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Three-Dimensional Evaluation Of The Stress-Strain Behavior Of The Jidalisay Earth Dam

P. Matkarimov
Namangan State Technical University, Namangan, Uzbekistan

D. Juraev
National Research University "Tashkent Institute of Irrigation and Agricultural Mechanization Engineers," Tashkent, Uzbekistan

Z.Kh. Kholboev
Namangan State Technical University, Namangan, Uzbekistan

S.Usmonhodzhaev
Namangan State Technical University, Namangan, Uzbekistan

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Abstract: In this paper, based on D'Alembert's variational principle, a mathematical model and algorithm are presented for studying the stress-strain state (SSS) of an earth dam with complex geometric parameters under static loads using a three-dimensional model. Taking into account the structural features of the dam, the SSS of the earth dam was investigated in a three-dimensional framework using the universal software package Abaqus.
It is shown that for analyzing the SSS of the Jidalisay Dam with complex geometric parameters under static loads, it is necessary to use exclusively three-dimensional models of the structure. The results demonstrated that deformations and stress states at each section depend on the dam's geometric parameters, height, and the location of the selected section. It was also found that the normal stresses within the dam body are approximately symmetrical relative to the core center and increase from the top toward the foundation. At the same time, vertical stress σ_{22} decreases in the core and its vicinity, forming the so-called "arch effect." This mechanical phenomenon arises due to the use of different types of soil in constructing the dam core, transition zone, and supporting prisms.

Keywords: Earth dam, three-dimensional model, stress state, self-weight, displacement and stress contour lines.

INTRODUCTION:

In earth dams subjected to their own weight, complex interactions occur between their individual elements. These interactions become more complicated under dynamic loads caused by seismic effects, as well as depending on the various topographical conditions of the dam's location. The problem of studying the stress-strain state (SSS) of such dams represents a complex three-dimensional problem in continuum mechanics, requiring consideration of the volumetric behavior of the structure and the variability of soil properties.

Currently, in the design of unique structures of this type, which have complex geometric parameters and dimensions and are located in seismically active regions, the SSS of such dams is, in most cases, studied using two-dimensional calculation schemes. However, existing scientific literature indicates the necessity of using three-dimensional models when analyzing these structures under both static and dynamic loads.

Scientific studies [2–8, 17] are devoted to evaluating the dynamic behavior and analyzing the SSS of earth dams, taking into account their structural features and the nonlinear physico-mechanical properties of soils, using various computational models.

In [9], the results of numerical modeling of the SSS of the foundation and body of the Elizavetinskoye Reservoir earth dam are presented, considering grouting with viscous-plastic clay-cement solutions. A geomechanical assessment of the effectiveness of using such solutions under specific engineering-geological conditions was performed.

In the study by L.N. Rasskazova and co-authors [10], the stress-strain state of earth dams under seismic loading was investigated, taking into account pore pressure.

The seismic stability of the downstream slope of an earth dam located in Eastern India was analyzed in [11] using pseudo-static and pseudo-dynamic methods. The minimum values of the stability factor for the selected seismic zone of India were 1.18 and 1.09, respectively.

Authors in [12] evaluated the seismic risk of a dam using probabilistic methods based on accelerograms, considering various seismic zones. The analysis was conducted for the maximum soil acceleration and within the period range corresponding to the main oscillations of the dam.

In [13], the dynamic behavior and seismic resistance of earth dams were studied in a plane finite element framework, taking into account pore pressure variations using a nonlinear material model.

In [14], a seismic analysis of the “dam–foundation” system was performed using finite element displacements and conical boundary conditions with locally irreversible behavior to model a semi-infinite soil foundation.

In [15], numerical finite element analysis was used to examine the effects of moisture conditions and hydrostatic pressure on inclined and vertical dam cores, as well as on slope stability. It was found that increasing the core inclination leads to greater water filtration and improved slope stability.

In the study by Ventrella C. and Pelecanos L. [16], a long-term (over 25 years) deformation analysis of an earth dam was conducted using nonlinear finite element modeling. The authors showed that seasonal fluctuations in the reservoir level cause minor settlement at the dam crest, while the majority of settlements are related to soil consolidation.

The analysis of these scientific works indicates that the stress-strain and dynamic behavior of dams constructed from local materials, considering their structural features and actual operating conditions, remain insufficiently studied. This makes the topic highly relevant and of significant scientific interest.

Based on the above, it can be noted that the development of a mathematical model and calculation method for assessing the stress-strain state of earth dams in a three-dimensional framework—taking into account their structural features, topography, geometric dimensions, and the properties of the soils used—is one of the current and important tasks in continuum mechanics.

METHODOLOGY

Let us consider a three-dimensional model of an earth dam with a complex geometric shape, having a total volume $V = V_1 + V_2 + V_3$, where V_1, V_3 и V_2 — are the volumes of the upper and lower prisms and the dam core, respectively (Fig. 1). The figure shows that the foundation and bank slopes of the dam, $\Sigma_0', \Sigma_0'', \Sigma_0'''$, are rigidly fixed, while the surfaces $\Sigma_1, \Sigma_2, \Sigma_3$ are considered stress-free. The foundation topography of the dam is uneven, with the crest (upper part) of the structure having an axial deviation in the central part, characterized by an inclination angle α.

The dam is subjected to its own weight $\vec{f}$,, which serves as the main source of external loading.

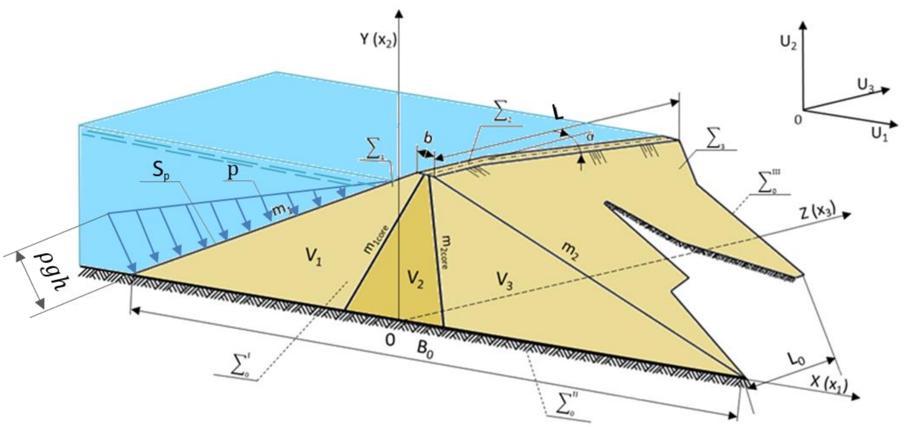

Fig. 1. Three-dimensional computational scheme of the earth dam

In Figure 1: L — length of the structure; L_o — length of the foundation; b — crest width; B_0 — width of the dam's foundation cross-section; m_1 and m_2 — slope coefficients of the upper and lower dam faces; m_{1core} and m_{2core} — slope coefficients of the dam core.

For the mathematical formulation of the problem, the principle of virtual displacements [4] was applied, according to which the sum of the work of all active forces acting on the system for any possible displacements must be equal to zero:

$$\delta A = -\int_V \sigma_{ij}\delta\varepsilon_{ij}dV + \int_V \bar{f}\delta\bar{u}dV = 0, i,j = 1,2,3 \tag{1}$$

kinematic boundary conditions:

$$\vec{x} \in \Sigma_0 = \Sigma_0' + \Sigma_0'' + \Sigma_0''': \vec{u} = 0 \tag{2}$$

When describing the physical properties of the dam material, the relationship between the stress and strain components was defined as follows:

$$\sigma_{ij} = \lambda_n\theta\delta_{ij} + 2\mu_n\varepsilon_{ij} \tag{3}$$

and the Cauchy relations take the following form:

$$\varepsilon_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) \tag{4}$$

In this expression: $\delta\bar{u}$, $\delta\varepsilon_{ij}$ are the components of the vectors of virtual displacements and strains; $\vec{u}$, ε_{ij}, σ_{ij} are the components of the displacement vector, strain tensor, and stress tensor; λ_n and μ_n are the Lamé constants for the n-th finite element; $\theta = \varepsilon_{kk}$ is the volumetric strain; $\{u_1, u_2, u_3\}$ are the components of the displacement vector of points in the dam; $\{x\} = \{x_1, x_2, x_3\} = \{x, y, z\}$ are the coordinates of a point in the body; $i, j, k = 1, 2, 3$.

As a result of applying the finite element method (FEM), the variational equations and relations (1)–(4), formulated for the volumetric regions occupied by the body, are reduced to a system of inhomogeneous algebraic equations, which is equivalent to the mathematical model presented above:

$$[K]\{u\} = \{P\} \tag{5}$$

Здесь: $[K]$ - матрица жёсткости для рассматриваемой системы (см.Рис.1), $\{u\}$ - вектор искомых перемещений в узлах конечных элементов,
$\{P\}$ - вектор внешних сил, приложенных к узлам конечных элементов (включая массовые силы и другие нагрузки).

Для решения пространственной задачи использовались универсальный программный комплекс Abaqus.

Here, [K] is the stiffness matrix for the considered system (see Fig. 1), {u} is the vector of unknown nodal displacements in the finite elements, and {P} is the vector of external forces applied to the finite element nodes (including self-weight and other loads).

The universal software package Abaqus was used to solve the three-dimensional problem.

RESULTS AND DISCUSSION

The article examines the three-dimensional stress-strain state (SSS) of the Jidalisay Reservoir earth dam, located in the Fergana Valley, under static loads. Using the mathematical model, method, and algorithm presented above, the SSS of the dam was studied taking into account the actual physico-mechanical properties of the soils, structural characteristics, geometric parameters, and the curvature of the dam axis.

The body of the Jidalisay dam consists of gravel soil, placed and compacted in layers. The upstream slope of the dam is covered with concrete of thickness t=20 cm. The dam height is H=62.8 m, with slope coefficients m_1=2.35 m and m_2=2.1. The dam core (denoted as 2) is made of clayey soil. The crest width is b=10 m, and the dam length is L=965 m. The longitudinal length of the foundation is L_0=364 m.

The calculation results include the displacement vectors u_1, u_2, u_3 and the stress tensor components $\sigma_{11}, \sigma_{22}, \sigma_{33}, \sigma_{12}, \sigma_{23}, \sigma_{31}$ at all points of the structure.

For ease of analysis, contour plots of the displacement and stress components were constructed for characteristic longitudinal and transverse sections of the Jidalisay dam. Longitudinal sections along the dam axis, labeled “I–I” through “IV–IV,” were selected, and contour plots of displacements and stresses under the action of the dam’s self-weight were generated for these sections (Figs. 3–5). The results obtained for each section were analyzed in detail and compared with one another.

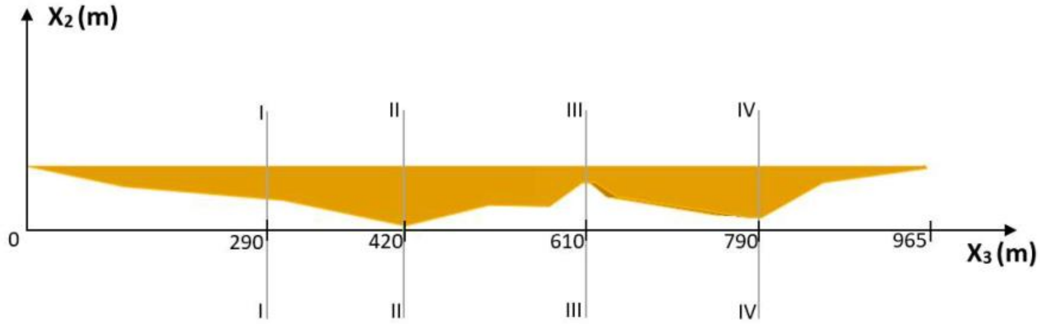

Fig. 2. Layout of the transverse sections along the X_3 axis of the Jidalisay dam

The analysis of the results shows that (Fig. 3a) in the transverse section I–I, located 290 m from the left bank, the horizontal displacements u1u_1u1 increase toward the centers of the upper and lower prisms of the dam. Within the dam core, horizontal displacements are minimal, while the maximum values are observed in the central parts of the upper and lower supporting prisms. The magnitude of the displacements depends on the location of points within the dam section and the distance of the section from the bank.

The distribution of vertical displacements u2u_2u2 throughout the dam body (Fig. 3b) shows an increase from the foundation toward the dam crest. Maximum vertical displacements occur in the upper part of the core and in the zones of the upper and lower supporting prisms. In the considered section, the dam height is H=35.2H = 35.2H=35.2 m. Minimum vertical displacements are observed near the foundation and are almost symmetrical relative to the core center.

a) u_1, m (section I-I) b) u_2, m (section I-I)

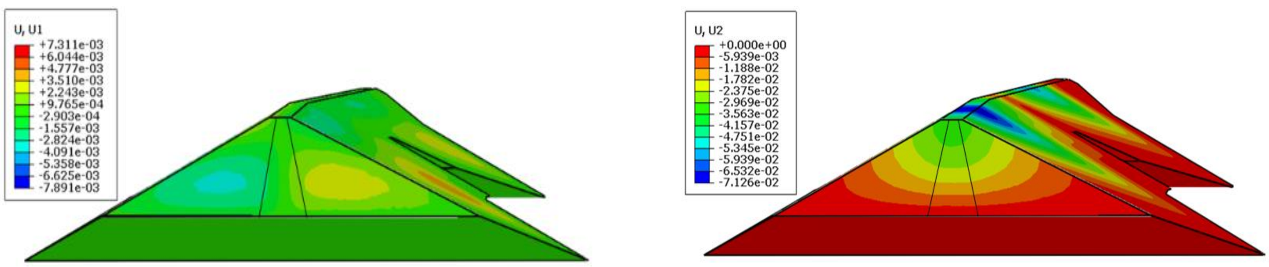

Fig. 3. Contour plots of uniform displacement distribution for section I–I of the Jidalisay earth dam under self-weight: a) *u_1* – horizontal displacement, b) *u_2* – vertical displacement.

In section II–II of the Jidalisay earth dam, horizontal displacements u_1 within the core reach minimum values. The maximum horizontal displacements are observed at the centers of the upper and lower supporting prisms (Fig. 4a). The displacement values depend on the location of points within the dam section and the distance of the section from the banks.

The distribution of vertical displacements u_2 throughout the dam body (Fig. 4b) increases from the foundation toward the top. Maximum u_2 values occur around the upper part of the core in both supporting prisms. The dam height in this section is H=62.8 m. Minimum vertical displacements are recorded near the foundation and are almost symmetrical relative to the central axis of the dam core.

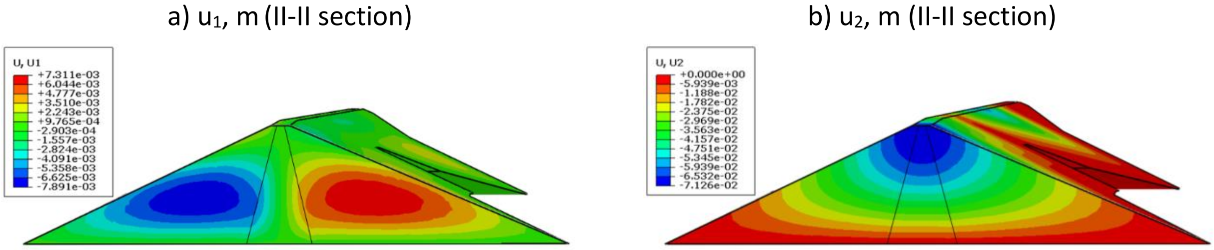

Fig. 4. Contour plots of uniform displacement distribution for section II–II of the Jidalisay earth dam under self-weight: a) *u_1* – horizontal displacement, b) *u_2* – vertical displacement

At the next stage of the analysis, the stress state of the dam was studied in a three-dimensional framework. For a detailed examination of the results, contour plots of the stress components $\sigma_{11}, \sigma_{22}, \sigma_{12}$ were constructed for both transverse and longitudinal sections of the dam.

Figure 5 shows the contour plots of the stress components σ_{ij} in section II–II, where the highest part of the dam is located.

The analysis of the results indicates that in the transverse section II–II, located 420 m from the left bank, the horizontal normal stresses $\sigma_{11}$are nearly symmetrical relative to the core center and increase from the crest toward the dam foundation. The highest σ_{11}values are concentrated in the central areas of the dam foundation (Fig. 5a).

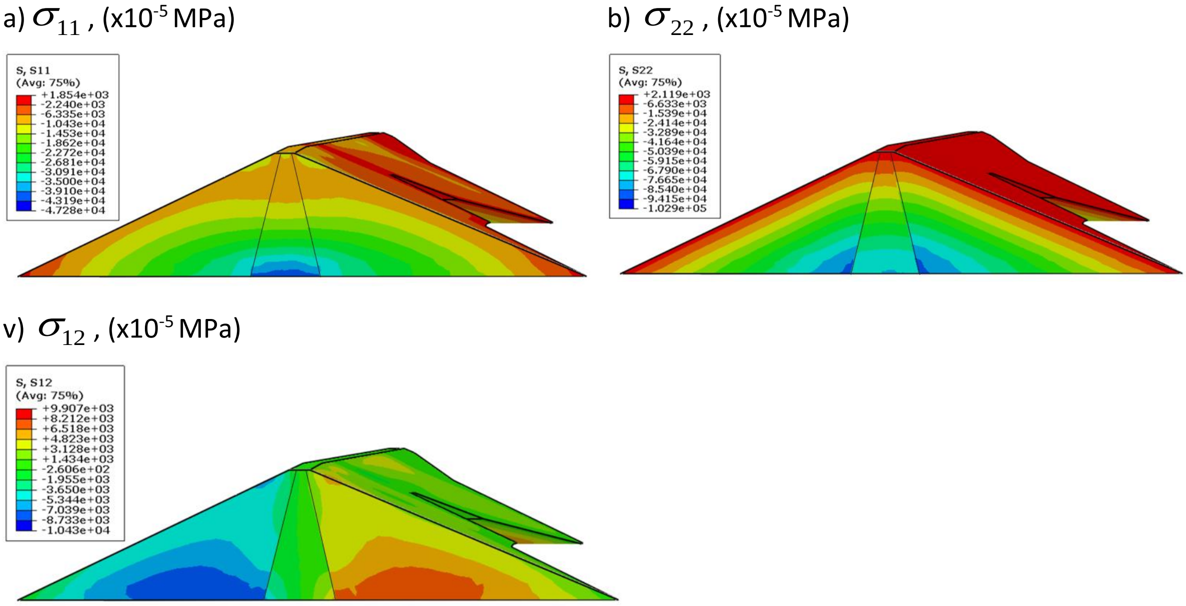

Fig. 5. Contour lines of the stress components σ_{ij} in the transverse section II–II of the dam

The analysis of the results shows that in the transverse section II–II, located 420 m from the left bank, the horizontal normal stresses σ_{11} are nearly symmetrical relative to the core center and increase from the crest toward the dam foundation. The highest σ_{11} values are concentrated in the central parts of the foundation (Fig. 5a).

The vertical normal stresses σ_{22} also increase from the crest to the foundation. In the core zone and the adjacent areas, a reduction in σ_{22} is observed, indicating the presence of the so-called "arch effect." The σ_{22} distribution also remains symmetrical relative to the core axis (Fig. 5b). Shear stresses σ_{12} are distributed symmetrically throughout the dam body, with values increasing away from the core. Within the core and transition zones, they are practically zero (Fig. 5c). The magnitude of the shear stresses depends on the position of points in the transverse section, the dam height, and the distance from the section to the bank slopes.

Based on these results, it can be concluded that for analyzing the stress-strain state of the Jidalisay earth dam with complex geometric parameters under static loads, it is advisable to use exclusively three-dimensional models of the structure.

CONCLUSIONS

1. A mathematical model based on the variational principle was developed to study the stress-strain state (SSS) of earth dams with complex geometric parameters, taking into account real operating conditions. This model was implemented as a three-dimensional computational scheme.
2. Using the developed model, algorithm, and the universal software package Abaqus, a three-dimensional analysis of the SSS of the Jidalisay dam under its self-weight, considering the local topography, was carried out, revealing significant mechanical effects.
3. Analysis of the results showed the following:

- with increasing height of the Jidalisay earth dam, vertical displacements u_2 in the upper part increase. Maximum vertical displacements occur in the highest part of the structure. Deformations in each section depend on the geometric parameters, height, and position of the considered section.
- normal stresses σ_{11} and σ_{22} in the dam body are nearly symmetrical relative to the core center, with values increasing from the crest to the foundation. The σ_{22} component decreases within the core and adjacent zones, indicating the presence of the arch effect. This mechanical phenomenon arises because the core, transition zone, and supporting prisms are constructed from different types of soils.
- it was concluded that exclusively three-dimensional models are necessary for analyzing the SSS of the Jidalisay earth dam with complex geometry and heterogeneous terrain under static loads.
- different sections of the dam exhibit distinct deformation and stress states.

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