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Assessment of the Impact of Hydrostic Water Pressure on the Stress State of Earth Dam in Three-Dimensional Formulation

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Abstract: Based on Lagrange's variational principle, the article provides a general mathematical formulation and methodology for solving problems on the stress-strain state of earth dams with complex geometric parameters using three-dimensional calculation schemes under the impact of their weight and hydrostatic water pressure. Numerical calculations are presented to study the stress-strain state of an earth dam in a three-dimensional formulation, considering non-homogeneous and design features using the ABAQUS universal program.

The results of numerical calculations showed that the strains at specific points in the dam body depend significantly on their location. As the height of the dam increases, the vertical stresses also increase, especially in the part of the body near the foundation. In the middle part, where the crest axis is curved and the dam height is lower, the distribution pattern of longitudinal stresses is complex. The stress-strain state within the dam is significantly influenced by the reservoir fill level, which alters the symmetrical pattern of strain and stress fields in the dam's cross-sections. When the reservoir is completely filled, the vertical stresses in the upper prism almost double. The water pressure significantly increases the value of horizontal stresses along the entire profile of the dam, leading to a decrease in its resistance to horizontal loads. It was determined that when studying earth dams of any height, it is necessary to consider the impact of water in the upstream pool as the hydrostatic water pressure significantly affects the stability of the dam structures and slopes, and the overall reliability of the structure.

Keywords: earth dam, three-dimensional model, stress state, non-homogeneity, hydrostatic pressure, stress and stress iso-fields.

1. Introduction

Hydro-technical structures built and operated in seismic regions must be stable, reliable, and safe when exposed to various types of static and intense dynamic loads, including seismic forces. Comprehensive studies are necessary to assess their static state, considering design features, actual geometry, and three-dimensional operation to ensure stable and reliable interaction of structures with water medium.

When designing these types of structures in highly seismic areas, in most cases, their stress-strain state is studied using a plane design scheme. The results found in existing scientific publications on the behavior of these types of structures indicate the need to use three-dimensional calculation schemes.

The solution to the above problem, considering the factors mentioned, can be most fully and accurately obtained using numerical methods; for example, the finite element method or the finite difference method [1, 2].

In [3-16], using various models of dams, the stress state and dynamic behavior of various earth dams were studied and assessed, considering design features and soil properties.

Reviewing scientific publications shows that studying the stress-strain state of dams built from local materials, considering their design features and actual structural performance is relevant in the

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mechanics of deformable rigid bodies. Therefore, research in this area is of great scientific interest. Based on the above, it can be noted that developing mathematical models and calculation methods for assessing the stress-strain state of earth dams in a three-dimensional formulation, considering design features, terrain, geometric dimensions, physical and mechanical properties of soils, and hydrostatic pressure of reservoir water is an urgent problem in mechanics of solids.

2. Methods

Let us consider a three-dimensional model of an earth dam of complex geometry (Fig. 1), with volume $V = V_1+V_2+V_3$ (V_1, V_3, and V_2 - are the volumes of the upper prism, lower prism, and the core). The area of the dam along the base and coastal slopes $\sum_o^{`}, \sum_o^{``}, \sum_o^{```}$ is rigidly fixed, and the crest Σ_2 and the downstream slope Σ_3 of the dam are load-free; hydrostatic water pressure acts on the upper slope S_p. The terrain at the dam's foundation and the axis of the dam crest at an angle α are considered. The structure in question is under the influence of its weight $\vec{f}$.

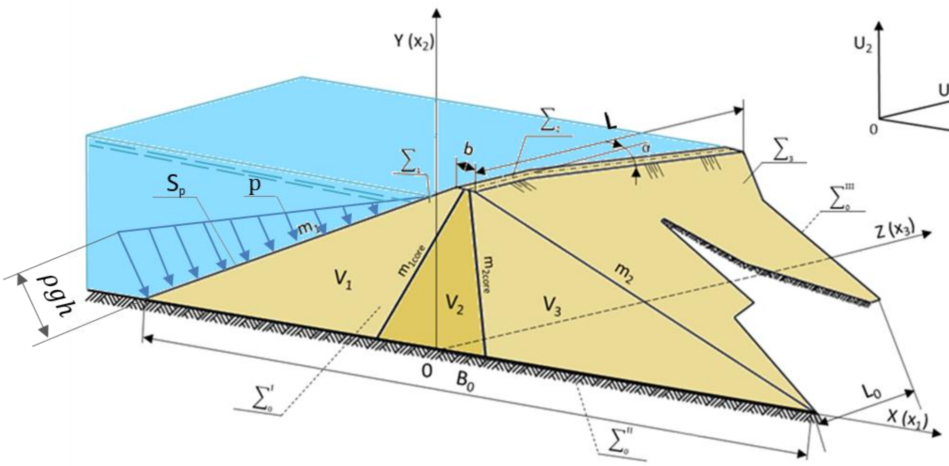


Fig. 1. Three-dimensional calculation model of an earth dam

Here: L is the crest length; L_o is the longitudinal length of the foundation; b is the crest width; B_0 is the width of the foundation of the dam in the transverse direction; m_1 and m_2 are the slopes of the upstream and downstream pools; m_{1core} and m_{2core} are the dam core slopes.

In this case, the variational equation, based on Lagrange's principle of virtual displacements, is written in the following form [1, 17]:

$$\delta A = -\int_V \sigma_{ij}\delta\varepsilon_{ij}dV + \int_V \vec{f}\delta\vec{u}dV + \int_{S_p} \vec{p}\delta\vec{u}dS = 0, \quad i, j = 1,2,3 \quad (1)$$

and the homogeneous boundary conditions at the foundation of the dam are used:

$$\vec{x} \in \sum{}_o = \sum{}_0^{'} + \sum{}_0^{''} + \sum{}_0^{'''} \quad : \quad \vec{u} = 0 \,. \quad (2)$$

To describe physical properties of the dam material, the relationships between the stress and strain components are accepted in the following form:

$$\sigma_{ij} = \lambda_n \theta \, \delta_{ij} + 2\mu_n \, \varepsilon_{ij} \quad (3)$$

and Cauchy relations are:

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

Here $\delta\vec{u}$, $\delta\varepsilon_{ij}$ are isochronous variations of the components of the displacement vector and strain tensors; $\vec{u}$, ε_{ij}, σ_{ij} are the displacement vectors, components of strain and stress tensors; $\vec{f}$ is the vector of body forces; λ_n and μ_n are the Lame constants for the *n*-th element of the dam; $\theta = \varepsilon_{kk}$ is the volumatric strain; $\{u_1,u_2,u_3\}=\{u,v,w\}$ are the components of the displacement vector of a body point; $\{x\}=\{x_1,x_2,x_3\}=\{x,y,z\}$ are the coordinates of a body point, $i, j, k = 1, 2, 3$.

In calculations, the hydrostatic water pressure on the upstream face of the dam is determined by the following formula:

$$p = \rho g(h - y). \qquad (5)$$

It is necessary to determine the fields of displacements and stresses that arise in the dam's body under the influence of $\vec{f}$ and $\vec{p}$, satisfying equations (1) - (4) for any virtual displacement $\delta\vec{u}$.

The variational problem posed by the finite element method using the developed algorithm is reduced to a resolving system of algebraic equations of the *n*-th order:

$$[K]\{u\} = \{F\}, \qquad (6)$$

in which the elements of the stiffness matrix $[K]$ are constant and depend on the elastic physical and mechanical parameters of the material; $\{u\}$ is the sought-for vector of nodal displacements; $\{F\}$ is the vector of external load (body forces and hydrostatic water pressure).

Kinematic boundary conditions (2) are considered when deriving equations (6). If the displacement components of a certain node are zero, then the corresponding rows in equation (2) are not generated. The *Abacus* universal program was used when solving the problems in a three-dimensional formulation. When solving specific problems, the order of the system of equations reached 77500.

3. Results and discussion

The article examines the stress-strain state of the earth dam of the Dzhidalisay reservoir, built in the Fergana Valley, considering its three-dimensional work under the influence of body forces and hydrostatic pressure of the reservoir water. Using the above mathematical model, method, and algorithm, the stress-strain state of the dam is studied with account for the real physical and mechanical characteristics of soil, design features, geometric parameters, terrain, and the curved axis of the dam.

The dam in question is an earth and rock-fill one. The upstream slope is lined with concrete with a thickness of t=0.20 m. Filtration cups are installed on the upstream berms. The water-retaining element has a loam core. Dzhidalisay dam has a height of H=62.8 m and slope coefficients $m_в$=2.35, $m_н$=2.1. Retaining prisms 1 and 3 are laid from gravel and pebbles, and core 2 is laid from loam. The transition zone is of sandy-gravel soil. The dam crest has a width of b=10m and a length of L=965m. The longitudinal length of the foundation is L_0=364 m.

The results of the calculation are the components of the displacement vectors u_1, u_2, u_3 and stress tensors σ_{ii} for all points of the structure.

For the convenience of analyzing the results in characteristic longitudinal and cross sections of the dam, iso-lines were plotted for the displacement components and stress tensors. Several characteristic cross-sections were selected along its longitudinal axis (see Fig. 2), and iso-fields of equal levels of displacement components and stress tensors under the effect of the structure's weight and the hydrostatic pressure of water were constructed. The results obtained for each section are analyzed in detail and compared.

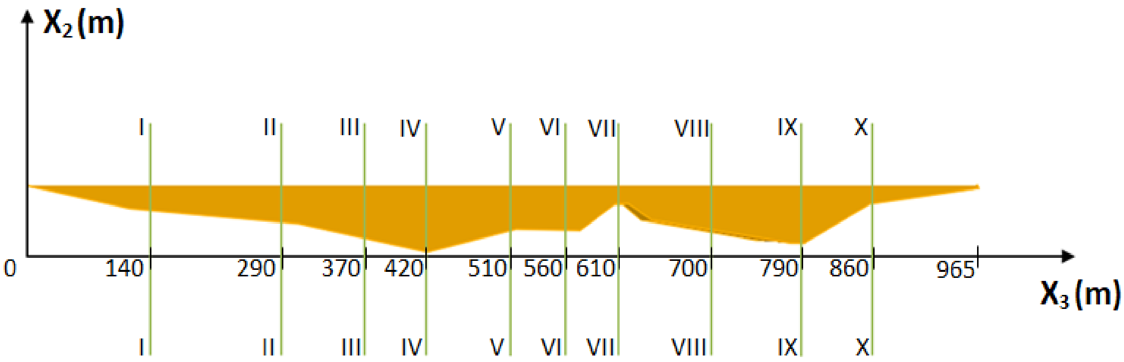


Fig.2. Layout of characteristic cross-sections of the Dzhidalisay Dam

Figure 3 shows fields of equal levels of horizontal u_1 and vertical u_2 displacements in sections IV-IV of the Dzhidalisay Dam with empty (a, b) and filled (c, d) reservoir.

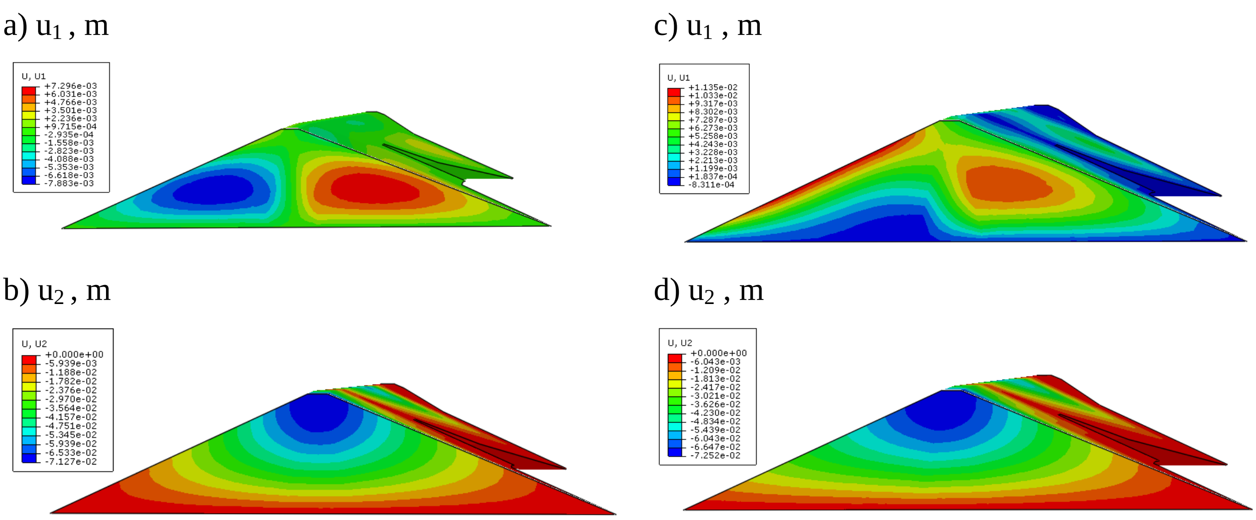


Fig. 3. Fields of equal levels of horizontal u_1 (a, c) and vertical u_2 (b, d) displacements in sections IV-IV of the Dzhidalisay Dam with empty (a, b) and filled (c, d) reservoir.

Analysis of the results obtained considering the dead weight of the dam when the reservoir is empty (see Fig. 3a) shows that with an increase in the dam height, the values of vertical displacements u_2 increase accordingly. These phenomena are observed mainly in the crest of the dam. The maximum value of vertical displacements is observed in the crest of the highest part of the dam. The strain pattern in dam sections significantly depends on the location of the selected section. In all sections considered, the displacements of points in the dam body relative to the vertical axis are approximately symmetrical.

Considering the hydrostatic water pressure in the upstream pool leads to a significant change in the dam's strain. The symmetrical nature of the movements relative to the vertical axis of the dam is violated, which is manifested when calculating the dam with a filled reservoir. The values of the displacement components u_1, u_2 of points in the upper retaining prism are much greater than the displacements of the points of the lower retaining prism. At points located in the core zone, horizontal displacements also appear.

The displacement field of the dam profile depends significantly on the water level in the reservoir. As the water level increases, the displacement field of the dam profile changes: when the reservoir is filled to half the height of the dam, only the displacement field of the upper retaining prism changes; as the water level increases, the displacement field gradually changes in the core and then in the lower retaining prism.

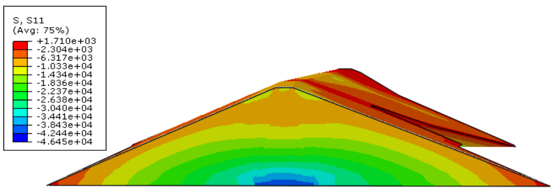
At the next stage of calculations, the stressed state of the dam is studied under the structure's weight and hydrostatic water pressure in a three-dimensional formulation, and iso-fields of equal levels of stress components σ_{ii} are constructed for all points of the structure (see Fig. 4).

The results on the stress state of the dam with an empty reservoir (Fig. 4) show that the values of stress components of the points depend on the height of the dam and the distance from the banks of the dam site. The results presented indicate that the stress state in all selected sections is almost symmetrical to the vertical axis of the structure. The core of the dam leads to the appearance of an arch effect and a change in the overall stress state of the dam. In each section under consideration, a different stress state is observed. As the height of the dam increases, the values of vertical stresses σ_{22} increase accordingly (see Fig. 4b), and this phenomenon is observed in the part of the body near the foundation. The isofield of longitudinal stresses σ_{33} along the x_3 axis (see Fig. 5e) shows that in the middle part, where the crest axis is curved and the height of the dam is lower, the stress distributions σ_{33} are of complex pattern. Such a complex pattern of the distribution of longitudinal stresses σ_{33} in the dam body is observed due to the influence of the base terrain and the curved axis of the dam on the stress-strain state of the dam as a whole.

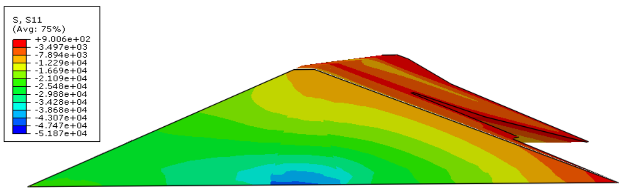
Considering the influence of water in the upstream pool leads to a redistribution of the stressed state of the earth dam. First, the symmetrical nature of the stress fields changes. Further, with an increase in the water level in the upstream pool, the change in stress covers an increasingly larger area. So, if the water level reaches half the height of the dam, the stresses change (compared to the calculation without considering water) only in the upper prism. As the water level increases, the area of its influence along the dam profile increases, i.e. gradual changes in stress values occur in the core and lower prism. When the reservoir is completely filled, in the upper prism, mainly near the slope, the values of vertical stress σ_{22} almost double. The highest values are achieved in the lower part of the upper slope of the dam. Shear stresses σ_{12} in the upper slope zones decrease, and in the core, they increase depending on the height of the dam.

Based on the results obtained, we can conclude that when studying the stress-strain state of the earth dam of the Dzhidalisay reservoir with complex geometric parameters, it is necessary to account for the influence of water in the upstream pool. Hydrostatic water pressure significantly affects the stability of dam structures and slopes, and the overall reliability of the structure.

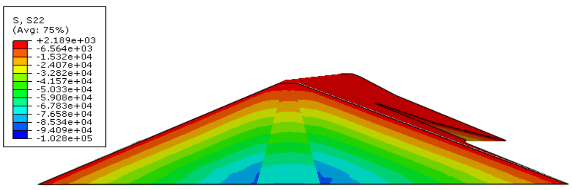
a) σ_{11} , ($x10^{-5}$ MPa)



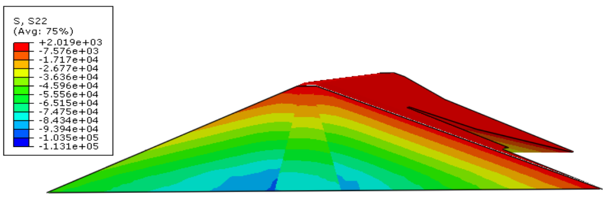
c) σ_{11} , ($x10^{-5}$ MPa)



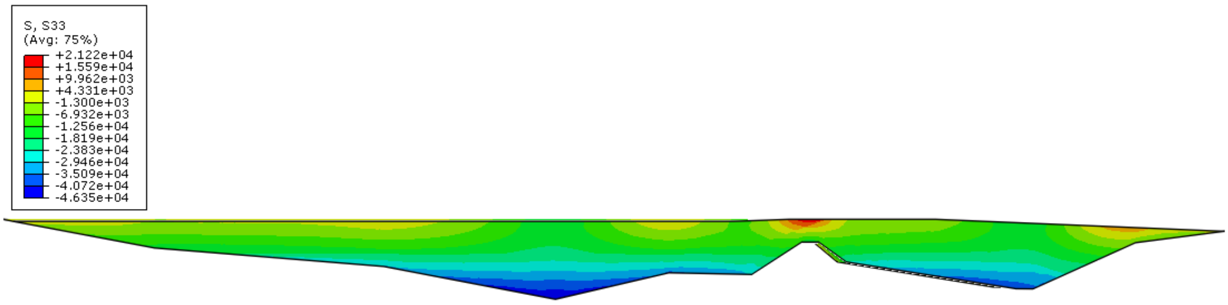
b) σ_{22} , ($x10^{-5}$ MPa)



d) σ_{22} , ($x10^{-5}$ MPa)



e) σ_{33}, ($x10^{-5}$ MPa)



f) σ_{33}, (x10^{-5} MPa)

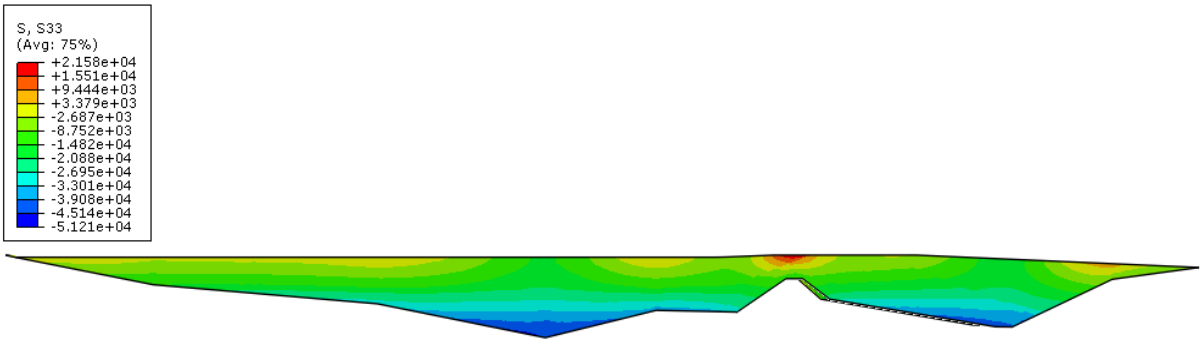


Fig. 4. Fields of equal levels of stress components σ_{ii} in transverse (a-d) (in sections V-IV) and longitudinal (e, f) sections of the dam with empty (a, b, e) and filled (c, d, f) reservoir.

4. Conclusions

1. Based on Lagrange's variational principle, a general mathematical formulation and methods for solving problems on the stress-strain state of earth dams with complex geometric parameters using three-dimensional calculation schemes are given, considering the real features and work of the structure.
2. As a result of numerical calculations, it was revealed that the distribution pattern of the stress-strain state of the dam significantly depends on the location of the selected section and its geometric parameters. The values of the displacement components and stress tensors of the points depend on the height of the dam and the distance from the banks of the dam site. The stress state in all sections is almost symmetrical relative to the vertical axis of the dam when the reservoir is empty. In this case, in each section, there is a different stress state.
3. The stress-strain state of the dam significantly depends on the level of the reservoir filling, which changes the symmetrical pattern of the strain and stress fields in the cross sections of the dam. When the reservoir is completely filled, the values of vertical stresses in the upper prism almost double. Water pressure significantly increases the value of horizontal stresses along the entire profile of the dam, which leads to a decrease in its resistance to horizontal loads.
4. When studying earth dams of any height, it is necessary to consider the influence of water in the upstream pool. Hydrostatic water pressure significantly affects the stability of dam structures and slopes, and the overall reliability of the structure.

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