Statistics of seismicity for Vrancea subcrustal source

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ABSTRACT:
Vrancea subcrustal seismic source is influencing more than two thirds of the Romanian territory as well as parts of Republic of Moldova and Bulgaria. In this paper we address the influences of the time period of earthquakes catalogue and of lower threshold magnitude upon the values of the seismicity parameters that are characteristic for Vrancea subcrustal source. The earthquake catalogue used in the statistical analysis of Vrancea subcrustal source is recently revised by the National Institute of Earth Physics of Romania. The *a* and *b* seismicity parameters are obtained through maximum likelihood method and the residuals between empirical and analytic values of mean annual rates of earthquakes exceeding a given magnitude are analyzed. The results are obtained within BIGSEES Project financed by the Romanian National Authority for Scientific Research.

Keywords: seismicity, subcrustal, Vrancea, aleatory, epistemic

1. GENERAL CONSIDERATIONS

The study of seismicity is of major importance in the seismic hazard analysis framework. In this paper we address the influences of the time span of earthquakes catalogue and of lower threshold magnitude upon the values of the seismicity parameters that are characteristic for Vrancea subcrustal (intermediate depth) source. The influence of the time span of the earthquake catalogue as well as the influence of the lower threshold magnitude are investigated by considering the last 100 years for earthquakes exceeding moment magnitude 5 and 200 years for earthquakes exceeding moment magnitude 6. The validity of the exponential distribution of probability for the mean annual rates of earthquakes exceeding a given magnitude is investigated through goodness-of-fit tests. The a and b seismicity parameters are obtained through maximum likelihood method and the residuals between empirical and analytic values of mean annual rates of earthquakes exceeding a given magnitude are analyzed. The results are compared and the consequences on the results of the probabilistic seismic hazard analysis are analyzed. Besides the aleatory uncertainties considered in the analysis, the epistemic uncertainties are taken into consideration as well through 90% confidence interval for the mean value of the moment magnitude of the earthquakes considered in the catalogue. The a and b seismicity parameters are also evaluated for the lower-bound and upper-bound values of the mean moment magnitude, and the analysis of residuals is presented.

2. SEISMIC SOURCES INFLUENCING ROMANIAN TERITORRY

The seismic sources contributing to the earthquake hazard of Romania are defined in the studies of the National Institute for Earth Physics (NIEP). In Figure 2.1 the seismic sources influencing the Romanian territory are presented: 13 sources of crustal depths and one enclosing the intermediate-depth seismicity manifested in Vrancea region. The contours of the seismic source's areas are refined starting from the definition given by (Radulian et al, 2000) to take into account the distribution of recent seismicity, keeping the same stress field characteristics. The SERBIA source is defined taking into account the known fault distribution and the epicentres of events with *Mw* at least equal to 5 as reported in SHARE catalogue. Sources in North Eastern Bulgaria are defined after (Simeonova et al, 2006).

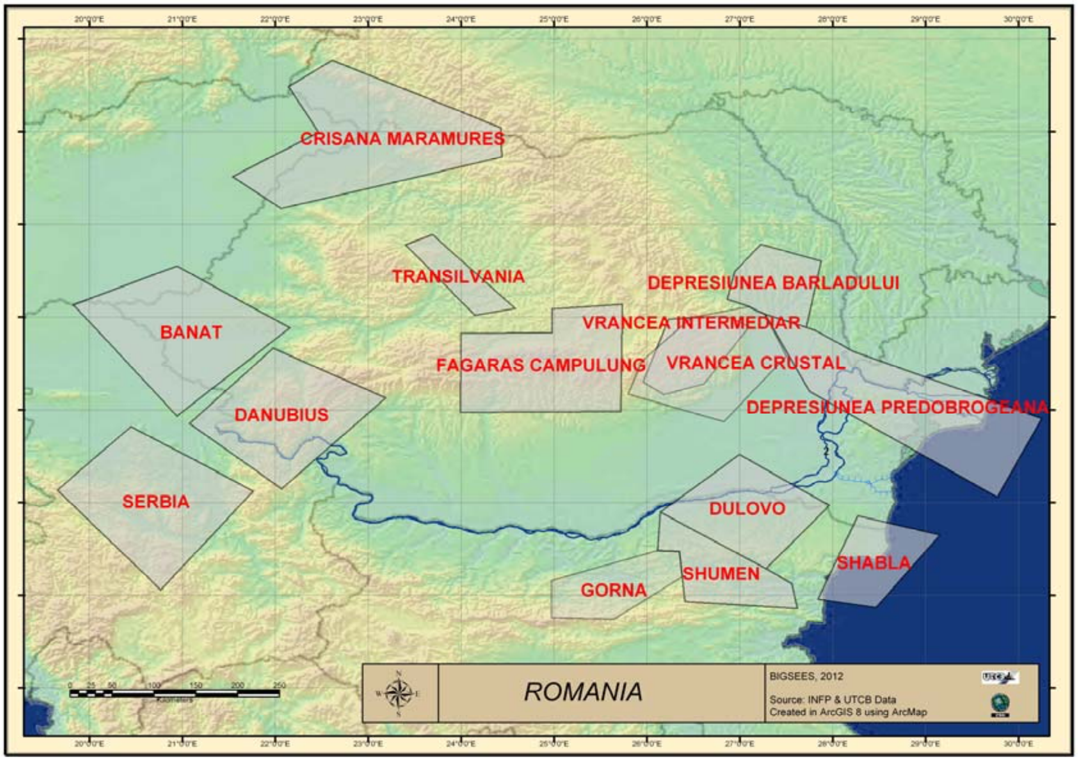

Figure 2.1. Sources contributing to the seismic hazard of Romania

3. VRANCEA SUBCRUSTAL (INTERMEDIATE DEPTH) SEISMIC SOURCE

Out of the 14 seismic sources presented in Figure 2.1, Vrancea subcrustal seismic source is the most active and powerful and is influencing more than two thirds of the Romanian territory as well as parts of Republic of Moldova and Bulgaria.

The major seismic hazard for the most part of Romania is generated by Vrancea subcrustal source (hypocentral depths between 60 and 170 km) (Lungu et. al., 2000). Most frequently the focal depths (Marmureanu et. al., 2010) are in the range of 90 to 120 km (e.g. earthquakes of 1738, 1838, 1977) or in the range of 130 to 150 km (earthquakes of 1802, 1940, 1986). The seismicity sharply decreases at depth larger than 170 - 180 km. The deepest focus in Vrancea is located at a depth of 218 km for a seismic event that occurred in 1982 (M_W = 4.1) (Ismail-Zadeh et. al., 2012). Most intermediate depth seismic events occurring in Vrancea have a rupture area propagating on the NE-SW direction, tangent to the Carpathian Mountains. Numerous studies are addressing the shape and the size of Vrancea epicentral area, i.e. (Lungu et. al., 2000; Ismail-Zadeh et. al., 2012; Sokolov et. al., 2008). In this paper the most recent revision of the contour of Vrancea subcrustal source shown in Figure 2 is considered. The Vrancea subcrustal seismic source is surrounded towards the exterior of the Carpathian Mountains by a zone of about 7000 km^2 in which normal-depth earthquakes are produced, named Vrancea crustal source (Marmureanu et. al., 2010) shown in Figure 3.1.

The focal mechanisms of Vrancea subcrustal earthquakes exhibit an extension in the vertical direction and compression in the horizontal direction (Radulian et. al., 2000). The mechanisms of the earthquakes generated by Vrancea subcrustal source have not been reliably identified and assumptions of an end of subduction process are being taken into consideration in (Mocanu, 2010). Under these assumptions it is probable that the subducting slab is still coupled to the upper lithosphere while being pulled down by gravitational forces (Sperner et.al., 2001). By studying the crustal stress observation in (Müller et al., 2010) it is concluded that the subducted slab beneath Vrancea is only weakly coupled to the crust. In (Milsom, 2005) it is suggested that due to the movement of the Vrancea seismic zone away from the areas of recent volcanic activity, there might be a form of detachment of it.

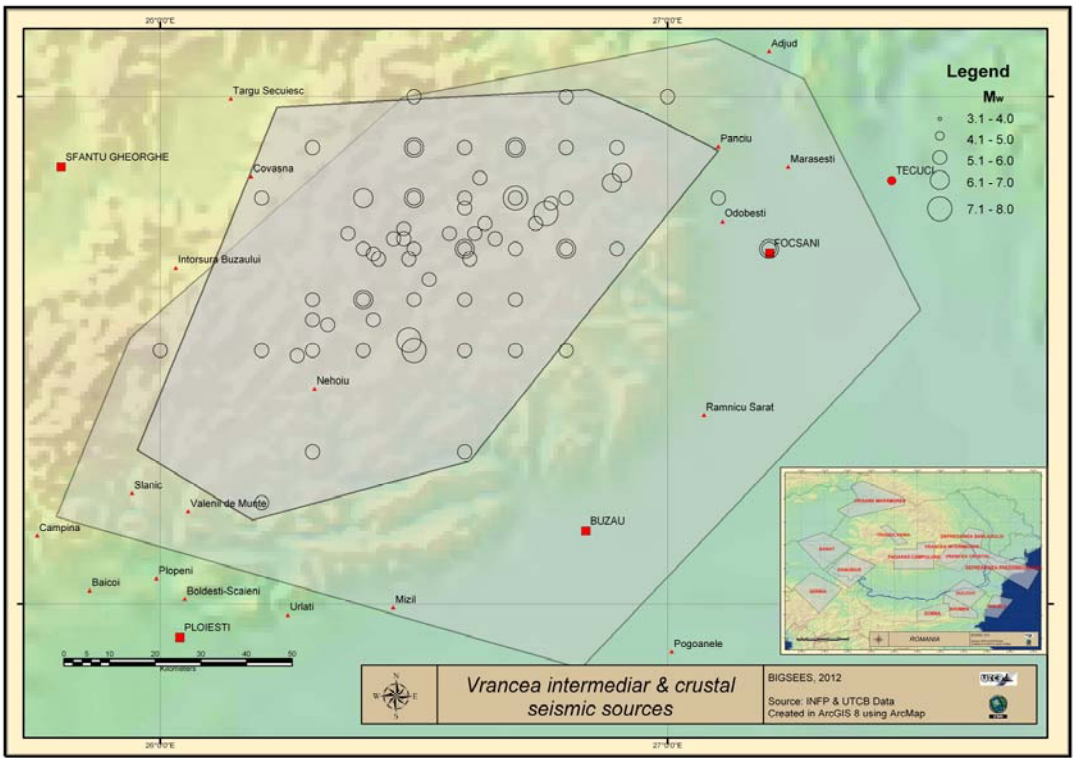

Figure 3.1. Vrancea subcrustal and crustal seismic sources and the epicentres of earthquake considered in the seismicity analysis

4. STATISTICS OF SEISMICITY FOR VRANCEA SUBCRUSTAL SOURCE

The earthquake catalogue used in the statistical analysis of Vrancea subcrustal source is recently revised by the National Institute of Earth Physics of Romania to take into account the recently achieved information on past strong earthquakes (Rogozea et al, 2012, Constantin et al, 2011) and results of the SHARE Project (Stucchi et al, 2012). The activity rate of Vrancea subcrustal source is characterized by 3 to 5 earthquakes of $M_W > 6.5$ per century (Ismail-Zadeh et. al., 2012). In the 20th century earthquakes with moment magnitudes of $M_W > 6.7$, occurred in October 1908 ($M_W = 7.1$, $h = 125$ km), November 1940 ($M_W = 7.7$, $h = 150$ km), March 1977 ($M_W = 7.4$, $h = 94$ km), August 1986 ($M_W = 7.1$, $h = 131$ km) and May 1990 ($M_W = 6.9$, $h = 91$ km), respectively.

The statistics of seismicity is performed considering a lower bound moment magnitude $M_{w,min}$ above which the completeness requirement of the catalogue is fulfilled and an upper bound (maximum credible) moment magnitude $M_{w,max}$. Vrancea catalogue of seismic events in the 19th and 20th century is complete for moment magnitudes above $M_{w,min} = 6.0$, while for the seismic events of 20th century the lower-bound moment magnitude is $M_{w,min} = 5.0$. The upper bound moment magnitude considered in the analysis is $M_{w,max} = 8.1$ (Lungu et. al., 2000; Lungu et. al., 1999). An excerpt of Vrancea subcrustal source seismic catalogue for the 19th and 20th centuries with earthquakes at least as large as moment magnitude 6 is given in Table 4.1.

Table 4.1. Vrancea subcrustal seismic source – earthquakes with moment magnitude larger or equal to M_w = 6.0 (excerpts)

Year	Month	Day	Lat.	Lon.	Depth, km	M_w
1802	10	26	45.70	26.60	150.0	7.90
1812	3	5	45.70	26.60	130.0	6.50
1821	2	10	45.70	26.60	150.0	6.60
1821	11	17	45.70	26.60	130.0	6.50
1821	9	29	45.70	26.60	150.0	6.10
1829	11	26	45.80	26.60	150.0	7.30
1831	8	3	45.70	26.60	100.0	6.10
1835	4	21	45.70	26.60	130.0	6.50
1838	1	23	45.70	26.60	150.0	7.50
1844	3	6	45.70	26.60	110.0	6.00
1848	1	1	45.70	26.60	130.0	6.50
1854	10	28	45.70	26.60	150.0	6.50
1862	10	16	45.70	26.60	130.0	6.50
1868	11	13	45.70	26.60	150.0	6.80
1868	11	27	45.70	26.60	135.0	6.50
1880	12	25	45.70	26.60	130.0	6.80
1888	8	19	45.70	26.60	100.0	6.50
1893	8	17	45.70	26.60	100.0	7.10
1893	9	10	45.70	26.60	99.9	6.50
1893	5	1	45.70	26.60	120.0	6.20
1894	8	31	45.70	26.60	130.0	7.10
1894	3	4	45.70	26.60	130.0	6.50
1896	3	11	45.70	26.60	150.0	6.60
1896	11	24	45.70	26.60	100.0	6.10
1903	9	13	45.70	26.60	70.0	6.30
1904	2	6	45.70	26.60	75.0	6.60
1908	10	6	45.50	26.50	125.0	7.10
1912	5	25	45.70	27.20	90.0	6.70
1912	5	25	45.70	27.20	100.0	6.10
1919	4	18	45.70	26.80	100.0	6.10
1919	8	9	45.70	26.60	120.0	6.00
1925	12	25	45.70	26.60	130.0	6.10
1928	3	30	45.90	26.50	120.0	6.00
1929	11	1	45.90	26.50	160.0	6.10
1929	5	20	45.80	26.50	100.0	6.00
1932	5	27	45.70	26.60	120.0	6.00
1934	3	29	45.80	26.50	90.0	6.60
1934	2	2	45.20	26.20	140.0	6.00
1935	7	13	45.30	26.60	140.0	6.00
1935	9	5	45.80	26.70	130.0	6.00
1936	5	17	45.30	26.30	140.0	6.00
1938	7	13	45.90	26.70	120.0	6.00
1939	9	5	45.90	26.70	120.0	6.20
1940	11	10	45.80	26.70	150.0	7.70
1940	10	22	45.80	26.40	125.0	6.50
1945	9	7	45.90	26.50	80.0	6.80
1945	12	9	45.70	26.80	80.0	6.50
1945	3	12	45.60	26.40	125.0	6.10
1946	11	3	45.60	26.30	140.0	6.00
1948	5	29	45.80	26.50	130.0	6.30
1973	8	20	45.74	26.48	73.0	6.00

1976	10	1	45.68	26.49	146.0	6.00
1977	3	4	45.77	26.76	94.0	7.40
1986	8	30	45.52	26.49	131.4	7.10
1990	5	30	45.83	26.89	90.9	6.90
1990	5	31	45.85	26.91	86.9	6.40
2004	10	27	45.84	26.63	105.4	6.00

The statistical analyses are performed in the following steps:

(i) empirical analysis (based on observation data) of number N_m of earthquakes with moment magnitudes at least equal to m and of mean annual frequencies λ_m of earthquakes with moment magnitudes at least equal to m, where $\lambda_m = N_m/t$ and t is the time interval considered in the analysis (the time duration of the catalogue considered in the analysis);

(ii) determination of seismicity parameters α and β (or a and b) using maximum likelihood method (McGuire, 2004); analytical determination of λ_m values using Gutenberg-Richter double truncated exponential law (McGuire, 2004):

$$\lambda_m = e^{\alpha - \beta m} \cdot \frac{1 - e^{-\beta (M_{\max} - m)}}{1 - e^{-\beta (M_{\max} - M_{\min})}} \qquad (4.1)$$

(iii) goodness-of-fit tests for the exponential distribution of probability of earthquake magnitudes; Kolmogorov-Smirnov, Chi square and Anderson-Darling tests (Soong, 2004) are performed;

(iv) determination of 90% confidence interval for the population mean $[\overline{m}_{0,05}; \overline{m}_{0,95}]$ in which, with 90% confidence, the “true” value of mean moment magnitude will lie; analytical determination of seismicity parameters α and β and λ_m using $\overline{m}_{0,05}$ and $\overline{m}_{0,95}$ values; the later values are obtained with t-Student distribution of probability (Soong, 2004):

(v) analysis of residuals between empirical and analytical values of λ_m; residuals are obtained as decimal logarithm of the ratio $\lambda_{m,\text{ empiric}} / \lambda_{m,\text{ analytic}}$. The sum of squared errors (SSE) is defined as:

$$SSE = \sum_{i=1}^{n} \left[\lg(\lambda_{m,empiric,i} / \lambda_{m,analytic,i})\right]^2 \qquad (4.2)$$

Steps (i)...(iii) incorporates in the analysis the effect of aleatory uncertainties upon the recurrence of seismic events, while steps (iv) and (v) incorporates the effect of epistemic uncertainties on the seismicity results.

The results of the statistical analysis described in steps (i) to (v) are presented hereinafter for the two cases of Vrancea catalogue described previously: seismic events of the 19th and 20th century with lower bound moment magnitude $M_{w,\min} = 6.0$; and seismic events of the 20th century with the lower-bound moment magnitude $M_{w,\min} = 5.0$. In both cases the upper bound moment magnitude is $M_{w,\max} = 8.1$. The seismicity parameters α and β (or a and b) are reported in Table 4.2, separately for the 20th century events exceeding moment magnitude 5.0 and for the 19th and 20th centuries events exceeding moment magnitude 6.0.

Table 4.2. Seismicity parameters for Vrancea subcrustal source

20th century; $M_{w,\min} = 5.0$				19th & 20th centuries; $M_{w,\min} = 6.0$			
α	β	a	b	α	β	a	b
10.3164	1.9589	4.4803	0.8507	10.6671	1.9887	4.6327	0.8637

The analytic mean annual frequencies of earthquakes obtained with Eq. (4.1) are represented in Figures 4.1.a & b with solid lines. The observed (empiric) mean annual frequencies are represented in Figures 4.1.a & b as well with crosses. One can notice the fit between empirical and analytical results. In Table 4.3 the values of the mean recurrence intervals of seismic events with moment magnitudes exceeding 5.0 up to 8.0 are presented. The values are based on the analytic values of mean annual frequencies λ_m of earthquakes with moment magnitudes at least equal to m. The results are in good agreement; nevertheless, one can notice a slightly stronger seismicity if one considers the earthquakes exceeding moment magnitude 6.0 in the 19th and 20th centuries. A moment magnitude 7.0 is likely to be exceeded, on average, three times per century and a moment magnitude 7.5 is likely to be exceeded, on average, once per century.

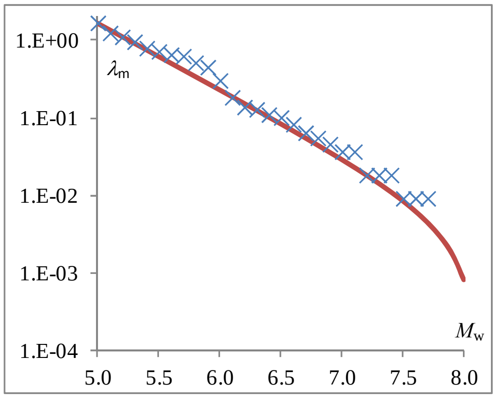

Figure 4.1.a. Mean annual rates of earthquakes, λ_m – empiric vs. analytic; 20th century; $M_{w,min}$=5.0

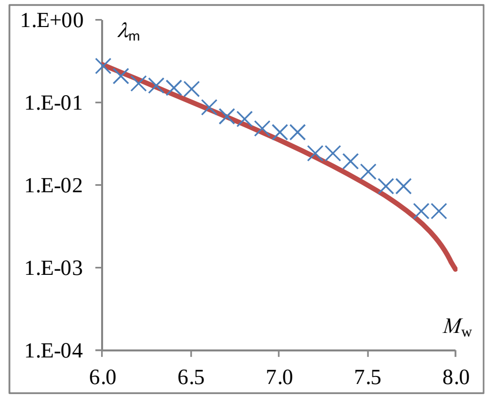

Figure 4.1.b. Mean annual rates of earthquakes, λ_m – empiric vs. analytic; 19th & 20th centuries; $M_{w,min}$=6.0

Table 4.3. Mean recurrence intervals of earthquakes exceeding moment magnitude M_w

20th century; $M_{w,min}$ = 5.0		19th & 20th centuries; $M_{w,min}$ = 6.0	
M_w	*MRI*	M_w	*MRI*
5.0	1	-	-
5.5	2	-	-
6.0	4	6.0	4
6.5	12	6.5	10
7.0	34	7.0	29
7.5	115	7.5	99
8.0	1187	8.0	1033

The goodness-of-fit of the exponential distribution of probability for earthquake magnitudes is checked by Q-Q plots in Figures 4.2. a & b as well as through Kolmogorov-Smirnov, χ^2 (chi squared) and Anderson-Darling tests. One can notice form Figures 4.2. a & b the appropriateness of the exponential distribution of probability for the earthquake moment magnitudes. Moreover, the results of the goodness-of-fit tests reveals acceptance of the exponential distribution hypothesis up to a significance level of 0.01.

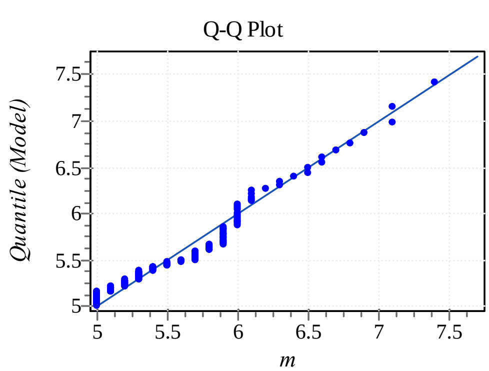

Figure 4.2.a. Q-Q plot for moment magnitude; 20th century; $M_{w,min}$=5.0

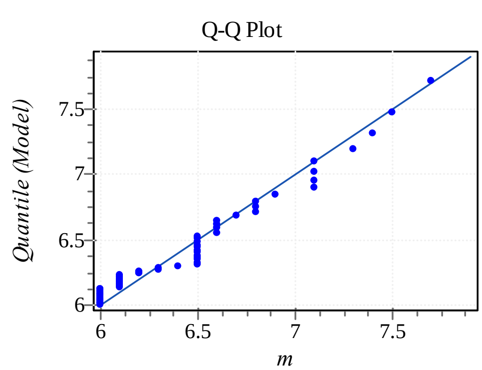

Figure 4.2.b. Q-Q plot for moment magnitude; 19th & 20th centuries; $M_{w,min}$=6.0

The lower and upper bounds of the 90% confidence interval for the population mean $[\overline{m}_{0,05};\overline{m}_{0,95}]$ in which, with 90% confidence, the "true" value of mean moment magnitude will lie are presented in Table 4.4. Based on the $\overline{m}_{0,05}$ and $\overline{m}_{0,95}$ values the seismicity parameters are reassessed with maximum likelihood method and their values are separately reported in Table 4.4. The empiric versus analytic results of mean annual rates of earthquakes are given in Figures 4.3.a & b.

Table 4.4. The lower and upper bounds of the 90% confidence interval for the population mean and the corresponding seismicity parameters

20th century; $M_{w.min}$=5.0				19th & 20th centuries; $M_{w.min}$=6.0			
$\overline{m}_{0,05}$ = 5.43		$\overline{m}_{0,95}$ = 5.57		$\overline{m}_{0,05}$ = 6.36		$\overline{m}_{0,95}$ = 6.58	
α	β	α	β	α	β	α	β
11.8519	2.2660	9.0749	1.7106	14.8721	2.6896	7.6364	1.4836

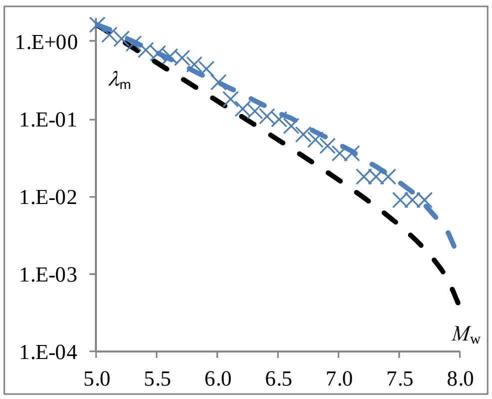

Figure 4.3.a. Mean annual rates of earthquakes, λ_m corresponding to 90% confidence– empiric vs. analytic; 20th century; $M_{w,min}$=5.0; empiric results are represented by crosses; analytic results are represented by dashed lines, as follows: black corresponds to the lower bound and blue corresponds to the upper bound

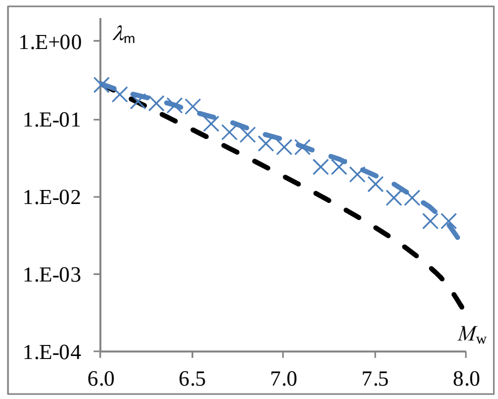

Figure 4.3.b. Mean annual rates of earthquakes, λ_m corresponding to 90% confidence– empiric vs. analytic; 19th & 20th centuries; $M_{w,min}$=6.0; empiric results are represented by crosses; analytic results are represented by dashed lines, as follows: black corresponds to the lower bound and blue corresponds to the upper bound

The SSE is obtained with Eq. (4.2) and the results are given in Table 4.5 for the sample mean $\overline{m}$ as well as for the lower bound $\overline{m}_{0,05}$ and upper bound $\overline{m}_{0,95}$ of the population mean. One can notice from Table 4.5 that the minimum value of SSE corresponds to the upper bound value of the population mean.

Table 4.5. SSE values for the observed vs. calculated mean annual rates of earthquakes

20th century; $M_{w,min}$=5.0 *SSE* for:			19th & 20th centuries; $M_{w,min}$=6.0 *SSE* for:		
$\overline{m}$	$\overline{m}_{0,05}$	$\overline{m}_{0,95}$	$\overline{m}$	$\overline{m}_{0,05}$	$\overline{m}_{0,95}$
0,38	2,41	0,29	0,42	3,76	0,17

5. CONCLUSIONS

The major part of seismicity in Romania is induced by Vrancea subcrustal seismic source. The basic information on earthquake occurrence time, position of hypocentre and moment magnitude is from the earthquake catalogue recently revised by the National Institute for Earth Physics of Romania. The statistics of the seismicity provided the parameters *a* and *b* to be used within the BIGSEES Project for probabilistic seismic hazard analyses. The residuals analysis revealed results for properly assessing the differences between observed and predicted values of mean annual rates of earthquakes. The seismicity of Vrancea subcrustal source of the past 100 years and 200 years respectively is statistically stable and reliable.

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