Stress state of an earth dam under main loads considering data from field observations

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Abstract. Reliable and safe operation of hydro-technical structures (earth dams), in the seismic regions of the republic, requires researchers to constantly improve the calculation methods in accordance with the requirements of regulatory documents for basic and special combinations of loads, including seismic ones. A calculation method is proposed for estimating the stress state on the example of an earth dam of the Charvak HPP (in operation for 47 years) in a plane elastic statement under main loads, taking into account the real piecewise-inhomogeneous physical and mechanical characteristics of soil of the structure body. Individual results of solving the problem were compared with the data of long-term field observations. The calculation method allows determining the kinematic characteristics (displacements, settlements, stresses, pore pressure) of an earth dam, which makes it possible to predict the state of the most vulnerable places in the structure and, if necessary, to develop appropriate measures to strengthen them. The problem was solved by the numerical finite element method. According to the developed technique, the problem by the numerical finite element method was reduced to solving a system of linear equations relative to the desired displacements. The calculation results are presented in the form of isolines of the stress-strain state of the dam body under the main loads (gravitational forces, hydrostatics). The numerical results of solving the problem and their comparison with the data of field observations make it possible to determine the reliability of the developed methods and software and thereby determine the vulnerable zones of the earth dam, where the loss of stable operation of the structure is possible. Based on the research results, appropriate recommendations were made.

1. Introduction

The design and construction of earth-and-rockfill dams in the Republic of Uzbekistan have become widespread due to their durability, reliability in operation, undemanding to the geological conditions of the alignment, to the type and quality of building materials used in their erection. At the same time, for the anti-seepage elements of the high dam profile, the issues of ensuring crack resistance and strength of their clayey barriers and cores arise. A number of issues also arise that were not solved with the degree of reliability that the design and operation of modern high dams require; these issues are: on the one hand, the development of a sound and reliable theory, and on the other hand, the organization of field studies, on the basis of which the state of the constructed structure could be assessed, and a forecast of changes in this state made. These changes include an increase in the magnitude of the element strain in the structure, its settlement and displacement; the change in the filtration regime in the body and foundation of the dam, etc. The materials obtained as a result of the analysis of field data should serve as a starting point for the development of new projects. The earth-
and-rockfill dam of the Charvak hydroelectric power plant, the construction of which was completed in December 1975, is the first structure in the former USSR, equipped with modern instrumentation and special devices (KIA and U)). Hydro-technical structures, in particular water-resistant structures (dams), are subjected to loads of both static and dynamic nature. The present normative methods for calculating earth dams for loads are based on a one-dimensional linear-spectral theory and do not take into account the non-one-dimensional nature of the structure, and its stress state. The problem considered here is based on determining the stress-strain state of an earth dam under the main loads - the force of gravity, hydrostatics, and comparing it with the data of field observations. Several articles [1, 2] are devoted to the analysis of field data of high and ultra-high rock-earth dams, for example, the world's highest Nurek dam; its settlement, horizontal displacements, stresses, pore pressure. The authors of these articles analyzed a number of publications devoted to field observations of dams and compared the results with field data obtained in the Nurek HPP to assess the quality of dam construction in the former USSR and abroad [1, 2]. Similar work was conducted to assess the state of the earth dam of the GotSATlin HPP in the process of filling the reservoir; [3] shows the results of field observations and numerical modeling. The article reveals the features of the filtration regime of the dam and the stress-strain state of the asphalt concrete diaphragm [3]. Mathematical models of the stress-strain state of an earth dam based on the analysis of field observations during the periods of construction and operation were conducted in [4]. The study of the stress-strain state of plane elastic earth dam under static loads for the choice of building material for a reinforced concrete face of the earth dams was proposed in [5,6].

2. Materials and 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 [7, 8]:

$$\delta \Pi - \delta W = 0$$  \hspace{1cm} (1)

where is the increment of the potential energy of the system, and $\delta W$ is the sum of the work of external forces on virtual displacements;

Equilibrium variational equations:

$$\delta A = \delta A_v + \delta A_p + \delta A_f = \int_\gamma \sigma\delta \varepsilon dV + \int \rho g \delta \varphi dV + \int \gamma h \delta dS = 0$$  \hspace{1cm} (2)

Here $V=V_1+V_2+V_3$; $V_1, V_3$—are the volumes of the upper and lower thrust prism; $V_2$ is the volume of the central core (Fig. 1).

![Figure 1. Design scheme.](image)

At present, when calculating the stress-strain state (SSS) of earth hydro-technical structures under load, numerical methods are used, since it is almost impossible to obtain analytical solutions for piecewise inhomogeneous characteristics of soils that compose the body of the structure and to account for its complex geometrical shape.

The boundary conditions on the surface of the upstream slope are as follows
\[
p_x = \sigma_{xx}l_x + \tau_{xy}m_x, \\
p_y = \tau_{xy}l_x + \sigma_{yy}m_x, \tag{3a}
\]

where \(p_x, p_y\) are the components of stresses from hydrostatic pressure on the surface of the upstream slope, equal to zero in the absence of hydrostatic pressure; \(l_x, m_x\) are the direction cosines of the upstream slope area.

Boundary conditions at the dam crest are:
\[
\tau_{xy} = 0; \sigma_{yy} = 0 \tag{3b}
\]
on the downstream slope they are
\[
\sigma_{xx}l_2 + \tau_{xy}m_2 = 0, \\
\tau_{xy}l_2 + \sigma_{yy}m_2 = 0, \tag{3b}
\]
where \(l_2, m_2\) are the direction cosines of the area of the downstream slope.

In the absence of hydrostatics, the surface of the side slopes and the crest of the dam are load-free. Then the static boundary conditions on these surfaces take the form
\[
\sigma_{ij}n_j = 0, \tag{4}
\]
where \(n\) is the normal vector to the surface.

An account for hydrostatics on the surface of the upper slope of the dam, which is in a homogeneous incompressible fluid of the reservoir, is reduced to setting the pressure on the slope surface, which linearly increases with depth
\[
p = \rho gz, \tag{5}
\]
where \(z\) is the depth measured from the free water surface; \(g\) is the acceleration of gravity.

The boundary conditions at the lower boundary of the base are expressed in the absence of horizontal and vertical virtual displacements:
\[
y = 0: \quad \delta u|_{y=0} = 0; \quad \delta v|_{y=0} = 0. \tag{6}
\]

A plane-deformable model (a cross-section) of an earth dam, located on a rigid elastic foundation (Fig. 1), is considered. The structure is considered under static loading (proper weight, hydrostatic water pressure), taking into account the piecewise inhomogeneous soil composition of the dam body (the presence of a core).

3. Results and discussion
To compare the results of calculations, displacements, and stresses, the dam sections were selected, where the KIA equipment (soil dynamometers (SD), piezodynamometers (PD) was installed during the construction (Fig. 2).
Figure 2. Location of soil dynamometers and piezodynamometers in the dam. Section 6.

In the calculations, as an example, section 6 of the Charvak earth dam was considered, with a height of 131 m; slope laying coefficients 1.8, slope = 0.2, physical and mechanical parameters of the prisms soil \( E = 60 \) MPa, volume weight \( \gamma_{dry} = 1950 \) kg/m\(^3\), \( \gamma_{int} = 2230 \) kg/m\(^3\); Poisson's ratio \( \mu = 0.3 \).

Parameters of core soil are: \( E = 30 \) MPa, volume weight \( \gamma_{dry} = 1760 \) kg/m\(^3\), \( \gamma_{int} = 2110 \) kg/m\(^3\), Poisson's ratio \( \mu = 0.3 \), slope coefficients 0.2.

High earth-and-rockfill dams are built with a loamy core containing pores in the clayey soil, therefore, the pore pressure arising when filling a reservoir during the operation of a hydrotechnical structure should be taken into account in building standards [9].

The calculation of the dam, which is a part of the hydrotechnical unit, must be made with account for the effect of hydrostatic pressure on the upstream slope. Pressure \( P \) acting along the normal to the surface of the upstream slope is determined by a function that varies linearly with depth \( h \), and is expressed by formula \( P = \gamma h \), where \( \gamma \) is the specific weight of water.

To check the reliability of the developed algorithm and software to calculate the static loads acting on a plane elastic structure, the results of the calculations were compared with the results obtained by other authors [10].

The calculated components of the stress state – the normal (horizontal, vertical) stresses in the body of the dam under its own weight and hydrostatics when filled at normal water level 125 m are shown in Figs. 3, 4. The readings of a soil dynamometer, piezodynamometer during the operation time of an earth dam were provided by JSC "Hydroproject".
b) **Figure 3.** Calculated diagrams of horizontal stresses $\sigma_x$ (tf/ m$^2$) in the body of the earth dam at the level of 780.0.

a)

b) **Figure 4.** Calculated diagrams of vertical stresses $\sigma_y$ (tf/m$^2$) in the body of an earth dam at the level of 780.0 m.

Comparison of the results of calculations of horizontal and vertical stresses in the body of an earth dam with the available data of field observations shows a difference of 5 and 9% for section 6, taking into account the pore pressure (see Figs. 3, 4)
The research results prove that the residual pore pressure is present at these levels and forms the core of the pore pressure, and the consolidation process occurs at the level of 780.0 m, which is practically at the base of the dam, but above the core base [11]. Consequently, the maximum pressure from the core of the dam, thrust prisms, and, accordingly, the pressure in the reservoir, occurs at this level.

4. Summary
A mathematical formulation of the numerical solution of a static elastic problem for an earth dam under the main loads (gravitational forces, hydrostatics) is given, taking into account data from field observations. The results of the studies of the earth dam under consideration contributed to the identification of the actual stress state, the role of the most important factors, the improvement of the calculation method, and the solution of various problems of a scientific and applied nature for the purpose of safe and reliable operation of the dam [12,13].

5. References
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