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Assessment Of The Stress–Strain State Of Earth Dams Under Static Loads

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Abstract: Based on the variational principle, a calculation scheme, mathematical model, and methodology have been developed to determine the stress–strain state (SSS) of the Rezaksay earth dam with a complex geometric configuration under its own weight in a plane strain condition. The calculations were performed using the licensed software complex Plaxis 2D, taking into account the structural features of the dam. Numerical studies made it possible to determine the nature of the SSS of the earth dam and reveal that the presence of an inclined core and a tooth in the structure leads to the formation of a complex stress state in the upper prism.

Keywords: Earth dam, plane model, stress–strain state, gravity, deformation and stress isolines.

Introduction

In seismically active regions, large and small hydraulic structures constructed and operated under various conditions must remain reliable, safe, and durable when exposed to static, dynamic, and seismic loads. Especially for hydraulic structures operating under water influence, extensive research and investigation are required to assess their static condition, considering the physical and mechanical properties of soils as well as the real geometric shape and structural characteristics of the structures.

Solving this complex problem—considering the real geometry and design features of earth dams—is possible using numerical methods such as the finite element method (FEM) or the finite difference method (FDM) [1, 2].

Many researchers [2–6] have thoroughly studied the SSS of earth dams using various models, structural configurations, and geometric parameters of dams, and have drawn appropriate conclusions.

The dynamic behavior and seismic stability of earth dams under plane strain conditions were studied in [7] using numerical methods, while pore pressure changes were modeled with a nonlinear material model.

In [8], the seismic stability of the downstream slope of an earth dam in India was analyzed using pseudo-static and pseudo-dynamic methods. The minimum safety factors obtained by these methods were 1.18 and 1.09, respectively, for the selected seismic zone of India.

Preliminary studies using the finite element method, considering soil saturation and plastic properties, were presented by A.R. Khoei, A.R. Azami, and S.M. Haeri [9].

An effective method for determining seismic stresses on downstream slopes of high dams was analyzed in [10], where, based on geological studies, static and dynamic testing, and slope stability analysis, an appropriate methodology was developed.

A review of scientific literature showed that the SSS of earth dams, considering their structural features and real operating conditions, has not been sufficiently studied—highlighting the need for further research in this direction.

Hence, one of the urgent problems in continuum mechanics is the development and justification of mathematical models and methods for calculating the SSS of earth dams under static loads, considering their structural characteristics, geometry, physical-mechanical properties of soils, and geological conditions of the construction site.

Methodology

Let us consider a plane model of the Rezaksay earth dam of complex geometric form $V = V_1 + V_2 + V_3$ (Fig. 1). Since the dam's length greatly exceeds the dimensions of its cross-section, and the acting loads are perpendicular to the longitudinal axis, the problem can be solved under plane strain conditions.

In Fig. 1, V_1, ,V_3 the upper and lower supporting prisms, V_2 the dam core. The dam is rigidly fixed along its foundation along the surface Σ_u. On the left base boundary Σ_1, sliding hinges are installed, allowing vertical displacements (i.e., when $x = 0$, $\delta u_1 = 0$). The surfaces of the upper and lower slopes Σ_2,Σ_4, as well as the top surface, are assumed to be free of external loads. Thus, the problem examines the SSS of the Rezaksay earth dam under its own weight.

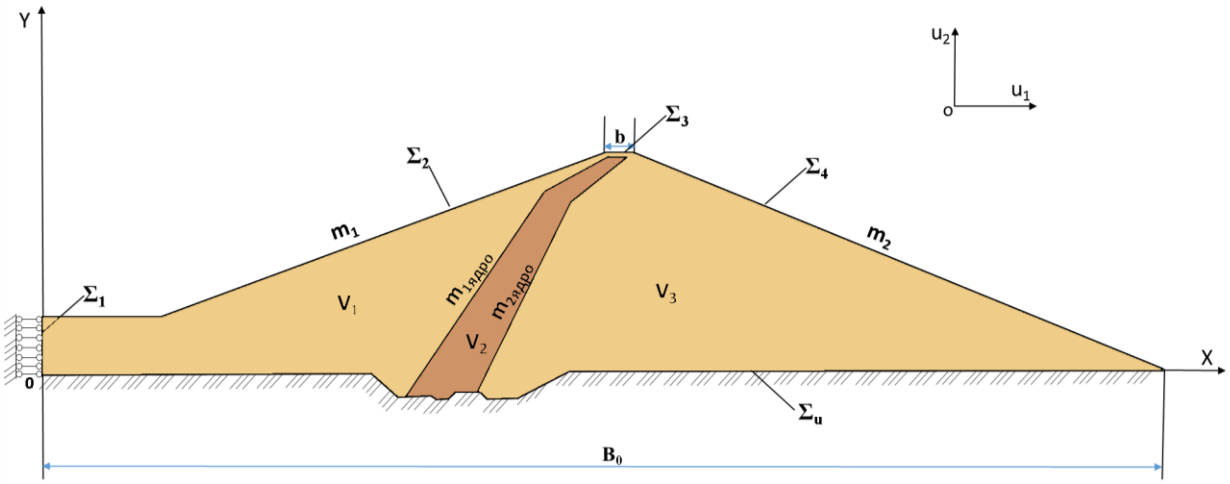


Fig. 1 – Plane computational model of the Rezaksay earth dam under self-weight

here: b – width of the dam crest; B_0 – width of the dam base; m_1, m_2 – coefficients of the upper and lower slopes; m_3, m_4 – coefficients of the core slopes.

To evaluate the processes occurring in the plane system (Fig. 1), we use the variational equation and kinematic boundary conditions based on the principle of virtual displacements, according to which the sum of the virtual works of the active forces is equal to zero [1].

$$\delta A = -\int_{V_1} \sigma_{ij}\delta\varepsilon_{ij} dV_1 - \int_{V_2} \sigma_{ij}\delta\varepsilon_{ij} dV_2 - \int_{V_3} \sigma_{ij}\delta\varepsilon_{ij} dV_3 + \\ + \int_{V_1} \vec{f}\delta\vec{u} dV_1 + \int_{V_2} \vec{f}\delta\vec{u} dV_2 + \int_{V_3} \vec{f}\delta\vec{u} dV_3 = 0 i, j = 1,2 \quad (1)$$

For the foundation and the left side of the dam, the boundary conditions are written as follows::

$$\vec{x} \in \sum_u; \ \ y = 0; \ \ \delta\vec{u} = 0: \\ \vec{x} \in \sum_1; \ \ x = 0; \ \ \delta u_1 = 0 \quad (2)$$

In this variational equation, to express the relationship between the stress and strain tensors that reflect the physical and mechanical properties of each part of the system, the generalized Hooke's law is used, namely [2]:

$$\left.\begin{aligned} \sigma_{11} &= \frac{E_n(1-\nu_n)}{(1+\nu_n)(1-2\nu_n)}\varepsilon_{11} + \frac{\nu_n E_n}{(1+\nu_n)(1-2\nu_n)}\varepsilon_{22} \\ \sigma_{22} &= \frac{E_n(1-\nu_n)}{(1+\nu_n)(1-2\nu_n)}\varepsilon_{22} + \frac{\nu_n E_n}{(1+\nu_n)(1-2\nu_n)}\varepsilon_{11} \\ \sigma_{12} &= \frac{E}{2(1+\nu_n)}\varepsilon_{12} \end{aligned}\right\} \quad (3)$$

The relationship between the strain tensors and the displacement vectors is expressed by the following Cauchy relations:

$$\varepsilon_{11} = \frac{\partial u_1}{\partial x_1}; \ \ \varepsilon_{22} = \frac{\partial u_2}{\partial x_2}; \ \varepsilon_{12} = \frac{\partial u_1}{\partial x_2} + \frac{\partial u_2}{\partial x_1} \quad (4)$$

here: $\vec{u}$, ε_{ij}, σ_{ij} – are the components of the displacement vector, strain tensor, and stress tensor; $\delta\vec{u}$, $\delta\varepsilon_{ij}$ – are the isochronous variations of the displacement vector and the components of the strain tensor; $\vec{f}$ is the body force vector; E_n and ν_n are the elastic parameters for the *n*-th element of the dam; $\vec{u} = \{u_1, u_2\} = \{\mathrm{u}, \mathrm{v}\}$ – are the components of the displacement vector at the dam points; $\vec{x} = \{x_1, x_2\} = \{\mathrm{x}, \mathrm{y}\}$ – are the coordinates of the dam points; when solving the plane problem, the indices *i, j* take the values *i, j = 1, 2*.

For any possible displacements $\delta\vec{u}$, it is necessary to determine the unknown components of displacements and stresses that arise in the body of the dam under the action of the loads $\vec{f}$, satisfying equations (1)–(4).

As a result of applying the finite element method to the regions occupied by the system, the variational equations and relationships (1)–(4) are reduced to a system of high-order nonhomogeneous algebraic equations, which is equivalent to the above mathematical model.

$$[K]\{u\} = \{F\}. \quad (5)$$

Here, [K] is the stiffness matrix for the system under consideration (Fig. 1); {u} represents the unknown displacements to be determined; {F} denotes the external forces (such as body forces, etc.). The Plaxis 2D universal software package was used to solve the plane problem.

Results and Discussion

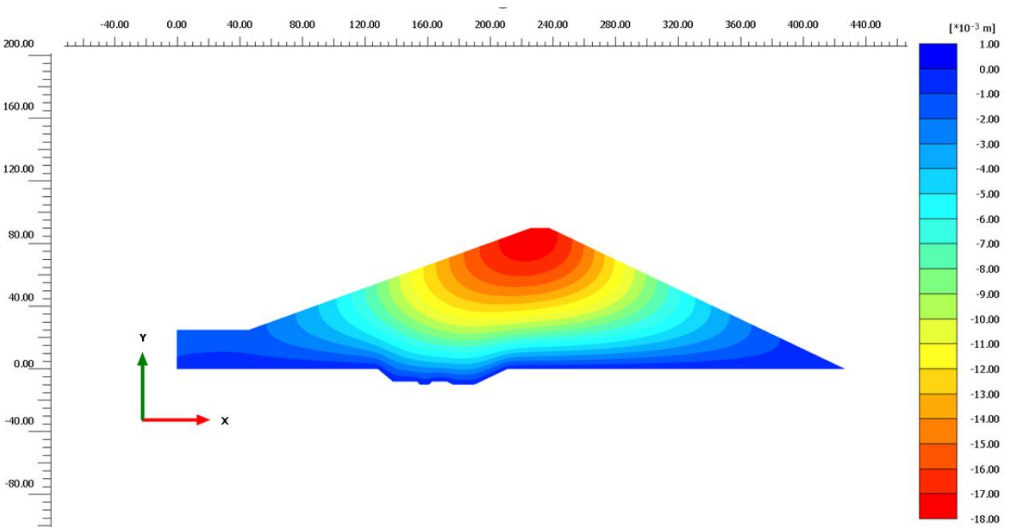
The article examines the stress-strain state of the

Rezaksay Reservoir earth dam, located in Namangan region, under the action of its own weight in conditions of plane deformation. Using the above-mentioned mathematical model, method, and algorithm, and taking into account the actual physico-mechanical properties of the soil, structural features, geometric parameters, and the dam's location on a heterogeneous foundation, its stress-strain state was investigated.

The Rezaksay earth dam under study has supporting prisms V_1 and V_3, composed of crushed-stone soil, placed and compacted in layers. The upper slope of the dam is reinforced with large stones. The dam's core, V_2, is made of soil with admixtures of sandy loam and loam. The dam has a height of H=90 m, with slope coefficients of the supporting prisms equal to m_1 = 2.1 and m_2 = 1.7. The crest width of the dam is b = 12 m, and its length is L = 4,400 m. The central part of the foundation has a width of B_0 = 427 m.

As a result of numerical calculations, the values of horizontal and vertical displacements u_1, u_2, as well as the stress components σ_{11}, σ_{22}, σ_{12}, were determined for all points of the structure, and their contour lines were plotted. The study was first conducted for a homogeneous dam, then taking the core into account, after which the obtained data were compared and corresponding conclusions were drawn.

a) u_2, [*10^{-3}m]



b) u_2, [*10^{-3}m]

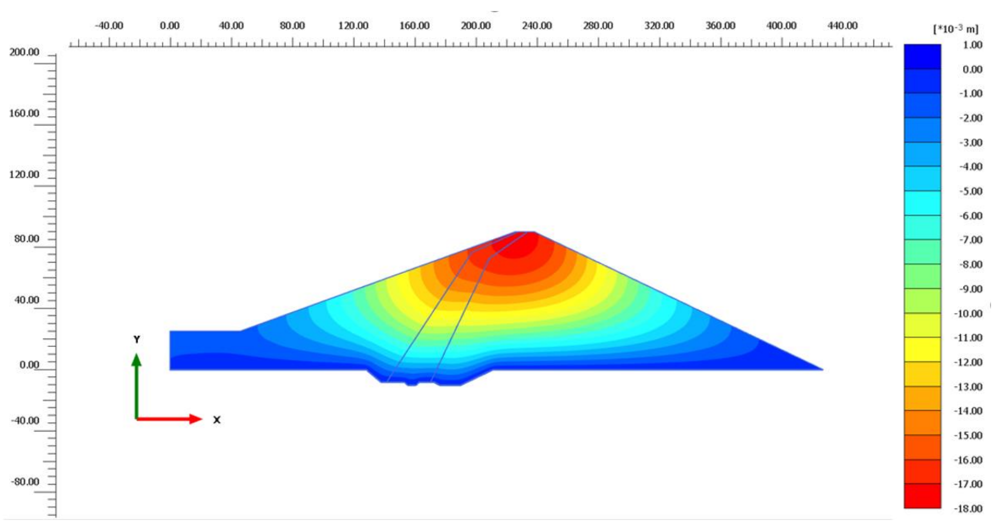


Fig. 2. Contour lines of equal vertical displacements u_2 in the cross-section of the Rezaksay earth dam under the action of its own weight in the following cases: a) homogeneous dam; b) dam with a core.

The analysis of the obtained results showed that, assuming a homogeneous dam material, the horizontal displacements u_1 reach their maximum in the central part of the supporting prisms and decrease toward the edges. In this case, displacements in the lower prism are positive, while in the upper prism they are negative. Due to the presence of a dam tooth at the base of the upper prism, its deformed state becomes more complex. Taking the dam core into account completely changes the deformation pattern in the upper prism: the complex deformed state is manifested primarily in the core and the adjacent zones.

The analysis of the numerical results also showed that the vertical displacements u_2, occurring in the dam's cross-section under the action of its own weight, increase with the height of the dam and reach their maximum values in the crest zone (Fig. 2). Near the dam's foundation, the displacement values decrease. For a uniform foundation, the displacement contours are practically symmetrical. Comparison of the results shown in Figs. 2a and 2b indicates that the core has a significant influence on the deformation behavior of the earth dam.

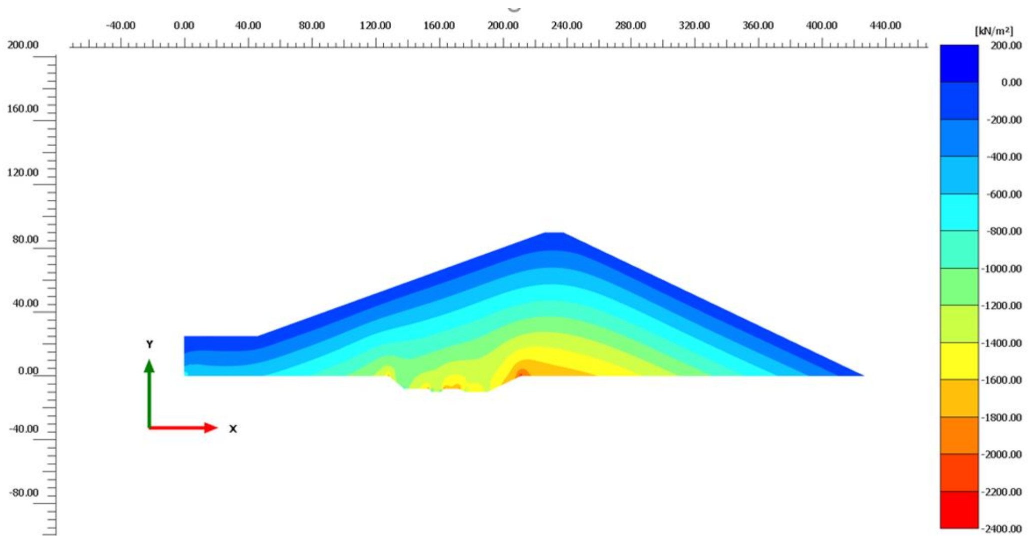
At the next stage of the study, the stress state of the dam was examined as a plane problem under the action of its own weight, and the values of the stress components σ_{ij} were determined.

The analysis of the results showed that the normal stress in the horizontal direction σ_{11}, in the dam's cross-section depends on the self-weight of the soil, the coordinates of the point within the structure, as well as on whether the soil material is homogeneous or heterogeneous. The values of σ_{11} exhibit a more complex pattern in the zone of the dam tooth.

The analysis of the results obtained for a homogeneous dam under the action of its own weight (Fig. 3a) shows that the values of the vertical stress σ_{22} at points within the considered cross-section depend on the dam's height and the distance of the given section from the surface. In this case, the magnitude of σ_{22} is small at the top of the dam, increases toward the base, and reaches its maximum at the foundation. Taking the core into account leads to a reduction in vertical stress σ_{22} in the upper supporting prism and, due to the increase of stresses from the crest to the base, causes a redistribution of stresses within the dam body, resulting in the disappearance of their symmetrical pattern (Fig. 3b).

The inclined arrangement of the core and the presence of a dam tooth in the design of the studied dam have a significant effect on the distribution pattern of vertical stresses σ_{22} across the section, with the property of symmetry not being observed. In addition to normal stresses, shear stresses σ_{12} also develop within the dam body. The inclined position of the core leads to a change in the stress state of the upper supporting prism.

a) σ_{22}, [kN/m^2]



b) σ_{22}, [kN/m^2]

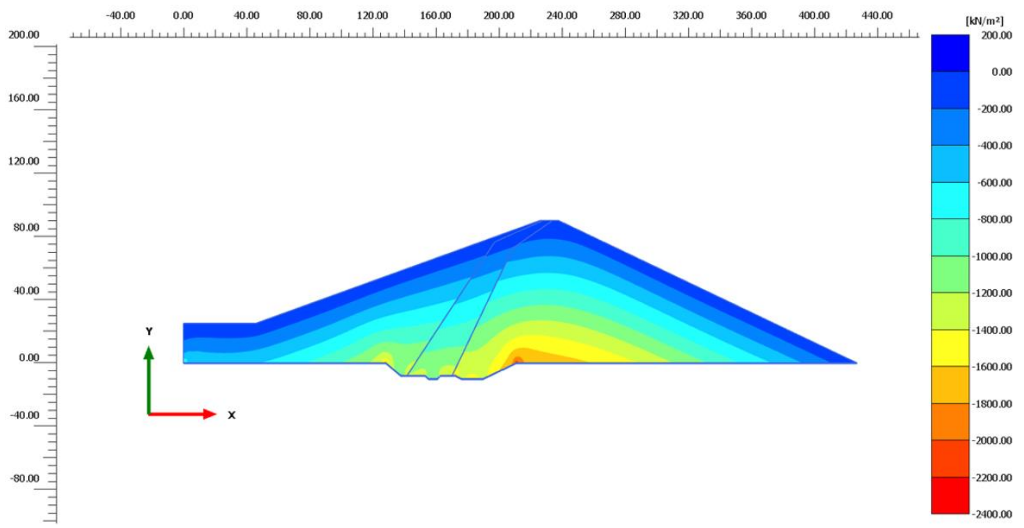


Fig. 3. Contour lines of the distribution of normal stresses σ_{22} in the cross-section of the Rezaksay earth dam under the action of its own weight in the following cases: a) homogeneous dam; b) dam with a core.

Conclusions

1. A two-dimensional mathematical model, calculation method, and algorithm have been developed for evaluating the stress-strain state of earth dams with complex geometric parameters, made of heterogeneous materials, and subjected to static loads.

2. Based on the analysis of the distribution of displacement components occurring in the dam body under plane deformation conditions, the following has been established:

- horizontal displacements u_1 reach their maximum in the central part of the supporting prisms and decrease toward the edges. Due to the presence of a dam tooth at the base of the upper prism, its deformed state becomes complex.
- vertical displacements u_2 increase from the base toward the top, reaching a maximum in the upper part of the core and in the adjacent supporting prisms. The core has a significant influence on the deformation state of the entire dam.

The analysis of the stress state showed that:

- the values of the normal stresses σ_{11}depend on the self-weight of the soil, the coordinates of the point within the dam body, as well as on whether the soil material is homogeneous or heterogeneous; their manifestation in the zone of the dam tooth is complex.
- the inclined arrangement of the core and the presence of a dam tooth in the design have a significant effect on the distribution pattern of vertical stresses σ_{22} across the section, leading to a loss of symmetry. In this case, the inclined core causes the formation of a complex stress state in the upper supporting prism.

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