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Strength of earth dams considering elastic-plastic properties of soil

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Abstract. The paper provides a detailed analysis of known publications devoted to various models and methods, as well as the results of the study of the stress state of structures, taking into account the elastoplastic properties of soil. A mathematical model, methods, and an algorithm to assess the stress-strain state of earth dams were built considering elastoplastic properties of soil, inhomogeneous structural features and the filling level of the reservoir under various influences. A variational equation of the principle of virtual displacements, and the finite element method and the method of elastic solutions were used to solve the problem. The reliability assessment of the results obtained was verified by studying the practical convergence of various model problems. The stress-strain state of three earth dams (of different heights) was investigated taking into account the elastic, elastoplastic properties of soil at different filling levels of the reservoir. At that, various mechanical effects were revealed, i.e., the appearance of additional strains in the most stressed places inside the dam body, and the occurrence of significant plastic shear strain in the slope zones and the smoothing of the arch effect in the core zone. It was found that an account of elastoplastic properties of soil at a completely filled reservoir significantly changes the pattern of shear stresses distribution in the body of the dam, i.e. they increase both in the upper retaining prism and in the lower prism.

1. Introduction

An assessment of strength parameters of earth dams is often made with account for elastic properties of soil only, which does not lead to adequate results.

Today, many different theories are applied to describe physical state of soil, most of them are difficult to implement when solving specific problems. One of the important problems in determining the strength parameters of earth dams is to take into account the elastic-plastic properties of soil that arise in the structure under various effects [1–11].

Recently, researchers have paid great attention to inelastic properties of soil when assessing the stress-strain state of earth dams.

Consider several publications:

- in [6, 10, 11] an assessment of strength and stability of dam slopes was given with account of plastic strains, the stage-by-stage erection of the structure and water seepage through the dam body;
- in [7], a numerical-analytical procedure was proposed to analyze the elastic-plastic “nonlinear” state of earth dam during earthquakes;

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- in [12] nonlinear models were given that satisfactorily describe the elastic-plastic properties of earth materials;
- in [13], a finite element method was used for numerical calculation of earth dams; it takes into account water-saturated (unsaturated) and plastic properties of soil. With the proposed model, three dams were calculated;
- in [14], the behavior of high dams with strengthened soil was modeled using an elastic-plastic model;
- in [15], the stability of earth dams' slopes was investigated using an elastic-plastic model;
- in [16], the results of the stress-strain state prediction of a high earth dam in an elastic-plastic statement were considered, taking into account the stage-by-stage erection of the dam and reservoir filling. It was shown that the operation of earth dam with a vertically located diaphragm at water-filled reservoir is characterized by horizontal displacement of the downstream retaining prism;
- in [17, 18], the methods were proposed for numerical study of elastic-plastic strain of bodies considering finite strains. It is assumed that the soil under strain obeys the law of dry friction. Total strain is represented as the sum of plastic and elastic strains. The defining relations of elastic strain are written in the form of Hooke's law;
- in [19], a geomechanical model of an enclosing fill hydro-technical structure – a dam – was proposed. A pattern of strain and displacement of a structure body was investigated in elastic-plastic statement by computer simulation methods;
- in [20], a two-dimensional problem of estimating the slope stress-strain state in elastic-plastic statement using a numerical method was solved;
- in [21], the possibility of using a structurally heterogeneous elastic-plastic calculation model to describe the strain behavior of water-saturated clay soils was considered.

Along with this, the studies in [22–35] deal with the stress-strain state and dynamic behavior of various structures considering their strain features.

These are just several publications in which along with elastic properties, the elastic-plastic properties of soil are taken into account when assessing the stress-strain state and stability of slopes of earth dams. Above review of publications shows that the assessment of strength parameters of earth structures in different studies is treated differently, and each theory or method used has its advantages and disadvantages.

As is known, at present a universal theory to determine strength parameters of earth structures, considering various soils characteristics under different loads, as well as the methods to determine strength properties of soils and structures is still under development.

An adequate assessment of strength parameters of earth dams with account for elastic-plastic properties of soil remains insufficiently studied and requires extensive research.

So, this problem is relevant and requires further research.

2. Methods

2.1. Models, methods and algorithms for assessing the stress-strain state of earth dams taking into account elastic-plastic properties of soil

To assess the stress-strain state of earth dams, considering elastic-plastic properties of soil under various effects, a plane-strained model of a dam is considered (Fig. 1); it takes into account inhomogeneous features of a structure. The base surface Σ_0 is rigidly fixed, the downstream slope surface Σ_3 is stress-free and on the surface Σ_1 (on the part of the upstream slope, i.e., on S_p), the hydrostatic water pressure $\vec{p}$ acts.

The dam material (earth) in various parts of a structure is considered as elastic or elastic-plastic one. In calculations, the mass forces $\vec{f}$, acting on the structure and water pressure $\vec{p}$ [34] acting on the surface S_p are taken into account.

The task is to determine the fields of displacements and stresses arising in the dam body (Fig. 1) under mass forces $\vec{f}$ and hydrostatic water pressure $\vec{p}$, taking into account elastic-plastic properties of soil in the case of a plane-strained state of a structure.

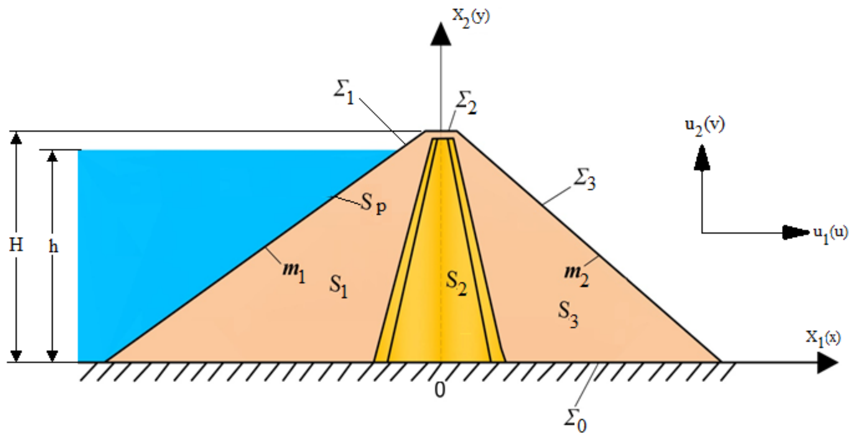

Figure 1. Plane model of an inhomogeneous earth dam.

To simulate the process of earth dam strain (Fig. 1), a variational equation based on the principle of virtual displacements is used:

$$-\int_{S_1}\sigma_{ij}\delta\varepsilon_{ij}dS-\int_{S_2}\sigma_{ij}\delta\varepsilon_{ij}dS-\int_{S_3}\sigma_{ij}\delta\varepsilon_{ij}dS+\int_{S_1+S_2+S_3}\vec{f}\,\delta\vec{u}dS+\int_{S_p}\vec{p}\,\delta\vec{u}dS=0. \quad (1)$$

Here, physical properties of the structure material are described by the relations between stresses σ_{ij} and strains ε_{ij} [22]:

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

the relationship between the components of the strain tensor and the displacement vector is described by Cauchy linear relations [22].

$$\varepsilon_{ij}=\frac{1}{2}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right). \quad (3)$$

To create mathematical models, homogeneous kinematic boundary conditions are also taken into account:

$$\vec{x}\in\sum\nolimits_0:\vec{u}=0. \quad (4)$$

Here $\vec{u}$, ε_{ij}, σ_{ij} are the components of the displacement vector, tensors of strains and stresses, respectively; $\delta\vec{u}$, $\delta\varepsilon_{ij}$ are isochronous variations of the components of displacements and strains; $\vec{f}$ is the vector of mass forces; $\vec{p}$ is the hydrostatic water pressure; index n = 1, 2, 3, means separate inhomogeneous parts of the dam to which this characteristic belongs.

λ_n and μ_n are the Lamé constants, determined through the Young's modulus E_n and Poisson's ratio ν_n as follows:

$$\lambda_n=E_n\nu_n/\left((1+\nu_n)(1-2\nu_n)\right);\mu_n=E_n/\left(2(1+\nu_n)\right). \quad (5)$$

The structure under consideration is inhomogeneous in the sense that the physical properties of its parts vary greatly.

The problem to be solved is considered in the framework of the plane-strained state of structures, i.e. the displacement vector in the coordinate system $\vec{x}=\{x_1,x_2\}=\{x,y\}$ has two components $\vec{u}=\{u_1,u_2\}=\{u,v\}$, in all ratios i, j, k = 1,2.

In the case when the dam material of the n-th part (Fig. 1) is elastic, the relationship between the stresses σ_{ij} and strains ε_{ij} tensor components is expressed through the generalized Hooke's law (2).

In the case when the material is elastic-plastic, the hypothesis of the energy forming is used to describe the equation of state of soil medium; here the transition from elastic state to the plastic one occurs at the point of soil medium $\sigma_i = \sigma_y$. The state of the medium in different parts of the dam under consideration is described differently (according to elastic or elastic-plastic law), depending on whether the yield strength of the material σ_y is overcome or not.

Here σ_y are the normal stresses in the yield strength of the material.

The intensities of normal stresses σ_i and strains ε_i are determined by the formulas

$$\sigma_i = \frac{1}{2}\sqrt{\left(\sigma_{11}-\sigma_{22}\right)^2 + \left(\sigma_{11}-\nu\left(\sigma_{11}+\sigma_{22}\right)\right)^2 + \left(\sigma_{22}-\nu\left(\sigma_{11}+\sigma_{22}\right)\right)^2 + 6\,\sigma_{12}^2},$$
$$\varepsilon_i = \frac{\sqrt{2}}{2(1+\nu)}\sqrt{\left(\varepsilon_{11}-\varepsilon_{22}\right)^2 + \varepsilon_{11}^2 + \varepsilon_{22}^2 + \frac{3}{2}\varepsilon_{12}^2}. \quad (6)$$

In the elastic-plastic case, relationships of the form (2) are used to describe the stresses-strains relations. Moreover, in quantities λ_n and μ_n instead of elastic parameters $E_n,\ \nu_n,\ \mu_n$, variable parameters $E_n^*,\ \nu_n^*,\ \mu_n^*$ are used, determined as follows [23, 26, 27]:

$$E_n^* = \frac{\dfrac{\sigma_i^*}{\varepsilon_i}}{1+\dfrac{1-2\nu_n}{3E_n}\dfrac{\sigma_i^*}{\varepsilon_i}};\ \ \mu_n^* = \frac{\sigma_i^*}{3\cdot\varepsilon_i};\ \ \nu_n^* = \frac{\dfrac{1}{2}-\dfrac{1-\nu_n}{3E_n}\dfrac{\sigma_i^*}{\varepsilon_i}}{1+\dfrac{1-2\nu_n}{3E_n}\dfrac{\sigma_i^*}{\varepsilon_i}}. \quad (7)$$

The relationship between the "variable elasticity parameters" has the same form as for elastic constants $E_n,\ \nu_n,\ \mu_n$, that is:

$$\mu_n^* = \frac{E_n^*}{2\left(1+\nu_n^*\right)}. \quad (8)$$

The changed physical-mechanical parameters (7)-(8), at every point of the dam (Fig. 1), are determined based on the reached strain state ε_i (strain intensity) and corresponding stress σ_i^* (stress intensity) according to strain diagram $\sigma_i^* = \sigma_i^*\left(\varepsilon_i\right)$ (Fig. 2), selected from experimental data for specific types of soil [2, 23, 24, 26].

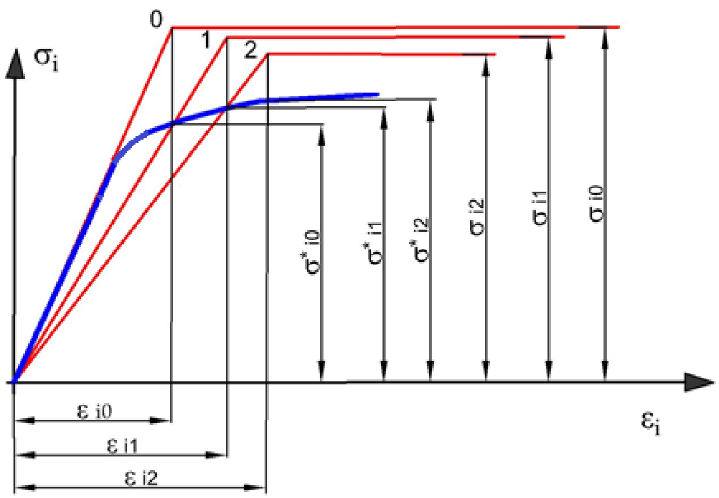

Figure 2. Elastic-plastic diagram of the material strain and the scheme for implementing the method of variable parameters of elasticity.

The variational problem for assessing the stress-strain state of earth dams (Fig. 1), taking into account elastic-plastic properties of the material and inhomogeneous features of the structure, can be formulated as follows: it is necessary to determine the fields of displacements $\vec{u}(\vec{x},t)$, strains $\varepsilon_{ij}(\vec{x},t)$ and stresses in an inhomogeneous elastoplastic system (Fig. 1) arising under mass forces $(\vec{f})$ and hydrostatic pressure $(\vec{p})$, satisfying equation (1) considering (2), (3), (5), (7), (8) and the corresponding kinematic boundary conditions (4) for any virtual displacement $\delta\vec{u}$.

The above stated variational problem is solved by the method of finite elements (FEM) [4, 36].

Using the procedure of the finite element method, the considered variational problem for a structure (Fig. 1) is reduced to a system of nonlinear algebraic equations of the form

$$\left[K\left(\sigma_i,\varepsilon_i\right)\right]\{u\}=\{F\}. \tag{9}$$

Here: $\{u\}$ is the sought for vector of nodal displacements; $\{F\}$ is the vector of amplitudes of total external loads (mass forces, and hydrostatic pressure, etc.).

The difference of equation (9) from ordinary systems of linear algebraic equations is that here the coefficients of equation (9), being the elements of stiffness matrix $\left[K\left(\sigma_i,\varepsilon_i\right)\right]$, depend not only on the geometric and elastic parameters of the materials, but also on the reached stress-strain state of a structure.

The calculation is carried out in several stages. The solution of equations (9) at each stage of the process is obtained by the Gauss method or the square root method.

At the first stage, an elastic calculation of earth structure (Fig. 1), which is in equilibrium under applied load, is performed. Then the transition to the second stage of the calculation is done; it consists of the stress-strain state (SSS) analysis in all the finite elements into which the structure is divided. If the stress intensity σ_i in finite elements exceeds the yield strength σ_y (σ_y is determined from experiments for specific materials), it is believed that plastic strains begin to develop in them due to the changes in the body shape.

Then, using (7)-(8), (5), (2), elastic parameters are determined for these finite elements; the stiffness matrices and then the general matrix $\left[K\left(\sigma_i,\varepsilon_i\right)\right]$ of equation (9) for the entire structure are compiled. The solution of the obtained new system of equations (9) taking into account elastic-plastic properties of the material for certain finite elements is analyzed; if necessary, new parameters of elasticity are introduced; then the process continues until the convergence of the sequence σ_i over the entire structure within the specified accuracy is reached. The described method is a method of variable parameters of elasticity [23, 26]. The implementation scheme of the method of variable parameters of elasticity is shown in Fig. 2.

In a plane-strained state, the following formulas are used to transform the relationship between stresses and strains [22, 23, 26]:

$$\begin{gathered}
\sigma_{11}=\frac{E_n^*\left(1-\nu_n^*\right)}{\left(1+\nu_n^*\right)\left(1-2\nu_n^*\right)}\varepsilon_{11}+\frac{\nu^*E_n^*}{\left(1+\nu_n^*\right)\left(1-2\nu_n^*\right)}\varepsilon_{22},\\
\sigma_{22}=\frac{E_n^*\left(1-\nu_n^*\right)}{\left(1+\nu_n^*\right)\left(1-2\nu_n^*\right)}\varepsilon_{22}+\frac{\nu^*E_n^*}{\left(1+\nu_n^*\right)\left(1-2\nu_n^*\right)}\varepsilon_{11},\\
\sigma_{12}=2\mu_n^*\varepsilon_{12}.
\end{gathered} \tag{10}$$

where $E_n^*,\ \nu_n^*,\ \mu_n^*$ are the variable parameters of elasticity determined by formulas (7) and (8).

Using the above methods, the stress-strain state of earth dams is studied taking into account the elastic-plastic properties of soil under various effects, with/without account of hydrostatic pressure of water and different levels of reservoir filling with water.

2.2. Study of practical convergence of the developed method of calculation on a test example

In this part of the paper, the practical convergence of the method of elastic-plastic calculation at individual points (Fig. 3) of the model problem is investigated. For this, the plane-strained state of a homogeneous dam as a model of earth structure is considered (Fig. 3) under its own weight, and with account for elastic and elastic-plastic properties of the material. The geometrical characteristics of the structure and the averaged physical and mechanical parameters of soil are taken as: the height of the structure H = 86.5 m; the crest width b = 10 m; the slope coefficients m_1 = 2.5, m_2 = 2.2; elastic modulus $E = 3.07 * 10^3$ MPa ; specific gravity γ = 1980 kgf/m^3; Poisson's ratio ν = 0.36. The elastic-plastic properties of soil [24] are described by a bilinear diagram (Fig. 2) with a degree of hardening $\vec{\lambda} = \left(1 - E_p / E\right) = 0.67$ and yield strength for soil $\sigma_y = 4 * 10^{-1}$ MPa. Here E_p is the inclination angle of the plastic part of the diagram.

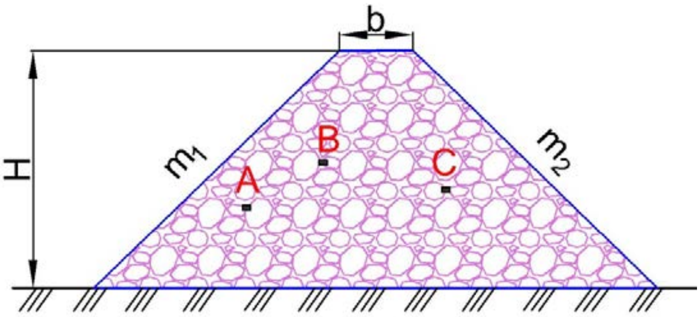

Figure 3. Check of solution convergence at individual points (A, B, C) of a structure.

The aim of solving this problem is to study the convergence of results ($u_2, \sigma_i, \sigma_{11}$) depending on the number of divisions of the model structure (Fig. 3) into a different number *N* of finite elements for elastic and elastoplastic problems. To do this, several points were selected in the structure (for example, A, B, C), and the results obtained in these points ($u_2, \sigma_i, \sigma_{11}$) at different number of divisions into finite elements were compared with the results of previous calculations. The research results are presented in Table 1.

Here u_2 is the vertical displacement of the considered point, σ_{11} is the horizontal normal stress; σ_i is the intensity of normal stresses. Stress values (σ_{11} and $\sigma_i * 10^{-1}$) are given in MPa.

The data in Table 1 show that elastoplastic strain leads to an increase in vertical displacements of structure points. Satisfactory accuracy is ensured when the structure is divided into no less than at N = 350 finite elements (Fig. 3), (Table 1).

Table 1. Numerical convergence of results.

Considered points of a structure	Types of quantities	Elastic solutions obtained for various finite element numbers		
		N = 280	*N* = 336	*N* = 576
1	2	3	4	5
		Elastic solution		
A	u_2	–0.009660	–0.007812	–0.007517
	σ_i	69.5095	66.4327	66.4696
	σ_{11}	–31.6746	–33.7946	–33.8024
B	u_2	–0.01630	–0.01633	–0.01634
	σ_i	627767	57.9882	58.3452
	σ_{11}	–22.0782	–20.1421	–19.8845
C	u_2	–0.003849	–0.005693	–0.005505
	σ_i	30.1014	27/9418	6/3410
	σ_{11}	–229702	–20.7274	–21.2614

Considered points of a structure	Types of quantities	Elastic solutions obtained for various finite element numbers		
		N = 280	N = 336	N = 576
1	2	3	4	5
Elastic-plastic solution				
A	u_2	–0.01686	–0.01559	–0.01595
	σ_i	64.3873	61.8528	61.7691
	σ_{11}	–36.2867	–38.6386	–39.2341
B	u_2	–0.02767	–0.03178	–0.03236
	σ_i	57.8172	53.9147	52.8176
	σ_{11}	–22.6110	–21.5393	–21.0727
C	u_2	–0.00444	–0.007457	–0.007936
	σ_i	27.3915	30.9518	29.9756
	σ_{11}	–32.9834	–29.2085	–30.6014

To validate the accuracy of the results obtained, a dam model with symmetrical slopes (i.e., $m_1 = m_2$) was considered. The fact that the shear stress is $\sigma_{12} = 0$ on the axis of symmetry confirms the reliability of results.

The solutions obtained for model problems show that, with the required number of finite elements, the developed technique works quite reliably when determining the dam SSS in a plane statement, with account for elastic and elastic-plastic properties of the structure material.

These results give reason to use the developed technique in solving specific problems for earth dams.

3. Results and Discussion

As a specific example, an assessment of the stress-strain state of the Sokh earth dam is considered taking into account elastic and elastic-plastic properties of soil under mass forces and the hydrostatic pressure of water at different levels of reservoir filling.

The Sokh dam is located in the northern foothill of the Alai Range in the lower reaches of the Sokh River. The main design parameters of the dam are as follows: the height of the dam – 87.3 m, the crest width – 10.0 m, the length along the crest – 487.3 m, the rate of slopes: the upper prism m_1 = 2.5, and the lower prism m_2 = 2.2.

The Sokh dam is built from local materials and is a stone-earth dam with a loamy core and side retaining prisms built of pebbles. The central core of the dam is vertical, symmetrical in shape with a width of 4.0 m at the upper part, 47.15 m at the base. The dam is built of sandy loamy soils and refers to the 1st class structure.

The recommended design physical-mechanical characteristics of the material are: γ is volumetric weight; G is shear modulus of elasticity; μ is Poisson's ratio. For the core: γ = 1700 kgf/m^3; G = 282 MPa; μ = 0.40. For the retaining prism: γ = 2100 kgf/m^3; G = 316 MPa; μ = 0.35. For the slope paving: γ = 1850 kgf/m^3; G = 310 MPa; μ = 0.35.

3.1. Elastic calculation

Using the developed methods, the stress-strain state of the Sokh dam was assessed taking into account the homogeneous and inhomogeneous features of the structure in an elastic statement.

Fig. 4 shows the isolines of strain intensity distribution ε_i and the components of shear strains ε_{12}, and Fig. 5 shows the intensities of normal σ_i and shear stresses σ_{12} of the Sokh dam, obtained considering elastic properties of soil with a central loamy core. An analysis of the results shows that due to the greater strain properties of loamy soil in the core, the values of vertical strains in the central part of the dam increase when comparing with homogeneous dams. Large strain intensities ε_i appear in the lower part of the dam (Fig. 4).

The distribution of shear stresses σ_{12} (Fig. 5) repeats the character of shear strains ε_{12} distribution throughout the dam cross section (Fig. 4). A zero level of shear strains (Fig. 4) is observed near the dam symmetry axis (since the dam has almost symmetrical slopes); with the distance from the axis, shear strains increase, reaching a maximum in the lower part of the slopes.

a) $\varepsilon_i * 10^{-5}$ **b)** $\varepsilon_{12} * 10^{-5}$

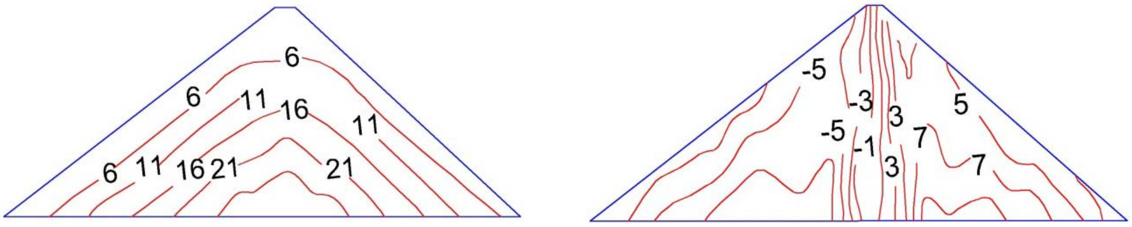

Figure 4. Isolines of strain intensity distribution ε_i and the component of shear strain ε_{12} in the inhomogeneous Sokh dam.

a) $\sigma_i * 10^{-1}$ MPa **b)** $\sigma_{12} * 10^{-1}$ MPa

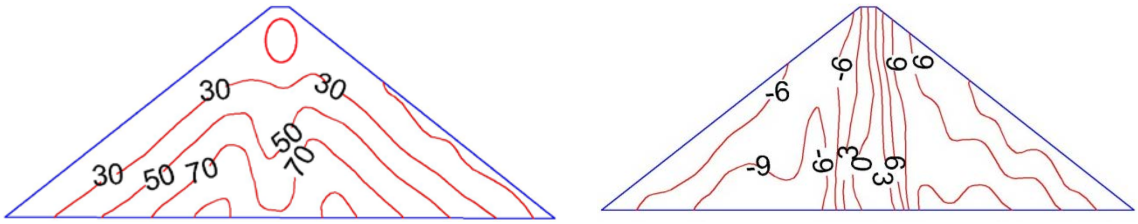

Figure 5. Isolines of the intensity distribution of normal σ_i and shear σ_{12} stresses in the inhomogeneous Sokh dam.

An analysis of the results showed that when considering inhomogeneous features of the structure, the stress state of the dam undergoes significant changes compared to a homogeneous structure; these changes are expressed in a decrease in intensity of normal σ_i and vertical σ_{22} stresses in the dam core by ≈ 25 %, in an increase in shear stresses σ_{12} by ≈ 40 %, and horizontal stresses σ_{11} by ≈ 10 %.

3.2. Elastic-plastic calculation

Using the developed methods, the stress-strain state of the Sokh dam was assessed taking into account homogeneous and inhomogeneous structural features in an elastic-plastic statement.

When assessing the stress-strain state of the Sokh earth dam, the elastic-plastic properties of soil are taken into account according to bilinear diagram $\sigma_i = f\left(\varepsilon_i\right)$ (Fig. 2) with a degree of hardening $\vec{\lambda} = \left(1 - E_p / E\right) = 0.75$, i.e. the inclination angle of plastic part E_p is supposed to be four times less than the inclination of elastic part E: $E_p = E/4$ [22]. The yield strength according to [24], is taken for the core material (loam) $-\sigma_i = 3 * 10^{-1}$ MPa, and for the material of retaining prisms within $\sigma_y = (45-50) * 10^{-1}$ MPa.

Fig. 6 shows the isolines of the intensity distribution of normal σ_i (*a*) and tangential – σ_{12} (b) stresses of the Sokh dam, obtained considering structural features and the elastic-plastic properties of soil under its own weight. Comparison of these results with the results obtained for the same dams in elastic statement (Fig. 5) shows that an account for elastic-plastic properties of soil of the prism and core leads to a change in values and nature of the dam stress state. An account for elastic-plastic properties of soil leads to a decrease in the stress intensity σ_i and vertical stresses σ_{22} in the core down to ≈ 20 %; the arch effect observed in the dam core zone increases.

The reason for this is the difference in strain properties and yield strengths of soil in the core and retaining prisms. Horizontal stresses σ_{11} increase to 5*10[–1] MPa, mainly in the upper part of the dam, as a result of which a change in the dam profile is possible. The values of vertical stresses σ_{22} decrease to ≈ 20 % in the middle and lower parts of the dam core. In sloping zones, the tangential stresses σ_{12} increase by (5-6)*10[–1] MPa, which can also lead to a change in the profile and to a decrease in the safety factor of the dam slopes.

Fig. 7 shows isolevel lines of strain intensity ε_i and shear strain ε_{12} in an inhomogeneous Sokh dam taking into account the elastic-plastic properties of soil.

a) $\sigma_i * 10^{-1}$ MPa **b)** $\sigma_{12} * 10^{-1}$ MPa

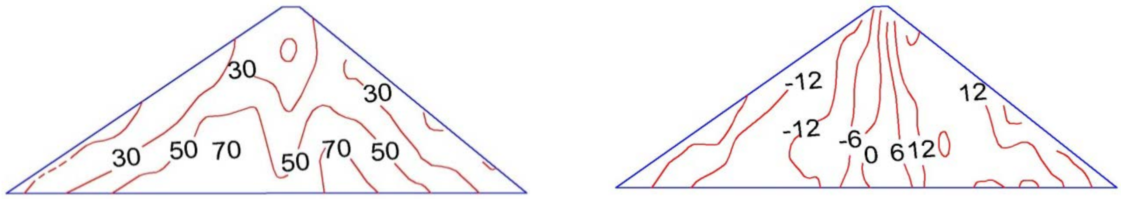

Figure 6. Isolines of intensity distribution of normal σ_i and shear σ_{12} stresses in the inhomogeneous Sokh dam, obtained taking into account the elastic-plastic properties of the material.

a) $\varepsilon_i * 10^{-5}$ **b)** $\varepsilon_{12} * 10^{-5}$

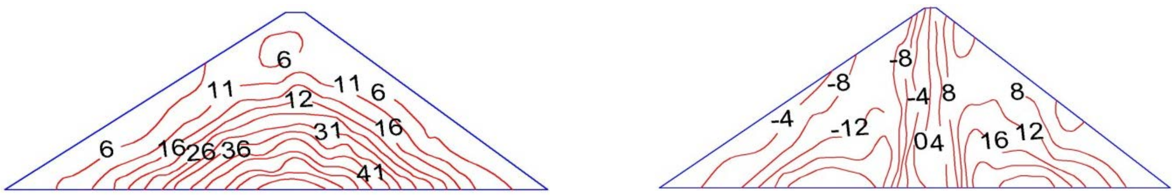

Figure 7. Isolines of strain intensity distribution ε_i and shear strain ε_{12} in the inhomogeneous Sokh dam taking into account the elastic-plastic properties of soil.

An analysis of the results obtained (Figs. 4 and 7) shows that an account for elastic-plastic properties of soil leads to the appearance of additional strain in the most stressed areas inside the dam body. Plastic strains do not appear near the slopes and crest surfaces. Despite this, significant shear strains ε_{12} occur in the slope zones.

The principal normal σ_1, σ_2 and maximum tangential stresses τ_{max} in the Sokh dam were studied with account for elastic and elastic-plastic properties of soil; the study showed that an account of elastic-plastic properties of soil leads to a decrease in stresses in the dam body and the arch effect smoothing in the core zone. The values of principal stress σ_1 in the zones of upstream and downstream slopes slightly decrease. The principal stress σ_2 decreases to a greater extent in the slope zones (to ≈ 10–17 %) and in the core (to ≈ 15–25 %). The value of the maximum tangential stress τ_{max} in the slope zones slightly increases near the core, and decreases by ≈ 20–50 % in the core.

The results obtained showed that with a decrease of plastic section slope in soil strain diagram $\sigma_i = f(\varepsilon_i)$, the difference in the results of solving elastic-plastic and elastic problems is more significant.

Therefore, a justified approach to the selection of the law of soil strain is necessary.

Similar studies were performed for high-rise earth dams, such as the Gissarak dam (H = 138.5 m) and the Tupolang dam (H = 185 m).

An analysis of the results obtained for high-rise dams of various geometries and heights showed that an account for elastic-plastic strain of the material of retaining prisms and cores significantly affects the change in the dam SSS. In the core of the Tupolang dam the values of stress intensity σ_i decrease to

≈ 18 %, and vertical stresses σ_{22} to ≈ 20 %, which increases the arch effect. In the upstream and downstream retaining prisms, tangential stresses σ_{12} increase significantly – up to ≈ 40–55 %. The greatest difference is observed near the slopes, which can lead to shear strains and the occurrence of landslides. In the core zone, the values of tangential stresses σ_{12} remain insignificant.

The above theoretical studies have shown that when designing high and medium-high dams, it is necessary to conduct calculations with account for structural features of the dam and real elastic-plastic properties of soil.

3.3. Elastic-plastic calculation taking into account the level of reservoir filling

Using the developed methods, the stress-strain state of the Sokh dam was assessed taking into account inhomogeneous features of the structure, elastic-plastic properties of soil and the level of reservoir filling with water. The stress-strain state of the dam obtained at each level of reservoir filling was compared with the results from section 4.2 when the reservoir filling was not taken into account.

Fig. 8 shows the isolines of intensity distribution of normal σ_i (a) and tangential σ_{12} (b) stresses of the Sokh dam, obtained considering elastic-plastic properties of soil with a fully filled reservoir.

When the reservoir is filled to the half height of the dam, the components of the stress tensor change only in the upper prism zone, the symmetric pattern of the stress distribution in the dam profile is violated. Here: σ_i increases by ≈ 30–40 %: σ_{11} up to 40–45 % and σ_{22} up to ≈ 40 %. The effect of water mainly manifests itself in the pattern of horizontal stresses σ_{11} distribution in the dam.

a) $\sigma_i * 10^{-1}$ MPa **b)** $\sigma_{12} * 10^{-1}$ MPa

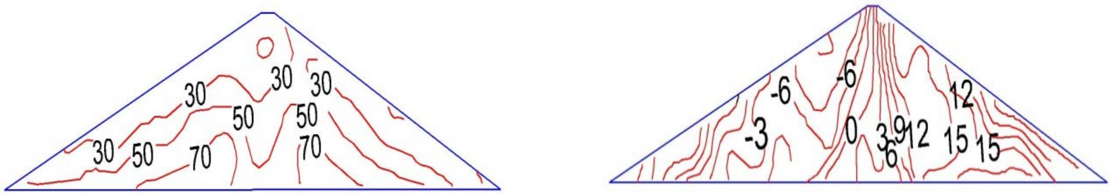

Figure 8. Isolines of intensity distribution of normal σ_i (a) and tangential stresses σ_{12} (b) in the Sokh dam, taking into account the elastic-plastic properties of soil at fully filled reservoir.

When the reservoir is fully filled (Fig. 8.), the stress-strain state of the dam is redistributed, symmetrical distribution of stress isolines is violated, and the values of stress components change significantly. The stress intensity σ_i (Fig. 8) in the Sokh dam increases to ≈ 70–100 % relative to the results obtained without water effect.

The changes are observed mainly in the upstream retaining prism. Horizontal stresses σ_{11} vary throughout the dam profile, they increase to ≈ 10–120 %, and the greatest difference in the results relates to the slopes of the upstream prism.

a) $\sigma_i * 10^{-1}$ MPa **b)** $\sigma_{12} * 10^{-1}$ MPa

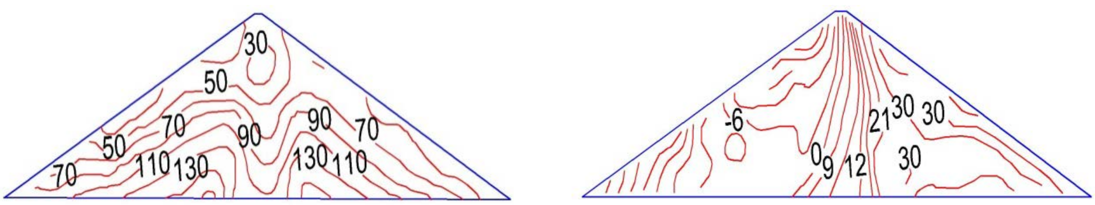

Figure 9. Isolines of the intensity distribution of normal σ_i (a) and tangential stresses σ_{12} (b) in the Tupolang dam, taking into account the structural features and the elastic-plastic properties of soil with fully filled reservoir.

Vertical stresses σ_{22} increase to ≈ 70–80 % and the greatest difference relates to the lower part of the upstream slope. The distribution pattern of shear stresses σ_{12} changes significantly throughout the dam profile. Values of tangential stresses in the downstream prism increase to ≈ 1–-20 %. These phenomena are undesirable, since they may cause the landslides (instability) in the downstream prism slope. Therefore, in the most cases, along with stability assessment of the upstream slope, the stability of the dam downstream slope is also evaluated. The need to assess the stability of the downstream slope is confirmed by the results of observation of strong earthquakes aftermath [2].

Fig. 9 shows the isolines of the intensity distribution of normal σ_i (a) and tangential σ_{12} (b) stresses in the Tupolang dam, taking into account the elastic-plastic properties of soil with fully filled reservoir.

An analysis of these results (Fig. 9) confirms the above reasoning on the stress distribution in the dam body, with the only difference in numerical values of stresses.

Based on the results obtained, it can be concluded that when assessing the strength of earth dams of any height, it is necessary to evaluate the strength taking into account the level of reservoir filling with water, since it significantly changes the stress distribution in the dam body, and the slope stability of the dam as a whole.

4. Conclusions

1. A mathematical model, methods and algorithms have been developed for assessing the stress-strain state of earth dams taking into account the elastic-plastic properties of soil under static impacts, based on the method of variable parameters of elasticity.

2. The stress-strain state of earth dams was investigated taking into account the elastic-plastic properties of soil and structural features of a dam at different levels of reservoir filling.

3. Studies have revealed that an account of elastic-plastic properties of soil leads to:

- a significant change in the stress-strain state of earth dams compared with the elastic case;
- the appearance of additional strains in the most stressed points inside the dam body, the strains ε_{11}, ε_{22} are insignificant near the surfaces of slopes and crests, significant plastic shear strains ε_{12} arise in the slope zones;
- the reduced stresses in the body of the dam and the smoothing of the arch effect in the core zone.

4. An account of both elastic-plastic properties of soil and the level of reservoir filling showed that:

- when the reservoir is half full, the changes in the values of stress tensor components occur only in the zone of the upstream retaining prism of the dam;
- when the reservoir is fully filled, the distribution pattern of tangential stresses in the dam body changes significantly, both in the upstream retaining prism and in the downstream prism;
- the greatest values of stress intensity σ_i are reached in the lower part of the upstream slope near the dam core.

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