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HIDDEN PERIODICITY IN THE "STREAM" OF EARTHQUAKES IN THE SOUTHERN PART OF THE BALKAN PENINSULA

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Abstract: *The results of a research of the periodic components of seismicity in the southern part of the Balkan Peninsula are presented. Time-stable periods have been found and a model has been consructed on this basis. Most of the obtained periods coincide or are close to the periods obtained for the global seismic process on Earth. In the spectrum of fluctuations in the intensity of the "stream" of seismic events there is a clear peak with a period of 11-12 years, which coincides with the period of change in solar activity. The obtained results shed light on the nature of modern deformation processes and cycles of crustal destruction during earthquakes in the southern part of the Balkan Peninsula.*

СКРИТА ПЕРИОДИЧНОСТ В „ПОТОКА“ ЗЕМЕТРЕСЕНИЯ В ЮЖНАТА ЧАСТ НА БАЛКАНСКИЯ ПОЛУОСТРОВ

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Ключови думи: *Сеизмология, Оценка на сеизмични параметри, Сеизмичен анализ*

Резюме: *Целта на настоящата работа е подробно проучване на периодичните компоненти на сеизмичността в южната част на Балканския п-ов. Намерени са устойчиви във времето периоди и е изграден модел на тази основа. Голяма част от получените периоди съвпадат или са близки с периодите получени за глобалния сеизмичен процес на Земята. В спектъра на колебанията в интензивността на потока на сеизмичните събития има ясно изразен пик с период от 11-12 години, който съвпада с периода на промяна на слънчевата активност. Получените резултати хвърлят светлина върху особеностите на сеизмичността в южната част на Балканския полуостров.*

Introduction

Effects of manifestations of "hidden" periodic fluctuations before strong earthquakes were found (Любушин, 1998), which can in principle be considered within the concept of self-organized criticality, in which a large role is attributed to the emergence of long-range correlations of seismic events (Соболев, 2003). However, the physical mechanism of possible long-range correlations applicable to sesmology is not clear. Theories of catastrophes and phase transitions in energy-open systems require detailed development for inhomogeneous environments, although the appearance of rhythms is common in the evolution of uneven systems (Nikolis & Prigogine, 1979).

The analysis of seismic catalogs is more complex than processing the time lines obtained by geophysical monitoring systems (seismic, magnetic, gravitational, GPS, .. etc.). This is related to the fact that the analysis of the sequence of earthquakes does not allow the direct use of the huge variety of methods, parametric models and algorithms developed in signal theory (Marpl, 1987). In order to use these methods, it is necessary to convert seismic catalogues in time lines of consecutive values with a step in time set. This can be achieved by calculating either the average values of a particular catalog parameter (e.g. the energy released) at successive time intervals of equal width, or the total value with a constant step in time (comulative curves). Even assessing the spectrum of the scale or finding periodic components in time lines could be ambiguous in the analysis of seismic catalogues and requires special approaches based on an assessment of the parameters of the point process model (Vere-Jones & Ozaki, 1982). Lubushin and Pisarenko offer a parametric method for assessing the impact of the seismic regime in several regions on the seismicity of the research region (Любушин & Писаренко, 1993).

The purpose of our work is a detailed study of the periodic components of seismicity in the southern part of the Balkan region. When establishing time-stable periods, a model is built on this basis, allowing to talk about a forecast of the "seismic time" for a certain period of time. In the case of a sharply unstable portrait of fluctuations in the seismic stream of the events, such prediction is problematic.

Data and method of interpretation

In this study a constantly updated catalog of the University of Athens for the period 1964-2020 is used (http://dggsl.geol.uoa.gr/en_index.html). The catalog of earthquakes covers data in a spatial window 32^o - 44^oN and 10^o – 30^oE. The total number of included earthquakes is 295029, as the depths vary from $0 \leq h \leq 220$ km, and the magnitude estimates Ml are in the range of $2.0 < M_l < 7.0$.

Duplicate events were recognized and removed algorithmically, and later checked by visual assessment. The catalog of independent events is defined as final after the identification and removal of clustered events by the Gardner & Knopoff algorithm (Gardner J.K & Knopoff, L., 1974). Any earthquake that occurred within the spatial-time window around and after each larger event is taken into account and is considered as a cluster event. The spatial-time window is larger in size for stronger previous events according to Gardner & Knopoff dependency. This step is relevant merely for our catalog data comprising large events with long aftershock and foreshock series.

To guarantee the completeness of data, analysis comprises only events with magnitudes equal to or larger than the threshold magnitude Mc. So, the next step has been the determination of minimum value of magnitude Mc for catalog completeness. The value of Mc usually decreases with time, as the number of seismic stations and their sensitivity increase [Wiemer S. & Wyss M., 2000]. The method of maximum curvature (Mmax curvature) is used to verify the estimates of Mc. The very final catalog includes 24750 events with Mc ≥4.0 limited mainly to a depth of 40 km (shallow earthquakes) – maximum depth is 70 km (Fig. 1).

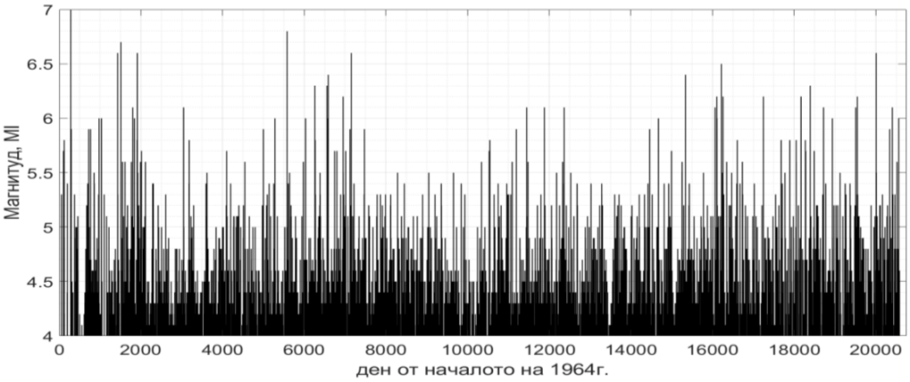

Fig. 1. The magnitude-time dependance of all used events

Taking into account the non-stationary of the seismic stream of events to detect hidden periodicity, a method proposed by Lubushin (Любушин и др., 1998) is applied. A model of time sequences of seismic events (point process) is considered, assuming that it contains a harmonious component

$$\lambda(t) = \mu(1 + a\cos(\omega t + \varphi)),$$

where ω – frequency, *a* - amplitude ($0 \leq a \leq 1$), φ –phase angle ($\varphi \in [0, 2\pi]$ и $\mu \geq 0$ – multiplier describing the Poisson part of the intensity are the parameters of the model.

The increase in the logarithmic function of the plausibility of the point process (Cox & Lewis, 1966) at a given frequency ω is found with the relation:

$$\Delta lnL(a,\varphi|\omega) = \sum_{t_i} \ln(1 + a\cos(\omega t_i + \varphi)) + Nln(\frac{\omega T}{\omega T + a(\sin(\omega T + \varphi) - \sin(\varphi))}) \ ,$$

where t_i - a sequence of time moments of the separated local maxima within a time window; N – the number of local maxima; T – the length of the time window.

The function

$$R(\omega) = \max_{a,\varphi} \Delta lnL(a, \varphi|\omega)\ ,\ \ 0 \le a \le 1,\ \varphi \in [0, 2\pi]$$

is considered as a generalized spectrum of the sequence of events, ie. it is an analogue of spectral analysis applied to point processes (Любушин и др., 1998). The maximum values in the graph of this function show the frequencies present in the flow of events, the greater the increase of the function, the greater the contribution of the corresponding harmonic in the flow of events.

If we denote by τ – the time mark of the right end of creeping time window with length T_w or the right end of a creeping window of the number of events of length T_w (number of events), the last relation actually becomes a function of two arguments - $R\ (\omega,\ \tau\ |\ T_w)$, which can be visualized as 2-dimensional and 3 -dimensional reliefs in the plane of the arguments $(\omega,\ \tau)$. These frequency-time and frequency-event diagrams allow to study the dynamics of occurrence and development of periodic components within the landed stream of events. The methodology had been used in the researchs of Любушин и др. (1998), Соболев (2003; 2004).

Results and discussion

- research results of all events

Fig. 1 presents the magnitude-time dependance of all events that are used for the purposes of this study. The all used 24750 earthquakes with magnitude M > 4 with a depth of hypocenters up to 70 km for the period 1964–2020 are presented in this sequence. The time is marked by the number of the days from the beginning – 01.01.1964.

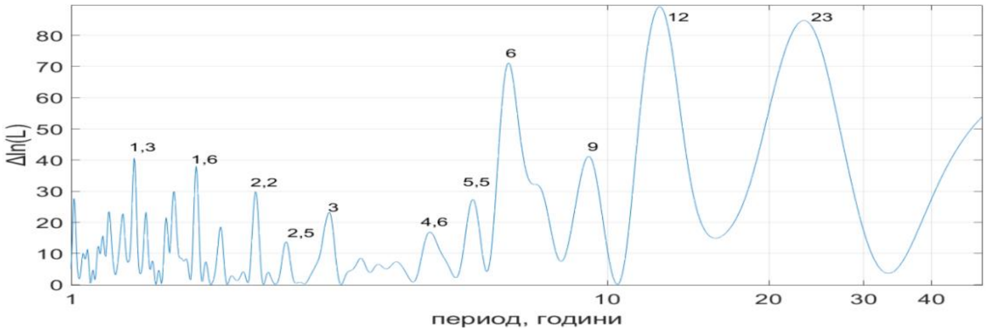

Fig. 2. Graph of the increase of the logarithmic likelihood function,
T_{min}=365 days, T_{max}=18250 days, number of sample periods N=1000.

Fig. 2 presents the graph of the increase of the logarithmic likelihood function for the whole sequence of the moments of earthquakes with M > 4, calculated for $T_{min}=365$ *days* - $T_{max}=18250$ *days* and the number of sample periods $N=1000$ (corresponding to the frequency ω). Above each of the amplitude peaks are the values of the periods in years. An asymptotic formula can be used to estimate the statistical significance of the peaks assuming that 24750 is a sufficiently large number of events. With a confidence probability of 90%, the confidence threshold will be $-\ln(0.1)\approx 2.3.$. In Fig. 2 it is seen that all marked peaks are significant. Most of the obtained periods (23; 12; 6; 2.5; 1.6) coincide or are close to the periods obtained by Lyubushin (23; 12.5; 6.5; 2.5; 1.5) for the global seismic process for the inner time 1901–2005, and with magnitude M > 7 (Любушин и др., 1998). There is also a group of peaks with multiple frequencies (2.5; 3; 6; 9; 12) in the spectrum of fluctuations in the intensity of earthquake flow.

Fig. 3c shows a frequency time diagram of the statistics $R(\omega,\ \tau|Tw)$calculated in a creeping time window with a length of 3650 days (10 years) and an offset of 365 days (one year) for trial values of the periods (corresponding to the frequency ω) of 10 up to 1000 days. The horizontal bands in Fig. 3 correspond to the spectral peaks (harmonics) in Fig. 2. Fig. 3c shows that the amplitudes of these harmonics change over time. Irregularly appearing strips in time indicate periodic fluctuations occurring in groups and between groups of earthquakes of lower magnitude. Fig. 3a shows the position of the right end of the creeping time window as a function of the cumulative number of events. Fig. 3b shows the dependence of the position of the right end of the creeping time window depending on the number of events falling in the time window, which in its essence represents the change of the seismic activity (number of earthquakes per unit time).

Figures 3a and 3b show that the peaks in the number of events falling into the time window (Fig. 3b) coincide with the high values of the increase in the logarithmic likelihood function. It follows that the amplitude jumps of *R(ω, τ|Tw)* are an indicator of high seismic activity. The red stars of both figures indicate the moments of earthquakes with M≥6.5, and in both figures these earthquakes are preceded by a period of high seismic activity, which in turn are preceded by a period of "seismic calm". The picture does not change radically when using a creeping window containing 500 events and offset 10 events.

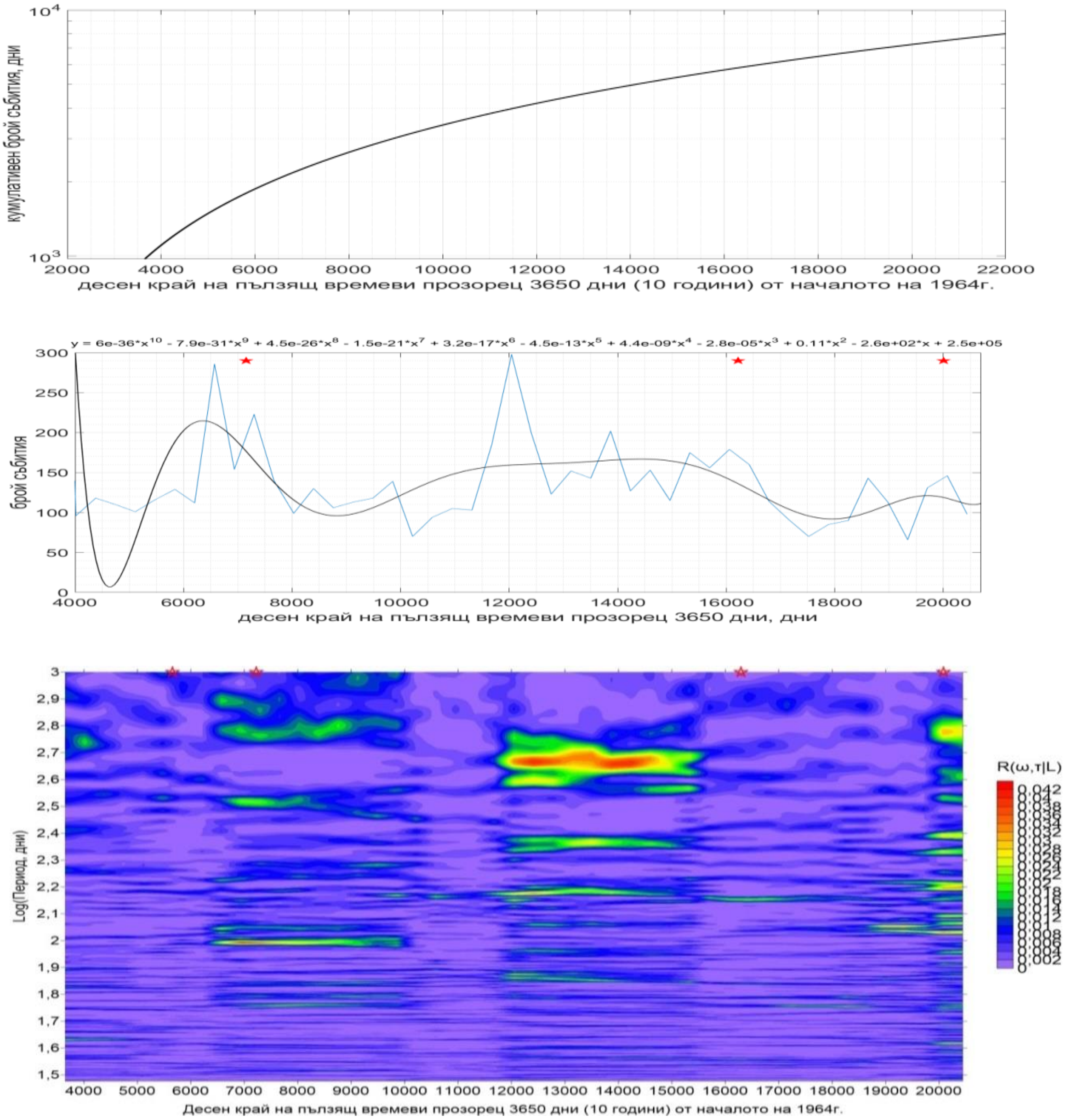

Fig. 3. a) position at the right end of the creeping time window of 3650 days and displacement of 365 days depending on the cumulative number of earthquakes; b) number of events contained in the time window (timemarks correspond to the right end of the window) c) a frequency-time diagram of the incremental logarithmic likelihood function calculated for the window described in (a); the timemarks are in days since the beginning of 1964, the moments of the earthquakes with Ml> 6.4 are marked with red stars

Therefore, the seismicity in the region is characterized by a discrete structure in time (possibly fractal) with many emerging and disappearing periods. However, the identification of common periods can help to create a trend-based multiharmonic model that allows to define a non-zero "seismic event forecasting horizon".

Verification of the time sequence of earthquakes for mixing with random fluctuations was done by the Hearst method. The ratio used is:

$$\frac{R}{S} = (aN)^H,$$

where *R/S* – normalized ratio, *N* – number of events, *a* – constant, *H* – Hirst index. Fig. 4 shows the result of the analysis - H = 0.71, which is an indicator of relatively high trend stability of the time series, and the ability to predict future trends.

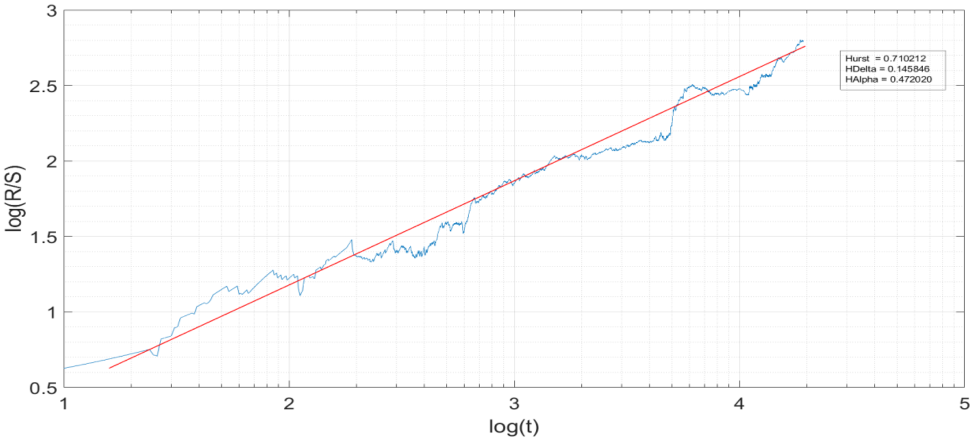

Fig. 4. Estimation of the H indicator by the Hirst method

- Results of the study of periodicity in three areas with significant earthquakes:

- 06.08.1983 г., To=15:43, 24.81E/40.08N, Ml=6.6, H=22 km

The procedure explaine above had been aplide to the polygon containing the epicenters of 1504 seismic earthquakes with magnitude Ml> 3.1, which represent the time series of events used to study the periodicity before and after the earthquake of 06.08.1983. The peaks from the graph of the increase of the logarithmic likelihood function corresponded to the main periodsof 5, 12, 25.5 and 35 years are clearly visible, as well as peaks close to multiple frequencies.

- 08.06.2008 г. To= 12:25 ч., 21.51E/37.98N, Ml=6.5, H=25 km

The same procedure had been aplide to the polygon containing the epicenters of 1106 seismic earthquakes with magnitude M1> 3.0, which represent the time series of events used to study the periodicity before and after the earthquake of 08.06.2008. The peaks corresponding to the main periods of 40 and 53 years are clearly visible, as well as peaks close to 2, 5.5, 11, 30 and 47 years.

- 25.10.2018 г. To= 22:45 ч., 20.51E/37.34N, Ml=6.8, H=10 km

The procedure of constructing the graph of the increase of logarithmic likelihood function had been aplide also to the polygon containing the epicenters of 3428 unseen earthquakes with magnitude M1> 3.2, which represent the time series of events used to study the periodicity before and after the earthquake of 25.10.2018. The peaks corresponding to the main periods of 4.2, 6.9 and 11.5 years are clearly visible.

Conclusion

Most of the obtained periods (23; 12; 6; 2.5; 1.6) coincide or are close to the periods obtained by Lyubushin (23; 12.5; 6.5; 2.5; 1.5) for the global seismic process for the time interval 1901–2005, and with magnitude M > 7 (Любушин и др., 1998). In the spectrum of fluctuations in the intensity of the flow of seismic events there is a dominant peak with a period of 11–12 years, which coincides with the period of change in solar activity. A group of peaks with periods of 1.3, 2.2, 2.5, 3, 3.3, 4.5, 5.5 and 6 years are also quite clear. The clear grouping of several stable periods in the interval of about 2-3 years is probably related to the above-mentioned alternation of strong earthquakes in seismogenic zones with deeper focus.

As an other result of the whole analysis we can summarize that the use of an events window of with the same volume of data allows a more accurate comparison of the statistical significance of the peaks of increase of the maxima of the logarithmic likelihood function for different periods and creeping time windows.

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