities. It is found that in more than 30 localities (out of 44 - over 80% of the data) the differences between reported and calculated intensity are below one degree. In half of the cases the differences are below 0.5 degrees. In just two cases the differences were more than two degrees in Tulcea (TL) and Stefanesti (AG), where unfortunately we only had one intensity report, which leads to a very low level of confidence in the information provided. In order to increase the number of macroseismic reports in the localities where there are seismic stations, a database of volunteers, willing to complete the macroseismic questionnaires, was started.
Figures 11 and 12 show the conversion relationships between PGA and I (MSK) for each station where we had information.

Figure 11. Conversion relations I (MSK) = f (PGA) for seismic station sites
Figure 12. Conversion relations \( I \) (MSK) = \( f \) (PGA) for seismic station sites

In Figures 13 and 14 are shown the conversion results for the whole data set of IDPs’ and PGAs’ pairs.
Figure 13. Correlation between the macroseismic intensity (MSK scale) and the maximum horizontal acceleration PGA (in cm / s²). With black circles are the observed data, and with red diamonds geometric mean (left) and arithmetic mean (right), for a given intensity unit. A) Regression made for geometric media. B) Regression made for arithmetic mean. σ represents the standard error of linear regression.

Figure 14. Correlation between the macroseismic intensity (MSK scale) and the maximum horizontal acceleration PGA (in cm / s²). Same symbols like in Figure 13

4. Conclusions
The main method of obtaining the values of macroseismic intensities is the interpretation of people online questionnaires. This is the only way to have real data about the movement of the soil due to earthquakes, in all inhabited areas. However, the number of reports is very small compared with the big number of people that lives in big cities, as there is no obligation to fill this form. For example, for Eq1, in Bacau, from Bacau County, where almost 750.000 inhabitants (of which 78% over 15 years old) we received only 18 completed macroseismic form, or even the case like Barlad, where large accelerations are recorded, we had 17 completed forms out of 50.000 inhabitants.

The quantitative study proposed by the present paper has its limitations. The most important one is due to the necessity of more monitoring equipment. Now, INCDFP has about 150 accelerometers installed in Romania, this number being much smaller than the number of existing localities on this territory. For this reason, the quantitative method can give us information only from accelerometer locations.
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