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STUDY OF STRESS-STRAIN STATE OF AN EARTH DAM USING A THREE-DIMENSIONAL MODEL OF THE STRUCTURE

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Abstract: The paper presents a mathematical model, methodology and algorithm for studying the stress-strain state (SSS) of an earth dam with complex geometric parameters using a three-dimensional model of the structure under the influence of static loads. The three-dimensional stress-strain state of a soil dam was studied, taking into account heterogeneous and design features using the universal program Abaqus.

As a result of the research, it was revealed that the deformation of the dam points significantly depends on the location of the selected section. The deformation in each section depends on the geometric parameters, the height and location of the selected section. In each section, a different deformation state is observed, differing from each other. The stress state in all sections is almost symmetrical with respect to the vertical axis of the dam. In this case, a different stress state is observed in each section. As the height of the dam increases, the values of vertical stresses correspondingly increase, and this is observed in the part of the body close to the base. In the middle of the part, where the axis of the crest is curved and the height of the dam is reduced, the nature of the distribution of longitudinal stresses is complex.

It was revealed that in order to study the stress-strain state of the Dzhidalisai reservoir dam with complex geometric parameters under static loads, it is necessary to carry out calculations only using three-dimensional models of the structure.

Keywords: earth dam, three-dimensional model, stress state, heterogeneity, mass forces, isopolies of deformations and stresses.

Introduction. In earth dams, under the influence of their own weight, a complex interaction occurs between the individual parts of the dam. This interaction is further complicated by dynamic loads from seismic impacts, and the conditions of the dam's abutment to heterogeneously steep coastal slopes.

The problem of studying the stress-strain state of soil dams is a complex spatial problem in the theory of continuum mechanics, in solving which it is necessary to take into account the spatial work of the structure, the variability of the properties of materials, the design features of structures, the timing of construction, operation, the type of acting loads, etc. When designing such types of unique structures with complex geometric parameters and dimensions in highly seismic areas, in most cases, their stress-strain state is studied using a flat design scheme. These circumstances, as well as existing scientific materials on the behavior of these types of structures under static and dynamic loads, show the need to use three-dimensional design schemes.

At the same time, the solution of particular problems with the adoption of certain assumptions and prerequisites, most completely and accurately, can be obtained using numerical methods, such as the finite difference method (FDM) or the finite element method (FEM) [2-6].

In works [7-13], using various dam models, the assessment of the dynamic behavior and the study of the stress state of various soil dams is considered, taking into account the design features and nonlinear properties of the soil.

In [14], seismic analysis of dams (earth and rock) was carried out using quasi-static and dynamic methods. The results of seismic analysis show that the settlement of the dam in the vertical direction is significant relative to the horizontal displacement, namely, the horizontal displacement in the upper, middle and lower sections of the dam is 66%, 55% and 52%. The highest subsidence rates were observed at the upper levels of the dam under both static and dynamic conditions.

Seismic stress in the soil massif [15] was determined based on the basic equations of continuum mechanics. The problem posed is solved by the MKR method, based on exact boundary and zero initial conditions. This takes into account the humidity regime, elasticity, viscosity and plasticity of the soil.

The paper [16] describes the main conclusions and scientific achievements, i.e. systematically summarizes the accumulated experience in the construction of high rock-earth dams, discusses the main technical issues, including control of deformations, seepage, slope stability, safety assessment and other issues related to earth dams .

The authors of the article [17] studied the dynamic characteristics of a damaged laboratory model of an arch dam. As a result of the study, changes in the dynamic characteristics of the dam were determined: natural frequencies, vibration patterns and damping coefficient before and after modernization. The dynamic characteristics obtained from all experimental variants are experimentally determined and compared with each other.

In work [18], the stressed state of soil joints under static and seismic influences is considered, taking into account elastic-plastic deformation of the dam soil, and the obtained numerical results are compared using the finite element method with the results of field measurements of the Wenchuan earthquake.

Work [19] presents studies of the dynamics of a concrete spillway dam of a river hydroelectric power station. A detailed review of the method for calculating the dynamic characteristics of structures and the results of assessing the response of structures to time-varying excitations and earthquake accelerograms are provided. The resulting response spectra made it possible to estimate the maximum horizontal accelerations.

In [20], using three-dimensional boundary elements, the dynamic behavior of the Soria arch dam (Gran Canari, Spain) was studied, taking into account the interaction with the soil base of the reservoir's filling, actually taking into account the geometry of the dam wall. It has been established that the influence of the dynamic characteristics of the dam is significantly influenced by the correct accounting of the properties of the material of the structure, the level of water filling and the correct accounting of the geometry of the dam.

In [21], the design of the Indirasagar gravity dam, located in the state of Andhra Pradesh, taking into account the dead weight of the dam and hydrostatic water pressure using the ANSYS software package.

As the review of scientific works shows, studies of the stress-strain state and dynamic behavior of dams built from local soils, taking into account their design features and the actual operation of structures, are not enough, therefore, research in this direction is of great scientific interest.

Based on the above, it can be noted that the development of mathematical models, calculation methods for assessing the stress-strain state of soil dams in a three-dimensional formulation, taking into account design features, terrain, geometric dimensions and real properties of materials is an urgent problem in continuum mechanics.

Methodology. We consider a three-dimensional model of an earth dam with complex geometry (Fig. 1), volume $V = V_1 + V_2 + V_3$ (V_1, V_3 and V_2 - the volume of the upper, lower prism and core). The area of the dam along the base and the coastal slope $\Sigma_0^{`}, \Sigma_0^{``}, \Sigma_0^{```}$ is rigidly clamped, and the surfaces Σ_1, Σ_2, Σ_3 are stress-free. The foundation of the dam takes into account the terrain relief, as well as the linear axis of the dam crest on coal α. The structure in question is under the influence of its own $\vec{f}$ weight.

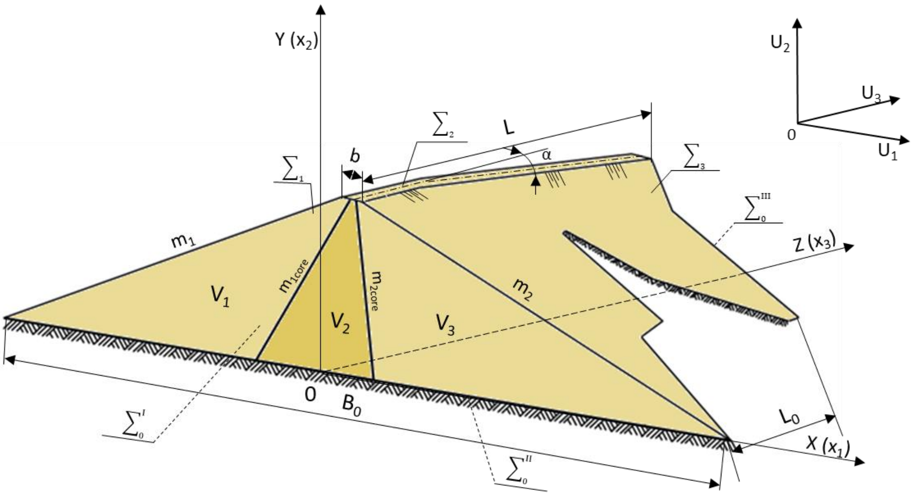


Figure 1. Three-dimensional calculation model of an earth dam.

In Figure 1 it is indicated: L – ridge length; Lo – longitudinal length of the base; b - ridge width; B_0 – width of the dam base in cross section; m_1 and m_2 – slopes of the upper and lower tails; m_{1core} and m_{2core} – slopes of the dam core.

The problem statement is formulated on the basis of Lagrange's variational equation and Alembert's principle [1], i.e.:

$$\delta A = -\int_{V_1} \sigma_{ij}\delta\varepsilon_{ij}dV_1 - \int_{V_2} \sigma_{ij}\delta\varepsilon_{ij}dV_2 - \int_{V_3} \sigma_{ij}\delta\varepsilon_{ij}dV_3 + $$
$$+\int_{V_1} \vec{f}_1 \delta\vec{u}dV_1 + \int_{V_2} \vec{f}_2 \delta\vec{u}dV_2 + \int_{V_3} \vec{f}_3 \delta\vec{u}dV_3 = 0, \quad i,j = 1,2,3 \qquad (1)$$

kinematic boundary conditions:

$$\vec{x} \in \sum\nolimits_o = \sum\nolimits_0' + \sum\nolimits_0'' + \sum\nolimits_0''' \;:\; \vec{u} = 0\,. \qquad (2)$$

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

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

and Cauchy relations

$$\varepsilon_{ij} = \left(\partial u_i/\partial x_j + \partial u_j/\partial x_i\right)/2 \qquad (4)$$

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} - displacement vectors, components of strain and stress tensors; $\vec{f}$ - vector of mass forces; λ_n and μ_n are the Lame constants for the nth element of the dam; $\theta = \varepsilon_{kk}$ - volumetric deformation; $\{u_1,u_2,u_3\}=\{u,v,w\}$ - components of the displacement vector of a body point; $\{x\}=\{x_1,x_2,x_3\}=\{x,y,z\}$- coordinates of a body point $i,j,k=1,2,3$.

When solving the variational problem (1) - (4), the area occupied by the body is divided into subregions having different physical and mechanical parameters, then these subregions are automatically divided into a final element in the form of a tetrahedron.

Using the FEM procedure [6], the variational problem (1)-(4) is reduced to a system of inhomogeneous algebraic equations of high order, i.e.:

$$[K]\{u\} = \{P\} \qquad (5)$$

Here: $[K]$ is the stiffness matrix for the body in question (Fig. 1); $\{u\}$ - the required components of the displacement vectors at the nodes of the finite element; $\{P\}$ - components of external mass forces acting on the nodes of the finite element.

When solving the problems in a three-dimensional formulation, a computer calculation program developed by the authors ECM and the universal Abaqus program were used. When solving specific problems, the order of the system of equations reached 85000.

Results and Discussion. The article examines the SSS of the soil dam of the Dzhidalisai reservoir, built on the territory of the highly seismic region of the Fergana Valley, taking into account its spatial operation under the influence of mass forces. Using the above mathematical model, method and algorithm, the stress-strain state of dams is studied, taking into account the real physical and mechanical characteristics of soils, design features, geometric parameters and the curved axis of the dams.

The dam is earthen, embankment. The thrust prisms are made using the method of laying gravel and pebble soil. 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 is a loam core. Dzhidalisai dam with a height of H=62.8 m with slope coefficients m_1=2.35, m_2=2.1. Thrust prisms 1 and 3 are laid from gravel-pebble soil with physical and mechanical parameters - E = 3550 MPa, specific gravity of the soil - γ = 2.05 t·f/m^3 and Poisson's ratio - ν = 0.27. Core 2 is laid from loam with physical and mechanical parameters - E = 2400 MPa, specific gravity of the soil - γ = 1.7 t·f/m^3 and Poisson's ratio - ν = 0.35. Transition zone of sandy-gravel soil. The dam crest is width b=10 m and length L=965 m. The longitudinal length of the base 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 σ_{11}, σ_{22}, σ_{33}, τ_{12}, τ_{23}, τ_{31} for all points of the structure.

For the convenience of analyzing the results in the characteristic longitudinal and cross sections of the dam, isolines of the displacement components and the stress tensor were constructed. At the same time, several characteristic cross sections “I-I” - “X-X” were selected along its longitudinal axis (see Fig. 2), and isopoles of equal levels of displacement components and stress tensors under the influence of the structure’s own weight were constructed for them. Next, the results obtained for each section are analyzed in detail and compared with each other.

First of all, the calculation examines the deformed state for the dam under consideration in a three-dimensional setting. For a detailed analysis of the results obtained in the transverse and longitudinal sections of the dam, isopolies of the displacement components u_1, u_2, u_3 are constructed and are given below.

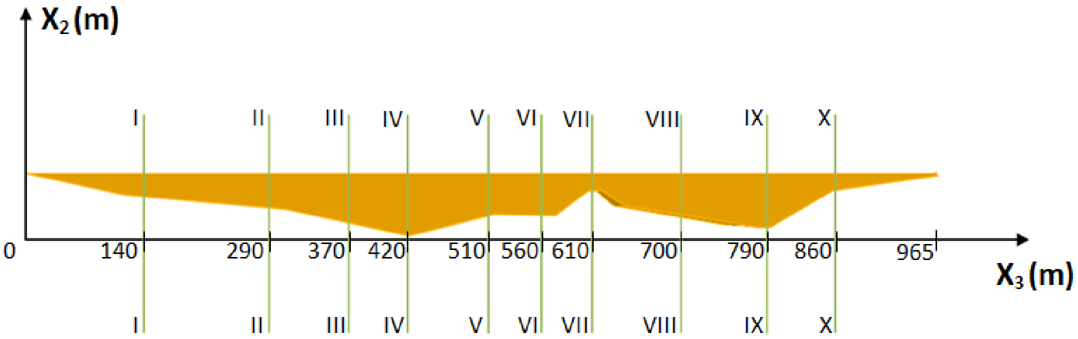
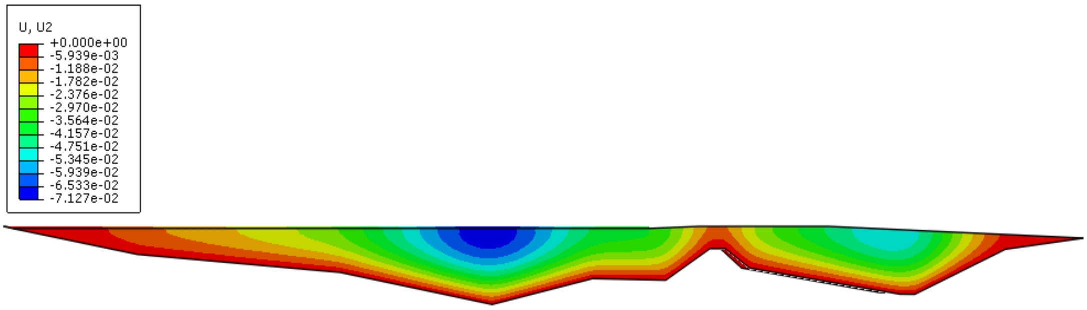


Figure 2. Layout of cross sections of the Dzhidalisai Dam along the longitudinal axis X_3.

Figure 2 shows the field of equal levels of vertical u_2 along the x_2 axis (a) and longitudinal u_3 along the x_3 axis (b) displacements in the longitudinal section of the Dzhidalisai dam under the influence of the structure’s own weight in a three-dimensional setting.

a) u_2, m



b) u_3, m

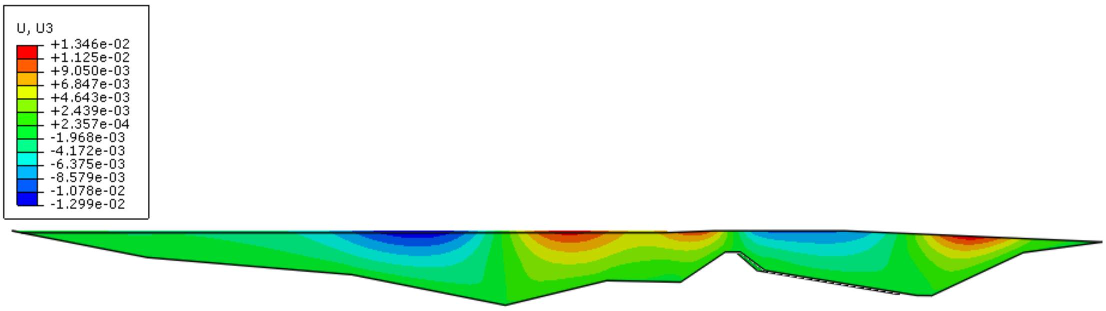
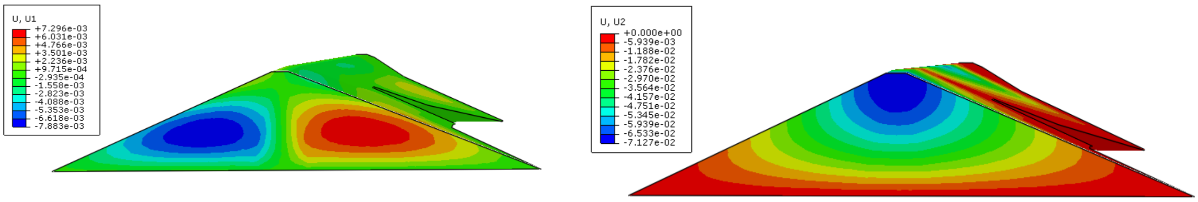


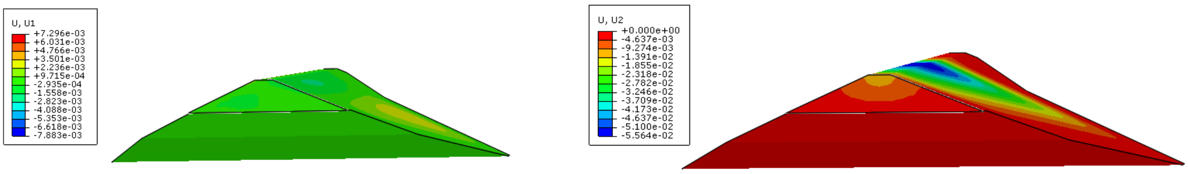
Figure 3. Field of equal levels of vertical u_2 (a) and longitudinal u_3 (b) displacements in the longitudinal section of the Dzhidalisai dam along the X_3 axis.

Figure 4 shows the field of equal levels of horizontal u_1 (a, b, c) and vertical u_2 (d, e, f) displacements in characteristic cross sections of the Dzhidalisai dam under the influence of the structure's own weight: namely, in section IV-IV (a, d); in section VII-VII (b, e) and in section IX-IX (c, f).

a) u_1 in sections IV-IV, м
d) u_2 in sections IV-IV, м



b) u_1 in sections VII-VII, м
e) u_2 in sections VII-VII, м



c) u_1 in sections IX-IX, м
f) u_2 in sections IX-IX, м

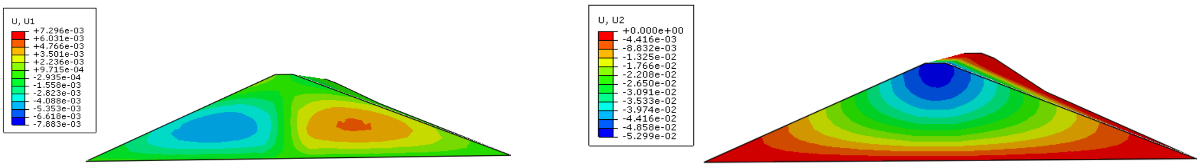


Figure 4. Field of equal levels of horizontal u_1 (a, b, c) and vertical u_2 (d, e, f) displacements in various cross sections of the Dzhidalisai dam

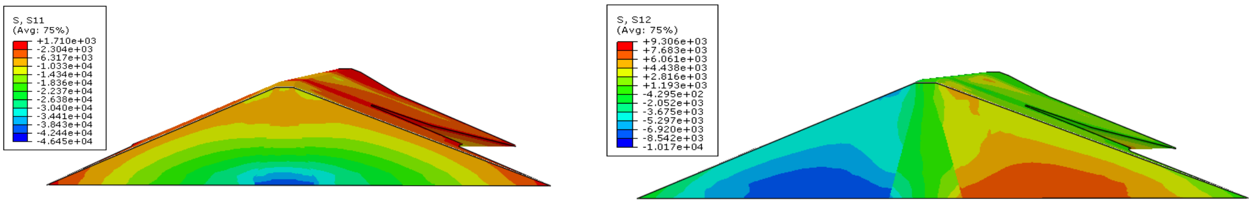
Analysis of the results obtained (see Fig. 3a) shows that the vertical movement of u_2 points in the longitudinal axis of the dam is complex. With increasing distance of body points from the left bank, the value of vertical displacements changes significantly and depends on the height of the dam. In this case, with increasing dam height, the values of vertical displacements u_2 increase accordingly. These phenomena are observed mainly in the crest part of the dam. In this case, the maximum value of vertical mixing is observed in the crest of the highest part of the dam. The isopoly of longitudinal displacements along the x_3 axis (see Fig. 3b) shows that in the middle of the part and near the right bank of the dam, the pattern of displacement u_3 is very complex. Here, in the crest part of the dam, mixing has a positive value, which is undesirable for soils. In the highest part of the dam u_3 has a small value, and their value increases towards the left banks of the alignment. Such a complex nature of the distribution of patterns of longitudinal movements u_3 in the body of the dam is observed, apparently under the influence of the topography of the base on the deformation of the state of the dam as a whole.

For a detailed analysis of the deformation of the structure, the deformation of ten cross sections of the dam along the X_3 axis is considered. The results obtained (Fig. 4) show that the nature of the deformation in the dam sections significantly depends on the location of the selected section. The deformation value of a point depends on the height of the dam and the distance from the banks of the site. In all selected sections, the movement of points in the dam body relative to the vertical axis is approximately symmetrical. In the core of the dam, the values of horizontal displacements are close to zero, and their magnitude increases towards the centers of the upper and lower thrust prisms. In this case, the movement of the point in the vertical direction predominates, since the calculations were made taking into account only the own weight of the structure. A comparison of the results obtained for different sections shows that the nature of the deformation of each section depends on the geometric parameters of the height and location of the selected dam section. In this case, in each section a different deformation state is observed, differing from each other. Based on this, we can conclude that to study the deformation of a dam with complex geometric parameters like the Dzhidalisai Dam, it is necessary to study the deformation state only using three-dimensional models of the structure.

In the next stage of the calculation, the stress state of the dam is studied in a three-dimensional setting. For a detailed analysis of the results obtained in the transverse and longitudinal sections of the dam, an isofield of equal levels of stress components σ_{11}, σ_{22}, σ_{33}, τ_{12}, τ_{23}, τ_{31} was constructed for all points of the structure, which is given below.

Figure 5 shows the isofield of stress components σ_{ii} in the transverse (sections IV-IV where the highest part of the dam) and longitudinal sections of the dam under the influence of the structure's own weight.

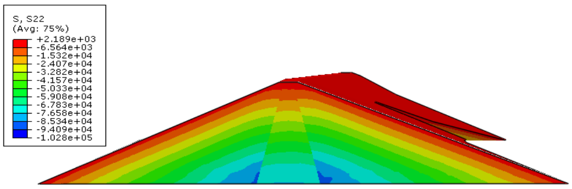
The results (Fig. 5) show that the nature of the stress pattern distribution in the dam sections significantly depends on the location of the selected section and their geometric dimensions. The value of the stress components of the points depends on the height of the dam and the distance from the banks of the site. The presented results indicate that the stress state in all selected sections is almost symmetrical in nature, relative 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 stress state pattern in the cross sections of the dam as a whole. Namely: the magnitude of horizontal stresses σ11 is approximately symmetrical relative to the center of the core, and its value increases from the top to the base. The magnitude of the vertical stress σ_{22} decreases around the core of the dam, forming an arch effect. And the distribution of tangential stresses σ_{12} in the dam body is symmetrical and practically equal to zero in the core and transition zones.



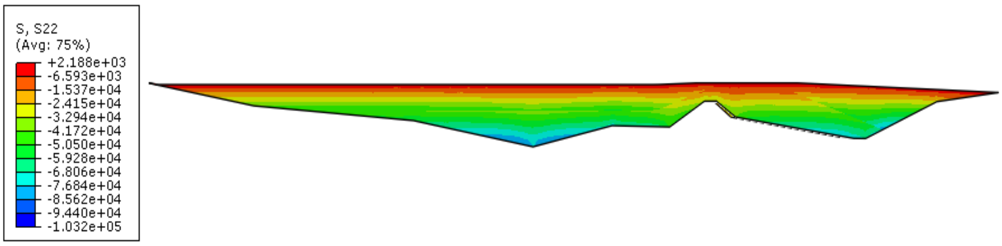
a) σ_{11} in sections IV-IV, (x10-5 MPa)

c) σ_{12} in sections IV-IV, (x10^{-5} MPa)

b) σ_{22} in sections IV-IV, (x10^{-5} MPa)



d) σ_{22} , (x10^{-5} MPa)



e) σ_{33} , (x10^{-5} MPa)

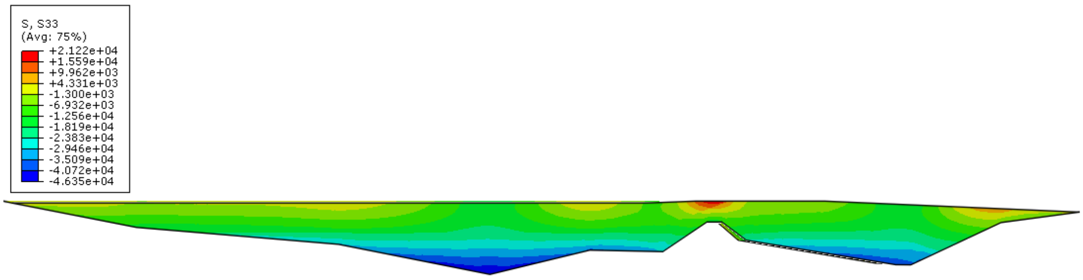


Figure 5. Field of equal levels of stress components in the transverse (sections IV-IV) and longitudinal sections of the dam.

A comparison of the results obtained for different sections shows that the nature of the stress distribution in each section depends on the geometric parameters, height and location of the selected section. In this case, a different stress state is observed in each section. As the height of the dam increases, the values of vertical stresses σ_{22} increase accordingly (see Fig. 5d), and this phenomenon is observed in the part of the body close to the base. The isopoly of longitudinal stresses σ_{33} along the x_3 axis (see Fig. 5e) shows that in the middle part, where the ridge axis is curved and the height of the dam is reduced, the nature of the stress distribution σ_{33} is very complex. Here, in the crest part of the dam, the longitudinal stress has a positive value, which is undesirable for soils. Such a complex distribution of the pattern of longitudinal stresses σ_{33} in the dam body is observed, apparently under the influence of the base terrain and the curved axis of the dam on the stress-strain state of the dam as a whole.

Based on these results, we can conclude that in order to study the stress-strain state of the Dzhidalisay reservoir dam with complex geometric parameters under static loads, it is necessary to conduct research only using three-dimensional models of the structure.

Conclusions.

1. To assess the SSS of soil dams with complex geometric parameters using three-dimensional calculation schemes, a mathematical model has been developed based on the variational principle of possible movements, taking into account the real features of the structure.

2. The spatial stress-strain state of the Dzhidalisay soil dam under the influence of the structure’s own weight was studied using the developed methodology, algorithm and universal program Abaqus.

3. As a result of studying the deformation of the dam, it was revealed that with an increase in the height of the dam, the values of vertical displacements u_2 in the crest part of the dam increase accordingly. The maximum value of vertical displacements is observed in the crest, the highest part of the dam. In the middle part and near the right bank of the dam under study, the values of longitudinal displacements u_3 are of a complex nature. This mechanical effect is observed, apparently under the influence of the terrain of the base on the deformation of the dam body. In this case, the nature of the deformation in the dam sections significantly depends on the location of the selected section. The deformation of each section depends on the geometric parameters, the height and location of the selected section. In this case, in each section different deformation states differing from each other are observed.

4. In the study of the stress state of the dam in a three-dimensional formulation, it was revealed that the nature of the distribution of the stress pattern in the dam sections significantly depends on the location of the selected section and their geometric parameters. The value of the stress components of the points depends on the height of the dam and the distance of the banks of the site. The stress state in all sections is almost symmetrical with respect to the vertical axis of the dam. In this case, in each section there is a different stress state that differs from each other. As the height of the dam increases, the values of vertical stresses σ_{22} increase accordingly, and this is observed in the part of the body close to the base. In the middle part, where the ridge axis is bent and the height of the dam is reduced, the nature of the stress distribution σ_{33} is complex.

5. Analyzing the results obtained, it was revealed that in order to study the stress-strain state of the Dzhidalisay reservoir dam with complex geometric parameters under static loads, it is necessary to carry out calculations only using three-dimensional models of the structure.

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ADVANCED PEDAGOGICAL TECHNOLOGIES IN EDUCATION

ECONOMICAL SCIENCES