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The calculation of the dynamic characteristics of the spillway of the dam

G.L. Kozinetc* ✉, *P.V. Kozinetc

Peter the Great St. Petersburg Polytechnic University, St. Petersburg, Russia

✉ *kozinets_gl@spbstu.ru*

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Abstract. The object of the presented studies is a concrete spillway dam of a run-of-river hydroelectric power station. The modes of vibrations are determined on the basis of a solid model, which is necessary to take into account possible resonant phenomena in the structure. A review of publications on the method of calculating the dynamic responses of structures is made. Computational studies were carried out by the finite element method based on the calculated three-component accelerogram. When processing the results, the possibilities of modal temporal calculation were used. The response of structures excited by forces, time-varying or earthquake is calculated. Based on the calculation results, the natural frequencies and vibration modes of the concrete spillway dam were determined. The description of the oscillations of the dam is made. According to the obtained response spectrum, the maximum horizontal accelerations were achieved. Based on the response spectra, a calculated three-component accelerogram was synthesized at the equipment installation marks.

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1. Introduction

When designing hydroelectric power plants in zones of seismic activity, an indispensable condition is the analysis of natural frequencies and forms of vibrations of structures. A feature of the seismic design of HPPs is the consideration of two levels of seismic impact, referred to in Russia as a design earthquake (DE) and a maximum design earthquake (MPE).

The first of them is the strongest earthquake that can actually occur during the estimated period of operation of the HPP, equal to 100 years; the second is the strongest earthquake, generally potentially possible at this site.

In the recommendations of the IAEA, the design basis earthquake is designated as SLI, and MSE as SL2.

American designations are widely used in the world: for OBE - OBE (Operating Basis Earthquake - safe stop earthquake).

The intensities of PZ and MSE are established on the basis of historical information about past earthquakes, as well as (primarily MSE) with the help of geophysical surveys. There are two main approaches to determining these intensities. (The first used in Russia and a number of other countries) -

probabilistic: an earthquake with a recurrence interval of 1 time in 100 years is taken as a PZ, and 1 time in 10,000 years as an MPS.

Under seismic action, the structure begins to oscillate. For the analysis of vibration modes and resonance phenomena, a prerequisite is the determination of natural frequencies and vibration modes or the dynamic characteristics of the structure.

The task of the research was to determine the natural frequencies and analyze the vibration modes of the spillway dam of the run-of-river hydroelectric power station, Fig. 1.

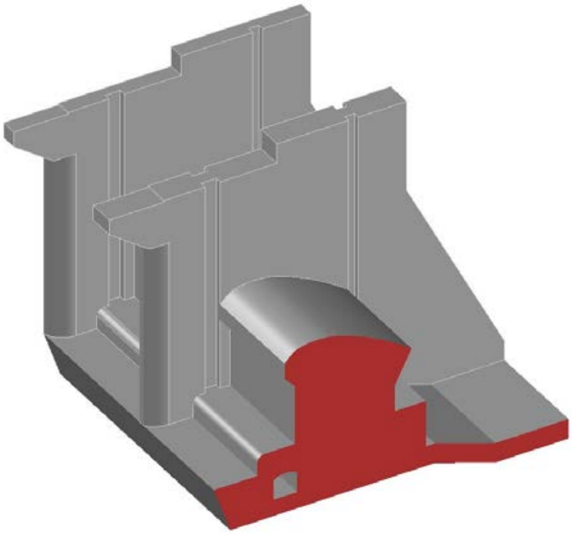

Figure 1. Volumetric geometric model of the spillway dam of a run-of-river HPP with a section along the spillway.

The initial data for the calculation are the geometric parameters of the spillway dam of the Nizhne-Bureya HPP on the Bureya River, the physical characteristics of the concrete material and the base soil, as well as the accelerogram of the dynamic seismic impact.

The spillway structure is designed to release water in case of overflow of the reservoir in front of the dam. The spillway structure consists of a dam divided across by concrete abutments (steers), which can serve as bridge supports for medium-pressure run-of-river hydroelectric power plants. Lifting mechanisms are mounted on the bulls, designed to maneuver the hydraulic gates that block the spillways.

Since there is equipment on the spillways, it is necessary to calculate the load on it during an earthquake. The elevation of the equipment supports is higher than the base surface, so the seismic load at the elevation of the supports is always greater than at the elevation of the spillway base.

Determining the seismic response or response spectrum at the equipment installation level is an actual dynamic problem.

The spillway dam of the run-of-river hydroelectric power station is a five-span concrete structure. Each spillway is limited by bulls, one of which is monolithic, and the other has an expansion joint in the middle of the bull. The spillway operation is provided by segment gates with smooth flow control.

The physical characteristics of B20 class concrete of the spillway dam are as follows: concrete density p_b = 2.36 t/m^3. Design resistance of concrete in compression R_b and tension R_{bt} for the limit states of the first group: R_b = 11700 kPa; R_{bt} = 900 kPa. The initial modulus of elasticity of concrete in compression and tension E_b = 3.0×10^7 kPa. The coefficient of transverse deformation of concrete (Poisson's ratio) for massive structures ν = 0.15.

The rocky base is composed of granites. Physical and mechanical properties and thermophysical characteristics of a rocky base made of granite:

Density p_{gr} = 2.65 t/m^3.

Modulus of elasticity E = 1.30×10^7 kPa.

Poisson's ratio ν = 0.35.

Adhesion c = 400 kPa. Angle of internal friction φ = 39°.

Thermal expansion coefficient α_{gr} = 1.4×10^{-5}°C^{-1}.

Thermal conductivity coefficient K_{gr} = 1.81 W / (m * K).

Studies of the dynamic characteristics of concrete structures is the first stage in the calculation of structures for seismic resistance.

Among scientists [1–24], who study seismic resistance and dynamic characteristics of structures, it is necessary to note the works of Ya.N. Aizenberg, A.N. Birbraer, S.P. Timoshenko, V.V. Lalin and others [1, 2, 10, 15, 20].

Many articles and books [8–14], [17–24] are devoted to methods for numerically solving problems of structure dynamics.

The theory of the finite element method is covered in the works of O Zenkevich, K. Morgan, G. Strang [4–6], and many other authors.

In studies [18], an analysis was made of comparing the dynamic parameters calculated from the processed experimental data with the parameters obtained from seismic data, and close values were obtained. A numerical modal analysis of the rockfill dam has been carried out, and the correspondence of the vibration parameter with the experimental data has been obtained.

The article [19] analyzes the modal and harmonic characteristics for the design of the power plant at the Kenir Dam in Terengganu, Malaysia. Modal analysis was carried out to obtain the dynamic characteristics of the power plant, which include natural frequencies and mode shapes. A real-scale three-dimensional (3D) model of the Kenyir Dam power plant was built using SolidWorks software and imported into ANSYS software for finite element analysis (FE). According to the results, the six most significant natural frequencies and modes of oscillation are selected, the phenomenon of resonance from external disturbing forces is checked.

Article [20] is devoted to substantiating the magnitude of the calculated dynamic loads on the process equipment of nuclear power plants in the event of an aircraft impact. A technique for calculating PS with the required probability is given. The place and angle of impact, the distance from it to the equipment are taken into account. A technique for probabilistic substantiation of calculated dynamic loads on equipment in the event of an intentional aircraft crash at a nuclear power plant (terrorist act) is proposed.

Paper [21] presents the results obtained during the first six months of operation of the dynamic monitoring system, which include the characterization of acceleration levels for opening weirs after heavy rain, and the change in the modal properties of the Baixo Sabor arch dam in northeastern Portugal. At the end of the article, a comparison of the results of natural frequencies obtained with external excitation and the results obtained in a forced vibration test, as well as predicted using a numerical model, is presented.

In the study [22], the control of damage and the behavior of the structure of an earthen dam during an earthquake was performed. Important factors such as plane stress, plane strain, data monitoring, application of the finite element method, analysis of free vibrations, seismic cracks are identified. It is noted that earth dam structures have an integrated response to an increase in acceleration or displacement on the crest.

In [23], a method is proposed for analyzing the time-varying dynamic reliability for a concrete gravity dam under seismic action, based on the generalized probability density evolution method (GPDEM). The method can be used to predict the time-varying seismic performance of concrete dams in terms of probability. The effectiveness of the proposed method and its suitability for complex non-linear structures subjected to seismic loads have been confirmed.

In [24], a 2D non-linear dynamic analysis (NDA) was performed for an Austrian dam during the 1989 Loma Prieta earthquake. up to 859 mm. The engineering properties of compacted fill materials are evaluated based on available test data for isotropically compacted undrained triaxial compressions and resonant columns.

The validity of the research is due to the fact that in order to calculate the seismic resistance of equipment, it is necessary to calculate the response spectrum at the dam elevations.

The purpose of the study is to calculate the seismic load for equipment standing on the elevations of the structure.

The strength and stability of the concrete dam was not included in this study, but was carried out when determining the geometric dimensions of the structure.

Research objectives:

1. Construction of a mathematical dynamic model "dam-foundation" of a spillway dam, including partitioning into finite elements, setting material properties, setting boundary conditions;

2. Calculation of natural frequencies and vibration modes of the spillway dam;
3. Dynamic calculation of the structure for the calculated accelelogram;
4. Generation of response spectra at given nodes at the elevations of the spillway dam;
5. At the 5th stage, graphs of the response spectra at given nodes and tables of digitization of spectral curves are constructed.

2. Methods

Computational studies were carried out within the framework of the spatial formulation of the problem by the Finite Element Method (FEM) using the SolidWorks program. The method and its application in structural calculations are presented in [17-24]. The construction of the calculation model was carried out on the basis of the geometric parameters of the spillway dam. The design model of the dam with symmetry conditions for a continuous bull is shown in Figure 2.

The “structure-base” model was divided into three-dimensional 4-node elements of the tetrahedron -TETRA, interconnected at the nodes. Coordinate system: OX axis - along the flow, OY axis - across the flow, OZ axis - vertically upwards.

The opposite bull has free movement within the expansion joint. The results of the calculation are presented in the form of a table of natural frequencies and fields of relative deformations (modes of oscillation) of the structure.

When processing the results, the possibilities of modal time calculation (Modal Time History Analysis) were used. The response of structures excited by forces, time varying or earthquake is calculated. Independent (uncoupled) modal equations of motion are solved using Newmark's step-by-step integration method. Response Spectra Generation. The response spectrum curves at the specified node are calculated using the previously obtained modal time responses of the structure for that node. This variant of dynamic calculation allows generating curves of the response spectrum in any node of the structure for any degree of freedom of movement. A curve is generated and represents the maximum response amplitudes as a function of frequency for a given damping factor. The initial excitation for this version of the calculation is the accelerogram, which specifies the acceleration relative to time at the specified point of the structure. To generate the curve of the response spectrum, the results obtained from the modal calculation of the temporal characteristics were used. Thus, the response spectrum is generated after modal timing is performed.

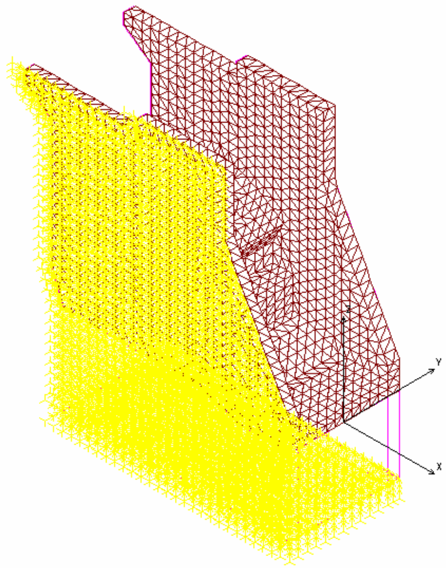

Figure 2. Calculation model of a spillway dam with boundary conditions.

3. Results and Discussion

In the work of A.I. Savich [25] carried out similar studies of the Sayano-Shushenskaya dam, including the behavior of the dam under static loads and seismic impacts. At the same time, the authors did not determine the response spectra on equipment marks.

As a result of solving problems 1 and 2 of our research, 15 first natural frequencies of the dam-foundation were obtained, ranging from 4.11 to 29.7 Hz (from 25.82 to 186.8 rad/sec), Table 1.

Table 1. Forms and frequencies of natural oscillations of the structure.

Form No.	Frequency	Frequency	Period
	Hz	Rad/sec	seconds
1	**4.11076**	**25.8287**	**0.243264**
2	5.48924	34.4899	0.182175
3	8.02316	50.4110	0.124639
4	10.6378	66.8391	0.0940046
5	12.0677	75.8234	0.0828660
6	14.4089	90.5337	0.0694016
7	16.4201	103.170	0.0609011
8	17.9924	113.050	0.0555789
9	18.9998	119.379	0.0526322
10	20.4634	128.575	0.0488677
11	23.1945	145.735	0.0431137
12	24.5038	153.962	0.0408100
13	25.6340	161.063	0.0390106
14	27.3885	172.087	0.0365117
15	29.7395	186.859	0.0336253

3.1. Analysis of the forms and frequencies of vibrations

The first form of oscillations with a frequency of 4.11 Hz (25.8287 rad/sec) shows local horizontal oscillations along the flow along the OX axis of one bull with a deformation joint, (Figure 3). The second continuous bull is not involved in oscillations, since the model symmetry conditions are set on its boundary.

The spillway is not involved in the oscillatory process due to the rigidity of the monolithic spillway dam. Gobies are relatively thin high spillway elements, so they experience large deformations during an earthquake.

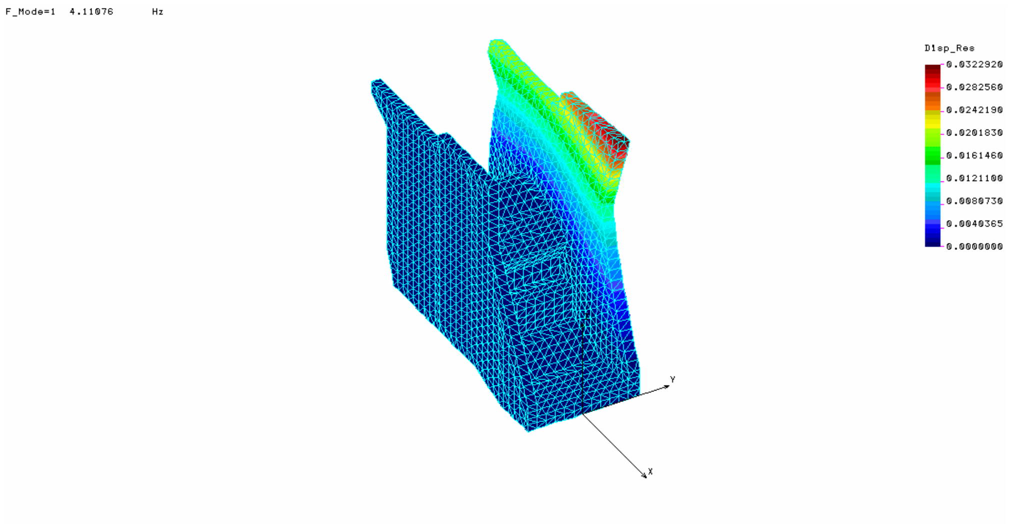

Figure 3. The first form of oscillation with a frequency of 4.11 Hz (25.8287 rad/s).

The second form of oscillations with a frequency of 5.48 Hz shows local horizontal oscillations with torsion across the flow along the OY axis of one bull with a deformation joint, (Figure 4). The main concrete of the spillway and the continuous steer do not participate in the vibrations.

The torsion of the steer occurs with the simultaneous action of longitudinal and transverse deformations of the relatively thin wall of the steer.

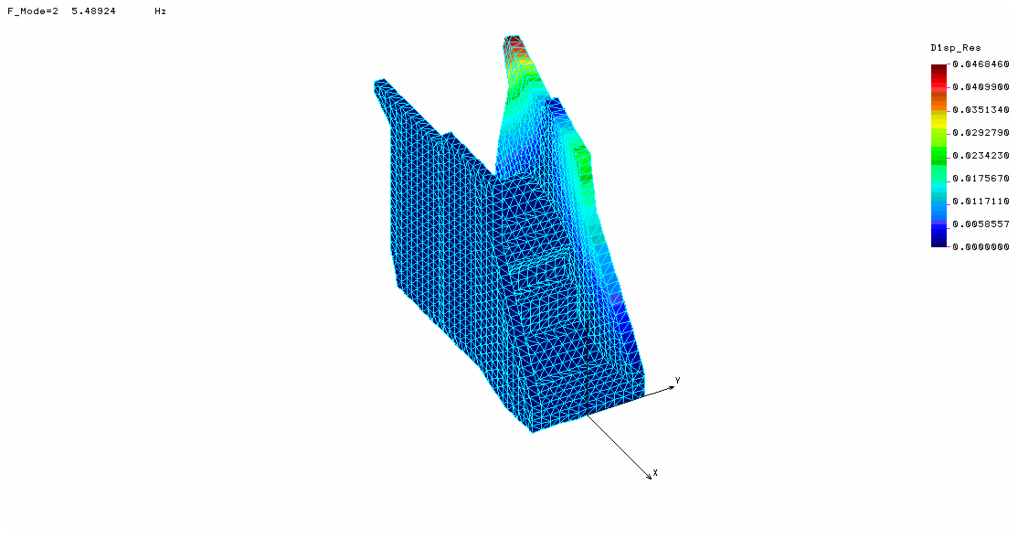

Figure 4. Second waveform with a frequency of 5.48 Hz (34.5 rad/s).

The third form of vibrations with a frequency of 8.02 Hz (50.4 rad/sec) represents the general horizontal vibrations of the dam along the flow along the OX axis; the entire weir is included in the oscillatory process. The steers of the structure experience the greatest relative deformations.

The spillway also oscillates along the horizontal axis OX. This form of oscillation is the most dangerous for the construction of the spillway dam as a whole.

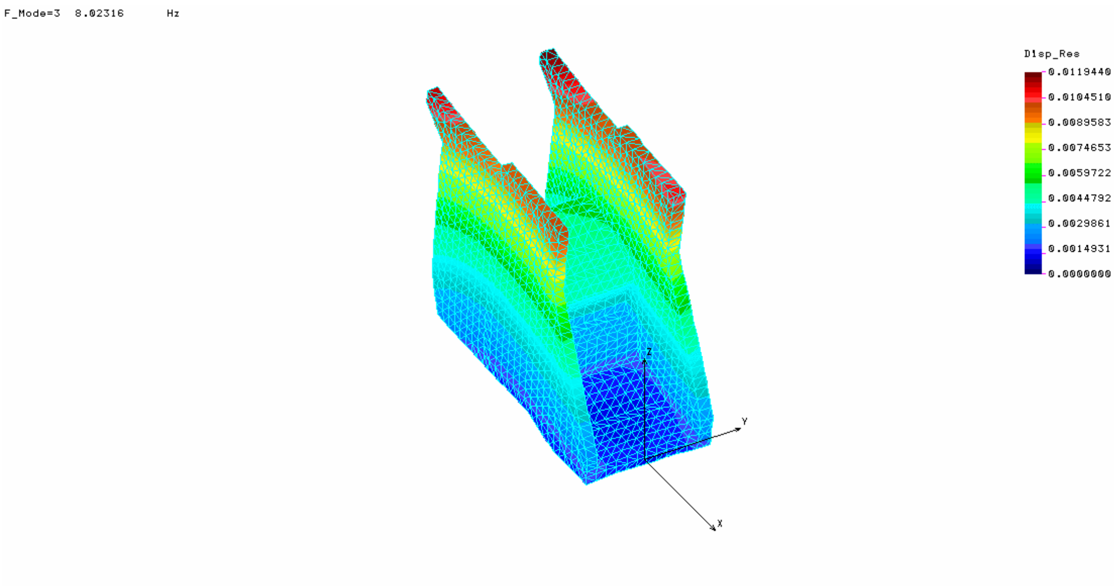

Figure 5. The third form of oscillation with a frequency of 8.02 Hz (50.4 rad/s).

The dynamic seismic impact on the structure is specified using a three-component calculated accelerogram, shown in Figure 6. The duration of the accelerogram is 8 seconds. Peak values of accelerations for each of the components are 1 m/s^2. The damping factor values for concrete are 0.05.

To evaluate the resonance phenomena, the response spectra were generated using the solution of the Duhamel integral:

$$F(t) = \frac{1}{\omega}\int_0^t F(\tau) e^{-\xi\omega(t-\tau)} \sin[\omega(t-\tau)]dt$$

where $F(t)$ is the force perturbation given by the accelerogram, ω is the natural circular frequency (rad/sec), ξ =0.05 is dimensionless damping factor.

As an example of the assessment of resonance phenomena, an analysis of the spectrum of the response obtained at the upper elevation of the dam bull was performed.

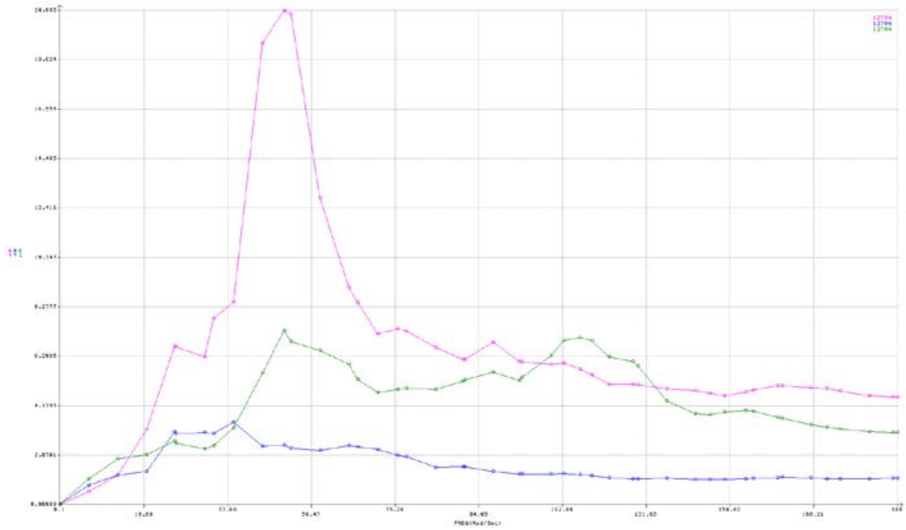

Figure 6. Response spectra at the top mark of the spillway dam bull (dependence of accelerations m/s2 on frequencies rad/s) red line – horizontal accelerations AX (along the flow); blue line – horizontal accelerations AY (across the flow); green line – vertical accelerations AZ.

The most dangerous is the horizontal component of the spectrum along the flow. According to the response spectrum obtained, the maximum horizontal accelerations of 20.693 m/s^2 correspond to a frequency of 50.01 rad/s and do not coincide with the first natural frequency of 25.8287 rad/s, so there will be no resonant phenomena during an earthquake.

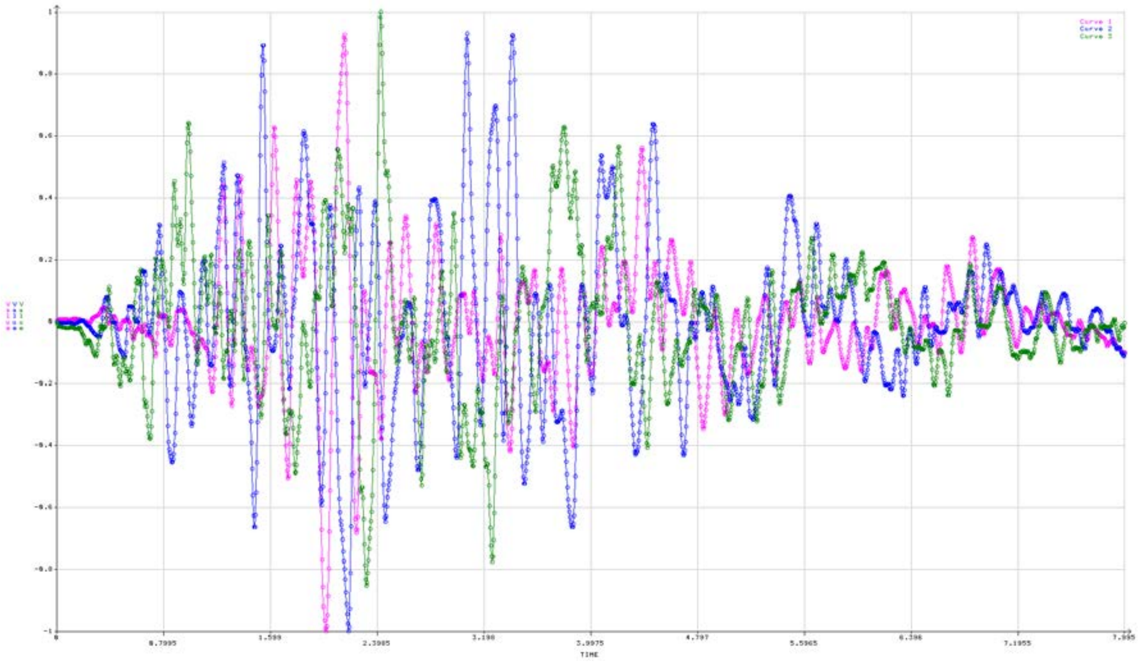

Figure 7. Estimated three-component accelerogram at equipment installation marks.

4. Conclusion

1. As a result of the dynamic calculation of the spillway dam-foundation system of the spillway HPP, the values of the natural vibration frequencies of the structure were obtained and the response spectra were plotted at the marks of the installation of mechanical equipment corresponding to the seismic impact of the MPE level of 8 points (Novobureysky settlement) [26].

2. Dynamic calculations are performed on the basis of the calculated three-component accelerogram.

3. Comparison of the frequency values of the response spectrum with the first natural frequency indicates the absence of resonant phenomena in the structure during an earthquake.

4. The response spectra obtained as a result of the calculation on the steers of the spillway dam can be set as a dynamic effect on the equipment installed on the steers of the spillway.

5. Based on the response spectra, a calculated three-component accelerogram was synthesized at the equipment installation marks.

6. Equipment installed on bullheads must be designed for seismic resistance according to the calculated response spectra or a three-component accelerogram.

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Information about authors:

Galina Kozinetc
Doctor of Technical Science
E-mail: kozinets_gl@spbstu.ru

Pavel Kozinetc
E-mail: pavelkozinetc@yandex.ru