Magazine of Civil Engineering. 2023. 118(2). Article No. 11807

Magazine of Civil Engineering

journal homepage: http://engstroy.spbstu.ru/

ISSN
2712-8172

Research article

UDC 627.8

DOI: 10.34910/MCE.118.7

Regularity of natural oscillations characteristics change of tall earth dams

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Keywords: dam, oscillation, period, accelerogram, strength characteristics of earth dams, hydraulic structure

Abstract. A preliminary assessment of the strength of earth dams under dynamic loads is one of the most important tasks associated with the design of such massive hydraulic structures. The present study is devoted to predicting the deformation of earth dams under the influence of strong earthquakes, which are possible in the immediate vicinity of the dam location. Recently, a number of large earthquakes have occurred in the world, which led to severe destruction and indicate high seismic risks associated with the potential instability of existing large earth dams. Under intense seismic impacts, the response of the dam depends on various factors, including its geometric dimensions, as well as the type of structure. A number of existing dams, which were designed and built according to the normative rules of their time, do not take into account modern real operating conditions, in particular, potential seismic loads. This article examines the influence of these factors on the stability and strength of earth dams, taking into account the real properties of the soils of the dam body and the base of the bottom of the hydraulic structure in accordance with the new regulatory requirements. On the basis of the proposed mathematical model, verification calculations for the strength and stability of such earth dams located in the seismic zone were carried out. To assess seismic safety of high earth dams built and operating in regions of complex climatic conditions, including frequent earthquakes, the proof of the method choice capable of reliable and valid results in terms of adopted assessment criteria is required. Correct mathematical model choice ensures, on the basis of computations, strength indices of the hydraulic structure under study. In particular, comparison and analysis of calculated date obtained in case of the plane calculation model and spatial model with the field measurements results and spectral analyses of the Sarsang dam accelerograms showed the suggested calculation models provided reliable strength indices results for the earth dams in the operating reservoirs. The use of more complex models of the physical and mechanical properties of the dams' soil leads to reliable results that are in good agreement with real field tests.

Citation: Vartanyan, A.A., Sarukhanyan, A.A., Veranyan, G.G., Tokmajyan, H.V. Regularity of natural oscillations characteristics change of tall earth dams. Magazine of Civil Engineering. 2023. 118(2). Article no. 11807. DOI: 10.34910/MCE.118.7

1. Introduction

The subject of this research is verification of earth dam slopes stability of built and running dams, as well as adjustment of the safety factor, which are aimed at providing not only solutions to urgent safety problems but also are of great economic importance. These problems are especially of vital importance in earthquake-prone areas where the loads calculated for the strength and stability of structures are due to seismic alternating-sign dynamic forces. Under these conditions, the discovery of the stress-strain model and on this basis the solutions to the problems of strength and stability of earth dams are of significant theoretical and economic importance.

Earth dams are the main hydraulic structures in those territories where their construction with other building materials is economically unjustified [1, 2]. This explains the fact that in Armenia and Nagorno Karabagh Republic earth dams have mainly been built. Compared to concrete or other types of dams, earth dams have not been deeply studied, which is associated with the constant refinement and adjustment of earth dams foundation soils and bodies' physical and mechanical properties [3, 4]. To assess the real state of earth dams in terms of strength and stability, the decisive factor is the choice of a mathematical model of the current stress-strain state of the soils of the foundation and the body of the dam [4, 5]. However, obtaining data on the current physical and mechanical state of soils requires the use of expensive measuring instruments and the availability of highly qualified operating personnel, which ultimately leads to an increase in the cost of the structure.

Due to the high risk of strong earthquakes in seismic zones, much attention is paid to the design, construction and operation of hydrotechnical dams in such places, namely, they constantly improve calculation methods to determine their strength and stability. These tasks are especially relevant in regions where, in addition to constant loads, there are alternating seismic loads.

The issues of stability of dams with vibrational effects of a hydraulic turbine are considered in [1]. Recommendations have been received to ensure the safe operation of dams with hydro-turbine units that cause strong vibrations. The influence of environmental vibrations on concrete dams with very diverse geometric characteristics has been studied. Methods have been developed for calculating the strength of concrete dams, taking into account the vibration of the environment [2]. The well-known finite element method for calculating the stability of slopes is sufficiently accurate and universal. Slope destruction occurs through zones in which the shear strength of the soil is insufficient to resist shear stresses. In [3], on the basis of the finite element method, an analysis of the stability of slopes was carried out in comparison with other methods. Finite element method and slope stability analysis is claimed to be a more accurate method.

The paper [4] considers methods for calculating buried structures for overall stability, taking into account arbitrary dynamic loads acting on an elastic herd. Methods for determining the mechanical properties of soils in the field under the action of static and dynamic loads, as well as the results of some experiments, are outlined.

Based on the results of experimental studies of the strength and deformation properties of soils in a complex stress state, a mathematical model has been developed, on the basis of which a complex method for calculating dams from soil materials under static and dynamic loads and a comparison of natural and calculated data are given [5].

Seismic characteristics of existing hydraulic structures can be determined by destructive and non-destructive methods. In [6], the seismic behavior of these structures is studied. In particular, by conducting a non-linear analysis, it is possible to calculate displacements, damages and stress distributions, on the basis of which it is recommended to develop engineering measures to preserve these structures.

In [7], an assessment of the stress state of earth dams in a three-dimensional formulation is proposed. To assess the stress-strain state and dynamic characteristics of earth dams, mathematical model, methodology and calculation algorithm have been developed based on finite elements. To ensure the required accuracy in assessing the stress state and dynamic characteristics of earth dams, it is proposed to carry out calculations using a three-dimensional model.

When designing and, especially, building earth dams, all technical requirements provided for by regulatory documents must be met. Only with strict observance of all requirements during the operation of earth dams can we expect their reliable and safe operation. Often, in order to increase the strength of soils, composite materials are used, a mixture of which with local materials provides high strength necessary for the construction of the core of earthen dams or the foundation of buildings and roads [8]. In [9], a review of the literature on assessing the state of earth dams under the influence of earthquakes was carried out. Using soft computing methods, two models have been developed to predict the slope deformations of earth dams during various earthquakes.

A technique has been developed to identify the patterns of the stress-strain state of soils based on the results of standard triaxial tests, including primary loading, unloading and repeated loading [10]. The impact of seismic loads on historical monuments located in the Imperial Valley was studied in [11], where the authors performed a deformation analysis using the finite element method.

The monograph [12] is devoted to the improvement of the basic concepts of seismic action, methods of calculation, design, erection and reinforcement of buildings and structures, as well as the development of methods for predicting accelerograms of strong soil movements depending on the seismic characteristics of the terrain.

According to the theory of random fields and the autocorrelation function, a modeling method was proposed to study the stress-strain state of the parameters of gravity dams, taking into account their spatial variability [13]. The modulus of elasticity and ultimate tensile strength are chosen as random variables. Based on the plasticity model of concrete damage, the influence of spatial variability of parameters on the dynamic characteristics of gravity dams in terms of damage development, residual displacement and energy dissipation was studied. The influence of the average value, coefficients of variation and seismic effects on structural damage was studied.

The attenuation of peak acceleration near the source according to the accelerograms of strong earthquakes that occurred from 1957 to 1993 is given in the materials of the Fifth US National Conference on Seismic Stability Issues [14].

In some special structures, when calculating seismic loads on structures, in addition to the three translational seismic excitations along the coordinate axes, rotational components around the axes should also be taken into account. The paper [15] presents the results of numerical calculations of seismic loads on a mine derrick.

To determine the dynamic characteristics of the arch dam, the optimal locations of the sensors were identified by testing for environmental vibration using a large number of acceleriometers. Based on the analysis of these dynamic characteristics, the optimal number of sensors was determined to reveal the dynamic characteristics of a structure [16].

The stress-strain response observed in monotonic and cyclic tests is captured by an elastoplastic critical state model used as a virtual simulation of experiments to determine the effect of the initial state on soil response. This dependence is introduced in equivalent linear elastic-ideally plastic models as a function of the state variable to study the propagation of shear waves through horizontally layered dumps and embankments. Seismic actions on dams with different soil densities and geometries are analyzed to see the role of these factors in soil response and embankment slip resistance. The study revealed the exceptionally high resistance of gravel, which allows embankments with steep abutments to withstand strong earthquakes [17].

The effects of strong forced vibrations through the railway embankment and natural soil are transferred to the structure of surrounding buildings, causing deformation and inconvenience to residents. In [18], methods have been developed to mitigate these vibrations by pumping drilling fluid during strong ground movements.

The study of the characteristics of polymer impervious layers of earthen dams under the influence of seismic loads is of great practical importance. The results of the seismic performance of an earth dam with a polymer impervious wall, together with a comparison of the response characteristics of earth dams with a concrete core, show that such an earth dam has good resistance to seismic failures [19, 20].

Under strong seismic actions, the response of the dam depends on various factors, including the geometric dimensions and type of the dam. In [21], the influence of these factors is studied by comparing the seismic characteristics of two idealized earth dams: homogeneous and with a core. The seismic response of the dams was evaluated using a non-linear dynamic analysis that used the same real-time ground motion input. It is shown that for strongly inelastic systems, such as those under consideration, in addition to the compatibility criteria with the calculated elastic response spectrum, it is necessary to take into account the duration of the input motion. The article highlights the features in the behavior of such earth dams, gives recommendations for a rational assessment of their seismic characteristics.

What are the reasons that lead to the assumption that the stress-strain state of the dam's body and as a result the necessity of carrying out investigations on verification of the dam body strength and stability and formation of appropriate conclusions.

First, during the design phase on the basis of calculation techniques were used simplest models which did not fully reflect running in reality processes.

Second, to perform calculations the basic equations were linearized and their some members were simplified, and influence of static and dynamic loads were considered as constants.

Third, in case of forced vibrations the dam was considered as an elastic body, hence, as a result plastic deformations occurring in the body were neglected. In consequence of this the degree of the dam stability reliability was artificially increased.

On the basis of insufficient substantiations of described model of the problem study, a method was suggested which allows to obtain reliable calculation criteria. Structures designed applying these criteria will have guaranteed strength and stability.

Methods for earth dams' slopes stability calculation have been developed under dynamic loading conditions of the soil [10, 11]. However, in the above mentioned calculation methods the stress state of the soil is considered under linear regularity. During earthquakes due to Earth crust fluctuations [12, 13], the change of the soil stress-strain state differs from the linear regulation [14], therefore, calculation of the earth dams' slopes stability and strength under nonlinear regularity conditions [4, 5] is not only of practical importance but also pursues the goal of precise determination of such structures dimensions.

In recent decades, strong earthquakes have occurred, resulting in a high seismic risk associated with the potential instability of existing earth dams. Under intense seismic impacts, the response of the dam depends on various factors, including the spatial geometric dimensions of the dam. In addition, regulatory requirements for taking into account seismic loads, due to various circumstances, often increase and it becomes necessary to check the strength and stability of existing dams. From this point of view, the task of developing a methodology for calculating the stability of existing earth dams under new, more stringent regulatory conditions is relevant. To obtain reliable results, it is necessary, in addition to seismic characteristics, to take into account also the physical and mechanical properties of the soil under the influence of dynamic loads and the geometric dimensions of the structure.

The proposed method enables to reveal the stress-strain state of the earth dam body, taking into account the actual stress state of the soil, can provide more accurate data.

2. Theoretical Basis

The earth dams under design and construction, in accordance with the current regulatory requirements for recording and assessment of man-made and natural disasters, corresponding to real indicators, have sufficient strength and stability ensuring their long and safe operation lifetime [15, 16]. However, most of the existing hydraulic structures, which were designed and built according to regulatory documents that do not take into account the real dynamic loads arising during earthquakes, were in an indefinite state [17, 18]. Thus, dams built on the territory of Armenia and Nagorno Karabakh Republic, according to the old regulatory documents, have been designed for seismic loads corresponding to a horizontal acceleration of 0.2 g.

However, after the 1988 Spitak earthquake, this normative indicator was significantly changed and increased to 0.43 g. It is clear that with a sharp deviation from this indicator, no active earthen structure can remain unharmed.

To check the real state of the existing eart dams according to the new regulatory requirements, the authors, on the basis of the proposed mathematical model, carried out verification calculations for the strength and stability of earth dams built on the territory of the Nagorno Karabakh Republic. The purpose of the calculations was to identify the real state of these structures, if necessary, to develop preventive measures to increase their reliability. An extremely unique structure is the Sarsang Dam, which is the tallest earth structure on the European continent [19, 22].

The Sarsang Dam is the most important strategic object in the Republic of Nagorno Karabakh and ensuring the requirements for its safe operation is of particular importance for the national economy. Based on the need of identifying the technical state of the Sarsang Dam, a 3D model of the relief of the dam foundation and lateral prisms was developed and to carry out computations of natural oscillations, spatial and flat design models were developed [23–25]. By numerical expansion of the DWG (drawing), the general plan of the structure was adjusted and the horizontals were restored, using new topographic data (Fig. 1).

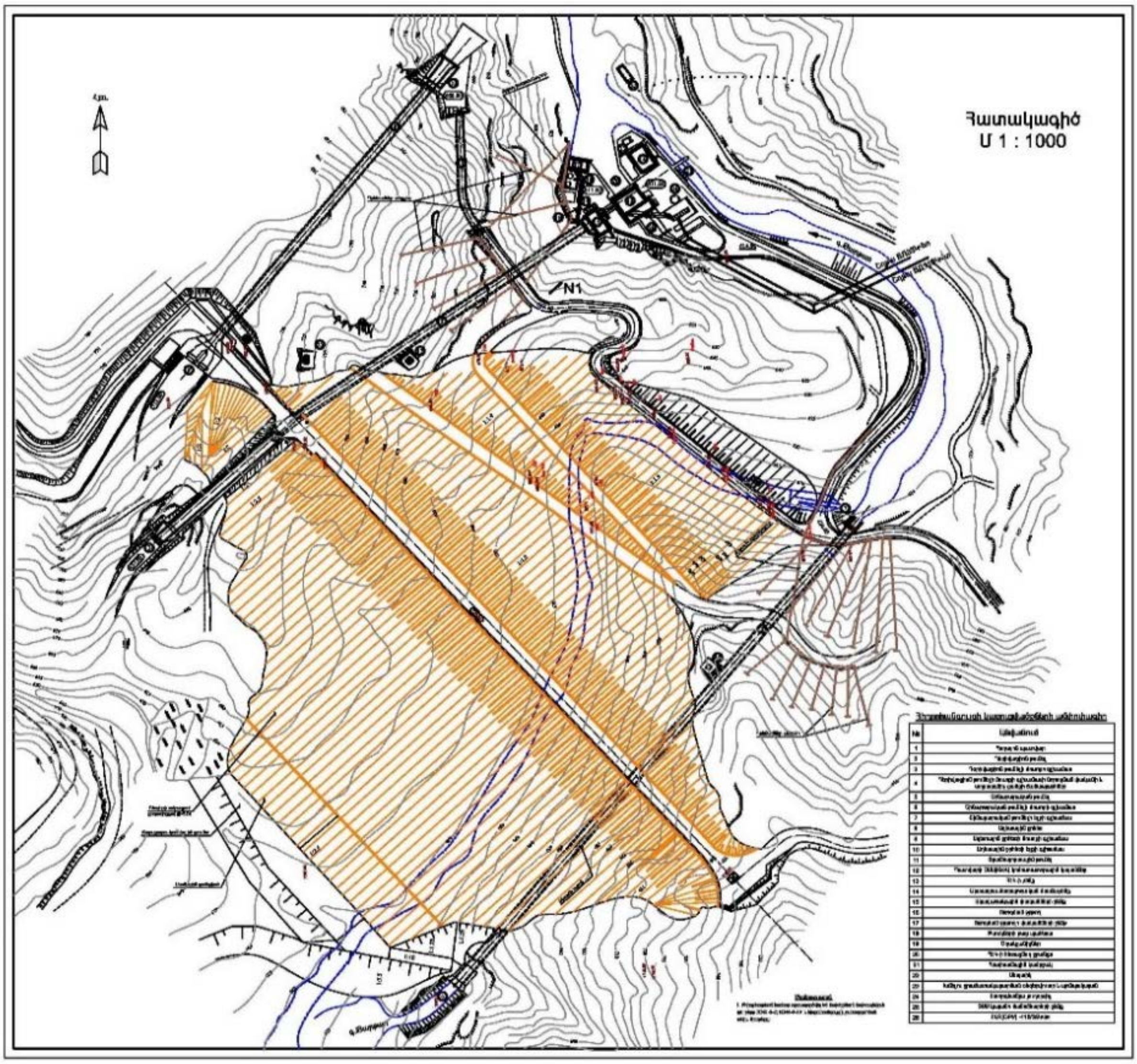

Figure 1. Corrected master plan of the Sarsang dam.

To estimate the real values of the accelerations of the propagation of elastic waves on the territory of platinum, experiments were carried out, the results of which are shown in the Table 1.

Table 1. Results of the Sarsang dam's area microzoning.

Site name	Oscillation period, s	Maximum expected horizontal acceleration A			
		Engineering-geological analogy	Acoustic stiffness	Impact	Final
Foot of the dam	0.09 – 0.28	0.4	0.45	0.45	0.45
Left-bank site	0.1 – 0.3	0.4	0.432	0.419	0.434
Right-bank site			0.434	0.421	

In the calculations, the mechanical parameters of the soil were obtained by the dynamic method [12], and the densities and physical and mechanical properties of the soil of the dam body and foundation were obtained making use of the results of laboratory studies of prototypes delivered from different depths of the dam body and the bottom of the hydraulic structure. The results of laboratory studies are shown in Table 1.

Table 2. Physical-mechanical properties of the dam body's soil and base.

N	Layer name	γ_{nat}, KN/m^3	V_e, m/s	V_s, m/s	μ	E, MPa	G, MPa	Logarithmic decrement
1	Loam and gravel mixtures up to 10–15% (from the core base to the mark 670m)	20.85	500	200	0.4	700	25	0.20
2	Loam and gravel mixtures (dam core, mark 670–726.0m)	20.3	450	190	0.39	600	22	0.22
3	Gruss-sandy soil (transitional prism)	17.5	550	300	0.29	1200	450	0.25
4	Gravelly-pebble soils (retaining prisms)	20.6	650	400	0.2	2300	950	0.26
5	Rock fill (body of the dam)	22.0	700	450	0.15	3000	1300	0.27
6	Tuffbreccia, detritus, weakly crumbling (base of the dam)	24.0	1450	800	0.28	11000	4500	0.3
7	Sediment	20.6	650	400	0.2	2300	950	0.24

To achieve the set goal, quantitative relationships of natural oscillations were identified depending on the relief forms and their comparative assessment was given using spectral accelerograms recorded by strong earthquakes.

3. Materials and Methods

First, a flat calculation model of the dam was built (Fig. 2).

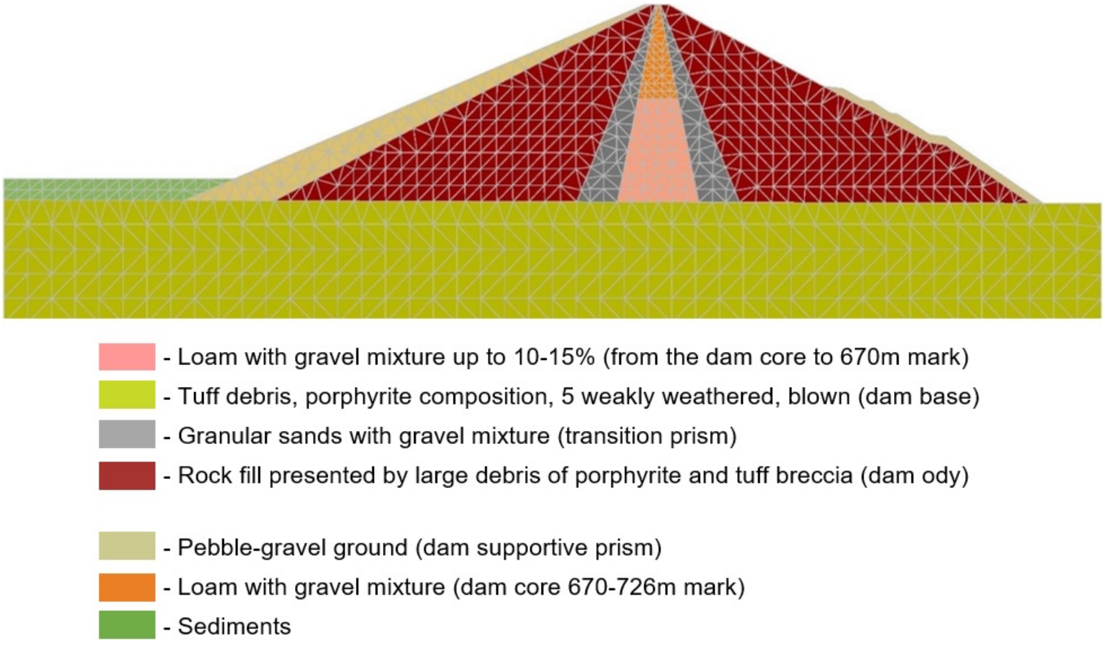

Figure 2. Design cross-section of the dam divided into finite elements.

From the master plan (Fig. 1) of the site and using the ArcGis program, a survey of the raster relief was built, placed in the computational grid (Fig. 3). Cartesian coordinates are defined in the center of each cell. By these coordinates and using the Mathematica program, triangular elevation models were built (Fig. 4). Further, the relief with triangular cells was entered into the AutoCAD program and a spatial site model was built (Fig. 5), on which the dam model was also built (Fig. 6), as well as the calculated plane model of the dam, taking into account the two most dangerous cross-sections, as a result of which the dam has the greatest height.

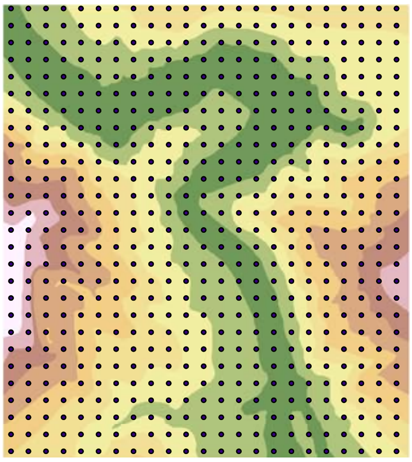

Figure 3. Raster grid by the middle points.

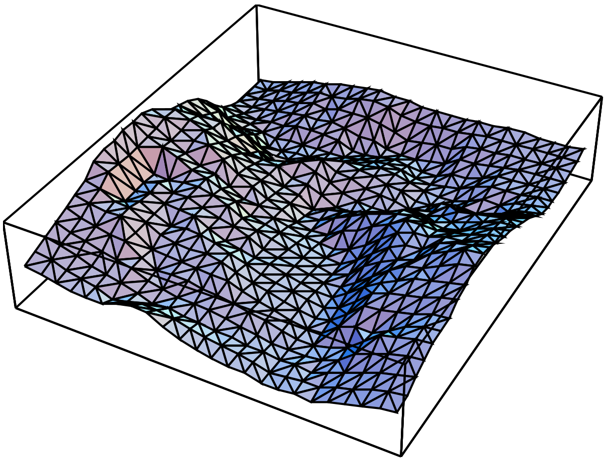

Figure 4. Triangular spatial model of the relief.

Figure 5. Spatial model of the site.

Figure 6. Spatial model of the dam and the site.

Since the building codes are based on elastic linear soil models [12], the proposed calculations was based on the methods of the theory of elasticity in order to be able to compare the calculation results with the results obtained according to regulatory documents.

A comparative analysis was carried out of the periods of natural oscillations, calculated by spatial flat models with the data of field measurements. It is important here to compare the results of spectral analyzes of accelerograms of strong earthquakes with the parameters of natural oscillations of earth dams. Accelerograms were used as accelerograms of strong earthquakes that occurred in Spitak (Armenia, 1988) (Fig. 7) and Izmir (Turkey, 1999) (Fig. 8), the scales of which are estimated at 0.45 g [10].

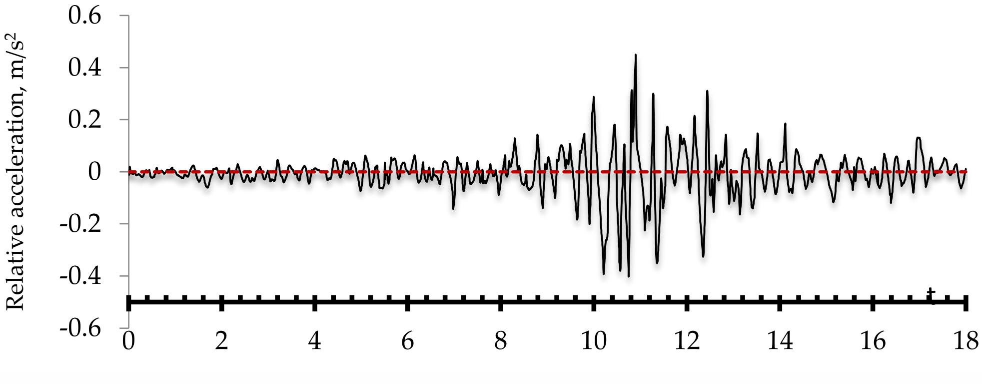

Figure 7. Accelerogram of horizontal accelerations of the 1988 Spitak earthquake on a scale of 0.45g.

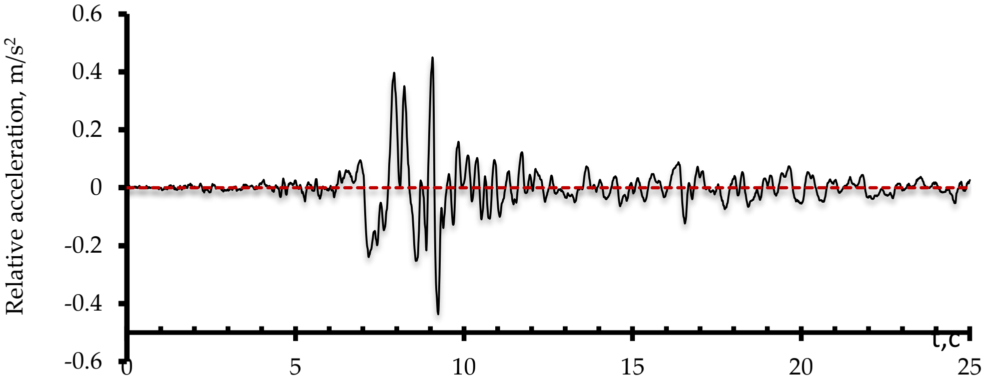

Figure 8. Accelerogram of horizontal accelerations of the 1999 Izmir earthquake at a scale of 0.45 g.

Accurate estimation of hydraulic structures stability is especially important from seismic impacts considerations. Toward this end it is necessary to solve a dynamic equilibrium equation in matrix form

$$[M]\{\ddot{a}\}+[D]\{\dot{a}\}+[K]\{a\}=\{F\}, \tag{1}$$

where $[M]=\int\limits_{s}\rho\{N\}^{T}\{N\}dS$ is the matrix of the mass, ρ is the specific mass, $[D]=\alpha[M]+\beta[K]$ is the damping matrix representing resistance of the material (extinction forces), $[K]=\int\limits_{s}[B]^{T}[C][B]dS$ is the stiffness matrix $\{F\}=\{F_b\}+\{F_L\}+\{F_n\}+\{F_g\}$ is the force vector at the node, $\{F_g\}$ is gravitation force, $\{\ddot{a}\}$ is the acceleration vector at the node, $\{\dot{a}\}$ is the velocity vector at the node, and $\{a\}$ is the node displacement matrix [14].

In case of elastic linear problems the constructive matrix $([C])$ is calculated according to Eq. (1.4) [15, 20]. Since real soils have non-linear properties, then the constructive matrix is calculated for each loading stage.

$$[C]=\frac{E}{(1+\nu)(1-2\nu)}\begin{bmatrix}1-\nu & \nu & \nu & 0\\ \nu & 1-\nu & \nu & 0\\ \nu & \nu & 1-\nu & 0\\ 0 & 0 & 0 & \dfrac{1-\nu}{2}\end{bmatrix}. \tag{2}$$

Dynamic (cyclic) loading increases porous pressure leading to the effective stress-strain state change of the body. That change is conditioned by respective change of mechanical properties of the material, i.e. the strength of soil material in case of dynamic loading acquires kinematic properties [11, 21].

The periods of natural oscillations of the dam and their shapes are determined by numerical integration of equation (1). However, in the case of considering the dam as an elastic body, Eq. (1) is modified in the form

$$[M]\{\ddot{a}\}+[K]\{a\}=0. \tag{3}$$

To integrate Eq. (3) by a physicomechanical method, taking into account the longitudinal and transverse components of the wave propagation velocity, Poisson's ratios (m) and Young's modulus (E) were determined. Using the data of the experiments carried out by formula (2), the stiffness matrix $[G]$ is calculated. The dynamic characteristics of soils are obtained from the reference book. Soil slip modulus and Poisson's ratio are determined by empirical formulas

$$G=\rho\times V_s^2, \tag{4}$$

$$\mu = \frac{0.5 - \gamma_v^2}{1 - \gamma_v^2}, \quad \gamma_v = \frac{V_s}{V_p}, \tag{5}$$

if σ_z > 0.2 MPa, then the value of V_s and V_p is determined by the following formulas

$$V_{p,s} = 1.3 \times V_{p_0, s_0} \times \left(\frac{\sigma_z}{\sigma_{z_0}} \right)^{1/6}, \tag{6}$$

$$G = 1.7 \times V_{s_0}^2 \times \left(\frac{\sigma_z}{\sigma_{z_0}} \right)^{1/3}, \tag{7}$$

where zero values of V_{s_0} and V_{p_0} are given in Table 2.

4. Results and Discussions

Equation (3) was integrated for the plane and spatial problems at various modes of oscillation, characteristic of the structure under consideration. However, the recommended forms of oscillation clearly do not correspond to the nature of the passing processes [20, 21]. In order to identify the true form of oscillations, calculations were carried out to determine the periods of oscillation.

As a result, oscillation periods were obtained for 20 different modes of oscillation (Fig. 8). Fig. 9 shows one of the modes of oscillations of the dam in the case of a plane problem, and in Fig. 10 – the same in the case of a spatial problem.

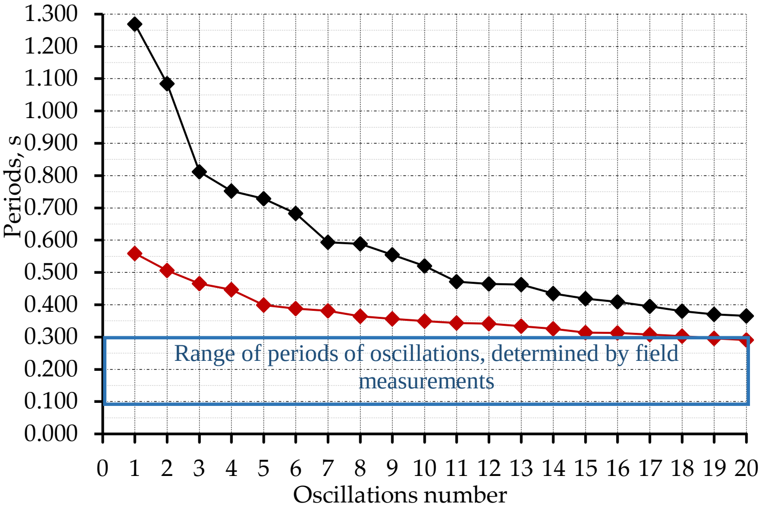

Figure 9. Graphs of periods of natural oscillations for different modes of oscillation: the graph above is the periods of natural oscillations for the plane problem, the graph below – the same for the spatial problem.

Fig. 10–13 show the results of calculations of natural vibrations for 4-puzzle flat design sections.

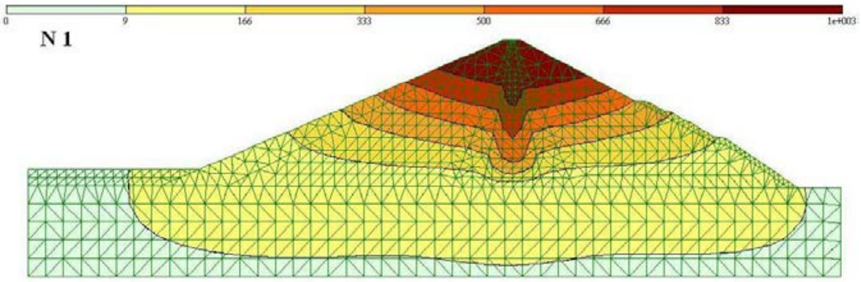

Figure 10. The form of natural oscillations of the dam in the design section for the plane problem. Form 1.

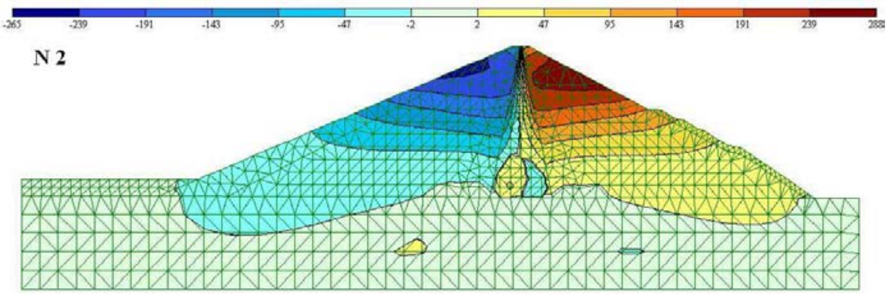

Figure 11. The form of natural oscillations of the dam in the design section for the plane problem. Form 2.

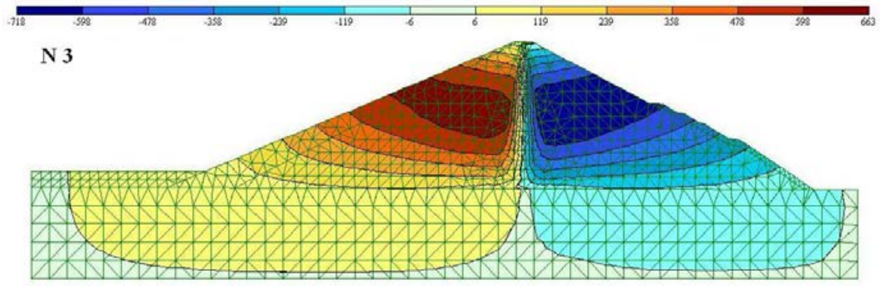

Figure 12. The form of natural oscillations of the dam in the design section for the plane problem. Form 3.

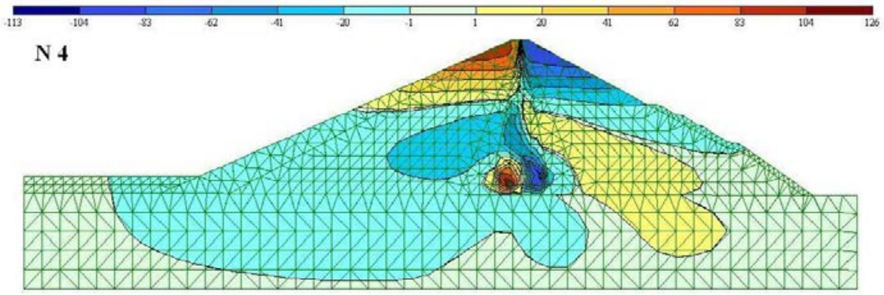

Figure 13. The form of natural oscillations of the dam in the design section for the plane problem. Form 4.

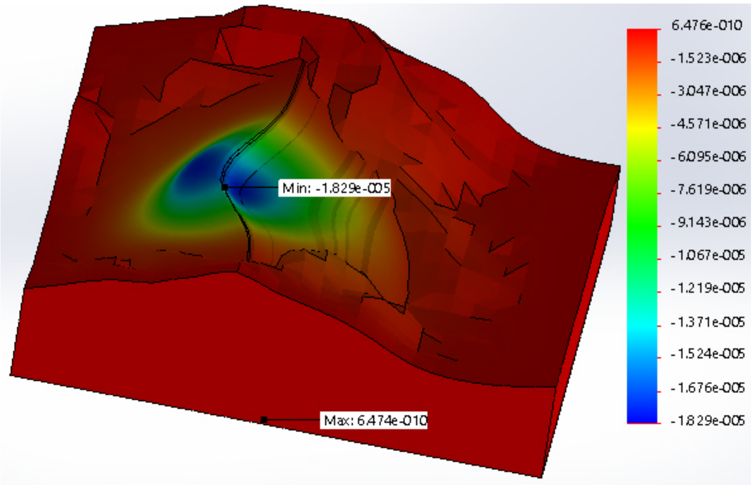

Figure 14. The form 1 of natural oscillations of the dam for the spatial problem.

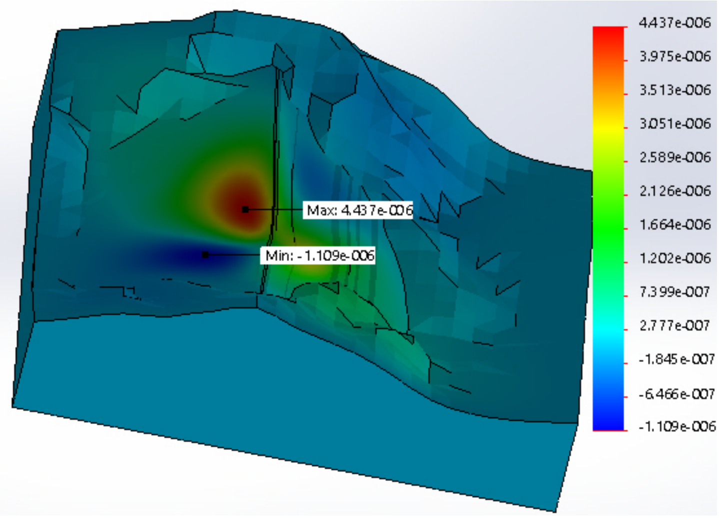

Figure 15. The form 2 of natural oscillations of the dam for the spatial problem.

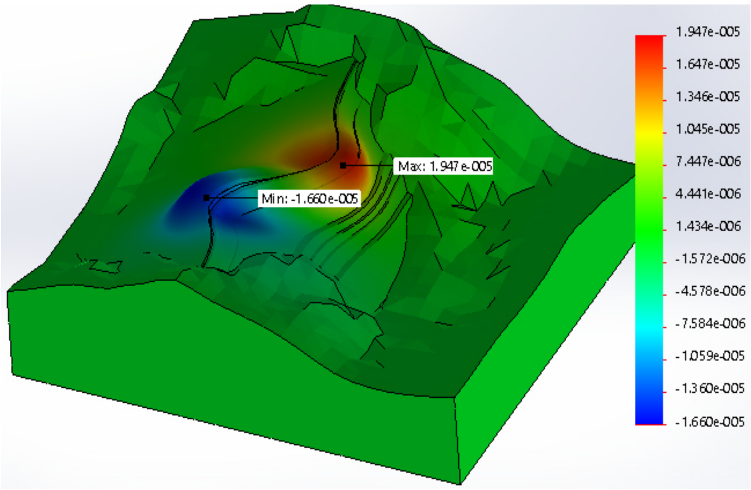

Figure 16. The form 3 of natural oscillations of the dam for the spatial problem.

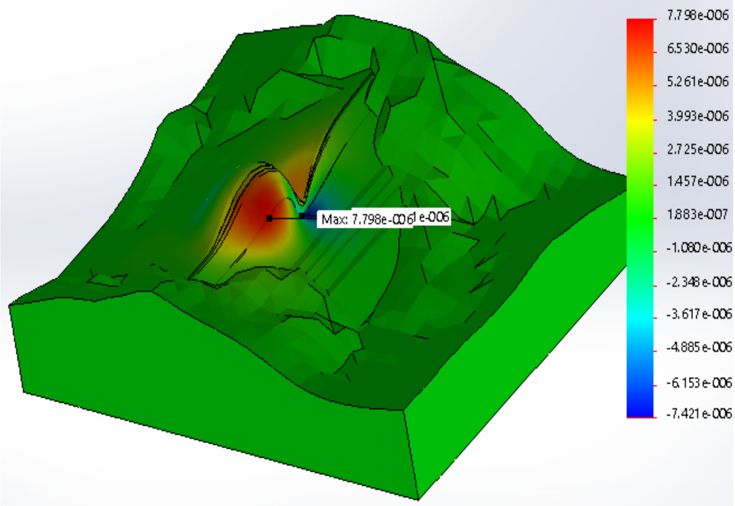

Figure 17. The form 4 of natural oscillations of the dam for the spatial problem.

The results of spectral analyzes of the Spitak and Izmir earthquakes accelerograms, carried out by the method of discrete Fourier transforms, are shown in Fig. 11 and Fig. 12. The calculations were carried out at different values of the logarithmic decrement, which correspond to the values of the soil properties of the dam body and foundation.

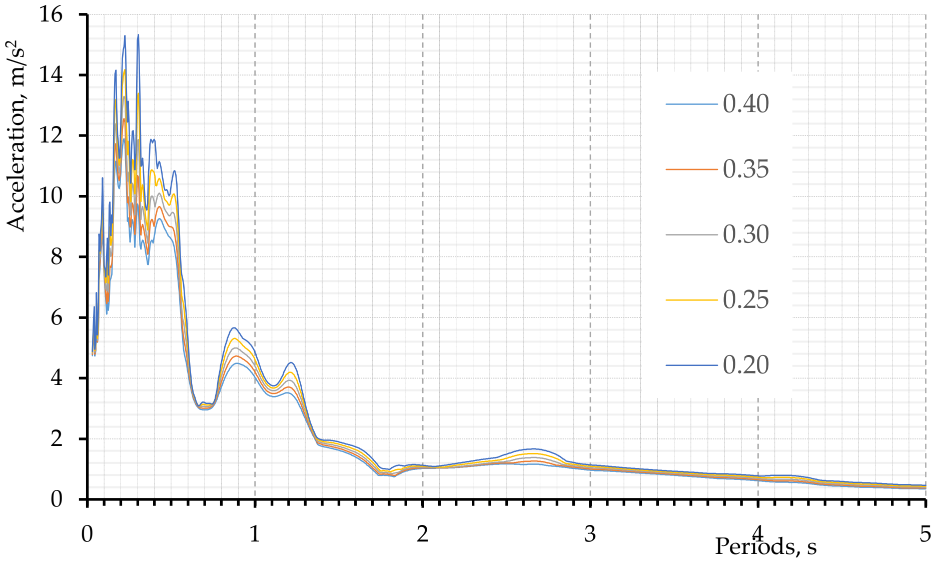

Figure 18. Spectral analysis of the asceliogram of the Spitak earthquake with an acceleration of 0.45g in the interval of the logarithmic determinant 0.2..0.4.

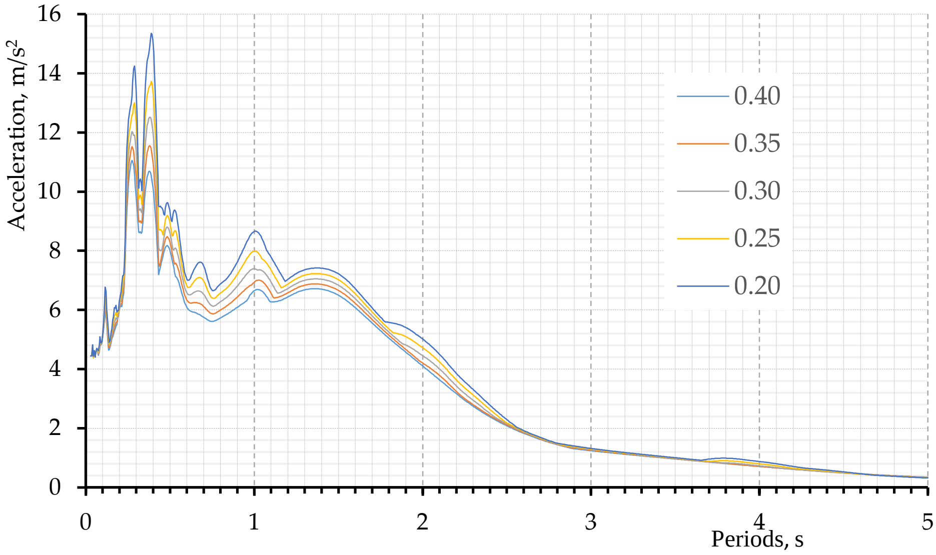

Figure 19. Spectral analysis of the asceliogram of the Izmir earthquake with an acceleration of 0.45g in the interval of the logarithmic determinant 0.2..0.4.

The analysis of the results obtained shows that the maximum horizontal accelerations are obtained in the interval of the oscillation period of 0.3 ... 0.4 s.

5. Conclusions

Comparison of calculated and measured data reveals the essence of dynamic phenomena and gives comparable results. In the case of an approximate plane problem, an excessively large range of periods of natural oscillations is obtained, which indicates an excessively elastic property of the structure. The spatial model gives more approximate values of the periods of natural oscillations. However, here we also neglect the nonlinear properties of the soil and the decay coefficient. It should be noted that in elastic models, where the effect of the decay coefficient is neglected, the value of natural oscillations becomes close to their maximum values.

The results of in-situ measurements by natural oscillations are obtained less than their calculated values. This means that, in reality, the properties of the soil are non-linear, and the process has a damping character.

The results of spectral analysis of accelerograms have shown satisfactory agreement with the results of natural oscillations field measurements, but there are some risks of resonance.

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Received 26.11.2021. Approved after reviewing 17.10.2022. Accepted 18.10.2022.