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Monitoring of the natural frequencies of Chirkey arch dam

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Abstract. The article presents a method for monitoring the natural frequencies of HPP dams according to continuous seismic observations. The object of the research is the largest arched dam in Russia, the Chirkey HPP located in the Caucasus. If damaged, it could cause great loss of property and human life, but disasters can be minimized by using effective dam structural health monitoring. The study for changes in the natural frequencies of engineering structures is one of the most common methods of remote control over their structural health. However, the determination of values of natural frequencies of huge concrete dams is a very difficult procedure due to their have complex construction. Moreover, interpretation of changes in the natural frequencies values is difficult due to the significant influence of the water level in the reservoir. Consequently, at the initial stage, we performed a detailed study of the natural oscillations of the dam using the method of coherent restoration of the standing wave fields with the definition of both the natural frequencies of the structure and their modes. They were conducted twice at the minimum and maximum upstream level and for the first time highlighted the features of seasonal changes in the full field of standing waves. The normal modes were determined that are present in oscillations at different upstream levels and which frequencies can be detected continuously from the records of seismic equipment. The series of frequency changes during the year are calculated. For the first time we established that, frequency changes are by 5 to 11 days behind reservoir level changes and assumed that relaxation processes of the dam body and / or its base cause the delay after the upstream level changes. We calculated dependencies for predicting the frequency values from the reservoir level, taking into account the delay time. As a result, we proposed an approach for monitoring of the dam structural health based on a comparison of the observed natural frequencies with the predicted ones. The developed method can be applied to monitor the structural health of concrete dams of other HPPs.

1. Introduction

For control of the health of engineering structures, monitoring methods based on the analysis of changes in time of various parameters of the field of standing waves (primarily, natural frequencies) are widely used [1–10]. At the same time, variations of the field of standing waves can be related not only with the appearance of any defects in the structure, but also with other factors. For example, this may be a time-varying external load, without causing defects. In the case of hydroelectric dams, such a load, which is usually seasonally varying, is the water pressure from the reservoir [7–8, 11–13]. In heavy and complex structures, which include hydroelectric dams, the standing wave field has a complex structure, to determine which, it is necessary to perform measurements with high detail [14]. Therefore, to avoid misinterpretation, before conducting research on the monitoring of the state of structures based on changes in their natural frequencies, it is necessary, firstly, to determine reliably these frequencies and, secondly, to study thoroughly all the factors affecting them. As the occasion requires making immediate decisions a method for determining, the current values of the frequencies (near real time) should be developed.

Thus, the main objective of the study is to develop a method for continuous real-time monitoring of the natural frequencies of the Chirkey arched dam.

There are various ways to study the natural frequencies of structures. For example, based on the registration of oscillation under the influence of artificial sources of vibration type or explosions [11, 15–16], or under the influence of earthquakes [9].

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Methods with artificial sources, especially in the study of large structures, such as hydroelectric dams, are quite labor-intensive and high-cost, and therefore not common for solving problems of operational monitoring of the structural health.

Methods based on the registration of earthquakes, due to the inability to predict the time and place of their occurrence, are also unacceptable. Nevertheless, these methods are implemented and give some information about the health of the structures, albeit with low accuracy [9].

There are also ways to study the natural frequencies of structures, based on the registration of background microseismic vibrations. Their main advantage is that many sources of microseismic vibrations are used. These methods are based on the well-known fact that practically in any engineering structure, due to its limited volume, forms a set of standing waves when oscillations propagate [14]. It does not matter where the sources of these oscillations are. A number of authors, using this property of standing waves, determine the natural frequencies from the maxima of the spectra of microseismic vibrations recorded at several points of the structure [7, 8, 13, 17]. This method is quite simple to implement. But due to difficulties in constructing natural oscillation modes possible errors in the identification of each of the natural frequencies could occur. In addition, various noises from operating hydroelectric equipment can be superimposed on the valid signal. The situation is complicated by the fact that in the case of an unsuccessful arrangement of sensors in the field of standing wave nodes, their frequencies are almost impossible to determine [18].

There is a way to determine the current values of the natural frequencies of a structure using continuous recordings of seismic stations located in its vicinity. In work [19], it is shown that standing waves forming in the dam of the Sayano-Shushenskaya HPP are a source of waves that, propagating in the earth, are recorded by highly sensitive stations of the seismological network at distances of several kilometers. A technique has been developed to isolate such oscillations by averaging the amplitude spectra of seismic records with duration from several hours to several days. This method assumes that the natural frequencies of the object have already been identified.

In work [14], a method of coherent recovery of standing-wave fields was proposed, which makes it possible to isolate coherent in time and space oscillations – standing waves from the data of the registration of microseismic oscillations. Through the use of registration at the reference point, the implementation of measurements is carried out by a limited number of sensors on an arbitrarily dense network of observations. This makes it possible to construct detailed modes for each of the natural frequencies and eliminates the error in their identification.

The object of the research is the Chirkey dam. It is located in the Caucasus, in an area with increased seismic activity (9 points on the general seismic zoning map); it has the largest arch type dam in Russia, 232 m high and 338 m long. The designed head of the generators is 170 m, and seasons fluctuations of the reservoir level are almost 40 m. In accordance with the standards, the hydroelectric station is equipped with a system of continuous seismometrical and seismological observations, the characteristics of which are given in work [20]. In the literature, there are no data on studies of changes in the parameters of the natural oscillations of the dam.

This paper proposes a method for monitoring the natural frequencies of a HPP dam using continuous seismic observations at stations installed inside the dam and / or at a distance from it. This problem was solved as follows. At the initial stage, a detailed study of the natural oscillations of the dam was carried out by the method of coherent restoration of the standing wave fields with the definition of the natural frequencies and modes of the structure. These studies were carried out at different levels of reservoir filling in order to determine the features of seasonal changes in standing wave fields. Later, using continuous recordings from seismic stations, averaged amplitude spectra were calculated, which were used to determine the current values of the natural frequencies of the dam and to analyze their changes over time. Changes in frequency values that were not related to the appearance of structural defects were established. Further, in case of detection of anomalous deviations of the values of natural frequencies, it is possible to draw conclusions about the appearance of defects in the structure.

2. Methods

To study the natural oscillations of the dam, we used the method of coherent restoration of standing wave fields, which allows us to construct a detailed field of standing waves from microseismic oscillations recorded at various points of a building or structure and to determine the natural frequencies and modes of object oscillations. The study can be divided into two stages: the first is the measurement of oscillations on a detailed grid using the reference point and the second is the signal processing of the received data in order to obtain a one-time field of standing waves and determine of natural frequencies and modes.

The measurement of microseismic oscillations was performed using autonomous three-component seismic stations “Baikal-ASN” (own development of GS RAS). GS-20DX velocimeters were used as seismic receivers. The frequency range of recorded oscillations is 1–60 Hz, the sampling frequency is 200 Hz.

To equalize the amplitude-frequency response of seismic receivers in the low-frequency domain (1–10 Hz), the method of low-frequency deconvolution of digital recording of a short-period seismometer, well-proven in seismological studies, was used [21]. Registration was carried out by a series of consecutive measurements of oscillations by 5 units of equipment. The recording time of each measurement is 10 minutes. Data were obtained at 287 different points located on 10 profiles at different levels, passing either through the galleries inside the dam or the balconies (Fig. 1). At the level of 290 m, the profile is forced to be broken due to the impossibility of installing seismic sensors (penstocks pass in this place). Additionally, three sets of equipment were used at reference points. They did not change their position in the course of measuring oscillations in moving points. Points number 1 and number 2 were set due to the fact that it was obviously not known where in the dam the nodal lines would pass, and as it is known, if the point falls close to the natural oscillation node, then the coherence value will be lowered [14]. During the analysis of the coherence functions, it was found that the position of point number 2 is more suitable for subsequent use (the coherence values for the set of selected modes are higher and, accordingly, the conversion accuracy is higher). Point number 3 was established for the purpose of the subsequent implementation of the assessment of the seismic stability of the dam. The orientation of the devices was carried out in the following way: the X-channel is directed in the radial direction relative to the dam, Y in the tangential direction, Z in the vertical direction. The measurements were carried out twice - with close to the minimum and maximum filling levels of the reservoir in order to determine the features of seasonal changes in the parameters of the fields of standing waves in the body of the dam.

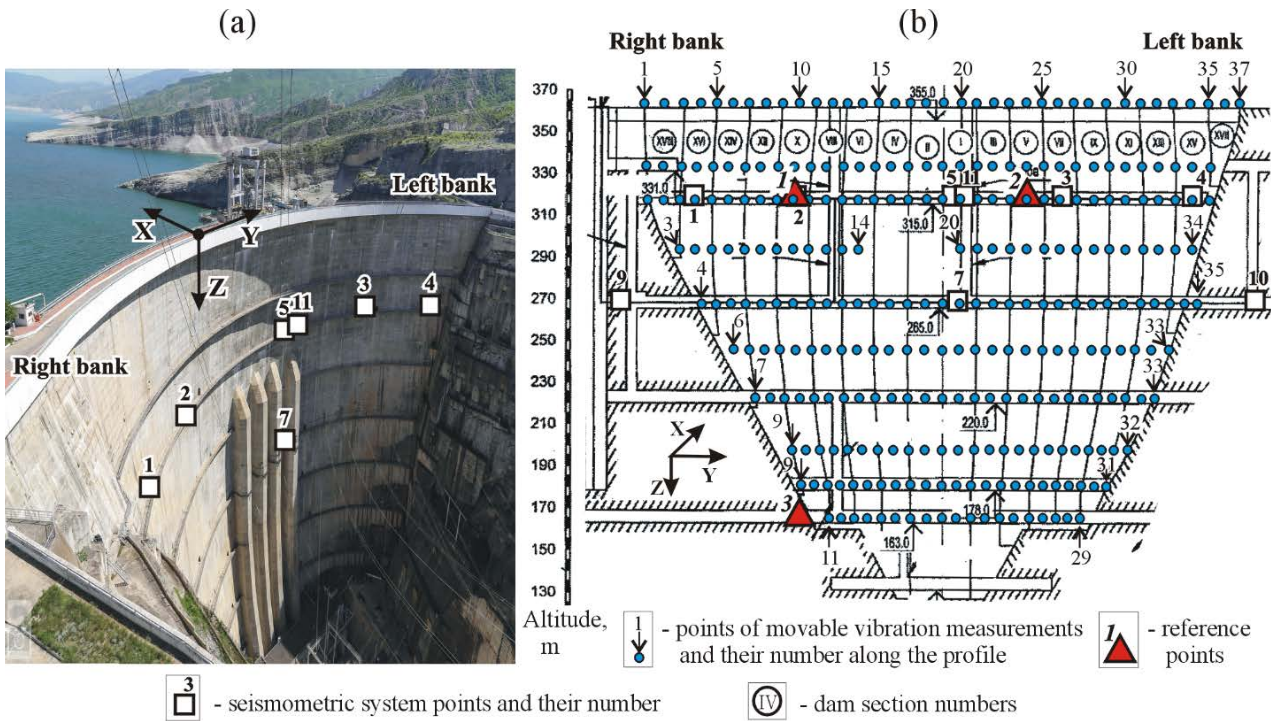

Figure 1. The appearance of the dam of the Chirkey HPP (a) and the scheme of seismic observations (b).

After registering according to the method described above, a set of continuous (10-minutes) multi-time records was obtained at N = 287 observation points. The task of digital processing was to bring time-varying seismic records to a single time, followed by the allocation of standing waves formed in the structure. For this, the method of calculating Wiener filters was used to recalculate the oscillations from the reference point to each of the N observation points, described in detail in work [14]. After receiving the filter set, at the final stage of processing, the oscillations recorded at the reference point were recalculated at each point on the structure. Below there are the basic formulas used for digital data processing.

The formula for calculating the Wiener filter, which provides the recalculation of oscillations from the reference point to the *i*-th, taking into account the splitting of the original record into disjoint time fragments, has the form:

$$h_i(\omega) = \frac{\sum_{j=1}^{n} \overline{F_{ij}}(\omega)\overline{F_{0j}}^*(\omega)}{\sum_{j=1}^{n} \left|\overline{F_{0j}}(\omega)\right|^2}, \quad (1)$$

where $h_i(\omega)$ is the frequency characteristic of the Wiener filter for recalculating the oscillations between the reference and *i-th* points, *i*=1,..,*N*; $\overline{F_{ij}}(\omega)$ and $\overline{F_{0j}}(\omega)$ - Fourier transforms of *j-th* fragments of simultaneous records in the *i-th* and reference points, respectively, and the superscript * means complex conjugation, *n* is the number of such fragments.

Formula (1) allows the calculation of the filter characteristics with an error that depends on the parameters of the registered implementation of the oscillations of the object being examined. Such parameters are: the sampling interval of the recorded oscillations with respect to time – Δt , the length of a single fragment, into which the recording of vibrations is divided – *T*, the number of fragments in the recording – *n*. The choice of the first two parameters is not difficult. The sampling interval is linked to the frequency range in which the oscillations of the object of research are studied – was chosen equal to 0.005 s. The length of a single fragment is related to the required resolution of the spectral analysis – $\Delta f = 1/T$. To survey complex objects that have a whole range of degrees of freedom and, accordingly, a whole series of resonant bandwidths in the frequency response, resolution is required, linked to the width of these resonant bandwidths and the frequency distances between them. Taking into account the experience of conducting such studies, the length of a single fragment was chosen to be 10 s, which corresponds to a resolution of 0.1 Hz. More difficult is the question of the number of fragments. The calculation by formula (1) is only a certain estimate of the filter characteristic, the error of which depends on the number of fragments *n* and the ratio of noise energy and useful signals, i.e., in fact, to what extent the change of oscillations from point to point is described by a linear system.

The expression for calculating the relative error of the amplitude characteristic of the filter (1) is:

$$\varepsilon\left(\left|h_{0i}(\omega)\right|\right) = \frac{\sqrt{1-\gamma_{0i}^2(\omega)}}{\left|\gamma_{0i}(\omega)\right|\sqrt{2n}}, \qquad (2)$$

where $\gamma^2(\omega)$ is the coherence function calculated by the formula:

$$\gamma^2(\omega) = \frac{\left|\sum_{j=1}^{n} \overline{F_i}(\omega)\overline{F_0}^*(\omega)\right|^2}{\sum_{j=1}^{n}\left|\overline{F}_0(\omega)\right|^2 \sum_{j=1}^{n}\left|\overline{F_i}(\omega)\right|^2} \qquad (3)$$

In accordance with (2), with an increase in the number of fragments for calculating the characteristic of a filter that recalculates oscillations from the reference point of the object being inspected to *i*-th, any given error in constructing the filter can be achieved. In order to improve the performance of measurements, it is necessary to choose the optimal value of *n* (or record length) so that the results are accurate enough, but the measurements would be performed as quickly as possible. With a small number of fragments, even a small increase in their number provides a significant decrease in error. For large values of *n*, the decrease in error with an increase in the number of fragments slows down. High accuracy of oscillation recalculation is quickly achieved with large values of $\gamma^2(\omega)$. For cases with small values of the coherence function, a large number of fragments in simultaneous recording is required. In our case, the values of $\gamma^2(\omega)$ were 0.64–0.81, and *n* = 60 (for 10-minute records, a single fragment with a length of 10 s), the relative error of the amplitude characteristic was 0.02–0.04.

At the final stage, after the construction of a set of filters using formula (1), the oscillations recorded at the reference point were recalculated at each point on the structure. As a result, a full field of coherent oscillations is obtained, analyzing which standing waves are distinguished – by the characteristic space-stable arrangements of alternating maxima (antinodes) and minima (nodes) of amplitude. For each of the standing waves, the natural frequencies of the structure are determined.

In order to further monitor the natural frequencies of the structure, averaged amplitude spectra are constructed from the records of microseismic oscillations. The values of the frequencies corresponding to the previously defined natural frequencies are determined by the local maxima of the amplitudes. Nevertheless, the frequencies are determined at points located in the antinodes of standing waves, in accordance with the method[18]. Further, the factors affecting changes in frequencies, but not related to changes in the structural health of the dam, are examined. For example, the changing level of the reservoir. Exclusion of such factors will increase the degree of reliability of the results of health monitoring of the structure.

3. Results and Discussion

The data in Fig. 2, show changes in the sets of amplitude spectra of coherent oscillations, according to the results of two experimental works – with maximum and minimum upstream level. It can be seen from the figure that in both cases the overwhelming part of the oscillation energy is concentrated on the X-component, which is directed radially (across the dam). It is noticeable that the X-component of the oscillations has both a general and a difference. For example, oscillations of the 1st, 2nd, and 4th modes (the mode number corresponds to the number of observed antinodes along the profile), although with different frequencies and intensities, are repeated at the maximum and minimum filling levels of the reservoir. At frequencies between the 2nd and 4th modes, another stable oscillation is observed, having one antinode, which can be classified as the secondary first mode. That is, in this case, the two first modes are observed with different oscillation frequencies. This phenomenon is due to the fact that the first and secondary standing waves are formed in objects that combine different sections of the dam. The same happens with the higher modes of oscillations, creating a very complex picture, which can only be understood when carrying out more detailed work. With these observations, the remaining oscillations are much less pronounced and do not repeat in shape with different modes of filling the reservoir. It can be said that the fields of standing waves at frequencies not equivalent to the two 1st, 2nd and 4th modes are completely different. Such a difference, in our opinion, can be caused by a significant change in the stress-strain state of the dam with a change in upstream level.

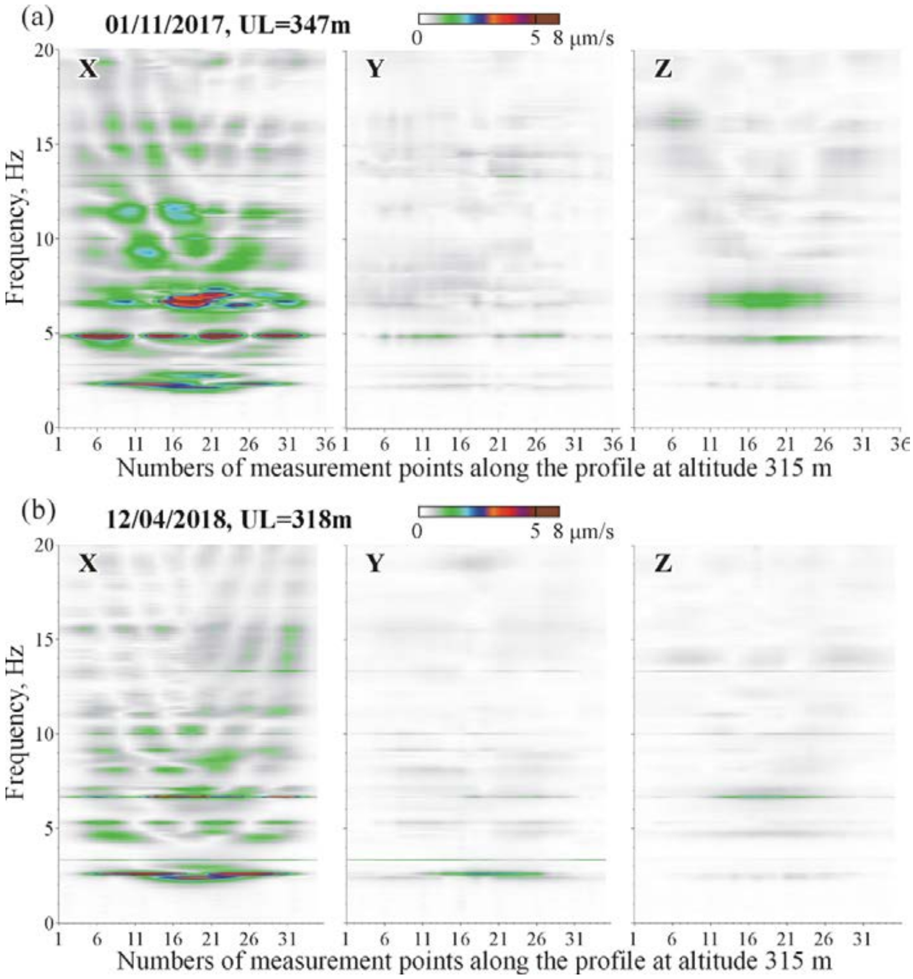

Figure 2. Sets of amplitude spectra of coherent oscillations of the dam along the profile at altitude 315 m at the maximum (a) and minimum (b) upstream level (UL).

Fig. 3 shows a more detailed image of changes in the low-frequency part of the spectra of transverse oscillations of the dam. It is seen that with the reduction of the upstream level (from 347 m to 318 m), the frequencies of the two 1st, 2nd and 4th modes increased by 0.20-0.45 Hz from the values of 2.15 Hz, 2.78 Hz, 2.30 Hz and 4.88 Hz to 2.39 Hz, 2.98 Hz, 2.59 Hz and 5.32 Hz, respectively. Fig. 4 shows the schematic images of the two 1st, 2nd, and 4th modes of natural oscillations of the dam of the Chirkey HPP, it is clear that at the maximum and minimum upstream level, they practically do not change, but only the frequencies change. Only some distortions of the form of the 1st mode are noticeable, which, in our opinion, are associated with a superposition of the oscillations of the 2nd mode, in frequency close to the 1st. This is possible due to the low quality factor of the oscillations.

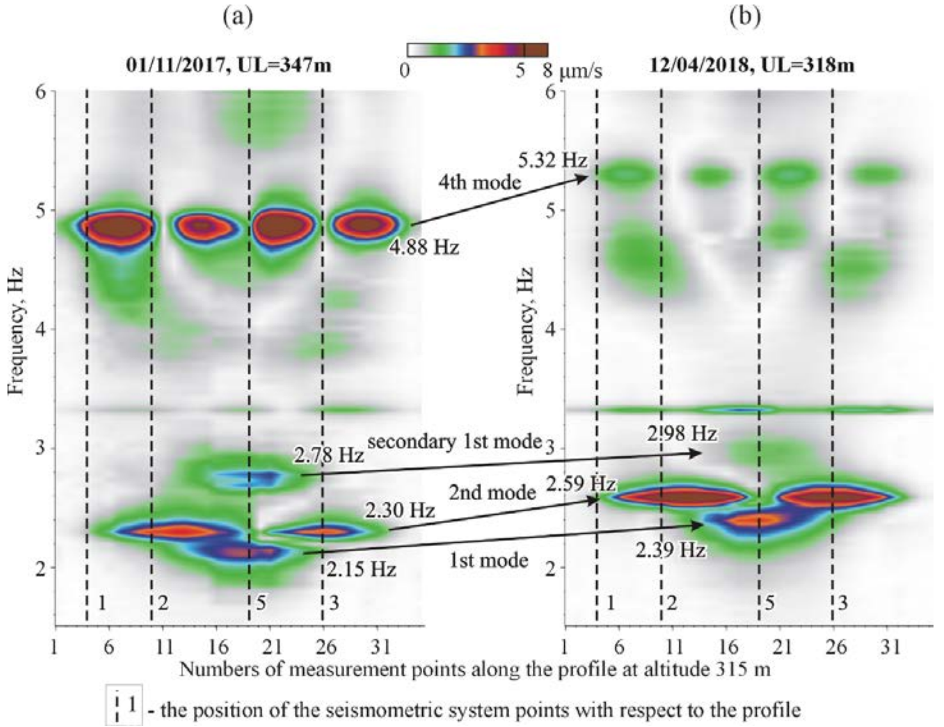

Figure 3. Changes in the amplitude spectra of transverse oscillations of the dam at the maximum (a) and minimum (b) levels of the reservoir (UL).

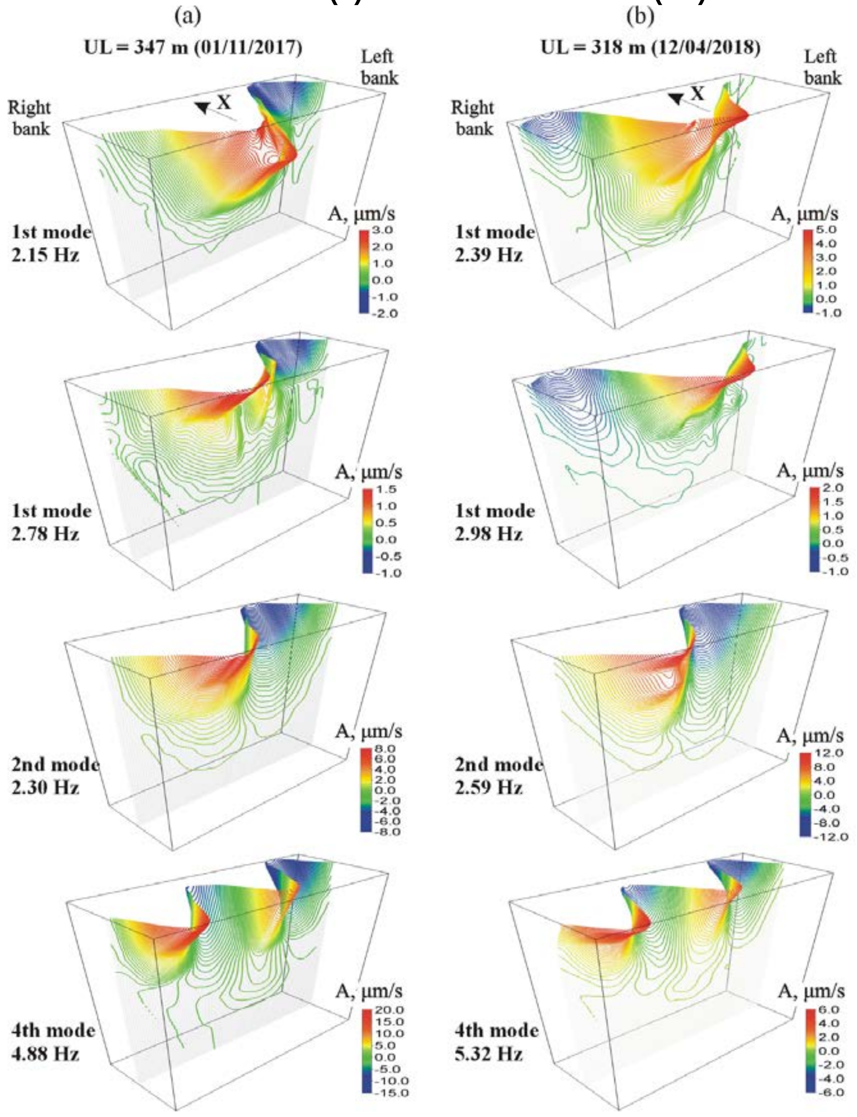

Figure 4. Schematic images of two 1st, 2nd and 4th modes of radial oscillations of the dam of the Chirkey HPP at high (a) and low (b) levels of the reservoir.

Due to the fact that the oscillations of only four modes (two 1st, 2nd and 4th) repeat with a high degree of reliability both at the minimum and at the maximum upstream level, these modes can be used for continuous monitoring of the structural health of the Chirkey dam. The remaining natural oscillations, of course, also carry information about the state of the dam. But, due to changes in the field of standing waves when changing the upstream level, it is expected that these oscillations will be observed only in limited time intervals.

The foregoing method of studying the natural oscillations of a dam compares favorably with methods using artificial sources. However, it should be understood that this method is not suitable for solving problems of continuous and operational monitoring of dam condition due to time spent on research. For example, it takes 2 days to field experiment and 1-2 days to perform digital data processing and analysis of the results, without taking into account the delivery of equipment and personnel. Therefore, for the purposes of further research, data of continuous recording of oscillations of the existing seismometric system in the dam body was used. The current frequency values were determined from the maxima of the amplitude spectra of seismic noise recordings at points located near the antinodes of each of the modes.

Consider the features of the recorded oscillations on a seismometric system, the location of the points of which was shown in Fig. 1. Fig. 5 shows the averaged amplitude spectra of the records of oscillations on the X-component, obtained in points 3 and 5 for the period of observations from 10/01/2015 to 12/28/2016. The method of their construction consists in calculating for each day of observations of sets of amplitude spectra for the fragments, each 100 s long, followed by averaging. Despite the fact that in this example, heterogeneous data is presented (registered values of accelerations and velocities), it is seen from the figure that the fields of oscillations at two different points are fundamentally different. This is caused by the different position of the points relative to the nodes and antinodes of the standing waves. For example, observation point No. 5 is located in the antinodes of the two first modes (Fig. 3) and simultaneously at the node of the second mode, therefore, only two vibration maxima are traced in the low-frequency (2–3 Hz) part of the spectrum. Observation point No. 3 is located in the antinodes of the second mode, therefore only one maximum of oscillations is traced. More clearly it can be seen from Fig. 6, which shows the averaged spectra with amplitudes normalized in a narrow frequency range. It can be seen that in point No. 5 for the entire observation period, oscillation maxima are observed with frequencies corresponding to the two first modes, and in point No. 3 – corresponding to the second mode. It is noticeable that there is a close correlation between changes in the level of the reservoir (upstream level) and frequencies - with increasing upstream level frequency decreases. It is more difficult to interpret changes in the frequency of the 4th mode. The design of the position of the points of the seismometric system of the Chirkey dam was carried out without taking into account the spatial position of the nodes and antinodes. Unfortunately, all available observation points were concentrated near the nodes of the 4th mode (see Fig. 3). This made it impossible to trace continuously changes in the frequencies of this mode (Fig. 6). In 2019, it is planned to upgrade the seismometric system in the dam of the Chirkey HPP with the addition of observation points and, if we take into account the spatial position of the 4th mode antinodes, it will be possible to investigate frequency changes of it.

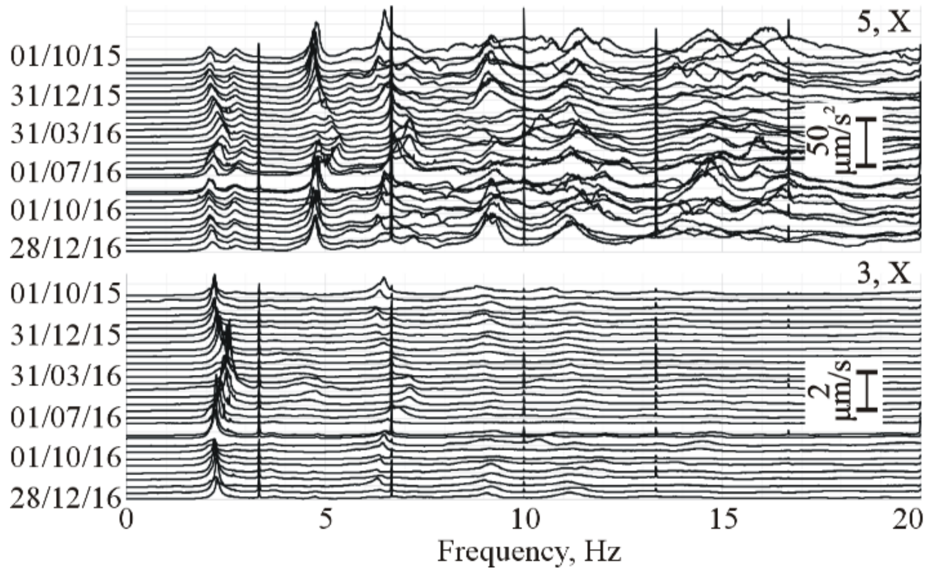

Figure 5. Averaged amplitude spectra of daily records of radial oscillations of the dam at two observation points.

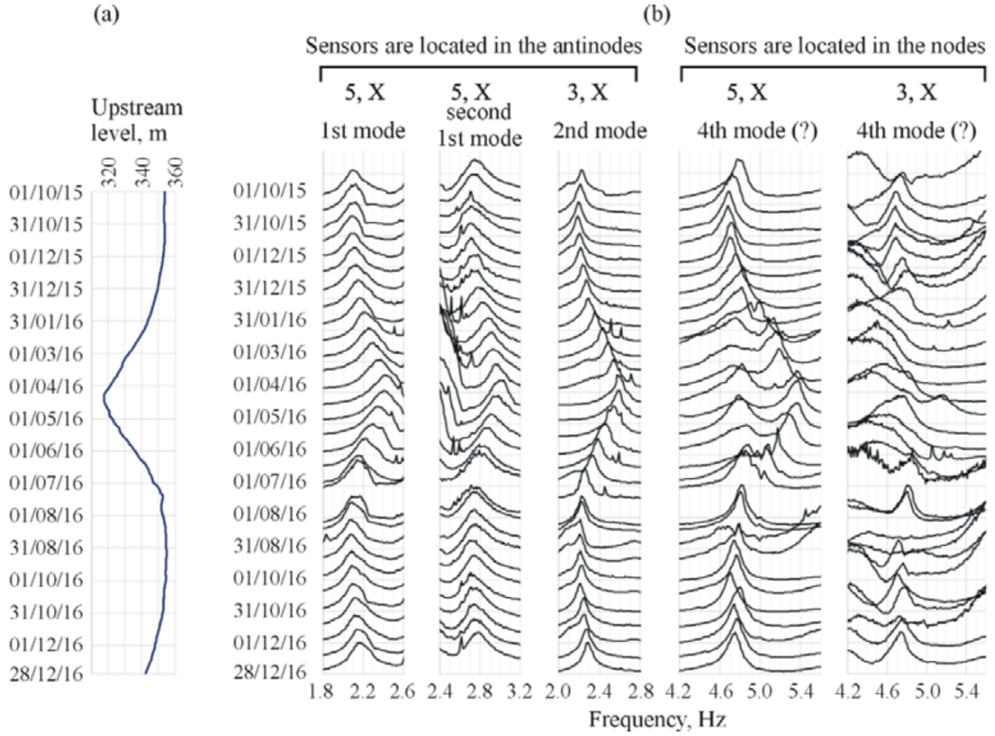

Figure 6. Changes of the upstream level of the Chirkey reservoir (a) and the normalized average amplitude spectra of daily records of the radial oscillations of the dam at two observation points (b).

Thus, the existing system of seismometric observations in the dam of the Chirkey HPP allows tracking continuous changes in the frequencies of the two first and second modes. Let us consider in more detail how these frequencies change over time and depending on the upstream level. Fig. 7 shows the graphs of these parameters for 2016. Given the variation in frequency values relative to the trend, it is possible to determine the error of their determination – it is about 0.01–0.02 Hz. In general, with the growth of the upstream level, the frequencies decrease. Such a dependence is characteristic of hydroelectric dams [7–8, 11–13] and is explained by researchers as the change in the added mass of water (the larger the mass, the lower the natural frequency). We then considered what other factors, in addition to the added mass, can affect the values of frequencies. To check this, we constructed dependencies between the values of frequencies and the upstream level (Fig. 8).

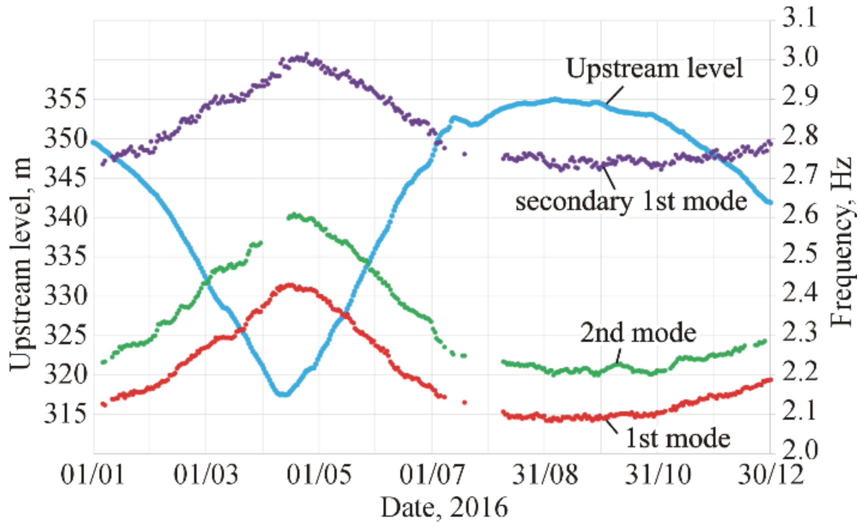

Figure 7. The changes of the upstream level of the Chirkey reservoir and of the values of natural frequencies of the dam.

Fig. 8a shows that the dependence between the values of frequencies and the upstream level is ambiguous. Graphs have differences depending on the mode of the reservoir – its filling or drawdown. In general, there is a lag in frequency changes from the course of changes in the upstream level. This leads to the formation of loops on graphs similar to hysteresis loops. It can be assumed that such a delay is due to the fact that the dam does not instantly react to changes in the level of the reservoir, but gradually relaxes. If this is not taken into account, then when monitoring the natural frequencies of the dam, an incorrect conclusion can be made about its condition.

The following study [22] can be an additional confirmation of the relaxation hypothesis. The results of studies of the relationship between seasonal changes in the water level in the reservoir and variations in the apparent electrical resistance of a rock mass inside a well located on the right bank near the dam are presented. The fact of the delay of the apparent resistance from the water level in the reservoir, which is 12 days, is established. One of the reasons for this delay, according to the authors of the study, is associated with a lag in the deformation of rocks from changes in the upstream level.

To estimate the relaxation time, we introduced a time shift between the series of changes in the upstream level and frequency values (Fig. 8b). It can be seen that after a shift of 5, 7 and 11 days for each of the three natural frequencies, the dependencies become more simple and unambiguous. They can be approximately approached by linear functions. Thus, by introducing a time shift, we took into account the relaxation time of the dam.

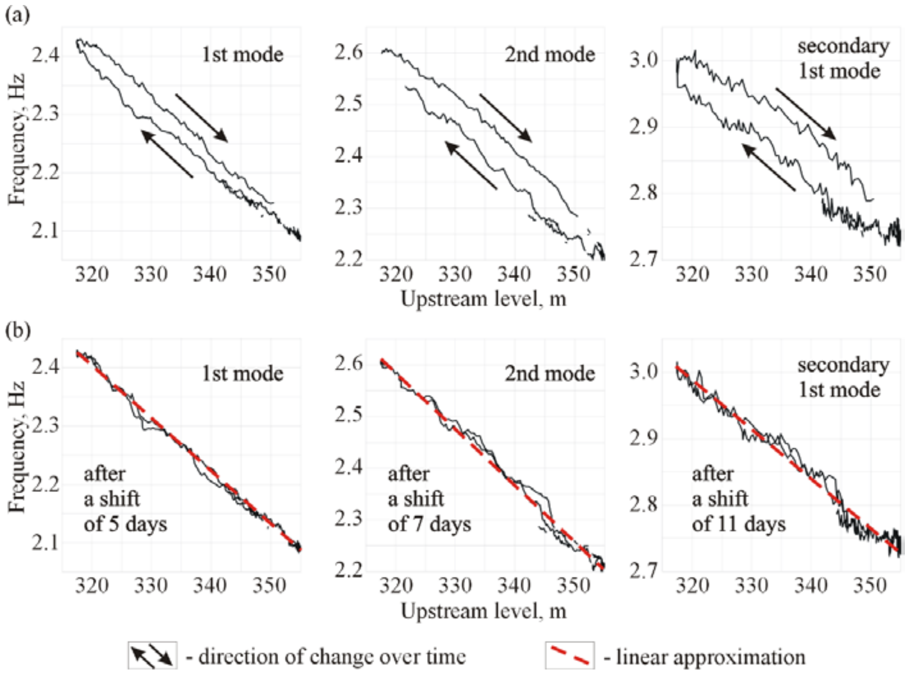

Figure 8. The dependencies of the natural frequencies of the dam on the upstream level for 2016: (a) one-time dependencies and (b) dependencies after the time shift.

As noted above, the natural frequencies of large structures can be determined from records of seismic stations located at some distance from them. At a distance of 5.5 km from the Chirkey dam, the Dubki seismic station (DBKG, Fig. 9a) is located. We tried to determine what information can be gained from the continuous records of this seismic station. For this purpose, a technique for determining the natural frequencies of structures from records of remote seismic stations was used. The analysis of the seismograms showed that from the records of microseismic vibrations on the seismic station, with a length of about 1 day, using the method of accumulation of spectra, it is possible to determine the frequencies of the first mode. To assess the reliability of such determinations, the obtained values were compared with the values determined from the vibration spectra recorded by the seismic system located in the dam body. As can be seen from fig. 9b, where the half-year series of changes in upstream level and frequency values of the 1st mode, defined in different ways, are presented, the latter is set with an accuracy of 0.03 Hz. Thus, if data on the vibrations of the body of the dam are absent then records of the Dubki seismic station can be used for monitoring purposes. However, it should be noted that this seismic station is located on the territory of the village of the same name, and at a distance of 5.5 km from the hydroelectric power station. Therefore, all sorts of interference complicate the records of the useful signal. Because of this, it is possible to determine the frequency of only the 1st mode with an error approximately twice as large. Therefore, records of the Dubki seismic station should be used only in exceptional cases. For example, in case of failure of the recording equipment located in the dam.

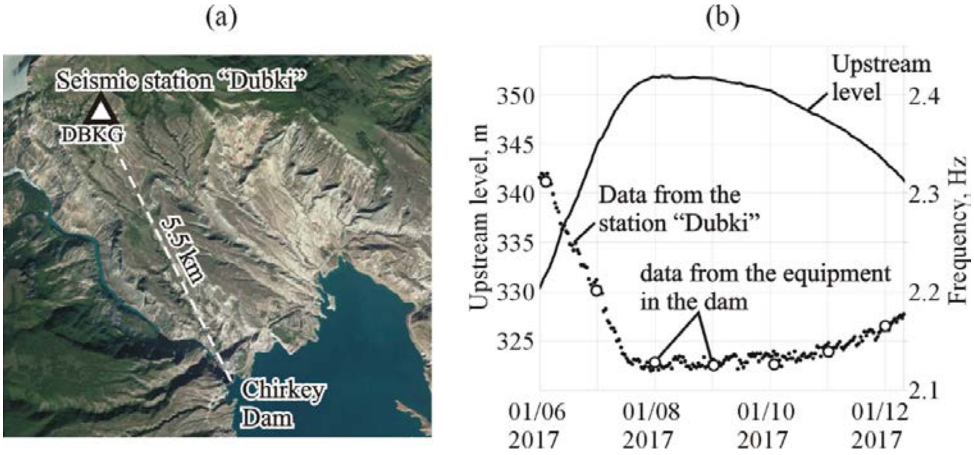

Fig. 9. Position of the Dubki seismic station (a) and changes in the frequencies of the 1st mode and the upstream level (b).

In order to develop a method for monitoring the natural frequencies of the dam, we approximated their dependence on the current values of the upstream level. For this, simple dependencies of the form were used:

$$f(t) = aH(t-\tau) + b\,, \quad (4)$$

where $f(t)$ is the approximated value of the natural frequency at time t, a and b are the coefficients of the approximation by a linear function, τ is the time shift that compensates for the delay in frequency changes relative to the changes in upstream level – $H(t)$. The approximation coefficients were determined by the least squares method according to the data presented in Fig. 8b. In addition, we calculated the value of the standard deviation σ of the experimental data with respect to linear regression. The results of determining these parameters are given in Table 1.

Table 1. The parameters of the approximation of the dependences of the natural frequencies from the upstream level according to the data for 2016.

Mode	*a* (Hz/m*10^3)	*b* (Hz)	τ (days)	σ (Hz)
1st	-8.996	5.279	5	0.008
2nd	-10.962	6.094	7	0.014
Secondary 1st	-7.285	5.317	11	0.014

It is proposed to monitor the natural frequencies of the dam as follows. First of all, the current frequency values of the two first and second modes are determined from the averaged spectra of seismic records at points located near the antinodes. Taking into account the data on the level of the reservoir, according to the formula (4) and with the parameters given in Table. 1, the predicted values of the natural frequencies are calculated. The experimental and predicted values of frequencies are compared. If the observed frequencies exceed the predicted ones by more than 3σ (a "three-sigma" rule is used), it is concluded that the technical condition of the dam has changed and there is need to establish the reasons for these changes.

An example implementation of the method is shown in Fig. 10, which presents the predicted values of the natural frequencies from the upstream level and the data of their experimental determination. The figure shows that the observed values are located within the confidence intervals. This means that in 2017 the technical condition of the dam remained stable (the same as in 2016).

The approaches presented in the article can be used on other arched and concrete dams of hydroelectric power stations. Other researchers are also developing approaches to monitoring the natural frequencies of dams for structural health monitoring of dam and damage detection. However, this technique is still new and not widely used. The main reason, in our opinion, is associated with large errors in determining the frequencies and difficulties in interpreting their changes, which are more dependent on changes in the reservoir water level. All this leads to a low degree of reliability in the research results.

Most of the errors can be eliminated by studying the natural oscillations of dams using very dense observation systems. The method of coherent reconstruction of standing wave fields, used in the work, allows such studies to be performed with high accuracy. Due to the possibility of implementing observations with a small amount of recording equipment, the technique is quite technologically advanced.

Some researchers took into account the effect of the reservoir water level by introducing a corrective function that depends only of the upstream level. In our study, we found that the natural frequency values are affected not only by seasonal fluctuations in the water level, but also by additional factors associated with relaxation processes in the dam or its foundation. These processes lead to the fact that the dependences between the reservoir water level and frequencies take the form of loops similar to hysteresis loops. Therefore, to consider this effect, we propose introducing an additional parameter into the correction function that describes the delay in frequency changes relative to changes in water level. Perhaps this effect also exists for other large hydroelectric dams. However, as far as we know, other researchers have not yet studied it.

It should be noted that changes in the structural health, for example, associated with the aging of concrete or with changes in the properties of the dam foundation, are quite long in time. Therefore, to identify such changes may take years or even decades of experimental observations.

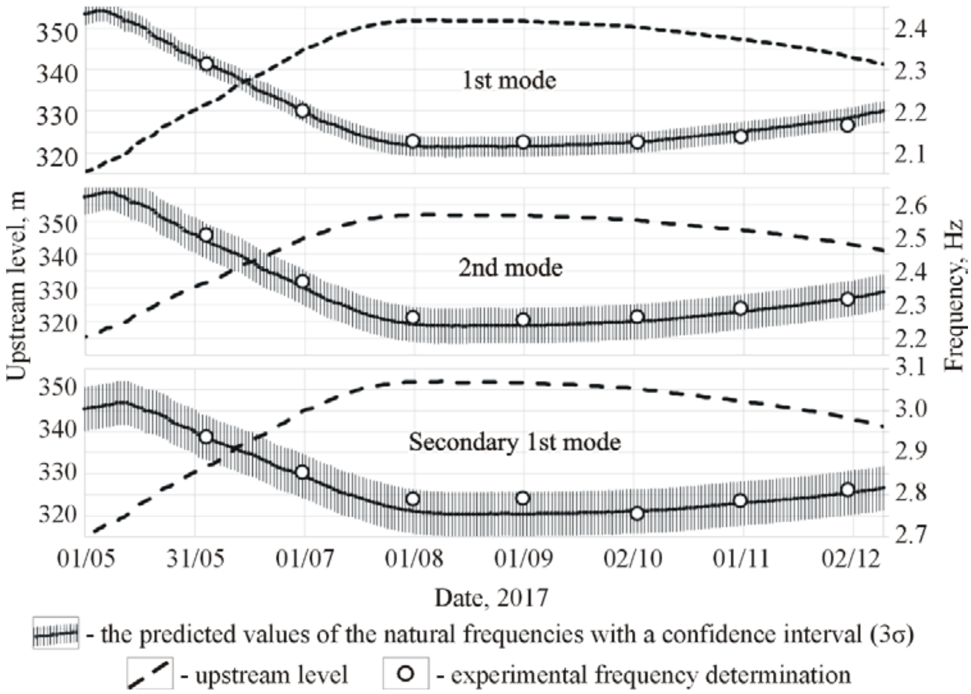

Figure 10. An example of the implementation of the method of monitoring the natural frequencies of the dam of the Chirkey hydroelectric power station.

4. Conclusions

1. Detailed studies of the Chirkey HPP dam were performed using the method of coherent restoration of standing wave fields at the maximum and minimum filling levels of the reservoir with the definition of natural frequencies and modes.

2. Our research has determined that the total field of standing waves changes when the upstream level changes, and two 1st, 2nd and 4th modes remain unchanged, the frequencies of which, in general, decrease with increasing reservoir level. These modes can be used for continuous monitoring of the structural health of the dam by periodically determine the frequency values from the records of seismic equipment. The points of the existing seismometric system are located near the 4-mode nodes, which do not allow to reliably determining the values of its frequencies.

3. It was determined that there are additional factors leading to the hysteresis effect in the dependence between the upstream level and natural frequencies, presumably related to relaxation processes in the dam body and / or in the dam-base system after changing the reservoir level. The time of such relaxation is from 5 to 11 days.

4. A method has been developed for monitoring the structural health of the dam, based on a comparison of the observed frequencies with the predicted ones. The latter are determined by linear dependencies on the upstream level taking into account the time shift associated with relaxation processes.

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