A PROCEDURE FOR ASSESSING SEISMIC HAZARD
GENERATED BY VRANCEA EARTHQUAKES
AND ITS APPLICATION. III. A METHOD FOR DEVELOPING
ISOSEISMAL AND ISOACCELERATION MAPS.
APPLICATIONS

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Abstract. A method for developing isoseismal and isoacceleration maps assumedly valid for future strong earthquakes ($M_{GR} > 6.7$) is described as constituting the third stage of a procedure for assessing the seismic hazard generated by Vrancea earthquakes. The method relies on the results of the former two stages (Enescu et al. [1-2], and on further elements that are presented in this paper. Moreover, it is based on instrument recording data.

Major earthquakes taking place in Vrancea (November 10, 1940 - $M_{GR} = 7.4$, March 4, 1977 - $M_{GR} = 7.2$ and the strongest possible) were examined as a way to test the method. The method is also applied for an earthquake of magnitude $M_{GR} = 6.7$. Given the successful results of the tests, the method can be used for predicting isoseismal and isoacceleration maps for future Vrancea earthquakes of various magnitudes $M_{GR} \geq 6.7$.

Key words: Vrancea earthquake, seismic hazard, isoseismal map; isoacceleration map.

INTRODUCTION

In two previous papers (Enescu et al. [1-2], we embarked on the difficult but crucial task of assessing the seismic hazard generated by Romanian earthquakes. It is a difficult task, as very scarce records are available concerning ground motion velocity or acceleration during major earthquakes in different areas of the country. It is a crucial task, as antiseismic building calculation and design make it imperative to know as many details on seismic hazard as can be possibly known.
As indicated in the earlier mentioned papers, seismic hazard studies have occasionally been conducted in Romania up to now. For various reasons, though, they have produced but scant, inadequate results. Those occasional studies mostly depended on the space distribution of macroseismic intensities – a quite subjective quantity. A few attempts have also been made at taking into account the very scarce acceleration and velocity records that have lately been obtained from Vrancea earthquakes. These attempts, however, yielded rather lackluster results.

We have therefore set off to develop and apply a seismic hazard assessment procedure that will make the most of our scarce records on strong/major Vrancea earthquakes. Following in the tracks of our two previous papers mentioned above, this third paper reflecting our enterprise presents a method for developing isoseismal and isoacceleration maps starting from instrument recording data.

2. METHOD FOR DEVELOPING ISOSEISMAL AND ISOACCELERATION MAPS.

A method for developing isoseismal and isoacceleration maps of the August 30, 1986 earthquake ($M_{GR} = 7.0; I_0 = 8.5$) and of the “etalon” earthquake was described in the first paper of this series (Enescu et al., [1]-Paper I). The “etalon” earthquake isoseismal and isoacceleration maps, chiefly based on the observation (recording) data concerning the August 30, 1986 earthquake, are shown in Figs. 1 and 2.

In another paper (Enescu et al. [2]-paper II), the “etalon” earthquake maps were used to plot attenuation curves for a large number of azimuths (30), so that the most peculiar shape of the Vrancea earthquake isolines should be represented as close to reality as possible. The attenuation curves were plotted in terms of both the epicentral distance, $D$, and hypocentral distance, $R$ (Figs. 3-14 in Paper II).

The family of attenuation curves for the “etalon” earthquake (Figs. 3-14 in Paper II) has the following equation:

$$\log \left( \frac{I_e}{I_{0e}} \right) Az = a(Az) - b(Az) \log \frac{R_e}{f(h_e)},$$

or

$$\log \left( \frac{I_e}{I_{0e}} \right) Az = a'(Az) - b(Az) \log R_e,$$

where: $I_{0e}$ is the maximum intensity of the “etalon” earthquake; $I_e$ is the intensity of the “etalon” earthquake at a hypocentral distance $R_e$ (along the direction defined by azimuth $Az$);

$$a' (Az) = a(Az) + b(Az) \log f(h_e);$$

$a$ and $b$ are constant coefficients for a given $Az$; $h_e$ is focal depth of the “etalon” earthquake.
Fig. 1 - Isoacceleration map of the "etalon" earthquake.
Fig. 2 – Isoseismal map of the “etalon” earthquake.
Fig. 3 – Epicentres $E$ and $I_0$ points corresponding to the four strong/major earthquakes ($M_{GR} \geq 6.7$) occurred in the last 65 years: November 10, 1940 ($M_{GR} = 7.4$); March 4, 1977 ($M_{GR} = 7.2$); August 30, 1986 ($M_{GR} = 7.0$) and May 30, 1990 ($M_{GR} = 6.7$) (after Enescu et al. [1]).
Fig. 4 – Explanatory sketch of the seismotectonic Vrancea model. Cross-section oriented NW-SE, which illustrates very schematically the present stage of the collision process in the Vrancea zone (after Enescu and Enescu [4]).
Fig. 5 – The domains $D_E$ and $D_{th}$ of strong/major Vrancea earthquakes.
Fig. 6 – Isoseismal map of a Vrancea earthquake of $M_{LR} = 7.4$ and $I_0 = 9.5$ (this paper).
Fig. 7 – Isoacceleration map of a Vrancea earthquake of $M_{e}=7.4$ and $I_{0}=9.5$ (this paper).
Fig. 8 – Isoseismal map of a Vrancea earthquake of $M_{GR}=7.2$ and $I_0=9$ (this paper).
Fig. 9 – Isoacceleration map of a Vrancea earthquake of $M_{GR}=7.2$ and $I=9$ (this paper).
Fig. 10 – Isoseismal map of the maximum possible Vrancea earthquake ($M_w=7.7; I_0=10$).
Fig. 11 – Isoacceleration map of the maximum possible Vrancea earthquake.
Fig. 12 – Isoseismal map of the November 10, 1940 (M=7.4) earthquake, calculated by us using the attenuation curves determined by Marza and Pantea [14].
Fig. 13 – Isoseismal map of the March 4, 1977 ($M_{\text{GR}}=7.2$) earthquake, calculated by us using the attenuation curves determinated by Marza and Pantea [14].
Fig. 14 – Composite isoacceleration map of a Vrancea earthquake of $M_{GR}=6.7$ and $I_0=8$ (this paper).
Fig. 15 – Composite isoseismal map of the Vrancea earthquake of $M_{w}=6.7$ and $I=8$ (this paper)
Fig. 16 – Seismic hazard generated by Vrancea earthquakes for different time periods $D$.

Using the data from Figs. 3-14 in Paper II, we computed by the least square method the coefficients $a(Az)$ and $b(Az)$ of attenuation curve family for the “etalon” earthquake (Table 1); $C_d$ is the coefficient of correlation. The values 0.900 – 0.992 of coefficient $C_d$ (Table 1) prove that the equation (2) represent well the attenuation curves of the “etalon” earthquake presented in Figs. 3-14 in Paper II.

The family of attenuation curves of the macroseismic intensity $I$ (along the directions defined by azimuth $Az$), in the case of an Vrancea earthquake occurring at a depth $80 \leq x < 160$ km, has the following equation (Enescu et al. [2]-Paper II):
\[ \log I_{X, A} = \log I_{0X} + \log \left[ \frac{I}{I_{0x}} \right]_{A} + b(Az) \log \left[ \frac{R_h}{f(x)} \right]_{A} + c \log \delta_{A}, \tag{4} \]

where: \( I_{0x} \) is the maximum intensity of an earthquake occurring at a depth \( h = x \); \( \delta \) is the directivity factor of the rupture propagation in the focus (see Paper II); \( c \) is the way how the directivity factor may influence the directivity of the seismic source (see Paper II); \( R_e = (D^2 + h_x^2)^{1/2} \); \( R_e = (D^2 + x^2)^{1/2} \); \( D \) represents the distance between the observation point and the point of maximum macroseismic intensity.

### Table 1

<table>
<thead>
<tr>
<th>Az</th>
<th>a</th>
<th>b</th>
<th>( C_d )</th>
<th>Az</th>
<th>a</th>
<th>b</th>
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</table>

The above relies on, among other things, the fault plane solution being virtually the same in all strong/major Vrancea earthquakes of magnitudes \( M_{GR} > 6.7 \) (Enescu and Enescu, [3]) and on the epicenters of these earthquakes spreading over a rather small area. As to the Vrancea earthquakes of magnitudes \( M_{GR} < 6.7 \), their fault plane solutions resemble those of the strong/major ones in some cases, or differ strongly from them in others (Enescu and Enescu [3]).

Equation (4) fails to provide a solution for another important problem arising as one draws the isoseismal and isoacceleration maps for future Vrancea earthquakes, namely the location of epicenter \( E \) or the point of maximum intensity \( I_0 \) (or the maximum acceleration of the ground motion). This problem needs to be resolved as we most obviously cannot know beforehand about future earthquakes what coordinates their epicenters (or their \( I_0 \) points) may take.
To resolve the problem, one has to consider the spatial distribution of the \( E \) and \( I_0 \) points of the latest strong/major earthquakes for which the locations of these points are known. The positions of the \( E \) and \( I_0 \) points of these earthquakes are therefore provided in Fig. 3. The epicenters of these seisms are seen to spread out along a NE–SW direction (AB in Fig. 3), coinciding with that of the entire epicentral area of Vrancea subcrustal earthquakes. The maximum intensity \( I_0 \) points likewise extend along the NE-SW direction (A'B' in Fig. 3), parallel to that of the epicenters.

Also for solving the problem of the area within which the \( I_0 \) (or \( E \)) points of strong/major earthquakes lie, one may resort to the semotectonic model of Vrancea area, as developed by Enescu and Enescu [4]. An explanatory outline of this model is given in Fig. 4. It shows a vertical NW-SE section sketchily illustrating the current stage of the Vrancea zone collision process. According to this model, the hachured area in Fig. 4 is the main area of Vrancea subcrustal hypocenters, which includes the strong/major earthquakes. Within this area, earthquakes take place on NE-SW-oriented, slanting (almost vertical), fault planes belonging to the contact surface between the tectonic units involved (Fig.4). As the model shows, earthquakes of lower magnitude \( M_{GR} < 6.7 \) occur on NE-SW or NW-SE fault planes of different slants, arising from the collision of the 3 units that are directly involved in Vrancea earthquakes but lying close to the contact area between them. In the current analysis, all that we care to know is that major Vrancea earthquakes arise from very steep, NE-SW oriented, fault planes pertaining to the contact area between the tectonic units involved in the local collision. This accounts for why the \( I_0 \) (or \( E \)) points of strong/major earthquakes are aligned along the NE-SW (AB or A'B' – Fig. 3).

If nothing but the above were taken into account, the epicenters and implicitly the \( I_0 \) points of strong/major Vrancea earthquakes (\( M_{GR} > 6.7 \)) would appear to be concentrated within very narrow domains (Fig. 3). The domain \( D_{I0} \) of the \( I_0 \) points corresponding to strong/major Vrancea earthquakes is about 10 km in width (Fig. 5). According to data in Fig. 3, the most probable length of the domain is 60 km at most.

So, if our procedure is used for calculating the seismic hazard generated by Vrancea strong/major earthquakes (\( M_{GR} > 6.7 \)) one needn’t consider the entire stretch over which the \( I_0 \) points of all subcrustal earthquakes in this area are spread, but just the sector figured in Fig. 5 by the rectangle \( D_{I0} \), which plays here the role the epicentral domain \( D_E \) might play in other methods. One has to admit it is not just the \( E \) and \( I_0 \) points of major earthquakes that are found in the domains \( D_E \) and \( D_{I0} \), but lower magnitude (\( M_{GR} < 6.7 \)) earthquakes will not be considered for now.

A similar problem arising as to the hypocenter depths of future Vrancea earthquakes is more easily resolved. It is well known that the deeper the seismic focus, the broader the area, also known as pleistoseismal area, that will be affected by serious earthquake effects.
Consequently, to be on the safe side, we will consider a depth $h = 150$ km, no matter what the depths of the strong/major Vrancea earthquakes in the future. Though the Vrancea hypocentral domain is deeper than that, we picked 150 km, because none of the major Vrancea earthquakes that we known has ever exceeded this depth. We will, therefore, admit $h = 150$ km and apply equation (4) for every one of the eight points $I_0 (i = 1, 2, 3 \ldots 8$; Fig. 5). For any given earthquake we will of course have to consider the maximum intensity values as being the same at every one of the eight points, i.e. $I_{01} = I_{02} = \ldots = I_{08}$. For every point $I_0$ one will obtain a family of isoseismal lines $I_{kj}$ (where $k$ defines the intensity degree expressed by the isoseismal) as though corresponding to a maximum intensity earthquake at the point $I_0$. The $I_k$ isoseismal that has been taken into account will be the envelope curve of the eight isoseismals $I_{kj}$. The resulting map can be used for any location of the point $I_0$ falling within the rectangle $D_{Io}$ (Fig. 5). The procedure for drawing an isoacceleration map is given in paper I. In this way, for any future given earthquake, some of the values on the map will in principle match the facts and others will be slightly overestimated, but there will never be any underestimated value whatever the location of $I_0$ within the domain $D_{Io}$.

Applying this procedure is a painstaking task. However a PC calculus program can be worked out easily resolve this problem when and if it becomes necessary to do so.

The above procedure is used for tracing isoseismal lines where more than one seismic source is taken into consideration for calculating the seismic hazard. The sources may be assumed to be punctual or not, but in the latter case they must be sufficiently far apart so that their fault planes should not coincide.

Fault plane dimensions in the major earthquake of November 10, 1940, were $58 \times 35$ km, and in the major earthquake of March 4, 1977, they were $50 \times 35$ km (according to Enescu [5]). According to evaluations by Iosif et al. [6], the dimensions for the major earthquake of March 4, 1977, were $63 \times 37$ km. It should be noted that both dimensions lie within the fault plane, one stretches in the NE-SW direction, i.e. the fault plane direction, and the other in the dip direction of the fault plane. As we can see, these dimensions were of the same order of magnitude as the epicentral zone length, which was about 60 to 70 km (Fig. 3).

It can therefore be admitted that faulting in the case of major Vrancea earthquakes (November 10, 1940; March 4, 1977; August 30, 1986; etc.) occurred on the same faulting surface (the area of the effective faulting surface depends on earthquake magnitude), only movement on this surface started from different points (hypocenters) and sometimes even in different directions.

The factor “$c \log \delta$” in equation (4) can be used to take account of the latter.

In view of the above and since the method described in this paper takes into account the non-punctual character of seismic sources (by using an etalon earthquake, which is also defined by non-punctual, natural source rather than a theoretic one), we conclude that one had better avoid relying on the data in Fig. 5 when tracing the isoseismal lines. We therefore suggest that, in order to trace
isoseismal maps, one should simply rely on our equation (4) where we consider explicit shapes for \( f(h); f(x); \) and \( \delta \). What we mean is that we will not have resort to this equation to reckon with several points \( I_{oi} (i = 1, 2, 3\ldots, \text{see Fig. 5}) \), nor, implicitly will we trace the envelopes of the isoseismal curves of all the points \( I_{oi} \). The fact that most \( I_{o} \) points are concentrated within a very small zone (Fig. 3) sustains our suggestion. To offset the effects of exceptional locations of \( I_{o} \) in potential earthquakes such as the March 4, 1977 one (Fig. 3), other conditions are used (see, for example, the map in Fig. 8, which is more comprehensive than the observed macroseismic map of the major earthquake of March 4, 1977).

3. APPLICATIONS

We will take into consideration strong/major earthquakes of intensity in epicentral zone (maximum intensity) \( I_o = 8.5 \) (“etalon” earthquake, see Figs. 1-2); 9.0; 9.5; 10.0 and respectively, of magnitude \( M_{GR} = 7.0; 7.2; 7.4 \) and 7.7. By applying our method described in Papers I, II and in the present paper, the maps in Figs. 6-11 were generated. For Vrancea subcrustal earthquakes, the domain of maximum intensity \( I_o = 8.5-10.0 \) corresponds to the domain of Gutenberg-Richter magnitude \( M_{GR} = 6.9 \) (7.0)-7.7 or to the moment magnitudes \( M_{W} = 7.1-7.9 \). If one compares the maps in Figs. 6 and 8 to previous results, one finds the following:

1) It is once again confirmed that Petrescu and Radu [7], then Radu [8] (after Shebalin, [9], and De Rubeis et al. [10] tampered with the isoseismal map Demetrescu [12] had drawn for the November 10, 1940 earthquake, lowering the original intensities. The alterations were supposed to lead to labor and materials “savings” (that were to prove extremely ill inspired) during a vast building spree that reached its height in 1961–1962 (Enescu [11]). It is obviously these “revised” data that were used for compiling the “Seismic Zoning Standard of Romania”. The consequences of this tampering commented in Enescu [11], were amply illustrated by the March 4, 1977 (\( M_{GR} = 7.2 \)) earthquake (see the isoseismal map drawn by Radu et al. [13]).

2) The maps in Figs. 6 and 8, which are indirectly based on objective recording data, do not entirely agree with those by either Demetrescu [12] or Radu et al. [13] that relied on subjective data on the earthquake effects, as reported by residents from different areas of the country.

The Demetrescu map therefore includes some overrated data, while in Radu et al. [13], the map referring to the March 4, 1977 earthquake contains both some understatements (e.g., the maximum intensity is given as \( I_o = 8 \), while in fact it was \( I_o = 9 \)) and some overstatements. We, for our part, will evidently stick with the data in Figs. 6 and 8.

3) To determine the curves of macroseismic intensity attenuation for Vrancea subcrustal earthquakes, Marza and Pantea [14] used isoseismal maps by various authors who had in turn relied on subjective data (in the same sense as defined
above). We wanted to check the validity of the Marza and Pantea curves and, to this end, used them to calculate the macroseismal maps of the major earthquakes of November 10, 1940, and March 4, 1977 (Figs. 12 and 13) (see [19]). One doesn’t need to take a close look at the maps in Figs. 12 and 13, to realize that they are hardly worth speaking of. They actually reflect the serious deficiencies of the isoseismal maps of Vrancea earthquakes that on which Marza and Pantea relied in developing their attenuation curves. Should one use maps such as those in Figs. 12 and 13 to draw seismic hazard maps, this might lead to even greater disasters than those generated by previous earthquakes.

4) The map in Fig. 9 also indicates the only maximum horizontal accelerations that were recorded at the stations of Bucharest-Pantelimon, Vrancioaia, and Niš (Yugoslavia) during the major earthquake of March 4, 1977. One finds these three values of maximum horizontal acceleration to be in very good accordance with the isoacceleration map (Fig. 9). Whereas these values are as few as three, they carry quite some weight, because the stations that recorded them are located at much different distances from the epicenter, at azimuths similarly different with respect to the epicenter, and in geologic conditions also much different from one another.

One has to keep in mind that the above results concern major/strong earthquakes \( M_{GR} > 6.7 \). In all these earthquakes, the two nodal planes are oriented in NE-SW direction, while the fault plane slopes toward the northwest [3, 4]. The focal mechanism of the Vrancea subcrustal earthquakes of magnitudes \( M_{GR} > 6.7 \) are either similar to those of the major/strong earthquakes, or pertain to fault planes oriented in NW-SE direction and slope toward the southwest [3, 4].

To illustrate the second category of earthquakes, we considered an earthquake of magnitude \( M_{GR} = 6.7 \). First, we traced the isoseismal and isoacceleration maps assuming the focal mechanism was similar to that of major earthquakes, i.e. by using the same procedure as used for tracing the maps in Figs. 6-11. Next, we took into consideration the maps traced by Enescu [15] for the earthquake of May 30, 1990 (\( M_{GR} = 6.7 \)) in which the fault plane was in NW-WE direction and sloped toward the southwest. By mixing the maps obtained in these two stages, we got the composite maps in Figs. 14 and 15, the values of which at any point correspond to the bigger values from the two potential situations: with the fault plane in NE-SW direction or NW-SE direction. We did so, because we have no way to know in advance which of the two focal mechanism categories will be at work in future earthquakes of magnitude \( M_{GR} \leq 6.7 \).

From Figs. 14 and 15 we find that in the southeast of Romania, more specifically in Dobruja, the values of intensity \( I \) and acceleration \( a_{max} \) are close to those found in the major Vrancea earthquakes (see, for example, Figs. 6 and 7). Based on these findings, some building experts have considered that in the event of major Vrancea earthquakes with fault planes oriented in NW-SE (rather than NE-SW) direction, the values of intensity \( I \) and acceleration \( a_{max} \) would considerably
exceed those that were taken into account in designing Cernavoda nuclear power plant. This could pose a serious danger. Yet, seismological researches [3, 4] have proved that major \( M_{GR} > 6.7 \) Vrancea earthquakes occur on fault planes NE-SW oriented; this fact was also taken into account in tracing maps in Figs. 6-11.

**4. AVERAGE RECURRENCE PERIODS. SEISMIC HAZARD CURVES**

Enescu *et al.* [16] were the first to apply to Vrancea earthquakes the Epstein – Lomnitz probabilistic model [17], based on the first distribution of extreme values (Gumbel [18]), which yielded-inter-alia-the following relation:

\[
\log_e N_M = 8.908 - 1.83 M_{GR}
\]  \( (5) \)

or

\[
\log_{10} N_M = 3.869 - 0.795 M_{GR},
\]  \( (6) \)

were \( N_M \) is the annual expected number of earthquakes of magnitudes equal to \( M_{GR} \) or higher.

The average recurrence period of an earthquake of magnitude equal to \( M_{GR} \) or higher is \( T_M = 1/N_M \), that is:

\[
\log_{10} T_M = 0.795 M_{GR} - 3.869,
\]  \( (7) \)

To establish equations (5) - (7), Enescu *et al.* [16] used the maximum annual magnitudes over the period 1934-1973.

Applying the same model to observed data from other periods yielded different pairs of values for the equation (7) coefficients. From among these values, we selected those provided by Moldovan [19] which has used the maximum annual magnitudes over the period 1934-1991:

\[
\log_{10} T_M = 0.796 M_{GR} - 3.906, \quad (8)
\]

We selected the coefficient values in equation (8), because they had been obtained by using the longest reliable segment from the series of extreme annual magnitudes, namely 1934-1991.

It is worth noting that the coefficient values in equations (7) and (8) are almost identical, though the time periods they cover are only partly coincident.

**Table 2**

<table>
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<th>( M_{GR} )</th>
<th>( M_{GR} \geq 6.7 )</th>
<th>( M_{GR} \geq 7.0 )</th>
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<td>30</td>
<td>50</td>
<td>70</td>
<td>100</td>
<td>This paper</td>
</tr>
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</table>
Table 2 gives the values of the average recurrence period, as calculated with relation (7) and relation (8) for the magnitudes of the earthquakes the isoline maps of which are shown in Figs. 1-2, 6-9, and 14-15. The average recurrence times may differ considerably from the real time intervals between earthquake of the same magnitude.

Therefore, in our view, the average recurrence period is not a very important parameter. In fact, it is a parameter devoid of physical meaning.

Table 2 does not show the average recurrence period for the most powerful possible earthquake, because we do not have the necessary elements to make such estimate. This period is therefore conventionally assumed to be $T_M = 200$ years, or $T_M = 475(500)$ years, or $T_M = 1.000$ years, or $T_M = 5.000$ years.

The seismic hazard or the probability of occurrence of a Vrancea earthquake of magnitude $M$ or higher within a period of $D$ years can be expressed, according to Enescu et al. [16], as being:

$$H_D(M) = 1 – \exp(-7391.55 \ De^{-1.83 M_{GR}}).$$ (9)

Relation (9) was used to calculate the seismic hazard curves generated by the subcrustal Vrancea earthquakes for different time periods $D$ (Fig. 16).

REFERENCES