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Response spectra at elevations of station dam equipment installation

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Keywords: concrete station dam, rock foundation, earthquake, natural frequency, waveform, finite element method, response spectrum, equipment

Abstract. The object of the study is a concrete station dam of a run-of-river hydroelectric power plant (HPP). A review of publications on the methods of calculating the dynamic responses of structures is presented. The calculation studies were carried out using the finite element method. The initial data for the calculation are the physical characteristics of the concrete material, steel and rock foundation, the geometric parameters of the dam obtained as a result of engineering surveys and strength calculations of the structure. To determine the natural frequencies and vibration modes of the station dam, eight dynamic calculations of the structure and foundation system were performed for eight design nodes at the equipment installation marks. An analysis is presented describing the dam vibrations and response spectra at the equipment installation marks of the station dam. The issues of strength and stability of the station dam are not included in this study, but were taken into account when determining the geometric dimensions of the structure. To calculate the response spectra at the structure marks, a finite element model of the "structure-foundation" station dam of the Nizhne-Bureyskaya HPP was built. The construction of the calculation model was based on the geometric and physical parameters of the station dam and foundation. The accelerogram is selected in accordance with the design period of the station dam of the Nizhne-Bureyskaya HPP, which is 0.23 sec. It corresponds to the first form of oscillations with a frequency of 4.43 Hz. Using the calculated accelerogram, eight dynamic calculations of the "structure-foundation" system were performed for eight calculated nodes at the elevations of the HPP equipment installation. The solution of the equations of motion with decomposition by the initial oscillation forms was performed for each of the eight calculated nodes. The calculated nodes were determined based on the condition of the location of the HPP equipment on them.

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1. *Introduction*

The object of the research is a concrete station dam of a run-of-river hydroelectric power plant (HPP), which is part of the main structures of HPPs. A special feature of HPPs is the presence of numerous equipment located at various elevations. Thus, mechanical and crane equipment is located at the water intake marks of the HPP. The water intake valves are closed in case of repair of the hydraulic unit. Turbine and transformer equipment is located at the elevations of the turbine room of the HPP. At the outlet marks of the HPP, there is mechanical and crane equipment for the outlet pipes. The outlets are closed during repair of the turbine equipment.

The concrete station dam ensures the supply of water to hydraulic units through a water intake device. The station structure consists of a water intake part of the dam, a water supply path, which includes a spiral chamber and suction pipes. On the upstream side of the HPP, there is a water intake part, on the downstream side, there are rear HPPs and a part of the dam that drains water from the hydraulic units. Lifting mechanisms are mounted on the bulls, designed to block the water intake openings. There is a lot of equipment located at the station dam elevations; therefore, it is mandatory to calculate the seismic load on this equipment.

When designing a station dam in zones of seismic activity, response spectra are calculated at various elevations of equipment installation. The action of seismic waves causes vibrations of the structure. The higher the mark, the stronger the amplitude of the oscillations.

A feature of calculating the response spectrum of a station dam is that the model considers several factors, such as the presence of a soil foundation in the model and the effect of water on the pressure face of the dam.

In the scientific literature, there are several studies of the seismic response of hydraulic structures to dynamic loads using numerical modeling methods.

The article [1] presents an analysis of response spectra, which estimates the peak response directly from the calculated earthquake spectrum. The study includes the effects of dam interactions with water and foundation, which are known to play an important role in the response of a dam to an earthquake. This paper provides a comprehensive assessment of the accuracy of the response spectrum studies by comparing them with the results obtained from monitoring the response spectrum of a dam. The modeling was carried out using the finite element method, including a dam-water-foundation model. A comparison of the results showed that the response spectrum procedure estimates stresses with a satisfactory degree of accuracy for the preliminary design stage of new dams and safety assessment of existing dams.

The article [2] is devoted to the analysis of the safety of concrete dams. Most existing station dams were designed without taking into account their dynamic behavior; therefore, monitoring their condition is of great importance to determine the appropriate safety level. This study provides a framework for dynamic monitoring of the structural health of concrete station dams under changing operating conditions.

The paper [3] presents an analysis of the dimensions of the foundation base in the dam-foundation-reservoir system. The study applied the finite element method to model mass, damping and wave propagation effects in foundations of dam-foundation-reservoir systems using ABAQUS software. The boundary condition is used to model the semi-infinite foundation and damping. Various mechanisms for modeling foundations, earthquake impacts, and boundary conditions in a given area are described. The implementation of the boundary condition in the program by the finite element method is verified by comparing it with the analytical results.

The article [4] presents a practical methodology with an example of determining the seismic resistance of concrete gravity dams using nonlinear seismic analysis from an accelerogram using simulation. Nonlinear seismic analysis is performed for ten tests at multiple ground motion levels until each test indicates an error. The ground motion variable includes ten sets of acceleration time histories obtained from actual earthquake records and mapped to a target response spectrum.

Many articles and books are devoted to the methods for numerically solving the problems of structure dynamics [5–9]. Among the scientists who studied seismic resistance and dynamic characteristics of structures, it is worth noting the works of Ya.M. Aizenberg, S.P. Timoshenko, L.A. Rozin [10].

The aim of the study is to determine the natural frequencies and analyze the vibration modes of the station dam, as well as to calculate the response spectra for further analysis of the seismic resistance of the equipment [11–13].

The study was carried out based on a model of the Nizhne-Bureyskaya HPP dam with a rock foundation (Fig. 1).

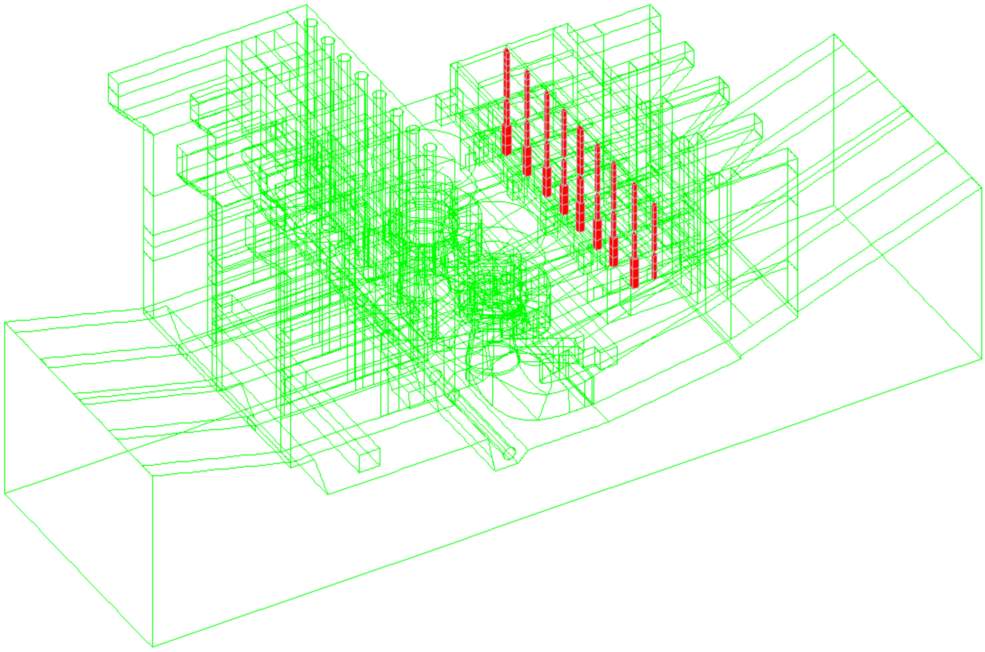


Figure 1. Three-dimensional geometric model of a station dam with a base.

2. Materials and Methods

The method describes the procedure for calculating seismic load response spectrum for equipment located at the station dam levels.

To calculate the response spectra at the elevations of the structure, a finite element "structure-foundation" model of the station dam of the Nizhne-Bureyskaya HPP was constructed. The "structure-foundation" model was divided into three-dimensional 4-node elements of the tetrahedron – TETRA, interconnected at the nodes. Coordinate system: OX axis – along the flow, OZ axis – across the flow, OY axis – vertically upward.

The calculation area was automatically divided into the following elements:

- The maximum size of a rock foundation element is 4 m.
- The maximum size of a concrete structure element is 1.5 m.
- In the areas where the rock foundation and concrete structure are connected, the grid has been increased to 1 m.
- Number of model nodes: 877615.

Description of boundary conditions:

- The nodes on the lower edge of the rock foundation are secured against movement and rotation along all axes.
- The nodes on the vertical faces of the rock foundation are secured against movement in the direction perpendicular to each face.
- The dimensions of the foundation soil are selected vertically to the depth of solid rocks without cracks. The depth of the soil layer is 30 m.
- The problem is solved in an elastic setting.

The issues of strength and stability of the station dam are not included in this study, but were taken into account when determining the geometric dimensions of the structure, which were used as input data for this work.

Computational studies were carried out within the framework of the spatial formulation of the problem by the finite element method [14–17] using the SolidWorks program. The method and its application in structural calculations are presented in [18–23]. The methodology for monitoring the condition of structures is presented in [24]. The calculation model was constructed on the basis of the geometric and physical parameters of the station dam and the foundation. The calculated model of the structure is presented in Fig. 2.

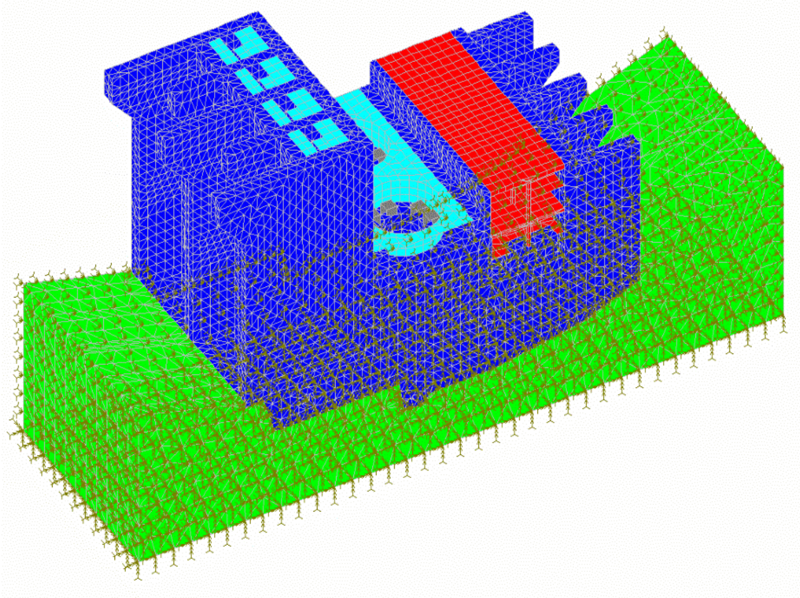


Figure 2. Finite element calculation model of a station dam with boundary conditions.

The initial data for the calculation are the physical characteristics of the material of concrete, steel and rock foundation, the geometric parameters of the station dam of the Nizhne-Bureyskaya HPP on the Bureya River, obtained as a result of engineering surveys and calculations of the strength of the structure. For dynamic calculations, an accelerogram of the dynamic seismic impact was used, obtained by the results of microseismic zoning at the station dam construction site.

The main objectives of the study are as follows:

1. Construction of a mathematical dynamic model “dam-foundation” of the station dam of the Nizhne-Bureyskaya HPP, including geometric construction, division into finite elements, setting the material properties and boundary conditions.
2. Determination of natural frequencies and vibration modes of the station dam. In this case, the calculation period corresponding to the first form of oscillation was determined. Based on the calculated period, a 3-component calculated accelerogram of the seismic impact was selected, in which the predominant period along the horizontal component G1 corresponded to the calculated period of the station dam.
3. Dynamic calculation based on the selected calculated 3-component accelerogram.
4. Calculation of response spectra at given nodes at the station dam marks and construction of graphs of response spectra at given nodes and tables of digitization of spectral curves.

3. Results and Discussion

First stage of research

Fig. 2 shows the finite element calculation model of the structure, together with the foundation. Boundary conditions are specified on the model.

Physical characteristics of materials

The station dam is made of hydraulic concrete class B20. Calculated resistance of concrete under compression R_b = 11700 kPa and tension R_{bt} = 900 kPa for the limit states of the first group.

Modulus of elasticity of concrete in compression and tension E_b = 3 × 10^7 kPa. The coefficient of transverse deformation of concrete (Poisson's ratio) for massive structures ν = 0.15. Density of concrete p_b = 2.36 t/m^3.

The metal frame of the HPP building is welded from sheet steel 09G2S GOST 19281–2014 (similar to DIN 13Mn6, JIS SB49, GB 12Mn).

Density p = 7.85 t/m^3.

Modulus of elasticity E = 2.1 × 10^8 kPa.

Poisson's ratio ν = 0.2.

Thermal expansion coefficient α = 1.2 × 10–5°C^{-1}.

The rock foundation is composed of granites. Physical and mechanical properties and thermophysical characteristics of granite rock foundation are:

Density p = 2.65 t/m^3.

Elastic modulus E = 1.3 × 10^7 kPa.

Poisson's ratio ν = 0.35.

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

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

Second stage of research

At the next stage, the calculation of the natural frequencies and vibration modes of the structure with the foundation was carried out.

In this calculation, the first 50 natural frequencies of the dam-foundation were obtained from 4.43 to 24.24 Hz (from 27.84 to 152.24 rad/sec). The first natural waveform with a frequency of 4.43 Hz is shown in Fig. 3.

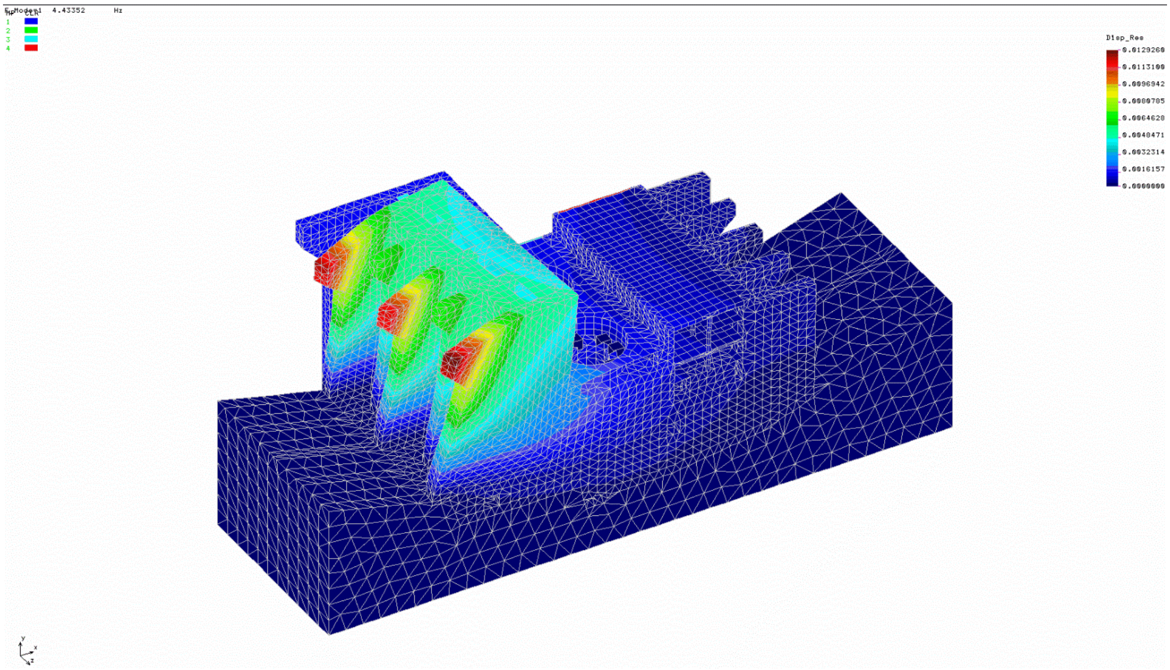


Figure 3. The first natural mode of vibration with frequency *f* = 4.43 Hz. General oscillations of the water intake part of the station dam with shift and rotation of the bulls across the flow.

Calculation period T corresponding to the first mode of dam vibrations with frequency $f = 4.43 Hz$ amounts to $T = 0.23$ sec.

$$T = \frac{1}{f} = \frac{1}{4.43} = 0.23\,\mathrm{sec}\,. \tag{1}$$

The response spectra at the equipment installation marks were determined using a calculated three-component accelerogram for the MPE (maximum probable earthquake) level of 7 points at the station dam site of the Nizhne-Bureyskaya HPP (Fig. 4).

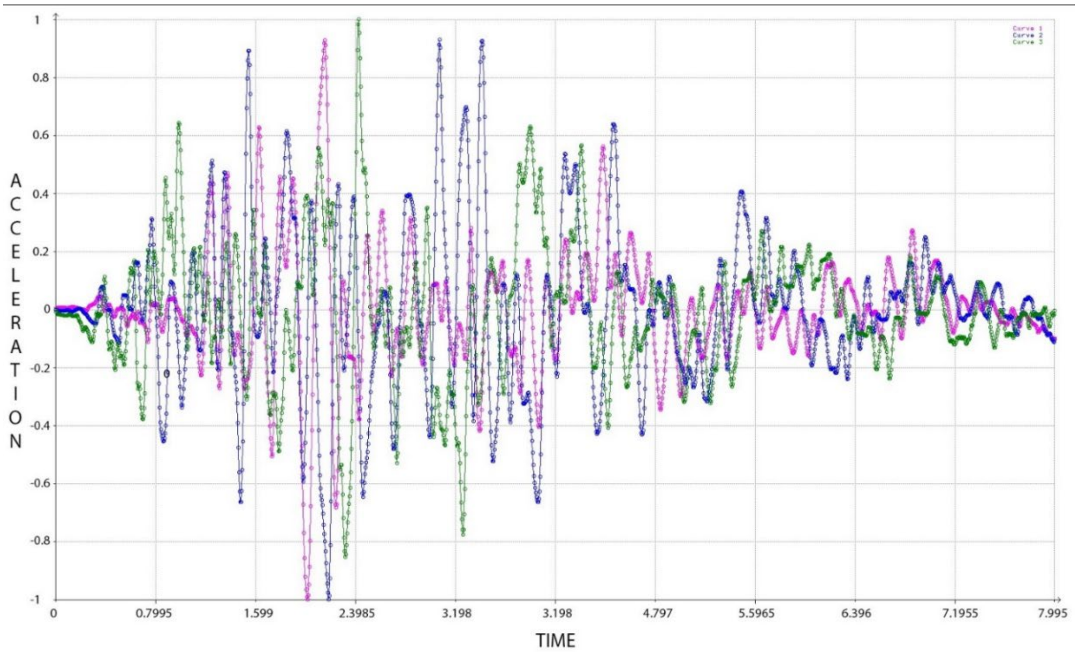


Figure 4. Calculated three-component accelerogram [25]: red line – horizontal component G1, along the OX axis; blue line – horizontal component G2, along the OZ axis; green line – vertical component B1, along the OY axis.

The choice of this accelerogram was made in accordance with the calculated period of the station dam of the Nizhne-Bureyskaya HPP, which is 0.23 sec, which corresponds to the first form of oscillation with a frequency of 4.43 Hz.

The predominant period for the horizontal component G1 is 0.24 sec, G2 is 0.16 sec, for the vertical component is 0.26 sec.

Third stage of research

Using the calculated accelerogram, eight dynamic calculations of the structure-foundation system were performed for eight calculation nodes at the installation marks of HPP equipment. The solution of the equations of motion with expansion in terms of the initial vibration modes was performed for each of the eight calculated nodes. The calculated nodes are determined from the conditions for the location of HPP equipment on them, Fig. 5.

1. Gantry valve, water inlet, elevation 142, node 931;
2. Console, water inlet, elevation 125.2, node 4273;
3. Main shutter, grate, water inlet, elevation 98.03, node 9045;
4. Gantry crane, suction pipes, elevation 122.5, node 11459;
5. Main valve, suction pipes, elevation 89.8, node 12315;
6. Transformer equipment, transformer site, elevation 122.5, node 20899;
7. Stator support, power unit, elevation 111.535, node 13763;
8. Spacer jack support, aggregate block, elevation 114.8, node 20219.

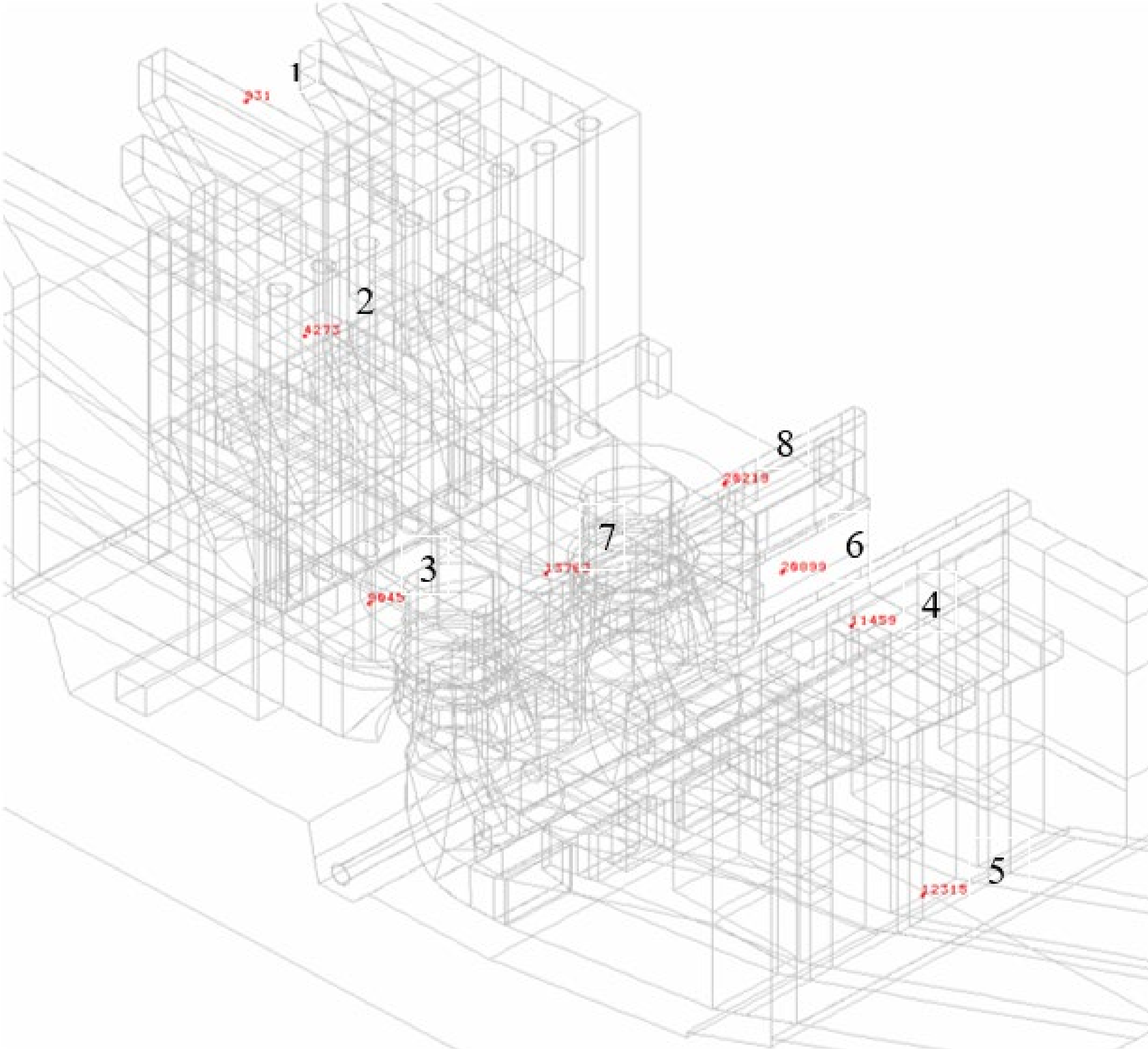
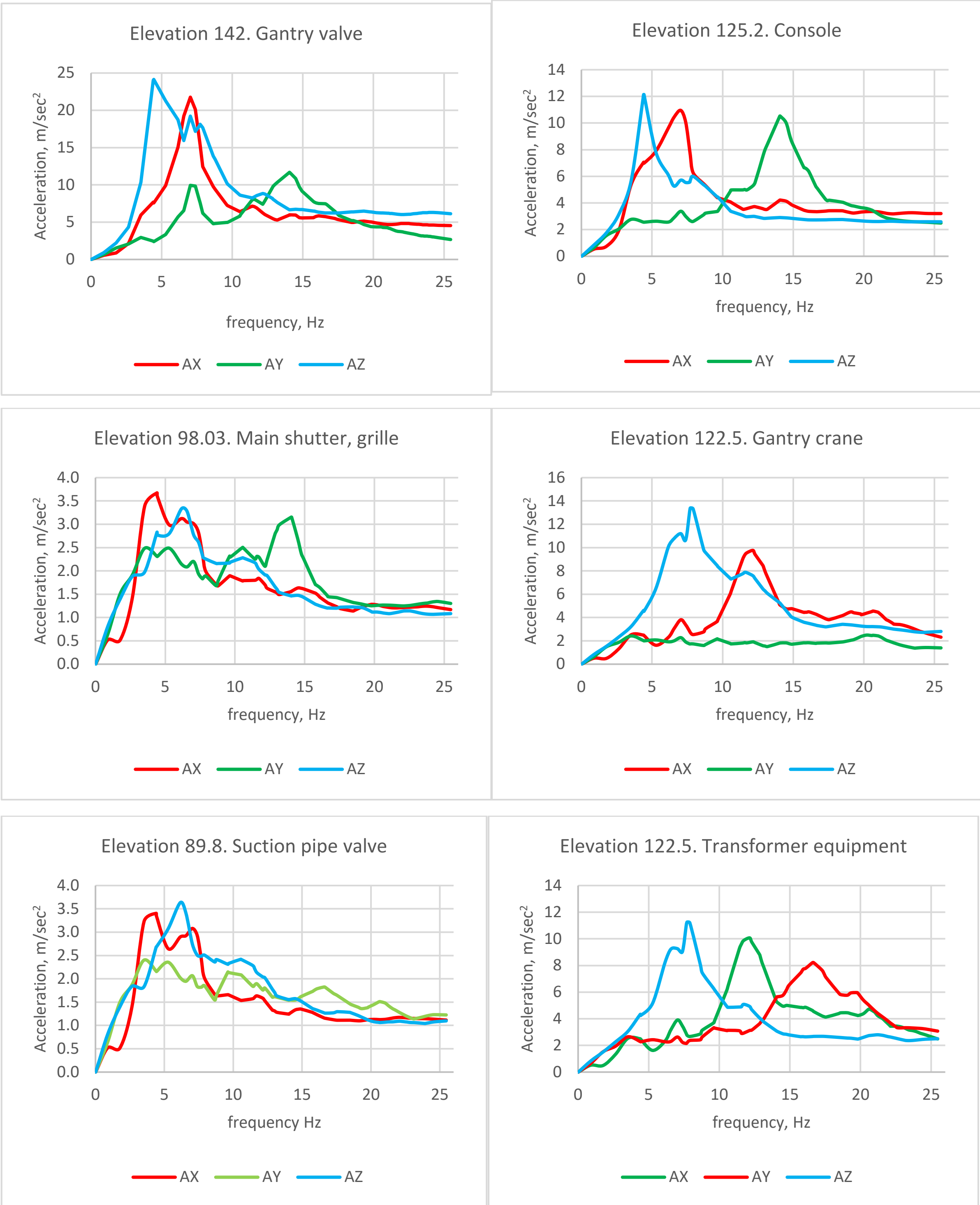


Figure 5. Equipment at station dam marks.

Fourth stage of research

Floor-by-floor response spectra were calculated at the installation marks of the station dam equipment, and graphs of acceleration m/sec^2 versus frequency Hz were obtained along all three axes (Fig. 6). Three-component spectral curves are presented. Table 1 shows the maximum acceleration values and the corresponding frequencies at the equipment installation marks for two horizontal AX and AZ and one vertical AY axes. The resulting spectra can be used to calculate equipment installed at the station dam elevations.


Elevation 142. Gantry valve
Acceleration, m/sec²
frequency, Hz
AX AY AZ
Elevation 125.2. Console
Acceleration, m/sec²
frequency, Hz
AX AY AZ
Elevation 98.03. Main shutter, grille
Acceleration, m/sec²
frequency, Hz
AX AY AZ
Elevation 122.5. Gantry crane
Acceleration, m/sec²
frequency, Hz
AX AY AZ
Elevation 89.8. Suction pipe valve
Acceleration, m/sec²
frequency Hz
AX AY AZ
Elevation 122.5. Transformer equipment
Acceleration, m/sec²
frequency, Hz
AX AY AZ

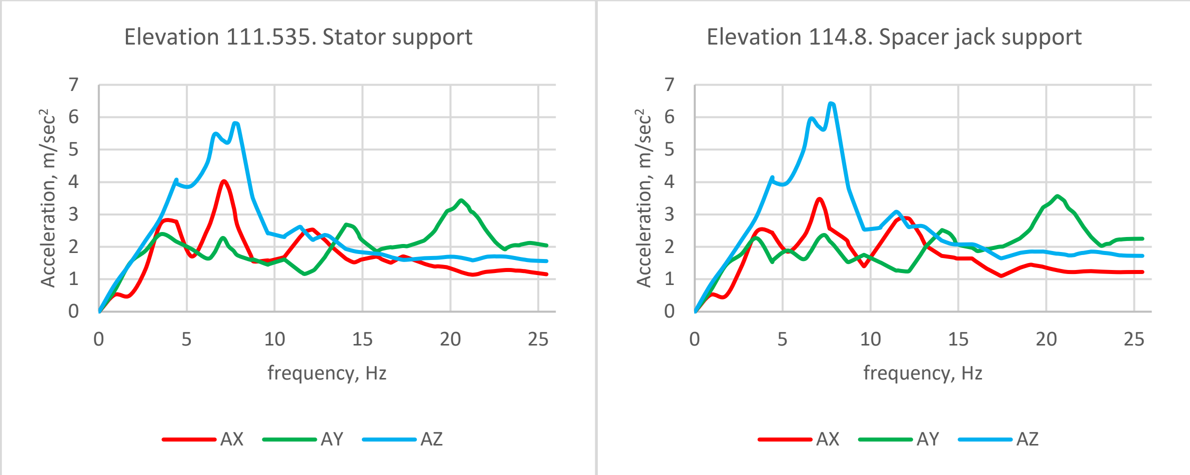


Figure 6. Response spectra at station dam elevations. Dependence of acceleration m/sec^2 on frequencies Hz: red line – horizontal accelerations AX (along the flow); green line – vertical accelerations AY; blue line – horizontal accelerations AZ (across the flow).

Table 1. Maximum acceleration values and corresponding frequencies at equipment installation marks.

№	Equipment name	Mark on the structure	Acceleration m/sec^2, Frequency Hz AX; FX	Acceleration m/sec^2, Frequency Hz AZ; FY	Acceleration m/sec^2, Frequency Hz AY; FZ
1	Gantry valve, water inlet	Elevation 142	7; 21.8	14; 11.7	4.4; 24
2	Console, water inlet	Elevation 125.2	7; 11	14.1; 10.5	4.4; 12.1
3	Main shutter, grille, water inlet	Elevation 98.03	4.4; 3.6	14; 3.2	6.2; 3.3
4	Gantry crane, suction pipes	Elevation 122.5	12.2; 9.8	3.5; 2.4	7.9; 13.3
5	Main valve, suction pipes	Elevation 89.8	4.4; 3.4	3.5; 2.4	4.4; 3.4
6	Transformer equipment, transformer site	Elevation 122.5	17.3; 7.7	12.3; 9.7	7.9; 11.2
7	Stator support, power unit	Elevation 111.535	7.4; 3.8	21.2; 3.1	7.7; 5.8
8	Spacer jack support, power unit	Elevation 114.8	7; 3.5	20.7; 3.6	7.7; 6.3

The parameters of the selected accelerogram are consistent with the research data of [12], in which, during an earthquake greater than 7 points, the prevailing period T multiplied by the peak acceleration $A_{\max}$ and the corresponding time t can be described by the parameter B, which is determined by the earthquake magnitude.

$$B = A_{\max} gT\tau = 0.95 \times 9.81 \times 0.24 \times 2 = 4.47\,\text{m} = 447\,cm\,. \quad (2)$$

For our study, parameter B is equal to 447 cm, which corresponds to a magnitude of 6.5 points, which is the calculated magnitude for the design area of the Nizhne-Bureyskaya HPP with a MPE level of 7 points.

Thus, when comparing the results of the study with the data of [12], the reliability of the determination of the accelerogram parameters used to calculate the response spectra of the concrete dam of the HPP is confirmed.

4. Conclusions

9. Calculations of the response spectra at the installation elevations of mechanical equipment corresponding to the seismic impact of a MPE level of 7 points were performed. The calculations of

the response spectra were used in the designs of the mechanical equipment of the Nizhne-Bureyskaya HPP, performed at JSC Lengidrostal.

10. The response spectra of the floors represent the calculated seismic load for each unit of equipment installed at the elevations of the station dam. The response spectra at the elevations were the calculated seismic load for the equipment of JSC Power Machines. As a result of the study, the points of the design area's estimated magnitude were found to correspond to the research data of Academician A.I. Savich et al.
11. The scientific novelty lies in the presented and implemented method for calculating the response spectra determined at the equipment installation marks, considering the choice of parameters of the estimated accelerogram.

References

1. Løkke, A., Chopra, A.K. Response Spectrum Analysis of Concrete Gravity Dams Including Dam-Water-Foundation Interaction. Journal of Structural Engineering. 2015. 141(8). Article no. 04014202. DOI: 10.1061/(ASCE)ST.1943-541X.0001172
2. Sevieri, G., De Falco, A. Dynamic structural health monitoring for concrete gravity dams based on the Bayesian inference. Journal of Civil Structural Health Monitoring. 2020. 10(2). Pp. 235–250. DOI: 10.1007/s13349-020-00380-w
3. Mohammadnezhad, H., Ghaemian, M., Noorzad, A. Seismic analysis of dam-foundation-reservoir system including the effects of foundation mass and radiation damping. Earthquake Engineering and Engineering Vibration. 2019. 18. Pp. 203–218. DOI: 10.1007/s11803-019-0499-4
4. Ghanaat, Y., Patev, R.C., Chudgar, A.K. Seismic fragility analysis of concrete gravity dams. Proceedings of the 15th World Conference on Earthquake Engineering, Lisbon, 24–28 September 2012.
5. Rybakov, V., Jos, V., Raimova, I., Kudryavtsev, K. Modal analysis of frameless arches made of thin-walled steel profiles. IOP Conference Series: Materials Science and Engineering. 2020. 883. Article no. 012197. DOI: 10.1088/1757-899X/883/1/012197
6. Zarubin, P.E., Baranovskij, M.Yu., Tarasov, V.A. Tekla Structures – is innovation of structres's calculation. Construction of Unique Buildings and Structures. 2013. 5(10). Pp. 1–8.
7. Kozinec, G.L. Generalization of the Methodology of Studying the Durability of Segmental Gates. Power Technology and Engineering. 2018. 52(4). Pp. 395–399. DOI: 10.1007/s10749-018-0964-7
8. Verret, D., LeBoeuf, D. Dynamic characteristics assessment of the Denis-Perron dam (SM-3) based on ambient noise measurements. Earthquake Engineering & Structural Dynamics. 2022. 51(3). Pp. 569–587. DOI: 10.1002/eqe.3580
9. Arbain, A., Ahmad Mazlan, A.Z., Zawawi, M.H., Mohd Radzi, M.R. Vibration Analysis of Kenyir Dam Power Station Structure Using a Real Scale 3D Model. Civil and Environmental Engineering Reports. 2019. 29(3). Pp. 48–59. DOI: 10.2478/ceer-2019-0023
10. Rozin, L.A., Chernysheva, N.V. Algorithm of combined method of 3D analysis for the boundary problems in infinite medium. Materials Physics and Mechanics. 2017. 31(1–2). Pp. 82–85.
11. Savich, A.I., Bronshtein, V.I., Groshev, M.E., Gaziev, E.G., Il'in, M.M., Rechitskii, V.I., Rechitskii, V.V. Staticheskoe i dinamicheskoe povedenie Saiano-SHushenskoi arochno-gravitatsionnoi plotiny [Static and dynamic behavior of the Sayano-Shushenskaya arch-gravity dam]. Gidrotekhnicheskoe Stroitel'stvo. 2013. 3. Pp. 2–13.
12. Savich, A.I., Burdina, N.A. On the Relationships between the Fundamental Parameters of Calculation Accelerograms. Power Technology and Engineering. 2016. 50. Pp. 38–47. DOI: 10.1007/s10749-016-0656-0
13. Rybakov, V., Lalin, V., Pecherskikh, M., Saburov, D. Accounting for rotational inertia in calculating structures for seismic impact. AIP Conference Proceedings. 2023. 2612(1). Article no. 040034. DOI: 10.1063/5.0113989
14. Pereira, S., Magalhães, F., Gomes, J.P., Cunha, Á., Lemos, J.V. Dynamic monitoring of a concrete arch dam during the first filling of the reservoir. Engineering Structures. 2018. 174. Pp. 548–560. DOI: 10.1016/j.engstruct.2018.07.076
15. Gordan, B., Raja, M.A., Armaghani, D.J., Adnan, A. Review on Dynamic Behaviour of Earth Dam and Embankment during an Earthquake. Geotechnical and Geological Engineering. 2022. 40. Pp. 3–33. DOI: 10.1007/s10706-021-01919-4
16. Chen, J., Jia, Q., Xu, Q., Fan, S., Liu, P. The PDEM-based time-varying dynamic reliability analysis method for a concrete dam subjected to earthquake. Structures. 2021. 33. Pp. 2964–2973. DOI: 10.1016/j.istruc.2021.06.036
17. Boulanger, R.W. Nonlinear Dynamic Analyses of Austrian Dam in the 1989 Loma Prieta Earthquake. Journal of Geotechnical and Geoenvironmental Engineering. 2019. 145(11). Article no. 05019011. DOI: 10.1061/(ASCE)GT.1943-5606.0002156
18. Wang, J.-T., Jin, A.-Y., Du, X.-L., Wu, M.-X. Scatter of dynamic response and damage of an arch dam subjected to artificial earthquake accelerograms. Soil Dynamics and Earthquake Engineering. 2016. 87. Pp. 93–100. DOI: 10.1016/j.soildyn.2016.05.003
19. Miquel, B., Bouaanani, N. Accounting for Earthquake-Induced Dam-Reservoir Interaction Using Modified Accelerograms. Journal of Structural Engineering. 2013. 139(9). Pp. 1608–1617. DOI: 10.1061/(ASCE)ST.1943-541X.0000726
20. Zacchei, E., Molina, J.L. Application of artificial accelerograms to estimating damage to dams using failure criteria. Scientia Iranica. 2020. 27(6). Pp. 2740–2751. DOI: 10.24200/sci.2018.50699.1824
21. Rebez, A., Sandron, D., Santulin, M., Peruzza, L., Tamaro, A., Eusebio, M., Mucciarelli, M., Slejko, D. Input accelerograms and expected accelerations for some dam sites in southern Italy. Proceedings of the 33rd Conference of the National Solid Earth Geophysics Group (GNGTS), Bologna, 25–27 November 2014. 2. Caratterizzazione sismica del territorio. Centro Stampa della Regione Emilia-Romagna. Bologna, 2014. Pp. 48–57.
22. Alegre, A., Carvalho, E., Matsinhe, B., Mendes, P., Oliveira, S., Proença, J. Monitoring vibrations in large dams. HYDRO2019. Concept to Closure: Practical Steps. 2019.
23. Aliberti, D., Cascone, E., Biondi, G. Seismic Performance of the San Pietro Dam. Procedia Engineering. 2016. 158. Pp. 362–367. DOI: 10.1016/j.proeng.2016.08.456
24. Badenko, V., Volgin, D., Lytkin, S. Deformation monitoring using laser scanned point clouds and BIM. MATEC Web of Conferences. International Scientific Conference on Energy, Environmental and Construction Engineering (EECE-2018). 2018. 245. Article no. 01002. DOI: 10.1051/matecconf/201824501002

25. Kozinetc, G.L., Kozinetc, P.V. The calculation of the dynamic characteristics of the spillway of the dam. Magazine of Civil Engineering. 2022. 113(5). Article no. 11312. DOI: 10.34910/MCE.113.12

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