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Strength Assessment of Earth Dams Under Various Kinematic Impacts

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Abstract. The article provides a detailed analysis of the current state of the problem. A mathematical model is presented to assess the dynamic behavior of earth dams under periodic kinematic effects, taking into account the viscoelastic properties of soil, using the Boltzmann-Volterra hereditary theory with the A.R. Rzhanitsyn kernel. To solve the problems considered, the finite element method was used together with complex arithmetic to reduce integro-differential equations to a high-order complex algebraic equation. The accuracy of the method was verified by solving test problems. Steady-state forced vibrations of the Pskem earth dam, 195 m high, were studied taking into account the real geometry and various properties of soil under resonant vibration modes. It was revealed that the maximum stress amplitudes in the body of the dam occur not only in the first resonance but they can occur at other dense spectra of eigenfrequencies, due to the interaction between close natural vibration modes. The strength of the dam under kinematic impact was tested using the Coulomb-Mohr theory of strength; the most dangerous sections of the dam were identified in terms of the highest stress and the safety factor for various parts of the dam body.

INTRODUCTION

Ensuring the safety of hydro-technical structures and protecting the population is of paramount importance in Uzbekistan; it is confirmed by the Law of the Republic of Uzbekistan **"On the safety of hydro-technical structures" dated 08.20.1999,** and by the Decree of the President of the Republic of Uzbekistan **No. PP-4794 dated 07.30.2020 "About measures for radical enhancement of system of ensuring seismic safety pf the population and the territory of the Republic of Uzbekistan"**, which dictates a serious attitude to the design, construction and operation of hydro-technical structures.

This, in turn, requires the development of improved calculation methods that take into account the real features of both the structure and its material, and the study of the structure strength [1]–[11].

At the same time, ensuring the strength and seismic resistance of the dam is one of the urgent tasks since dams, with reservoirs and accumulation of large volumes of water, pose a threat to the downward territories [1]-[11], [12], [13].

Recently, a number of studies were published where the stress-strain state and dynamic behavior of various dams were considered.

These scientific works include:

- the studies conducted in [14] consider the mitigation to the dam damage during strong earthquakes using a damping protective layer (a layer consisting of river sand) between the foundation and the base in the model of an earth dam. The eigenfrequencies of such a system were determined using the ANSYS program. The study of the physical model of such a system was conducted on a vibrating table under various resonant oscillation modes. Without an insulating layer, the dam model was significantly damaged. The best test results were obtained when the thickness of the layer was one-fourth the height of the dam;

- in [15], the results of studies of natural oscillations and harmonic responses for the power plant structure of the Kenyir dam in Terengganu (Malaysia) were presented. The dynamic characteristics of the power plant were determined using the ANSYS software. The frequency response of the points of the structure was obtained in a large frequency range by applying a force to the structure. A real-scale 3D model of the Kenyir Dam power plant was built using Solid Works software and ANSYS software. The maximum deviation of 0.90361 m in the direction of the z-axis was obtained at a resonant frequency of 5.4 Hz;

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- reference [16] describes the vibration tests conducted in Iran to evaluate the dynamic behavior of the structures of the Masjed-Soleiman (MS) earth dam. During the tests, the response of the dam body in three directions was measured under triaxial excitation. Eigenfrequencies, vibration modes and damping of the dam body were estimated. In addition to dynamic tests in-situ, a two-dimensional and three-dimensional analysis of the natural oscillations of the dam body was performed using the ANSYS software, taking into account the filling of the reservoir with water. It was determined that the influence of water on eigenfrequencies of the dam for a completely filled reservoir reduces the eigenfrequency of the dam by approximately 10%;

- in [17] , some aspects of the influence of foundation flexibility on the seismic response of concrete gravity dams were considered. The influence of the foundation flexibility on the seismic response was investigated, and the eigenmodes of the dam-foundation model were analyzed. A finite element model, a model with continuous parameters, and a model with three degrees of freedom were used to evaluate the dynamic behavior of concrete gravity monoliths on flexible foundations. The accuracy of the discrete model was evaluated by comparing the frequency response functions of the relative displacement of the dam crest;

- the dynamic characteristics of the dam, which presents a reinforced concrete structure of a cylindrical shape with a crest length of 170 m and a height of 46 m, were experimentally studied in [18]. The dam oscillations were excited with a 32 kN servo-hydraulic shaker and its response was measured at 270 points in three directions. 20 eigenmodes with frequencies f = 3.6...12.9 Hz were determined and the calculation model of the dam was updated based on the results of these tests;

- in [19], when determining the eigenfrequencies of an earth dam, the results of two methods (an analytical shear-beam method and a finite element method) were compared. The results obtained differ significantly from each other. The analytical method leads to better results since it does not take into account the dam strain. This difference becomes even more significant when determining higher eigenfrequencies since the finite element method captures the frequencies that the analytical method did not capture;

- in [20], to describe the dynamic behavior of an earth dam erected from homogeneous isotropic linearly elastic materials, the corresponding equation was obtained using the shear-beam theory. The partial differential equation was reduced to an ordinary differential equation of the Bessel type, solved with the appropriate boundary conditions; an infinite number of eigenfrequencies and vibration modes of the considered dams were obtained. The stresses arising at different oscillation frequencies were estimated;

- in [21], full-scale tests were conducted to assess the dynamic behavior of the concrete arch dam Shahid Raji (Iran). The dynamic behavior of the dam-reservoir-foundation system was studied by the finite element method. The main eigenfrequencies of the system for symmetric and antisymmetric shapes were obtained under different vibration modes. Experimental and theoretical results obtained were compared;

- the dynamic characteristics of arch dams were studied in [22] using external vibration. For this purpose, a prototype model of an arch dam was built under laboratory conditions, taking into account the reservoir and the foundation. Eigenfrequencies of the dam were determined under external and forced vibrations, at various levels of reservoir filling. An impact hammer excited the forced vibrations of the dam. The results of the study of dynamic characteristics obtained for different levels of reservoir filling were compared. It was determined that a completely filled reservoir significantly changes the behavior of the dam;

- in [23], the effect of the foundation and the reservoir on the eigenfrequencies of the Pine Flat gravity dam (USA) was studied. Using the ANSYS APDL software, the dynamic characteristics of the models of the "dam-foundation-reservoir" systems were studied. The analysis of the obtained results showed that an account for the foundation, base and filling of the reservoir, reducing the eigenfrequencies of the considered systems, indicated the importance of these factors when designing dams;

- in [24], it was noted that the knowledge of the natural periods and mode shapes of oscillations of earth dams is a serious problem when performing a specific probabilistic analysis of seismic hazards. Therefore, when assessing seismic hazards, the determination of the main oscillation period of the system plays a major role. The problem of determining the parameters of natural oscillations can be solved using analytical, numerical or empirical methods. Therefore, that article presents a complete solution to the FEM eigenvalue problem for a number of earth dams in Southern Italy. The interaction of the dam with the foundation and soil base was taken into account. The analysis of the results obtained showed that to accurately determine the behavior of the dam, it is necessary to take into account the foundation and soil base. The obtained numerical results were compared with the analytical ones;

- in [25], numerical studies and evaluation of the seismic behavior of earth dams were performed. The finite-difference method, with accounts for the ideal plastic properties of soil and the damping was used to study the nonlinear dynamic behavior of the Raevskaya dam. The numerical model constructed was comprehensively calibrated using tests on a centrifuge, and conducting full-scale tests, both in terms of time and frequency parameters. A good agreement between the calculated and measured results was observed. A parametric study was conducted to identify the influence of the height of the dam and input excitation characteristics on the seismic response of earth dams;

- in [26], it was noted that today, there are many methods for determining the eigenfrequencies of various structures. However, the equations describing the behavior of hydro-technical structures, i.e. various slopes, the dam support group, and retaining walls, are less developed. When determining seismic parameters for various sizes and weights of earth dams, the eigenfrequencies, strain, and other parameters of structures, considering the foundation-structure interaction are of paramount importance. To achieve this goal and take into account the flexibility of the foundation, a spring was used in the simulation. An equation was obtained to determine the eigenfrequency of earth dams by analytical methods. The advantages of this method include a more accurate assessment of seismic parameters and an account for the flexibility of the foundation of earth dams. The results obtained using this technique were compared with the ones obtained using the GeoStudio-2007 finite element software;

- the response of the Chenderoh dam (Malaysia) to the water-induced vibrations was investigated in [27], using the ANSYS software. The results of the frequency domain response and waveforms from the impact of vibrations caused by the water flow were compared with eigenfrequencies and waveforms of the dam. The analysis of the results showed that the transient water-induced vibrations occurred at a frequency of 13.3 Hz, while the eigenfrequency of the left bank section of the dam was 52.3 Hz, which indicated the absence of a resonance phenomenon for the water flow. This result is useful for the operation of the dam to avoid any disaster to the dam structure;

- in [28], the dynamic behavior of the dam was studied by the finite element method using the ANSYS program, considering the soil foundation. To describe the properties of soil, the Davydenkov soil model was used. At the same time, the damping properties and the boundary state of soil, and the nonlinear dam-soil relationship were taken into account. As a result of the analysis, it was found that an account for the damping properties of soil reduces the response of the structure and increases the seismic resistance of the system as a whole;

- in [29], the displacement and acceleration in the upper part of the earth dam and the stress state in the body of the dam were studied with and without considering the water saturation of soil. The calculations were conducted using the finite difference method and the FLAC program. The results obtained were compared with the ones obtained by the conventional method for homogeneous dams. It was assumed that the soil shear modulus varies depending on the average effective stress for both saturated and unsaturated zones of the dam. It was argued that an account for this state when determining the dynamic characteristics, leads to a more complex analysis;

- in [30], to assess the seismic characteristics, the tailing dam model was tested on a vibrating table, for a horizontal peak ground acceleration. Test results showed that the tailing dam was stable, while the entire dam tended to slide forward. It was argued that the resulting dynamic behavior of the tailing dam subject to the earthquakes could serve as a guide for seismic design and technology advancement;

- the nonlinear seismic analysis of earth dams was conducted in [31], using the finite element method with the Geo-Studio software. In the numerical study, a nonlinear finite element analysis was used, taking into account the linear and elastic-plastic components of the model to describe the properties of soil. The initial analysis of the stress state of the dam was performed before the earthquake event, and then these results were used in the seismic analysis as the initial data. The record of a real earthquake was used as input data. The analysis made it possible to give a general pattern of the dam behavior, i.e. the change in the contours of displacements and stresses of the dam;

- the study in [32] was devoted to assessing the effect of soft soil foundation on the dynamic behavior of earth dams since the effects of a yielding foundation are more pronounced when assessing the dynamic behavior of earth dams during earthquakes. The finite element method was used to study the response of earth dams during an earthquake. It was shown that the presence of a soft base layer increased the main oscillation period of the dam. This, depending on the properties of the dam and foundation, can lead to an increase or decrease in seismic accelerations. The results obtained indicated the need to take into account (during the dam projecting) the frequency content of the earthquake and the natural frequencies of the dam structure together with the foundation;

- in [33], [35] the stress state and natural oscillations of two earth dams were studied in a spatial statement. When assessing the strength, some dangerous sections of the dam were identified and natural frequencies not considered in a flat model were determined.

- in [34], the stress-strain state of earth dams under the action of a harmonic load was numerically studied. A two-dimensional problem for the cross-section of a dam was considered using the equation of state, taking into account structural changes in moisture properties of soil. The problem was solved numerically by the finite differences method. The results were presented in the form of graphs and analyzed.

- references [36], [37] present a detailed analysis of well-known publications devoted to various models and methods for assessing the strength of earth dams, taking into account the elastic-plastic properties of soil, at different levels of reservoir filling under various impacts. It was stated that an account for the elastoplastic properties of soil with a completely filled reservoir significantly changes the distribution pattern of shear stresses in the body of the dam, i.e. they increase in the upper retaining prism and in the lower prism.

Despite the large number of articles published on this issue, the study of the dynamic behavior of earth dams located in our Republic was not practically conducted.

Therefore, conducting such a study is an urgent problem.

METHODS

Mathematical model. A nonhomogeneous system (an earth dam) under consideration (Figure 1.) occupies volumes $V=V_1+V_2+V_3+V_4+V_5$; it is in interaction with the water environment. The body V is a model of an earth dam (V_1,V_2,V_3,V_5 are the retaining prisms, V_4 is the core); the material properties of the dam are assumed nonhomogeneous in volume. The lower part of the dam rests on a rigid foundation Σ_u .

Periodic kinematic impact $\vec{u}_0(x,y,t)$ is applied to surface Σ_u , and hydrostatic water pressure $\vec{p}_S(x,y)$ acts on $\boldsymbol{S_p}$, body forces $\vec{f}$ are taken into account, and the soil in some sections of the dam has viscoelastic properties.

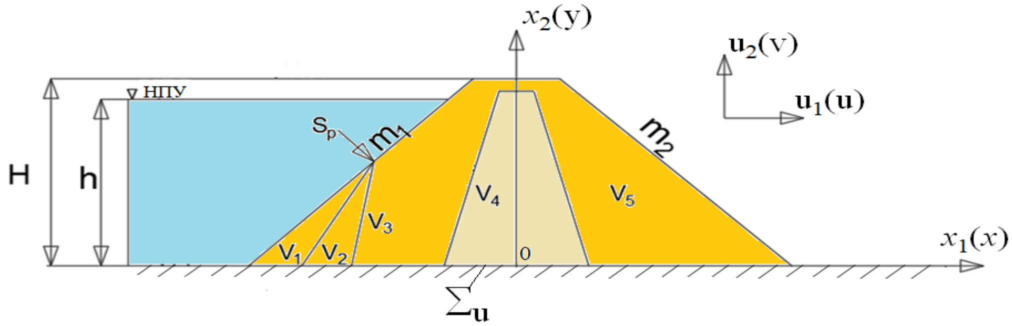

FIGURE 1. Scheme of an nonhomogeneous system

It is necessary to investigate the steady-state forced oscillations of the system in a plane strain state (Figure. 1) under the action of periodic kinematic influences $\vec{u}_0(x,y,t)$, body forces $\vec{f}$ and hydrostatic water pressure $\vec{p}_S(x,y)$.

The study of this type of oscillations of the system makes it possible to reveal the dependences of the maximum amplitudes of displacements and stresses at any point of the dam on the parameters of the system and external impacts. In this case, the intensity of the value of resonant amplitudes of displacements and stresses is taken as a quantitative estimate.

To simulate dynamic processes in the system (Figure 1.), the principle of virtual displacements based on the d'Alembert principle is used, i.e.:

$$\delta A=-\int_V \sigma_{ij}\delta\varepsilon_{ij}dV-\int_V \rho_n\ddot{\vec{u}}\delta\vec{u}dV+\int_V \vec{f}\delta\vec{u}dV+\int_{S_P}\vec{p}_S\delta\vec{u}dS=0, \quad (1)$$

kinematic boundary conditions are

$$x\in\sum\nolimits_u:\vec{u}_o(\vec{x},t)=\vec{\psi}_1(t), \quad (2)$$

Here $\vec{u}$, ε_{ij}, σ_{ij} are the components of the displacement vector, strain and stress tensors, respectively; $\delta\vec{u}$, $\delta\varepsilon_{ij}$ - are the isochronous variations of displacements and strains; ρ_n is the density of the material of the elements of the considered system (n=1,2,3,4,5); {u1,u2}={u,v},{x}={x1,x2}={x,y} are the displacement vector components and body coordinate point, respectively; $\vec{f}$ is the vector of body forces; $\vec{\psi}_1(t)$ is the periodic function of time; $i, j, k = 1,2$.

Hydrostatic water pressure is determined by the following formula [38].

$$\vec{p}_C = \rho_o g(h-y), \tag{3}$$

where ρ_o is the density of water; *(h-y)* is the depth of a point on the upstream face of the dam.

Physical relations between stresses σ_{ij} and strains ε_{ij} of the form [38], [39] are also used:

$$\sigma_{ij} = \tilde{\lambda}_n \varepsilon_{kk} \delta_{ij} + 2\tilde{\mu}_n \varepsilon_{ij} \tag{4}$$

To describe the viscoelastic properties of the material, Volterra integral operators are used [39], [40]:

$$\left.\begin{aligned} \tilde{\lambda}_n \varphi &= \lambda_n \left[\varphi(t) - \int_{-\infty}^{t} \Gamma_{\lambda_n}(t-\tau) \varphi(t) d\tau \right] \\ \tilde{\mu}_n \varphi &= \mu_n \left[\varphi(t) - \int_{-\infty}^{t} \Gamma_{\mu_n}(t-\tau) \varphi(t) d\tau \right] \end{aligned}\right\} \tag{5}$$

where λ_n, μ_n are the Lame constants; $\Gamma_{\lambda_n}, \Gamma_{\mu_n}$ are the relaxation kernels; $\varphi(t)$ is an arbitrary function of time.

The Cauchy relation [39] is used:

$$\varepsilon_{ij} = \frac{1}{2}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right), \quad i, j = 1,2 \cdot \tag{6}$$

Now for the system (Fig. 1) it is necessary to determine $\vec{u}(\vec{x}, t)$, $\sigma_{ij}(\vec{x}, t)$ in the structure, arising under the influences (2), (3) and $\vec{f}$, satisfying equations (1), (4), (5) (6) and the periodicity conditions for any virtual displacement $\delta\vec{u}$.

Solution method. The solution of the variational problem (1)–(6) is sought in the following form

$$\vec{u}(\vec{x}, t) = \vec{u}_o(\vec{x}, t) + \vec{u}^*(\vec{x}) \cdot \exp(-i\Omega t), \tag{7}$$

where Ω is the specified frequency of external influences; $\vec{u}^*(\vec{x})$ is the vector of sought-for displacement amplitudes, i is the complex number.

In this case, (5) can exactly be replaced by an expression in the following form

$$\left.\begin{aligned} \tilde{\lambda}_n \varphi &= \lambda_n \left[1 - \Gamma_{\lambda_n}^C(\Omega) - i\Gamma_{\lambda_n}^S(\Omega) \right] \varphi \\ \tilde{\mu}_n \varphi &= \mu_n \left[1 - \Gamma_{\lambda_n}^C(\Omega) - i\Gamma_{\lambda_n}^S(\Omega) \right] \varphi \end{aligned}\right\}, \tag{8}$$

where $\Gamma^S_{\lambda_n}(\Omega), \Gamma^C_{\lambda_n}(\Omega), \Gamma^S_{\mu_n}(\Omega),\ \Gamma^s_{\mu_n}(\Omega)$ are the sines and cosines of the Fourier image of kernels $\Gamma_{\lambda n}(\tau), \Gamma_{\mu n}(\tau)$.

Substitution of (7) into (1) reduces the variational equation (1) to the following form:

$$-\int_V \sigma^*_{ij}\delta\varepsilon_{ij}dV + \Omega^2\int_V \rho_n \vec{u}^*\delta\vec{u}^*dV = -\int_V f\ \ \delta\vec{u}^*dV + \\ + \int_V \rho_n \ddot{\vec{u}}_o \delta\vec{u}^* dV - \int_{S_p} \vec{p}_c(\vec{x})\delta\vec{u}^*dV, \tag{9}$$

where σ^*_{ij} is the complex amplitude of the stress tensor components; $\vec{u}^*(\vec{x})$ is the sought-for complex amplitude.

The procedure of the finite element method [41] allows us to reduce the variational equation (9) to a complex nonhomogeneous algebraic system of the following form

$$\left([K]-\Omega^2[M]\right)\{u\}=\{f\} \tag{10}$$

where $[K]$ is the complex stiffness matrix; $[M]$ is the matrix of masses of the system (Fig. 1); $\{u\}$ is the vector of sought-for complex displacement amplitudes; $\{f\}$ is the load vector from kinematic impact, hydrostatic pressure and body forces. Elements $k_{ij}(\Omega)$ of matrix $[K]$ are functions of the impact frequency Ω.

Now the resulting complex system of algebraic equations (10) at fixed frequencies of external impacts is solved by the Gauss method or the square root method.

To implement the developed mathematical model and method for solving the problems under consideration, a program was developed on the IBM PC using complex arithmetic.

RESULTS AND DISCUSSION

In this section, the steady-state forced vibrations of the projected Pskem earth dam, 195 m high, are studied, taking into account their actual geometry and nonhomogeneous features of the structure.

According to the design data, the Pskem dam has the following characteristics: dam height = 195 m, upstream slope coefficient $m_1=2.4$, downstream slope coefficient $m_2=2.0$, crest width $b = 12.0$ m, width of the lower part of the core = 130.0 m. Core material properties are: deformation modulus $E_{\partial e\phi} = 15$ MPa, Poisson's ratio $\nu=0.32$; specific gravity of soil $\gamma=1.7$ tf/m^3, angle of internal friction $\varphi = 24^0$, soil cohesion coefficient $c = 20$ kPa. Prism material properties are: deformation modulus $E_{\partial e\phi} = 95$ MPa, Poisson's ratio $\nu=0.27$; soil specific gravity $\gamma=1.97$ tf/m^3, internal friction angle $\varphi = 42^o$, soil cohesion coefficient $c = 7$ kPa.

To describe the viscoelastic properties of soil, the kernels of the form [42] were used:

$$\Gamma(t) = Ae^{-\beta t}t^{\alpha-1} \tag{11}$$

Parameters A, α, β of the kernel (11) for various types of soil were determined in [43] from the experimental data of soil using the technique described in [39].

Then, the steady-state forced oscillations of the dam were studied under two-component periodic kinematic effects at the base of the structure, i.e.:

$$\vec{x} \in \sum\nolimits_u \begin{cases} u_{10}(t)=B\exp(-i\Omega t) \\ u_{20}(t)=C\exp(-i\Omega t) \end{cases} \qquad (12)$$

where B, C, Ω are the amplitudes and frequency of the kinematic impact, respectively.

Based on the results obtained, the frequency response for a number of characteristic points of dams, i.e.: displacements - (u_1, u_2), stresses σ_{11}, σ_{22}, σ_{12}, principal stresses - σ_1, σ_2, τ_{max}, and intensity of normal stresses σ_i at various kinematic impacts "Ω" (12) were built in the range from 1.0 to 20.0 rad/sec. At that, B/C = 2.0 (B = 0.01m).

To check the adequacy of the developed mathematical models and the accuracy of the method for solving the problem, the frequency response of displacements (u_1, u_2) for various points of the dam (Figure 2) is shown, as an example, for points A (x_1=-7.0 m, x_2=195.0 m) and F (x_1=-102.9 m, x_2=70.4 m), not considering body forces and viscoelastic properties of soil.

If the impact frequency «Ω» coincides with any of the frequencies of the natural vibrations of the dam, i.e. ω_1 =0.2138 Hz; ω_2 =0.2880 Hz; ω_3 =0.3630 Hz; ω_4 =0.3649 Hz; ω_5 =0.4600 Hz, then, elastic resonance occurs; this confirms the reliability of the developed technique (Figure 2).

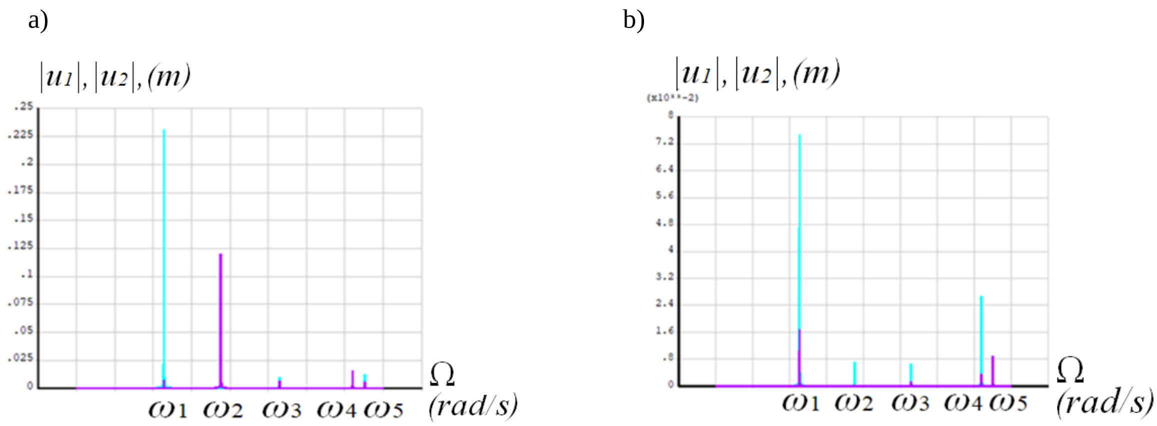

FIGURE 2. Amplitude-frequency response of displacements ($|u_1|$, $|u_2|$) of points A - (a) and F - (b) of the elastic Pskem dam, obtained without considering body forces: (——) - horizontal displacements (u_1); (——) - vertical displacements (u_2).

Figure 3. a shows the frequency response of horizontal u_1 and vertical u_2 displacements of point F (x_1=-102.9 m, x_2=70.4 m), and Figure 3. b shows the frequency response of horizontal and vertical normal stresses at point F1 (x_1=-36.9m, x_2=163.4m) of the Pskem dam, taking into account the viscoelastic properties of the material and without considering body forces.

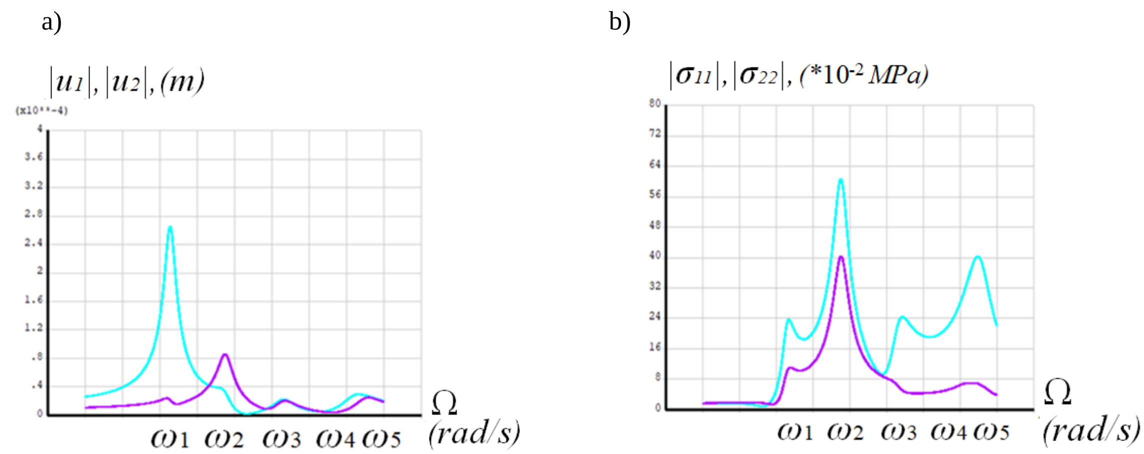

FIGURE 3. Amplitude-frequency characteristics of displacements - $|u_1|, |u_2|$ for point F, and horizontal and vertical stresses $|\sigma_{11}|, |\sigma_{22}|$ or point F1 of the Pskem earth dam, taking into account the viscoelastic properties of the material: ( ) - horizontal displacements (u_1); ( ) - vertical displacements (u_2); ( ) - stress σ_{11}; ( ) - stress σ_{22}.

Analysis of Figure 3. a shows that for many points of the dam at the first resonance, the amplitudes $|u_1|$ are much higher than $|u_2|$. At the second resonance, on the contrary, $|u_2|$ has a sufficiently commensurate amplitude in comparison with $|u_1|$ (Figure 3.a) since the first mode of oscillation is a shift of the central section, and the second mode is the vertical deformation of the dam, etc.

Analysis of Figure 3. b i.e., frequency response by stresses, shows that the maximum stress amplitudes at the points of the dam occur when frequency Ω coincides with ω_1. Along with this, the maximum amplitudes of oscillations for various points can arise when frequency Ω coincides with ω_1 and with a dense spectrum of eigenfrequencies, i.e. ω_3 - ω_4 (Figure 3. b). This is due to the interaction of eigenmodes with similar frequencies, which create a single peak with a high amplitude; this also can be dangerous.

The main normal and maximum shear stresses in the body of the dam were studied under steady-state oscillations at different frequencies Ω of impact, i.e. before resonance, near resonance, and after resonance. At the same time, separate dangerous areas in the structure were identified where the maximum stresses occur.

Along with this, the isolines of the distribution of equal values of the safety factor ***K*** in the section of the Pskem dam are shown; they were obtained using the Coulomb-Mohr theory of strength [44], taking into account the viscoelastic properties of soil and without considering body forces, at impact frequency Ω between the first and second resonant frequencies (Figure 4.). It is assumed that for K>1- in this section of the structure the soil is in a pre-limit state and has a margin of safety; for K= 1- the soil is in the condition of limit equilibrium; and for K<1 - the soil strength in this section of the structure is violated and an instability zone is formed.

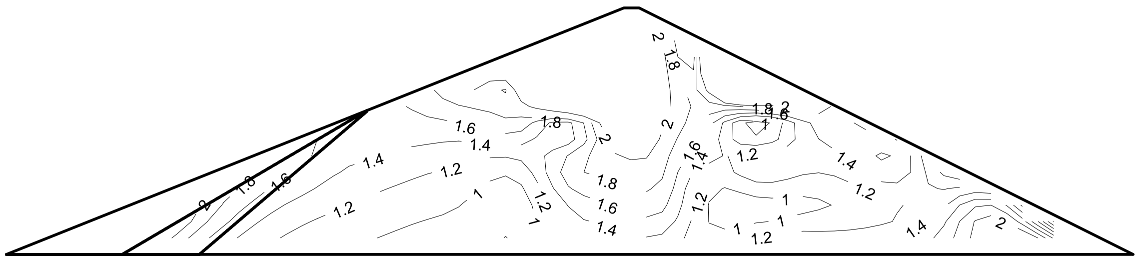

FIGURE 4. Isolines of the distribution of equal values of the safety factor K in the section of the Pskem dam, obtained at an impact frequency Ω between the first and second resonant frequencies, taking into account the viscoelastic properties of soil and not considering the body forces

An analysis of the results (Figure 4.) shows that at this frequency of the impact, the sections of the dam located in the middle of the lowest part of the upstream and downstream prisms of the dam have the minimum strength. The remaining sections of the dam have adequate strength.

CONCLUSION

1. The article provides a detailed overview of known publications related to the evaluation of the dynamic behavior of various dams.
2. A mathematical model was developed that takes into account the viscoelastic properties of soil using the Boltzmann-Volterra hereditary theory.
3. A method and algorithms for solving dynamic problems for earth dams in a plane-deformed state using the Boltzmann-Volterra hereditary theory under stationary kinematic effects are presented.
4. Steady-state forced vibrations of a high earth dam were studied, taking into account the viscoelastic properties of soil under resonant vibration modes.
5. The maximum amplitudes of oscillations of the points of the body and dangerous sections of the dam were revealed in terms of the highest stress at various resonant frequencies.
6. The strength of the dam was tested at various frequencies of kinematic impact using the Coulomb-Mohr theory of strength and the safety factors for various points of the dam were determined.

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