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APPLICATION OF CROSS-SPECTRAL ANALYSIS AND FAST FOURIER TRANSFORM TO DETECT SOIL VIBRATIONS IN THE NATURAL AND TECHNICAL GEOSYSTEM OF THE DNIESTER PSPP

The main purpose of the study is to identify the relationship between changes in water level and soil deformation, where the cyclic change in loads on the reservoir bed is the stress deviator, i.e., the PSPP reservoir acts as an oscillator of transverse vibrations, and the soil extensometer performs the function of reading and recording these vibrations. Methodology. Solution of the problem requires recording the time series of water level fluctuations and extensometer sensor fluctuations on all depth horizons. It is also necessary to perform a fast Fourier transform for water level fluctuations separately and similarly to each extensometer sensor fluctuation. We need to separately calculate the signal power spectrum of all sensors in the soil, and compare the amplitude-frequency, phase-frequency components of the power spectra of water level oscillations and vertical oscillations of the extensometer sensors. Results. During the studies, it was found that the PSPP reservoir is a source of low-frequency vibrations in a wide spectral range. These vibrations have a very long wavelength, measured in tens of thousands of kilometers, which can propagate over long distances, both along the front of geological layers and in depth. Scientific innovation. The research in this article allows us to more accurately assess the frequency spectrum of vibrations and identify possible resonance phenomena that may occur in soils during the operation of a power facility. In addition, this study was conducted in a specific region, which makes it possible to obtain more accurate data on the impact of low-frequency vibrations on the geosystem in this region. Thus, this paper may be of interest to specialists in the field of geotechnics, geology, and energy. It can also be used in the planning and operation of other power facilities in similar conditions. Practical significance. Low-frequency waves can be detected by seismic instruments such as seismometers. The results of this study will help to correct the analysis and interpretation of seismograms, which is important for understanding the processes occurring in the hydroelectric power plant operation area.

Key words: oolitic limestone; geotechnical monitoring; extensometer; pumped storage power plant; soil base; soil condition; spectral density; Fast Fourier Transform.

Introduction

The article focuses on the need to study the interaction of hydraulic structures with the soil bases on which they are located, as well as to find methods that allow determining the characteristics of these interactions. The paper discusses their impact on the geosystem as a whole. The relevance of the topic is due to the fact that humanity at the current level of development needs cheap and renewable energy sources, such as hydropower. The Dniester pumped storage power plant is a unique example among the objects of study. The Dniester PSPP was built in complex engineering and geological conditions characterized by a large elevation difference and steep slopes [Sidorov, Perij, & Sarnavskyj, 2015]. Its construction involved quite serious anthropogenic interventions in the existing natural structure of the massif, as well as in the processes taking place in it. The cyclical nature of the plant's operation also leads to an additional anthropogenic load, and changes in the hydrodynamic regime [Sidorov, Perij, & Sarnavskyj, 2015]. This in turn affects the stress-strain state of the soils underlying the structure [Zyhar, et al., 2021]. Therefore, it is important to have reliable data on the possible consequences of the impact of the energy facility operation on the geosystem as a whole and the processes occurring in soils in particular.

To gain a better understanding of how water level changes affect soil deformation when hydraulic structures are in operation, it is essential to refer to previous studies. One such study is the article by Zyhar et al. (2021), which examines the impact of filling the reservoir tank on the stress-strain state of the structure. The authors used remote inclinometers to record horizontal soil deformations and tangential stresses. This study provides valuable insights into the topic.

Noteworthy is the work [Bubniak, et al, 2020] in which the authors focus on tectonic disturbances in the PSPP operation area. Considering some examples of scientific papers on this topic, the study investigated the impact of water level fluctuations in the Three Gorges Basin on soil deformation [Bao, et al, 2015]. During the study, soil deformation tests were conducted under conditions of water level fluctuations, and the impact of this factor on soil properties was assessed [Jadid, et al, 2020]. The article is devoted to the study of the impact of water level fluctuations on the stability of slopes in the vicinity of the reservoir. Similar studies are reflected in the papers [Herget, 1973; Tang, et al, 2019].

Purpose

The main objective of the study is to identify the relationship between changes in water level and soil deformation. The stress deviator is the cyclic change in loads on the reservoir bed, i.e., the PSPP reservoir acts as an oscillator of transverse vibrations. The soil extensometer performs the function of reading and recording these vibrations. In order to address the issue, it is crucial to monitor the changes in water levels and extensometer sensors at all depths of the site over time. We can then analyze the data by conducting a fast Fourier transform for both water level and sensor fluctuations, and determining the signal power spectrum for each sensor in the soil. We can gain further insights by comparing the amplitude-frequency and phase-frequency components of the power spectra for water level fluctuations and vertical oscillations of the sensors. Details on the methods of cross-spectral analysis can be found in [Cooley et al, 1965; Sorensen, et al, 1987; Molénat, et al, 2000; Zolfaghari, et al, 2012; Takemiya, 2008; Lin, H. C., & Ye, Y. C. 2019].

Methods

The Dniester PSPP (pumped storage power plant) is located 8 km northeast of the town of Sokyryany, Chernivtsi Oblast (48°30′49″N, 27°28′24″E). Its construction began in 1983. To date, the first stage of construction has been completed 4 hydraulic units (out of 7 designed). As a result of the construction of the Dniester PSPP, the Dniester Upper Reservoir was formed with a mirror area of 3.0 km² and a useful volume of 32.70 km³ [Ukrhydroenergo, 2023]. The Dniester upper reservoir is located on a plateau 125 m above the level of the Dniester channel buffer reservoir and was constructed by excavating and filling soil into a screen of bottom and dams with a height of up to 20 meters. To study the stress-strain behavior of soils within the mountain plateau (Fig. 1) on which the Dniester PSPP is located, an extensometric borehole was drilled (Fig. 2). The well covers two main structural and stratigraphic complexes that contribute to the geological structure of the region – the basement of the East European Platform (Proterozoic) and its sedimentary cover (Phanerozoic formations). The well is equipped with stationary vertical five-point extensometric sensors connected by Geokon anchors model 1150 (A-3) [Geokon, 2019], with a depth step of 10 meters. The depth of the well bottom is 50 meters. All sensors are automated using microelectromechanical system technology (MEMS). These sensors take measurements automatically every hour. The period from 01.01.2020 to 31.12.2021 was chosen for the study. During this period an average of 8,760 values were obtained separately for each of the points, and a total of 52,560 values were processed together with the water level sensors.

It should be noted that the the sensors operate by measuring the differential capacity to detect deviations in the control mass. This method can be used to determine vertical soil fluctuations caused by dynamic factors such as vibration or shocks. To identify the stratigraphic location of the geological horizon for the well (shown in Fig. 2), we analyzed core samples, conducted rock deformability pressure tests, and calculated the Young's modulus (E) of the layers in the laboratory (as shown in Table 1). Additionally, we gathered comprehensive information about the geological structure of the study site [State Service of Geology and Mineral Resources of Ukraine, 2021].

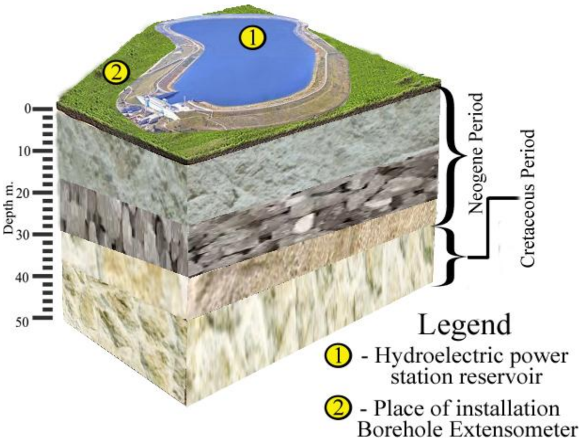


Fig. 1. Schematic of the location of the reservoir and extensometer at a depth of 50 meters.

Table 1

Physical and mechanical properties of soils

Geological layer number	The name of the geological layer	Density, t/м^3	Angle of internal friction tg ϕ	Poisson's ratio, ν	Young's modulus, E, MPa
1	Oolitic limestone	2.70	0.75	0.25	1,500
2	Quartz sand	2.66	0,45	0.3	50
3	Silicon in sand aggregate	2.64	0.50	0.32	120
4	Mergel with siliceous fossils	2.60	0.55	0.33	120
5	Sandstone	2.70	0.75	0.25	400

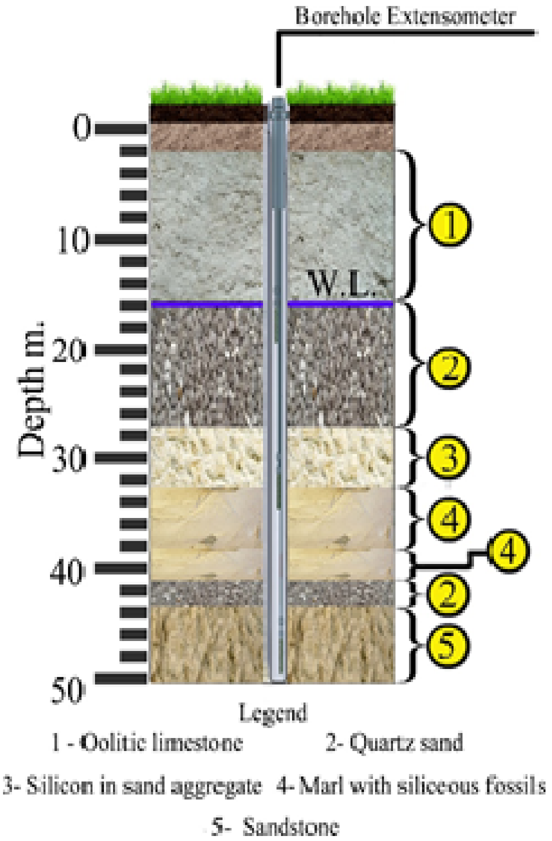


Fig. 2. Transverse section along the extensometer borehole showing geologic layers.

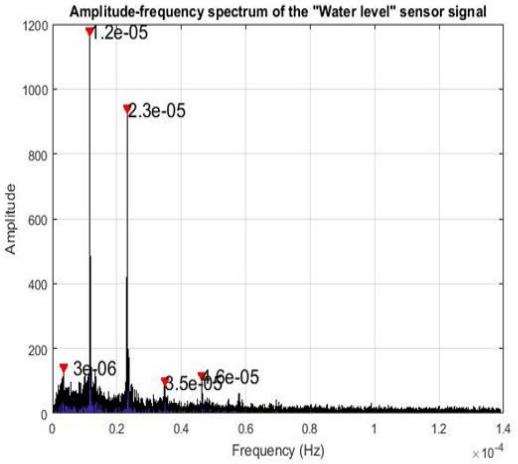


Fig. 3. Amplitude-frequency spectrum of water level fluctuations in a reservoir.

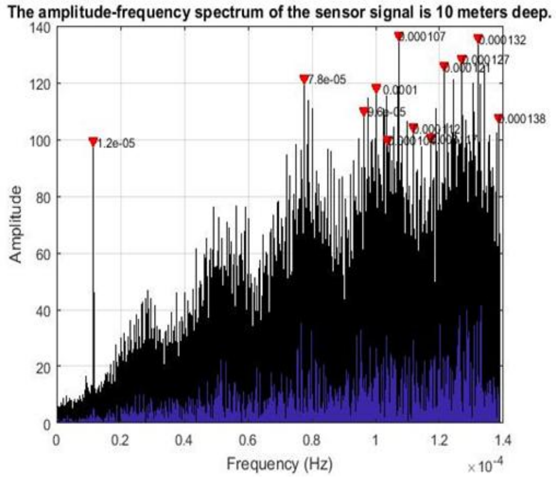


Fig. 4. Amplitude-frequency spectrum of soil vibrations at a depth of 10 meters.

Results

The cross-spectral analysis begins with the Fourier transform. For this type of study, we used its simplified form proposed by [Cooley & Tukey, 1965], the Fast Fourier Transform, for each signal to obtain their power spectra.

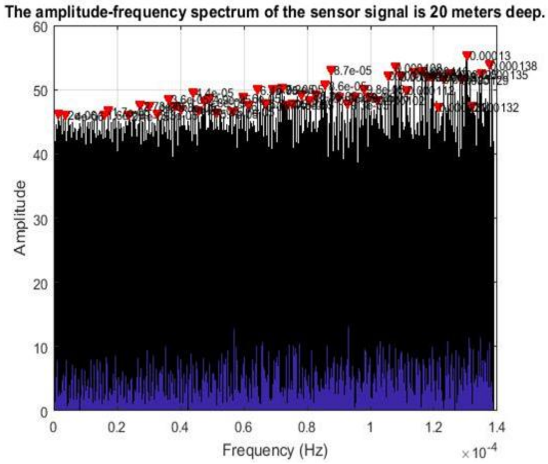


Fig. 5. Amplitude-frequency spectrum of soil vibrations at a depth of 20 meters.

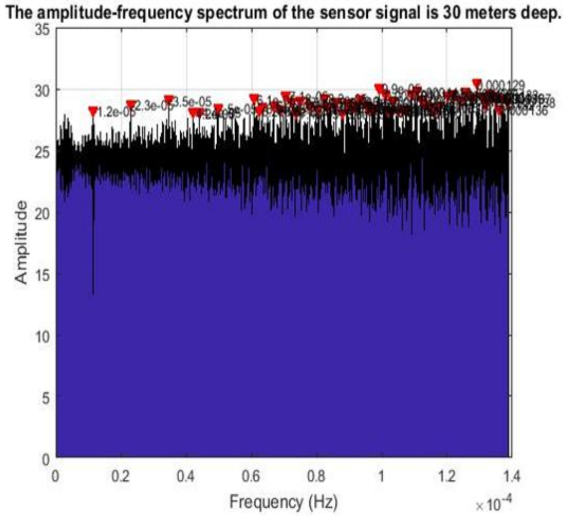


Fig. 6. Amplitude-frequency spectrum of soil vibrations at a depth of 30 meters.

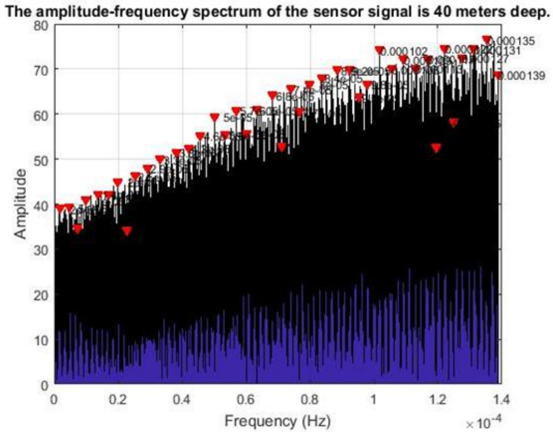


Fig. 7. Amplitude-frequency spectrum of soil vibrations at a depth of 40 meters.

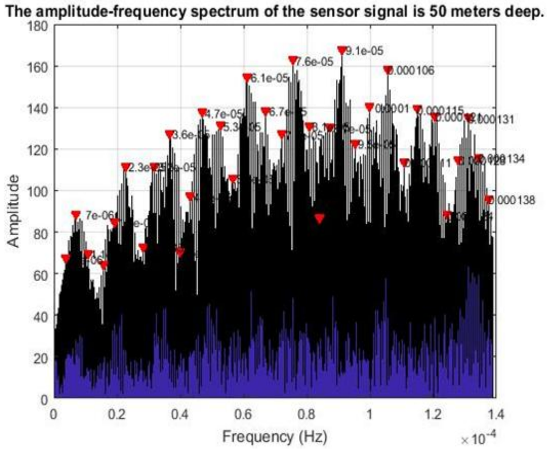


Fig. 8. Amplitude-frequency spectrum of soil vibrations at a depth of 50 meters.

Thus, the performed transformations allowed us to analyze the spectral pattern of the hydroelectric power plant's operation in 2020 (Fig. 3). We managed to determine the frequency spectrum width of 1.4 × 10^{-4} Hz, which is equivalent to 140 μHz. From the harmonic oscillations, a significant energy contribution of frequencies is clearly seen: 3 μHz, 12 μHz, 23 μHz, 35 μHz, and 46 μHz. The main energy density of the spectrum is concentrated in the range from 3 μHz to 60 μHz. Such small values should not be considered as "noise" because the environment in which the measurements were made is almost completely controlled.

A stepped, sinusoidal frequency spectrum with an increasing amplitude trend is observed at a depth of 10 meters in the soil layer of oolitic limestone (Fig. 4). Such a spectrum can be characteristic of signals with repetitive pulses, which can be represented as the sum of harmonic components. In such cases, the spectrum will contain several narrow peaks at frequencies that are multiples of the fundamental pulse frequency, with increasing amplitude values at higher frequencies. The increase in spectrum frequency could be attributed to various factors such as the geological layer, soil temperature, and hydrostatic pressure of groundwater. This could be due to resonance effects caused by the relatively high elasticity of the material, in our case, oolitic limestone with an elastic modulus of $E = 1500$ MPa and a density of 2.7 t/m^3 [P. N. J, 1996; Johnson, et al, 1996; Priya et al, 2001; Cao, 2018; Babacan, & Akın, 2018]. In support of the theory of the reasons for the stepwise increase in amplitude, within a radius of 20 meters from the extensomeric well, the water table is at a depth of 17 meters (Fig. 9) shows the graph of groundwater level changes. In this case, if the amplitude of oscillations increases, it may indicate an increase in the stiffness of the oolitic limestone. At the same time, if the groundwater level decreases, the hydrostatic pressure on the soil layer changes. Changes in hydrostatic pressure at the boundary of layers can affect the stiffness of the soil, in particular, its ability to absorb loads.

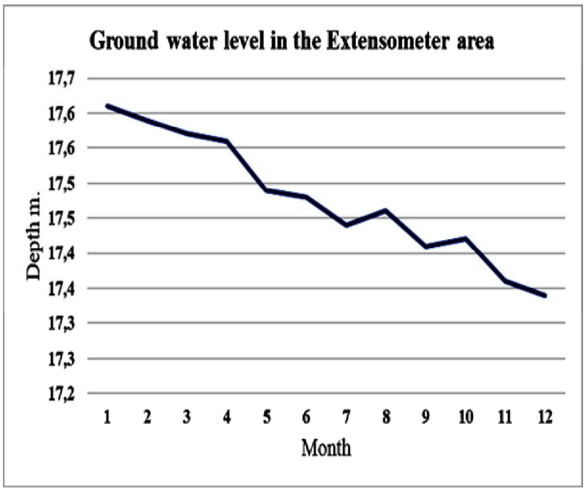


Fig. 9. Graph of changes in the groundwater level within a radius of 20 meters from the extensometric well.

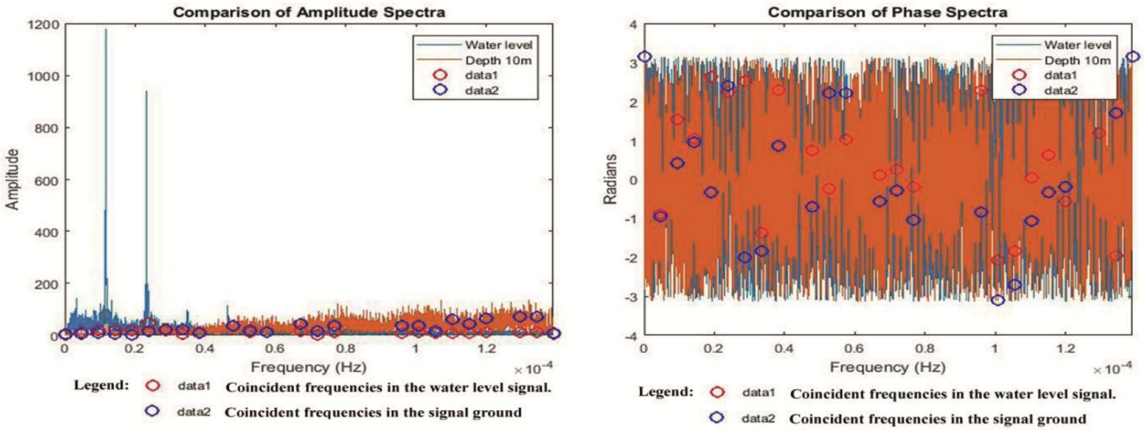
At depths of 20 and 30 meters, there are geological layers with relatively low elastic moduli. Namely, quartz sand with an elastic modulus of E = 50 MPa, and silicon in sand fill with E = 120 MPa, respectively. It should not be assumed that these soil rocks are weak and unstable to mechanical vibrations. On the contrary, they are quite strong and compressed, and contain inclusions of siltstones, heavy clays, etc. The value of (tg φ) (see Table 1) can be interpreted as an indicator of the number of soil defects. In the natural state, these defects are held together by so-called structural bonds, and when such bonds are broken, the soil becomes loose and tends to form a natural slope angle based on Coulomb's theory [Karl, 1962; Vainberg, 1993; Zyhar et al., 2021; Geidt, et al., 2021]. The signal spectrum in sandy soil is very noisy. This may mean that the signal contains many random noise components that mask the main signal components. This noise can be caused by various factors, such as the water content of the horizon, and temperature noise. In sandy soil, oscillations are possible due to many factors, such as gravity, friction, and the interaction of soil particles with each other.

To improve the quality of the amplitude-frequency spectrum, signal processing algorithms will need to be used to extract signals from noisy data, such as filtering or amplifying the main signal components. A similar situation is observed in the spectrum of vibrations at a depth of 40 meters (Fig. 7) of the geological layer of marls in the flinty fill.

At a depth of 50 meters, there are sandstone layers with E = 400 MPa (Fig. 8). Similarly to the oolitic limestone, a stepwise, sinusoidal frequency spectrum is observed. The main difference is that the amplitude dampens with increasing frequency.

One of the possible explanations for this effect is seasonal temperature fluctuations, along with the dynamic load from the operation of a hydropower facility. The cross-spectral density method was used to determine the relationship between the signals, i.e. the correlation between them. The cross-spectral density can be calculated using various methods, including the correlation function method, Fourier analysis, harmonic analysis, and others. In this study, we used the harmonic analysis method described by [Thomson, 1982].

The results of calculating the cross-spectral density are presented in a graph, The results of calculating the cross-spectral density are presented in a graph. It shows that the relationship between two signals depends on the frequency at a depth of 10 meters (Fig. 10), similarly at a depth of 20 meters (Fig. 11), 30 meters (Fig. 12), 40 meters (Fig. 13), and 50 meters (Fig. 14). It shows that the relationship between two signals depends on the frequency



a

b

Fig. 10. Comparative cross-spectral density of signals from the “Water Level” sensor and the eccentric sensor at a depth of 10 meters (a); Comparison of phase spectra (b).

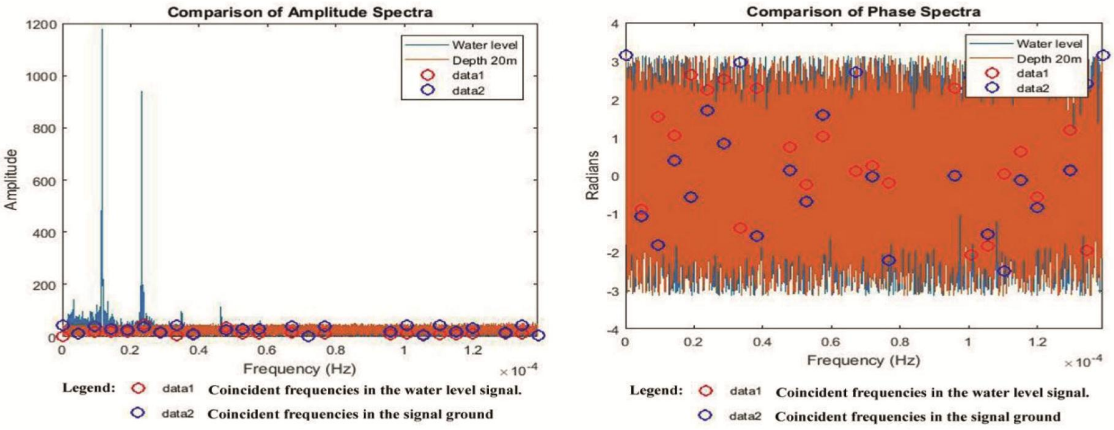


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Fig. 11. Comparative cross-spectral density of signals from the “Water Level” sensor and the eccentric sensor at a depth of 20 meters (a); comparison of phase spectra (b).

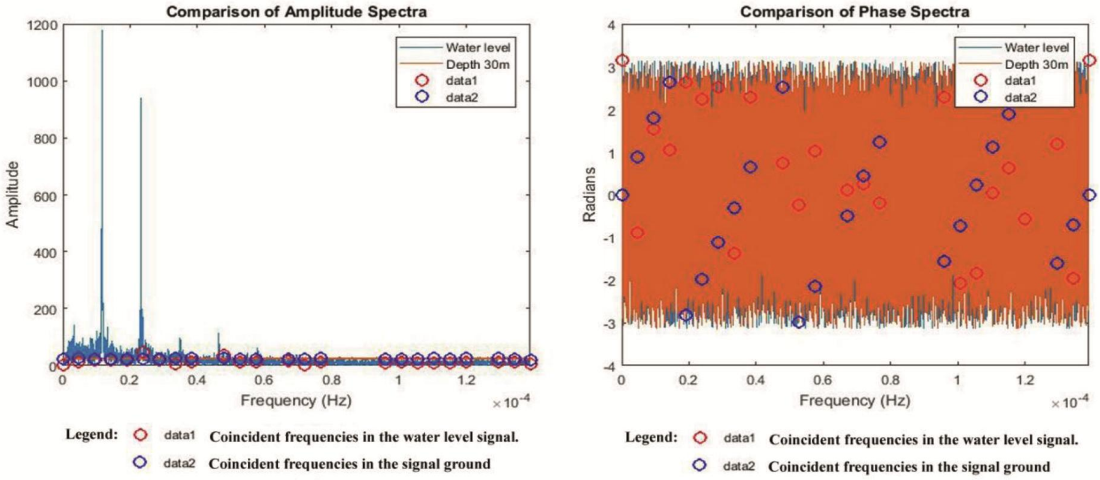

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Fig. 12. Comparative cross-spectral density of signals from the “Water Level” sensor and the eccentric sensor at a depth of 30 meters (a); comparison of phase spectra (b).

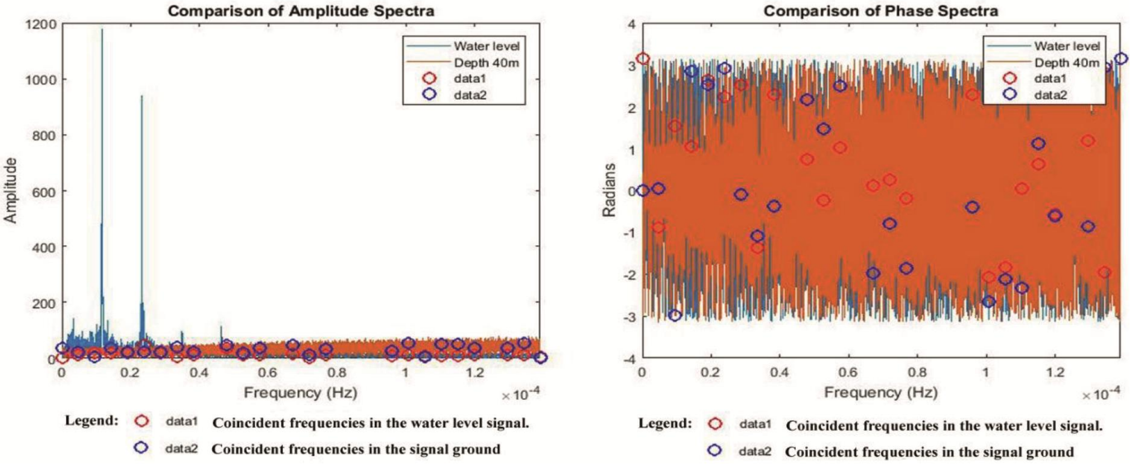

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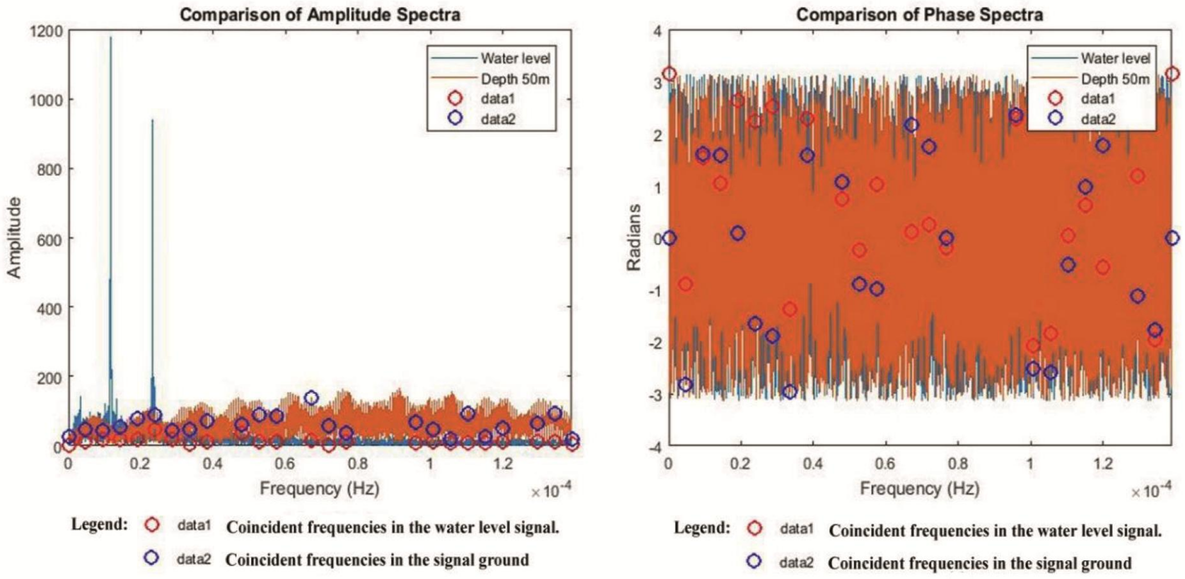
Fig. 13. Comparative cross-spectral density of signals from the “Water Level” sensor and the eccentric sensor at a depth of 40 meters (a); comparison of phase spectra (b).



a b

Fig. 14. Comparative cross-spectral density of signals from the “Water Level” sensor and the eccentric sensor at a depth of 50 meters (a); comparison of phase spectra (b)

Originality

The research in this article makes it possible to more accurately assess the frequency spectrum of oscillations and identify possible resonance phenomena that may occur in soils during the operation of a power facility. In addition, this study was conducted in a specific region, which makes it possible to assess the risks and obtain more accurate data on the impact of low-frequency vibrations on the geosystem in this region. Thus, this paper may be of interest to specialists in the field of geotechnics, geology, and energy. It can also be used in the planning and operation of other power facilities in similar conditions.

Practical significance

Low-frequency waves can be detected by seismic instruments such as seismometers. The results of this study will help to correct the analysis and interpretation of seismograms, which is important for understanding the processes occurring in the hydroelectric power plant operation area.

Conclusions

The results of the study confirmed that there is a certain relationship between changes in water level and soil deformation. In this case, the role of the stress generator is played by the cyclic change in the loads on the reservoir bed, i.e., the PSPP reservoir plays the role of a transverse wave oscillator. This is demonstrated in the graphs comparing the phase spectra. In addition, the study revealed that the spectra of vertical water and soil level oscillations have significant overlap, which indicates the presence of resonant phenomena in the structure-base system. The main characteristics of the soil vibration spectrum, such as shape and amplitude, were determined. This can help in further studies of the dynamic soil properties.

After the transformations, we can analyze the spectral pattern of the hydroelectric power plant's operation for 2020 and determine the frequency spectrum width of 1.4×10^{-4} Hz, which is equivalent to 140 μHz. From the harmonic of the oscillations, a significant energy contribution of frequencies can be clearly seen: 3 μHz, 12 μHz, 23 μHz, 35 μHz, and 46 μHz. Low-frequency waves have very long wavelengths, measured in thousands of kilometers, and can propagate over long distances. The path of the wave and its scattering will depend on the properties of the soil in which it propagates. When a wave propagates into more elastic soil, it can continue its movement. However, as the wave passes from one type of soil to another, it may be reflected, refracted, and scattered, which affects its shape and amplitude. Low-frequency waves can be detected by seismic instruments such as seismometers. The results of this study will help to correct the analysis and interpretation of seismograms, which is important for understanding the processes occurring in the hydroelectric power plant operation area. The study found that the low-frequency vibrations that were analyzed do not have a negative impact on human health and are safe, and do not require additional safety measures or warnings. In fact, studies have shown that low-frequency vibrations can increase the seismicity factor in regions where power facilities are located. For example, if we consider a cubic sample of oolitic limestone measuring 10×10 meters and study its natural vibrations, the initial resonance frequency will start at an average of 300 Hz. However, if you perform the calculation for a cubic sample with a face length of 100 meters, the resonant mode will start at 6 Hz. Thus, low-frequency vibrations can affect large geologic blocks and cause stresses to accumulate in the faults between them.

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ЗАСТОСУВАННЯ КРОС-СПЕКТРАЛЬНОГО АНАЛІЗУ ТА ШВИДКОГО ПЕРЕТВОРЮВАННЯ ФУР'Є ДЛЯ ВИЯВЛЕННЯ КОЛИВАНЬ ҐРУНТУ В ПРИРОДНО-ТЕХНІЧНІЙ ГЕОСИСТЕМІ ДНІСТРОВСЬКОЇ ГАЕС

Основна мета дослідження полягає у виявленні залежності між змінами рівня води та деформацією ґрунту, девіатором напружень якого є циклічна зміна навантажень на ложе резервуара водосховища, тобто резервуар ГАЕС виконує роль осцилятора поперечних коливань, а ґрунтовий екстензометр – функцію зчитування та фіксації цих коливань. Методика. Для вирішення завдання потрібно записати часовий ряд коливань рівня води та часовий ряд коливань датчиків екстензометрів на всіх горизонтах заглиблення, виконати швидке перетворення Фур'є для коливань рівнів води окремо, далі аналогічно коливань кожного із датчиків екстензометра, розрахувати спектр потужності сигналів окремо всіх датчиків у ґрунті, зіставивши амплітудно-частотні, фазово-частотні складові спектрів потужності коливань рівня води та вертикальних коливань екстензометричних датчиків. Результати. Під час досліджень встановлено, що водосховище ГАЕС, є джерелом генерації низькочастотних коливань у широкому спектральному діапазоні. Ці коливання мають дуже довгі хвилі, вимірювані десятками тисяч кілометрів, які можуть поширюватися на великі відстані, як по фронту геологічних шарів, так і вглиб. Наукова новизна. Дослідження дають змогу точніше оцінити частотний спектр коливань і визначити резонансні явища, що можуть виникати в ґрунтах під час роботи енергооб'єкта. Крім того, це дослідження виконано в конкретному регіоні, що дає змогу отримати точніші дані про вплив низькочастотних коливань на геосистему в цьому регіоні. Отже, це дослідження може становити інтерес для фахівців у галузі геотехніки, геології та енергетики, а також може бути використане під час планування та експлуатації інших енергооб'єктів у подібних умовах. Практична значущість. Низькочастотні хвилі можна виявити за допомогою сейсмічних приладів, таких як сейсмометри. Результати цього дослідження допоможуть коригувати аналіз та інтерпретацію сейсмограм, що важливо для розуміння процесів, які відбуваються в зоні експлуатації гідроелектростанції.

Ключові слова: оолітовий вапняк; геотехнічний моніторинг; екстензометр; гідроакумулююча електростанція; ґрунтова основа; стан ґрунту; спектральна щільність; швидке перетворення Фур'є.

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