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Numerical Analysis of the Stress State of Earth Dam under Dynamic Loads

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ABSTRACT: Design, construction and operation of hydro-technical structures in seismic regions, as is the territory of the Republic of Uzbekistan, require continuous improvement of computational methods to assess their strength, stability and efficiency under static and dynamic loads. Damage or accidents of such important structures can result in loss of material resources, environmental disasters, as well as loss of human resources in the territories located downward the dams. The proposed methods to calculate an earth dam in a plane elastic statement for seismic effects by the finite element method allows us to take into account engineering features of the structure, piecewise-inhomogeneous physicomechanical characteristics of soil under the structure and at its base. On the basis of the developed methods and the system of applied programs, the problem of determining the stress state of the designed high earth dam was solved at the 9 points seismicity of the location area, taking into account the design features and the real inhomogeneous physical and mechanical characteristics of soil.

KEY WORDS: hydraulic structure, earth dam, physical and mechanical characteristics of soil, seismicity of the area, stresses, finite element method, safety.

I. INTRODUCTION

The reliability assessment of water retaining hydro-technical structures, in particular, earth dams, is an urgent task, since their potential breakthrough poses a threat to the lower territories [1]. The reliability and safety of water retaining earth structures is largely determined by the stresses and strains that occur in the dam under various loads, including seismic ones.

Current regulatory methods for calculating earth structures (in one-dimensional statement) for seismic effect [2-4] do not take into account the geometry of the structure, and in homogeneity of physical and mechanical characteristics of soil under the structure and at its base. Therefore, a preliminary prediction of the stress-strain state of the structure in a plane statement, taking into account its design features, soil characteristics under the structure and at the underlying base, dynamic (seismic) effect typical for the area of the object location, the degree of soil moisture-content allow us to identify areas where the allowable margins are exceeded and make the appropriate correction.

II. METHODOLOGY

A plane design model representing a cross section of an earth dam located on a siltstone base is considered in the paper. The calculation method is a widely used finite element method (FEM). This method allows to take into account the in homogeneity of the structure, its real geometry, and various boundary conditions. A technique has been developed for solving the problem of determining the stress-strain state (SSS) using the example of a projected earth dam of the Pskem HPP under seismic effect, taking into account the added water mass in the upstream slope.

To calculate the SSS of a dam operating in difficult conditions under various loads, a plane design model (channel cross section of the dam) was selected, under plane strain conditions (Fig. 1). The model includes not only the body of the dam with the core, but the siltstone base as well.

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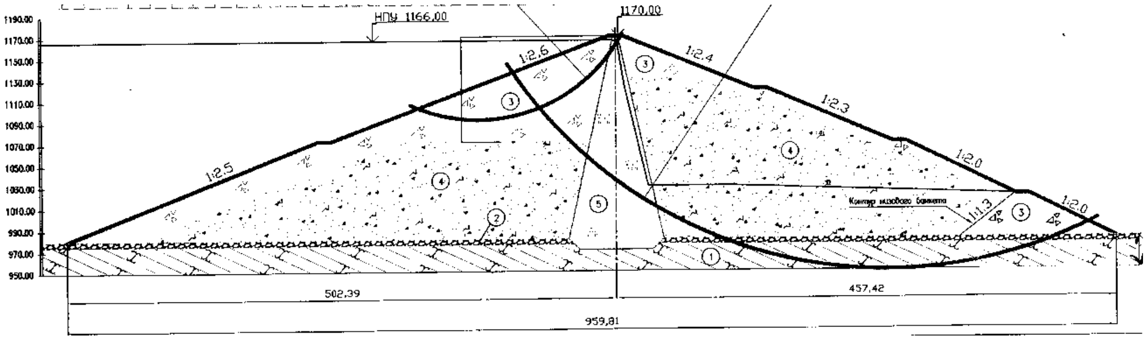

Fig.1. Plane model of the Pskem dam with siltstone base.

Geometrical parameters of the dam model are as follows: height H = 200m; the width of the crest 10m; coefficients of slopes steepness: upstream m_1 = 2.55, downstream - m_2 = 2.25, symmetric core m_{core} = 0.2.
The physicomechanical characteristics of the earth materials for each dam site are provided by the design organization JSC Hydroproject and are presented in Table 1.

Table 1. Calculated characteristics of soils under the body and at the base of the Pskem dam.

NN of layer	Name of soils	γ_{nat} – specific weight, t/m^3	γ_{satur} – specific weight, t/m^3	φ – an angle of internal friction	C – cohesion force, t/m^2
1	Siltstone	2,37	2,42	31	5,00
2	Alluvium	2,15	2,20	39	-«-
3	Coarse fragment stone	1,95	2,23	42	-«-
4	Stone retaining prisms	1,95	2,23	39	-«-
5	Loamy soil	1,72	2,11	24	2,00

Calculated characteristics - Young's modulus E of soil - are determined on the basis of a formula reflecting the propagation velocity of a transverse wave

$$v_s = \sqrt{\frac{E}{2\gamma(1+\mu)}},$$

where v_s=500 m/s; γ is the density of soil of different moisture-content (Table 1); Poisson's ratio is μ=0.3 for all types of dam soil.
The stress-strain state of plane model of the Pskem dam is calculated by the finite element method [5-6], widely used nowadays; it allows to take into account engineering features of the structure, the properties of the material (soil) and carry out static and dynamic calculations of the object on various loads and effects.
The idea of the method is to approximate a plane model of the "dam-base" system by a set of finite elements (triangular or rectangular) connected in nodes, each of which has two possible displacements in plane – horizontal and vertical ones. The exceptions are the fixed nodes on the lower – rigid boundary of the base, and the nodes on the vertical boundaries of the base, where vertical displacements are possible. Acting loads are the elastic forces, own weight, inertial forces (under seismic influence), distributed over all nodal points of the model, and the hydrostatic pressure acting on the upstream slope – distributed over nodal points of the slope only, taking into account the pressure increasing in depth.

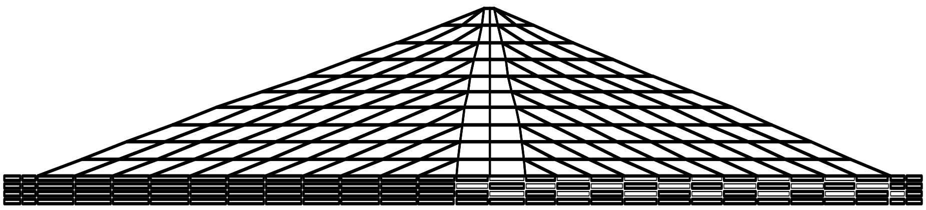
Fig.2. Finite element discretization of the plane model of the "dam-base" system

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To calculate the dam on seismic effect, a spectral method was taken, according to which the calculated seismic load S_{ik} in the selected direction, applied to the point k and corresponding to the *i*-th tone of the structure's natural oscillations, is determined by formula [3]

$$S_{ik}= K_1 K_2 Q_k A\beta_i K_w n_{ik}. \quad (1)$$

Besides various coefficients from the SNiP (Building Code) tables, this formula includes Q_k - the weight of the structure, referred to the point k; β_i - the dynamic coefficient representing the *i*-th frequency of natural oscillations of a structure and n_{ik} -the *i*-th mode of natural oscillations of a structure.
Thus, the first step in calculating the seismic effect is to determine dynamic characteristics of the structure - the frequencies and modes of natural oscillations.
Dynamic characteristics of plane model of the "dam-base" system are also calculated by the finite element method, and the resolving system of equations in this case is represented as a homogeneous algebraic system [5-6]

$$([K]-\omega^2[M])\{q\}=0 \quad (2)$$

where [K], [M] are the stiffness and mass matrices of the system obtained in the process of finite element discretization; ω is the eigenfrequencies and {q} is the vector of its own form. The last two parameters are determined in the course of solving the eigenvalue problem (2). After they are found, seismic load S*i* is determined (depending on the number of modes taken into account) and the solution of the problem of the stress-strain state of the dam under seismic effect is reduced to solving static problem

$$[K]\{u\}=\{S_i\} \quad (3)$$

Below are the results of dam calculation on seismic effect with the first mode.
Basic frequency resulting from the solution of system (2) is ω_1 = 0.728 Hz, the corresponding period is T = 1.37 sec. The principal mode of natural oscillations of the dam is shown in Fig.6 and represents the dam shear in the transverse direction.

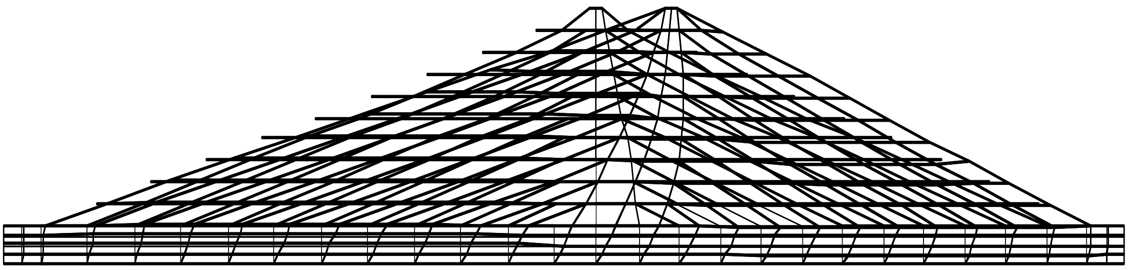

Fig.3. The first mode of natural oscillations of the Pskem dam at a frequency *ω*=0.728Hz and period T=1.37 sec

As a result of the substitution of the mode vector η_1, dynamic factor β_1~1/T into the formula of seismic load S_1 (1) and solution of the resulting system (3), the stress state of the dam caused by this seismic load is determined.
It should be noted that in addition to these parameters, other factors are included in the formula of seismic load (1). Since the problem is solved in an elastic linear statement, the change in these factors, which cause a proportional change in the components of the stress-strain state of the system, does not affect the value of the safety factor *K* [7].

$$K=\frac{0{,}5[(\sigma_1+\sigma_2-2\tau_{Max}\cdot\sin\varphi)\cdot tg\varphi+2C]}{\tau_{Max}\cos\varphi}$$

where σ_1, σ_2 – are the principal stresses; τ_{max} – are the maximum shear stresses; φ – is the angle of internal friction of soil; *C*– is the cohesion force of soil.

III. RESULTS

The calculation results of displacements, stresses and the safety factor of the dam under seismic effect are shown in Fig.4. Hydrostatic load on the upstream slope is also taken into account.

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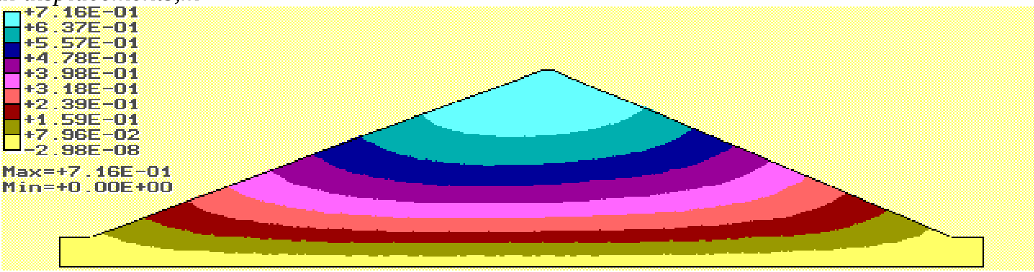
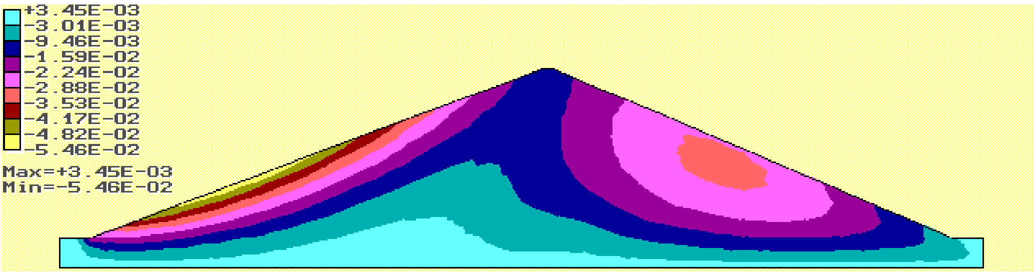
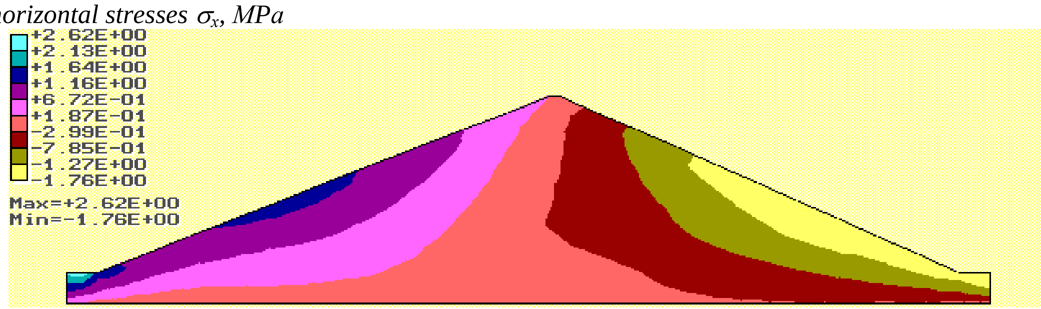
a) horizontal displacements,m



b) vertical displacements, m

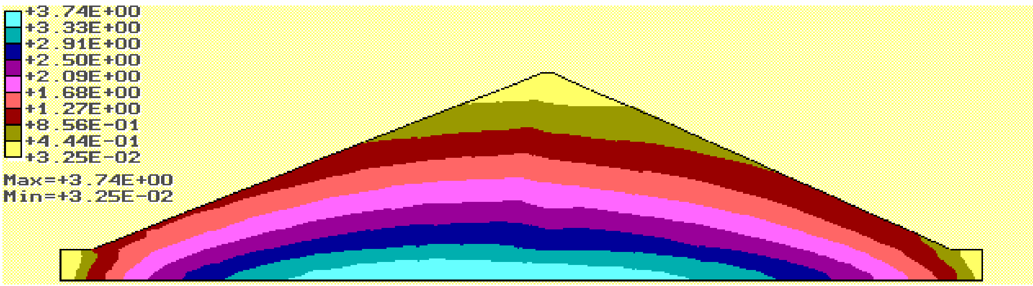


c)normal horizontal stresses σ_x, MPa



d) normal vertical stresses σ_y, MPa

e) shear stresses τ_{xy},MPa



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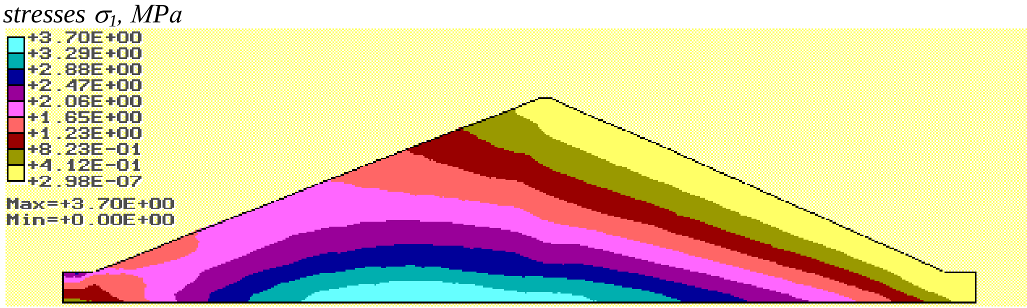
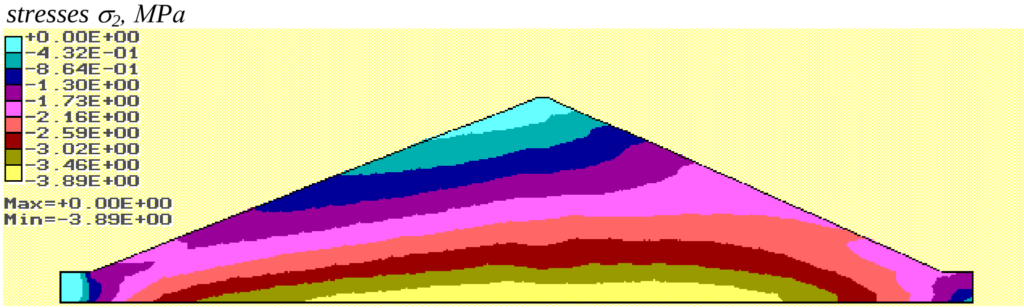
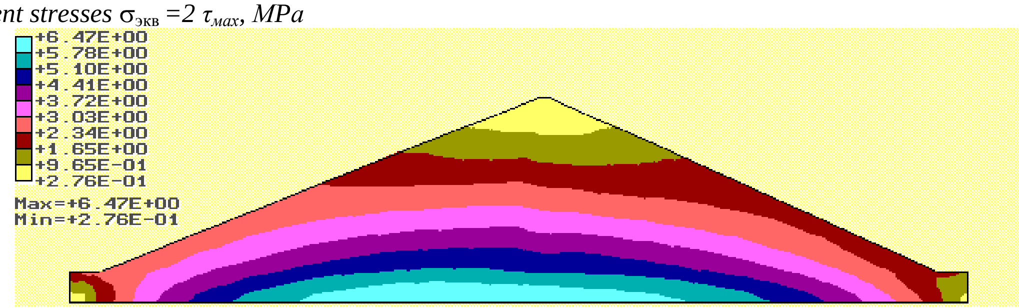
f) principal stresses σ_1, MPa



g) principal stresses σ_2, MPa



H) equivalent stresses $\sigma_{экв} = 2\,\tau_{max}$, MPa



i) isolines distribution of strength safety coefficient К

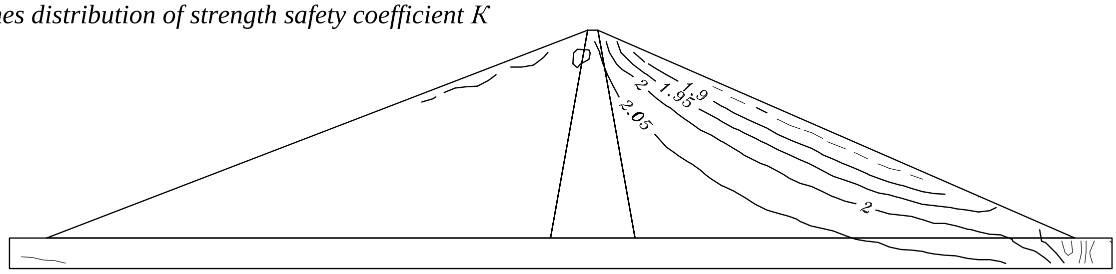


Fig.4. Components of the stress-strain state of the dam under seismic effect and hydrostatic pressure on the upstream slope

The results show that under horizontal seismic effect the dam oscillates in transverse direction (Fig. 3). Here, horizontal stresses σ_x (Fig. 4c) reach values of ± 1.6 MPa on the slopes, where a positive sign indicates a tension of the upstream slope, and a negative sign indicates a compression of downstream slope. The maximum vertical stresses σy are observed in the lower part of the upstream slope (-1.5 MPa) (Fig. 4d), where the maximum hydrostatic pressure is reached. Maximum shear stresses (about 3 MPa) (Fig. 4e) appear at the base of the dam and on the surface of the downstream slope, where the risk of strength loss at shear is greater. However, the safety factor K (Fig. 4i) is quite high (K> 1), which indicates a sufficient margin of safety for the slopes of the Pskem dam.

Thus, it is shown that the developed methods are quite suitable for assessing the strength of earth structures under basic static and seismic loads. They take into account the design features of the dam and soil moisture-content.

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IV. CONCLUSION

The calculations of the stress-strain state of the dam under seismic effect, carried out on the basis of the finite-element method, and the analysis of the results obtained made it possible to establish:
- the maximum normal stresses (σ_x, σ_y) in the plane of the cross section arise at the bottom of the central - the highest - part of the dam, and the maximum values of shear stresses (σ_{xy}) – along the slopes and in the upstream retaining prisms;
- consideration of hydrostatic pressure leads to the deflection of the part of the surface of the upstream slope, which is below the water level;
- the possibility of strength violation of individual sections of the dam was revealed, mainly on the contact of soils with different physico-mechanical characteristics: on contact with the loamy core and on contact with a yielding base;
- on the basis of source data provided by the project documentation, dam slopes have an adequate margin of safety.
A preliminary analysis of the results of the stress-strain state of the designed Pskem earth dam confirms the reliability of the structure under seismic effect which is proved in the feasibility study of design and construction.

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