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Estimation of the earth dam strength with inelastic soil properties

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Abstract. The study aims to develop the models, methods, and algorithms for assessing the earth's structure strength with inelastic-plastic properties of soil and to evaluate the strength of earth dams. For the mathematical statement of the problem, the principle of virtual displacements, the finite element method, and the elastic solution method were used. To assess the safety factor at each point in the structure, the Coulomb – Mohr theory of strength was used. The stress-strain state (SSS) of specifically designed earth dams with a height of 195 m was studied under various static effects, with inelastic elastic-plastic properties of soil. The isolines of equal values distribution of safety factor for a dam body, as a whole, were obtained, which allow stating the presence, size, and location of the zones in which the strength condition is met.

1. Introduction

Underactive loading, elastic, visco-elastic, and elastic-plastic strains occur in soil and nonlinear strains develop. The listed features of soil strain fully relate to coarse-grained soils (rock mass, gravel, and pebble soils), from which high earth dams are built [1, 2].

In the Central Asian region, of the greatest concern are the conditions of more than 300 dams aimed to regulate the water flow on Transboundary Rivers. Dams and other waterworks, built more than 30-40 years ago, due to their aging and reduced quality of operation, pose a danger to the population and facilities located in developed areas downstream the dams. Therefore, compliance with design requirements, maintenance of hydrotechnical structures in good condition, ensuring the required level of reliability and maintainability is of paramount importance [3–5].

Over the past 70 years, more than a thousand accidents in large hydrotechnical structures have occurred in the world, the main causes of which are: cracks, destruction of slopes, settlement of the foundation of earth dams, and insufficient discharge capacity of spillway structures [6]. World experience shows that timely prevention is much more economical and more effective than the elimination of the consequences associated with flood events and accidents on earth hydrotechnical structures. Therefore, the organization of monitoring and forecasting of possible emergencies, the implementation of protective engineering, and technical measures to increase the stability of earth dams come to the fore [5-7].

As is known, increased demands are made on the strength and seismic resistance of unique earth dams, since their destruction can lead to catastrophic consequences. The sites on which the earth dams were built were taken as 7 - 8 point zones, today the seismicity of these sites has been increased to 8 - 9 points. When assessing the strength of these earth dams, the real work of the structure itself or the soil material without an account. To create stably and reliably operating structures of hydro-technical

structures, complex research is required to evaluate their static and dynamic state within the framework of a unified methodology with their design features, real geometry, spatial work of the structure and complex properties of the material, such as water saturation and limit stress state of soil [8–13].

Thus, the development of adequate models, methods, algorithms and computer programs for predicting the stress-strain state and dynamic behavior of earth dams using mathematical models with the nonlinear deformation of the material, complex geometry and heterogeneity of the structure under various influences is an urgent modern problem of hydro-technical engineering.

2. Methods

Consider an inhomogeneous system – a dam (Figure 1) in a plane-deformable state; it occupies a volume of $V=V_1+V_2+V_3$. The upper part and the lower prism of the dam are stress-free, and the lower part of the dam is rigidly fixed. On the surface Σ_p (on the part of the upstream slope, i.e., on S_p), the hydrostatic pressure of water $\vec{p}$ acts.

The structural inhomogeneity of the structure, its real geometry, and elastic and elastic-plastic properties of the material of each part of the structure with an account. The earth structure is under the influence of gravitational forces and hydrostatic pressure of water.

1 is curve of depression, $\vec{p}$ is hydrostatic pressure of water

Figure 1. Design scheme of an inhomogeneous system on a rigid base
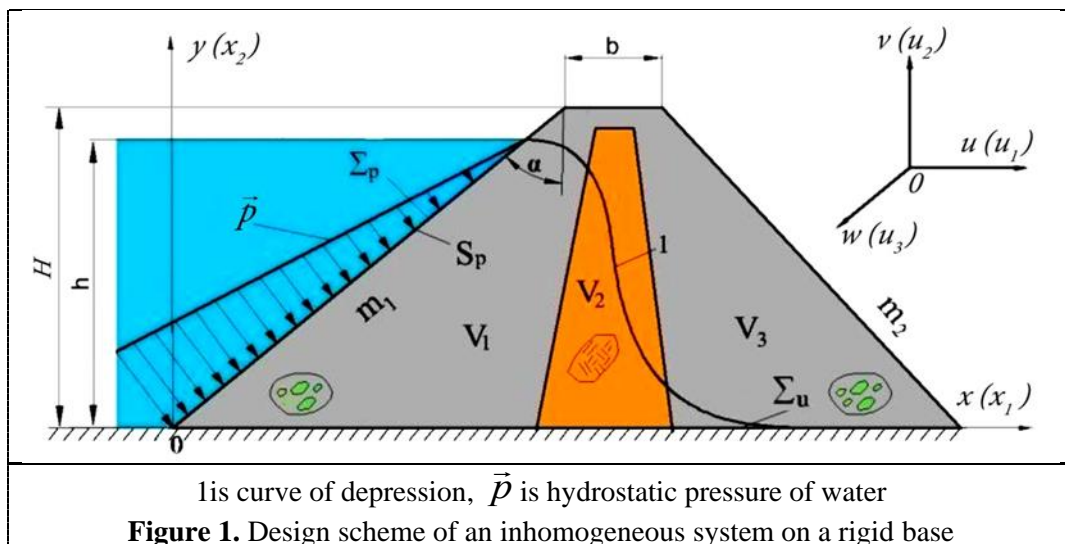
For the statement of the problem, the principle of virtual displacements, kinematic boundary conditions, Cauchy relations, and the Hook generalized law were used. Physical properties of an individual part of the system, i.e. V_1, V_2, V_3 are described by the relations between the components of the stress σ_{ij} and strains ε_{ij} tensor in the form [14]:

$$\sigma_{ij} = \tilde{\lambda}_n \varepsilon_{kk} \delta_{ij} + 2\tilde{\mu}_n \varepsilon_{ij} \tag{1}$$

In the case when the *n*-th element of the system is elastic, the quantities $\tilde{\lambda}_n$ and $\tilde{\mu}_n$ are Lame constants. If the elastic-plastic law of strain of the materials with the account, the values of $\tilde{\lambda}_n$ and $\tilde{\mu}_n$ are the variables determined from the experiment for each section of the diagram $\sigma_i = f(\varepsilon_i)$ (index *n* = 1, 2, 3 – refers to a body with corresponding mechanical characteristics).

When considering small strains, the relationship between the components of the strain tensor and the displacement vector is described by linear Cauchy relations [14].

$$\varepsilon_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right), \ i,j = 1.2.$$ (2)

2.1. For an elastic system.

When considering the stress-strain state of elastic systems, the variational equation of the principle of virtual displacements has the form:

under the action of mass forces $\vec{f}$ -

$$\delta A = -\int_{V_1}\sigma_{ij}\delta\varepsilon_{ij}dV - \int_{V_2}\sigma_{ij}\delta\varepsilon_{ij}dV - \int_{V_3}\sigma_{ij}\delta\varepsilon_{ij}dV + \int_V \vec{f}\delta\vec{u}dV = 0$$ (3)

- under the action of mass forces $\vec{f}$ and hydrostatic pressure of water $\vec{p}$ -

$$\delta A = -\int_{V_1}\sigma_{ij}\delta\varepsilon_{ij}dV - \int_{V_2}\sigma_{ij}\delta\varepsilon_{ij}dV - \int_{V_3}\sigma_{ij}\delta\varepsilon_{ij}dV + \int_V \vec{f}\delta\vec{u}dV + \int_{S_P}\vec{p}\delta\vec{u}dS = 0$$ (4)

In this case, kinematic boundary conditions are introduced to equations (3) and (4)

$$\vec{x} \in \Sigma_u, \ \vec{u} = 0, \ \delta\vec{u} = 0$$ (5)

In calculations, various levels of reservoir filling are considered; accordingly, the hydrostatic pressure of water at the pressure face of the dam is determined by the formula

$$\vec{p} = \rho g(h - y)$$ (6)

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 the isochronous variations of displacement and strain components; $\vec{f}$ is the vector of mass forces; $\vec{p}$ is hydrostatic pressure of water; where ρ_o is the water-mass density; (*h-y*) is the depth of the point on the pressure face of the dam.

In all the problems under consideration, the displacement vector has two components $\vec{u} = \{u_1, u_2\} = \{u, v\}$ in the coordinate system $\vec{x} = \{x_1, x_2\} = \{x, y\}$.

It is necessary to determine the field of displacements and stresses arising in the body of an inhomogeneous system (Figure 1.) upon the effect of $\vec{f}$ and $\vec{p}$, satisfying equations (1), (2) and ((3) or (4)) with conditions (5) for any virtual displacement $\delta\vec{u}$.

2.2. For elastic-plastic systems

The degree of manifestation of the elastic-plastic properties of soils depends on many factors, but first of all, on its stress and strength conditions. In high earth structures, the soil is in a difficult stress state, which constantly changes depending on external loads. Therefore, in earth dams the elastic-plastic strain of soils is especially pronounced.

For this case, the variational equations ((3) or (4)), the kinematic boundary conditions (5) and the Cauchy relation (2) remain unchanged.

A hypothesis of the energy forming is used to describe the equation of state of the soil. According to this hypothesis, the transition from the elastic state to plastic one in the considered particle of the medium occurs when the stress intensity at a given point σ_i (the second invariant of the stress tensor) reaches the yield strength σ_T. Therefore, the state of soil medium is described differently in different parts of the considered inhomogeneous region of the system (Figure 1) depending on whether the yield strength has been overcome.

In the deformation theory of plasticity, it is believed that the tensors of stress and strain have the same direction [4, 15]. It is assumed that the dependence of stresses and strains is determined by the

current state of the soil. It is assumed that it can be written in the form of Hooke's law, but, the material constants used in this law should vary depending on the current stress state of the soil, not being constant [2]. Using the relationship between the components of the stress and strains tensor of the form (1), the Lame constant $\tilde{\lambda}_n$ and $\tilde{\mu}_n$ can be represented as:

$$\tilde{\lambda}_n = \frac{E^* v^*}{(1+v^*)(1-2v^*)} \qquad \tilde{\mu}_n = \mu^* = \frac{E^*}{2(1+v^*)} \tag{7}$$

where E^*, v^*, μ^* are variable elastic parameters, defined as [15-17]

$$E^* = \frac{\dfrac{\sigma_i^*}{\varepsilon_i}}{1+\dfrac{1-2v}{3E}\dfrac{\sigma_i^*}{\varepsilon_i}} ; \qquad \mu^* = \frac{\sigma_i^*}{3\cdot\varepsilon_i} ; \qquad v^* = \frac{\dfrac{1}{2}-\dfrac{1-2v}{3E}\dfrac{\sigma_i^*}{\varepsilon_i}}{1+\dfrac{1-2v}{3E}\dfrac{\sigma_i^*}{\varepsilon_i}} \tag{8}$$

As follows from formulas (7), the relationship between "variable elasticity parameters" has the same form as for elastic constants E, μ, v , but with altered physical and mechanical parameters (8), which in each element are determined based on the reached strain state ε_i (strain intensity) and corresponding σ_i^* (stress intensity) according to the selected strain diagram $\sigma_i^* = \sigma_i^*(\varepsilon_i)$ [17].

The transition from elastic state to plastic one is characterized by equality $\sigma_i = \sigma_T$. And for the plastic zone, the plasticity relations (a flat problem) are valid, transformed with account for $\sigma_i > \sigma_T$ [16]:

$$\varepsilon_{11} = \frac{1}{E^*}\left[\sigma_{11} - v^* \cdot \sigma_{22}\right]$$

$$\varepsilon_{22} = \frac{1}{E^*}\left[\sigma_{22} - v^* \cdot \sigma_{11}\right] \tag{9}$$

$$\varepsilon_{12} = \frac{1}{\mu^*}\sigma_{12}$$

Considering the above, the tasks are formulated as follows. It is necessary to determine the field of displacements and stresses arising in the dam body under the effect of $\vec{f}$ and $\vec{P}$, satisfying equations (1), (2), ((3) or (4)), (7), (8) and (9) with (5) at any virtual displacement $\delta\vec{u}$.

The problem under consideration using the finite element procedure [16] is reduced to a revolving system of algebraic equations of the N-th order

$$\left[K(\sigma_i,\varepsilon_i)\right]\{u\} = \{P\} \tag{10}$$

where $\left[K(\sigma_i,\varepsilon_i)\right]$ is the stiffness matrix of the structure, depending on the physicomechanical parameters of the material and the stress-strain state of the structure. {u} is the sought for the vector of nodal displacements, {P} is the vector of external load (mass forces and hydrostatic pressure of water) acting on the structure.

The obtained algebraic equations (10) are solved by the Gauss method. In this case, at the first stage of the solution, an elastic calculation of earth structure is performed, the structure is in equilibrium under the action of the applied load. Then the transition to the second stage of calculations is realized; it consists of the stress-strain state analysis in all finite elements of the system. If the stress intensity σ_i in individual finite element exceeds the yield strength σ_T (σ_T 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 (8), elastic parameters are determined for these elements,

the stiffness matrices are compiled, and then a common matrix $[K(\sigma_i, \varepsilon_i)]$ for the entire system is written. The solution of the obtained new system of equations (10) is analyzed: if necessary, new elasticity parameters are introduced, and then the process continues until the sequence σ_i converges throughout the structure within the specified accuracy. The described method is a method of variable elastic parameters [12, 18, 19].

3. Results and Discussion

Studies of the structures stress state make it possible to reveal the essence of mechanical processes occurring both in the dam body and in sloping zones. Usually, by comparing the values of normal stresses σ_{11} and σ_{22}, it is possible to establish the zones where horizontal stresses are greater than vertical ones, which can lead to undesirable phenomena in these zones, that is, to a possible heaving of a part of soil [20–22]. To ensure the strength of earth structure, the normal stresses (σ_{11}, σ_{22}), as well as the principal stresses (σ_1, σ_2) should be compressive, i.e. with a minus sign (-).

By studying the stress state in the dam body, the zones of stress concentration can also be established. This is especially important for tangential stresses τ_{max}; its excess over the limiting values near the slopes can lead to local instability in these sections, [20–22].

Therefore, to identify the above-noted features occurring in the structure, the stress-strain state of a newly built stone-earth dam with a height of $H = 195$ m with the inelastic properties of soil, was studied. The dam under consideration has a crest width of 12 m. the steepness of the upstream slope is $m_1 = 2.5$ and the downstream slope is $m_2 = 2$. The length along the crest is 1660 m. The central vertical core made of loam is an anti-filtration element of the dam. The steepness of the core slopes is $m = 0.32$. The specific gravity of loam is $\gamma = 1.7$ tf/m^3 at optimal humidity $W = 17\%$. The width of the core at the bottom is 130 m. The width of the core on the top is 5 m. The packing density of the material of retaining prisms (quarry stone and conglomerate-pebble rocks of excavations) is $\gamma \geq 1,95$ t/m^3 (at $\sigma \leq 8$ kg/cm^2, $\varphi = 42^0$, at $\sigma > 8$ kg/cm^2, $\varphi = 39^0$). The dam is assigned to class 1 structures.

The calculation results obtained later, i.e. the distribution of the displacement field (u), the components of the strain (ε_{ij}) and stresses (σ_{ij}) tensors, as well as the components of the principal stresses ($\sigma_1, \sigma_2, \tau_{max}$) in the dam body, were obtained using the above structural features of dams and the physicomechanical properties of the material. Here, $\sigma_T = 50$ tf/m^2.
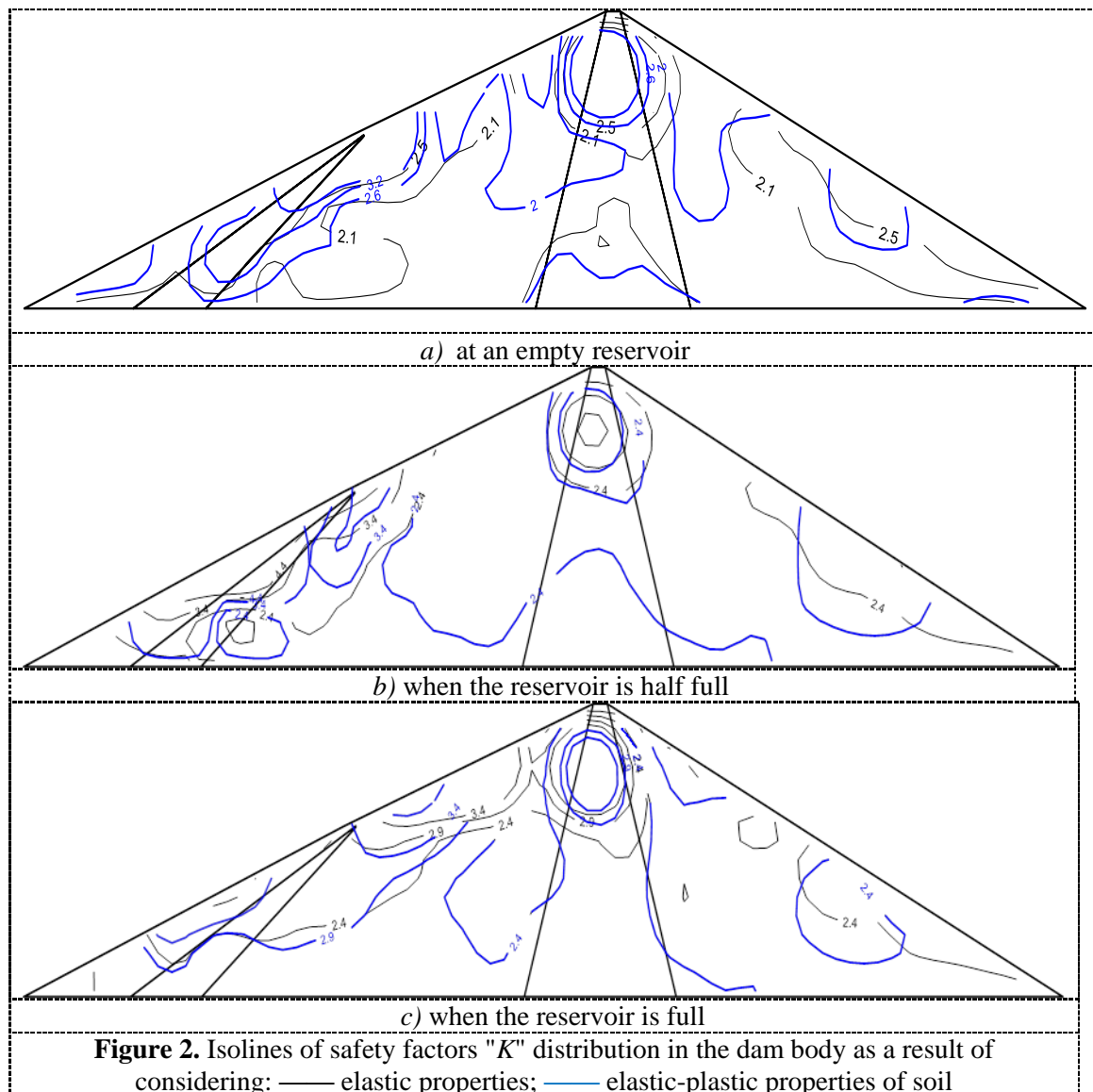
The safety factor was determined by the Coulomb – Mohr theory of strength [20, 21].

$$K = \frac{0,5[(\sigma_1 + \sigma_2 - 2\tau_{max} \times \sin\varphi)tq\varphi + 2C]}{\tau_{max} \cos\varphi} \tag{11}$$

Here: $\sigma_1, \sigma_2, \tau_{max}$ are the components of the principal stresses, C is the soil cohesion force; φ is the angle of internal friction of soil.

It was taken that: at $K > 1$ soil in this section of the structure has a margin of safety, at $K=1$- soil is in the limit equilibrium; at $K < 1$ - soil strength is violated.

Figure 2 shows the isolines of equal values distribution of the safety factor "K" for earth dams with a height of 195 m, under the action of their weight and hydrostatic pressure of the reservoir water.

a) at an empty reservoir

b) when the reservoir is half full

c) when the reservoir is full

Figure 2. Isolines of safety factors "*K*" distribution in the dam body as a result of considering: ——— elastic properties; ——— elastic-plastic properties of soil

An analysis of the results shows that an account for elastic-plastic properties of soil changes the positive picture of the redistribution of isolines of equal values distribution of the strength coefficient due to the hydrostatic pressure of water. In the upper retaining prism of the dam, both at empty and completely filled reservoir under the action of static load (mass forces and hydrostatic pressure), the necessary strength is ensured. The distribution pattern of the safety factor in the lower retaining prism of the dam under the action of these loads practically did not change with account for elastic and elastic-plastic properties of soil.

4. Conclusion

1. A mathematical model, method, and algorithm have been developed for assessing the strength of earth structures with inelastic-plastic properties of soil using the finite element method and the method of variable parameters of elasticity.

2. The stress-strain state of earth dams under the influence of its weight and hydrostatic pressure of water was studied to predict the structure strength with the inhomogeneous design features and inelastic properties of soil.

3. The obtained isolines of equal values distribution of the safety factor as a whole for the dam body allows us to establish the presence, size and location of the zones in which one of the following three conditions is met: at *K> 1* - the strength of the structure is ensured in this region; at *K=1*- in this region soil is in limit equilibrium; at *K <1* - the soil strength is violated in this region.

4. The developed methodology is suitable for assessing the strength of earth structures operating in a plane-deformed state with the structural features and elastic-plastic properties of soil.

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