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RESEARCH ARTICLE

Monitoring of the hydraulic units operation of the Sayano-Shushenskaya hydroelectric power plant using remote seismic observations

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Abstract

After a major accident in August 2009 at the Sayano-Shushenskaya Hydroelectric Power Plant (SS HPP), all 10 hydroelectric units (HU) with a total capacity of 6400 MW failed. After investigating the causes of the accident and the reconstruction of the hydroelectric power plant, there was to develop a methodology for monitoring the operation of the newly commissioned HU. For inspection, a method was developed based on monitoring the natural frequencies of the dam structures and forced vibrations caused by the operation of the equipment. The article presents the main results of this study. Within the framework of the proposed approach, monitoring was carried out at various observation points of the dam structures and the turbine hall, as well as on a network of remote seismic stations. Based on the data recorded since 2009, an assessment of the parameters of dynamic impacts arising from the operation of hydraulic units of various types in different load modes on the elements of the HPP structure was carried out, and cause-and-effect relationships between changes in the operating modes of equipment and recorded vibrations in dam structures were investigated. An estimate of the general level of vibrations during the operation of various types of hydraulic units is given. As a result, the operating modes of hydraulic units are determined, in which there is a multiple increase in the amplitude of natural vibrations of the dam, an assessment of the operational characteristics of hydraulic units is given, taking into account the impact of seasonal conditions and changes in the water level in the reservoir.

KEYWORDS

dam, dynamic effects, hydraulic unit, natural vibrations, passive seismic monitoring

1 | INTRODUCTION

Hydraulic structures, like any large engineering structures, are objects of increased responsibility. They are subject to external impacts caused by changes in natural conditions, the impact of natural and man-made factors. Natural impacts include deformations of the soil foundation of the structure, movements of the earth's crust, lateral water pressure on the dam, changes in seasonal and climatic conditions, changes in the physicochemical state of the construction structure

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1. The possibility of evaluating the reaction of the structure design to dynamic effects resulting from the influence of various sources on them (operation of hydraulic units, vibration sources, etc.)
2. By analyzing monitoring data, it is possible to fix and localize the formation or development of structural defects caused by various natural (activation of faults, earthquakes, freezing, etc.) and technogenic factors, changes in frequencies, and decreases of attenuation of the structure's natural vibrations.
3. A set of natural vibration frequencies of a structure was determined by analyzing the seismic wave field recorded at various points in the turbine hall and the HPP dam.

FIGURE 1 Sayano-Shushenskaya hydroelectric power plant

and adjacent rocks, seismic effects, etc. Technogenic factors are a consequence of human activity: vibration created by the operation of massive systems of hydraulic units, spillways and machinery can also lead to the appearance of structural defects. In view of this, during the operation of hydraulic structures, it is necessary to monitor both the technical condition of the object and the dynamic impacts acting on it, which may be dangerous both for the structure as a whole and for its parts.

This paper presents an experiment in creating a system for monitoring the state of the Sayano-Shushenskaya hydroelectric power station (SS HPP), which we developed after August 17, 2009, the largest accident in the history of Russian hydropower at the SS HPP which caused the death of 75 people. SS HPP is an arch-gravity dam with a height of 242 m, located on the Yenisei River 100 km south of Abakan (Republic of Khakassia, Russia). The dam (Figure 1) is the highest in Russia and one of the highest in the world. As a result of the accident, all 10 hydroelectric units (HU) with a total capacity of 6400 MW failed. The Technical Investigation Commission found that the cause of the accident was the destruction of the pins for fastening the turbine cover of hydroelectric unit No. 2 caused by additional dynamic loads of a variable nature, which was preceded by the formation and development of fatigue damage to the fastening units, which led to the failure of the cover and flooding of the turbine hall of the station.[2] Subsequently, the old-style hydraulic units with 16 blades were gradually replaced by 10 new-type hydraulic units with 15 blades. Also in 2011, in order to prevent flooding of adjacent territories by flood waters, a spillway was put into operation, the capacity of which was 13090 m^3/s of water. The restoration of the station was generally completed on November 12, 2014 after the launch of the last hydroelectric unit of the new model.

Today, the management of large dams and their safety control are usually based on automatic monitoring, including the so-called static structural health monitoring (SSHM) systems using the latest technologies for automatic measurement, data collection, and transmission. It is known that the most common types of monitoring the stability of engineering structures can be divided into three types: static (the effect of wind, temperature, deformation, stress, etc.), dynamic (vibration of the structure from the operation of equipment, vibrators, seismic events, environment, etc.) and visual monitoring, examples of which are well demonstrated in refs.[3–7]

In the works of refs.[8–12] study of various dams using dynamic monitoring method is presented and various types of mathematical models and approaches are proposed to refine their frequencies and to determine existing defects. These studies[13–17] proposed options for monitoring engineering structures based on the accumulation and isolation of natural vibrations from the signal, as well as various approaches to interpretation and processing of the material. The paper[18] presents the study of using structural health monitoring (SHM) on the example of channel dams in Slovenia, describes a method for monitoring the dynamic response of dams and important structural elements using accelerometers and portable vibrometers. Qu et al.[19] present a comprehensive approach based on both of the above approaches for determining the frequencies and modes of the Baixu-Sabor dam. The papers[21–22] also present comprehensive methods for assessing the state of dams with automated modal analysis systems and assessing the impact of water levels in reservoirs. An approach to studying the dynamic properties of a concrete gravity dam based on monitoring its structural state using a laser Doppler vibrometer is presented in[23] for the Brežice dam installed on the cascade system of the Sava River in Slovenia. As a result of the survey, the reaction of the dam to the operation of turbines was determined, a numerical model of the structure was constructed, in which the aging process of concrete and its effect on natural frequencies is modeled by changing Young's modulus.

On the other hand, it is important to monitor and predict the vibration of hydraulic equipment, since vibration has a great impact on its performance and the vibration of the structure itself. The book[24] gives a detailed description of the structure of the hydraulic unit of hydroelectric power plants, presents new achievements and the latest developments in this area. A complete analysis of the existing and prediction of possible vibrations of the hydraulic unit is given, the impact of fluid pressure pulsations on them is calculated, and mathematical models are constructed. The existing systems for monitoring the vibrations of a hydraulic unit are shown, and approaches are proposed for predicting the vibration of hydraulic equipment. The review paper[25] comprehensively reviews studies on determining the stability of dams and power plants, the impact of equipment vibration and fluid pressure vibrations on them. The existing structure of various types of dams and their turbines, modeling methods and approaches to the analysis of vibrations registered in structures are described.

The study by Antonovskaya et al.,[26] which shows a similar, in some aspects, approach to the analysis of data obtained at the hydroelectric power station in Chirkey (Caucasus Mountains, Russia) can be considered the closest in terms of the topic of the study. The paper shows that according to the data of seismic stations installed in the dam, it is possible to quickly detect hydraulic disturbances in the turbine outlet pipe. The developed monitoring system can distinguish between earthquake events, turbulence triggers, and other movements.

This paper will assess the impact of reconstruction after the accident on the dynamic characteristics of the dam body and industrial machinery (hydraulic units). For this purpose, the method of non-destructive engineering-seismological examination of the physical condition of the object was used, and a system for timely recording changes in the dynamic characteristics of the structure was created, aimed at ensuring the safety and integrity of the structure. The initial data for the study were seismograms recorded in the dam structure and the turbine hall with portable equipment during the launch of newly commissioned hydraulic units. In addition, continuous seismograms of several seismological stations located in the vicinity of the hydroelectric power station (~4 km) were used for analysis.

2 | EXPERIMENTAL METHOD AND EQUIPMENT

For seismic data processing and qualitative analysis of recorded seismograms, the spectrogram construction technique was used via the "SpectrumSeism" software.[27] The principle of their construction is as follows: the amplitude spectra are calculated by seismic recording in a sliding time window. The set of such spectra forms a two-dimensional image, on one scale of which the current time is plotted, on the other, frequency. The amplitudes of the spectral components are displayed in color according to the selected color scale. The spectrogram shows how the amplitude-frequency composition of the record changes over time. Figure 2 shows an example of a seismic recording spectrogram from a sensor installed on the GA-6 unit block (new design) of the Sayano-Shushenskaya HPP. The figure shows that when load changes on the hydraulic unit, the amplitude-frequency composition of the record changes: in some modes low-frequency vibrations prevail, in other, high-frequency vibrations. Seismic diagnostics can be carried out by calibrating the spectrogram scale in such a way that, for example, the vibration amplitudes dangerous for a hydraulic unit or structure are indicated in red.

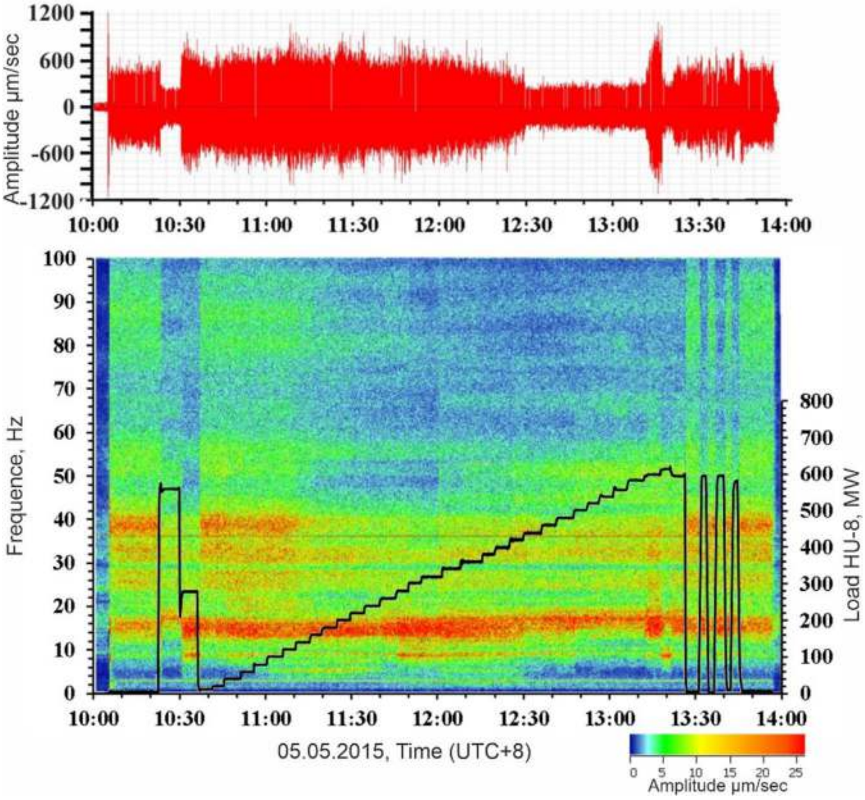

FIGURE 2 Seismic record obtained during trial test of the 2nd hydraulic unit of the new design of the Sayano-Shushenskaya HPP (05.05.2015), its spectrogram and the corresponding load on GA-2

The need to separate the seismogram into frequency components by the construction of spectrograms is due to the fact that, as a rule, the recorded signal contains the sum of vibrations from several different sources, and it is not always possible to isolate the source of interest from this entry because the amplitude of this "useful" signal may be lower than the amplitude of signals from other sources that create a noise background. A working hydraulic unit is a collection of different seismic sources, the peculiarity of which is that they operate at certain frequencies. Each source emits its own frequency plus multiple frequencies. If it is known to which source a certain frequency (or set of frequencies) corresponds, it is possible to control the operation of a given source by changes in the amplitude of the spectrum at that frequency(s). For example, if the operation of the hydraulic unit significantly increases vibrations at its rotational frequency, it is due to the fact that the unbalance of the turbine has changed, which means that this mode can lead to a malfunction of the bearings. If some modes have significantly increased the amplitude of vibration at their natural frequencies of the structure, then under such a mode there is a harmful effect on the structure.

Spectrograms show more qualitative picture of change of amplitude-frequency composition of recording over time. For more clarity, an approach to construct graphs of changes of vibration amplitudes at fixed frequencies was proposed. The principle of construction of graphs is as follows: by seismic recording in a sliding time window, the amplitude of the harmonic signal of a given frequency is calculated according to the following equation[28]:

$$A_f(t) = \frac{2}{T}\left|\int_{t-T/2}^{t+T/2} F(\tau)\, e^{-i2\pi f\tau} d\tau\right| \tag{1}$$

where $F(\tau)$ is the recorded seismic signal (in units of measured amplitude), f is the frequency for which the graph is plotted (Hz), t is time, T is the interval of time (window) in which the amplitude $A_f(t)$ is determined, $|\ldots|$ – denotes the module of complex number. In this equation, an important parameter is the length of the window (T) – on it directly depends on the resolution of the graph by time.

But it is impossible to significantly reduce the length of the window, as it reduces the permissibility of the construction by frequency. For example, we usually use a window length of 10 s. This means that we cannot study signals with a duration of less than 10 s. However, the frequency resolution of 0.1 Hz means that any signals on a seismogram with frequencies more than 0.1 Hz apart from the frequency of the studied signal will not affect the result of the amplitude determination according to Equation (1).

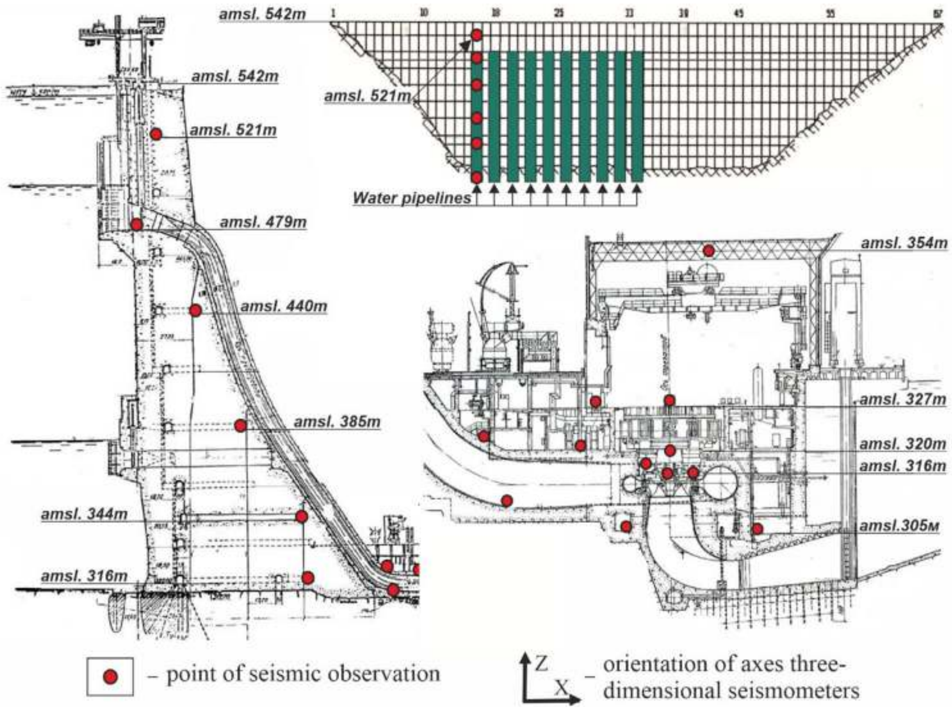

FIGURE 3 Schema of seismic observations in the dam and in the power plant building during commissioning of the hydraulic unit 1

It should be noted that the value of the time interval T is set on the basis of the quality of the recorded data: first, the larger the interval, the more accurate the value of the amplitude is calculated but the resolution of the result is reduced in time; Second, the higher the useful signal amplitude compared to the noise, the smaller the interval can be set for a satisfactory amplitude assessment. It has been experimentally established that the optimal interval T for the experiment is about 10 s.

The results of seismic observations at various points of the dam and in the building of the turbine hall were used for analysis. Figure 3 shows an example of an installed monitoring network for the newly commissioned hydraulic unit 1.

The recording of seismic vibrations in the hydroelectric dam and the structure of the hydroelectric power plant was carried out continuously and included the recording of vibrations alternately for each of the hydraulic units being put into operation at different modes, both during operation and during shutdown. Each observation point in the dam and the turbine hall of the HPP consisted of autonomous seismic recorders "Baikal-ASN" and three-component seismic receivers of various types: A1738 (acceleration sensor), GS-20DX (velocity sensor), GS-ONE (velocity sensor) or CMG-5T (acceleration sensor). The directions of the axes of the three-component seismic receivers are as follows: X or N – directed through the river, Y or E – across the river, and Z – vertically. To equalize the amplitude-frequency characteristic, an identity test was conducted and a deconvolution function was applied.[30,31] The sampling rate was chosen to be 500 Hz since the natural frequencies of the structure were studied, which were usually quite low.

3 | MONITORING OF NATURAL FREQUENCIES IN SAYANO-SHUSHENSKAYA HYDROELECTRIC DAM

According to the work of refs.,[29,32,33] a set of natural frequencies of the dam were isolated during dynamic vibration testing and standing wave testing, respectively. The method of standing waves is a passive method, without the use of vibration sources,[32,34–36] which makes it possible to isolate the standing waves field from the data of the microseismic vibrations field recorded in an engineering structure. It is based on the coherence property in the time vibrations of standing waves and converts recorded signals of the observation network consisting of a reference point and points changing its position into «one-time» records of standing waves. Figure 4 presents a scheme of observations and the result of data analysis using the method of standing waves. The natural frequencies obtained by the two methods are shown in Table 1. It can be emphasized that both methods showed similar results.

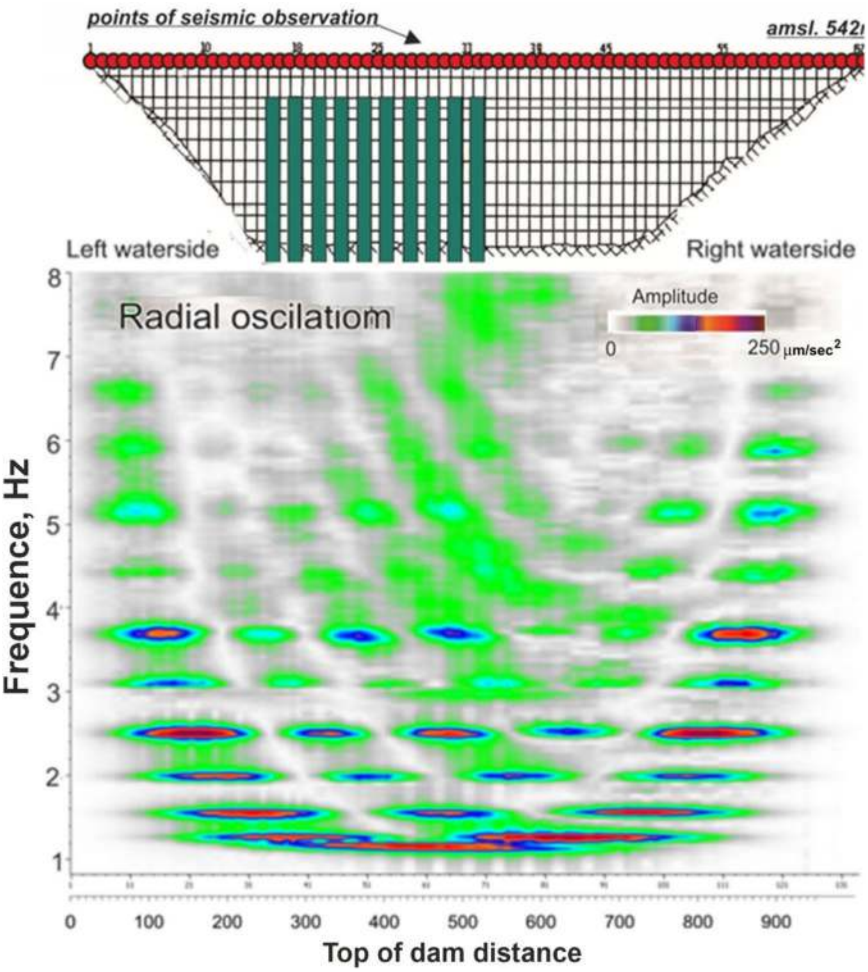

FIGURE 4 Schema of observation (at the top) and spectra of natural vibrations of the dam (at the bottom[29])

TABLE 1 Natural frequencies of the dam obtained by dynamic experiment and standing wave method

Modes number	1	2	3	4	5	6	7
Natural frequencies obtained in dynamic experiment, Hz	1.25	1.33	1.65	2.0	2.5	3.1	3.7
Natural frequencies obtained in the experiment by the method of standing waves, Hz	1.12	1.27	1.56	2.0	2.48	3.07	3.71

It should be noted that the amplitude of the natural vibrations of the structure, determined by the spectra of seismic records, will always depend on the location of the seismic sensors. Let us explain this in the following example. One of the tasks of the present research was to determine the parameters of natural vibrations of the Sayan-Shushenskaya hydroelectric dam (primarily, frequencies and amplitudes) and to establish the relationships between their changes and changes in the operation of the hydroelectric power plant. On any object in the field of standing waves, there are nodal points in which the amplitude of vibrations of a certain form of standing waves is zero, so they cannot be recorded by seismic sensors. In the presence of a background noise, these nodes become areas in which the amplitude of vibrations is small compared to the interference and also cannot be recorded.

Thus, from a methodological point of view, in order to determine the parameters of the natural vibrations of a structure, seismic sensors should be installed not arbitrarily, but in places where the amplitudes of its natural vibrations are maximal, that is, in the places of antinodes. Using the results of the study of the method of standing waves (Figure 4), a monitoring system was installed according to Figure 3.

It is worth mentioning that the studies were carried out for hydraulic units of different samples, and the analysis of the data showed that the operation of hydraulic units with 15 blades (new) in certain modes leads to multiple (10–20 times) values of natural vibrations of the dam, which was not observed in the operation of hydraulic units of the old model.

As noted above, a set of natural frequencies is distinguished in the low-frequency part of the vibration spectra of the dam. During the analysis, changes in the amplitude of the natural frequencies of the Sayano-Shushenskaya hydroelectric

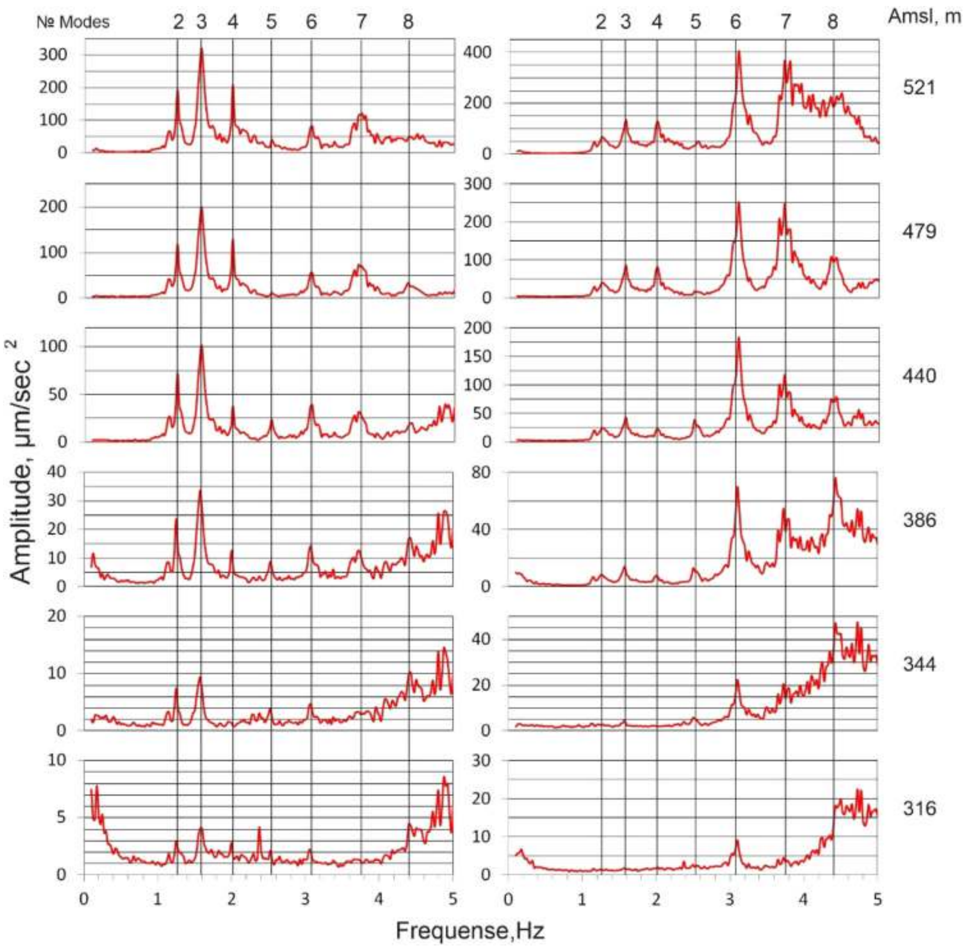

FIGURE 5 Amplitude spectra (low-frequency part) of the radial vibrations of the dam at different levels along the hydraulic unit axis 2. The load is 480 MW (left) and 200 MW (right)

dam along the axis of each of the hydraulic units under study were considered during their trial test at different altitudes levels. For example, Figure 5 shows the data along the section of the dam 18 corresponding to the axis of the hydraulic unit 2 (new sample). The figure shows that different natural frequencies of the dam are excited at different loads on the hydraulic unit.

Let's consider in more detail the influence of changes in operating modes of hydraulic unit on natural vibrations of dam Sayano-Shushenskaya HPP using the example of studies conducted during trial test period of hydraulic unit No. 8 (new sample) in 2015.

Figure 6 considers the readings of one of the sensors of the vibration monitoring system, installed on the support of the pod (vertical component) and the readings of seismic equipment, installed in the upper part of the dam Sayano-Shushenskaya HPP (radial component). During the test period of the hydraulic unit 8, the load was gradually increased, while at the same time the load modes of adjacent hydraulic units were changed No. 2, No. 1, No. 4, No. 6, No.10, in different ranges from 20 to 630 MW. An increase in the amplitudes of natural vibrations of the dam for frequencies ranging from 1 to 3 Hz (1–5 modes) was observed for eight hydraulic units loads within 300–480 MW (maximum for 1 mode at 380 MW reaches 720 μm/s^2) and for 3–5 Hz (6.7 modes) – 80–260 MW (maximum value for 6th mode at 200 MW reaches 520 μm/s^2). In these ranges, the influence of third-party hydraulic units can be neglected, since the load on them was 480–570 MW, and at such loads the amplitude of their natural vibrations in the frequency range of 3–5 Hz was not observed. At the same time, it should be noted that, in the above-mentioned ranges, the reading of one of the sensors of the vibration monitoring system installed on the support of the pod also increases to 150 μm. It should be noted that the maximum vibration level is approximately 10 times higher than that for which the hydraulic unit was shut down.

Unfortunately, there are no standards for vibration of hydraulic structures in Russia, as well as requirements for dynamic calculations of dam vibrations and their elements arising from the pulsation of the flow of idle discharges and the

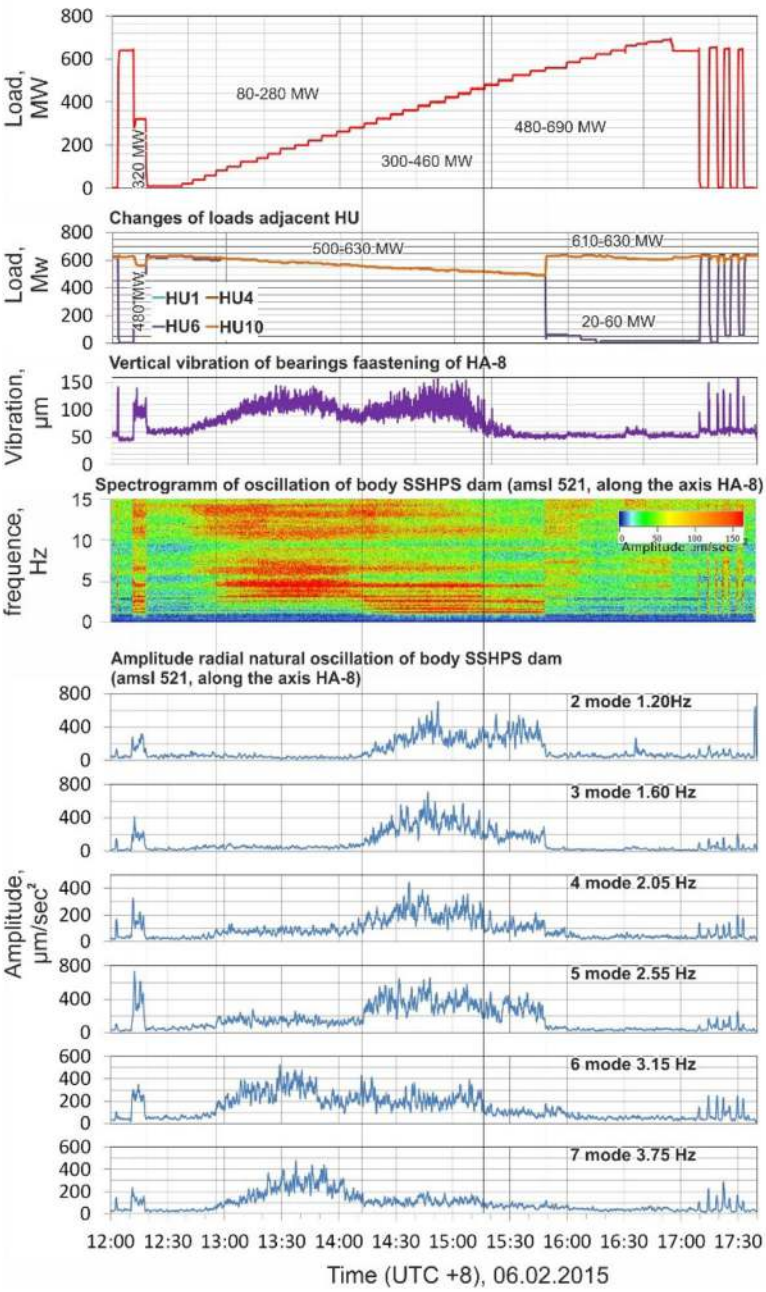

FIGURE 6 Relationship between changes in the operating modes of GA-8, readings of one of the sensors of the vibration monitoring system and seismic equipment installed in the upper part of the Sayano-Shushenskaya dam

operation of hydraulic units. However, the magnitude of the vibration of individual elements of the hydraulic structures of the Sayano-Shushenskaya HPP is comparable to the normalized limit values of vibrations corresponding to the maximum permissible dynamic deflection of some building structures.[1,33] Therefore, changes in vibration parameters and operating modes of hydraulic units recorded during monitoring, leading to resonance in various elements of the HPP structure (even at unknown permissible threshold values) may indicate a potential threat to the normal operation of the plant.

Figure 7 shows the diagram of the temporary operating characteristic of GA-1 (old type 16 blades), on which the intervals of loads are applied, at which the increased amplitudes of the natural vibrations of the dam SS HPP appear or are absent. These intervals depend on the water pressure, the difference between the elevations of the upstream and downstream, where the upstream and downstream are sections of the river above the hydroelectric power plant and below the hydroelectric power plant, respectively. According to this operational characteristic, at a pressure level of 175 m, the load ranges at which increased vibrations are absent in the ranges of 0–180 MW and 430–700 MW, and occur at 180–440 MW. When the water level rises in the reservoir, these ranges shift to higher values,

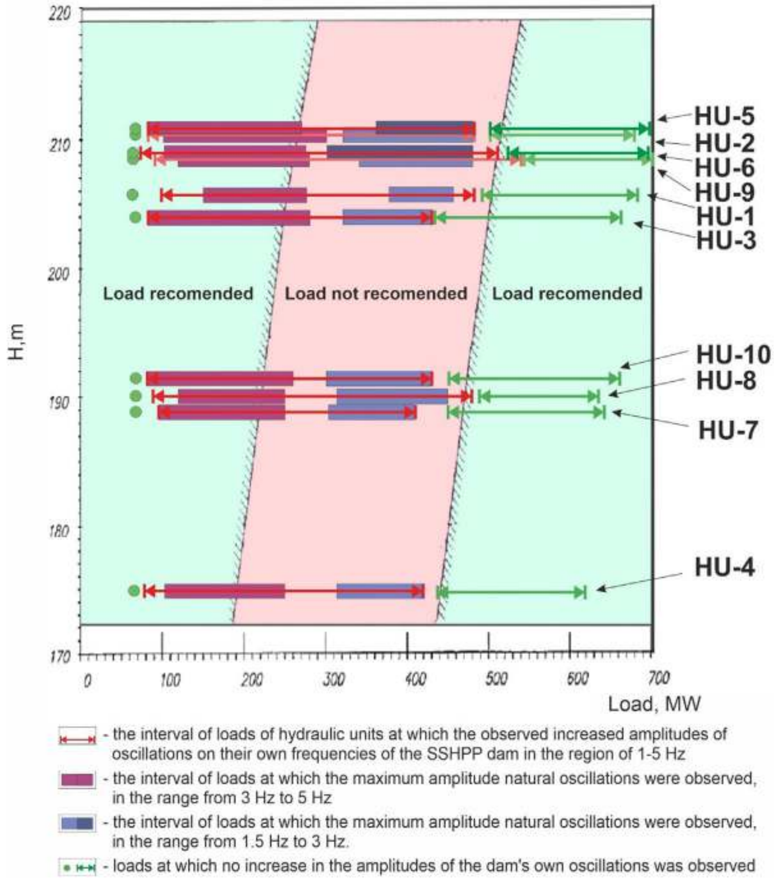

FIGURE 7 Time performance characteristic of GA-1 (old type) with applied intervals of loads (at which there is or is no increase in the amplitude of its natural vibrations) 15 blades from different seasonal water pressure

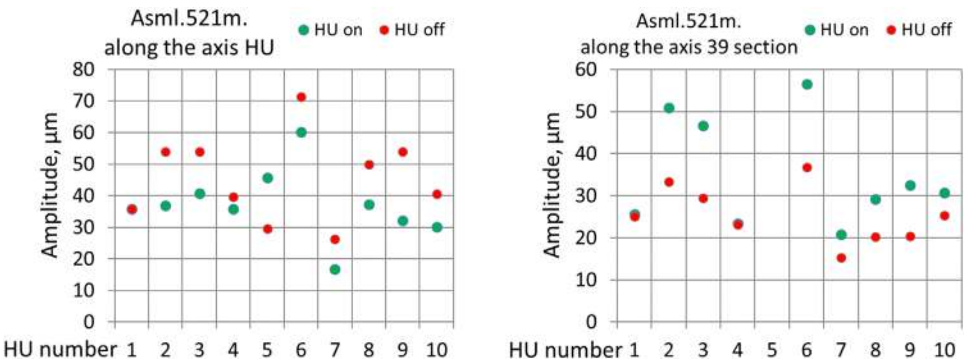

FIGURE 8 Maximum amplitude of vibrations at the start-up and shutdown of the Sayano-Shushenskaya hydroelectric power plant recorded in the upper part of the dam

to values at a pressure of 220 m – 0–270 MW and 540–700 MW (no increased vibrations), 280–530 MW (increased vibration).

On top of this operational characteristic are applied intervals of loads, at which there is or is no increase in the amplitude of natural vibrations of the dam, obtained when examining each of hydraulic units with 15 blades from different seasonal pressure of water. It can be seen that in the area of 0–250 MW, which is recommended for operation of the old type of hydraulic unit, the hydraulic units of the new type do not increase the amplitude of their natural vibrations of the dam. The area in which exploitation is not recommended is characterized by the fact that it contains increased amplitudes of its natural vibrations, mainly in the frequency range from 1 to 3 Hz (1–5 shape). The low load zone, located to the left of the area not recommended for operation, is characterized by the fact that it observes increased amplitudes of its natural vibrations in the frequency range from 3 to 5 Hz (6–8 modes).

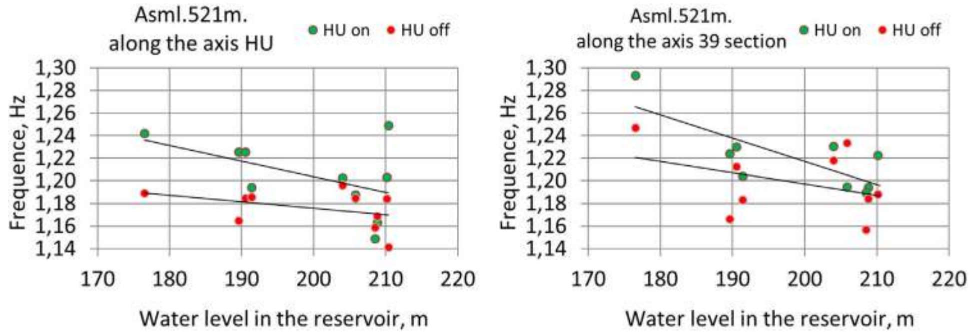

FIGURE 9 The value of the apparent frequency of oscillations of the SS HPP dam caused by the processes of starting/stopping hydraulic units, depending on the water pressure

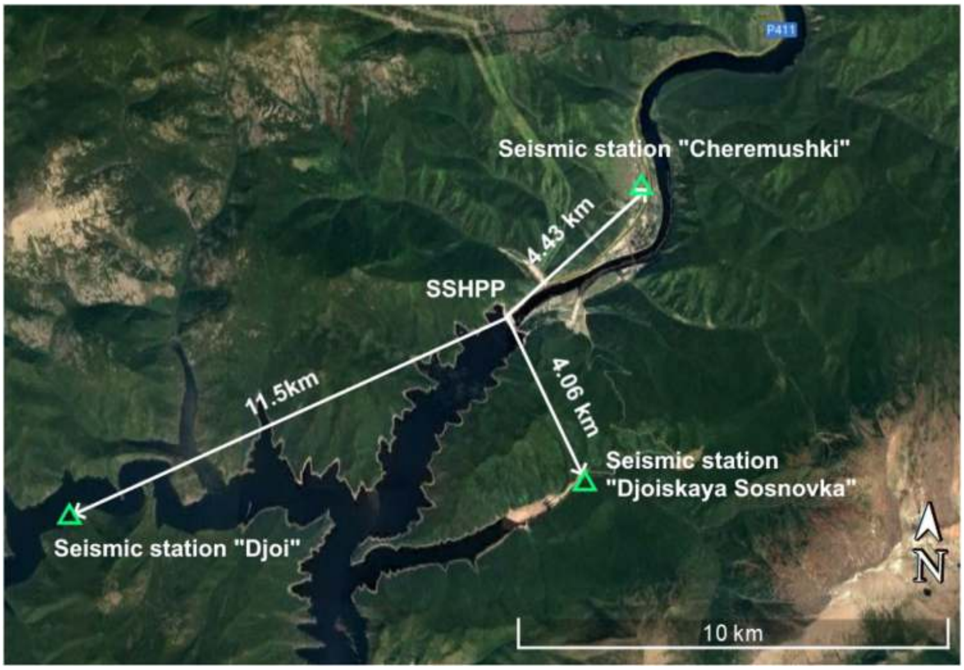

FIGURE 10 Seismological network stations of Sayano-Shushenskaya HES

An assessment of seismic impacts caused by the start-stop processes of hydraulic units at the upper levels of the dam SS HPP was also performed. In Figure 8, the values of the maximum amplitude of vibrations recorded when switching on/off of each of the hydraulic units are given. The largest amplitude of vibrations was observed in a study conducted on a hydraulic unit No. 6 (new type) and reached 60–70 μm.

Based on the results presented above, an empirical relationship was established between the influence of the water pressure on the maximum amplitude of vibrations of the dam caused by the start-up/shutdown of ten hydraulic units at different levels of the reservoir. At the moment of activation and unloading of hydraulic units, increased water pressure is found to increase the exposure. And if you turn off the GA the increase is higher. From seismograms recorded during the switching on and off of the hydraulic units at various observation points at the upper levels of the dam, the visible frequency of vibration of the dam was determined. Comparing this frequency with the water level at the time of the study of a hydraulic unit, the following pattern was obtained (Figure 9). The graph shows that, depending on the increase in pressure, the apparent vibration frequency decreases. The decrease in the visible frequency is caused by the effect of decreasing the natural frequencies of the Sayano-Shushenskaya hydroelectric dam with an increase in the reservoir level.

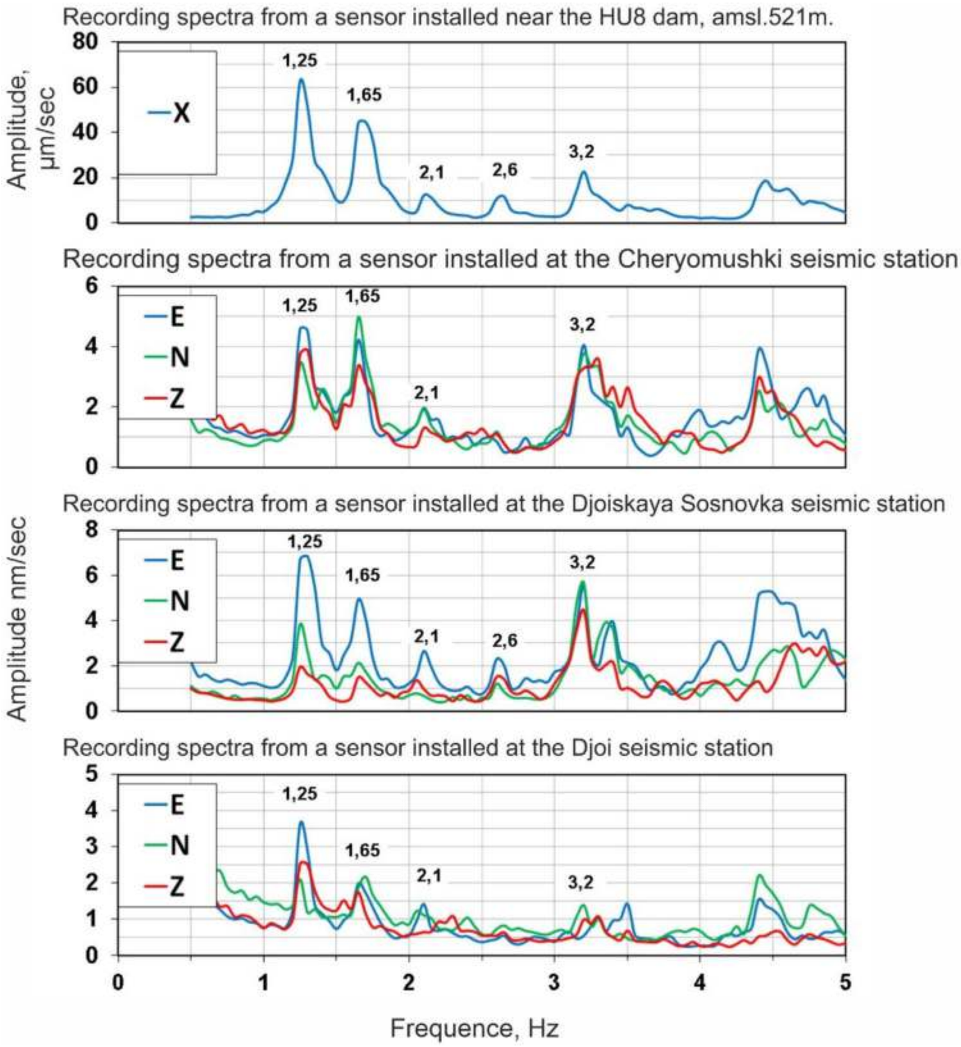

FIGURE 11 Amplitude spectra (low-frequency part) of seismic records recorded in the upper part of the dam (SS HPP) and at the station «Cheremushka». The operation of the hydraulic unit of HPP No. 8 with a load of 360 MW

4 | REMOTE MONITORING OF THE NATURAL FREQUENCIES OF THE SAYANO-SHUSHENSKAYA HYDROELECTRIC DAM

It should be noted that the above results can be obtained not only from the direct analysis of the data recorded in the dam body, but also through the analysis of data at remote seismic stations.[29,37–40] In our case, these are seismic stations located approximately 4 and 11 km from the dam (Figure 10).

In Figures 11–12 presents the result of comparison of readings of seismic stationary stations Cheremushka, Djoi, Jojskaya Sosnovka (spectra and spectrograms of recording E-W-component) and observation point in the upper part of the dam (X-component) with changes of loads on hydraulic unit No. 8. It can be seen that at certain loads on hydraulic units in the wave field, high amplitude vibrations are emitted in the frequency range from 1 to 5 Hz. The source of these vibrations is the natural vibrations of the Sayano-Shushenskaya hydroelectric dam, which increase under certain loads on hydraulic units. It can be seen that the low-frequency vibrations associated with the natural vibrations of the dam increase in amplitude approximately within the same range as in the example discussed earlier (see Figure 6). Thus, vibrations from 3 to 5 Hz are the highest in 80–260 MW hydraulic units and from 1 to 3 Hz in 300–480 MW hydraulic units. The signal/noise readings at the Djoi station[28] are much lower, unlike other stationary stations, due to its remoteness.

These signals are very weak (a few orders of magnitude lower) compared to the micro seismic background (Figure 12). And it is not always possible to isolate one's natural vibrations outside the operating modes when they come into resonance. The following procedure was therefore applied to isolate these signals. The seismic record, lasting up to 5 days, was

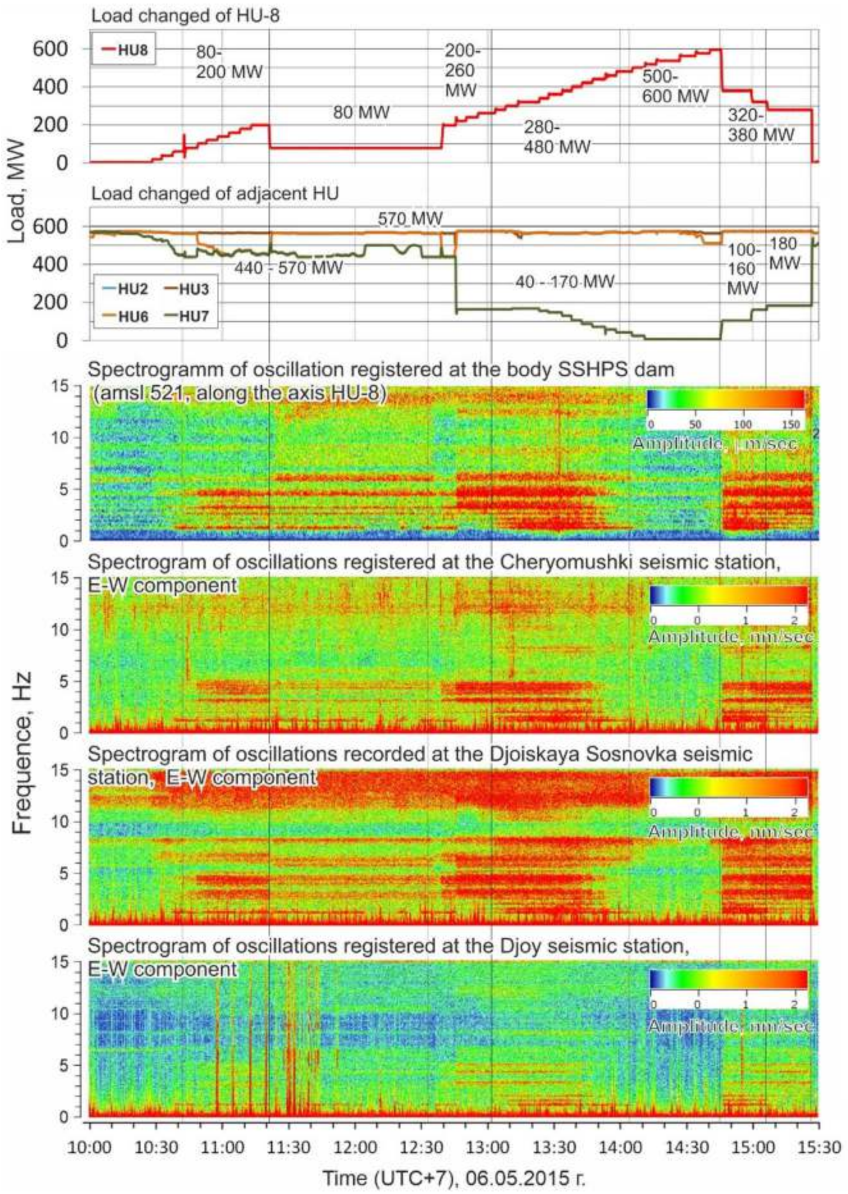

FIGURE 12 Relationship between changes in the modes of operation of hydraulic units and seismic equipment installed at stationary stations on 06.05.2015

divided into 300 s fragments, for each of them the amplitude spectrum was calculated, then the obtained spectra were averaged. From additional digital processing procedures, the zero-off of high-amplitude short-term disturbances caused, for example, by near earthquakes (area with increased seismic activity), or technogenic sources, which significantly distort the results of the calculation of spectra. In the final stage, according to the obtained spectra, the frequencies of the dam's natural vibrations were distinguished. Figure 13 shows the result of determining the values of the first seven natural frequencies of Sayano-Shushenskaya dam for the 15-day period from 2001 to 2015. It can be seen that during each year the fluctuating frequencies of the SS HPP dam change and these changes are correlated with changes in the level of the reservoir: with an increase in the upper reservoir level, the frequencies decrease and vice versa. In general, the results of the studies showed that during the 15-year period the frequency dependence on changes in the upper reservoir level did not change, which indicates that there was no irreversible change in the technical condition of the dam during this period. The most detailed information about this approach is given in the work.[29]

5 | DYNAMIC MONITORING OF SAYANO-SHUSHENSKAYA HPP EQUIPMENT

The study made a comparative assessment of the vibration state of hydraulic units of old and new design. Figure 14 shows examples of amplitude spectra constructed from records of seismic vibrations in the turbine hall near various types of

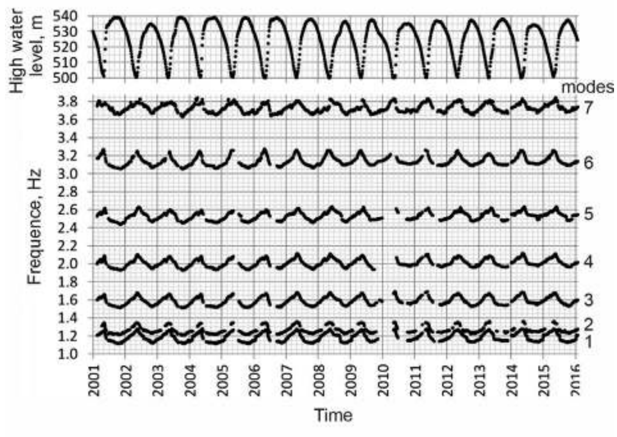

FIGURE 13 Changes in the values of the reservoir level and the proper frequencies of the Sayano-Shushenskaya hydroelectric dam[39]

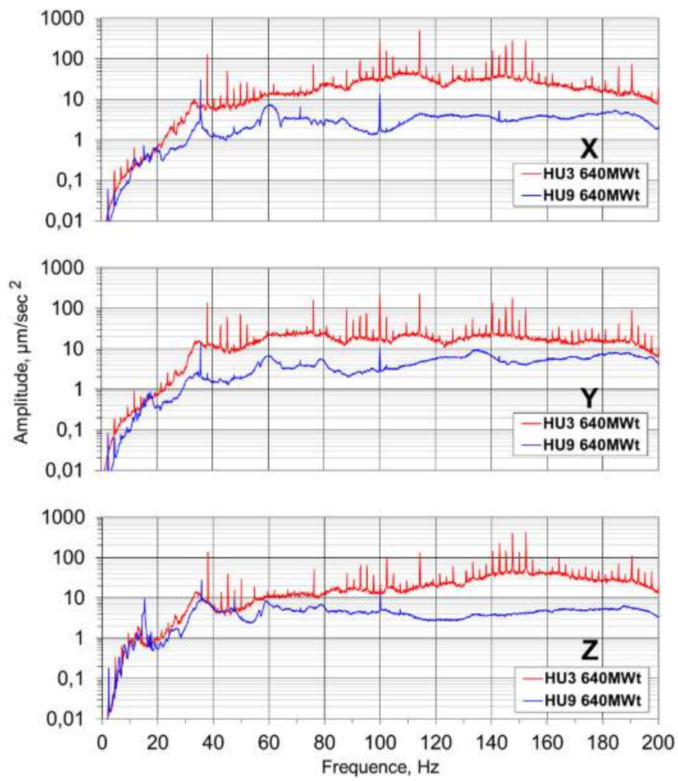

FIGURE 14 Amplitude spectra of seismic oscillations recorded on the turbine cover GA-9 (new design) and GA-3 (old design)

hydraulic units (the position of the observation point relative to each of the hydraulic units is the same – 327 m) at similar load modes. It can be seen that the vibration amplitude recorded near hydraulic units of new constructions (15 blades) at 480 MW and 640 MW is several times lower than the vibration amplitude measured near old constructions (16 blades). This may indicate that the vibrational state of the new hydraulic units has improved due to modernization.

At the same time, it should be noted that vibrations with a frequency of 100 Hz are distinguished in the vibration spectra from the new hydraulic units (possibly associated with generator vibrations), which was much weaker in the vibrations of the "old" design hydraulic units.

6 | CONCLUSION

The article shows the possibility of creating a technology for timely recording changes of dynamic characteristics of constructions by means of non-destructive engineering-seismological monitoring of the structure both directly inside the structure and remotely. The possibility of evaluating the reaction of the structure design to dynamic effects resulting from the influence of various sources on them (operation of hydraulic units, machines, vibration sources, etc.) was demonstrated.

By analyzing monitoring data using mathematical algorithms, it is possible to fix and localize the formation or development of structural defects caused by various natural (activation of faults, earthquakes, blurring, freezing, etc.) and technogenic factors, changes in frequencies and decreases of attenuation of the structure's natural vibrations.

In general, a set of natural vibration frequencies of the SSH HPP dam was determined by analyzing of the seismic wavefield recorded at various points in the turbine hall and the HPP dam. It has been found that for all reconstructed hydraulic units under load, on average, from 100 MW to 480 MW, there is a significant (10–20 times) increase in the amplitude of the dam's natural vibration (mainly at low frequencies, between 1 and 5 Hz) relative to background values.

The maximum values of the vibration amplitudes (seismic impacts) caused by each of the hydraulic units were determined for all the registration points in the turbine hall and the hydraulic dam, and a comparative analysis of the dynamic impacts recorded during the study of hydraulic units of old and modern designs was carried out. The analysis showed that the vibration amplitudes measured in the immediate vicinity of each of the reconstructed hydraulic units were generally 2–3 times lower than the vibrations recorded earlier in the operation of hydraulic units of the old design.

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CONFLICT OF INTEREST

No potential conflict of interest was reported by the authors.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study is not available in any public domains. However, the obtained experimental data can be made available to reviewers from the corresponding author upon reasonable request.

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