A NEW APPLICATION OF BENIOFF GRAPHS AND WIENER PREDICTIVE FILTER TO FORECAST VRANCEA (ROMANIA) EARTHQUAKES

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The application of the first method indicates that the next Vrancea earthquake ($M_W \approx 6.7$) will occur in the time period 2010–2011(?), or in the case 2012–2013(?), while according to the second method the major event would occur in the period 2018–2019. For this purpose, I use two alternative approaches based on the Benioff graphs and on the theory of Wiener filters, respectively.

Key words: earthquake prediction; Benioff graphs; seismic energy; time series.

1. INTRODUCTION

The data are from a previous work [1]. In a recent work [2], the temporal evolution of the state of stress in the Vrancea region was estimated. It is on application of the Wiener predictive filter and the Benioff graphs to forecast [3].

The part of the elastic energy E is considered which is stored up during the earthquake preparation stage, changes into seismic energy E_s. The square root of the energy E_s is proportional to the elastic force that generates the earthquake.

2. METHOD

It is well known the relation between the Gutenberg – Richter magnitude (M_{GR}) and the seismic energy M_s:

$$\log E_s = 1.5\, M_{GR} + 11.8 \quad (1)$$

In the case of intermediate – depth Vrancea earthquakes it was shown that:

$$M_{GR} = 0.56\, I_{max} + 2.18 \quad [4] \quad (2)$$

where I_{max} is the maximum seismic intensity.

So, we can write:

$$\log E_s = 11.8 + 1.5\,(0.56\, I_{max} + 2.18) = 0.84\, I_{max} + 15.07 \quad (3)$$

or,

$$\log E_s^{0.5} = 0.42\, I_{max} + 7.535 \quad (4)$$

We also know that $M_{GR} = (M_W - 0.81)/0.92 = 1.087\ M_W–0.88$, where the moment magnitude M_W is known. Then, it results:

$$\log E_s = 11.8 + 1.5\ (1.087\ M_W - 0.88) = 11.8 + 1.63\ M_W - 1.32$$

Thus we can write:

$$\log E_s^{0.5} = 0.815\ M_W + 5.24 \quad (5)$$

So, finally we have:

$$E_s = 10^{(1.63\ M_w\ + 10.48)} \quad (6)$$

From relation (6) we obtained all the values of the seismic energy $E_s^{0.5}$ for the moment magnitude M_W = 3.0, 3.1, 3.2 …….7.9, 8.0; The obtained results are presented in Table 1.

Table 1

Years	**[$E_s^{0.5}$]**	**$E_s^{0.5}$**	**M_W**	**Years**	**[$E_s^{0.5}$]**	**$E_s^{0.5}$**	**M_W**
1870–1871	[0.74]	0.68	5.3	1952–1953	[2.42]	1.47	5.5
1872–1873	[0.05]	0.03	3.9	1954–1955	[3.60]	0.93	5.8
1874–1875	0	0	0	1956–1957	[1.43]	0.21	4.7
1876–1877	0	0	0	1958–1959	[4.33]	1.20	5.5
1878–1879	[2.12]	0.72	5.3	1960–1961	[3.52]	1.12	5.9
1880–1881	[6.89]	6.05	6.8	1962–1963	[3.15]	1.54	5.8
1882–1883	0	0	0	1964–1965	[0.77]	0.21	5.0
1884–1885	[0.04]	0.04	4.1	1966–1967	[3.24]	1.12	5.9
1886–1887	[0.04]	0.04	4.7	1968–1969	[2.11]	0.30	5.2
1888–1889	[3.45]	3.45	6.5	1970–1971	[0.21]	0.12	4.7
1890–1891	0	0	0	1972–1973	[1.50]	1.35	6.0
1892–1893	[19.70]	10.63	7.1	1974–1975	[0.79]	0.63	5.3
1894–1895	[16.59]	10.63	7.1	1976–1977	[20.67]	18.66	7.4
1896–1897	[6.91]	4.16	6.6	1978–1979	[1.61]	0.25	5.3
1898–1899	[0.83]	0.44	5.4	1980–1981	[1.96]	0.53	5.5
1900–1901	[15.58]	12.83	7.2	1982–1983	[2.00]	0.64	5.6
1902–1903	[4.01]	2.37	6.3	1984–1985	[2.95]	1.23	5.8
1904–1905	[4.47]	4.16	6.6	1986–1987	[13.13]	10.64	7.1
1906–1907	[0.34]	0.17	4.9	1988–1989	[2.25]	0.10	4.6
1908–1909	[10.82]	10.67	7.1	1990–1991	[14.00]	7.31	6.9
1910–1911	[0.17]	0.08	4.5	1992–1993	[1.52]	0.12	4.7

(Continued)

1912–1913	[10.28]	7.84	6.7	1994–1995	[1.18]	0.06	4.3
1914–1915	[1.98]	0.44	5.7	1996–1997	[1.73]	0.10	4.1
1916–1917	[8.76]	2.86	6.4	1998–1999	[2.65]	0.25	4.5
1918–1919	[3.14]	1.63	6.1	2000–2001	[2.12]	0.13	4.4
1920–1921	[0.36]	0.36	5.3	2002–2003	[1.62]	0.15	4.3
1922–1923	[0.21]	0.12	4.7	2004–2005	[4.20]	3.30	6.1
1924–1925	[1.70]	1.63	6.1	2006–2007	[2.32]	0.23	4.5
1926–1927	[1.25]	1.12	5.9				
1928–1929	[4.10]	1.63	6.1				
1930–1931	[0.04]	0.04	3.9				
1932–1933	[3.05]	1.35	6.0				
1934–1935	[9.21]	8.25	6.6				
1936–1937	[2.65]	1.35	6.0				
1938–1939	[2.11]	1.93	6.2				
1940–1941	[40.80]	32.80	7.7				
1942–1943	[3.60]	0.60	5.9				
1944–1945	[10.48]	9.25	6.8				
1946–1947	[3.17]	1.35	6.0				
1948–1949	[3.12]	2.37	6.3				
1950–1951	[4.18]	1.12	5.9				

3. RESULTS

The $E_s^{0.5}$ values were considered only for the years: 1891-1895; 1896–1900; 1901–1905 … and 2001–2005. The values $\sum E_s^{0.5}$ were determined as: 33.189, 7.353, 9.707, 10.912, 13.395, 7.466, 2.110, 6.266, 11.994, 54.913, 25.787, 15.738, 8.266, 8.750, 5.421, 5.015, 2.191, 25.177, 7.090, 28.926, 4.702, 6.362, 7.721. All these values constituted the steps for the Benioff graph. The data suggests that the period of time before the years 2011-2015 is characterized by seismic activity with earthquakes of magnitudes $M_{GR} < 6.5$.

In this study, we first calculated the $E_s^{0.5}$ values for consecutive time periods of 5 years and the obtained results are similar to those already published (Enescu, 2008).

In table 1 we present the values $E_s^{0.5}$ for the years 1870–1871; 1872–1873; … 2008–2009; 2010–2011; 2012–2013; 2014–2015; 2016–2017; 2018–2019; 2020–2021; 2022–2023. As it can be noticed, in this study we took into account the $E_s^{0.5}$ and $[E_s^{0.5}]$ values for consecutive time periods of two years, starting with 1870.

We hope that this will improve our results.

We know that the M_W magnitude is significantly larger compared to the M_{GR} magnitude, especially at larger magnitudes.

So, we can consider $M_W < 6.7$ to be about the same as $M_{GR} < 6.5$.

For example, the large earthquakes in 1940, 1977 and 1990 had Gutenberg – Richter magnitudes, M_{GR}, of 7.4, 7.2 and 6.7 respectively, while the moment magnitudes, M_W, for the same earthquakes were of 7.7, 7.4 and 6.9 respectively.

Thus, the period of time before the years 2011–2015 is characterized by earthquakes with $M_W \geq 6.7$.

We considered first a Benioff model in the time period 1935–2005 and made extrapolation for the time period after 2005, until the time periods 2006–2010 and 2011–2015. [1].

We also tried extrapolations for the time periods used in the paper [2], in which results are also obtained from the application of Wiener filters.

The Benioff graphs are presented in Figs. 1 and 2. They are expressed for the case 2010–2011, or in the case 2012–2013 (?).

The graphs in Figs. 1 and 2 show that the time axis can be divided in cycles of 36–38 years. One half-cycle is characterized by earthquakes with magnitudes $M_W < 6.7$, while the other half-cycle is characterized by earthquakes with magnitudes $M_W \geq 6.7$. As expected, the average slope of the graph for the half-cycles with earthquakes of magnitudes $M_W < 6.7$ is smaller than the average slope for the half-cycles with $M_W \geq 6.7$.

The data will enable us to draw up a prediction bulletin for the seismic activity in Vrancea over the next years. In view of this prediction, we have applied the predictive Wiener filter (Wiener, 1979) to time series represented by the distribution in time of the seismic energy E_s released by earthquakes in Vrancea. This method has also been applied to other seismic regions. Thus, for instance, Molnar (1971) tried to predict the earthquakes in Comarno (Slovakia) considering the maximum intensity I_o of the earthquakes as a parameter.

We have tried to raise the occurrence of the data by means of parameter $E_s^{0.5}$ and not by the intensity I_o. The parameter $E_s^{0.5}$ also allows for a more complete interpretation of the predicted values.

Furthermore, we have completed Molnar's paper by some contributions concerning the processing and interpretation of data.

The prediction procedure applied to a time series leads to the extrapolation in the future by means of the existing statistical correlations between known values for the past and those for the future.

The time series which represented the input and the desired output are stationary, that is their statistical properties remain unchanged in time. The operation for the signal prediction is assumed to be a linear operation applied on the available information, i.e. it is carried out by a linear operator which is invariant in time. In practice, only physically realisable finite operators can by achieved.

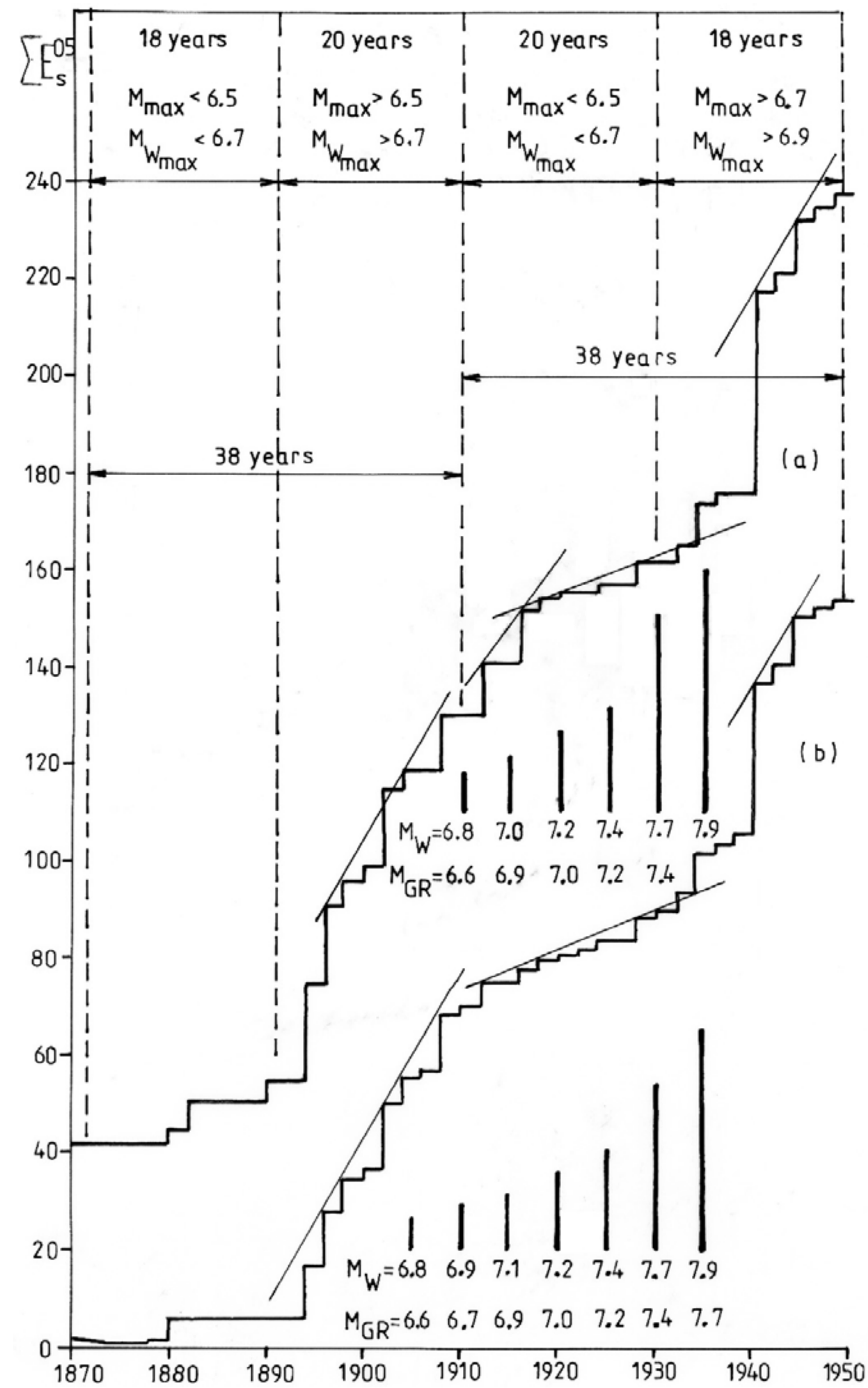
18 years
20 years
20 years
18 years
$M_{max} < 6.5$
$M_{W_{max}} < 6.7$
$M_{max} > 6.5$
$M_{W_{max}} > 6.7$
$M_{max} < 6.5$
$M_{W_{max}} < 6.7$
$M_{max} > 6.7$
$M_{W_{max}} > 6.9$
38 years
38 years
(a)
(b)
M_W=6.8 7.0 7.2 7.4 7.7 7.9
M_{GR}=6.6 6.9 7.0 7.2 7.4
M_W=6.8 6.9 7.1 7.2 7.4 7.7 7.9
M_{GR}=6.6 6.7 6.9 7.0 7.2 7.4 7.7
1870 1880 1890 1900 1910 1920 1930 1940 1950

Fig. 1.

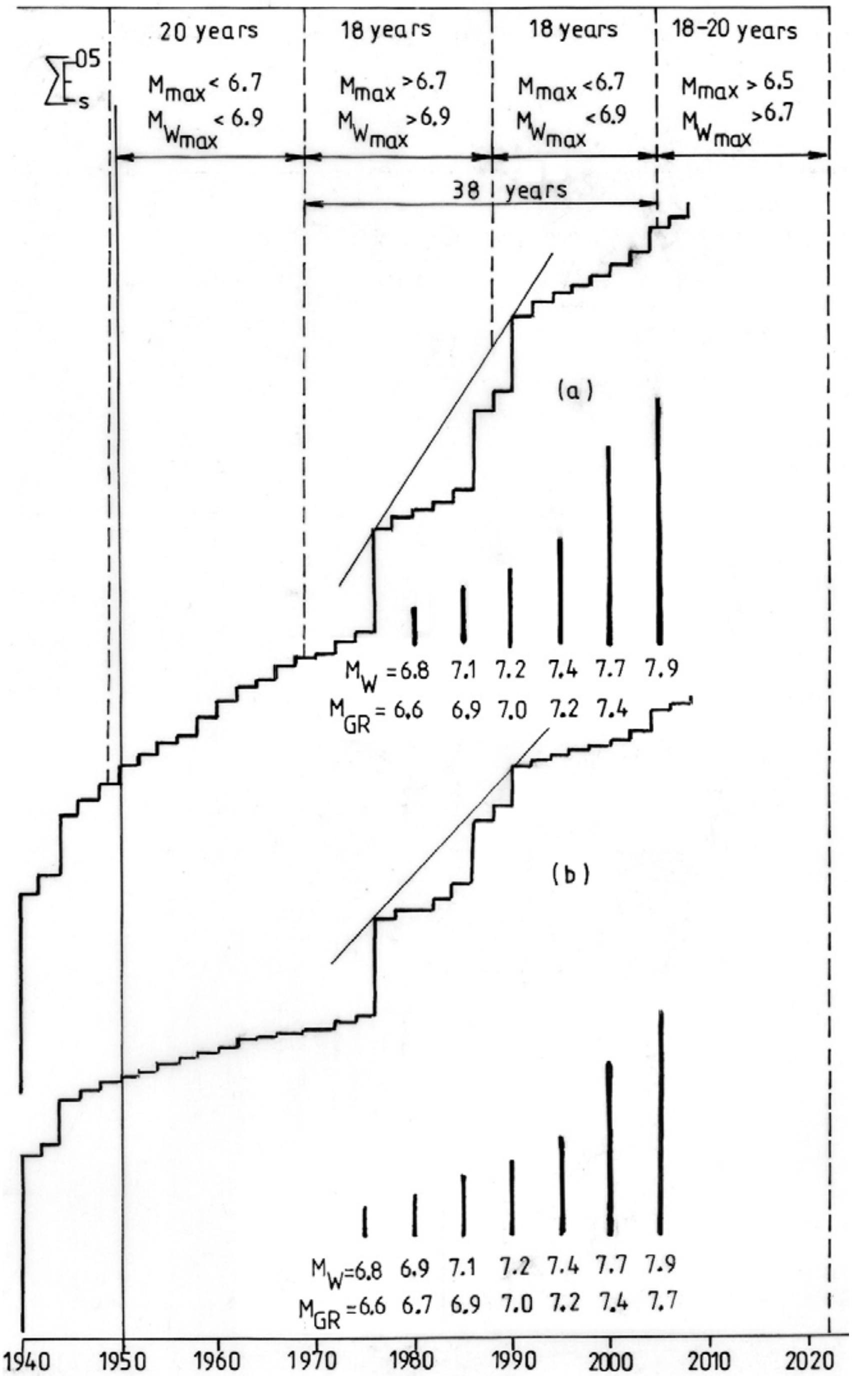
20 years
18 years
18 years
18–20 years
$\sum E_s^{0.5}$
$M_{max} < 6.7$
$M_{W_{max}} < 6.9$
$M_{max} > 6.7$
$M_{W_{max}} > 6.9$
$M_{max} < 6.7$
$M_{W_{max}} < 6.9$
$M_{max} > 6.5$
$M_{W_{max}} > 6.7$
38 years
(a)
M_W = 6.8 7.1 7.2 7.4 7.7 7.9
M_{GR} = 6.6 6.9 7.0 7.2 7.4
(b)
M_W=6.8 6.9 7.1 7.2 7.4 7.7 7.9
M_{GR} =6.6 6.7 6.9 7.0 7.2 7.4 7.7
1940 1950 1960 1970 1980 1990 2000 2010 2020

Fig. 2.

The applied procedure is based on the statistical correlation that exist between the known values of $E_s^{0.5}$ of the past and the ones we would like to predict by extrapolation to be future.

The calculations have been made the sequences of earthquakes (1870–2007, Δt = 2 years and 1936–2007; Δt = 2 years). Thus, the sequences of earthquakes, we have used the absolute values:

$$X_{t-k} = \left(\sum_{i=1}^{pk} [E_{s,i}^{0.5}] \right)_{t-k} \quad (7)$$

The input time series was obtained by calculating the sequare root of the seismic energy of Vrancea intermediate-depth earthquake for the time periods 1936–1937, 1938–1939, … 2006–2007. From the data we get the following values for the parameter X_{t-k}: 2.65, 2.11 … and 0.21 for the time periods 1936–1937 … 1940–1941, up to 1970–1971 respectively.

The parameter p_k represents the number of earthquakes that were considered in the time interval t–k. The time periods 1972–1973 up to 2006–2007 are characterized by the following values. X_{t-k} = : 1.50, 0.79, 20.67, 1.61, … 1.62, 4.20, 2.32, respectively.

The predicted (prediction interval p = 4) for the time periods 1972–1973 up to 2006–2007 is represented by the values 1.63, 0.83, 19.22, 1.38, 1.66, 2.03, 2.76, 14.03, 4.28, 13.27, 2.52, 1.67, and 1.27, respectively.

For the time periods 2008–2009; 2010–2011; 2012–2013; 2014–2015; 2016–2017; 2018–2019; 2020–2021 and 2022–2023, the predicted values are 2.13, 3.23, 2.45, 3.11, 5.23, 15.13, 3.19 and 4.21, respectively.

Table 2

Sampling interval Δt = 2 years

Type of series	**Time interval Δt (years)**	**Values [$\sum E_{s,i}^{0.5}$] ($10^{10\ erg.\ 0.5}$)**
Actual series Absolute values	2008–2009	2.13
	2010–2011	3.23
	2012–2013	2.45
	2014–2015	3.11
	2016–2017	5.23
	2018–2019	15.13
	2020–2021	3.19
	2022–2023	4.21

From these data it is noticed that the time period with a maximum predicted value of the parameter $\sum_{i=1}^{pk} E_{s,i}^{0.5}$ is 2018–2019, for both absolute – values.

4. DISCUSSION AND CONCLUSIONS

We hypothesized that the next major event will occur in one of the years 2006, 2007, or 2008 [1]. We made also a different hypothesis that the next $M_{GR} \geq 6.5$ earthquake could occur later than the year 2010 [1]. We can summarize the conclusions of the present paper as follows:

1. The Benioff graphs seem to indicate that the next Vrancea event will occur earlier in the time period 2010–2011(?), or in the case 2012–2013(?), ($M_{GR} \approx 6.5$; $M_W \approx 6.7$)(?)
2. The results obtained using the predictive Wiener filter suggest that the next major Vrancea earthquake $M_W > 6.7$ will occur in the time period 2018–2019.
3. The Vrancea earthquakes with $M_{GR} < 6.5$ or $M_W < 6.7$ could occur any time; they are not considered dangerous.

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