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Soil vibrations as a reliable recorded characteristic of geodynamics in the dam area of a large hydroelectric power station

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Abstract. The paper considers geodynamic within the area of the Zhigulevskaya hydroelectric power station: the signs of present activity of the Zhiguli fault including soil vibrations during water discharges that demonstrate instability of geological environment, the atmospheric phenomena, the risks for the dam and reservoir caused by the activation of geodynamics.

1. Introduction

The reservoir of Zhigulevskaya HPP is the largest in Europe and the only one regulating among those in the cascade of Volga HPP.

In Russia, hydroelectric power plants (HPP) were constructed mainly during the period when regional tectonics and geodynamics were ignored, or the information on these problems was concealed. Even on the platforms, including the Russian platform, geodynamic processes can bear a potential threat, create a high risk in the areas with concentrated population and industry.

During the construction of Zhigulevskaya HPP, difficulties were observed already on the stage of choosing the place for the dam. Complex geological features of the territory, high degree of destruction of rocks composing the Volga River valley were the result of the movements in the earth faults. However, at that time there was no information proving tectonic movements to be in progress on the territory. At last, the Zhigulevskaya HPP building was established not on the destroyed hard rocks, but in the mouth of a ravine, where limestone is covered by a thick layer of clay. The building of the HPP was placed on the right bank of the Volga River, and the spillway dam – on the left bank, near the Togliatti City. The ground dam was constructed between the HPP unit building and the spillway dam.

Soil vibrations in the area of the Togliatti City adjacent to the Zhigulevskaya HPP were first recorded in 1979 during the passage of extreme spring flood through the spillway dam. Large idle discharge caused intensive vibrations of the spillway dam, soils and buildings in the surrounding area. The vibrations of the dam and soils were measured at several points above and below the dam. After this, stand simulations were conducted, and new models for passing of idle water discharges were developed. In these models real geological conditions of the territory were not taken into account. New models of idle water discharge turned out ineffective in actual practice [1].

In 1991, when idle water discharge exceeded standard values, vibration of soils and buildings occurred unexpectedly. Later, using Fourier analysis, it was proved that soil vibrations arise exactly



during idle water discharge through the spillway dam. It was believed that loose ground, sands and loams do not transmit vibration over several kilometers without attenuation. The data on the geodynamics of the territory explained the intensity of ground vibrations. Zhigulevskaya HPP is constructed on a deep fault, its flanks – the right and the left banks of Volga – move towards each other, creating the compression stress. Therefore, relatively weak vibrations of the dam can spread over long distances in grounds according to the type of signal modulation. In other words, the distance to which the dam vibration spreads characterizes the tension of the earth's crust in this area.

In December 2000, an earthquake of 4–5 points' intensity occurred in the area of Zhigulevskaya HPP, as well as in Samara, Saratov, and Kazan [2, 3]. The earthquake did not lead to the revision of the seismicity assessment of the territory. However, such an earthquake occurred for the first time during the existence of the dam and the reservoir of Zhigulevskaya HPP, as well as of the whole cascade of Volga HPP.

The cities located on the Volga banks – Volgograd, Saratov, Samara–Togliatti, Ulyanovsk, Kazan, Cheboksary, Nizhny Novgorod – grew substantially after the construction of the HPP cascade. In these cities, high concentration of population, large and dangerous enterprises, oil refining and chemical plants, dams, two nuclear objects and others create high geodynamic risk. Zhigulevskaya HPP creates risk for all the territories located downstream of the Volga River. The study of geological materials showed that the area of Zhigulevskaya HPP, the Samara region and the Volga region lie in a zone of active movements of the earth's crust which occur along large faults [2, 3]. These are deep faults of the mantle foundation to which the Volga valley is confined. The territories near these faults can be distinguished as a separate structural element of the Russian Plain [4]. The movements of the earth's crust here are caused by the rise of the mantle matter in the Middle Volga region and external pressure of other plates on the edges of the Russian platform. In the case of increased mantle lifting, geodynamic processes and the seismicity associated with them may intensify and create geodynamic risk not only for Zhigulevskaya HPP, but also for Balakovskaya Atomic Power station [3].

Now the shift of layers of the right and the left wings of the deep fault in the Zhigulevskaya HPP area reaches approximately 1 km, the speed of modern vertical movements is estimated a few mm/year. The right bank is the raised wing of the fault, and the left bank is now descending. The geologists evaluated a potential geodynamic risk in the area of Zhigulevskaya HPP as high – up to 9 points. Unfortunately, such evaluation without temporary frameworks does not attract serious attention. Regular seismic control is not held. Only a few seismic stations operate in the Volga region. After the 2000 earthquake, a seismic monitoring of the area of Zhigulevskaya HPP was carried out for a short period, which recorded a number of important though weak earthquakes. The current geodynamic activity in the area of Zhigulevskaya HPP and the Samara region is confirmed by the radon level, thermal waters, gravity anomalies, heat flow anomalies, etc. However, these phenomena have always been existing.

The article considers geophysical characteristics indicating that an acceleration of geodynamic processes takes place in the area near Zhigulevskaya HPP. One of such characteristics is soil vibrations under idle discharges passing through the overflow dam. For a long time, the vibrations of soils were studied only at a few Russian HPP [5–10]. During the last decade, several works appeared which studied soil vibrations near one of the HPP in China [11–14].

Soil vibrations are considered to be a negative impact of a working hydroelectric station on the territory. It is important to take them into account for the safety of the dam and the adjacent areas. The data of long-term monitoring of soil vibrations should be used for this.

2. Materials and methods

We analyzed the data on the vibration of soils, buildings and constructions near the dam of Zhigulevskaya HPP during the flood periods (idle discharges). The measurements were taken in 1999–2017 at the seismic station located downstream the dam by pendulum-type seismometers installed on a concrete base at a depth of 3 m. The registration range of the seismometer is 0.5–20 Hz. The registration frequency is 100 Hz per channel.

The measurements of the soils vibration velocity along three orthogonal components were taken continuously or discretely. A certain measurement took several (mostly 5–15) minutes. The data was saved on the computer.

For each recording session, the averaged values of each orthogonal component of the soil vibration velocity were calculated. The results showed that velocity variations occur synchronously and proportionally. For further study, the vertical velocity of soil vibrations V_z (mkm/s) was chosen [5]. Water discharge was used for quantitative assessment of the dam operation. The values of water flow passing through the overflow dam were taken from the hydrological service of the Togliatti post of the Volga hydrometeorological department. V_z values were compared with the values of water discharge passing through the overflow dam Q (m³/sec), and the correlation graphs were built. Each data record is displayed on the graph as a point. The correlation between V_z and Q was approximated by linear regression equation, and regression lines were used to demonstrate it [5]. The accuracy of approximation was estimated statistically. The change of regress lines location on the coordinate plane was estimated which characterizes the change of V_z/Q correlation.

Method of graphic analysis of possible transformations of territorial biophonic systems having natural and anthropogenic genesis [6] was used to analyze the changes of this correlation. The method was originally developed for complex biological lake systems and then adapted to complex natural-technical system. A dam with the basement, the adjacent part of the reservoir, the banks, the slopes of the valley, surface soils, etc, presents such a system [6, 7].

Soil vibrations proved to be the key factor of the system allowing to evaluate its stability. This is important in case if the components of the system, namely the dam – the geological environment, and relation between them are not known. The method of graphic analysis allows determining the type of a system transformation: oscillation, directional change or transition of the system into another state. Probable change of the V_z/Q correlation and the reasons for it were studied. Probable reason for gradual parallel displacement of linear regression diagram of the V_z/Q correlation towards high values of V_z was analyzed in detail, in particular – the impact of powerful external factor [6, 7]. Different factors which could serve as powerful external factor to the system “the dam – geological environment” were investigated. The research of other geophysical data was conducted to find any parameter which could also change under the influence of the same factor.

As a part of these works, the field of average air temperature was concerned basing on the data from more than 80 meteorological stations of the Volga Basin and the adjacent territories [15]. Air temperature of the cold period (November to May) for the period 1966–2010 was analyzed. Coefficients of linear trend appeared to differ along the basin. Possible reasons for this were estimated and analyzed. Anthropogenic factors, namely, the dynamics of population growth, urban development, growth of industrial production were studied. The possibility of connection of this difference with the latest geodynamics was studied using scientific publications, geological reports, expert assessments, geological maps.

3. Results and discussion

The results of soil vibrations monitoring demonstrate that they are increasing by years under equal values of water discharge through the overflow dam of Zhigulevskaya HPP. This is manifested by the displacement of linear regression lines of V_z/Q correlation for different years (figure 1).

Gradual parallel displacement of linear regression line of V_z/Q correlation upwards in 1999–2001 and after 2003 is observed. This is possible in case if the transformation of the territorial biophonic systems of natural and anthropogenic genesis takes place under some powerful constant external factor causing gradual irreversible changes. Taking into account the size of the dam, only some global geological process can serve as such a factor [7, 8]. For the area of Zhigulevskaya HPP, active geodynamic in Zhigulevsk fault most probably can be such a factor. The growth of compressing strain takes place at counter horizontal movements (by type of overthrust). In 2003 during one day on the peak of the high water, soil vibration increased three times. At the same time, vibrations of the overflow dam did not increase. The reason for this has not been found yet.

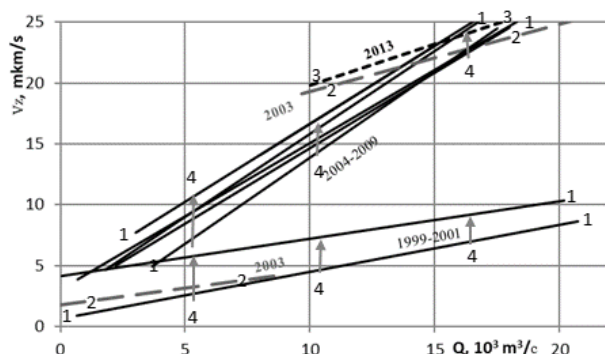


Figure 1. Correlation (linear regression) between vertical velocity of soil vibrations (V_z) and water discharge through the overflow dam (Q).

- 1 - trend lines for different time periods;
- 2 - trend line for 2003;
- 3 - trend line for 2013;
- 4 - the direction of change in the amplitudes of V_z under the same values of Q .

Most likely, the triple increase in soil vibrations in 2003 is also associated with new geodynamics. It is impossible to prove this hypothesis experimentally: monitoring of compression strain is absent.

The analysis of the time-series of winter air temperature proved its increase in the Volga Basin after 1980, its intensity changing along the territory [15]. Against the background of a general decrease of this intensity from west to east, three sites stand out, where the growth rate is more than in neighboring areas. All these three areas geographically coincide with the regions of present geodynamic activity on the Russian platform.

After 1980, an intensive increase in winter air temperatures was observed on the Middle Volga territory, its temps being maximal in the west and descending eastwards. However, three sites stand out, where the growth rate is more than in neighboring areas. The first area corresponds geographically to the Samara and Saratov regions, the second one to Kazan, and the third – to Kolomna in the Moscow Region. More rapid increase in winter air temperatures was discovered near the Zhigulevsk fault as far back as in 2006 [7, 8].

The comparison of the map of winter temperature trends with the map of present geodynamic activity on the Russian platform shows that the Saratov–Samara and Kazan areas correspond to the section of geodynamic activity in the Volga basin. The region of Kolomna is less studied; it is not marked out on the geodynamic activity map. However, the Kolomna region is characterized by maximal possible seismicity within the Moscow region – 4 points. Geographically, Kolomna is located at the confluence of the Moscow River and the Oka River, which already indicates the presence of faults. In the area of Kolomna, three faults of the second rank cross [16]. Several parts (in the south) of these faults in the Kolomna region are marked as active. Fault activity is observed here: for example, the release of gases from the Earth interior. The Zhigulevsk fault and other faults in the Middle Volga Basin are of the first rank.

The interaction between the processes in the crust and atmosphere is not well studied. It is necessary to check whether the received results are valid in the basins of other major rivers flowing under similar geological conditions. The possibility of temperature anomalies in the Volga basin under the influence of standard climatic factors should be studied in detail. The time series of soil temperatures for this region should be analyzed.

4. Conclusions and recommendations

Soil vibrations during releases through the dam depend on the geodynamics of the territory:

- a) They reflect the stress-strain state of the crust;
 - b) The change in the velocity of vibrations reflects the change in the stresses of the earth's crust.
- Together with the change in other geophysical fields – the temperature field – they probably indicate an increase in the rate of geodynamic processes;

Soil vibrations can serve as an indicator, a reliable recorded characteristic of changes in the state of the environment near the dam.

Monitoring of soil vibrations in the area of the Zhigulevskaya HPP should be continued, using the results of monitoring on other large dams.

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