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A STUDY OF THE INFLUENCE OF WATER LEVEL FLUCTUATIONS ON THE GEODYNAMIC SITUATION IN THE NATURAL AND TECHNICAL GEOSYSTEM OF THE DNIESTER HPP AND PSPP CASCADE

Purpose. Statistical information for the period from 2016 to 2021 was used to analyze seismic activity. Objective. The aim of the study is to identify the relationship between changes in water level and local seismic activity in the region. Using HPP and Psing filtering, the hypocenters of earthquakes within a radius of 30 km from the seismic station with the NDNU index were selected, and using geographic information technology tools, the hypocenters of earthquakes were compared with the geological structure of the region. Methodology. Statistical information for the period from 2016 to 2021 was used to analyze seismic activity. Using filtering, the hypocenters of earthquakes within a radius of 30 km from the seismic station with the NDNU index were selected, and using geographic information technology tools, the hypocenters of earthquakes were compared with the geological structure of the region. Results. The studies revealed a correlation between seismic events and water level fluctuations in the reservoir. The paper also established the density of episodes concentrated in the reservoir operation area, as well as the magnitude and shallow depth, indicated the probability of activation of faults located in geological layers close to the ground surface. The stresses in the soils were assessed. Using the Coulomb-Mohr theory, the ultimate stresses leading to the destruction of structural ties were calculated approximately, and the optimal modes of operation of the reservoir were determined. Originality. The research in the article allows us to more accurately assess the effect of the stress gradient in the soils on the background seismicity in the reservoir operation area. Practical significance. The practical significance of this study is understanding the effect of the stress gradient on induction earthquakes. The described method, which is based on the principles of Coulomb's law and Mohr's theory, allows us to remotely study the behavior of the material under different loading conditions. This study and the development of a geomechanical model helps to better understand and predict earthquake behavior and determine safe loading zones. This has practical implications for the design and construction of structures, as well as for risk assessment and appropriate safety measures.

Key words: seismic station, hydroelectric power plant, PSPP, geosystem, geodynamics, earthquake, geology, water level fluctuations, reservoir, induced earthquake, magnitude, tectonic fault.

Introduction

The topic of local seismic activity in the area of the Dniester hydroelectric cascade is quite important and interesting for research to help better understand and predict earthquake behavior and determine safe loading zones. The Dniester hydroelectric power plant is a large complex of hydroelectric power plants, including HPPs and PSPPs, located along the Dniester River in Ukraine and Moldova. Dniester PSPP-1 is located 2 km northeast of the city of Novodnistrovsk in Chernivtsi Oblast (48°35′35″N, 27°27′17″E). Construction began in 1975. The last sixth power unit was commissioned in 1983. The installed capacity of Dniester PSPP-1 is 702 MW. As a result of the construction of HPP-1, the Dniester reservoir was created with a length of 194 km, a water surface area of 142 km^2 and a useful volume of 2000 km^3 This complex is one of the largest hydropower facilities in Europe and plays an important role in the region's energy system [Ukrhydroenergo, 2023].

Dnistrovska PSP-2 is located 1 km south of the village of Nahoryany in Vinnytsia Oblast (48°29′10″N, 27°34′14″E). Construction began in 1982. The last third hydroelectric unit was launched in December 2002. The installed capacity of Dniester PSP-2 is 40.8 MW. As a result of the construction of HPP-2, the Dniester buffer reservoir was created with a length of 19 km, a water mirror area of 5.9 km^2 and a useful volume of 23.4 km^3 [Ukrhydroenergo, 2023].

The Dniester PSPP is located 8 km northeast of the town of Sokyryany in Chernivtsi Oblast

(48°30′49″N, 27°28′24″E). Construction began in 1983. Currently, the first stage of construction has been completed – 4 hydroelectric units out of 7 planned. The installed capacity of the Dniester PSPP is 1263 MW in turbine mode and 1684 MW in pumping mode (design capacity is 2268 and 2947, respectively). The construction of the PSPP resulted in the creation of the Upper Dniester reservoir with an area of 3.0 km^2 and a volume of 32.70 km^3. The Upper Dniester Reservoir is located on a plateau at an altitude of 125 m above the level of the Dniester Buffer Reservoir and was constructed by excavating and filling soil into a 20 m high screen of the bottom and dams [Ukrhydroenergo. 2023].

But, during the operation of a hydroelectric power plant, a number of problems arise due to the possibility of seismic events that can cause various consequences for the safety of the hydroelectric power plant and the surrounding area [Tretyak & Brusak, 2022; Brusak et al., 2022; Zyhar et al., 2021; Brusak, I., & Tretyak, K. 2021; Savchyn & Pronyshyn, 2020; Savchyn, I., & Vaskovets, S. 2018]. In this context, the analysis of local seismic activity and its connection with the operation of the hydroelectric power plant is of great importance to ensure the safety and stability of this important facility. The main objective of the study is to identify the relationship between changes in water level and local seismic activity in the region where the HPP and PSPP cascade operates.

Purpose

The purpose of the research is to identify the relationship between changes in water level and local seismic activity in the region where the HPP and PSPP cascade operates.

Methods

To analyze seismic activity, we used statistical information collected from 2016 to 2021, obtained from an open source [International Seismological Center]. Using filtering, the hypocenters within a radius of 30 km from the seismic station with the NDNU index were selected, and using geographic information technology tools, the hypocenters of earthquakes were mapped (Fig. 1).

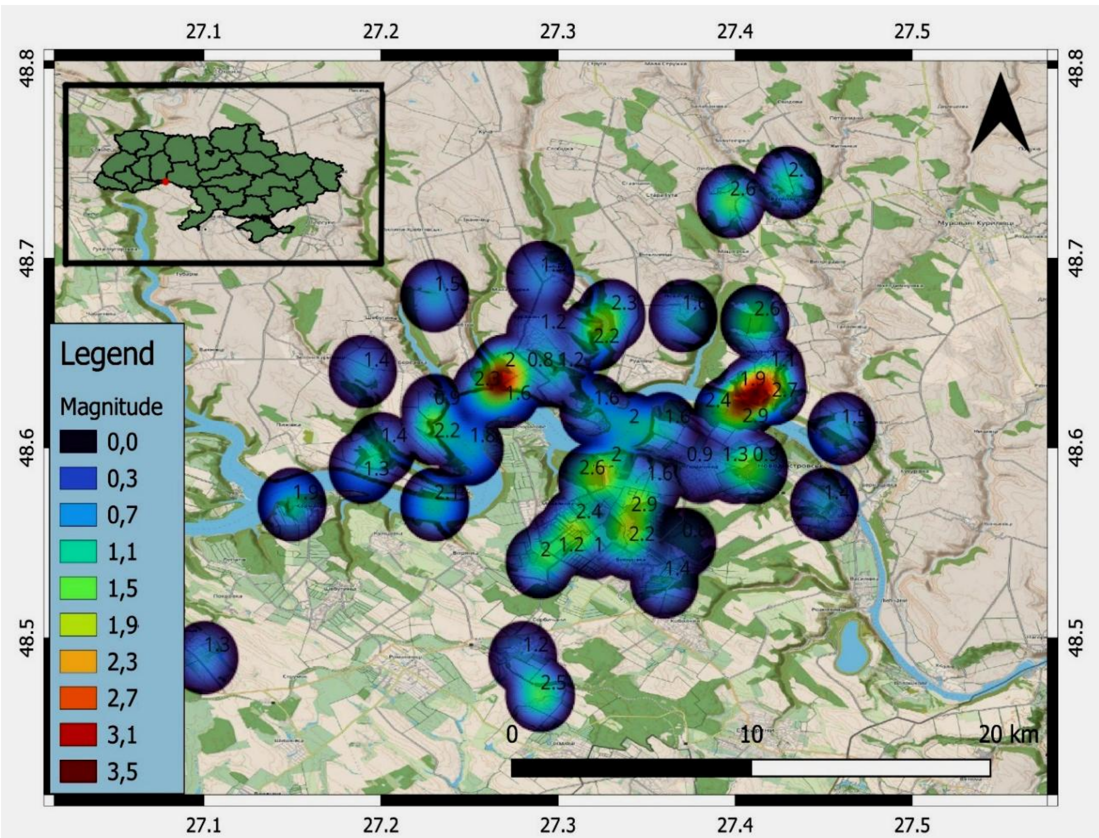

Fig. 1. Map of the density of seismic events for the period from 2016 to 2021

As we can see (see Fig. 1), the region under consideration has areas with a high density of seismic events, especially the coordinates of the hypocenters are concentrated in the NE, S, and central parts of the map, mostly with low magnitude. Similarly, in the WGS-84 coordinate system, based on information from the International Seismological Center, the depths at which earthquakes were recorded were plotted on the base map (Fig. 2).

Results

Taking into account the information on the density of episodes concentrated in the reservoir operation area, as well as the magnitude and shallow depth, the following conclusions can be drawn: the low depth of the earthquake hypocenter indicates the proximity of the hypocenter to the earth's surface and the activation of faults buried in geological layers. Usually, deep earthquake centers (over 70 km) are associated with tectonic plates [Purcaru & Berckhemer, 1982]. Low magnitude may indicate the induction of seismic episodes due to changes in ground stresses [Chopra & Chakrabarti, 1973; Day et al., 1998; Zhao et al., 2022]. For further analysis of seismic activity, it is necessary to refer to the geological map [State Service of Geology and Mineral Resources of Ukraine. 2021], (Fig. 3), which shows the foci of earthquake hypocenters. To confirm the hypothesis of a possible connection between seismic activity and fault lines, it is necessary to check for a correlation between the location of these centers and the location of fault lines on the map.

Based on the analysis of the geological map (Fig. 3) with earthquake hypocenters and fault lines, it can be concluded that there is a clear correlation between earthquake hypocenters and fault lines. This may indicate that the activation of these fault zones occurs as a result of dynamic effects associated with fluctuations in the water level in the reservoir. Thus, it can be assumed with greater certainty that earthquakes occur in areas adjacent to the faults. The study of the geological map with earthquake hypocenters and fault lines showed that some hypocenters are located on faults that are marked as "probable" on the map, namely fault 1, fault. This indicates that the occurrence of earthquakes in the probable fault zones has been confirmed and that these zones should be considered as potentially dangerous in terms of seismic activity. In order to investigate the relationship between the frequency of earthquakes and changes in the water level in the Dniester reservoir, it was necessary to collect information from gauging stations that reflected the dynamics of water level changes over time. About 40,000 measurements of water level fluctuations in the reservoir were processed for the period from 2016 to 2021. It was also necessary to synchronize the time of the seismic event, which is counted according to international time, to the local time in which the water levels were measured (Fig. 4).

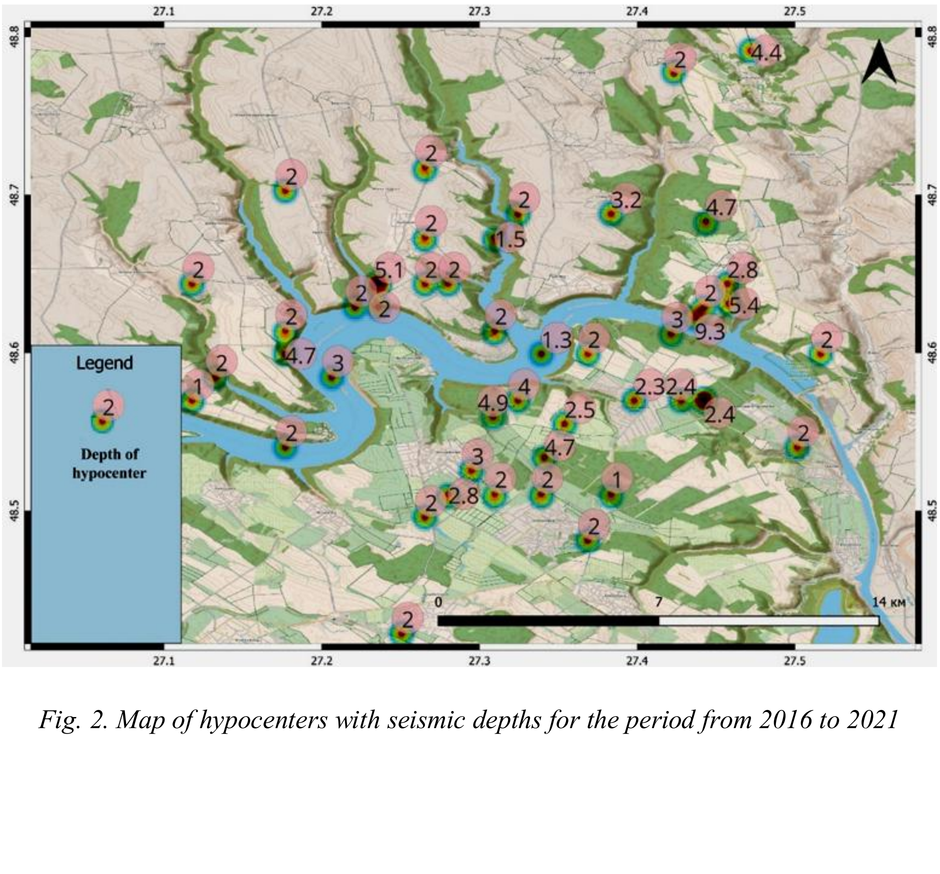

Fig. 2. Map of hypocenters with seismic depths for the period from 2016 to 2021

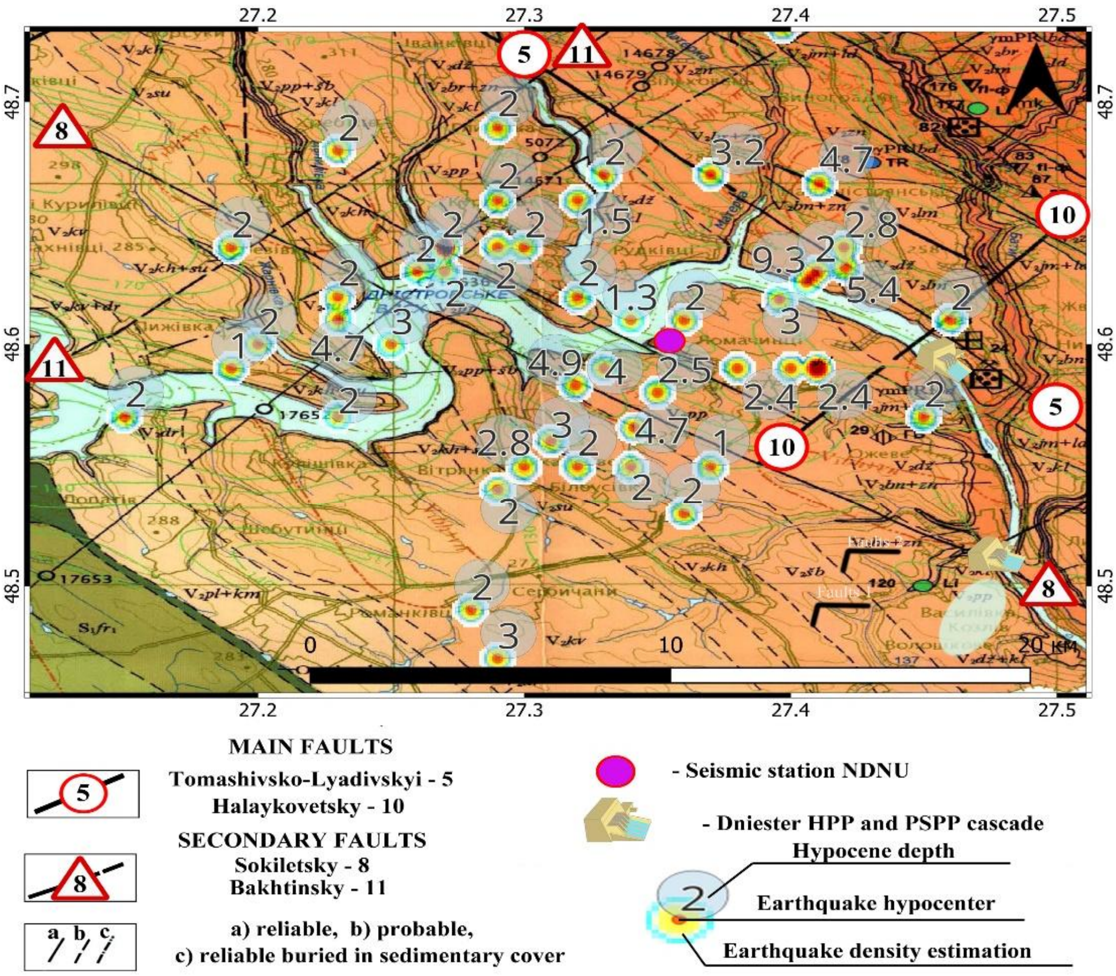

Fig. 3. Localized section of the geological map of the Pre-Mesozoic formations

Analyzing the graph (Fig. 4), we observe a classic example of the so-called "induced earthquakes". It is known that induced earthquakes can occur as a result of various human activities, including the filling of reservoirs. Such earthquakes, as shown in the graph, have their own characteristic relationship between magnitude and water level changes. Despite the fact that this phenomenon is not new and has been studied for a long time, namely, disclosed in the works (Keith et al., 1982; Gupta, H. K., 1992; Talwani, 1997], it remains relevant today and requires constant attention from the scientific community, as it can lead to negative consequences for human activity and the environment.

To conduct a more detailed analysis, the influence of water temperature measured in the bottom layers of the reservoir (Fig. 5) on seismic events was investigated. The results of the analysis do not clearly establish a direct link between the water temperature regime and the occurrence of seismic events. Instead, the data obtained confirm the hypothesis that the activation of earthquakes is mainly related to the cyclical changes in the stresses in soils and, accordingly, in faults.

Given the above, let us conduct a thought experiment. Imagine that we have a plane to which a stress vector is applied at an angle other than normal, and we know that this stress will always be decomposed into normal (δ) and tangential (τ) stresses according to the Coulomb-More theory [Howells, 1974; Talwani, 1976; Talwani & Acree, 1986; Parotidis et al., 2003]. Let us try to imagine our plane perpendicular to the stress force, then we will have the maximum normal stresses, and the tangents will be zero. Taking into account that we do not have precise information about the geological structure of the reservoir and the azimuths of the fault dip, we reduce the condition to the statement that only normal (δ) stresses act on the reservoir bed [Zoback, 2010].

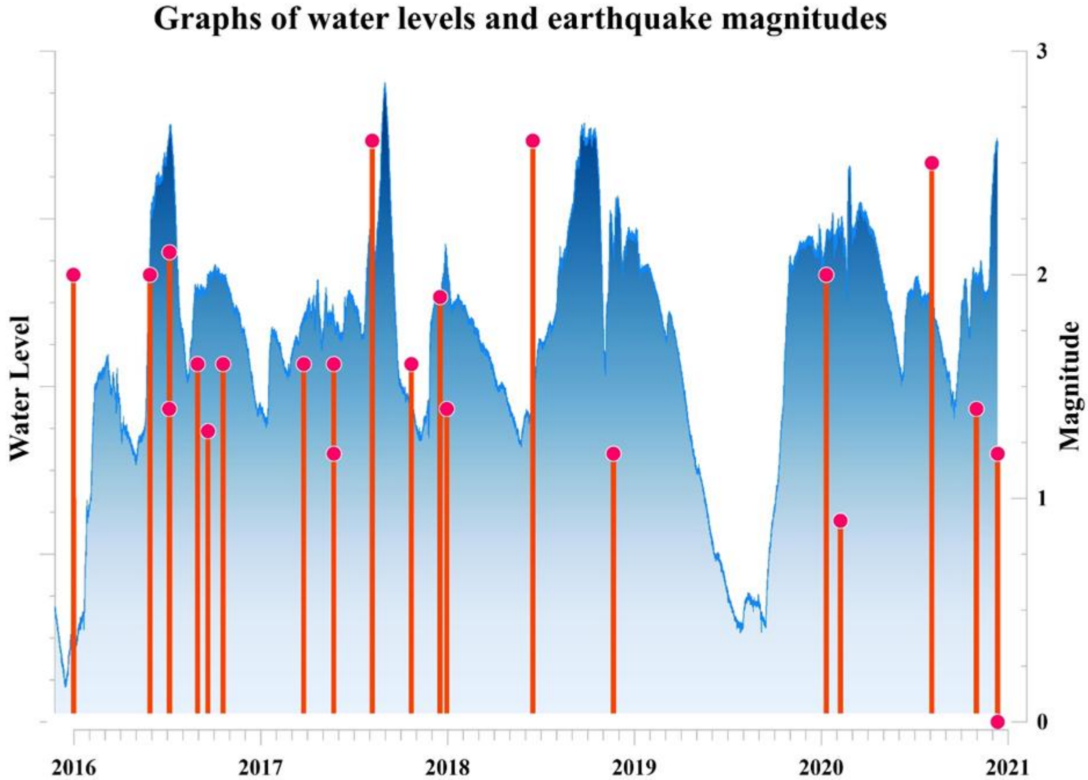

Fig. 4. Graph of the dependence of water temperature per month on the magnitude of earthquakes with synchronized event dates

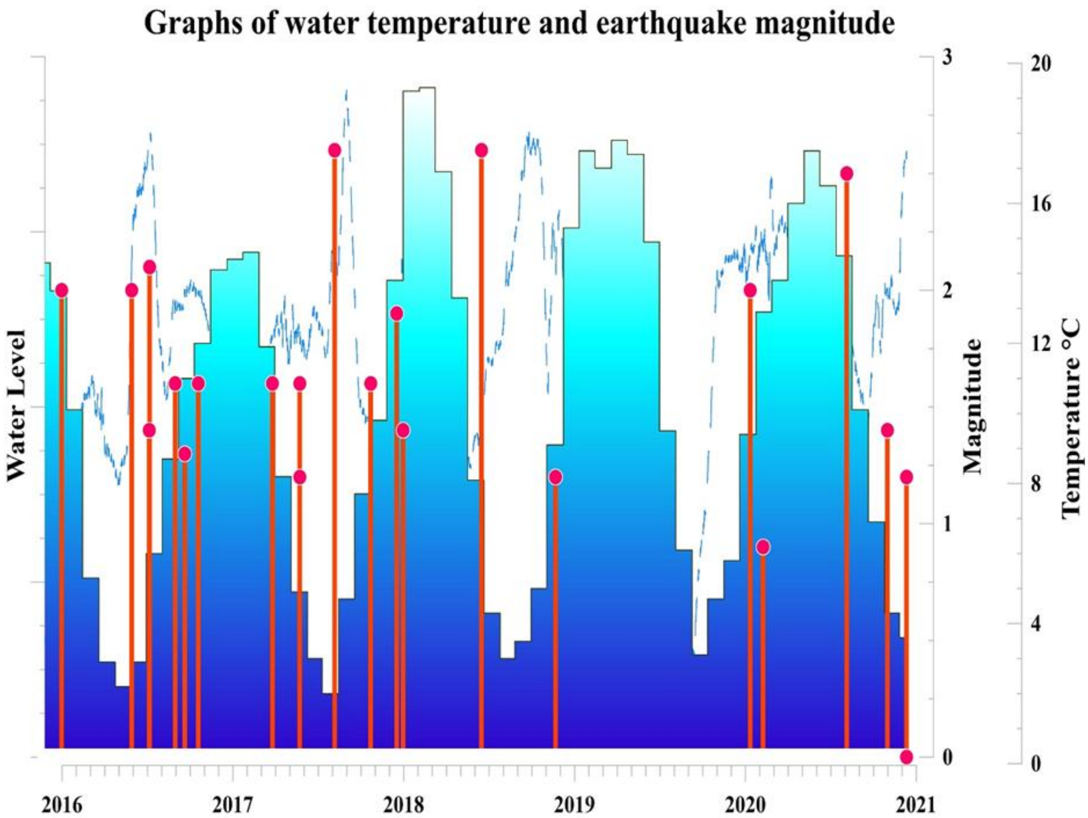

Fig. 5. Graph of water temperature versus earthquake magnitude with synchronized event dates

We assume that the reservoir bed is subjected to a vertical stress, in the form of a water column, and two horizontal stresses that are mutually perpendicular. Given that our plane is located at the interface between soil and water, we can assume that only the vertical component of the stress, namely the water column, acts to simplify the geomechanical model and creates a pressure of MPa on the soil [Célérier, 2008; Petruccelli et al., 2019; Geidt et al., 2021]. To describe the geomechanical model, we use the classification [Anderson, 1905], namely the "dropout mode". This is the most common mode of interaction between tectonic blocks along a fault line. Without any special mathematical calculations, we can graphically estimate the stresses in the soil. In the laboratory, a single-plane section device is used to create vertical pressure without applying lateral stresses. Such an experiment is carried out until the sample is completely destroyed. Similarly, it can be assumed that the destruction of structural bonds in the soil leads to an earthquake.

The main indicator that characterizes the strength of these structural bonds is the coefficient of adhesion (C). Using the Coulomb-Mohr theory, the ultimate stresses that lead to the destruction of structural bonds are determined. The tangential stress (τ) of the Y-axis, according to the condition of the problem, is absent and equal to zero, on the X-axis we apply the stress value in MPa, at the moment of which the earthquake occurred (Fig. 6), and so on for each episode of the seismic phenomenon. The value of the vertical stress is calculated by Pascal's law, knowing the height of the water column.

Thus, having calculated, we can assume that the main density of earthquakes occurs in soils with an internal cohesion coefficient C = 0.2 MPa. Given that there is no information on pore pressure values according to Karl Terzaghi's theory, the higher the pore pressure (u), the less external mechanical pressure (σ) is transmitted to the soil skeleton (Karl, 1962), this indicator will be higher (see Fig. 6) as depicted by a dashed line, and the angle of internal friction tgφ = 0.17, at a depth of mainly 2–3 km. The obtained values of geotechnical indicators allow us to characterize the soil as sufficiently strong and dense, as evidenced by the angle of internal friction tgφ = 0.17, which can be interpreted as an indicator of the number of soil defects. In their natural state, these defects are held together by a cohesive force of C = 0.2 MPa. Accordingly, such soils are characterized by fragility. Therefore, it is important to observe careless gradients in the rate of load discharge. Analyzing the above, we can approximately determine the optimal operating conditions of the reservoir, this indicator will be in the range of 0.2–0.3 MPa (Fig. 7).

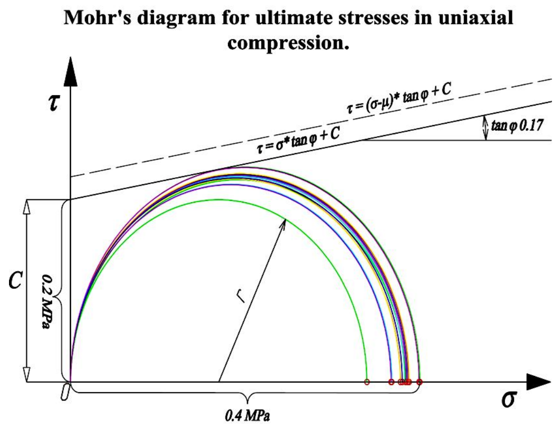

Fig. 6. Mohr's diagram for the ultimate stresses in soils located in the Dniester reservoir operation area

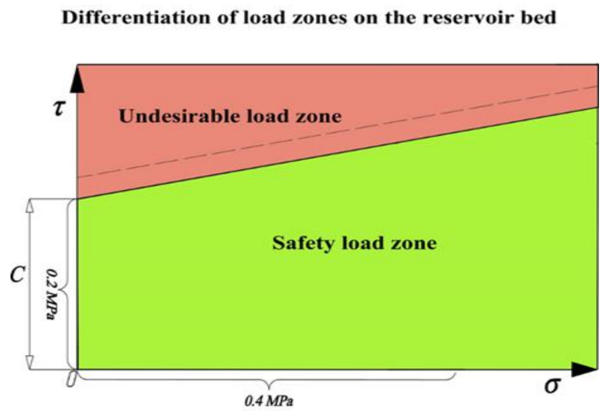

Fig. 7. Mohr's diagram for the ultimate stresses in soils located in the Dniester reservoir operation area

Originality

The research in this article allows us to more accurately assess the influence of the stress gradient in the ground on the background seismicity in the reservoir operation area.

Practical significance

This study's practical significance is understanding the effect of the stress gradient on induction earthquakes. The described method, which is based on the principles of Coulomb's law and Mohr's theory, allows us to remotely study the behavior of a material under different loading conditions. This study and the development of a geomechanical model allow us to better understand and predict earthquake behavior and determine safe loading zones. This has practical implications for the design and construction of structures, as well as for risk assessment and appropriate safety measures.

Conclusions

The study found that the density of episodes concentrated in the reservoir operation area, as well as the magnitude and shallow depth, indicate the probability of activation of faults located in geological layers close to the earth's surface. Typically, deep earthquake centers (over 70 km) are associated with tectonic plates. However, a low magnitude may indicate the induction of seismic episodes due to changes in ground stresses. There is a tendency for earthquake hypocenters to gravitate toward fault lines, which indicates possible activation of fault zones. Some hypocenters are located on faults that are labeled as "probable" on the map, namely, conditionally, fault 1, and conditionally, fault 2. This indicates that the occurrence of earthquakes in the areas of probable faults has been confirmed, and that these areas should be considered potentially dangerous in terms of seismic activity. The combination of the graphs of the amplitude of vibrations and seismic events synchronized in time reflects a classic example of the so-called "induced earthquakes". This fact confirms that induced earthquakes can occur as a result of various human activities, including the filling of reservoirs. According to the information obtained about the density of episodes concentrated in the reservoir operation area, we can conclude that it is necessary to constantly monitor earthquakes in such areas and develop a risk management strategy. Thus, our research confirms the relevance of studying the impact of water level fluctuations on the geodynamic situation in the natural and technical geosystem of the Dniester HPP and PSPP cascade, as well as the importance of continuous monitoring and development of risk management measures in the operation areas of power facilities.

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ДОСЛІДЖЕННЯ ВПЛИВУ ЗМІНИ РІВНЯ ВОДИ ДНІСТРОВСЬКОГО ВОДОСХОВИЩА НА ГЕОДИНАМІЧНУ СИТУАЦІЮ В ПРИРОДНО-ТЕХНІЧНІЙ ГЕОСИСТЕМІ КАСКАДУ ДНІСТРОВСЬКИХ ГЕС І ГАЕС

Метою досліджень є виявлення залежності між змінами рівня води та локальною сейсмічною активністю регіону, в якому функціонує каскад Дністровських ГЕС та ГАЕС. Методика. Для аналізу сейсмічної активності використано статистичну інформацію за період 2016–2021 рр. Використовуючи фільтрацію, відібрано гіпоцентри землетрусів в радіусі 30 км від сейсмічної станції з індексом NDNU, за допомогою інструментів геоінформаційних технологій, гіпоцентри землетрусів співставлені з геологічною будовою регіону. Результати. Під час проведених досліджень встановлено залежність між сейсмічними подіями та коливаннями рівня води у резервуарі водосховища, щільність епізодів, сконцентрованих в зоні експлуатації водосховища, а також магнітуда і невелика глибина вказують на ймовірність активації розломів, розташованих у геологічних шарах, близьких до поверхні землі. Виконана оцінка напруги в ґрунтах. За допомогою теорії Кулона-Мора наближено вирахувано граничні напруження, які призводять до руйнування структурних зав’язків, визначено оптимальні режими роботи водосховища. Наукова новизна. Дослідження в статті дають змогу точніше оцінити вплив градієнта напруги в грунтах на фонову сейсмічність в зоні експлуатації водосховища. Практичне значення цього дослідження полягає в розумінні впливу градієнта напруги на індукційні землетруси. Описаний метод, який базується на принципах закону Кулона та теорії Мора, дає змогу дистанційно дослідити поведінку матеріалу за різних умов навантаження. Це дослідження і розробка геомеханічної моделі допомагають краще зрозуміти і передбачати поведінку землетрусів, визначити безпечні зони навантаження. Це має практичне значення під час проєктування та будівництва споруд, а також для оцінювання ризиків і вжиття відповідних заходів щодо забезпечення безпеки.

Ключові слова: сейсмостанція, ГЕС, ГАЕС, геосистема, геодинаміка, землетрус, геологія, коливання рівнів води, водосховище, індукований землетрус, магнітуда, тектонічний розлом.

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