Strength Evaluation of the Charvak Earth Dam in a Plane Formulation

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ABSTRACT

Currently, the Republic of Uzbekistan is undergoing rapid development in the sphere of the hydropower complex. In the next five years, it is planned to commission more than 20 HPPs of large and small capacity; the water retaining structure of which are the earth dams. The reliable and safe operation of earth dams, especially in the seismic regions of the republic, requires designers and researchers to constantly improve the design normative methods for their calculation in order to identify safety margins and stability under various kinds of loads. The aim of the study is to develop a method for calculating the stress state of an earth dam of the Charvak HPP (in a plane elastic formulation) under loads, taking into account the levels of the reservoir filling. Structural and piecewise inhomogeneous physical and mechanical characteristics of the structure body soil were provided by the design organization. The developed methods made it possible to compare the calculation results - kinematic characteristics (displacements, settlements, stresses, pore pressure) with long-term data of field observations. To predict the state of a structure under certain loads for safe operation in accordance with the standards, it is necessary to identify the stress-strain state of the most vulnerable areas. This problem was solved by the numerical finite element method. In accordance with the developed technique, the considered statics problem was reduced to solving a system of linear equations with respect to the sought-for displacements. The obtained results of calculations are presented in the form of isolines of horizontal and vertical displacements, normal and tangential stresses in the body of the dam under the main loads in comparison with the measurement data by control and measuring equipment. The eigenfrequencies obtained as a result of the calculations are compared with the previously obtained experimental results.

KEYWORDS: *finite element method, stresses, displacements, pore pressure, earth dam of the Charvak HPP.*

Introduction.

Stone-earth dams have become widespread in the world and in particular in the Republic of Uzbekistan, (which is a seismic region) due to their durability, reliability in operation, unpretentiousness to the geological conditions of the alignment, to the type and quality of building materials used for their construction. For the anti-seepage elements of the profile for high dams, questions arise about the strength of clay screens and cores. The design and safe operation of modern high dams require, on the one hand, the development of a sound and reliable theory of earth dams, and, on the other hand, the organization of field studies, on the basis of which the state of the constructed structure is assessed and a forecast of its change is made. The stone-earth dam of the Charvak hydroelectric power station, which has been in operation since 1975, was the first structure in the former USSR, sufficiently detailed with modern instrumentation and special devices. Water retaining structures, in particular, dams are subjected to loads: static (gravitational forces, hydrostatics, etc.), and dynamic (vibrations, seismic, etc.). In contrast to the current normative method for calculating earth dams for loads based on the linear spectral theory, the method developed by the authors, the complex of applied programs for solving statics problems for an earth dam (in a plane elastic formulation) was tested by solving test problems, as well as by comparing with available data of field studies. The task is based on the determination of the stress-strain state of an earth dam under the main loads - the force of gravity, hydrostatics. Such aspects were covered in, which analyze the data of field observations (precipitation, horizontal displacements, stresses, pore pressure) at the world's highest Nurek earth dam. The authors of these publications compared the results of field observations of dams with the results of calculations based on field data of the Nurek HPP. Comparison of the results of numerical modeling and field observation data when assessing the state of the earth dam of the Gotsatlinskaya HPP is given in.

Based on the data of field observations and the results of geotechnical control, mathematical models of the stress-strain state in and the thermal regime of the dam were developed for the periods of construction and operation. The process of model calibration is presented and the results of predictive calculations of the state of the structure by the finite element method are presented. The solution of such problems of predicting the state of an earth dam by identifying the main patterns of behavior under loads, taking into account the real geometry, piecewise heterogeneous characteristics of soils (central core, thrust prisms) makes it possible, if necessary, to develop effective anti-seismic measures that ensure the trouble-free operation of structures. In these articles, on the basis of plane and spatial design schemes, the tasks of assessing the strength of operating earth dams in the republic that are subject to high seismic risk were solved. The linear and nonlinear deformation of soil, such as plasticity, viscoelasticity, moisture content, as well as structural features were considered. In these studies, the analysis of the stress-strain state of earth dams was made in the framework of: - plane model and spatial model. In the computational models, the base of the dam is assumed to be absolutely rigid.

When solving the problems of studying the dynamic behavior of an earth dam under loads, a numerical method was used - the finite element method, which allows taking into account the nonlinear properties of soils.

In this article, the following problems were solved: 1-static problem on the study of stress-strain state of an earth dam under basic loads (gravitational forces, hydrostatics); 2- dynamic task (determination of dynamic characteristics).

The results of solving the problem: statics - kinematic characteristics (displacements, stresses) were compared with long-term data of field observations provided by JSC "Hydroproject"; eigenfrequencies were compared with experimental ones.

Methods

The mathematical formulation of the problem is based on the Lagrange variational principle, according to which the work of all forces on a virtual displacement is zero. In this case, the equations is written in the following form [1,2]:

$$\delta A = -\sum_n \left(\int_{V_n} \sigma_{ij} \delta\varepsilon_{ij} dV - \int_{V_n} \rho_n \ddot{\vec{u}} \delta\vec{u} dV + \int_{V_n} \vec{f}_n \delta\vec{u} dV \right) + \int_S \vec{p} \delta\vec{u} dS = 0 \quad i,j = 1,2,3 . \; (1)$$

where $\vec{u}$, ε_{ij}, σ_{ij} - are the vector of displacements, tensors of strains and stresses, respectively; ρ_n is the density of the materials of the system; the index *n* takes the following values: for the structure *n* = 1, for the area of the anhydrite zone (*n* = 2) and for the area of the base (*n* = 3); $\vec{f}_n$ is the vector of mass forces (weight); $\vec{p}$ - is the hydrostatic pressure on the surface *S* of the system in contact with water (at the base, on the upper and lower slopes); $V=V_1+V_2+V_3$; V_1,V_3– are the volumes of the upper and lower retaining prism; V_2– is the volume of the central core (Fig. 1).

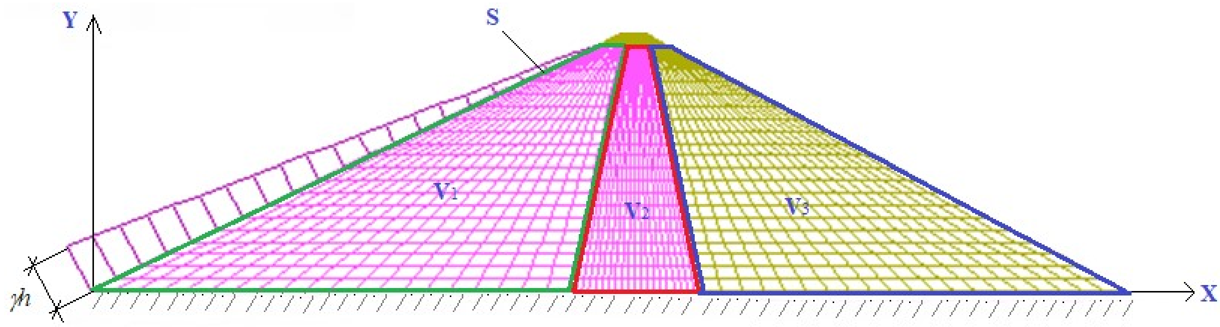

Fig. 1. Calculation model of an earth dam (plane formulation) on a rigid base taking into account hydrostatics

The variational method applied to the solution of the problem under consideration is a well-known method for solving mathematical problems by minimizing a certain functional based on the use of a test function that depends on a small number of parameters.

At present, when calculating the stress-strain state (SSS) of earth hydro-technical structures, numerical methods are used since it is almost impossible to obtain analytical solutions for inhomogeneous, nonlinearly deformable bodies of a complex geometric shape.

For the surface of the upper slope, the boundary conditions are as follows:

$$p_x = \sigma_{xx} l_1 + \tau_{xy} m_1, \quad p_y = \tau_{xy} l_1 + \sigma_{yy} m_1. \qquad (2)$$

where p_x, p_y –are the components of stresses from hydrostatic pressure, equal to zero in the absence of pressure; l_1, m_1, – are the direction cosines of the upstream slope area.

Boundary conditions at the crest of the dam and at the surface of the downstream slope are:

$$\tau_{xy} = 0, \quad \sigma_{yy} = 0. \qquad (3)$$

$$\sigma_{xx} l_2 + \tau_{xy} m_2 = 0, \quad \tau_{xy} l_2 + \sigma_{yy} m_2 = 0. \qquad (4)$$

where l_2, m_2, – are the direction cosines of the area of the downstream slope.

In the absence of loads acting on the slopes and the crest of the dam, the static boundary conditions on these surfaces are

$$\sigma_{ij} n_j = 0, \qquad (5)$$

where n –is the normal vector to the surface.

An account for the hydrostatic pressure on the upstream slope is reduced to setting the pressure which linearly increases with depth on the slope surface

$p=\rho gz,$ (6)

where z –is the depth measured from the free surface of water; *g* is the acceleration of gravity.

The boundary conditions at the lower boundary of the base are rigid, which is expressed in the absence of horizontal and vertical virtual displacements:

$y=0: \quad \delta u|_{y=0,}=0; \ \ \delta v|_{y=0,}=0.$ (7)

When solving the problem of statics for an earth dam, the variational equation (1) is rewritten in the form (8) that is, there is no integral related to inertia [13-20]:

$$\delta A = \delta A_\sigma + \delta A_P + \delta A_P = -\int_V \sigma_{ij}\delta\varepsilon_{ij}dV + \int_V \rho g \delta v dV + \int_S \gamma h \delta v dS = 0 \qquad (8)$$

Thus, a plane-deformable model (a cross-section) of an earth dam, located on an elastic foundation, is considered. When solving problems: 1) of statics, the stress-strain state of the dam is investigated under the main loads; 2) of dynamics, dynamic characteristics taking into account the piecewise inhomogeneous characteristics of soil of the dam body (the presence of a core) are determined.

Hooke's law and Cauchy relations are added to the above-mentioned plane elastic formulation of problems.

For the numerical solution of the problems posed, the finite element method is used [1,2]. With the developed methods, algorithms for solving statics problems are reduced to a system of homogeneous linear first-power algebraic equations, which can be solved with respect to displacements of nodal points; in the dynamic calculation [1,2], the variational problem (1) - (4) is reduced to an algebraic problem of eigenvalues

$([K]-\omega^2[M])\{X\}=0,$ (9)

here [K] and [M] are the stiffness and mass matrices of the structure; ω, {X} – are the eigenfrequencies and vibration modes of the structure. The Muller method was used to find the roots of this system of algebraic equations, and the square root method was used to construct eigenforms [1,2].

Solving test problems. To check the reliability of the developed methods and a set of applied programs for the study of the stress-strain state of a plane structure under static loads, the results of the dynamic calculations were compared with the experimental given and previously solved.

Results and discussion

In the calculations, as an example, the section of the Charvak earth dam of a height of 131 m was considered; slope ratio coefficients 1.8, cores - 0.2, physical and mechanical parameters of the soil of the prisms for section 6 E = 60 MPa, volumetric weight $\gamma_{сух}$= 1950 kg/m^3, $\gamma_{нас}$= 2230 kg/m^3; Poisson's ratio μ = 0.3. parameters of the soil of the core are: E = 30 MPa, bulk density $\gamma_{сух}$= 1760 kg/m^3, $\gamma_{нас}$= 2110 kg/m^3, Poisson's ratio μ = 0.3, slope coefficients 0.2 (data of JSC "Hydroproject").

In accordance with the acting norms of Sections KMK, for the dam with a loamy core under consideration, the pore pressure arising during filling of the reservoir and operation of the hydrotechnical structure should be determined. In calculations, section 6 of the dam was considered, due to the fact that during the construction process there were installed KIA - soil dynamometers (SD), piezodynamometers (PD) (see Fig. 2)

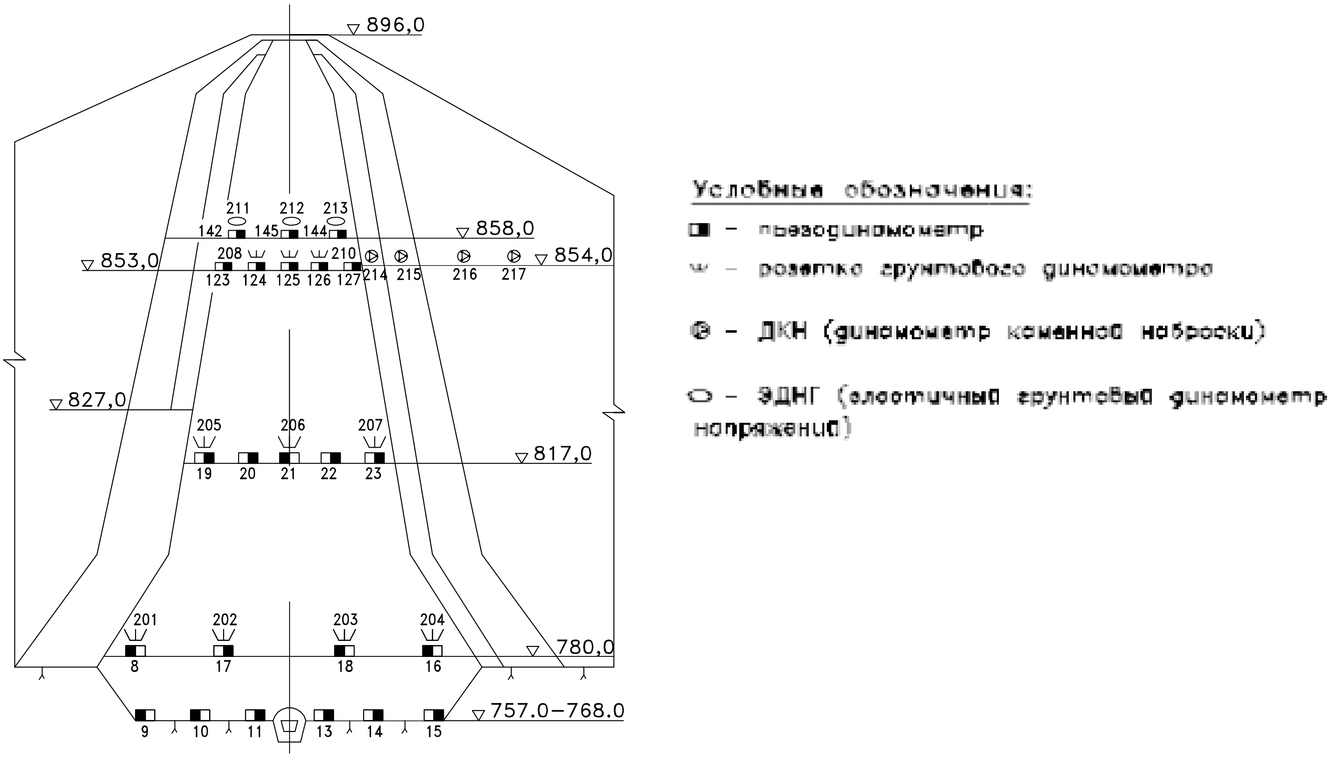

Fig. 2. Layout of soil dynamometers and piezodynamometers in the dam. Section 6

The hydrostatic pressure P on the upstream slope acts along the normal to the surface of the upstream slope and is determined by a linear function by the formula $P = \gamma h$, where γ is the specific gravity of water; h is the depth.

The result of the solution of the problem is the distribution of lines of equal stresses in the body of the dam, taking into account the forces of gravity and hydrostatics at a NSP 125m. Figure 3 shows the distribution of lines of equal vertical stresses in the dam body with the above factors at an elevation of 780.0 m. The readings of a soil dynamometer (SD), piezodynamometer (PD - for pore pressure) from the time of operation of an earth dam are presented by JSC Gidroproekt (Fig. 4).

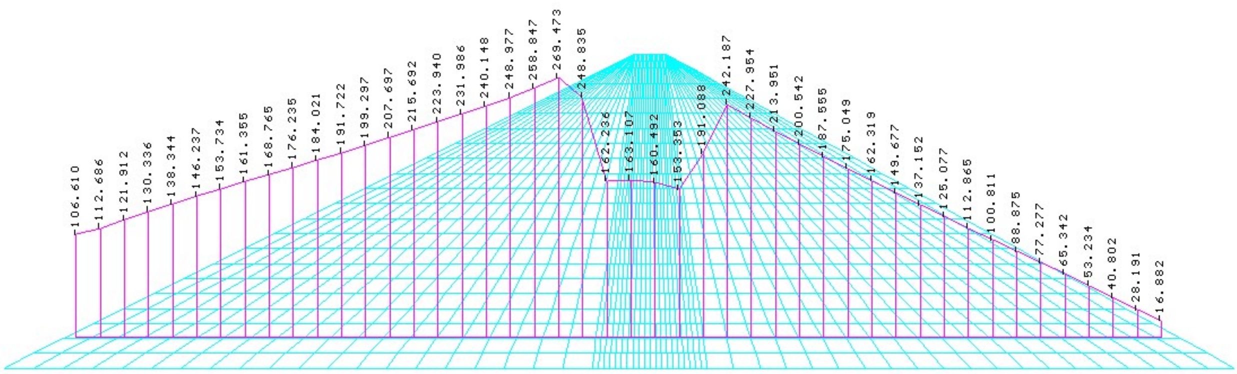

Fig. 3. Design diagrams of vertical stresses σ_y (t/m^2) in the body of an earth dam at an elevation of 780.0 m.

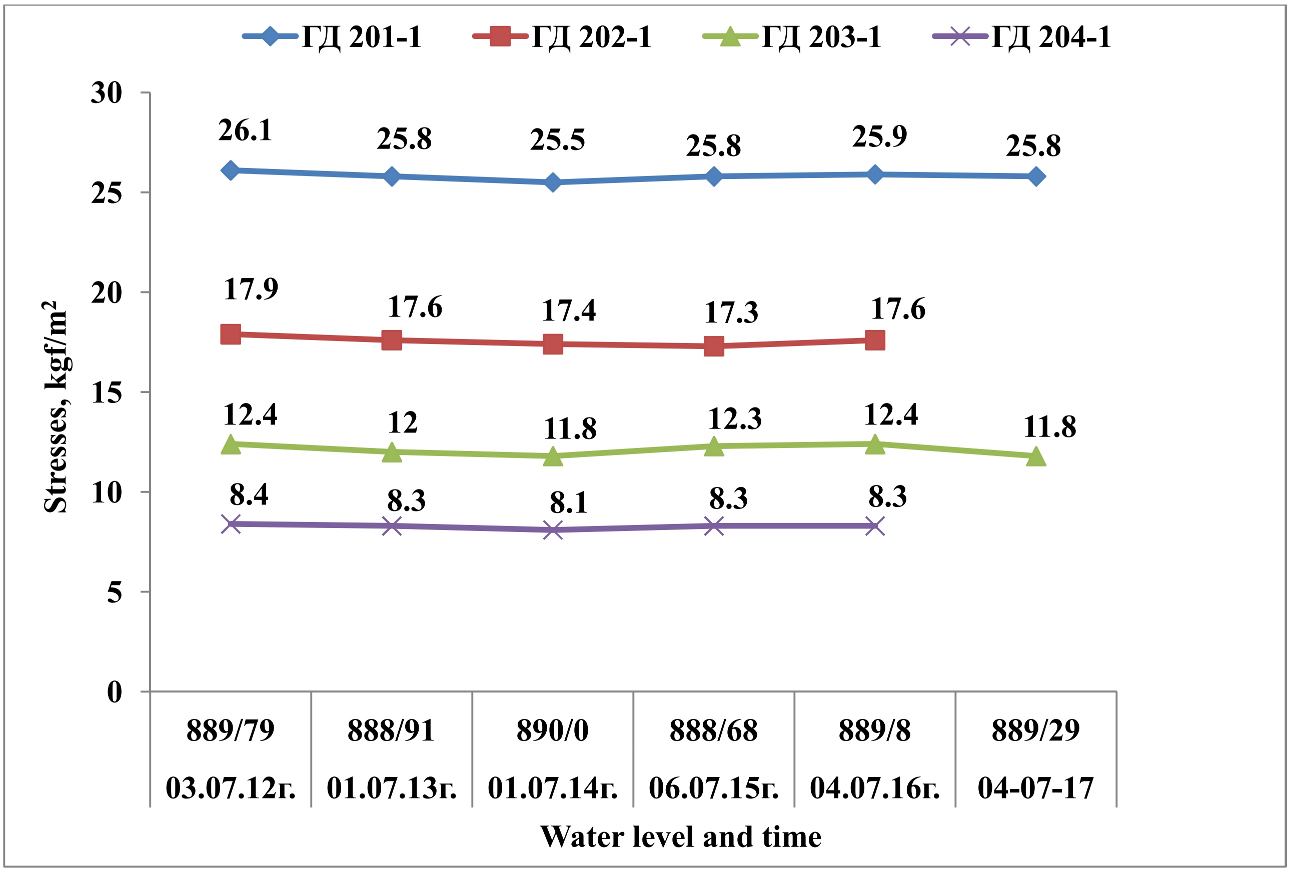

Fig. 4. Data of field observations of vertical stresses σ_y (kgf/sm^2) at the water level 780.0 m, depending on the service life

Comparison of the results of calculations in the body of an earth dam for horizontal and vertical stresses with the available field data shows a difference of 5 and 9% for section 6, taking into account the pore pressure (see Figs. 3, 4). This proves that the residual pore pressure is present at these elevations and forms a core of pore pressure; the consolidation process takes place at an elevation of 780.0 m, which, as seen from Figs. 3.4, is practically at the base of the dam, but above the base of the core. Consequently, at this elevation, the maximum pressure occurs from the core of the dam, thrust prisms and, accordingly, the pressure in the reservoir. When designing an earth dam, a scheme of control signs is developed for each section along which displacements are monitored.

The results of calculating horizontal and vertical displacements in the body of an earth dam and field observations for section 6, where the control signs are installed, are shown in Figs. 5,6.

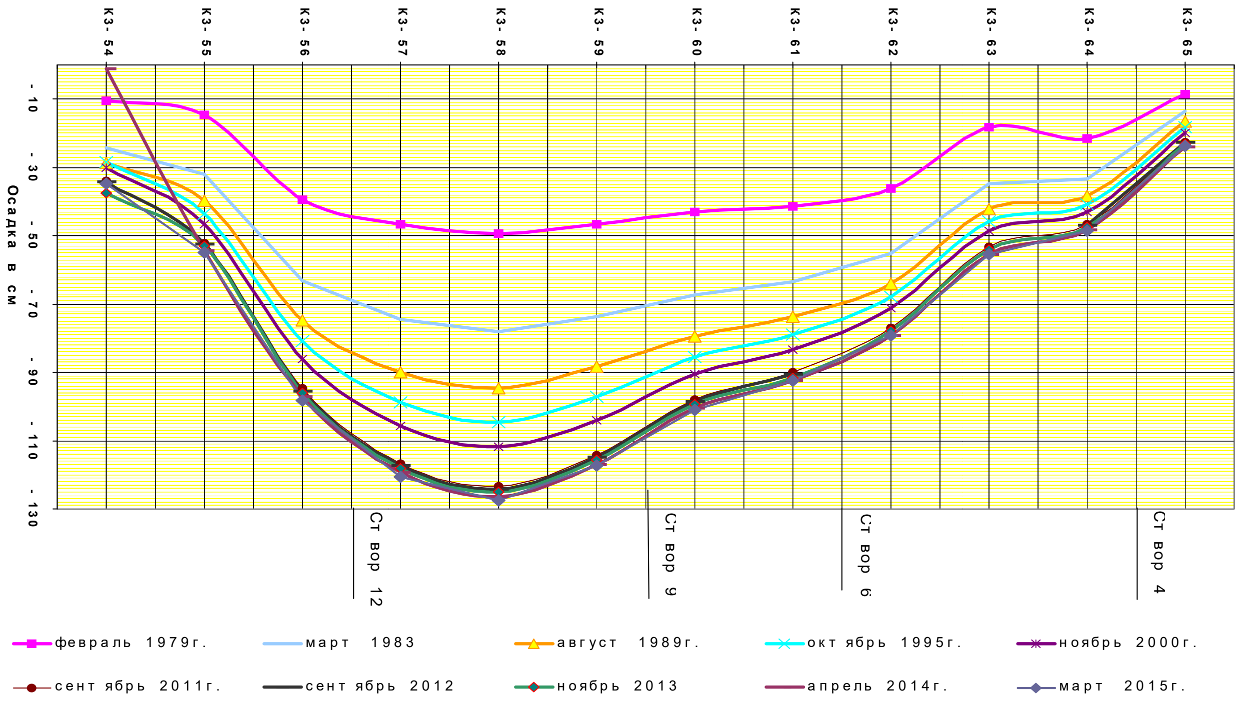

Fig. 5 Settlement of the berm of the upper thrust prism of the dam at the elevation of 872.0 m during the operational period

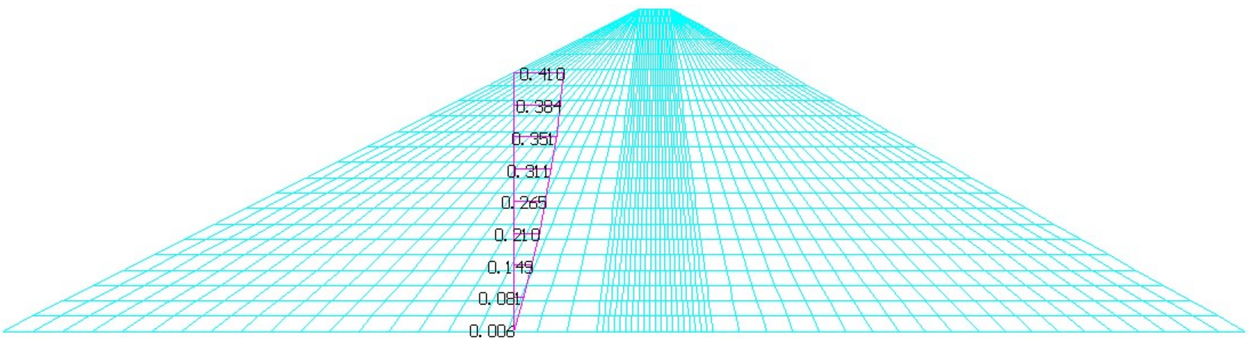

Fig. 6 - Diagrams of vertical displacements (m) (settlement) of the dam, taking into account the forces of gravity and hydrostatics (mark 872.0). Section 6

Comparison of the results of calculations of vertical displacements with field data shows a difference of 8% for section 6 and 9% for section 9 (Figs. 5, 6).

The calculated settlements of the earth dam taking into account hydrostatics after the completion of construction are shown in Fig. 5 (February 7, 1979). Comparison of the results of calculations with the data of field observations to determine the dam settlement under the filled reservoir indicated their complete coincidence, which proves the reliability of the developed calculation program and the complete consistency of their nature with the well-known solutions obtained by Prof. Goldin A.S.

Dynamic characteristics (eigenfrequency, mode of vibration and damping coefficient) of a structure are their main characteristics (a passport). Knowing the eigenfrequencies of vibrations, we can estimate the possibility of the occurrence of resonance phenomena and dissipative properties in general, and the known modes of vibrations make it possible to determine the displacements and stresses arising in a structure under various impacts.

As an example of the calculation, the channel section of an earth dam was taken at averaged physical and mechanical characteristics of the dam body material: H = 168 m, V_S = 2500 m/s, $\nu = 0.3, \rho = 0.27$ t/m^3. The values of the eigenfrequencies obtained by calculation and experimentally are shown in Table 1.

Table 1-Natural vibration frequencies (Hz).

No. of vibration tone	$f_{одн}$	$f_{экп}$ [17]
1	1.2786	1.3-1.6
2	1.9779	1.8-2.0
3	2.4001	
4	2.5717	2.5-2.8
5	3.1013	
6	3.2601	3.3-3.6
7	3.8697	
8	3.9664	
9	4.0776	4.2-5.
10	5.6659	
11	4.8144	
12	5.2612	
13	5.3422	
14	5.5821	
15	5.7389	6.2-6.5

Comparison of the calculated and experimental frequencies indicates the reliability and convergence of the results.

Conclusions:

- the formulation of a static and dynamic problem for an earth dam (in a plane elastic formulation) is given; the methods and algorithms for solving problems by the finite element method were developed;
- when comparing the results of calculating the horizontal and vertical stresses in the earth dam under the main loads with field data, a difference of 5 and 9% was established for section 6, taking into account the pore pressure.
- comparison of the results of calculating the maximum horizontal displacements in the body of an earth dam under main loads with field data showed a difference of 14% for section 6 and 18% for section 9.
- comparison of the results of calculations of vertical displacements in the body of an earth dam under main loads with field data revealed a difference of 8% for section 6 and 9% for section 9.
- the numerical results obtained from studies on determining the stress-strain state under main loads of an earth dam give grounds to assert the possibility of determining the reliability of operating facilities;
- the calculated dynamic characteristics of the earth dam were compared with the experimental ones, which proves the reliability of the results obtained;
- the solution of the above problems makes it possible to predict the state of an earth dam under static and dynamic loads, confirmed by a statistical analysis of damage and to develop appropriate recommendations.

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