EARTHQUAKE RISK CLASSES FOR DAMS SITUATED IN THE SOUTH-WESTERN PART OF ROMANIA (DANUBE, OLT, JIU AND LOTRU RIVERS)*

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Abstract. The main goal of this paper is rating the dams from the South-Western part of Romania (Danube, Olt, Jiu and Lotru rivers) into seismic risk classes. Dam owners and regulators must ensure that dams are safely operated and present no risk to the public in case of an earthquake. While most old or new dams in recognized seismic regions have been evaluated and analyzed for seismic loads, dams located in areas of moderate or infrequent seismicity have been given less systematic attention. In such cases, owners of many dams or officials in charge of dam safety programs may consider comparative assessment of the seismic risk associated with their dams and establish priorities, as needed. Risk classes can be used to establish the necessity of detailed assessment of seismic safety of the dams and to establish the priorities of these evaluations.

The methodology which is used in this paper offers an easy way to evaluate the most vulnerable hydrotechnical facilities among the multitude of dams in the Western part of Romania that are affected by crustal-depth earthquakes from Banat and Danubian regions and by Vrancea intermediate depth earthquakes. The risk is expressed as a product between hazard and vulnerability. In particular, seismic risk in the case of hydrotechnical arrangements is computed as a product between seismic hazard (corresponding to the location of the respective hydrotechnical arrangement) and the seismic vulnerability of the respective arrangement. Various risk factors and weighting points can be used to approximately quantify the Total Risk Factor (TRF) of any dam. The TRF depends on the dam type, age, size, the downstream risk potential, and the dam vulnerability, which depends on the seismic hazard of the site. The dam structure influence is represented by the sum of capacity, height, and age risk factors. The downstream hazard factor is based on population and property at risk. The vulnerability rating is a function of the site-dependent seismic hazard and observed performance of similar dams, as defined by a predicted damage factor.

This procedure can be used to quickly assess the potentially most vulnerable facilities in a large dam inventory. The risk classification based on the TRF, provides guidance to dam safety officials to select appropriate evaluation procedure and to assign priorities for seismic safety evaluation of the most critical dams.

Key words: seismic hazard, risk classes, dams.

1. INTRODUCTION

The paper deals with a complex activity of research concerning the settlement of the seismic risk class for each big dam from the South-Western part of Romania situated on Danube, Olt, Jiu, and Lotru rivers. These dams are framed and pursued in time by the meaning of modern statistical and structural investigation of these buildings and of their sites, as well, offering an precious instrument for the risk evaluation that these structures represents in the event of a major earthquake. The seismic risk assessments are very important to specialized organizations, as these studies reveal (physically meaning) the neuralgic points of certain sites that contain hydrotechnical constructions having large accumulation capacity, representing real centers of potential disasters when stroked by natural catastrophes and having large socio-economical impact.

The analysis that we propose implies: (1) geometrical definition of all seismic sources affecting the region, (2) estimation of the maximum possible magnitude, (3) estimation of the frequency magnitude relationship, (4) estimation of the attenuation law, (5) computing probabilistic seismic hazard (PSH) for the South-Western part of Romania and, finally, (6) rating the dams from Olt, Jiu, Lotru and Danube rivers into seismic risk classes.

2. SEISMIC SOURCES CHARACTERISTICS

The first step in the determination of PSH consists in defining the seismogenic sources. It is necessary to point out and to delimit the seismic areas that can affect the Western part of the Romanian territory. The seismogenic sources that are detailed in this paper are: Vrancea intermediate depths source (VRI), Fagaras-Campulung-Sinaia crustal source (CMP), Banat crustal source (BAN), Danubian crustal earthquakes (DAN) and Serbian zone (IBAR) (Fig. 1) [1].

2.1. THE VRANCEA SUBCRUSTAL SOURCE (VRI)

Vrancea subcrustal zone represents a complex and particular seismic region with a continental convergence of at least three major tectonic units: East European Plate, Intra-Alpine and Moesian Subplate [2]. The seismic activity is concentrated at intermediate depths (60–220 km), in a nearly vertical and extremely narrow subducting slab. It is a challenging task to explain how 3-5 major shocks ($M_w > 7$) occur per century in such a small focal volume. The seismic moment rate is high (approximately $1.2 \times 10^{19}$ Nm/year) and makes Vrancea zone the most concentrated seismic zone of Europe.
The geometry of the Vrancea subcrustal source together with the epicentral
distribution of the earthquakes with $M_w > 5.0$ occurred between January 1900 and
June 2010 are plotted in Fig. 1. The average annual number of earthquakes with
magnitude greater than 5 is equal to 1.762380 earthquakes /year.

To define the source geometry only earthquakes generated after 1950 were
considered, for which more complete instrumental information is available. The
location coordinates and magnitudes are taken from the Romanian catalogue [3, 4, 5].

The frequency-magnitude distribution for Vrancea subcrustal region is
estimated on the magnitude interval [5.0, 7.7]. The distribution is plotted in Fig. 2.
The equation of the regression line is given in equation (1):

$$\log N_{\text{cum}} = (-0.84 \pm 0.03) M_w + (6.45 \pm 0.16),$$  \hspace{1cm} (1)

with the correlation coefficient $R = 0.99$ and the standard deviation $\sigma = 0.07$.
Because the program that will be used for hazard assessment [6] deals with
epicentral intensities ($I_0$) [7], [8] and not with magnitudes, all the input parameters
were converted to intensities.

For Vrancea intermediate source the relation between $M_w$ and $I_0$ is given in
equation (2) [9]:

$$M_w = 0.58 I_0 + 2.08.$$  \hspace{1cm} (2)
Equation (1) becomes equation (3):
\[
\log N_{\text{cum}} = -0.49I_0 + 4.71. \tag{3}
\]

The parameters of equation (3) that will be used for hazard computing are:
\(a_i = 4.71, b_i = 0.49, \alpha_i = a_i \ln 10 = 10.3008, \beta_i = b_i \ln 10 = 1.1085\) and are all presented in Table 1.

2.2. FAGARAS-CAMPULUNG-SINAIA (CMP) CRUSTAL SOURCE

The source is located in the Southern Carpathians, Romania, adjacently to the West of Vrancea seismic region and is part of the major dome uplift of the Getic Domain basement.
The **CMP crustal source** is bordered at Northern and Southern edges by first order crustal fractures and consist of three seismogenic subzones: Fagaras, containing Lovistea Depression and North Oltenia, Campulung and Sinaia subzones. The earthquake activity is related to intracrustal fractures extending from 5 to 30 km depth.

The earthquakes in CMP zone are generated at South, on deep fractures extending on inherited hercynian lines along NW and NE alpine origin directions and at North, throughout Transylvania, along a stepped fault system separating the Carpathian orogen from its intermountain depression [2]. In the Western part of Fagaras Mountains, the earthquakes have a typical polikinetic character, with many delayed aftershocks, especially for large events, as the one produced in 1916. Preferential centers and lines of seismicity were identified after the occurrence of the large earthquakes and the subsequent aftershock activity.

Most of the earthquakes are of low energy, but once per century a large destructive event with epicentral intensity larger than VIII is expected in Fagaras area. The last major shock occurred in **January 26, 1916, \( M_w = 6.5, I_0 = \text{VIII–IX} \)**. Fagaras seismogenic subzone is the second seismic source in Romania as concerns the largest observed magnitude (\( M_w = 6.5 \)), after the Vrancea intermediate-depth source (with maximum magnitude \( M_w \sim 7.7–7.8 \)).

The frequency-magnitude distribution for **CMP crustal source** was computed for 3 sets of data, as given in equations (4, 5 and 6) and are all plotted in Fig. 3:

- for Romplus whole catalogue and a completeness magnitude \( M_c = 2.4 \),
  \[
  \log N_c = - (0.47 \pm 0.04) M_w + (3.46 \pm 0.19), \quad \text{upper line} \quad (4) 
  \]
  with \( R = 0.95, \sigma = 0.22 \)
- after 1900 and \( M_c = 2.4 \),
  \[
  \log N_c = - (0.66 \pm 0.04) M_w + (3.88 \pm 0.20), \quad \text{middle line} \quad (5) 
  \]
  with \( R = 0.97, \sigma = 0.22 \)
- after 1900 and \( M_c = 2.9 \),
  \[
  \log N_c = - (0.57 \pm 0.04) M_w + (3.39 \pm 0.13), \quad \text{lower line} \quad (6) 
  \]
  with \( R = 0.98, \sigma = 0.14 \).

Equation (6) was used for hazard computations and for this reason we have converted it into epicentral intensities using equation (7) [9]:

\[
M_w = 0.66 I_0 + 1.23. \quad (7) 
\]

Equation (6) becomes equation (8):

\[
\log N_{cum} = - 0.38 I_0 + 2.27 \quad (8) 
\]

and the statistical parameters for PSH assessment (Table 1) are: \( a_i = 2.27, b_i = 0.38, a_t = a, \ln 10 = 5.2284, \beta_t = b_t \ln 10 = 0.8662 \).
2.3. CRUSTAL SOURCES FROM THE WESTERN PART OF ROMANIA AND SERBIA

The Western and South-Western territory of Romania is the most important region of the country as concerns the seismic hazard determined by local crustal earthquakes sources. The seismic risk in the region is high due to local risk factors and vulnerabilities: weak dwellings, old and unprotected buildings in the large cities, dams and chemical factories, high density of localities, great towns (Timisoara, Arad and Oradea), and so on (Fig. 1). More than 30 hydroenergetic dams are located in this area, the largest ones being “Portile de Fier I” (PFI) and “Portile de Fier II” (PFII)".

Fig. 3 – The frequency-magnitude distribution for Fagaras-Campulung-Sinaia crustal source, for 3 sets of data.
The contact between the Panonian Depression and the Carpathian orogen lies entirely along the Western part of the Romanian border. Even if no significant tectonic or geostructural differences are noticed, two enhancements in the seismicity distribution can be identified in two relatively distinct active areas: **Banat zone (BAN)** to the South and Crisana-Maramures zone (CM) to the North. The seismicity of the Banat zone is characterized by many earthquakes with magnitude \( M_w > 5 \), but not exceeding 5.6 \([1]\). The largest earthquake occurred after 1900 is the one from **July 12, 1991** \((M_w = 5.6)\). The **Serbian seismogenic source** named IBAR \([10]\) is characterized by the occurrence of numerous crustal earthquakes with \( M_w > 5.0 \). The largest earthquake occurred in the zone on **April 08, 1893**, has the magnitude \( M_s = 6.6 \) \([11]\).

**Banat region (BAN)** on the magnitude interval \([4.0, 5.6]\), for the entire time interval of the catalogue (equation 9) and after 1900 (equation 10):

\[
\log N_{\text{cum}} = - (0.82 \pm 0.08) M_w + (4.73 \pm 0.38) \quad \text{– upper line,} \quad (9)
\]

with the correlation coefficient \( R = 0.98 \) and the \( \sigma = 0.12 \).

\[
\log N_{\text{cum}} = - (0.74 \pm 0.06) M_w + (4.31 \pm 0.27) \quad \text{– lower line,} \quad (10)
\]

with the correlation coefficient \( R = 0.99 \) and the \( \sigma = 0.09 \).

Equation (10) was used for hazard computations and for this reason we have converted it into epicentral intensities using equation (11) \([12]\):

\[
M_w = 0.6 I_0 + 0.5. \quad (11)
\]

Equation (10) becomes equation (12):

\[
\log N_{\text{cum}} = -0.44 I_0 + 3.94 \quad (12)
\]

and the statistical parameters for PSH (Table 1) are: \( a_i = 3.94, \ b_i = 0.44, \ a_i = a_i \ln 10 = 9.0722, \ b_i = b_i \ln 10 = 1.0131 \).

The **Danubian seismogenic zone (DAN)** represents the Western extremity, adjacent to the Danube River, of the orogenic unit of the Southern Carpathians. The rate of seismic activity is relatively high, especially at the border and beyond the border with Serbia, across the Danube River. The magnitude does not exceed 5.6.

The fault plane solutions are available for three earthquakes (the largest earthquake \( M_w = 5.6 \) occurred in **July 18, 1991** and indicate normal faulting with the T axis striking roughly N-S, in agreement with the general extensional stress regime in the Southern Carpathians \([1]\).

**Danubian crustal earthquakes (DAN)** were determined for magnitudes between 4.0 and 5.6 for two time intervals. One for the whole catalogue of earthquakes (equation 13) and the other for the earthquakes occurred after 1900 (equation 14):
\[
\lg N_{\text{cum}} = - (0.82 \pm 0.09)M_w + (4.94 \pm 0.46) - \text{upper line,} \quad (13)
\]
with \( R = 0.97 \) and \( \sigma = 0.15 \).

\[
\lg N_{\text{cum}} = - (0.62 \pm 0.06)M_w + (3.74 \pm 0.31) - \text{lower line,} \quad (14)
\]
with \( R = 0.98 \) and \( \sigma = 0.10 \).

Equation (14) was used for hazard computations and for this reason we have converted it into epicentral intensities using equation (11). Equation (14) becomes equation (15):

\[
\lg N_{\text{cum}} = -0.37I_0 + 3.43, \quad (15)
\]

and the statistical parameters for PSH (Table 1) are: \( a_i = 3.43 \), \( b_i = 0.37 \), \( \alpha_i = a_i \ln 10 = 7.8979 \), \( \beta_I = b_i \ln 10 = 0.8520 \).

The noncumulative and cumulative distributions for both time intervals and regions are plotted in Figure 4.

The frequency–magnitude distribution for the Serbian seismogenic source is estimated for the magnitude interval \([3.7, 6.6]\) in equation (16) and for the intensity interval \([4.5, 9.0]\) in equation (17). Both distributions are plotted in Figure 5.
Earthquake risk classes for dams

3. ATTENUATION LAWS

It is essential, for a probabilistic estimation of the seismic hazard, to constrain as much as possible how the energy of the seismic waves attenuates when propagating from the source to the site. The attenuation law for the used seismic sources is given in the equation (18) [13] modified by [14] and [1]:

\[ I = I_0 - c_1 \log(D_h/h) - c_2 \alpha \log(e^{D_h} - h); \]  

where: \( I \) is the intensity, \( I_0 \) is the epicentral intensity, \( c_1, c_2 \) and \( a \) are different for each region; \( \log e = 0.006514; D_h \) is the hypocentral distance, and \( h \) is the depth presented, for each seismic source, in Table 1.

For Vrancea we have used: \( c_1 = 3.16, c_2 = 3.02 \) and \( a = 0.0015 \) (1/m) obtained by [9].

For Fagaras-Campulung-Sinaia zone we have used: \( c_1 = 3.46, c_2 = 3.12 \) and \( a = 0.0013 \) (1/m) and for the active zones from the South-Western part of Romania (BAN, DAN) and from Serbia (IBAR) we have used the attenuation law obtained by [15], with \( c_1 = 3.0, c_2 = 3.0 \) and \( a = 0.0015 \) (1/m).

\[ \log N_{cum} = -(0.87 \pm 0.03)M_s + (5.68 \pm 0.18), \]  

with \( R = 0.99 \) and \( \sigma = 0.11 \),

\[ \log N_{cum} = -0.50I_0 + 4.82 \]

and the statistical parameters for PSH (Table 1) are: \( a_i = 4.82, b_i = 0.50,\alpha_i = a_i \ln10 = 11.0985, \beta_i = b_i \ln10 = 1.1513. \)
4. PROBABILISTIC SEISMIC HAZARD ASSESSMENT

The parameters presented in Table 1 are input parameters for the seismic hazard assessment [6], [16] used for the implementation of the risk classes theory [17] in anti-seismic protection in the case of special constructions and strategic objectives, such as, in our case, the dams situated on Danube, Olt, Jiu and Lotru rivers. Table 1 presents the characteristics of each source that will be used in the seismic hazard assessment.

Table 1

<table>
<thead>
<tr>
<th>Seismic sources</th>
<th>Coordinates</th>
<th>Average depth</th>
<th>Mmin</th>
<th>Mmax</th>
<th>b</th>
<th>Imin</th>
<th>Imax</th>
<th>b_i</th>
<th>Activity rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMP</td>
<td>24.00/45.00 – 26.00/45.00</td>
<td>15</td>
<td>4.0</td>
<td>6.5</td>
<td>0.76</td>
<td>5.0</td>
<td>8.5</td>
<td>0.50</td>
<td>1.15325</td>
</tr>
<tr>
<td></td>
<td>24.00/46.00 – 26.00/46.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DAN</td>
<td>21.00/44.90 – 22.30/44.15</td>
<td>15</td>
<td>4.0</td>
<td>5.6</td>
<td>0.71</td>
<td>5.5</td>
<td>9.0</td>
<td>0.43</td>
<td>0.98091</td>
</tr>
<tr>
<td></td>
<td>21.80/45.70 – 23.00/44.80</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BAN</td>
<td>21.00/44.90 – 21.90/45.80</td>
<td>10</td>
<td>4.0</td>
<td>5.6</td>
<td>0.82</td>
<td>5.5</td>
<td>9.0</td>
<td>0.50</td>
<td>1.16056</td>
</tr>
<tr>
<td></td>
<td>20.70/46.10 – 21.30/46.40</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>IBAR</td>
<td>19.80/44.00 – 20.80/44.60</td>
<td>14</td>
<td>3.7</td>
<td>6.6</td>
<td>0.87</td>
<td>4.5</td>
<td>9.0</td>
<td>0.54</td>
<td>1.24340</td>
</tr>
<tr>
<td></td>
<td>21.00/43.10 – 21.80/43.80</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>VRI</td>
<td>26.00/45.50 – 26.45/45.25</td>
<td>130</td>
<td>5.0</td>
<td>7.7</td>
<td>0.72</td>
<td>4.0</td>
<td>10.5</td>
<td>0.48</td>
<td>1.10524</td>
</tr>
<tr>
<td></td>
<td>26.43/46.10 – 27.10/45.87</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For the input data set obtained in the present work and presented shortly in Table 1, we applied the algorithm and the computer program of [6] to compute the annual seismic hazard values \( H_a \) in 324 points covering the Western half of Romania, delimited by the following 4 corners: long E 20.0/ lat N 43.5; long E 24.5/ lat N 43.5; long E 20.0/ lat N 48.0; long E 24.5/ lat N 48.0.

Using equation (19) we have computed the hazard values \( H_{Tr} \) for different return periods \( (Tr) \). These values were represented as hazard maps for the Western part of Romania.

\[
H_{Tr} = 1 - (1 - H_a)^{Tr},
\]

(19)

In Fig. 6 are represented on a map the studied dams, situated on Olt, Lotru, Jiu and Danube rivers from the South-Western part of Romania.
In Fig. 7 we present the hazard maps in terms of probability of exceedence for a seismic exposure period of $T_r = 475$ years and for 2 values of macroseismic intensities ($I = VIII$ and IX) and highlight the hazard values in the dam’s sites.

Fig. 7 – Seismic hazard maps for the Western part of Romania expressed in terms of macroseismic intensities for one return periods of $T_r = 475$ years and two intensities VIII and IX.

The hazard maps in terms of macroseismic intensities for different return periods ($T_r = 50, 100, 475$ and $1000$ years) and highlight the intensity values in the dam sites are presented in Fig. 8.
Fig. 8 – Seismic hazard maps for the South-Western part of Romania expressed in terms of macroseismic intensities for 4 return periods of $T_r = 50, 100, 475$ and 1000 years.

5. DAMS RATING IN SEISMIC RISK CLASSES

Dam owners and regulators must ensure that dams are safely operated and present no risk to the public in case of an earthquake. While most old or new dams in recognized seismic regions have been evaluated and analyzed for seismic loads, dams located in areas of moderate or low seismicity have been given less systematic attention. In such cases, owners of many dams or officials in charge of dam safety programs may consider comparative assessment of the seismic risk associated with their dams and establish priorities, as needed.

Various risk factors and weighting points can be used to approximately quantify the total risk factor (TRF) of any dam [16]. The TRF depends on the dam
characteristics \(^{(i)}\) as type, age, size, the downstream risk potential \(^{(ii)}\), and the dam vulnerability, which depends on the seismic hazard of the site evaluated in the previous section of this paper \(^{(iii)}\).

\(^{(i)}\) The dam structure influence is represented by the sum of capacity, height, and age risk factors (\(CRF + HRF + ARF\)). The capacity risk factor \((2 \leq CRF \leq 6)\) and the height risk factor \((2 \leq HRF \leq 6)\) indicate that high dams or large reservoirs can cause significant flooding. The age rating factor \((1 \leq ARF \leq 3)\) expresses that old dams are often more vulnerable than modern dams because of possible deterioration, lack of maintenance, use of obsolete modes of construction (concrete masonry or hydraulic fill), insufficient compaction, reservoir situation, or insufficient foundation treatment. For dams with unknown age we have considered the \(ARF = 3\). The characteristics needed for the computation of \(CRF\), \(HRF\) and \(ARF\) using the tables given by [17] were taken from [18].

\(^{(ii)}\) The downstream hazard factor (\(DHF\)) is based on population and property at risk. The overall downstream hazard factor (\(DHF\)) is defined as: \(DHF = ERF + DRI\), where the downstream evacuation requirements factor (\(ERF\)) depends on the human population at risk. The downstream damage risk index (\(DRI\)) is based on the value of private, commercial, industrial, or government property in the potential flood path. These factors should preferably be obtained from a combination of detailed dam breach, inundation mapping, and economic studies.

The \(DHF\) should be updated whenever new information becomes available or when the dam is repaired, modified, or raised. When it is not cost-effective to obtain the \(ERF\) and \(DRI\) from detailed studies, the downstream hazard potential rating of the NID can be used to obtain a substitute value of the \(DHF\).

\(^{(iii)}\) The vulnerability rating is a function of the site-dependent seismic hazard and observed performance of similar dams, as defined by a predicted damage factor: \(PDF = 2.5 \times f(ESI)\), where: \(ESI = \) the severity index, a graphical information depending on two parameters: the dam type (Table 3, Column 11) and the maximum possible ground motion value (Table 2) and was assessed using [17].

Using the formulas of [12], the local intensities obtained in Section 4, using PSH assessment, for the dams situated on Danube, Olt, Jiu and Lotru rivers, for a return period of \(T_r = 1000\) years were converted into ground accelerations and presented in Table 2 together with the severity index \(ESI\).

The ground motion parameters obtained in the previous chapter for each dam site are input parameters for the evaluation of the \(PDF\) used for the implementation of the above described theory in anti-seismic protection in the case of special constructions and strategic objectives, such as, in our case, the most important dams situated in the area (Table 2).

Using the above described methodology, the peak ground accelerations from Table 2, the characteristics of dams and the downstream geographical information we have computed the seismic risk classes (Table 3) for all dams situated on Danube, Olt, Jiu and Lotru rivers (Table 2).
Table 2
The maximum expected ground accelerations for the sites where are located the dams from Danube, Olt, Jiu and Lotru rivers using the probabilistic approach

<table>
<thead>
<tr>
<th>No.</th>
<th>DAM</th>
<th>RIVER</th>
<th>LONG</th>
<th>LAT</th>
<th>I (MSK) $(T_r = 1,000)$</th>
<th>Acc(cm/s²) $T_r = 1,000$</th>
<th>ESI</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>GOGOSU</td>
<td>Danube</td>
<td>22.521</td>
<td>44.405</td>
<td>8.6</td>
<td>315</td>
<td>5.600944</td>
</tr>
<tr>
<td>2</td>
<td>POR FIER I</td>
<td>Danube</td>
<td>22.53</td>
<td>44.672</td>
<td>8.7</td>
<td>320</td>
<td>5.62432</td>
</tr>
<tr>
<td>3</td>
<td>POR FIER II</td>
<td>Danube</td>
<td>22.565</td>
<td>44.304</td>
<td>8.5</td>
<td>290</td>
<td>5.600944</td>
</tr>
<tr>
<td>4</td>
<td>CURTISOARA</td>
<td>Jiu</td>
<td>23.269</td>
<td>45.057</td>
<td>8.7</td>
<td>320</td>
<td>17.8969</td>
</tr>
<tr>
<td>5</td>
<td>TARGU JIU</td>
<td>Jiu</td>
<td>23.269</td>
<td>45.057</td>
<td>8.7</td>
<td>320</td>
<td>19.75943</td>
</tr>
<tr>
<td>6</td>
<td>TURCINESTI</td>
<td>Jiu</td>
<td>23.269</td>
<td>45.057</td>
<td>8.7</td>
<td>320</td>
<td>19.75943</td>
</tr>
<tr>
<td>7</td>
<td>VADENI</td>
<td>Jiu</td>
<td>23.348</td>
<td>45.13</td>
<td>8.7</td>
<td>320</td>
<td>19.75943</td>
</tr>
<tr>
<td>8</td>
<td>V. SADULUI</td>
<td>Jiu</td>
<td>23.382</td>
<td>45.183</td>
<td>8.7</td>
<td>320</td>
<td>12.32765</td>
</tr>
<tr>
<td>9</td>
<td>TURCENI</td>
<td>Jiu</td>
<td>23.385</td>
<td>46.099</td>
<td>8.6</td>
<td>315</td>
<td>11.56055</td>
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The TRF is expressed in equation (20):

$$TRF = \left[ \left( CRF + HRF + ARF \right) + DHF \right] PDF.$$  \hfill (20)

If the TRF is less than 120, the risk class is considered moderate (II) and if $120 \leq TRF \leq 250$, the risk class is considered high (III). For values of TRF higher than 250 the risk class is extreme (IV).

5. CONCLUSIONS

This work is a useful tool for the assessment of the seismic risk and implementation of anti-seismic protection measures in the case of special constructions and strategic objectives, such as, hydroenergetic large constructions.

From Table 3 we can conclude that almost all dams have a high risk class equal to III. The only exception is Bradisor Dam with a moderate to high risk. The explanation is given by the fact that Bradisor is an arch dam and this type of dams had always the best behavior during an earthquake and the PDI risk factor is much smaller than for other kind of dams.

REFERENCES

4. *** Romplus catalogue-updated until 2010 by the department of Data Acquisition of the National Institute for Earth Physics-Bucharest.


