THE RISK ANALYSIS OF SEISMIC ACTIVITY INCIDENCE IN ROMANIA

I. M. Dragan, Al. Isaic-Maniu
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Academy of Economic Studies, Bucharest, Romania

e-mail: irina.dragan@csie.ase.ro, al.isaic-maniu@csie.ase.ro

ABSTRACT

In Romania there is one of most powerful seismic activity region from Europe, known as Vrancea. In the past 300 years, a single major seismic event occurred with an epicenter outside this area (1916). This paper starts from going over all major seismic events, with a magnitude of over 6 degrees on Richter's scale, which were documented. Was tested the most plausible statistic behavioral model and was determined the probabilities for future large scale earthquakes, by different time horizons.

Key words: seismic risk, modeling, validation, prediction, statistic distribution

1 INTRODUCTIVE FEATURES

Europe, from the geologically point of view, confirms high seismic risk areas such as Italy, Turkey, Iceland, Serbia, Bulgaria, Greece and Romania, as in figure 1. The seismic intensity zones are marked by color code. So in Romania stand out the Eastern region of the country (Figure 2) the Carpathian Mountains. Agglomerations of black dots on the map represent earthquakes frequencies. One can remark a region of high concentration of earthquakes, which is known as the Vrancea area.

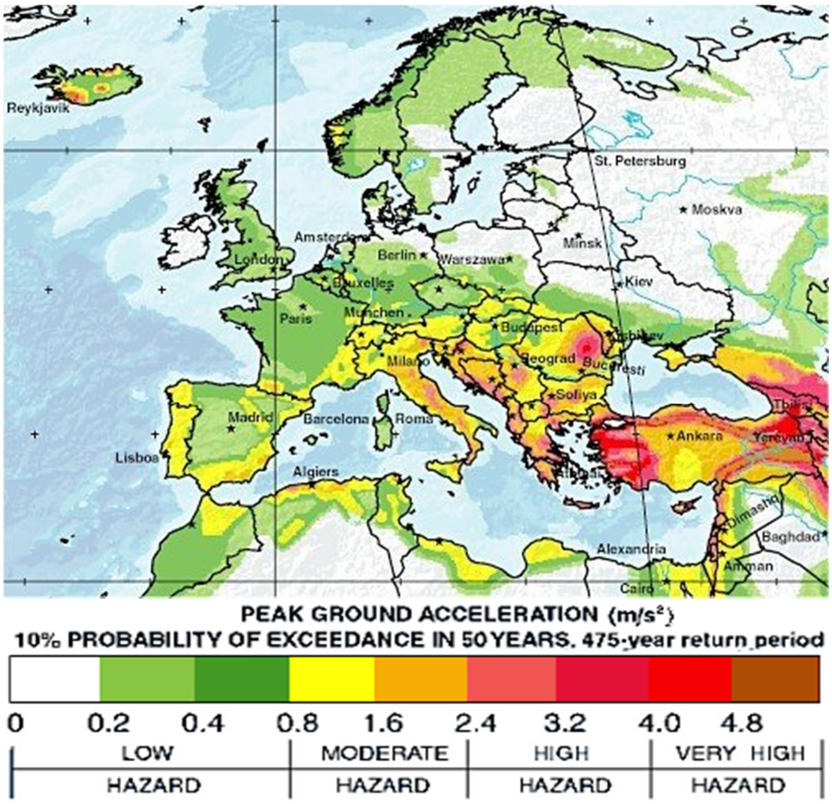
In general, is recognized that the occurrence of major seismic phenomena is a "rare event" from a statistical point of view. Due to the very large time horizon that can be taken into observation as against to registering events in artificial systems, as well as the non-periodicity of these events, there is the possibility of interpretation and statistical modeling of these seismic phenomena. In Romanian: Dragomir (2009), Lungu (1999), Lungu and Arion (2000), Radulescu (2004).

The statistical studies regarding the earthquakes usually start from the fact that rare events are best described using the exponential law – if considering the succession of time intervals between events, or Poisson's law – if it is intended to model the frequency of earthquakes (Săcuiu & Zorilescu, 1978; Johnson, Kotz & Balakrishnan, 1994; Evans, Hasting & Peacock, 2000).

The easiness of using these two distribution laws, distinct in nature, consists of the fact that they are defined by the same parameter, characterizing the same phenomenon – the behavior of a system in time, from both continuous and discrete points of view. A previous study made on seismic phenomena in Romania (Voda & Isaic-Maniu, 1983) covering the time period 1400-1977, has failed to confirm the hypothesis of an exponential behavior, the confirmed model being the bi-parametric Weibull model.

In the followings, we shall extend the area of investigation starting with the year 1100, with some additions to the identified supplementary information, as well as to the earthquake in 1977, the last one taken into account in the previous study.

We considered major seismic events those with a level of over 6 degrees on Richter's scale. Obviously, historical assessments are somewhat subjective, as the intensity was evaluated indirectly, since Mercalli (1931) and Richter's (1956) scales are more recent. The chronicles used to register that: "the earth had been shaken and the bells were ringing by themselves in Golia's tower" (n.n. Iasi – Romania), which indicates that an important seismic event took place. We used information in the profile literature (Constantinescu & Marza, 1980) as well as other official sources as those of the National Institute for the Physics of Earth (www.infp.ro).



Source http://geology.about.com/

Figure 1. The hazard of seismic activity in Europe

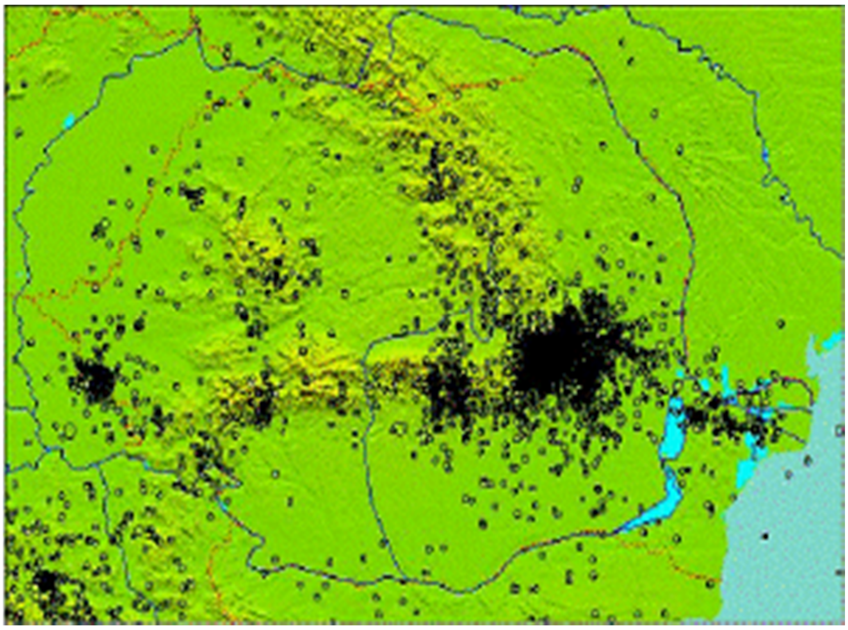


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Figure 2. The seismic activity in Romania

2 THE RECORD OF MAJOR SEISMIC ACTIVITY

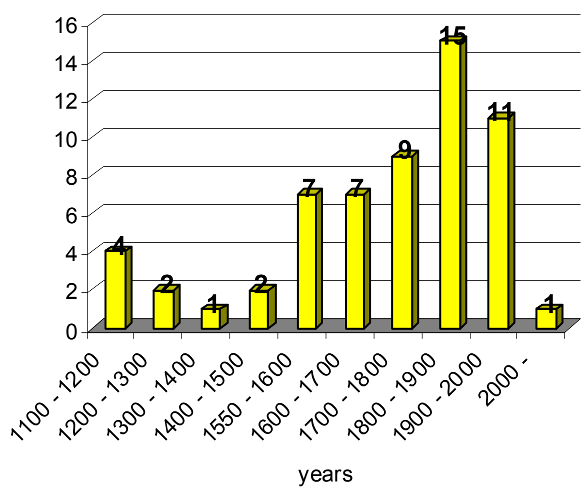
The main seismic events which occurred in Romania, and their characteristics, as they were recorded at the time in documents, or in modern and official registrations, were as follows in table 1.

Table 1. The main indicators of risk and reliability

November 5th, 1107	6.2 degrees Richter	January 18th, 1778	6.1 degrees Richter
August 8th, 1126	6.2 degrees Richter	March 18th, 1784	5.8 degrees Richter
April 1st, 1170	7.0 degrees Richter	April 6th, 1790	7-8 degrees Richter
February 13th	7.0 degrees Richter	December 8th, 1793	6.1 degrees Richter
May 10th, 1230	7.1 degrees Richter	October 26th, 1802	7.9 degrees Richter
year 1276	6.5 degrees Richter	March 5th, 1812	6.5 degrees Richter
year 1327	7.0 degrees Richter	January 5th, 1823	6.0 degrees Richter
October 10th, 1446	7.3 degrees Richter	November 26th, 1829	7.5 degrees Richter,
August 29th, 1471	7.1 degrees Richter	October 15th, 1834	6.0 degrees Richter
November 24th, 1516	7.2 degrees Richter	January 23rd, 1838	7.5 degrees Richter
July 19th, 1545	6.7 degrees Richter	October 15th, 1847	6.2 degrees Richter
October 16th, 1550	7.2 degrees Richter	October 17th, 1859	6.0 degrees Richter
November 2nd, 1558	6.1 degrees Richter	April 27th, 1865	6.4 degrees Richter
August 17th, 1569	6.7 degrees Richter	November 13th, 1868	6.0 degrees Richter
May 10th, 1590	6.5 degrees Richter	November 23rd, 1868	6.5 degrees Richter
August 10th, 1590	6.1 degrees Richter	November 26th 1868	6.1 degrees Richter
August 4th, 1599	6.1 degrees Richter	October 10th, 1879	6.2 degrees Richter
May 3rd, 1604	6.7 degrees Richter	August 31st, 1894	7.1 degrees Richter
November 24th 1605	6.7 degrees Richter	September 13th, 1903	6.3 degrees Richter
January 13th, 1606	6.4 degrees Richter	October 6th, 1908	7.1 degrees Richter
October 8th, 1620	7.9 degrees Richter	May 25th, 1912	6.3 degrees Richter
August 9th, 1679	6.8 degrees Richter	January 26th, 1916	6.4 degrees Richter
August 8th, 1681	6.7 degrees Richter	March 29th, 1934	6.9 degrees Richter
June 12th, 1701	7.1 degrees Richter	November 10th, 1940	7.7 degrees Richter
October 11th, 1711	6.1 degrees Richter	March 4th, 1977	7.4 degrees Richter
May 31st, 1738	7.0 degrees Richter	August 30th, 1986	7.1 degrees Richter
December 7th, 1746	6.5 degrees Richter	May 30th, 1990	6.9 degrees Richter
year 1750	6.0 degrees Richter	October 27th, 2004	6.0 degrees Richter

In the area of Vrancea (analyses of the area in Ivan, 2007; Ivan, 2011; Ardelean, 1999) there are registered almost daily earthquakes under 3 degrees.

Figure 3. The distribution of major seismic events in 100 years intervals in Romania



3 THE STATISTIC REPRESENTATION OF MAJOR SEISMIC ACTIVITY

The registered data were processed firs of all, statistically descriptive. The results as distribution series are presented in Table 2, the grouping being done in intervals of 100 years.

Table 2 - The distribution of major seismic events in 100 years intervals

No.	Interval(years)	Number of major seismic events
1	1100 – 1200	4
2	1200 – 1300	2
3	1300 – 1400	1
4	1400 – 1500	2
5	1500 – 1600	7
6	1600 – 1700	7
7	1700 – 1800	9
8	1800 – 1900	15
9	1900 – 2000	11
10	2000 –	1
	TOTAL	n = 59

The series (Table 2 and Figure 3) seems to suggest an acceleration of events in the last 250 years: in the first decade D_1 one earthquake was registered; $Q_2(M_e) = 5.5$ earthquakes, and in $D_9 - 14.6$. This could be the effect of an energetic acceleration in the intensity of the activity of the terrestrial crust, but most probably it is the result of information inconsistencies in the medieval period which seem to suggest this seismic intensification. The maximum value in an interval of 100 years is 15 major seismic events (1800 – 1900). The total number of major earthquakes is 59. The average in a 100 year interval is 5.9, with a standard deviation of $\sigma = 4.75$ and a variation coefficient of CV = 0.805 which suggests a strong heterogeneity of the observation series. Standard error = 0.502.

Table 3 – Descriptive statistics

Statistic	Value
Sample Size	10
Range	14
Mean	5,9
Variance	22,544
Std. Deviation	4,7481
Coef. of Variation	0,80476
Std. Error	1,5015
Skewness	0,72385
Excess Kurtosis	-0,36372

The shape of the series is completed (table 3) with the values of the Skewness coefficient: $\hat{\beta}_1 = \frac{\mu_3}{(s^2)^{3/2}} = 0.724$ (where μ_3 is the centered moment of rank 3, and s^2 – the centered moment of rank 2), and respectively $\hat{\beta}_2$ - Kurtosis coefficient: $\hat{\beta}_2 = \frac{\mu_4}{\left(s^2\right)^2} = -0.364$ (where μ_4 is the centered moment of rank 4). The minimum value in a 100 year interval was 1, and none of intervals frequencies were zero. The value of the first quartile was Q_1 = 1.75 and the third was Q_3 = 9.5 respectively.

4 THE STATISTIC MODEL OF THE SEISMIC INCIDENCE ACTIVITY

In order to analyse the process of earthquake occurrence, we tested several distribution laws, obviously starting with "the law of rare events" – Poisson, continuing with the exponential law (Evans, 2000) and Weibul (Isaic-Maniu, 1983). For the series of 50 years interval (Dragan & Isaic-Maniu, 2011), the best results were obtained for the log-logistic statistic model (Johnson, Kotz & Balakrishnan, 1995; Evans & Hastings, 2000; Stephens, 1979; Paiva, 1984; Ahmad, Sinclair & Werritty, 1988) by filtering three different selection tests.

Probability Density Function (PDF)

$$f(x) = \frac{\beta}{\alpha}\left(\frac{x-\gamma}{\alpha}\right)^{\beta-1}\left(1+\left(\frac{x-\gamma}{\alpha}\right)^{\beta}\right)^{-2} \tag{1}$$

Cumulative Distribution Function (CDF):

$$F(x) = \left(1+\left(\frac{\alpha}{x-\gamma}\right)^{\beta}\right)^{-1} \tag{2}$$

For the distribution of 100 years interval, the best results were obtained for the Beta statistic model. The general formula for the probability density function of the beta distribution is:

$$f(x) = \frac{(x-a)^{\alpha_1-1}(b-x)^{\alpha_2-1}}{B(\alpha_1,\alpha_2)(b-a)^{\alpha_1+\alpha_2-1}}, a \le x \le b; \alpha_1, \alpha_2 > 0 \tag{3}$$

where α_1 and α_2 are the shape parameters, *a* and *b* are the lower and upper bounds, respectively, of the distribution, and $B(\alpha_1,\alpha_2)$ is the beta function. The beta function has the formula

$$B(\alpha,\beta) = \int_0^1 t^{\alpha-1}(1-t)^{\beta-1}\,dt \tag{4}$$

The case where *a* = 0 and *b* = 1 is called the standard beta distribution. The equation for the standard beta distribution is

$$f(x) = \frac{x^{\alpha_1-1}(1-x)^{\alpha_2-1}}{B(\alpha_1,\alpha_2)}, 0 \le x \le 1; \alpha_1, \alpha_2 > 0 \tag{5}$$

Typically we define the general form of a distribution in terms of location and scale parameters. The beta is different in that we define the general distribution in terms of the lower and upper bounds. However, the location and scale parameters can be defined in terms of the lower and upper limits as follows: location = *a*; scale = *b* – *a*.

Since the general form of probability functions can be expressed in terms of the standard distribution, all subsequent formulas in this section are given for the standard form of the function.

The following (figure 4) is the plot of the beta probability density function for four different values of the shape parameters

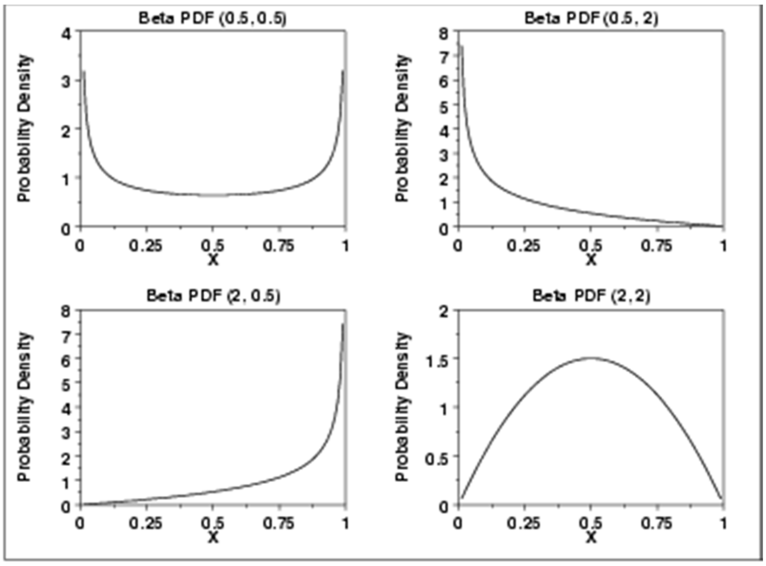


Figure 4. The beta probability density function

The formula for the cumulative distribution function of the beta distribution is also called the incomplete beta function ratio (commonly denoted by $\boldsymbol{I_x}$) and is defined as

$$F(x) = I_x(\alpha_1,\alpha_2) = \frac{\int_0^x t^{\alpha_1-1}(1-t)^{\alpha_2-1}\,dt}{B(\alpha_1,\alpha_2)}, 0 \le x \le 1; \alpha_1,\alpha_2 > 0 \tag{6}$$

where B is the beta function defined above.

The formulas below are for the case where the lower limit is zero and the upper limit is one.

Mean	$\frac{\alpha_1}{\alpha_1+\alpha_2}$
Mode	$\frac{\alpha_1-1}{\alpha_1+\alpha_2-2}, \alpha_1,\alpha_2 > 1$
Range	0 to 1
Standard Deviation	$\sqrt{\frac{\alpha_1\alpha_2}{(\alpha_1+\alpha_2)^2(\alpha_1+\alpha_2+1)}}$
Coefficient of Variation	$\sqrt{\frac{\alpha_2}{\alpha_1(\alpha_1+\alpha_2+1)}}$
Skewness	$\frac{2(\alpha_2-\alpha_1)\sqrt{\alpha_1+\alpha_2+1}}{(\alpha_1+\alpha_2+2)\sqrt{\alpha_1\alpha_2}}$

First consider the case where a and b are assumed to be known. For this case, the method of moments estimates are

$$\alpha_1 = \bar{x}\left(\frac{\bar{x}(1-\bar{x})}{s^2} - 1\right) \tag{7}$$

$$\alpha_2 = \left(1-\bar{x}\right)\left(\frac{\bar{x}\left(1-\bar{x}\right)}{s^2}-1\right) \tag{8}$$

where $\bar{x}$ is the sample mean and s^2 is the sample variance. If a and b are not 0 and 1, respectively, then replace $\bar{x}$ with $\frac{\bar{x}-a}{b-a}$ and s^2 with $\frac{s^2}{\left(b-a\right)^2}$ in the above equations.

For the case when a and b are known, the maximum likelihood estimates can be obtained by solving the following set of equations

$$\phi\left(\alpha_1\right)-\phi\left(\alpha_1+\alpha_2\right)=\frac{1}{n}\sum_{i=1}^{n}\lg\left(\frac{Y_i-a}{b-a}\right) \tag{9}$$

$$\phi\left(\alpha_2\right)-\phi\left(\alpha_1+\alpha_2\right)=\frac{1}{n}\sum_{i=1}^{n}\lg\left(\frac{b-Y_i}{b-a}\right) \tag{10}$$

The maximum likelihood equations for the case when a and b are not known are given in pages 221-235 of Volume II of Johnson, Kotz & Balakrishnan (1994).

5 FITTING THE DISTRIBUTION

In order to test the statistic nature of the distribution, we used the Kolmogorov-Smirnov, Anderson-Darling and Pearson-Fisher tests (Stephans, 1979; www.mathwave.com; www.vosesoftware.com).

Kolmogorov-Smirnov

The test is defined for the hypothesis

H_0: the distribution of earthquakes is Beta

H_1: the distribution of earthquakes is not Beta.

We compute the empirical distribution function $\hat{F}\left(x\right)$:

$$\hat{F}\left(x\right)=\frac{1}{n}\sum_{i=1}^{n}I_{X_{i\le x}} \tag{11}$$

where $I_{X_{i\le x}}$ is the indicator function, equal to 1 if $X_i \le x$ and equal to 0 otherwise.

The Kolmogorov-Smirnov statistic for a given cumulative distribution function $F\left(x\right)$ is

$$D_n = \sup_x\left|\hat{F}\left(x\right)-F\left(x\right)\right| \tag{12}$$

and F(x) the theoretical values of distribution.

The D_n computed value is compared to the maximum admitted equivalent.

The statistic computed value for the presented case resulted in $D_n = 0{,}19999$ is inferior to the critical level 0.48893 for a significance level of $\alpha = 0{,}01$, respectively inferior to value 0.40925 for 95%. The Beta distribution hypothesis is not rejected even for $\alpha = 0{,}2$.

The Anderson-Darling test – is also a distance test, proposed by Wilbur Anderson and Donald A. Darling in 1952.

The statistic of the test is

$$A^2 = -N - S \tag{13}$$

where:

$$S = \sum_{i=1}^{n} \frac{(2i-1)}{N} \left[\ln F(X_i) + \ln\left(1 - F(X_{n+1-i})\right) \right] \quad (14)$$

in which *F* is the cumulative distribution function. For a significance level α, we validate one of the two hypotheses H_0 and H_1. The critical values for various specified distributions are computed by Stephens (1979).

The value of the statistics of the test: 4.3274 refute the Beta distribution for $\alpha = 0{,}01$, with critical value 3.9074, respectively 2.5018 for $\alpha = 0{,}05$

Pearson-Fisher Statistic

Chi Square or Pearson-Fisher (χ^2) test was proposed as a measure of random departure between observation and the theoretical model by Karl Pearson (Pearson 1900). The test was later corrected by Ronald Fisher trough decrease of the degrees of freedom by a unit (decrease duet of the existence of the equality relationship between the sum of observed frequencies and the sum of theoretical frequencies, (Fisher 1922), and by the number of 692 unknown parameters of the theoretical distribution when they come as estimated from measures of central tendency (Fisher 1924).

The chi-square test is used to test if a sample of data came from a population with a specific distribution. An attractive feature of the chi-square goodness-of-fit test is that it can be applied to any uni-variate distribution for which you can calculate the cumulative distribution function. The chi-square goodness-of-fit test is applied to binned data (i.e., data put into classes).

The test is defined for the hypothesis

H_0: The data follow a specific distribution

H_1: The data do not follow the specific distribution

The statistic is calculated as (in original):

$$\chi^2 = S\left\{\frac{(x-m)^2}{m}\right\} : \chi^2 = \sum_{i=1}^{k} \frac{(O_i - E_i)^2}{E_i} \quad (15)$$

where O_i is the observed frequency for bin *i* and E_i is the expected frequency for bin *i* and is calculated by

$$E_i = N\left(F(Y_u) - F(Y_i)\right) \quad (16)$$

where *F* is the cumulative distribution function and Y_u and Y_i are the upper and lower limits for class *i*.

The test statistic follows, approximately, a chi-square distribution with *(k - c)* degrees of freedom where *k* is number of non-empty cells and *c* - the number of estimated parameters for the distribution +1.

Therefore, the hypothesis that data are from a population with the specified distribution is rejected if

$$\chi^2 > \chi^2_{\alpha,k-c}$$

where $\chi^2_{\alpha,k-c}$ is the chi-square percent point function with *k - c* degrees of freedom and a significance level of α.

The computations lead to a value of the $\chi^2_c = 7{,}3289\text{E-8}$ statistic inferior to the critical value $\chi^2_{0{,}01} = 6{,}6349$, so that the H_0 hypothesis is accepted with a probability of 99%. Either for different values of α (0.02; 0.05; 0.1) respectively 0.2 (critical value 1.6424) the Beta distribution hypothesis is not rejected.

Considering the three applied tests (Kolmogorov-Smirnov, Anderson-Darling and Pearson-Fisher), two of them confirm with a high confidence degree the Beta distribution, by parameters:

$\alpha_1 = 0.34225$

$\alpha_2 = 0.63562$

$a = 1.0$

$b = 15.0$

The Probability Density Function (pdf) for the estimated values of the parameters is presented in Figure 5 and The Hazard Function in Figure 6.

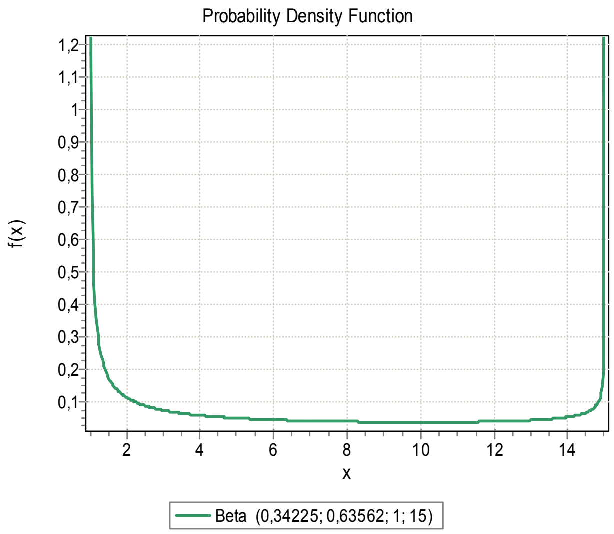


Figure 5. The Probability Density Function

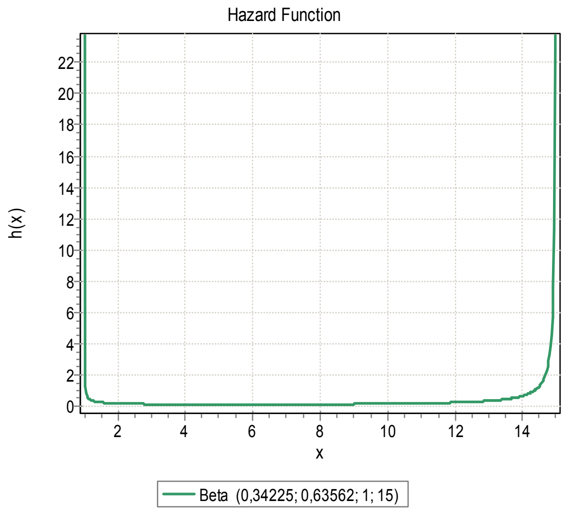


Figure 6. The Hazard Function

Table 4 presents the values of the main indicators of the Beta distribution for a number of x = 1, …, 15 events.

Table 4. The Values for pdf, CDF, h(x) şi S(x)

Statistic Functions	Values computed for **x** (earthquakes) equal to:														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
pdf- probability density function	-	0.115	0.075	0.059	0.051	0.045	0.042	0.040	0.039	0.038	0.039	0.040	0.044	0.054	-
CDF - cumulative distribution function	0.000	0.328	0.419	0.485	0.539	0.587	0.631	0.672	0.711	0.749	0.788	0.827	0.869	0.918	1.000
h(x) - hazard function	-	0.171	0.129	0.115	0.110	0.110	0.114	0.122	0.134	0.153	0.183	0.234	0.338	0.655	-
S(x) - distribution	1.000	0.672	0.581	0.515	0.461	0.413	0.369	0.328	0.289	0.251	0.212	0.173	0.131	0.082	0.000

6 CONCLUSIONS

In the followings, through simulation operations for the values of the Beta distribution, we formulate various hypotheses on the occurrence of seismic events, for the confirmed statistic model.

Thus, if we limit, for a 100 years interval, the number of major seismic events between $x_1 = 2$ and $x_2 = 10$ respectively, we have:

$P(x < x_1) = 32.51\ \%$

$P(x > x_1) = 67.19\ \%$

$P(x_1 < x < x_2) = 42.14\ \%$

$P(x < x_2) = 74.95\ \%$

$P(x > x_2) = 25.05\ \%$

It is an optimistic variant that the chances for less than two major seismic events to occur in a 100 year interval are around 33%, and for more than 10 major seismic events is reduced to 25%.

If we modify the limits to $x_1 = 1$ and $x_2 = 3$ major seismic events, then:

$P(x < x_1) = 0\ \%$
$P(x > x_1) = 99.99\ \%$
$P(x_1 < x < x_2) = 41.89\ \%$
$P(x < x_2) = 41.89\ \%$
$P(x > x_2) = 58.11\ \%$

So, there is a small probability that in Romania, less than 1 earthquake will occur, and slim chances that more than 3 earthquakes will occur. There is a probability of approximately 42% that in an interval of 100 years, between 1 and 3 events could occur.

If we modify the limits to $x_1 = 4$ and $x_2 = 12$ major seismic events, then:

$P(x < x_1) = 48.5\ \%$
$P(x > x_1) = 51.5\ \%$
$P(x_1 < x < x_2) = 34.3\ \%$
$P(x < x_2) = 82.7\ \%$
$P(x > x_2) = 17.3\ \%$

Romania represents an unique case in the world, from a seismic point of view: earthquakes of over 7 degrees Richter in magnitude which originate from Vrancea affect approximately 50% of the territory and approximately 60% of the population, including the capital, Bucharest. Nonetheless, the earthquake in 1977 was not the most powerful. It was only the fourth in magnitude among the earthquakes in the last 200 years. In Romania, there were 6 earthquakes of over 7 degrees Richter in the last 200 years. More technical details on the area Vrancea can be found in Ivan (2007, 2011).

In the case of Romania, the warning period for an earthquake is 25-30 second, which is relatively short in comparison to Mexico City - 60 seconds. However, it is enough to interrupt dangerous activities: nuclear reactors, heavy water production, chemical industry, gases, electricity and water. For trains and subways, stopping the electrical power is enough to stop the carriages.

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