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DYNAMIC CALCULATION OF THE PLANE ELASTIC "DAM-FOUNDATION" SYSTEM

Abstract: design, construction, and reliable and safe operation of earth dams (more than 60 of them are in operation in the Republic of Uzbekistan located in seismic region) put forward requirements for the continuous improvement of the calculation methods for loads; as required by regulatory methods for fundamental (static) and special (dynamic) load combinations. These regulatory methods do not take into account the nonhomogeneous nature of the behavior and piecewise heterogeneity of the characteristics of foundation, and the stress-strain state (SSS) of an earth dam under constant or temporary loads, which is necessary for reliable and safe operation, especially in seismic regions. A general mathematical formulation of problems for earth dams in a plane elastic formulation is given. Dynamic calculations were conducted to determine the stress-strain state of an earth dam, taking into account the design features and real piecewise-nonhomogeneous physical and mechanical characteristics of soil of the structure body and base (these characteristics were provided by the design organization). The problem was solved by the numerical finite element method. The eigenfrequencies and modes of vibrations of the plane "structure-foundation" system are determined, considering the homogeneous and piecewise-nonhomogeneous characteristics of the foundation soil; the corresponding analysis of the behavior of the system was made. The stress-strain state of the "dam-foundation" system was investigated using calculated frequencies. The calculation results were lines of equal displacements (horizontal, vertical), normal and shear stresses in the "dam-foundation" system.

Keywords: dynamic calculation, eigen frequencies, modes of vibrations, stress-strain state, finite element method, earth dam

Introduction

One of the advantages of earth dams operating in the Republic of Uzbekistan is that they are erected from local material (soil) that meets the requirements for the type and quality of construction. As is known, all hydro-technical structures are subjected to loads - fundamental (gravitational forces, water pressure, etc.) and special combinations of loads (seismic loads). The acting normative methods for calculating earth dams for dynamic loads are based on a one-dimensional linear-spectral theory and cannot take into account the non-uniform nature of the structure's behavior, and the piecewise non-homogeneous characteristics of the foundation soil [1, 2]. The problem considered here is based on the dynamic calculation of an earth (stone-earth) dam and the determination of the stress-strain state.

Due to the fact that the republic is located in a seismically active zone, much attention is paid to the issues of reliable and safe operation of hydro-technical structures, in particular, earth dams since their damage or accidents can lead to colossal consequences of a moral and material nature on the downstream territories [3, 4]. Therefore, in all critical hydro-technical structures, such as high earth dams (with a height of more than 100 m), automated monitoring of their condition is performed based on the results of engineering and seismometric service data (in particular, the vibration spectrum of the structure is recorded during an earthquake) [5, 6], as well as field observations data from measuring equipment [7, 8, 9]. To improve the calculation methods for the dynamic calculation of earth dams, it is envisaged to compare the monitoring data with theoretical results.

In [10, 11], problems were proposed and solved to determine the stress-strain state of the earth dam of the Charvak HPP under non-stationary dynamic impact, taking into account the real dissipative properties of soil that make up the body of the dam. The authors of the references [7, 8, 9] provided an analysis of field data of an earth dam (precipitation, horizontal displacements, stresses, pore pressure) for 47 years of observation at the highest earth dam in the republic, the Charvak HPP. An analysis of a number of publications devoted to field observations of dams was given in those articles and the results were compared with field observations for the earth dam of the Nurek HPP to assess the quality of dam construction in comparison with other dams built in the former USSR and abroad [12, 13]. The formulation and solution of dynamic problems for a number of earth dams in a plane formulation, taking into account the adjacent soil base, was done in [14, 15]. Investigation of the stress-strain state of a

plane elastic earth dam under static loads for the selection of building materials as a reinforced concrete screen in soil dams was studied in [16, 17].

Foundation deformation in soil structures, their defects and damage affect the technical condition of the entire structure. The main causes of defects and damage are dynamic loads (seismic and explosive ones); aging of waterproofing materials; change in the groundwater level and underestimation of the physical and mechanical characteristics of the base soil during the construction and operation stages.

The most characteristic signs of deformations of earth foundations are nonuniform and local subsidence; actual precipitation exceeding permissible values; bulging of the base soil from under the foundation bed, washing out of the base; soil heaving.

At present, in the calculation of soil structures for certain loads, the soil of the structure body is considered as piecewise homogeneous medium or piecewise nonhomogeneous (continuous, isotropic) medium. The characteristics of the contacts of the heterogeneous massifs elements are also important: rigid cohesion, lack of cohesion, friction displacement, and initial stress-strain state.

According to regulatory documents, when designing earth dams, it is necessary that its foundation consists of firm (rocky, semi-rocky, etc.) soils [2], otherwise, it is necessary to develop reinforcing measures. In practice, there are cases when an inclusion (weakened (anhydrite) zone) with a low modulus of elasticity is observed in the earth foundation. The purpose of this study is to develop a methodology and algorithm for solving a dynamic problem for a soil dam with a piecewise nonhomogeneous base. The problem was solved in a plane elastic formulation for a specific earth dam of the Tupolang HPP operated in Uzbekistan (the operating period is more than 30 years; the seismicity of the territory is 9 points). The Institute of «Hydroproject» JSC provided the initial data for the calculation. After pilot drilling of wells the characteristics of the foundation soil at a depth of more than 100 m from the bed of the high earth dam of the Tupolang HPP were determined.

Intense and long-term dynamic and seismic effects can significantly affect the dynamic behavior and the overall pattern of stress distribution in earth structures and their foundations, related to the nature and intensity of the impact, its duration and frequency spectrum, and changes in the physical and mechanical characteristics of soil.

The use of analytical methods is unacceptable to assess the stress-strain state of earth dams, taking into account the design features, the real physical and mechanical characteristics of soil that make up the body and foundation of the dam. These methods do not allow investigating the stress-strain state of an earth dam and constructing vibrations for structures of complex geometry. The solution to such problems is feasible only on the basis of modern computational methods, the use of which makes it possible to solve the problems of natural vibrations of nonhomogeneous structures of various geometries. The most widely used method for solving problems of structural dynamics is the numerical finite element method with domain discretization by plane triangular elements. Relatively simple logic makes it almost ideal for solving many problems of mechanics of solid.

Methods and Materials

An earth structure is considered under plane strain (Fig. 1).

Fig. 1. Plane model of a longitudinal section of an earth dam (1) in a nonhomogeneous soil (3) with an inclusion (anhydrite zone) (2)

In the mathematical formulation of the problem of the dynamic behavior of a nonhomogeneous model (Fig. 1), a variational principle is used, according to which the sum of the work of all forces (elasticity, inertia, mass and hydrostatic pressure) on virtual displacements is zero [18, 19, 20].

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

$i, j = 1, 2, 3$

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; 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).

The boundary conditions are as follows:

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

$$y = 0: \delta u|_{y=0} = 0; \delta v|_{y=0} = 0 \quad (2)$$

2. On the hinged-movable (vertical) side boundaries of the base, horizontal displacements of the contour points are not allowed:

$$\left. \begin{aligned} \delta u|_{x=0} &= 0; \delta v|_{x=0} \neq 0 \\ \delta u|_{x=l} &= 0; \delta v|_{x=l} \neq 0 \end{aligned} \right\} \quad (3)$$

3. On the crest and side edges of the structure not in contact with water

$$\sigma_{ij} n_j = 0 \quad (4)$$

where n is the normal vector to the surface.

4. On surfaces in contact with water, an account for hydrostatics is reduced to setting hydrostatic pressure, linearly increasing with depth

$$p = \rho g z \quad (5)$$

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

The use of a numerical FEM assumes a partition of a plane model into finite elements with approximating functions [18].

To obtain the resolving system of equations by the finite element discretization method, the elements are combined at the nodal points, the displacements of which are the solution to the variational equation (1), realizing the extremum (minimum) of the functional of work.

The finite element method procedure reduces the solution of the dynamic problem of eigenfrequencies and modes of vibration to the solution of the problem of eigenvalues, where (ω) are the eigenfrequencies; and $\{u\}$ is the vector of the corresponding eigenform)

$$([K] - \omega^2 [M]) \{u\} = 0 \quad (6)$$

In equation (6), $[K]$, $[M]$ are the stiffness and mass matrices of the entire model, formed from the corresponding matrices of individual elements; $\{u\}$ is the sought-for vector of nodal displacements; $\{\ddot{u}_0\}$ is the acceleration of the base.

According to the modes obtained in the course of solving system (6), which represent the displacements $\{u\}$ of nodal points of the model, displacements within each element were determined (using approximating functions), and then deformations in the elements were determined using the Cauchy equations

$$\begin{aligned}\varepsilon_x &= \frac{\partial u}{\partial x} \\ \varepsilon_y &= \frac{\partial v}{\partial y} \\ \gamma_{xy} &= \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\end{aligned}\quad (7)$$

The stresses were determined based on the strains obtained

$$\begin{aligned}\sigma_x &= \frac{E}{1-\mu^2} \left(\frac{\partial u}{\partial x} + \mu \frac{\partial v}{\partial y} \right) \\ \sigma_y &= \frac{E}{1-\mu^2} \left(\frac{\partial v}{\partial y} + \mu \frac{\partial u}{\partial x} \right) \\ \tau_{xy} &= \frac{E}{2(1+\mu)} \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)\end{aligned}\quad (8)$$

When carrying out dynamic calculations of hydro-technical structures for kinematic (seismic) impact, it is necessary to determine seismic load according to the spectral method of calculating the seismic resistance of structures, by the following formula [1]

$$S_{ik} = Q_k A \beta_i \eta_{ik} \quad (9)$$

where Q_k is the weight acting on the k -th node; A is the calculated seismicity (0.1-7 points, 0.2-8 points, 0.4-9 points); β_i is the dynamic factor (inversely proportional to the period of natural vibrations); η_{ik} are the coefficients of the mass-normalized eigenforms obtained by solving the eigenvalue problem.

Thus, the first step in dynamic calculations is to find the fundamental frequencies and modes of natural vibrations of the object under study, which enter the formula for the conditional seismic load. The dynamic characteristics of the “dam-nonhomogeneous foundation” system are determined in the absence of static and dynamic loading.

To check the developed methods and software algorithm, a test problem for the Nurek earth dam was solved and compared with the methods previously obtained in [19].

Table 1

Comparison of the fundamental eigenfrequencies of the Nurek dam

№ of eigenfrequencies	Values of eigenfrequencies of the Nurek dam		
	Results given in [19]		Results obtained by the author
	VNII Gidrotechnik	NIS Hidroproekt	
ω_1	0.8136	0.8070	0.8088
ω_2	1.2470	1.2400	1.2415
ω_3	1.4653	1.4749	1.4680

Results and Discussions

In the course of solving the eigenvalue problem, the dynamic characteristics (frequencies and modes) of the Tupolung dam ($H = 165\text{m}$) were obtained in two versions: on a homogeneous rock foundation (without a weakened zone) ($E = 13000\text{ MPa}$, $\rho = 2.56\text{ t/m}^3$, Poisson's ratio – 0.3) [20] and on a rocky foundation in the presence of weakened zone (anhydrite zone) with physical and mechanical characteristics of soil $E = 16\text{ MPa}$, $\rho = 1.58\text{ t/m}^3$, Poisson's ratio – 0.3. The parameters of the dam soil were taken as follows: slope ratios 2 and 1.9 for the upstream and downstream slopes, respectively, $E = 3500\text{ MPa}$, $\rho = 2.04\text{ t/m}^3$, Poisson's ratio – 0.3. Along the entire diagonal at the base, there is an anhydrite zone, 50 m high (two finite elements – along the height). In the first version of the calculation – for the case of a homogeneous foundation – the parameters of this strip are chosen the same as in the surrounding soil [20]. In the second version, the parameters of this strip correspond to the parameters of an inclusion (weakened (anhydrite) zone).

The modes shown in the figures are shear in the transverse direction (1st mode), vertical shape (shrinkage) (2nd mode) and complex shear shape (3rd mode). The rigid rock base remains undeformable.

Dynamic characteristics of a dam located on a non-homogeneous foundation (with a weakened zone) are shown in Fig. 2.

Comparison of the fundamental modes and frequencies in two versions shows that the presence of a weakened zone at the base changes the spectrum of the fundamental frequencies: it decreases noticeably since, in general (due to the weakened zone), the stiffness of the base decreases. While with a homogeneous rock base, the fundamental modes include the deformation of the structure [20], as a less rigid part of the model; in the presence of a weakened zone, all the fundamental modes include nonuniform vertical deformation of the base. At that, the structure tilts like a solid body, almost without deforming, which is indicated by the vertical component of deformation shown in Fig. 3 at the first mode of natural vibrations of the "dam-nonhomogeneous foundation" model. The maximum value of the vertical deformation (dark color) falls on the right side of the anhydrite zone, and the "+" sign indicates the vertical tension of this area.

Fig. 2. Fundamental frequencies and corresponding modes of natural vibrations of a dam on the foundation with an anhydrite zone

Fig. 3. Distribution of vertical deformation in the "dam-nonhomogeneous base" model under shear at the first mode

Thus, the first mode and the corresponding frequency reflect the vibrations of the part of the base with the structure located above the weakened zone; the deformation of the structure itself and of this part of the base is insignificant.

The distribution of the stress state components in a dam on a non- nonhomogeneous foundation (with a weakened zone) at the first mode of vibration is shown in Fig. 4.

Fig. 4. Distribution of displacements: horizontal (a), vertical (b); and equivalent stresses (c) in the section of the dam on a nonhomogeneous foundation at the fundamental mode of vibration

As compared to the previously obtained results for a dam on a homogeneous base [20], where minor vertical displacements were observed as a result of a shift in the dam section and amounted to ± 0.02 m on the dam slopes, the vertical settlement with a weakened zone (Fig. 4b), increases uniformly over the entire base section, reaching 0.07m on the lower prism (Fig. 4b). The base area above the weakened zone is also subject to vertical settlement. There are no vertical displacements of the base below this zone. The maximum stresses in a nonhomogeneous base fall on the contact zone with the weakened zone (0.1 MPa) - Fig. 4c and are significantly inferior to the stresses arising at the contact of the dam with a homogeneous base (2.1 MPa). Thus, the weakened zone, located along the entire central section of the dam, is a kind of shock absorber that absorbs the settlement of the dam along with the upper part of the rock base.

Fig. 5. Vertical deformation ϵ_y in the section of the dam on a nonhomogeneous foundation at the second (a) and third (b) modes of vibrations

Vertical deformation along other fundamental modes (second and third modes) of the dam model on a nonhomogeneous foundation is shown in Fig. 5.

Thus, with all the fundamental modes of vibration of the dam model on a nonhomogeneous foundation (Fig. 3, 5), mainly the weakened layer of the nonhomogeneous foundation is subject to vertical deformation. So, at the first mode of vibrations (Fig. 3), the base under the lower prism is subjected to deformation. At the second mode, tension-compression deformation covers the entire area under the structure (in Fig. 5a – “+” sign shows tension under the upper prism, and “-” sign shows compression under the lower prism). At the third mode, the area located at the foot of the upstream slope is subjected to compression (Fig. 5b).

Conclusions

Comparing the results obtained, it should be noted that in the model on a homogeneous rock foundation, vertical displacements of the structure prevail and there are practically no displacements at the base. At that, for all modes of vibrations, the displacements are symmetrical, relative to the central axis of the dam. The presence of a weakened layer at the base violates the noted symmetry in all fundamental modes of vibration. The weakened layer initiates vertical displacements of the part of the rock base located above it, and this leads to nonuniform settlement of the structure (a dam). Under the anhydrite zone, vertical movement of soil is insignificant.

Thus, the presence of a weakened zone at the base causes nonuniform settlement of the structure. This can cause shearing and crack forming in the rock base and structure.

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