УДК 556.3.06 DOI: https://doi.org/10.24028/gj.v45i6.293312

Earthquake prediction based on the analysis of water level fluctuations in the control well

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Received 3 July 2023

This study examines the methodology and results of earthquake forecasting based on the assumption that the earthquake preparation process can be linked to the development of rupture mechanisms. The analysis focuses on water fluctuations in a control monitoring well, which provides valuable information about the earthquake's preparation period well in advance. Studies on the territory of the Kryvyi Rih iron ore basin (Kryvbas) confirmed that the underground waters in a deep well (815 m deep) depend on the processes of the current lithosphere deformations evidenced by the changing elastic-deformation state of the crust in tectonic areas. The Kryvyi Rih-Kremenchuk crust-mantle fault produces a system of different-scale faults in the crystalline basement which determine the hydrodynamics of the Kryvbas underground filtration. The earthquake preparation process exhibits clear indicators of the rupture process, characterized by a periodic component of water fluctuations superimposed on the main level-changing process during the preparatory phase. The frequency of the periodic component increases as the date of the earthquake approaches. With this approach, an earthquake with a magnitude of 4.1 in Kryvbas was successfully predicted one and a half year before the event, based on monitoring water level fluctuations for 120 days between February and June 2016. The efficacy of forecasting local earthquakes was evaluated using the retro-forecast of earthquakes in Kryvbas on July 29, 2017. The methodology was validated through testing, confirming the initial assumptions. This technique was tested to predict the exacerbation of the seismic situation in the iron ore mining area caused by powerful blasting activities.

Key words: amplitude trend, blue-up process, forecast model, shocks environment criticality, Kryvyi Rih-Kremenchuk deep fault, underground waters.

Introduction. In recent years, advancements in hardware infrastructure and mathematical tools have provided new opportunities for addressing the challenges of earthquake prediction through the study of physical and chemical processes in groundwater [Biagi et al., 2000; Wang, 2007; Wang, Manga, 2010; Nagornyi, 2018]. Extensive research conducted over the past 40—50 years has yielded significant results in this field [Pigulevskiy, Svistun, 2011a; Kopylova, Boldina, 2019, 2021; Hwang et al., 2020; Nagornyi, Pigulevskiy, 2022]. These include the creation of geodynamic polygons, the implementation of comprehensive hydrogeological and geophysical monitoring methods, the identification of reliable earthquake precursors, the establishment of spatio-temporal regularities of earthquake precursors, and the development of source models and earthquake preparation processes.

For an earthquake forecast to be consi-

Citation: *Pigulevskiy, P.I., & Nahornyi, V.V.* (2023). Earthquake prediction based on the analysis of water level fluctuations in the control well. *Geofizicheskiy Zhurnal*, *45*(6), 144—152. https://doi.org/10.24028/gj.v45i6.293312.

dered practically reliable, it must predict three key elements of future events in advance: the location, intensity (magnitude), and timing. The prediction of the impact time is particularly crucial. Each forecast stage relies on specific precursor indicators, primarily observed through geophysical surveys that precede and foreshadow earthquakes. The abundance of earthquake precursors enables the utilization effective earthquake prediction methods employing various algorithms for their identification [Nagornyi, Pigulevskiy, 2022]. The abundance of earthquake precursors enables the utilization of original foundations and effective earthquake prediction methods employing various algorithms for their identification [Nagornyi, Pigulevskiy, 2022].

The early 21st century saw novel developments in the hydrogeology focusing on earthquake prediction based on high-precision and continuous monitoring of the changes in the groundwater's state in wells, known as hydrogeoseismic variations. These variations are influenced by the processes of earthquake formation and passage. This approach expands the possibilities of using groundwater levels for earthquake prediction in aseismic regions worldwide, including the Ukrainian Shield within the East European Platform [Pigulevskiy et al., 2010; Pigulevskiy, Svistun, 2011a,b; Nagornyi et al., 2020; Panda et al., 2021]. This article explores one of these methods in detail.

Research Methodology. The research methodology employed in this study involved presenting the earthquake's preparation as a process evolving in the blow-up mode. In dynamic systems operating in blow-up mode, a periodic process overlays the main trend of the monitored parameter. This process is described by a model wherein one of the coefficients corresponds in value and dimension to the moment of system failure or a significant alteration in its evolution pattern [Podlazov, 2009]. These modes can be described by the following equation:

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

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

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

To obtain a practical solution of (2), we pass from the real exponent *a* to the complex one $\alpha+\beta i$. This transformation enables us to derive an equation of the following form:

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

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:

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

This expression is a smooth trend onto 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 frequency of log-periodic oscillations enhances their sensitivity to the course of catastrophically developing processes well before the blow-up moment.

If we identify the moment of the earthquake (T) as the moment of the catastrophe (t_f), then the period of earthquake preparation can be classified as a blow-up process. To enhance the accuracy of earthquake prediction (predicting the moment T), it is crucial to isolate and analyze the sensitive log-periodic part of the recorded signal. This involves separating the periodic component of the overall signal from the smooth trend and examining its behavior independently throughout the earthquake preparation period.

The periodic component A_{PER} plays a key role in the technique. Periodic processes 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, Chapter, 1997].

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

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

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

$$A_{\mathrm{CON}}(t) = A_{\mathrm{TR}} + A_{\mathrm{PER}} . \qquad (5)$$

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

$$B_{\mathrm{TR}} = a_0 \left(T - t\right)^{-\alpha} . \qquad (6)$$

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

$$A_{\mathrm{PER}} = -0.25 A_{\mathrm{CON}\,i-1} + +0.5 A_{\mathrm{CON}\,i} - 0.25 A_{\mathrm{CON}\,i+1} . \qquad (7)$$

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

$$B_{\mathrm{MOD}} = a_1 \cos\left(\beta \ln \frac{T-t}{\tau}\right). \qquad (8)$$

For the convenience of further research, expression (8) should be reduced to the classical form of the log-periodic function (9).

$$A_{\mathrm{MOD}} = A_0 \cos\left(\omega \ln\left(T-t\right) - \varphi\right),$$

where

$$A_0 = a_1 \left(T - t\right)^{-\alpha}; \ \omega = \beta; \ \varphi = \beta \ln\left(\tau\right). \qquad (9)$$

Expression (9) contains four unknown parameters: T, ω, φ, A_0. The first three parameters are determined by solving the system of two nonlinear equations (10).

$$\begin{cases} \ln(T - t_n) - \ln(T - t_{n+1}) = \dfrac{2\pi}{\omega}, \\ \ln(T - t_{n+1}) - \ln(T - t_{n+2}) = \dfrac{2\pi}{\omega}. \end{cases} \qquad (10)$$

Equations (10) 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 they 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 extremes occurrence time:

$$\rho = \frac{t_{n+1} - t_n}{t_{n+2} - t_{n+1}}, \ \rho > 1 . \qquad (11)$$

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 of discrete values of A_{EXT} extremes of the periodic component A_{PER}.

The solution of system (11) gives the following expressions for the first three unknowns of equation (12) [Urentsov, 2008]:

$$T = \frac{t_{n+1}^2 - t_{n+2} t_n}{2t_{n+1} - t_{n+2} - t_n}, \ \omega = 2\pi / \ln\left(\rho\right),$$

$$\varphi = \pi - \omega \ln\left(T - t_{n+2}\right). \qquad (12)$$

To check the correctness of the obtained unknowns' values (12) and, if necessary, to refine them, the difference between the components of the array of extreme values A_{EXT} and their model B_{MOD} (9) is minimized. In this case, the parameter A_0 is also determined:

$$\sum_{i}^{m}\left(A_{\text{EXT}i} - B_{\text{MOD}i}\right)^2 \Rightarrow \min. \qquad (13)$$

In practice, the array of extreme values A_{EXT} contains a few components, indicating the polyharmonic nature of the oscillations of the periodic component A_{PER}. Therefore, when refining the values of parameters (12), as a model A_{MOD} (predictive model) describing an array of extreme values A_{EXT}, one should use a trigonometric polynomial composed of log-periodic functions (Fourier series):

$$A_{\text{MOD}} = \frac{a_0}{2} + \sum_{k=1}^{n}\begin{bmatrix} a_k \cos\left(k\omega \ln\left(T - t\right)\right) \\ +b_k \sin\left(k\omega \ln\left(T - t\right)\right)\end{bmatrix}. \qquad (14)$$

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

$$\begin{cases} a_0 = \dfrac{1}{t_0 - t_m}\displaystyle\int_{t_0}^{t_m} A_{\text{EXT}} \frac{1}{T-t} dt, \\ a_k = \dfrac{2}{t_0 - t_m}\displaystyle\int_{t_0}^{t_m} A_{\text{EXT}} \cos\left(k \frac{2\pi}{t_0 - t_m} \ln(T-t)\right)\frac{1}{T-t} dt, \\ b_k = \dfrac{2}{t_0 - t_m}\displaystyle\int_{t_0}^{t_m} A_{\text{EXT}} \sin\left(k \frac{2\pi}{t_0 - t_m} \ln(T-t)\right)\frac{1}{T-t} dt. \end{cases} \qquad (15)$$

Methodology and results of studies of the groundwater regime. In order to investigate the changes in the filtration properties of water-saturated reservoirs resulting from local and remote strong earthquakes in the Kryvbas region, a precision monitoring program has been implemented since October 2007. The monitoring involves measuring the groundwater level in a specific well within the Kryvyi Rih-Kremenchuk deep fault zone. The measurements were conducted in Well 14431, which has a depth of 815 m and an average static water level of 106 m below the surface.

The study of the groundwater regime, specifically the hydrogeodeformational field, was carried out using the MiniDiver autonomous recording sensors manufactured by Schlumberger (as referenced in [Pihulevskyi, Svistun, 2011a,b]). These sensors are designed to record various parameters related to the groundwater system.

From October 2007 to June 2023, data were recorded with a variable frequency, and observation intervals ranged from 2 to 20 min. The sensors used in the study are highly sensitive: 0.1 cm for measuring the water level, 1 mm Hg for atmospheric pressure, and 0.01 °C for temperature.

Studying the deformation mechanism in water-saturated reservoirs is a crucial task with both practical and theoretical significance. It aims to qualitatively understand and quantitatively describe the geomechanical and hydrogeodynamic processes taking place in such reservoirs. Two types of stress models are commonly used to describe the hydrogeological responses of fluid-saturated reservoirs: static and dynamic.

The static deformation model deals with irreversible changes in reservoir properties resulting from the propagation of fractures, faulting, and displacements caused by seismic activity. These changes are observed as coseismic step-wise and gradual alterations in the groundwater level.

On the other hand, models of dynamic deformation of fluid-saturated reservoirs are based on the theory of poroelasticity, as referenced in works by [Hsieh et al., 1987; Kopylova, Boldina, 2019]. These models consider the response of pore pressure to variations in the stress-strain state of the rock's mineral skeleton and the groundwater level when subjected to changes.

The zone of the Kryvyi Rih-Kremenchuk deep fault holds significance in tectonic terms. It is widely regarded as a mantle fault, separating the Middle Dnieper megablock from the West Ingulets-Kryvyi Rih-Kremenchuk suture zone to the west. This fault extends beyond the borders of the Ukrainian Shield and can be traced over a considerable distance [Azarov, 2006; Omelchenko, Pigulevskyy, 2020].

The West-Ingulets (Kirovograd) zone, adjacent to the Ingul megablock from the east, forms part of the suture zone. The Ingulets-Kryvyi Rih zone is located between the Kryvyi Rih-Kremenchuk and Ingulets faults. The Kryvyi Rih-Kremenchuk fault serves as the western boundary of this zone [Pigulevskyy et al., 2016]. The Kryvyi Rih-Kremenchuk fault zone extends over a length of more than 275 km and has a width of 7—10 km [Gintov, 2015]. Within it, the Kryvyi Rih-Kremenchuk structural-formation zone is found, traversing the Ukrainian Shield in a meridional direction. This area has been extensively studied due to the presence of the largest Precambrian iron ore basins in Europe, namely Kryvyi Rih and Kremenchuk.

According to the results of seismic observations, the fault has a westerly dip [Sheremet, 2011; Tiapkin et al., 2017]. It can be traced throughout the earth's crust with dip angles from 75—80° (at the basement surface) to 45—55° (at the bottom). Also, younger large tectonic faults of the sublatitudinal direction were traced in the earth's crust. Analysis of regional gravimetric and magnetometric maps [Omelchenko, Pigulevskyy, 2020; Svistun, Pigulevskiy, 2021] shows that in the north direction, it can be traced through the entire Dnieper-Donetsk depression, and in the south, it goes to the Black Sea. The Kryvyi Rih-Kremenchuk fault zone in the territory of Kryvbas is characterized by natural weakening associated with slow geodynamic processes in the lithosphere. It is also subject to a high variable level of technogenic load, which is associated with significant movements in space of huge masses of rocks from quarries and mines to dumps and tailings. This is the reason for their increased sensitivity to neotectonic processes occurring in fault zones [Pigulevskyi et al., 2021]. Monitoring these zones with the help of control wells makes it possible to identify the presence of elastic-deformation changes in the tectonic zone and the precursors associated with them, which begin to behave anomalously before strong seismic events [Nagornyi et al., 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 the model (18), which describes the behavior 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 ACON(t) (9), Fig. 1.) for the analysis were registered from February 1 to April 4, 2016, in the observation well (Kryvyi Rih).

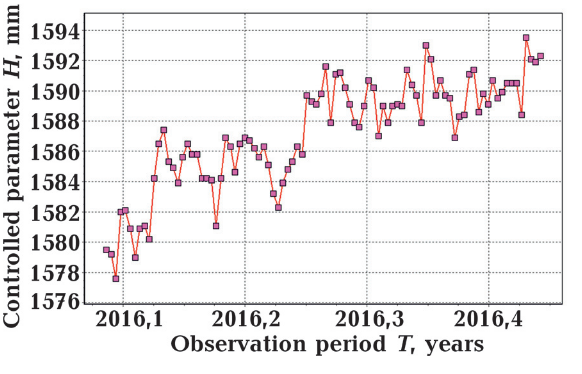

Fig. 1. Change in water level in the control well during the observations (controlled parameter $A_{CON}(t)$ (9).

Fig. 2 shows the change over the periods of observation of the earthquakes of the periodic component A_{PER} (11), superimposed on the controlled parameter $A_{CON}(t)$ (9) (see Fig. 1).

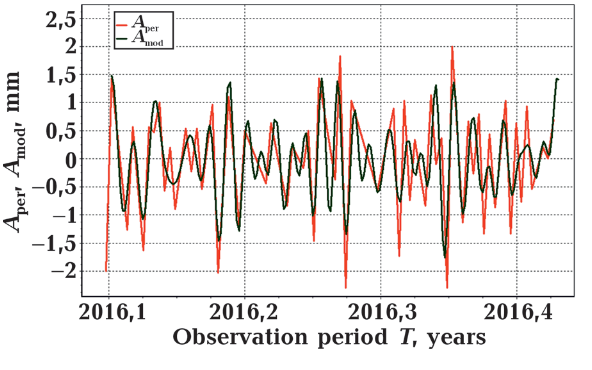

Fig. 2. Change over the observation period of the periodic component of A_{PER} (11) and its models A_{MOD} (18).

Fig. 3. shows the parameter (15), and Fig. 4, the frequency (16) of oscillations of the periodic component A_{PER} (11).

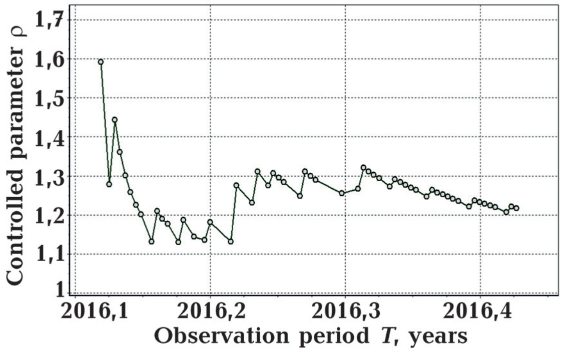

Fig. 3. Change of parameter ρ (15) over the observation period.

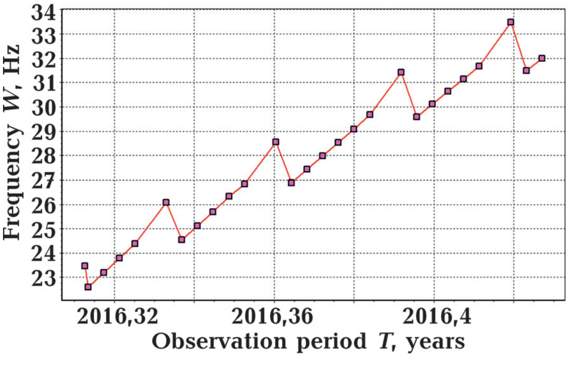

Fig. 4. Change frequencies ω (16) over the observation period.

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

The comparison of the actual date of the earthquake and the statistical analysis of its forecast are presented graphically in Fig. 5.

Below is the Forecast Protocol.

PROTOCOL
earthquake forecast
Forecast date:
1.6.2016
FORECAST:
The forecast of the most probable date of the earthquake is:
22.7.2017
and changes with confidence probability
P=0.95
within the following limits:
from 21.7.2017 to 23.7.2017

PROTOCOL
earthquake forecast
Forecast date:
2.6.2016
FORECAST:
The forecast of the most probable date of the earthquake is:
22.3.2017
and changes with confidence probability
P=0.95
within the following limits:
from 21.3.2017 to 23.3.2017

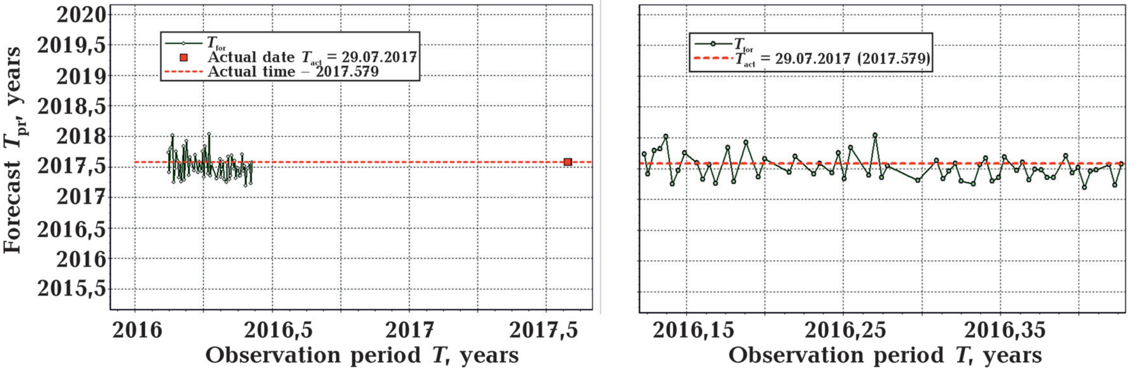

Fig. 5. Forecasting time of the earthquake: *a* — visualization of the relationship in time between the actual date of the earthquake and its forecast; *b* — statistical analysis of the forecast (the forecast of the date of the earthquake changes from 9.03. 2017 to 15.01. 2018; average forecast value T_{av}=6.07.2017; skz=0.233 year.

Earthquake forecast (actual date of the earthquake was 29.7.2017)

Data forecast	28.5.2016	1.6.2016	2.6.2016	4.6.2016
Forecast data of the earthquake	21.6.2017	22.7.2017	22.3.2017	28.7.2017
Deviation of the forecast from the actual data	–0.8 %	–0.03 %	–1.7 %	–0.02 %

PROTOCOL
earthquake forecast
Forecast date:
4.6.2016

FORECAST:
The forecast of the most probable date of the earthquake is:
28.7.2017
and changes with confidence probability
P=0.95
within the following limits:
from 27.7.2017 to 29.7.2017

Conclusion. The analysis of water fluctuations in the control well reveals that they provide information about the preparatory period of an earthquake well in advance. The presence of a periodic component in the water fluctuations, as shown in Fig. 2, indicates the blow-up process during the earthquake preparation phase. This periodic component is observed alongside the main process of changing the water level in the control well during the preparatory period, as depicted in Fig. 1.

According to the peculiarities of the processes occurring in the blow-up mode, the parameter ρ, which characterizes the decrease over time of the oscillation period of the periodic component, decreases (see Fig. 3). The oscillation frequency ω of this component increases accordingly (see Fig. 4). This allowed to predict the event's actual date one and a half years beforehand (Fig. 5, Table, Forecast protocol). The earthquake took place in Kryvbas on July 29, 2017. Moreover, for the forecast, it turned out to be sufficient to observe the fluctuations in the water level for 120 days in February—Jun 2016. The control well is located in the area of Kryvyi Rih.

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Прогнозування землетрусів на підставі аналізу коливань рівня води в контрольній свердловині

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Розглянуто методику та результати прогнозування землетрусів. Методика заснована на припущенні, що підготовку землетрусу можна віднести до процесів, які розвиваються в режимі розриву. Дослідження на території Криворізького залізорудного басейну (Кривбасу) підтвердили, що коливання рівня підземних вод у глибокій свердловині (завглибшки 815 м) залежать від процесів сучасної деформації літосфери Землі, проявом яких є зміна пружно-деформаційного стану земної кори в тектонічних зонах. Криворізько-Кременчуцький розлом коромантійного закладання формує в кристалічному фундаменті різнорангову систему розломів, які визначають гідродинаміку підземної фільтрації території Кривбасу.

Наведені у статті результати аналізу коливань води в контрольній моніторинговій свердловині засвідчують наявність інформації про підготовчий період задовго до землетрусу. Крім того, процес підготовка землетрусу має явні ознаки процесу розриву. На це вказує наявність періодичної складової коливань води, яка накладається на основний процес зміни рівня води в свердловині у підготовчий період. Частота періодичної складової коливань води збільшується в міру наближення дати землетрусу. Відповідно до особливостей процесів, що відбуваються в режимі розширення, параметр, який характеризує зменшення з часом періоду коливань періодичної складової води, зменшується, а частота коливань цієї складової відповідно зростає. Це дало можливість передбачити землетрус у Кривбасі 29 липня 2017 р. з магнітудою 4,1 за півтора року. Крім того, для прогнозу землетрусу виявилося достатньо спостережень за коливаннями рівня води протягом 120 днів у лютому—червні 2016 р. На прикладі ретропрогнозу землетрусу, що стався на території Кривбасу 29 липня 2017 р., було оцінено можливості методики прогнозування локальних землетрусів. Результати тестування методики підтвердили покладені в неї припущення. Апробація методики дала змогу прогнозувати час загострення сейсмічної обстановки на території видобування залізної руди потужними вибуховими роботами.

Ключові слова: тренд амплітуди, процес поглинання, модель прогнозу, критичність середовища поштовху, Криворізько-Кременчуцький глибинний розлом, підземні води.