VIBRATION PREDICTION BASED ON PRESENTING IT PREPARATION PERIOD AS A BLUE-UP PROCESS

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The method of forecasting vibrations is considered. The technique is based on the assumption that the vibration preparation process can be attributed to the processes developing in the blowup mode. The properties of the technique are demonstrated on the example of a retro forecast of vibrations that took place in Turkey on February 6 and 20, 2023. The results of testing the methodology confirmed the assumptions underlying it. Approbation of the methodology made it possible to predict the time of exacerbation of the seismic situation in the region of the globe, which is very remote from the control point of the initial seismic information for forecasting.

KEYWORDS

Trend of the amplitude, blue-up process, forecast model, shocks environment criticality

1 INTRODUCTION

Since ancient times, mankind has been trying to predict strong vibrations using natural phenomena that were noticed by previous generations. With the development of the hardware base and mathematical apparatus, scientists around the world began to pay more attention to the problem of earthquake prediction [Nagornyi 2018a,b,c,d]. Over the past 50-60 years, many unique results have been obtained in this field of knowledge [Pigulevskiy 2011a, Nahornyi 2022]:

– geodynamic polygons were created;

– monitoring of a complex of hydro-geological-geophysical methods was organized;

– the presence of reliable and promising precursors of earthquakes has been proved;

– spatio-temporal patterns of earthquake precursors have been established;

– models of the source and processes of earthquake preparation have been developed.

An earthquake forecast can be considered practically significant if three elements of a future event are predicted in advance: the place, intensity (magnitude) and time of the event. [Zaborowski 2007, Jurko 2011-2013, Panda 2011-2013, Mrkvica 2012, Monkova 2013, Kurdel 2014 & 2022, Michalik 2014, Svetlik 2014, Baron 2016, Rimar 2016, Valicek 2016, Labun 2017 & 2019, Murcinkova 2019, Olejarova 2017, Vagaska 2017 & 2021, Balara 2018, Chaus 2018, Duplakova 2018, Straka 2018a,b, Flegner 2019 & 2020, Modrak 2019, Pollak 2019 & 2020, Sedlackova 2019, Zaloga 2020]. Moreover, the prediction of the time of the push is the main element of the forecast. Each stage of the forecast is based on a certain set of precursors - mainly geophysical phenomena that precede and foreshadow the occurrence of an earthquake. At present, there are several hundred earthquake precursors of different nature all over the world. The presence of a huge number of precursors makes it possible to develop the scientific foundations for effective earthquake prediction methods using different algorithms for their search [Nahornyi 2022].

Over the course of many centuries, it has been established that in a number of cases, large earthquakes were preceded by anomalous changes in the level of groundwater, both in wells and wells, and in springs. But a significant part of the earthquakes did not cause significant changes in the aquifers before the earthquakes. At the beginning of the 21st century, with the development of the base of microprocessor electronics, a new stage began in the formation of hydro geological research in order to predict earthquakes, which are based on high-precision and continuous in time registration of changes in the parameters of the groundwater regime in wells under the influence of the processes of formation and passage of earthquakes (hydrogeoseismic variations), which significantly expanded the possibilities of using groundwater level fluctuations in earthquake prediction [Nahornyi 2020, Panda 2021, Pigulevskij 2010 & 2011a,b].

One of these methods is proposed in this article.

2 RESEARCH METHODOLOGY

The research method consisted in presenting the earthquake preparation period as a process developing in the blow-up mode. In dynamic systems developing in blow-up mode, a periodic process is superimposed on the main trend of the controlled parameter. This process is described by a model, one of whose coefficients coincides in value and dimension with the moment of system destruction or a radical change in the law of its development [Podlazov 2009]. Such modes are described by the following equation

$$\frac{dx}{dt} = x^{1+1/\alpha}. \qquad (1)$$

The equation solution increases without limit as we approach the peaking moment t_f:

$$x(t) \sim \left(t_f - t\right)^{-\alpha}. \qquad (2)$$

To obtain a solution acceptable for practice (2), we pass from the real indicator a to the complex one $\alpha + \beta i$, which allows us to obtain an equation of the following form:

$$x(t) = \mathrm{Re}\sum_k a_k \left(t_f - t\right)^{-\alpha + k\beta i} = \left(t_f - t\right)^{-\alpha} \cdot F\left(\ln\left(t_f - t\right)\right). \qquad (3)$$

The function $F(\cdot)$ is described by several multiple harmonics, characterizing in the general case the significant nonlinearity of systems developing in the blow-up mode. However, in practice [Urentsov 2008], the function $F(\cdot)$ is limited to one first harmonic:

$$x(t) = \left(t_f - t\right)^{-\alpha} \cdot \left(a_0 + a_1 \cos\left(\beta \cdot \ln\frac{t_f - t}{\tau}\right)\right). \qquad (4)$$

This expression is a smooth trend, on which log-periodic fluctuations are superimposed, which serve as precursor of approaching the blow-up moment t_f. Taking $t \to t_f$ the oscillation frequency tends to infinity, which meets the dynamic law requirements followed by the blow-up mode. The continuous increase in the log-periodic oscillations frequency allows them to react sensitively to the course of catastrophically developing processes long before the blow-up moment.

If we consider the moment of the earthquake T as the moment of the catastrophe t_f, then the period of earthquake preparation can be attributed to blow-up processes. At the same time, to improve the quality of predicting the moment of the earthquake T, it is necessary to isolate the sensitive log-periodic part of the recorded signal. In practice, this means that the total signal periodic component must be separated from the smooth trend and its behavior should be analyzed separately throughout the entire period of earthquake preparation.

The periodic component A_{PER} plays a key role in the technique. Periodic processes in general, apparently, are one of the foundations for constructing theories in the most diverse fields. “Periodicity - the regular repetition of something in time and (or) space - convinces us of the cognoscibility of the world, of the causality of phenomena. In essence, periodicity is the basis of the worldview of determinism. Understanding its nature allows you to predict events, say, eclipses or the appearance of comets. And such predictions are the main proof of the power of science” [Shnol 1997].

In this regard, in the process of forecasting, it was precisely the periodic component of A_{PER} that was analyzed. For this purpose, it was separated from the original A_{CON} (t) information signal.

The periodic component model should be subjected to direct analysis, which fully describes the complex polyharmonic in structure of the actually recorded signal.

The controlled parameter A_{CON} (t) is considered as the sum of the smooth (trend) B_{TR} and the periodic component A_{PER}.

$$A_{CON}(t) = B_{TR} + A_{PER} \tag{9}$$

According to (4), at $T = t_f$, B_{TR} is determined from the following expression

$$B_{TR} = a_0 \cdot (T - t)^{-\alpha}. \tag{10}$$

The periodic component A_{PER} is extracted from the information (total) signal A_{CON} (t) by decomposing it into empirical modes [Myasnikova 2011] .

$$A_{PER} = -0.25 A_{CON\,i-1} + 0.5 A_{CON\,i} - 0.25 A_{CON\,i+1} \cdot \tag{11}$$

The model of the periodic component B_{MOD}, according to (4), is determined from the following expression

$$B_{MOD} = a_1 \cdot \cos\left(\beta \cdot \ln \frac{T-t}{\tau}\right). \tag{12}$$

For the convenience of further research, expression (12) should be reduced to the classical form of the log-periodic function (13).

$$B_{MOD} = A_0 \cos(\omega \cdot \ln(T - t) - \varphi),$$
$$\text{where } A_0 = a_1 \cdot (T-t)^{-\alpha};\ \omega = \beta; \varphi = \beta \cdot \ln(\tau). \tag{13}$$

Expression (13) contains fore unknown parameters: T, ω, φ, A_0. The first three parameters are determined by solving the system of two nonlinear equations (14).

$$\begin{cases} \ln(T - t_n) - \ln(T - t_{n+1}) = \dfrac{2\pi}{\omega}, \\ \ln(T - t_{n+1}) - \ln(T - t_{n+2}) = \dfrac{2\pi}{\omega}. \end{cases} \tag{14}$$

Equations (14) are based on the knowledge of the time t_n, which account for the extremes A_{EXT} of the periodic component A_{PER}.

To search for these extremes, the following algorithm is used:

– at least three local extremes stand out in the periodic component A_{PER}. They are separated from each other in phase by an angle 2π, and there are consecutive and identical in sign (maximum or minimum);

–the time t is marked when extremes occur (t_n, t_{n+1}, t_{n+2});

–the parameter ρ is calculated that characterizes the relationship between the extreme’s occurrence time.

$$\rho = \frac{t_{n+1} - t_n}{t_{n+2} - t_{n+1}}, \rho > 1. \tag{15}$$

Parameter ρ must exceed one. This indicates a decrease in the period of its oscillations, characteristic of the log-periodic function, over time.

A decrease in the period leads to an increase in the oscillation frequency of the log-periodic function in the limit to infinity. This function feature was the basis for choosing it as a model B_{MOD} (13) for describing systems operating in the blowup mode [Podlazov 2009].

The set of extremes forms an array composed of discrete values of A_{EXT} extremes of the periodic component A_{PER}.

The solution of system (14) gives the following expressions for the first three unknowns of equation (13) [Urentsov 2008]:

$$T = \frac{t_{n+1}^2 - t_{n+2} t_n}{2t_{n+1} - t_{n+2} - t_n},$$
$$\omega = 2\pi / \ln(\rho), \tag{16}$$
$$\varphi = \pi - \omega \cdot \ln(T - t_{n+2}).$$

To check the correctness of the obtained unknown values (16) and, if necessary, to refine them, the difference between the components of the array of extreme values A_{EXT} and their model B_{MOD} (13) is minimized. In this case, the parameter A_0 is also determined.

$$\sum_i^m \left(A_{EXT\,i} - B_{MOD\,i}\right)^2 \Rightarrow \min \cdot \tag{17}$$

In practice, the array of extreme values A_{EXT} contains a number of components, indicating the polyharmonic nature of the oscillations of the periodic component A_{PER}. Therefore, when refining the values of parameters (16), as a model A_{EXTM} (predictive model) describing an array of extreme values A_{EXT}, one should use a trigonometric polynomial composed of log-periodic functions (Fourier series).

$$A_{EXTM} = \frac{a_0}{2} + \sum_{k=1}^{n} \left[\begin{array}{l} a_k \cos(k \cdot \omega \cdot \ln(T - t)) \\ + b_k \sin(k \cdot \omega \cdot \ln(T - t)) \end{array} \right]. \tag{18}$$

The coefficients of the series a_0, a_k, b_k are determined from the following expressions

$$\begin{cases} a_0 = \dfrac{1}{t_0 - t_n} \displaystyle\int_{t_0}^{t_m} A_{EXT} \cdot \frac{1}{T-t} dt, \\ a_k = \dfrac{2}{t_0 - t_n} \displaystyle\int_{t_0}^{t_m} A_{EXT} \cdot \cos\left(k \cdot \frac{2\pi}{t_0 - t_m} \cdot \ln(T - t)\right) \cdot \frac{1}{T-t} dt, \\ b_k = \dfrac{2}{t_0 - t_n} \displaystyle\int_{t_0}^{t_m} A_{EXT} \cdot \sin\left(k \cdot \frac{2\pi}{t_0 - t_m} \cdot \ln(T - t)\right) \cdot \frac{1}{T-t} dt. \end{cases} \tag{19}$$

The remaining useful life T_{RUL} is determined from the following expression.

$$T_{RUL} = T - t. \tag{20}$$

3 RESULTS

On Ukraine, within the Krivoy Rog iron ore structure (Krivbass), there is the largest Precambrian iron ore basin in Europe. In tectonic terms, the structure is located in the eastern part of the Ingulets-Krivoy Rog-Kremenchug suture zone. The zone crosses the Ukrainian Shield (USh) in the meridional direction and has a length of more than 300 km and a width of 10-30 km. As our long-term observations show, it is currently the source of modern seismicity in the central part of the USh [Pihulevskyi 2021].

According to the results of seismic observations, the Krivoy Rog-Kremenchug fault has a westerly dip [Pigulevskiy 2012]. It is traced through the entire earth's crust with angles of incidence from 75-80^{O} (at the basement surface) to 45-55^{O} (at the bottom of the earth's crust). Also, younger large tectonic faults of the sublatitudinal direction were traced in the earth's crust. An analysis of regional gravimetric and magnetometric maps [Svistun 2021] shows that in the north direction it is traced through the entire Dnieper-Donetsk depression, and in the south, it goes into the Black Sea. The zone of the Kryvyi Rih-Kremenchug fault in the territory of Kryvbas, in addition to natural weakening associated with slow geodynamic processes in the lithosphere, is also subject to a high variable level of technogenic load, which is associated with significant movements in space of huge masses of rock from quarries and mines to dumps and tailings, which increases their sensitivity to neotectonic processes taking place in fault zones [Pihulevskyi 2021].

Figure 1. Observation well in Ukraine and earthquakes in Turkey

Monitoring these zones by means of control wells located within them (Fig. 1) makes it possible to identify the presence of elastic-deformation changes in the tectonic zone and associated precursors that begin to behave anomalously before strong seismic events, while the size of these areas may be different [Nahornyi 2020].

Over time, the monitoring results form a time series describing the change in water level over a large observation period. When predicting an earthquake, this series is approximated by model (18), which describes the behaviour of the controlled parameter as a process developing in the blow-up mode. The model parameter T determined in this case coincides in value with the desired moment of seismic aggravation. At the same time, aggravation is understood as the beginning of a period of increased control over an approaching earthquake.

The initial data (the controlled parameter A_{CON} *(t)* (9), Fig. 2.) for the analysis were registered from November 26, 2022, to February 19, 2023, in observing well as shown in Fig. 1. The forecast was divided into two periods. In the first period, an earthquake was predicted, which took place on February 6, in the second - on February 20.

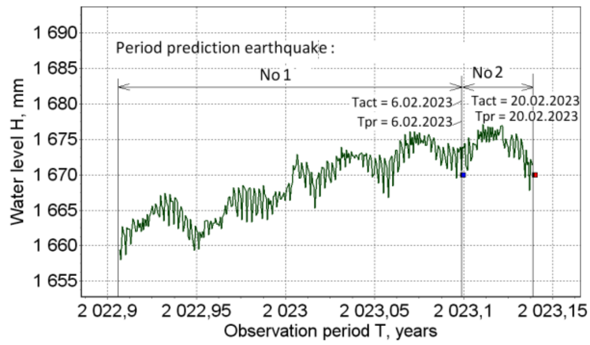

Figure 2. Change in water level in the control well during the observations (controlled parameter ACON (t) (9))

3.1 Prediction of the first earthquake

Fig. 3 shows the change over the periods of observation of the February earthquakes of the periodic component A_{PER} (11), superimposed on the controlled parameter A_{CON} (t) (9) (Fig.2).

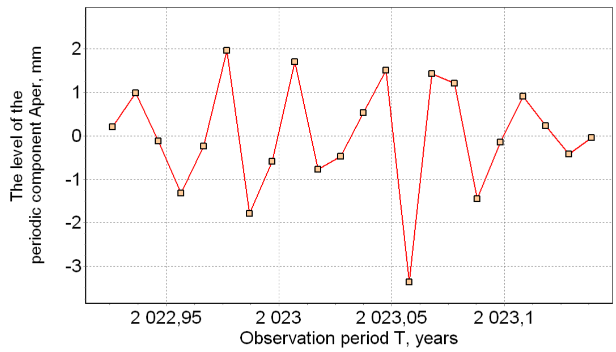

Figure 3. Change over the observation period of the periodic component of APER (11)

The results of the first earthquake short-term forecast are presented in Table 1.

Table 1. Forecast of the first earthquake (actual date of the earthquake 6.02.2023)

Date forecast	29.1.2023	1.2.2023	2.2.2023	3.2.2023
Forecast date of earthquake	6.2.2023	11.2.2023	6.2.2023	6.2.2023
Deviation forecast from average date in %	0.0 %	-0.0 %	0.0 %	0.0 %
Deviation forecast from average date in days	-1.38	4.05	-1.38	-1.38

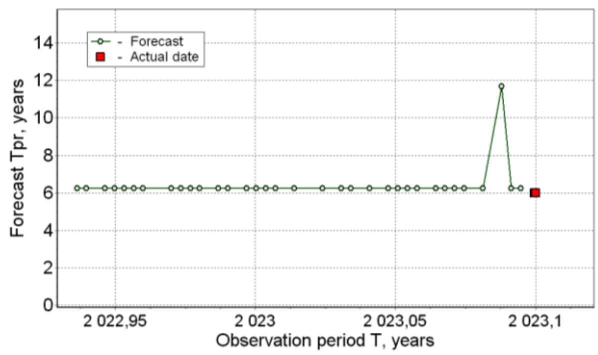

Figure 4. Forecasting time of the first earthquake

The forecast (16) over the observation period first earthquake is shown in Fig. 4.

Below is the "Forecast Protocol..."

PROTOCOL

earthquake forecast

===================

|| Forecast date: ||

|| 6.12.2022 y. ||

====================

FORECAST:

The forecast of the most probable date of the earthquake is:

6.2.2023 y.

and changes with confidence probability P=0.95 within the following limits:

from 6.2.2023 y. to 6.2.2023 y.

PROTOCOL

earthquake forecast

==================

|| Forecast date: ||

|| 2.2.2023 y. ||

===============

FORECAST:

The forecast of the most probable date of the earthquake is:

6.2.2023 y.

and changes with confidence probability P=0.95 within the following limits:

from 6.2.2023 y. to 6.2.2023 y.

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|| Forecast date: ||

|| 3.2.2023 y. ||

====================

FORECAST:

The forecast of the most probable date of the earthquake is:

6.2.2023 y.

and changes with confidence probability P=0.95 within the following limits:

from 6.2.2023 y. to 6.2.2023 y.

3.2 Prediction of the second earthquake

The forecasting results are shown in Fig. 5, Tabl.2 and in the «Protocol …». The results of the short-term forecast second earthquake are given in Table 2.

Table. 2 Forecast of the second earthquake (actual date of the earthquake 20.02.2023)

Date forecast	18.2.2023	18.2.2023	19.2.2023	19.2.2023
Forecast date of earthquake	20.2.2023	20.2.2023	20.2.2023	20.2.2023
Deviation forecast from average date in %	-0.0 %	-0.0 %	-0.0 %	-0.0 %
Deviation forecast from average date in days	0.00	0.00	0.00	0.00

The forecast (16) over the observation period is shown in fig.5.

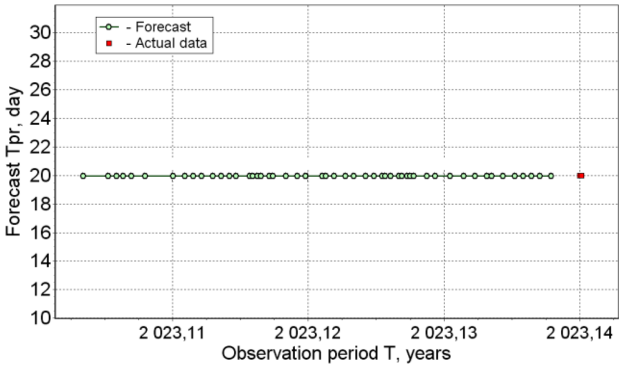

Figure 5. Forecasting time of the second earthquake

Below is the " **F**orecast Protocol..."

PROTOCOL

earthquake forecast

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|| Forecast date: ||

|| 7.2.2023 y. ||

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FORECAST:

The forecast of the most probable date of the earthquake is:

20.2.2023 y.

and changes with confidence probability P=0.95 within the following limits:

from 20.2.2023 y. to 20.2.2023 y.

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|| Forecast date: ||

|| 19.2.2023 y. ||

====================

FORECAST:

The forecast of the most probable date of the earthquake is:

20.2.2023 y.

and changes with confidence probability P=0.95 within the following limits:

from 20.2.2023 y. to 20.2.2023 y.

4 DISCUSSION

The results of approbation of the earthquake forecasting technique confirmed the assumption that the process of earthquake preparation can be considered as a blow-up process. The proof of this is the fact that the initial data for prediction (Fig. 2) contain a periodic component (Fig. 3). The analysis of the periodic component, carried out in accordance with the considered methodology, made it possible to determine the date of the earthquake with zero prediction error. The effectiveness of forecasting was confirmed twice when determining the dates of the earthquakes that took place in Turkey on February 6 and 20, 2023.

5 CONCLUSIONS

The technique considered in the article, developed on the presentation of the earthquake preparation process as a blow-up process, and has confirmed its effectiveness in predicting two earthquakes that took place in Turkey in February 2023.

Approval of the methodology enables the anticipation of seismic activity escalation in a global region, even if it is geographically distant from the point where the initial seismic information for forecasting is monitored.

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