ANALYSIS OF ATTENUATION FOR RECENT VRANCEA INTERMEDIATE DEPTH EARTHQUAKES*  

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The development of the strong motion array in Romania made it possible to obtain during last years numerous (more than 150) valuable strong motion records during the strong Vrancea earthquakes of 1977.03.04 (MGR = 7.2), 1986.08.30 (MGR = 7.0), 1990.05.30 (MGR = 6.7) and 1990.05.31 (MGR = 6.1). Most of them refer to the ground motion, while the rest are referring to the motion of upper floors of relatively high rise buildings.  

The Vrancea intermediate depth seismogenic zone is by far the most important seismogenic zone of Romania, releasing in the average per century more than 95% of the total energy released in Romania [1].
The availability of relatively rich instrumental information has contributed considerably to a better understanding of the seismicity of Romania, especially from the viewpoint of the features of the Vrancea intermediate depth earthquakes.

To provide some data of interest for the paper, the seismological zonation map [13] (expressed in terms of MSK intensities) is reproduced in Fig. 1, while the maps used for engineering design [14] are reproduced in Fig. 2 (a and b).

Fig. 1 – Seismological zonation map of Romania (expressed in terms of intensities). 92, zone of intensity IX (MSK scale). The indices 1 and 2 specify a return period of minimum

50 years or 100 years, respectively [13].

Fig. 2 – Engineering design zonation maps of Romania (expressed in terms of design parameters) [14]. a, zonation of territory from the viewpoint of the values of the
coefficient $k_S$ of the code P100-1992; b, zonation of territory from the view-point of corner periods $T_c$(sec) according to the code P100-1992.

The maps used for engineering design refer to the basic design coefficient, $k_s$, and to the velocity/acceleration corner period, $T_c$, respectively. The concern for their gradual improvement is of obvious importance for engineering design and the results presented in the paper can contribute to it.

One of the main aspects of earthquake features is of course the phenomenon of attenuation, which can be examined in depth based on the instrumental information. The paper deals essentially with this aspect. The work presented in the paper continues the work initiated in [10], going this time up to the analysis of attenuation in directional and spectral terms.

2. DATABASE

The basic data used in view of analyzing the attenuation consisted of the accelerograms having become available subsequently to the earthquakes referred to.

The geographic distribution of the accelerographic strong motion stations considered (which cover the eastern part of Romania) is presented in Fig. 3, as follows: in Fig. 3a, stations considered during the analysis completed in 1995 [10]; in Fig. 3b, stations considered more recently. The stations of Fig. 3a pertain to the network of INCERC (National Building Research Institute), while the stations of Fig. 3b pertain also to the networks of INCDFP (National Institute of Earth Physics) and of Bulgaria. A detailed map of the network for the City of Bucharest is presented in Fig. 4.
3. METHODOLOGICAL ASPECTS

3.1. MEASURES OF GROUND MOTION

The quantitative ground motion characteristics used throughout the paper are as follows:
– peak ground acceleration, \(PGA\);
– peak ground velocity, \(PGV\);
– peak ground displacement, \(PGD\);
– effective peak acceleration (adapted), \(EPAS\);
– effective peak velocity (adapted), \(EPVS\);
– global spectrum based intensity, \(I_S\);
– frequency dependent spectrum based intensity, \(i_s(\varphi)\) (\(\varphi\): frequency, Hz);
– frequency dependent spectrum based intensity, averaged upon a frequency interval \((\varphi', \varphi'')\), \(i_{s-}(\varphi', \varphi'')\).

The characteristics \(PGA, PGV, PGD, EPAS\) and \(EPVS\) refer to individual directions each (horizontal motion directions only were used in fact). The characteristics \(I_S, i_s(\varphi)\) and \(i_{s-}(\varphi', \varphi'')\) may refer to individual directions or to the ensemble of two orthogonal horizontal directions. The definitions of \(EPAS, EPVS, I_S, i_s(\varphi)\) and \(i_{s-}(\varphi', \varphi'')\) are as given in [11] (together with definitions of other characteristics, not referred to in this paper), where rules of averaging for two orthogonal horizontal directions and of averaging upon a frequency interval were given too. The calibrations adopted for the constant free terms of the various intensity measures rely on a statistical correlation and regression analysis, aimed at reaching the best fit between the alternative definitions adopted, presented in [11]. Part of the developments of [11] are nevertheless reproduced further on.

The definitions used for \(EPAS\) and \(EPVS\) are, respectively,
\[
EPAS = \max_T S_{aa}(\varphi, 0.05) / 2.5 \quad (1a)
\]
\[
EPVS = \max_T [S_{aa}(\varphi, 0.05) \times T / (2\pi)] / 2.5 \quad (1b)
\]
or, alternatively (and better),
\[
EPVS' = \max_T S_{va}(\varphi, 0.05) / 2.5 \quad (1b')
\]
where \(S_{aa}(\varphi, n)\) (\(m/s^2\)) and \(S_{va}(\varphi, n)\) (\(m/s\)) represent response spectra for the absolute acceleration and for the absolute velocity respectively, as functions of the frequency \(\varphi\) and of the fraction of critical damping \(n\).

The definition used for \(I_S\) is
\[
I_S = \log_4 (EPAS \times EPVS) + 8.0 \quad (2)
\]
The rule of averaging \(I_S\) for two orthogonal directions (\(x\) and \(y\)) is
\[
I_{x,y} = \log_4 (EPAS_x \times EPVS_x + EPAS_y \times EPVS_y) + 7.5 \quad (2')
\]
The definition used for \(i_s(\varphi)\) is
\[
i_s(\varphi) = \log_4 [S_{aa}(\varphi, n) \times S_{va}(\varphi, n)] + 7.7 \quad (3)
\]
The rule of averaging for two orthogonal directions (\(x\) and \(y\)) is
\[
i_{x,y}(\varphi) = \log_4 [S_{aa}(\varphi, n) \times S_{va}(\varphi, n) + S_{aa}(\varphi, n) \times S_{va}(\varphi, n)] + 7.2 \quad (3')
\]
The rule of averaging (for a single direction) for an interval of frequencies \((\varphi', \varphi'')\) is
\[
i_{\varphi}^{-}\ (\varphi', \varphi'') = \log [1/\ln (\varphi''/\varphi') \times \int_{\varphi'}^{\varphi''} [S_{\text{sa}} (\varphi, n) \times S_{\text{va}} (\varphi, n)] \, d\varphi/\varphi] + 7.7 \ (4)
\]
A corresponding rule is adopted when dealing with two orthogonal horizontal directions.

It may be mentioned that a good correlation exists between \(I_s\) and macroseismic estimates, \([6]\), and that the frequency related intensities \(i_{\varphi}^{-}\ (\varphi', \varphi'')\) are well correlated with the statistical damage spectra presented in \([1]\), which relied on the survey carried out subsequently to the destructive earthquake of 1977.04.03.

3.2. TYPE OF ATTENUATION RELATIONS

The attenuation relations used rely on Blake’s relation \([2]\), with some extension introduced in \([7]\), based on data of \([1]\) concerning the relationship between epicentral intensity and magnitude. The attenuation relations used consider a lumped source, located at a depth \(h\) (km). Two steps are considered:
- determination of the expected epicentral intensity \(I_0^{-}\);
- determination of the expected intensity decrease \(\Delta I^{-}\) corresponding to the epicentral distance \(r\) (km).

The severity of an earthquake is quantified by the Gutenberg-Richter magnitude, \(M_{\text{GR}}\), while the severity of the ground motion is quantified in terms of intensities, which are considered as \(I_s\), according to relations (2), (2’); they are practically equivalent \([6]\) (with the approximation of rounding up) with \(MSK\) \([5]\) or \(EMS\) \([4]\) intensities.

The expected epicentral intensity is given by the expression
\[
I_0^{-} = (1.3 + 0.25 \times \lg h) \, M_{\text{GR}} - (3.0 \times \lg h - 2.0) \ (5)
\]
(lg: decimal logarithm; \(h\): source depth) while the expected intensity reduction is given by the expression
\[
\Delta I^{-} = b \, \rho \ (6)
\]

The coefficients \(b\) and \(\rho\) were defined as
\[
b = (3.0 + 1.5 \, \lg h) \ (7a)
\]
\[
\rho = \lg [(1.0 + r^2/h^2)^{1/2}] \ (7b)
\]

The expected intensity at a site \(A\), \(I_A^{-}\), is thus obtained as
\[
I_A^{-} = I_0^{-} - \Delta I^{-} \ (8)
\]

A recalibration of \(I_0^{-}\) and \(b\) for the various events of Romania referred to on the basis of the instrumental information at hand is discussed further on.
3.3. ATTENUATION ANALYSIS

The attenuation analysis was performed (separately for each of the events of 1986.08.30 \( M_{GR} = 7.0, h = 133 \) km>, 1990.05.30 \( M_{GR} = 6.7, h = 89 \) km> and 1990.05.31 \( M_{GR} = 6.1, h = 79 \) km>, for which rich instrumental information was at hand) stepwise, as follows:

- determination of regression functions homologous to expression (8), irrespective of direction and frequency band;
- determination of directionality characteristics on the basis of Fourier analysis with respect to the azimuthal angle (measured clockwise from \( N \)) related to the epicentre;
- determination of directionality characteristics for various frequency bands.

Given the fact that the r.m.s. deviations with respect to the regression functions determined were generally the smallest for the parameter \( I_S \), it was found preferable to refer the Fourier analysis with respect to the azimuthal angle primarily to this latter parameter. In case \( i \) is the index of recording stations and \( IS_i \) is the spectrum based intensity determined for the geographic point referred to, the values \( IS_i (\rho_i, \alpha_i) \) were intended to be expressed as

\[
IS_i (\rho_i, \alpha_i) \approx IS_~ (\rho_i) + \sum_n (a_n \cos n\alpha_i + b_n \sin n\alpha_i) \quad (n = 1, 2, 3\ldots)
\]

where \( IS_~ (\rho) \) is the expression obtained from the regression analysis irrespective of direction. Since a complete condition of minimization of errors for the Fourier analysis would have been laborious, a simplified condition was adopted for determining the Fourier coefficients:

\[
E_n = \sum_i [\Delta IS_i - (a_n \cos n\alpha_i + b_n \sin n\alpha_i)]^2 = \text{min.} \quad (10)
\]

where \( \Delta IS_i \) is the difference

\[
\Delta IS_i = IS_i - IS_~ (\rho_i) \quad (11)
\]

The partial derivatives of \( E_n \) (10) with respect to \( a_n \) and \( b_n \) led to the linear conditions

\[
\frac{\partial E_n}{\partial a_n} = \sum_i [\Delta IS_i - (a_n \cos n\alpha_i + b_n \sin n\alpha_i)] \cos n\alpha_i = 0 \quad (12a)
\]

\[
\frac{\partial E_n}{\partial b_n} = \sum_i [\Delta IS_i - (a_n \cos n\alpha_i + b_n \sin n\alpha_i)] \sin n\alpha_i = 0 \quad (12b)
\]

with the solution

\[
a_n = \frac{(2 / \Delta)}{\{ \sum (1 - \cos 2n\alpha_i) (\sum IS_i \cos n\alpha_i) - (\sum \sin 2n\alpha_i) (\sum IS_i \sin n\alpha_i) \}} \quad (13a)
\]

\[
b_n = \frac{(2 / \Delta)}{\{ [\sum \sin 2n\alpha_i] (\sum IS_i \cos n\alpha_i) + [\sum (1 + \cos 2n\alpha_i)] (\sum IS_i \sin n\alpha_i) \}} \quad (13b)
\]

where
\[ \Delta = \left[ \sum_i (1 + \cos 2n\alpha_i) \right] \left[ \sum_i (1 - \cos 2n\alpha_i) \right] - \left[ \sum_i \sin 2n\alpha_i \right]^2 \] (14)

3.4. ADDENDA

The attenuation analysis carried out in spectral terms was related in principle to the 36 dB frequency band (0.25 Hz, 16.0 Hz), adopted as reference, divided into six 6 dB subintervals:
- (0.25 Hz, 0.5 Hz), referred to as subinterval 61;
- (0.5 Hz, 1.0 Hz), referred to as subinterval 62;
- (1.0 Hz, 2.0 Hz), referred to as subinterval 63;
- (2.0 Hz, 4.0 Hz), referred to as subinterval 64;
- (4.0 Hz, 8.0 Hz), referred to as subinterval 65;
- (8.0 Hz, 16.0 Hz), referred to as subinterval 66.

Out of these, results were considered relevant for subintervals 62 to 65, and presented further on.

The attenuation analysis carried out in directional terms was expressed in graphic terms by means of the epicentral distances at which the intensities 7.0, 6.0 and 5.0, respectively, are expected to be reached in each azimuthal direction.

4. PREVIOUS RESULTS

The results of a first period of analysis activity were presented in [10]. The input data were to some extent different at that time (data for less stations, as in Fig. 3a, different accelerogram processing techniques). A summary view of the results of that period is given in Table 1.

<table>
<thead>
<tr>
<th>Event</th>
<th>Parameters</th>
<th>Average attenuation of I₅</th>
<th>R. M. S. values of ground motion parameters</th>
<th>Fourier coefficients for azimuthal I₅ distribution</th>
<th>Dominant radiation azimuth for I₅</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>log₂PGA</td>
<td>log₂PGV</td>
<td>log₂PGD</td>
<td>log₂EPAS</td>
</tr>
<tr>
<td>1986. 08.30</td>
<td></td>
<td>7.7 – 7.6 ρ</td>
<td>0.925</td>
<td>0.999</td>
<td>1.025</td>
</tr>
<tr>
<td>1990. 05.30</td>
<td></td>
<td>7.2 – 2.1 ρ</td>
<td>0.662</td>
<td>0.790</td>
<td>0.901</td>
</tr>
<tr>
<td>1990. 05.31</td>
<td></td>
<td>5.9 – 2.6 ρ</td>
<td>0.910</td>
<td>0.916</td>
<td>0.756</td>
</tr>
</tbody>
</table>
The examination of the results presented makes it possible to emphasize following features of the attenuation phenomenon:

– unexpectedly (since the source was deeper), the attenuation was faster for the event of 1986.08.30 ($h = 133$ km) than for the events of 1990.05.30 ($h = 89$ km) and 1990.05.31 ($h = 79$ km);

– the scatter of various parameters, expressed in units that are comparable with intensity, was high, ranging for the various parameters from about 0.6 to 1.0 intensity units;

– the general scatter tendency (expressed in terms of the comparable units referred to) tended to be highest for peak ground motion parameters $PGA$, $PGV$ and $PGD$, lower for peak spectral values $EPAS$ and $EPVS$ and lowest for the intensity $I_s$;

– the directionality of radiation was strong in all cases (see Fourier coefficients $a_2$ and $b_2$);

– while the radiation tended to be rather symmetrical for the first two events, it was strongly non-symmetrical for the last one (see the relatively high value $b_1 = 0.63$, which meant strong deviation to the East of the macroseismic epicentre);

– the radiation directionality was different for the three events considered: approximately NE-SW on 1986.08.30 (as observed on a macroseismic basis for the destructive events of 1940.11.10 ($M_{GR} = 7.4$) and of 1977.03.04 ($M_{GR} = 7.2$) too), N-S on 1990.05.30 and E on 1990.05.31).

5. NEW RESULTS

Before presenting the present work data on attenuation analysis, it is interesting to present the displacement seismograms along two alignments crossing Bucharest, oriented N–S and E–W respectively. They are related to the events of 1986.08.30 (Fig. 5) and 1990.05.30 (Fig. 6), respectively. It may be remarked that the similarity of the displacement seismograms for all events, alignments and directions, was unexpectedly strong.
Fig. 5 – Displacement seismograms for event of 1986.08.30.

The geographic coordinates of the stations considered are given in Table 2, together with the coordinates of other stations referred to subsequently.
**Fig. 6 – Displacement seismograms for event of 1990.05.30.**

**Table 2**

Geographic coordinates of the stations referred to in Figs. 5 and 6

<table>
<thead>
<tr>
<th>No.</th>
<th>Location of station</th>
<th>Lat. North</th>
<th>Long. East</th>
<th>Symbol 1986.08.30</th>
<th>1990.05.30</th>
<th>1990.05.31</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Baia-Tulcea</td>
<td>44.723</td>
<td>28.679</td>
<td>BAA</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>2</td>
<td>Bărlad</td>
<td>46.228</td>
<td>27.666</td>
<td>BIR1</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>3</td>
<td>Bucharest - Baia Albă (s)</td>
<td>44.413</td>
<td>26.169</td>
<td>BLA</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>4</td>
<td>Bolintin Vale</td>
<td>44.444</td>
<td>25.757</td>
<td>BLV</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>5</td>
<td>Brâneşti</td>
<td>45.269</td>
<td>27.966</td>
<td>BRN</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>6</td>
<td>Buzău - Cartier Micro (s)</td>
<td>45.147</td>
<td>26.809</td>
<td>BUZ</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>7</td>
<td>Câmpina - Centre</td>
<td>45.119</td>
<td>25.736</td>
<td>CMN1</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>8</td>
<td>Bucharest - Carlton (s)</td>
<td>44.436</td>
<td>26.102</td>
<td>CRL</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>9</td>
<td>Cernavodă-Centru</td>
<td>44.340</td>
<td>28.030</td>
<td>CVD1</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>10</td>
<td>Bucharest - Drumul Sârții</td>
<td>44.419</td>
<td>26.059</td>
<td>DRS</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>11</td>
<td>Focșani - Centre</td>
<td>45.693</td>
<td>27.192</td>
<td>FOC2</td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>12</td>
<td>Giurgiu - Police</td>
<td>43.893</td>
<td>25.982</td>
<td>GRG</td>
<td>*</td>
<td>*</td>
</tr>
</tbody>
</table>

(continues)
Table 2 (continued)

<table>
<thead>
<tr>
<th>No.</th>
<th>Location</th>
<th>Latitude</th>
<th>Longitude</th>
<th>Code</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>Bucharest - INCERC</td>
<td>44.442</td>
<td>26.161</td>
<td>INC</td>
<td>*</td>
</tr>
<tr>
<td>14</td>
<td>Bucharest - Met. Berceni</td>
<td>44.376</td>
<td>26.119</td>
<td>MET</td>
<td>*</td>
</tr>
<tr>
<td>15</td>
<td>Bucharest - Militari</td>
<td>44.431</td>
<td>26.028</td>
<td>MLT</td>
<td>*</td>
</tr>
<tr>
<td>16</td>
<td>Bucharest - Metro IMGB</td>
<td>44.367</td>
<td>26.144</td>
<td>MTR</td>
<td>*</td>
</tr>
<tr>
<td>17</td>
<td>Oneşti - Centre</td>
<td>46.250</td>
<td>26.762</td>
<td>ONS</td>
<td>*</td>
</tr>
<tr>
<td>18</td>
<td>Otopeni</td>
<td>44.549</td>
<td>26.071</td>
<td>OTP</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td>Ploieşti (s)</td>
<td>44.930</td>
<td>26.020</td>
<td>PLS</td>
<td>*</td>
</tr>
<tr>
<td>20</td>
<td>Bucharest - Panduri</td>
<td>44.426</td>
<td>26.065</td>
<td>PND</td>
<td>*</td>
</tr>
<tr>
<td>21</td>
<td>Perioşi - Brătuleşti</td>
<td>44.676</td>
<td>26.019</td>
<td>PRS</td>
<td>*</td>
</tr>
<tr>
<td>22</td>
<td>Râmnicul Sărat (school)</td>
<td>45.380</td>
<td>27.040</td>
<td>RMS2</td>
<td>*</td>
</tr>
<tr>
<td>23</td>
<td>Bucharest-Titulescu</td>
<td>44.452</td>
<td>26.080</td>
<td>TIT</td>
<td></td>
</tr>
<tr>
<td>24</td>
<td>Vălenii de Munte</td>
<td>45.183</td>
<td>26.038</td>
<td>VLM</td>
<td>*</td>
</tr>
<tr>
<td>25</td>
<td>Vaslui</td>
<td>46.637</td>
<td>27.733</td>
<td>VLS</td>
<td>*</td>
</tr>
</tbody>
</table>

Note: * records obtained (for Bucharest – INCERC: additionally, a record on 1977.03.04)

The results obtained during the more recent statistical analysis activities are represented first in graphic terms, as follows:

a) presentation irrespective of directionality (in each case, the regression line of one of the parameters referred to below, against the non-dimensional epicentral distance $\rho$, represented as ordinate, is presented), as follows: presentations, separately for the three events referred to, in Fig. 7: regression lines for abscissae $I_s$ and for $i_{s2}$, $i_{s3}$, $i_{s4}$ and $i_{s5}$, respectively (using notations as referred to in subsection 2.4), in each case;

b) results of directionality analysis, in Figs. 8a and 8b, in terms of curves representing the epicentral distances where the intensities 7.0, 6.0 and 5.0 are expected to be reached, presented at alternative scales, as follows:

– in Fig. 8a, using different scales, in order to best visualize each of the plots;

– in Fig. 8b, presenting the plots up to a common radius of 1,000 km.

In order to provide more specific information, the relationship between $I_s$ and earthquake magnitude is presented in Fig. 9 for stations of Bucharest, [8] (see map of Fig. 4) and in Fig. 10 for stations of province towns (see maps in Figs. 2a and 3).

The numerical results on the features of attenuation are summarized in two tables:

– expressions of linear regression functions, as related to various frequency bands, as well as Fourier coefficients of the azimuthal directionality of radiation, in Table 3;

– r.m.s. values for various ground motion parameters, as related to regression functions and to the synthesis of the azimuthal Fourier expansion, respectively, in Table 4.
The results obtained lastly make it possible to come up with the following remarks:

– the methodology developed led to a more complete insight into the features of attenuation, going up to the analysis in directional and spectral terms;

– the results of [10] were generally confirmed, but corrections had to be brought to the dominant azimuthal angles;

– out of the frequency bands considered, the band (2.0 Hz, 4.0 Hz) appeared to correspond to the highest intensities; this was followed by the bands (4.0 Hz, 8.0 Hz) and (1.0 Hz, 2.0 Hz), while the lowest frequency band, (0.5 Hz, 1.0 Hz), corresponded to the lowest intensities;

– differences between the dominant azimuthal angles for different frequency bands could be observed, especially for the event of 1990.05.30;

– the peculiarities of the 1990 events, which do not follow the “standard” radiation pattern are confirmed and raise problems concerning the features of the seismogenic zone activity.

It may be stated that the results obtained should be considered for the improvement of seismic zonation of the Romanian territory.
<table>
<thead>
<tr>
<th>Event</th>
<th>1986.08.30, $M_{\text{eq}} = 7.0$</th>
<th>1990.05.30, $M_{\text{eq}} = 6.7$</th>
<th>1990.05.31, $M_{\text{eq}} = 6.1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_5$</td>
<td><img src="1986.08.30.png" alt="Image" /></td>
<td><img src="1990.05.30.png" alt="Image" /></td>
<td><img src="1990.05.31.png" alt="Image" /></td>
</tr>
<tr>
<td>$I_6^{62}$</td>
<td><img src="1986.08.30.png" alt="Image" /></td>
<td><img src="1990.05.30.png" alt="Image" /></td>
<td><img src="1990.05.31.png" alt="Image" /></td>
</tr>
<tr>
<td>$I_6^{63}$</td>
<td><img src="1986.08.30.png" alt="Image" /></td>
<td><img src="1990.05.30.png" alt="Image" /></td>
<td><img src="1990.05.31.png" alt="Image" /></td>
</tr>
<tr>
<td>$I_6^{64}$</td>
<td><img src="1986.08.30.png" alt="Image" /></td>
<td><img src="1990.05.30.png" alt="Image" /></td>
<td><img src="1990.05.31.png" alt="Image" /></td>
</tr>
<tr>
<td>$I_6^{65}$</td>
<td><img src="1986.08.30.png" alt="Image" /></td>
<td><img src="1990.05.30.png" alt="Image" /></td>
<td><img src="1990.05.31.png" alt="Image" /></td>
</tr>
</tbody>
</table>

Fig. 8a – Directionality of attenuation, for various events and frequency bands (best visualization).
<table>
<thead>
<tr>
<th>Event &amp; Magnitude</th>
<th>1986.08.30, $M_{LR} = 7.0$</th>
<th>1990.05.30, $M_{LR} = 6.7$</th>
<th>1990.05.31, $M_{LR} = 6.1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_s$</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
<td><img src="image3.png" alt="Image" /></td>
</tr>
<tr>
<td>$I_s$</td>
<td><img src="image4.png" alt="Image" /></td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
<tr>
<td>$I_s$</td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
<td><img src="image9.png" alt="Image" /></td>
</tr>
<tr>
<td>$I_s$</td>
<td><img src="image10.png" alt="Image" /></td>
<td><img src="image11.png" alt="Image" /></td>
<td><img src="image12.png" alt="Image" /></td>
</tr>
</tbody>
</table>

Fig. 8b – Directionality of attenuation, for various events and frequency bands (common scale, up to epicentral distance of 1000 km).
Fig. 9 – Relationship between magnitudes and intensities $I_S$ for various events and stations of Bucharest (see Fig. 4).

Fig. 10 – Relationship between magnitudes and intensities $I_S$ for various events and stations, mostly outside of Bucharest (see Fig. 4).
### Table 3
Results of the regression analysis in spectral and directional terms

<table>
<thead>
<tr>
<th>Event</th>
<th>Regression functions $I^<em>_g - b^</em>_g$ for</th>
<th>Fourier coefficients $a_1, b_1, a_2, b_2$ for</th>
<th>Dominant radiation azimuth for $I^*_g$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1986.08.30</td>
<td>$I_g$ 7.352-8.019 $i_g^<em>$ 6.791 $i_g^</em>$ 5.649 $i_g^<em>$ 1.218 $I_g^</em>$ 0.743 $i_g^<em>$ 0.869 $I_g^</em>$ 0.908 $i_g^<em>$ 0.717 $I_g^</em>$ 0.753</td>
<td>$a_1^<em>$ 0.316 $b_1^</em>$ 0.564 $a_2^<em>$ 0.345 $b_2^</em>$ 0.274 $a_3^<em>$ -0.274 $b_3^</em>$ 0.292</td>
<td>$N 53^\circ E$</td>
</tr>
<tr>
<td>1990.05.30</td>
<td>$I_g$ 7.312-2.800 $i_g^<em>$ 3.323 $i_g^</em>$ 2.457 $I_g^<em>$ 0.192 $i_g^</em>$ 0.398</td>
<td>$a_1^<em>$ -0.084 $b_1^</em>$ -0.256 $a_2^<em>$ -0.193 $b_2^</em>$ -0.093 $a_3^*$ -0.044</td>
<td>$N 209^\circ E$</td>
</tr>
<tr>
<td>1990.05.31</td>
<td>$I_g$ 6.86-3.62 $i_g^<em>$ 4.386 $i_g^</em>$ 4.468 $I_g^<em>$ 0.170 $i_g^</em>$ 0.081</td>
<td>$a_1^<em>$ 0.170 $b_1^</em>$ 0.175 $a_2^<em>$ 0.149 $b_2^</em>$ 0.143</td>
<td>$N 143^\circ E$</td>
</tr>
</tbody>
</table>

### Table 4
R.M.S. values of ground motion parameters
(with respect to regression lines / with respect to Fourier synthesis)

<table>
<thead>
<tr>
<th>Event</th>
<th>$\log_2 PGA$</th>
<th>$\log_2 PGV$</th>
<th>$\log_2 PGD$</th>
<th>$\log_2 EPAS$</th>
<th>$\log_2 EPP'S$</th>
<th>$I_g$</th>
<th>$i_g^*$ 62</th>
<th>$i_g^*$ 63</th>
<th>$i_g^*$ 64</th>
<th>$i_g^*$ 65</th>
</tr>
</thead>
<tbody>
<tr>
<td>1986.08.30</td>
<td>0.910</td>
<td>0.975</td>
<td>0.965</td>
<td>0.892</td>
<td>0.926</td>
<td>0.871</td>
<td>1.124</td>
<td>1.022</td>
<td>0.900</td>
<td>0.926</td>
</tr>
<tr>
<td>1990.05.30</td>
<td>0.648</td>
<td>0.752</td>
<td>0.809</td>
<td>0.613</td>
<td>0.755</td>
<td>0.631</td>
<td>0.936</td>
<td>0.763</td>
<td>0.617</td>
<td>0.657</td>
</tr>
<tr>
<td>1990.05.31</td>
<td>0.656</td>
<td>0.639</td>
<td>0.814</td>
<td>0.667</td>
<td>0.571</td>
<td>0.561</td>
<td>0.700</td>
<td>0.729</td>
<td>0.679</td>
<td>0.730</td>
</tr>
<tr>
<td>1990.05.31</td>
<td>0.761</td>
<td>0.801</td>
<td>0.931</td>
<td>0.842</td>
<td>0.914</td>
<td>0.844</td>
<td>0.864</td>
<td>1.037</td>
<td>0.846</td>
<td>0.659</td>
</tr>
<tr>
<td>1990.05.31</td>
<td>0.843</td>
<td>0.909</td>
<td>1.004</td>
<td>0.953</td>
<td>1.073</td>
<td>0.986</td>
<td>0.920</td>
<td>1.165</td>
<td>0.975</td>
<td>0.680</td>
</tr>
</tbody>
</table>
6. FINAL CONSIDERATIONS

The developments presented in the paper are of two basic kinds: methodological and factual. The methodological developments refer to the ways of performing the attenuation analysis, while the results obtained on this basis provide new information about the features of attenuation of the Vrancea seismogenic zone.

The main methodological developments that can be referred to concern:

– the measures of ground motion presented in subsection 3.1, used alternatively, with emphasis of the intensity measures $I_S$ (global) and $I_{\tilde{\omega}}$ ($\phi', \phi''$) (frequency related, considered for various frequency bands ($\phi', \phi''$));

– the use of a generalization on Blake’s attenuation law [2], as presented in subsection 3.2;

– the ways of performing a statistical regression analysis, presented in subsections 3.3 and 3.4.

It may be stated that the use of the approaches presented made it possible to get a comprehensive insight of the attenuation features for the Vrancea events referred to.

The remarks on attenuation presented at the end of section 4 were generally confirmed by the new step of work, summarized in section 5. We may present nevertheless some additional remarks in this view:

– the attenuation analysis was performed separately for the three events considered; in case one would have taken them together, the attenuation scatter would have increased considerably;

– the results presented add new insights on the features of seismicity of Romania (due to the Vrancea earthquakes) presented in [1], [3], [8], [9], [12].

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