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THE CONSEQUENCES OF THE CATASTROPHIC TURKISH EARTHQUAKE ON THE TERRITORY OF KRYVBAS ON FEBRUARY 6TH

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Abstract. The results of the study of the impact of powerful Turkish earthquakes on February 6, 2023: at 01:17:36 (UTC) with a magnitude of 7.8Mw (Kahramanmarash-Gaziantep); at 10:24:50 with a magnitude of 7.5Mw (Ekinozu-Kahramanmarash) for monitoring seismic and hydrophysical observations on the territory of the city of Kryvyi Rih were analyzed.

Comprehensive analysis and interpretation of data from hydrogeological and geophysical studies made it possible to assess changes in deep physical processes hundreds of meters from the surface.

Analysis of monitoring observations of hydrogeological and geophysical processes occurring on the territory of Kryvbas showed the relationship between the Earth's lithosphere and territories more than 1,300 km away from the centers of powerful earthquakes, which manifested in a short-term decrease in the level of groundwater in the geological environment of Kryvbas. Monitoring observations of the water level in the exploratory well recorded local changes in the geodeformation processes of the earth's crust, which occurred after the powerful Turkish earthquakes on February 6, 2023 at 01:00. 17 min. 36.1 seconds with a magnitude of 7.8 and at 10 a.m. 24 min. 49.6 seconds with a magnitude of 7.5 after 1 hour. 6 (12) min. in the form of a decrease in its level by 2–3 cm. For the first time, the speed of propagation in the upper part of the lithosphere of the deformation front was calculated, which was ≈19.0 km/min. (±0.5 km/min). The recorded decrease in the level of groundwater in the monitoring well allowed us to conclude that after the earthquake, short-term crustal stretching processes took place in the zone of the Kryvyi Ryh-Kremenchuk, which could contribute to the migration of groundwater to greater depths and increase the inflow of water into mines and quarries.

Studies have confirmed that fluctuations in the level of underground water in a deep well depend on the processes of modern deformation of the Earth's lithosphere, the manifestation of which is a change in the elastic-deformation state of the earth's crust in the zones of tectonic faults in the territory of Kryvbas. The Kryvyi Rih fault of the coro-mantle foundation forms in the crystalline basement a heterogeneous system of subsequent faults and associated zones of increased permeability for water, influencing the formation and speed of geodynamic processes and determining the hydrodynamics of underground filtration of the Kryvbas territory.

The results of the research will allow solving a number of important problems of mining geology: determining the connection of groundwater with the processes of modern deformation of the Earth's lithosphere, the influence of the geological and tectonic structure on the development of the processes of flooding mines and quarries and on residential and industrial buildings.

Keywords: geodynamic processes, hydrogeodeformation processes, earthquake, monitoring, seismic observations, groundwater.

1. Introduction

On February 6, 2023, powerful earthquakes struck Turkey, with a magnitude of 7.8Mw at 01:17:36 (UTC) in the Kahramanmaraş-Gaziantep region and a magnitude of 7.5Mw at 10:24:50 in Echinozu-Kahramanmaraş [source: https://www.emsc-csem.org; 15; 16]. The epicenters were situated at the convergence of three tectonic plates – Anatolian, Arabian, and African – along a fault line at a depth of 18 km. The shallow depth contributed to the widespread devastation, as destructive shocks propagated over hundreds of kilometers. Tectonic plate movements caused visible cracks on the surface, traversing cities and, in some cases, running directly through buildings. Intensely powerful tremors affected numerous densely populated cities and towns, resulting in the destruction of thousands of buildings, burying residents, and rendering thousands homeless.

The seismic impact of the earthquakes, with magnitudes of 7.8 and 7.5 Mw, reached southern Ukraine and Crimea. Seismological stations at the S. Subbotin Institute of Geophysics and the Main Special Control Center of the National Space Agency (NSA) of Ukraine recorded the event.

The seismological station "Kryvyi Rih," situated at the address: Geological Street, 2, Kryvyi Rih, within the framework of the Dnipropetrovsk geophysical expedition "Dniprogeofizika," clearly detected tectonic movements at the earthquake's epicenter (Fig. 1). Furthermore, our monitoring observations of the water level in the exploratory deep well (815 m) also captured the earthquake's impact on the fault-block tectonics of the Kryvbas territory (Fig. 2, 3).

2. Methods

The Kryvyi Rih seismological station conducted the recording of aftershocks resulting from the impactful Turkish earthquakes on February 6, 2023. The analysis of digital recordings of seismic events involved the examination of their specific spectral-temporal patterns using the spectral diagrams method. These diagrams effectively illustrate the evolving spectrum of events over time. The Geotool interactive program [2] was employed for the spectral-temporal analysis of digital records.

Figure 1 displays the unfiltered recording of the Turkish earthquake that occurred on February 6, 2023, with a magnitude of 7.8Mw at 01:17:36 (UTC), captured by the "Kryvyi Rih" seismological station. The frequency band examined in this figure is 1.0–2.0 Hz.

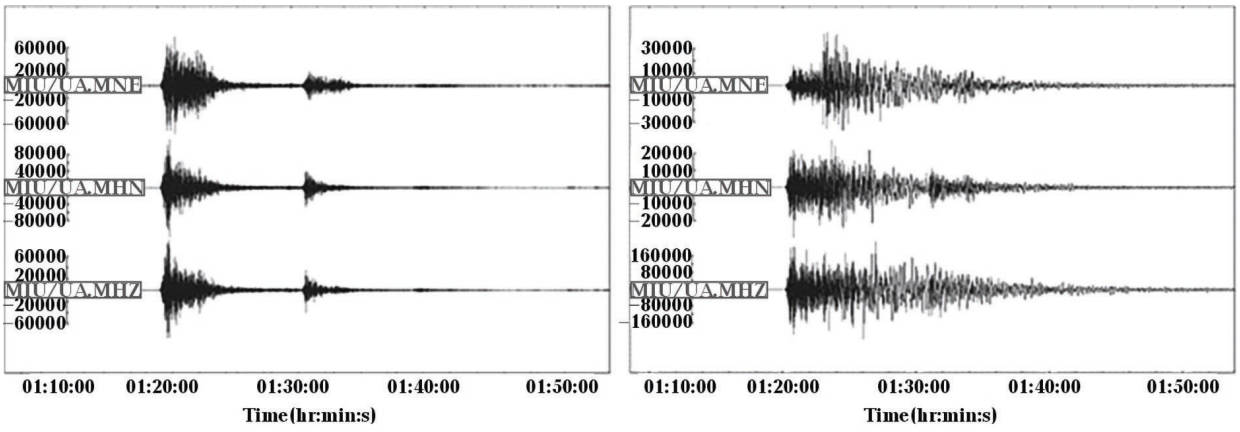


Figure 1 – Record of the Turkish earthquake on February 6, 2023 with a magnitude of Mw=7.8 at 01:17:36 (UTC) Kryvyi Rih s/c, frequency band 1.0–2.0 Hz (a); unfiltered (b)

The records of distant powerful earthquakes (see Fig. 1b) depict a distinct, sudden emergence of seismic energy spanning a wide frequency range within the volume wave recording interval, succeeded by an exponential decay. The peak of spectral energy density is evident in the low-frequency region during the recording interval of surface waves.

The results derived from processing the digital records at the Kryvyi Rih seismological station are presented in Table 1. The earthquake parameters, obtained through this processing, reveal a ground acceleration of 2.6×10^{-2} g at the observation point

[1], corresponding to a shaking intensity of less than 3 points on the MSC-64 scale [2]. This implies that vibrations from the Turkish earthquakes could only be perceptible to a limited number of individuals in areas lacking man-made seismic activity.

Table 1 – Earthquake parameters obtained as a result of processing digital records of the Kryvyi Rih seismological station

Seismological station	Station coordinates		Acceleration at the point of registration	Intensity at the registration point	Distance to epicenter (km)
«Kryvyi Rih»	47.9295	33.3311	$2{,}6\times10^{-2}$ g	< 3 scale	1309

Concurrently with seismological observations, precise monitoring of groundwater levels in an exploratory well is underway. The research aims to investigate alterations in the filtration properties of water-saturated fault zones resulting from both local and distant powerful earthquakes. Groundwater level measurements are being conducted in well No. 14431, situated within the Kryvyi Rih-Kremenchuk deep fault zone, reaching a depth of 815 meters and maintaining an average static water level of 106 meters from the contemporary relief.

The examination of the groundwater regime, particularly the hydrogeodeformation field, employs autonomous MiniDiver recording sensors produced by Schlumberger (refer to [7]). These sensors are designed to capture various parameters related to the groundwater system.

Data recording was carried out with variable frequency from October 2007 to June 2023, with observation intervals ranging from 2 to 20 minutes. The sensors utilized in the research exhibit high sensitivity: 0.1 cm for water level measurement, 1 mm Hg. for atmospheric pressure, and 0.01°C for temperature.

To assess the response of the geological environment in the Kryvbas territory to induced seismicity from potent Turkish earthquakes, we will examine the seismotectonic characteristics of its structure.

3. Theoretical part

General Characteristics of the Geological Structure of the Kryvbas Territory. The Kryvyi Rih structural-facies zone, comprising a synclinorium and monocline, is situated in the eastern part of the West-Inhulets-Kryvyi Rih-Kremenchuk suture zone (ZIKKSHZ), within the vicinity of the Kryvyi Rih-Kremenchuk crustal-mantle fault [1, 7, 8, 10]. To the east, it interfaces with the Saksahan dome, consisting of ancient Archaean granitoid and metabasite-ultrabasite rocks, while to the west, it connects with the Inhulets rampart, consisting mainly of Neoarchaean plagiogranitoid rocks. The structure displays synclinal and anticlinal folds of high order, with the hinge of the synclinorium dipping northward. The maximum calculated depth of the structure in the Sukha Balka and Khodzynsk mines area is approximately 7.0–7.5 km based on geophysical data.

The eastern wing of the synclinorium comprises a complete section of the Kryvyi Rih series, while the western wing is intersected by the Western and Tarapakiv faults. The internal complexity of the structure is attributed to the presence of an ancient

subduction zone, evident from a robust zone of extended seismic platforms descending into the crust at angles of 45°–40° to the east and the thickening of the lithosphere beneath this zone [2, 8, 11].

Rocks within the Kryvyi Rih structure are intricately folded and fractured by numerous transverse and longitudinal faults. The oldest formations within the sedimentary rock complex belong to Paleogene (Eocene) sediments. The spatial distribution of Eocene formations in trough-like depressions of the crystalline bed results in their scattered island-like occurrence. These deposits include sands, carbonaceous clays, and lignites, with a total thickness ranging from 25 to 42 m. Overlying the Paleogene deposits are Neogene layers of the Sarmatian and Pontic levels, characterized by alternating layers of limestone, clay, and sand, with a total thickness of 11.0 to 24.0 m.

Quaternary formations cover the Neogene sediments throughout the district, featuring two common types of loam:

- Yellow-brown and pale-yellow loamy loams with frequent carbonate nests and veins containing gypsum inclusions.
- Brown and red-brown loams and clays with inclusions of carbonates and gypsum.

In river valleys and deep ravines, erosion has led to the partial or complete removal of sedimentary complex rocks, replaced by alluvial formations consisting of sand-clay and silty rocks, often interlayered.

Main Discontinuous Tectonic Disturbances. The internal complexity of the Kryvyi Rih structure is attributed to several significant submeridional faults, including the Western, Tarapakiv, Saksahan, Eastern, and South-Eastern faults. These faults are interpreted as breaks defining the primary structural-tectonic line of the transregional Kryvyi Rih-Kremenchuk deep fault in the crust-mantle deposit. This fault serves as the western boundary of the Kryvyi Rih structure [2, 3, 5, 11]. Its trace spans the entire crust, evident in the displacement of seismic reflective elements [9], extending for over 200 kilometers in both north and south directions outside the Ukrainian shield (USH) [2, 9], with a western dip. The fault's dip undergoes a transition from a steep angle near the surface of the crystalline basement (75–80°) to a gentler one in the lower crust (45–55°) as depth increases.

In addition to these faults, large, nearly orthogonal, and feathering (shear) tectonic disturbances are discernible in the Earth's crust. These disturbances are characterized by abrupt shifts in seismic horizons, changes in crustal material composition, and other geological and geophysical features.

Typically, these described disturbances are marked by various types of brittle deformations, such as brecciation, cataclasis, and mylonitization, with thickness ranging from a few meters to several hundred meters or more. Alongside brittle deformations, fault zones also exhibit a wide range of visco-plastic formations.

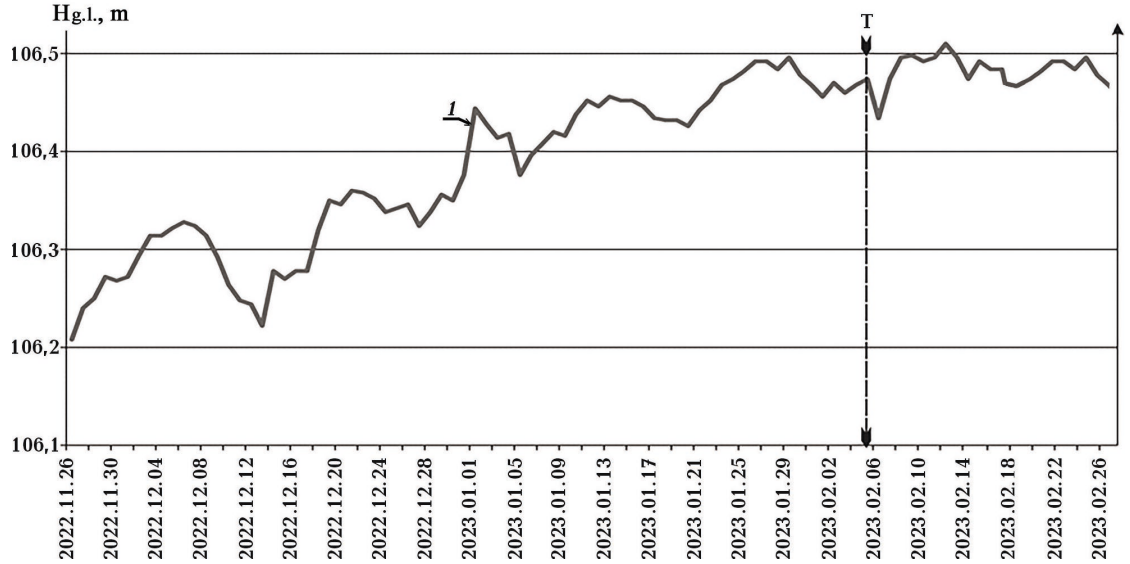
The analysis of local earthquakes and their locations indicates that the Kryvyi Rih tectonic system, along with the entire eastern flank of the Western-Inhulets-Kryvyi Rih-Kremenchuk suture zone with the Proterozoic, remains a geodynamically active structure. Here, thrust and shear tectonic processes are discernible in the contemporary geological stage, albeit possibly with a reduced amplitude over time.

The hydrogeological conditions of this territory are intricate and influenced by various factors. Firstly, geologically, the area comprises a complex combination of intrusive and metamorphic rocks from the Precambrian period, covered by diverse Cenozoic sediments characterized by a wide range of lithological compositions. Secondly, the intricate tectonic structure of the region results in the presence of extensive zones of crushed and cracked rocks, facilitating groundwater movement in certain areas, while other regions exhibit almost complete absence of such zones with significant mantle development of massive crystalline rocks. Thirdly, the highly developed rafter-beam network contributes to unfavorable hydrogeological conditions.

4. Results and discussion

Hydrogeo-deformation monitoring results [4] reveal general trends of water level decrease or increase, along with time intervals indicating rapid (abrupt) changes. These changes are associated with minor neotectonic movements in the Kryvyi Rih-Kremenchuk suture zone. The study of the deformation mechanism in water-saturated fault zones is a crucial task with practical and theoretical significance. It aims to qualitatively understand and quantitatively describe geomechanical and hydrogeodynamic processes in such reservoirs [6, 7].

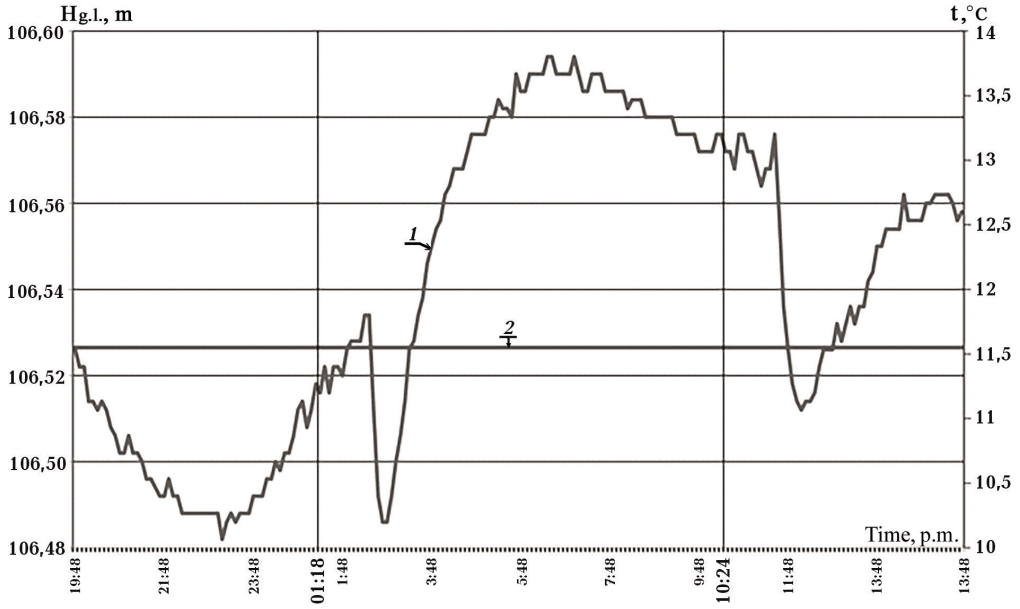
Two stress models are commonly used to describe hydrogeological responses in fluid-saturated formations: static and dynamic. The static deformation model addresses irreversible changes in reservoir properties resulting from the propagation of cracks, faults, and displacements caused by seismic activity. These changes manifest as coseismic stepwise and gradual alterations in groundwater levels. The dynamic deformation model addresses reversible changes in reservoir properties, leading to rapid adjustments in groundwater levels (Fig. 2, 3).



1 – level of groundwater in the well, m; T is the beginning of Turkish earthquakes

Figure 2 – Graph of fluctuations of the groundwater level in a deep monitoring well from November 2022 to February 2023 (discrete 24 hours, counting at 12 hours (UTC))

Figure 2 illustrates the groundwater level fluctuations in the monitoring well from November 2022 to February 2023, with observations taken at discrete intervals of once per day (at 12 a.m.). The fluctuations are intricately linked, primarily with slow neotectonic movements of crustal blocks, representing the main rising trend in the well. Additionally, they are associated with faster geodynamic processes in the fault zone [4, 5], evident in local anomalies of short-term rising or sinking of the water level (Fig. 2). These anomalies serve as precursors to earthquakes, and deciphering them is crucial for successful forecasting [2].



1 – groundwater level, m; 2 – underground water temperature, °C

Figure 3 – Graph of groundwater level fluctuations during earthquakes in Turkey on February 6, 2023 (discrete 6 min)

The Kryvyi Rih-Kremenchuk fault zone within the Kryvbas territory, besides experiencing natural weakening due to slow geodynamic processes in the lithosphere, is also subjected to a high and variable man-made load. This load is linked to significant movements over time and space of massive rock masses from quarries and mines to dumps and tailings. This increased sensitivity to neotectonic processes in fault zones is associated with the ongoing monitoring of these environments using wells located within their boundaries. Such monitoring reveals elastic-deformation changes in the tectonic zone, reflecting the effects of powerful distant earthquakes and related precursors that indicate anomalous changes before significant seismic events. The magnitude of the seismic dynamics' influence can vary.

By altering the discrete time of monitoring observations (6 minutes) in the designated well (815 meters), the reaction of the underground hydrosphere to deformation processes in the Earth's lithosphere was documented after the Turkish earthquakes of February 6, 2023 – the first at 01:17:36.1 with a magnitude of 7.8 and the second at 10:24:49.6 with a magnitude of 7.5 (Fig. 3). The analysis of the results indicates that the underground hydrosphere in the earth's crust of the Kryvbas territory is highly

dynamic and sensitive not only to local changes but also to powerful external tectonic fields that form a hydrogeodynamic system (hydrogeodeformation field). This allows disturbances to be recorded at a considerable distance from the origin. An essential feature of this field is its response to changes in the stress state of the earth's crust and upper mantle caused by rock densification due to geodynamic shifts in fault zones (Western, Tarapakiv, Saksahan, Eastern, and smaller faults), leading to subsequent changes in water saturation. For the first event, groundwater withdrawal occurred at 2:24 (30) a.m., i.e., in 1 hour and 6 (12) minutes, with a minimum level at 2:42 (48) a.m., showing an amplitude of 3 to 4 cm. The geological environment was restored by 3:30 a.m. Groundwater withdrawal for the second event was noted at 11:30 (36) a.m., i.e., in 1 hour and 6 (12) minutes, with a minimum level at 12:06 (18) p.m., ranging from 3 to 4 or more centimeters (Fig. 3). The geological environment was restored by 12:36 (54) p.m.

The distance from the epicenters of the earthquakes to the Kryvyi Rih seismological station is 1,309 km, and the reaction of the geological environment to the deformation front began after 1 hour. 6 (12) min., and the propagation speed of oscillations in the upper part of the lithosphere was ≈19.0 km/min. (±0.5 km/min). Taking into account that a decrease in the level of groundwater in the monitoring well was recorded, it is possible to conclude that after the earthquake, short-term crustal stretching processes took place in this part of the Ukrainian shield. But based on the results of observations in one well, it is impossible to unambiguously establish the mechanism of the process that took place in the Kryvyi Rih-Kremenchuk fault zone. Obviously, only one thing - there was a general micro-opening of the zones of the Western, Tarapakiv, Saksagan, and Eastern faults and their satellites. In general, it is possible to assume that the European Plate (its southwestern part of the East European Platform) has been pushed against the Anatolian, Arabian, and African tectonic plates along the Mediterranean Sea – Black Sea (Tethys zone) line. The process we predicted covered the entire south and south-west of Europe, where a whole series of earthquakes of various magnitudes took place. At the same time, to the south of the hypocenters of the powerful Turkish earthquakes on February 6, 2023, they were not recorded, which allows us to assume a "monolithic" area of compression during the right-lateral strike [https://www.emsc-csem.org].

4. Conclusions

The results of our research, which were obtained as a result of processing digital records of the Kryvyi Rih seismological station, show that the ground acceleration at the observation point is 2.6×10^{-2} g, which corresponds to a shaking intensity of less than 3 points. Such fluctuations from the Turkish earthquakes could be felt by a small number of people in places where there is no man-made seismicity.

The recorded decrease in the level of groundwater in the monitoring well allowed us to conclude that after the earthquake, short-term crustal stretching processes took place in the zone of the Kryvyi Rih -Kremenchuk fault, which contributed to the migration of groundwater to greater depths and increased the inflow of water into mines and quarries.

Changes in the level of groundwater in the well with its rapid installation show that the processes in the earth's crust took place according to the model of dynamic deformation.

Monitoring observations of the water level in the exploratory well recorded local changes in the hydrogeodeformation processes of the earth's crust, which occurred after the powerful Turkish earthquakes on February 6, 2023 at 01:00. 17 min. 36.1 seconds with a magnitude of 7.8 and at 10 a.m. 24 min. 49.6 seconds with a magnitude of 7.5 after 1 hour. 6 (12) min. in the form of lowering their level by 2–3 cm, and is an additional criterion for the prevention of powerful seismic events.

According to monitoring observations, the propagation speed of the deformation front in the submeridional direction (from south to north) in the upper part of the lithosphere was ≈19.0 km/min. (±0.5 km/min).

Short-term processes of stretching the earth's crust after the Turkish earthquakes in the Kryvyi Rih–Kremenchuk fault zone show that the entire territory of Kryvbas is a fairly dynamic area and powerful earthquakes can affect the condition of large man-made hazardous objects. The presented research results show that in order to ensure the required level of seismic hazard in the city of Kryvyi Rih, it is necessary to increase the requirements for seismic safety during the construction of new or reconstruction of old buildings, especially in conditions of changes in the seismic properties of soils (DBN B.1.1-12).

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НАСЛІДКИ КАТАСТРОФІЧНОГО ТУРЕЦЬКОГО ЗЕМЛЕТРУСУ НА ТЕРИТОРІЇ КРИВБАСУ 6 ЛЮТОГО

Пігулевський П. Г., Свистун В. К., Анісімова Л. Б.

Анотація. Виконано аналіз результатів дослідження впливу потужних Турецьких землетрусів 6 лютого 2023 року: о 01:17:36 (UTC) з магнітудою 7,8 Mw (Кахраманмараш-Газіантеп); о 10:24:50 з магнітудою 7,5Mw (Екинозу-Кахраманмараш) на моніторингові сейсмічні і гідрофізичні спостереження на території м. Кривий Ріг.

Комплексний аналіз та інтерпретація даних гідрогеологічних і геофізичних досліджень дозволили оцінити зміни глибинних фізичних процесів в сотнях метрів від денної поверхні.

Аналіз моніторингових спостережень за гідрогеологічними та геофізичними процесами, виникаючих на території Кривбасу, показали взаємозв'язок літосфери Землі і територій віддалених на більш ніж 1300 км в від осередків потужних землетрусів, які проявилися в недовготривалому зниженні рівня підземних вод в геологічному середовищі Кривбасу. Моніторингові спостереження за рівнем води в розвідувальній свердловині зафіксували локальні зміни в геодеформаційних процесах земної кори, які відбулися після потужних Турецьких землетрусів 6 лютого 2023 року о 01 год. 17 хв. 36,1 сек з магнітудою 7,8 та о 10 год. 24 хв. 49,6 сек з магнітудою 7,5 через 1 год. 6 (12) хв. в вигляді пониження її рівня на 2–3 см. Вперше була розрахована швидкість розповсюдження в верхній частині літосфери фронту деформації, яка склала ≈19,0 км/хв. (±0,5 км/хв). Зафіксовані зниження рівня підземних вод в моніторинговій свердловині, дозволили зробити висновок, що після землетрусу відбулися короткоперіодні процеси розтягнення земної кори в зоні Криворізько-Кременчуцького розлому, що могло сприяти міграції підземних вод на більші глибини та підвищити приплив води в шахти та кар'єри.

Дослідження підтвердили, що коливання рівня підземних вод в глибокій свердловині залежать від процесів сучасної деформації літосфери Землі, проявом яких є зміна пружно-деформаційного стану земної кори в зонах тектонічних розломів на території Кривбасу. Криворізький розлом коро-мантійного закладання формує в кристалічному фундаменті різнорангову систему послідуючих розломів і пов'язані з ними зони підвищеної проникливості для води, впливаючої на формування і швидкість геодинамічних процесів та визначають гідродинаміку підземної фільтрації території Кривбасу.

Результати досліджень дозволять вирішити ряд важливих проблем гірничої геології: визначити зв'язок підземних вод з процесами сучасної деформації літосфери Землі, впливу геолого-тектонічної будови на розвиток процесів підтоплення шахт і кар'єрів та на житлові і промислові будівлі.

Ключові слова: геодинамічні процеси, гідрогеодеформаційні процеси, землетрус, моніторинг, сейсмічні спостереження, підземні води.