REPREZENTATION OF SEISMIC ACTION IN THE NEW ROMANIAN CODE FOR DESIGN OF EARTHQUAKE RESISTANT BUILDINGS P100-2003

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SUMMARY

A proposal for a new earthquake resistant design code (P100-2003) was developed in 2003 at Technical University of Civil Engineering Bucharest. It follows EUROCODE 8 [1] format. The present paper focuses on the representation of seismic action. A predictive contour map for peak ground acceleration PGA was prepared using GIS technology. The map also includes the contributions of all crustal sources affecting Romanian territory. The paper presents the zonation of the control period of response spectra Tc for the strong ground motions recorded in Romania, and the new proposed design spectra.

INTRODUCTION

According to the number of people lost in earthquake disasters during 20th century as well as in a single event (March 4, 1977: 1574 deaths, including 1424 in Bucharest), Romania can be ranked the 3rd country in Europe, after Italy and Turkey. Romania is followed by the former Yugoslavia and by Greece (Bolt, [2] Coburn and Spence, [3]). The World Bank [4] loss estimation after the 1977 earthquake indicates that from the total loss (2.05 Billion US $) more than 2/3 were in Bucharest, capital city of Romania.

The Vrancea region, located where the Carpathians Mountains Arch bends, is a source of subcrustal seismic activity, which affects more than 2/3 of the territory of Romania and an important part of the territories of Republic of Moldova, Bulgaria and Ukraine. According to the 20th century seismicity, the epicentral Vrancea area is confined to a rectangle of 40x80km² having the long axis oriented N45E and being centered at about 45.6° Lat.N and 26.6° Long. E.

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The Vrancea source induces a high seismic risk in the densely built zones of the South-East of Romania. On March 4, 1977, during the most destructive Vrancea earthquake of this century, in the capital city of Romania, Bucharest, 1424 casualties were registered and 32 reinforced concrete high-rise buildings completely collapsed.

The first and the most important free-field strong ground motion in Romania was recorded at INCERC seismic station in Eastern Bucharest during March 4, 1977 Vrancea earthquake (\(M_w=7.5\), \(h=109\ km\), epicentral distance to Bucharest 105 km). The accelerogram (characterized by 0.2g peak ground acceleration and by 1.6s long predominant period of soil vibration) was recorded on a SMAC-B Japanese instrument and digitized and processed by the Observational Committee of Strong Motion Earthquake of the Building Research Institute, Japan [5].

During the last 60 years, Romania experienced 4 strong Vrancea events: Nov.10, 1940 (moment magnitude \(M_w=7.7\), focal depth \(h=150\ km\)), March 4, 1977 (\(M_w=7.5\), \(h=109\ km\)), Aug 30, 1986 (\(M_w=7.2\), \(h=133km\)) and May 30&31, 1990 (\(M_w=7.0&6.4\), \(h=91&79\ km\)).

**SEISMIC STRONG MOTION NETWORKS OF ROMANIA**

In the decade following the 1977 strong earthquake, on the territory of Romania were installed 3 strong motion networks: INCERC (National Building Research Institute), INFP (National Institute of Earth Physics) and GEOTEC (Institute for Geotechnical and Geophysical Studies). The seismic instrumentation at INCERC was developed for earthquake engineering purposes. INCERC network is the largest and the richest seismic network of Romania (in terms of number of recorded strong ground motion). The network of INFP was developed with UNESCO support. In the last decade the Geophysical Institute of Karlsruhe University installed a significant number of digital accelerometers as one of the components of the SFB 461 German-Romanian project on Vrancea earthquakes. The GEOTEC seismic network is related to dam and hydraulic structures monitoring.

In 2003 a new seismic network of the National Center for Seismic Risk Reduction NCSRR was created in the frame of the Japan International Cooperation Agency (JICA) Technical Cooperation Project [6] "Reduction of Seismic Risk for Buildings and Structures". A more detailed description of the seismic networks in Romania is presented in Aldea et al. [7].

**CATALOGUES OF STRONG VRANCEA EARTHQUAKES**

The catalogues of earthquakes that occurred on the territory of Romania were compiled by Radu [8] and Constantinescu and Marza [9]. The catalogues can be divided into separate catalogues corresponding to various seismic regions/zones of Romania. Of course, the majority of the events from the catalogues refers to earthquakes in Vrancea zone. The Radu’s catalogue is the most complete one, even the majority of significant events are also included in the Constantinescu and Marza catalogue. The magnitude in the Radu catalogue is the Gutenberg-Richter magnitude \(M_{G,R}\). The magnitude in the Constantinescu & Marza catalogue is the surface magnitude \(M_S\); tacitly, \(M_S\) magnitude was later assimilated as Gutenberg-Richter magnitude (Marza [10]). For Vrancea subcrustal source, the conversion of Gutenberg-Richter magnitude into moment magnitude might be approximated by \(M_w=M_{G,R} + 0.3\) for \(6.5 < M_w < 7.8\) (Lungu et al.[11]). Radu last manuscripts containing the latest version of catalogues were processed and published in Lungu et al. [12]. Radu’s catalogue indicates an average of 1 event/century with maximum intensity \(I_0>9.0\) during the period 984-1900 and 2 events/century with \(M_{G,R}>7.2\) (\(I_0>9.0\)) during the period 1901-2000. In Table 1 is presented an excerpt from Radu's catalogue of Vrancea earthquakes during 20th century, in comparison with data from other catalogues.
Table 1. Catalogue of subcrustal Vrancea earthquakes ($M_w \geq 6.3$), 20th century

<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>$h$, km $I_o$</td>
<td>$M_{GR}$</td>
<td>$M_s$</td>
</tr>
<tr>
<td>1903 Sept 13</td>
<td>45.7</td>
<td>26.6</td>
<td>&gt;60 7 6.3</td>
<td>-</td>
<td>6.5 5.7 6.3</td>
</tr>
<tr>
<td>1904 Feb 6</td>
<td>45.7</td>
<td>26.6</td>
<td>75 6 5.7</td>
<td>-</td>
<td>6.6 6.3 6.6</td>
</tr>
<tr>
<td>1908 Oct 6</td>
<td>45.7</td>
<td>26.5</td>
<td>150 8 6.8</td>
<td>-</td>
<td>8.6 8.8 7.1</td>
</tr>
<tr>
<td>1912 May 25</td>
<td>45.7</td>
<td>27.2</td>
<td>80 7 6.0</td>
<td>-</td>
<td>7.4 6.4 6.7</td>
</tr>
<tr>
<td>1934 March 29</td>
<td>45.8</td>
<td>26.5</td>
<td>90 7 6.3</td>
<td>-</td>
<td>8.6 6.3 6.6</td>
</tr>
<tr>
<td>1939 Sept 5</td>
<td>45.9</td>
<td>26.7</td>
<td>120 6 5.3</td>
<td>-</td>
<td>6.6 6.1 6.2</td>
</tr>
<tr>
<td>1940 Oct 22</td>
<td>45.8</td>
<td>26.4</td>
<td>122 7/8 6.5</td>
<td>-</td>
<td>7.0 6.2 6.6</td>
</tr>
<tr>
<td>1940 Nov 10</td>
<td>45.8</td>
<td>26.7</td>
<td>150 9 7.4</td>
<td>-</td>
<td>8.7 7.4 7.7</td>
</tr>
<tr>
<td>1945 Sept 7</td>
<td>45.9</td>
<td>26.5</td>
<td>75 7/8 6.5</td>
<td>-</td>
<td>7.5 6.5 6.8</td>
</tr>
<tr>
<td>1945 Dec 9</td>
<td>45.7</td>
<td>26.5</td>
<td>80 7 6.0</td>
<td>-</td>
<td>7.2 6.2 6.5</td>
</tr>
<tr>
<td>1948 May 29</td>
<td>45.8</td>
<td>26.5</td>
<td>130 6/7 5.8</td>
<td>-</td>
<td>6.5 6.0 6.3</td>
</tr>
<tr>
<td>1977 March 4</td>
<td>45.34</td>
<td>26.30</td>
<td>109 8/9 7.2</td>
<td>7.5</td>
<td>9.7 7.2 7.4</td>
</tr>
<tr>
<td>1986 Aug 30</td>
<td>45.53</td>
<td>26.47</td>
<td>133 8 7.0</td>
<td>7.2</td>
<td>- - 7.1</td>
</tr>
<tr>
<td>1990 May 30</td>
<td>45.82</td>
<td>26.90</td>
<td>91 8 6.7</td>
<td>7.0</td>
<td>- - 6.9</td>
</tr>
<tr>
<td>1990 May 31</td>
<td>45.83</td>
<td>26.89</td>
<td>79 7 6.1</td>
<td>6.4</td>
<td>- - 6.4</td>
</tr>
</tbody>
</table>

1) Maximum seismic intensity
2) Main shock

SEISMICITY OF THE VRANCEA SUBCRUSTAL SOURCE IN ROMANIA

Even the available catalogues of Vrancea events were prepared using the Gutenberg-Richter magnitude $M_{GR}$, the recurrence-magnitude relationship presented here (Lungu et al. [11]) were determined using the moment magnitude $M_w$. The relationship is determined from Radu’s 20th century catalogue of subcrustal magnitudes with threshold lower magnitude $M_w = 6.3$.

The average number per year of Vrancea subcrustal earthquakes with magnitude equal to and greater than $M_w$, in the Gutenberg-Richter format of magnitude recurrence relationship is given by:

$$\log n(\geq M_w) = 3.76 - 0.73 M_w.$$   \hspace{2cm} (1)

If the source magnitude is limited by an upper bound magnitude $M_{w,max}$ (maximum credible magnitude), the recurrence relationship can be modified into the truncated Gutenberg-Richter relationship.

For Vrancea source the truncated relationship was firstly applied using Gutenberg-Richter magnitudes (Elnashai & Lungu [13]). Using moment magnitudes, the following relation was obtained (Lungu [11]):

$$n(\geq M_w) = e^{8.654 - 1.687 M_w} \frac{1 - e^{-1.687(8.1-M_w)}}{1 - e^{-1.687(8.1-6.3)}}$$    \hspace{2cm} (2)

The maximum credible magnitude of Vrancea source was estimated using Wells and Coppersmith [14] relations. The maximum values of surface rupture area ($SRA$) and surface rupture length ($SRL$) were estimated using data from past earthquakes and experts opinion, and were used with Wells and Coppersmith equations for "thrust fault" type of focal mechanism. Even those equations are intended for crustal earthquakes, the experience of subcrustal Vrancea events fits quite well the mentioned equations.
Figure 1. Magnitude recurrence relation for Vrancea subcrustal source \((M_w \geq 6.3)\)

According to Romanian geologists Sandulescu & Dinu [15], in Vrancea subduction zone: \(SRL \leq 150 \pm 200 \text{ km}\) and \(SRA \leq 8000 \text{ km}^2\). Based on this estimation one gets \(M_{w,\text{max}} = 8.1\) (Lungu et al.[11]).

In Eq. (2), the threshold lower magnitude is \(M_w = 6.3\), the maximum credible magnitude of the source is \(M_{w,\text{max}} = 8.1\), and \(\alpha = 3.76 \ln(10) = 8.654\), \(\beta = 0.73 \ln(10) = 1.687\).

The damage intensity of the Vrancea strong earthquakes is the combined result of both magnitude and location of the focus inside the earth. In case of Vrancea source, an interesting and important correlation was noticed between the focal depth and earthquake magnitude. The relationship between the magnitude of a potentially destructive Vrancea earthquake \((M_w \geq 6.3)\) and the corresponding focal depth (using Radu’s 20\textsuperscript{th} century catalogue) shows that higher the magnitude, deeper the focus (Lungu et al.[16]):

\[
\ln h = -0.866 + 2.846 \ln M_w - 0.18 P
\]  

(3)

where \(P\) is a binary variable: \(P=0\) for the mean relationship and \(P=1.0\) for mean minus one standard deviation relationship. The depth dependence of high magnitudes is plotted in Figure 2.

Figure 2. Correlation of large magnitude with focus depth for Vrancea source
The mean minus one standard deviation curve in Figure 2 should be used in hazard analysis as pessimistic correlation of Vrancea magnitude with focus depth. The earthquakes with $M_w \leq 6.3$ display no correlation.

**ATTENUATION RELATIONS FOR THE PEAK GROUND ACCELERATION FOR VRANCEA SOURCE**

The research devoted to the prediction of attenuation of Vrancea ground motions started in 1994. An increased accuracy in selection of the free-field accelerograms and the re-processing (1996-1999) of the accelerograms of INCERC seismic network allow the refinement (Lungu et al. [16]) of the previous predictions obtained at Technical University of Civil Engineering - Bucharest by Lungu et al. [17], [18], [19], [20].

The database used for the analysis of the Vrancea ground motions attenuation contains 71 accelerograms recorded at 47 free-field stations in Romania. The database was completed with 9 free-field accelerograms recorded in Rep. of Moldova and Bulgaria. The accelerograms obtained at the ground level or the basement of 1-2 storey buildings were considered to be free field records. The accelerograms recorded with instruments installed at the basement of mid-rise and tall buildings (3+12 storeys) were not used. The epicentral distance of data goes up to 300km. In the majority of cases the records were obtained at soil sites. The distribution of the recorded accelerograms is given in Table 2.

<table>
<thead>
<tr>
<th>Seismic network</th>
<th>Romania</th>
<th>Republic of Moldova</th>
<th>Bulgaria</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earthquake</td>
<td>INCERC</td>
<td>INFP</td>
<td>GEOTEC</td>
<td>IGG</td>
</tr>
<tr>
<td>March 4, 1977</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Aug. 30, 1986</td>
<td>24</td>
<td>8</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>May 30, 1990</td>
<td>23</td>
<td>10</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Total</td>
<td>48</td>
<td>18</td>
<td>5</td>
<td>4</td>
</tr>
</tbody>
</table>

$^1$INCERC, National Building Research Institute, Bucharest
$^2$INFP, National Institute for Earth Physics, Bucharest-Magurele
$^3$GEOTEC, Institute for Geotechnical and Geophysical Studies, Bucharest
$^4$IGG, Institute of Geophysics and Geology, Moldavian Academy of Science, Chisinau

The maximum of the two horizontal components of the ground motions was considered for PGA attenuation. The distributions of maximum PGA with with epicentral distance and corresponding earthquake magnitudes are presented in Figure 3 and Figure 4.
The following attenuation model was selected for the attenuation analysis:

$$ln \, PGA = c_0 + c_1 \, M_w + c_2 \, lnR + c_3 \, R + c_4 \, h + \varepsilon \quad (4)$$

where:

- $PGA$ is peak ground acceleration at the site,
- $M_w$ - moment magnitude,
- $R$ - hypocentral distance to the site $R = \sqrt{h^2 + \Delta^2}$,
- $h$ - focal depth,
- $c_0, c_1, c_2, c_3, c_4$ - data dependent coefficients and
- $\varepsilon$ - random variable with zero mean and standard deviation $\sigma_{\varepsilon} = \sigma_{ln \, PGA}$.

The extrapolation of data in the range of large magnitudes ($M_w \geq 7.5$) is entirely based on the peak ground acceleration recorded in Bucharest during 1977 event. The coefficients obtained from the regression are given in Table 3 (Lungu et al. [16]).

| Table 3. Regression coefficients for horizontal peak ground acceleration |
|-----------------|----------------|----------------|----------------|----------------|----------------|
|                  | $c_0$          | $c_1$          | $c_2$          | $c_3$          | $c_4$          | $\sigma_{ln \, PGA}$ |
| All data         | 3.098          | 1.053          | -1.000         | -0.0005        | -0.006         | 0.502            |

The attenuation relation from Eq. (4) can be used to predict the 84 percentile of horizontal $PGA$, produced by a magnitude having specified recurrence interval and an associated focal depth (Eq.3 with $P=1.0$).

**Prediction of the peak parameters of the ground motion in Bucharest**

For the city of Bucharest the use of Eq. 4 is illustrated in Figure 5. The experienced epicentral distance for Bucharest is $\Delta = 135 \pm 30 \, km$. Figure 5 also presents the $PGA$ values obtained using the P100-92 (code in force) requirements ($MRI= 50 \ & \ 100 \, yr$) and using the EUROCODE 8 recommendation ($MRI= 475 \, yr$).
\begin{tabular}{|c|c|c|c|}
\hline
$h, \text{ km}$ & $M_w = 7.3$ & $M_w = 7.6$ & $M_w = 7.9 - 8.0$ \\
\hline
90 & 264 & 343 & 580 \\
100 & 231 & 328 & 526 \\
110 & 217 & 295 & 477 \\
120 & 196 & 284 & 432 \\
130 & 177 & 256 & 390 \\
140 & 160 & 208 & 353 \\
150 & 145 & 188 & 319 \\
\hline
\end{tabular}

Figure 5. Prediction of peak ground acceleration $PGA$ in Bucharest ($\Delta=135 \text{ km}$)

ZONATION MAPS

In Figure 6 (Lungu et al. [21]) is illustrated the present seismic zonation of Romania, Republic of Moldova, Bulgaria and Ukraine. The general pattern (which is based on deterministic macroseismic observations) as well as the content of the Table 4 describing the conversion of seismic intensity into peak ground acceleration are self-explanatory. They clearly suggest the need for regional harmonization of seismic macrozonation maps and prove the need for a joint zonation of the seismic hazard in the influence area of the Vrancea source.

Figure 6. Seismic zonation maps for countries affected by Vrancea earthquakes
Table 4. Conversion of MSK seismic intensity into PGA in Romania, Rep. of Moldova and Bulgaria

<table>
<thead>
<tr>
<th>MSK Intensity</th>
<th>ROMANIA P100-92&amp; SR 11100/1-93</th>
<th>Rep. of MOLDOVA, UKRAINE SNIP II-7-81</th>
<th>BULGARIA 1987 code</th>
</tr>
</thead>
<tbody>
<tr>
<td>IX</td>
<td>0.32</td>
<td>0.40</td>
<td>0.27</td>
</tr>
<tr>
<td>VIII</td>
<td>0.25</td>
<td>0.20</td>
<td>0.15</td>
</tr>
<tr>
<td>VII</td>
<td>0.16</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>V</td>
<td>0.12</td>
<td>-</td>
<td>0.05</td>
</tr>
</tbody>
</table>

It is emphasized that the present seismic code of Romania, P100-92, defines the earthquake hazard with 50 yr. mean recurrence interval (i.e., 63% exceedance probability in 50 yr). However, the American code ASCE 7-95/98, [22] and EUROCODE 8 [1] recommend a mean recurrence interval of 475 yr. (i.e., 10% exceedance probability in 50 years).

Based on the results of seismic hazard assessment from Vrancea source and taking into account the macroseismic fields from the crustal seismic sources around Romania, in Figure 7 is presented the proposed seismic hazard map for the P100-2003 proposal of earthquake resistant design code. The map presents the design ground acceleration for an event with mean recurrence interval \( MRI=100 \text{ years} \), that represents a transition value towards a more conservative hazard map (with \( MRI=475 \text{ years} \)).

Figure 7. The design ground acceleration for an event with \( MRI=100 \text{ yr} \).
In the actual code P100-92, as well as in the P100-2003 proposal, the ground conditions are characterized indirectly by the control period of response spectra $T_c$.

A direct characterisation/classification of ground conditions based on soil data (soil profile and shear velocities profile) is, unfortunately, not yet possible due to the lack of sufficient soil data correlated with recorded ground motions. The few cases where such information exists (i.e., soil data and earthquake records) showed that importing criteria and corresponding design spectra from other countries is not recommended, especially in the area under the influence of Vrancea source and where deep sediment deposits exists (Aldea [23]).

As an example, for the Bucharest INCERC record from 1977 earthquake, obtained at a site where the upper geology is characterized by shear wave velocities around 300m/s, the ground motion was characterized by a long predominant period and it’s acceleration response spectra displayed high amplifications at long periods (1.4-1.6s).

The studies made on the complete data base of strong motion accelerograms of Romania showed that the control period of response spectra $T_C$ is a reliable and stable indicator for characterizing the frequency content of ground motions, and indirectly the ground conditions. The $T_C$ zonation for the P100-2003 proposal is presented in Figure 8, based on processed ground motion records and GIS technology.

**Figure 8. Zonation of control period of response spectra, $T_C$**

**DESIGN SPECTRA**

For each of the three zones in Figure 8, a normalised acceleration response spectrum is recommended in the P100-2003 code proposal.
The normalised acceleration response spectrum $\beta(T)$ for the horizontal ground motion and for 5% damping, is following the EUROCODE 8 format, and is given by the following equations:

1. $T \leq T_B$  
   \[ \beta(T) = 1 + \left( \frac{\beta_0 - 1}{TB} \right) T \]  
   \[ (5) \]

2. $T_B < T \leq T_C$  
   \[ \beta(T) = \beta_0 \]  
   \[ (6) \]

3. $T_C < T \leq T_D$  
   \[ \beta(T) = \beta_0 \frac{T_C}{T} \]  
   \[ (7) \]

4. $T > T_D$  
   \[ \beta(T) = \beta_0 \frac{T_C T_D}{T^2} \]  
   \[ (8) \]

where:

- $\beta(T)$ – normalised acceleration response spectrum (elastic);
- $\beta_0$ – maximum dynamic amplification factor;
- $T$ – fundamental period of vibration of a single degree of freedom structure.

The control periods of response spectra $T_B, T_C, T_D$ are given in Table 5.

| Control periods of response spectra $T_B, T_C, T_D$ for horizontal ground motion |
|---------------------------------|--------|--------|--------|
| $T_B$, s                        | 0.07   | 0.10   | 0.16   |
| $T_C$, s                        | 0.7    | 1.0    | 1.6    |
| $T_D$, s                        | 3      | 3      | 2      |

The normalised acceleration response spectra for the three zones characterised by $T_C = 0.7s$, $T_C = 1.0s$ and $T_C = 1.6s$ are presented in Figure 9.

The elastic response spectra for horizontal ground motion is defined as:

\[ S_e(T) = a_g \beta(T) \]  
\[ (9) \]

The acceleration design spectra $S_d(T)$ is an inelastic response spectra obtained with the following relations:

1. $0 < T \leq T_B$  
   \[ S_d(T) = a_g \left[ \frac{\beta_0 - 1}{TB} \right] \left[ 1 + \frac{q}{T_B} T \right] \]  
   \[ (10) \]

2. $T > T_B$  
   \[ S_d(T) = a_g \frac{\beta(T)}{q} \]  
   \[ (11) \]

where

- $S_d(T)$ - in m/s$^2$.
- $T$ – period, in sec.
- $q$ – behavior factor.
Figure 9. Normalised acceleration response spectra for horizontal ground motion in zones characterised by control periods $T_C = 0.7s$, $T_C = 1.0s$ and $T_C = 1.6s$, in the P100-2003 code proposal
The behaviour factor \( q \) is given in the P100-2003 code proposal following EUROCODE 8 recommendations, for different types of materials and structural systems.

The seismic action quantified by the above design spectra is for ultimate limit state design.

The P100-2003 code proposal was developed at Technical University of Civil Engineering, Bucharest in 2003 within a contract with the Ministry of Transports, Constructions and Tourism, and will be published in 2004 for offering to the Romanian professional and scientific community a base for discussions, analysis and improvements, in a format that follows the EUROCODE 8.

**CONCLUSIONS**

The actual description of seismic action in Romanian P100-92 design code must be modified toward the requirements of the EUROCODE 8. The seismic zonation should be done using instrumental data and probabilistic seismic hazard assessment. The design spectra should correspond to different ground categories. The present proposal for modification uses a transition value of \( MRI=100\text{years} \) instead of \( MRI=475\text{years} \) required by EUROCODE 8 for the PGA zonation, and, due to the lack of ground data, it includes design spectra for regions characterized by different control (corner) period of response spectra \( T_C \). The P100-2003 code proposal follows EUROCODE 8 requirements.

**Acknowledgement**

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