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Strength parameters of earth dams under various dynamic effects

Прочностные параметры грунтовых плотин при различных динамических воздействиях

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Abstract. The paper provides the methods for evaluating the strength parameters of earth dams under forced oscillations. The methods of solving the problem are based on the expansion of sought for solution in terms of eigenmodes of elastic structure oscillations. Linear steady-state and unsteady forced oscillations of three different earth dams were studied with account of structural heterogeneity and viscoelastic properties of structure material under various dynamic effects. To describe the viscoelastic properties, the Boltzmann-Volterra hereditary theory of viscoelasticity is used. The results of investigations made it possible to reveal a number of effects that arise under forced oscillations in a dam in the pre-resonant, resonant, and post-resonant modes of oscillations.

Аннотация. В статье приводится методика для оценки прочностных параметров грунтовых плотин при вынужденных колебаниях. Методика решения задачи основана на разложении искомого решения по собственным формам колебаний упругого сооружения. Исследованы линейные установившиеся и неустановившиеся вынужденные колебания 3 различных грунтовых плотин с учетом конструктивной неоднородности и вязкоупругих свойств материала сооружения при различных динамических воздействиях. Для описания вязкоупругих свойств использована наследственная теория вязкоупругости Больцмана-Вольтерра. Результаты исследований позволили выявить ряд эффектов, возникающих при вынужденных колебаниях в плотине в дорезонансных, резонансных и пост резонансных режимах колебаний.

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1. Introduction

Dynamic behavior and assessment of stress-strain state of various earth dams under certain types of kinematic effect are considered in the paper.

Natural oscillations, steady-state and unsteady forced oscillations are mainly considered in studying the dynamics of structures. Natural oscillations in a structure are the most ordered motions of the structure in the absence of external effects.

In the study of natural oscillations, the following dynamic characteristics are determined - natural frequencies, oscillation modes and damping factors of the structure, which are the main regulatory characteristics (the passport) of the structure in question, allowing to evaluate in advance the dynamic properties of the structure as a whole.

Steady-state forced oscillations of the structure occur in the presence of external periodic effects. In this case, the initial conditions are not taken into account. The dissipative properties of the structure are manifested mainly in resonant modes. The values of the resonance amplitudes of displacements and stresses are used as a quantitative estimate of the intensity of dissipative processes

Unsteady forced oscillations of the structure occur as a result of non-periodic effects, which essentially depend on the initial configuration and the loading rate. This makes it possible to determine the maximum values of displacements, strains and stresses in any part of the dam during the entire process of time of external effects, to reveal dangerous sections of structures in terms of strength and to develop the means to reduce the stress-strain state (SSS), taking into account certain material parameters and structural features of the structure.

At the same time free oscillations of structures are considered as a particular case of unsteady forced oscillations, which is the result of initial excitations at time $t=t_0$ in the absence of external effects in subsequent moments.

Recently, a number of papers have been published that take into account the manifestation of elastic, viscoelastic linear and nonlinear as well as elastoviscoplastic and other soil properties, which, along with the above mentioned, describe dissipation in material under dynamic influences. A summary of some of them is given below.

Dynamic response of earth dams [1] is studied taking into account the nonlinear and viscoelastic properties of soil; the dependence of the magnitude of arising dynamic responses on the loading and mechanical properties of soil is established.

Dynamic behavior of earth dams, taking into account the nonlinear properties of material, is considered in [2]. Transient dynamic processes and creep effects under cyclic influences are studied. The problems are solved by the Newmark method.

In [3], using the nonlinearly rheological models, the stress state of the dam is investigated. The possibility of using this model is demonstrated by comparing the numerical results with the results of laboratory tests.

In [4] a model and a set of defining relationships for the rheological model of soft soils are proposed. The possibility of using this model is confirmed by a number of rheological consolidation experiments at different loading rates.

In [5], the properties of coarse-grained materials of a rockfill dam are investigated using the rheological models. It is shown that for strain modeling a unified description of the interaction of various factors is necessary. The obtained results of numerical simulation are compared with the available experimental data for the rockfill material.

To describe the dissipative properties of soil, the Boltzmann-Volterra hereditary viscoelasticity theory has been used recently [6–9].

The behavior of specific structures using the hereditary theory of viscoelasticity under dynamic load conditions has not been sufficiently investigated. Moreover, the overwhelming number of publications related to the dynamic problems of hereditary theory of viscoelasticity is devoted to the design of thin-walled structures: beams, plates and shells [10–17].

The scheme for solving dynamic viscoelasticity problems for thin-walled structures is fairly standard. Selecting a coordinate function that satisfies the boundary conditions, the original problem can be reduced to the problem of oscillations of a system with a finite number of degrees of freedom, i.e., to a system of linear or nonlinear integral-differential equations with one independent time variable. As a rule, trigonometric or beam functions are used as coordinate functions. Such a choice of coordinate functions limits the class of solved problems to the simplest structural configurations - beams of constant sections, a rectangular plate, a cylindrical shell [12–14, 17].

The above authors, while admitting a number of inaccuracies in the selection of coordinate functions, try to improve the accuracy of solving the system of integral-differential equations. However, for constructions with real geometry it is impossible to select the analytic coordinate functions that satisfy the boundary conditions of the problem.

Therefore, for the structure of complex geometry, it would be useful to use as coordinate functions, the eigenmodes of oscillations, which are intrinsic ones and take into account all features of the structure under consideration.

Expansion of the solution in terms of eigenmodes of oscillations in solving specific problems for the first time was used in [18]. Then the eigenmodes of oscillations for the expansion of solution of real structures and complex viscoelastic shells under forced vibrations were used in [10, 11, 19, 23].

This review of known works shows the need to assess the stress-strain state and dynamic behavior of earth structures, taking into account the viscoelastic properties of soil, as well as the heterogeneous structural features and real geometry.

Therefore, the evaluation of the strength parameters of earth dams under various dynamic effects, taking into account the real features of the structure and the dissipative properties of the structure material, is an actual task and represents both theoretical and practical interest.

The aim of this work is to develop a methodology, an algorithm and a computer program for assessing the dynamic behavior and stress-strain state of an earth dam, taking into account the viscoelastic properties of the material and the actual geometry of the structure under various effects, as well as studying the dynamic characteristics and stress-strain state of various earth dams under some types of kinematic influences.

Considering this problem, the Boltzmann-Volterra hereditary theory of viscoelasticity [8. 21], using the Rzhanitsyn-Koltunov kernel [11, 22], is used to take into account the viscoelastic properties of soil. To formulate the problem, the principle of virtual displacements is used, and the variation problem is solved by expanding the solution in terms of the eigenmodes of vibrations of the elastic problem [10, 11, 19]. The resulting system of integral-differential equations is solved exactly for periodic effects or using quadrature formulas at nonstationary kinematic effects.

In this paper, the methods, algorithm, and results of research on strength parameters of earth dams (of various height) are presented taking into account the viscoelastic properties of soil and the heterogeneous structural features in resonant oscillation modes under various dynamic effects.

2. Methods

Consider the earth dam (Fig. 1); the volume is $V=V_1+V_2+V_3+ V_4+V_5+V_6$,. It is assumed that the lower part of the dam is located on rigid base Σ_u, where the kinematic effect $\vec{u}_o(\vec{x},t)$ is applied. The hydrostatic pressure acts on the S_p part of the surface Σ_1 . The rest of the surface (Σ_2,Σ_3) is stress-free. The dam (Fig. 1) is a massive body, so mass forces $\vec{f}$ are taken into account in the calculation. The material of different parts (V_1,V_2,V_3,V_4,V_5,V_6) of the dam is considered linearly elastic or linearly viscoelastic. At the boundaries of individual parts of the dam, the components of displacements and stresses are continuous.

The task is to determine the displacement and stress fields arising in the dam (Fig. 1), under the effect of mass forces $\vec{f}$, water pressure $\vec{P}_c$ and kinematic influences at the base $\vec{u}_o(\vec{x},t)$.

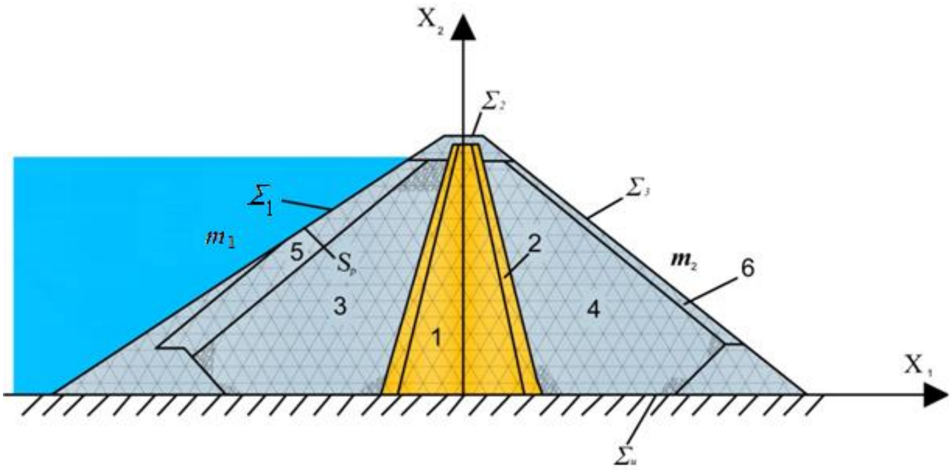


Figure 1. Model of earth dam

For the statement of the problem, the principle of virtual displacements is used, according to which the sum of the work of all active forces, including inertia ones, on the virtual displacements is zero:

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

Here, $\vec{u}$, ε_{ij}, σ_{ij} – are the displacement vector and the components of strain and stress tensors; respectively, $\delta\vec{u}$, $\delta\varepsilon_{ij}$ – are isochronous variations of displacements and strains; ρ_n – density of material of elements ($V_1, V_2, V_3, V_4, V_5, V_6$) of the system under consideration; $\vec{f}$ – is a vector of mass forces; $\vec{P}_c$ – is hydrostatic water pressure.

To describe the viscoelastic properties of material, the Boltzmann-Volterra linear hereditary theory is used [21]:

$$S_{ij} = G_n\left[e_{ij} - \int_o^t \Gamma(t-\tau)e_{ij}(\tau)d\tau\right], \quad (2)$$
$$\sigma = K_n\theta.$$

The following designations are accepted: S_{ij}, e_{ij} – are the components of stress and strain deviator; σ – a hydrostatic component of stress tensor; K_n,G_n – are the instantaneous bulk and shear moduli of elasticity; Γ – a relaxation kernel; $\theta = \varepsilon_{ii}$ - a volume strain. The index n = 1, ..., 6 refers to respective volume V_n. i,j = 1,2.

The connection between the strain tensor and the components of the displacement vector is described by the Cauchy linear relations

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

Kinematic conditions at the base are given

$$\vec{x} \in \Sigma_u : \vec{u}_0(\vec{x},t) = \vec{\psi}(t), \quad (4)$$

and initial conditions at t=0:

$$\vec{x} \in V : \vec{u}(\vec{x},0) = \vec{\chi}_1(\vec{x});$$
$$\dot{\vec{u}}(\vec{x},0) = \vec{\chi}_2(\vec{x}), \quad (5)$$

where $\vec{\psi}$ – is a given function of time; $\vec{\chi}_1, \vec{\chi}_2$ – are given functions of coordinates.

An approximate solution of the problem in question is sought in the form of an expansion in terms of the eigenmodes of oscillations of the elastic problem for heterogeneous systems (Fig. 1) [10, 11, 19], i.e.:

$$\vec{u}(\vec{x},t) = \vec{u}_o(\vec{x},t) + \sum_{k=1}^{N} \vec{u}_k^*(\vec{x}) y_k(t); \; \delta\vec{u} = \sum_{k=1}^{N} \vec{u}_k^*(\vec{x}) \delta y_k(t), \tag{6}$$

where $\vec{u}_0(\vec{x},t)$ – is a known function (4), which satisfies the boundary conditions of the problem; $\vec{u}_k^*(\vec{x})$ – are the eigenmodes of oscillations of the elastic problem for heterogeneous systems; $y_k(t)$ – are the sought-for functions of time; $\delta y_k(t)$ – are arbitrary constants; N – is a number of eigenmodes retained in the expansion (6).

When using this approach, the main difficulty lies in the choice of coordinate functions $\vec{u}_k^*(\vec{x})$, which are quite simple in the case of bodies of simple shape and fastening conditions. For the bodies of complex shape, the choice of coordinate functions $\vec{u}_k^*(\vec{x})$ reducing the original system of variation equations (1) to a system of resolving equations with a finite number of degrees of freedom presents a difficult problem. Using the eigenmodes of oscillations allows one to accurately describe the real geometry and various features of bodies of complex shapes under different effects. This explains the choice of eigenmodes of oscillations as coordinate functions. Therefore, in this paper, first, taking into account all the factors, by the finite element method (FEM), the eigenmodes of oscillations of a heterogeneous dam are determined (Fig. 1) in a linear elastic statement. Further, the solution of the problem of forced oscillations of the system, taking into account the viscoelastic properties of material, is constructed in the form of an expansion in accordance with the found eigenmodes of oscillations of the elastic problem.

In the case of steady-state forced oscillations under periodic kinematic effects, taking into account the viscoelastic properties of dam material, the problem under consideration, after substitution of (6) into (1), is reduced to solving a system of linear integral-differential equations of the form

$$M_{ik}\ddot{y}_k(t) + K_{ik}y_k(t) - C_{ik}\int_{-\infty}^{t} \Gamma\,(t-\tau)y_k(\tau)d\tau = -\left(f_{1i}\ddot{\psi}_1(t) + f_{2i}\ddot{\psi}_2(t)\right), \tag{7}$$

$i=1,2,\dots,N;\; k=1,2,\dots,N.$

The order of the system (7) is equal to the number N of eigenmodes of oscillations of elastic structure retained in the expansion (6). In studying steady-state forced oscillations, the lower bound of the integral in expression (2) is taken from minus infinity. In this case, the initial conditions are not taken into account. The system of equations (7) has an exact solution [23].

The system of integral-differential equations (7) describes the dynamic behavior of earth dams, taking into account the viscoelastic properties of soil under periodic kinematic effects. This allows one to investigate the dynamic behavior of earth dams at various external effect frequencies, including the options, when the frequency of the effect is equal to the natural frequency of the structure (resonant mode).

Under unsteady forced oscillations of the dam, the variation problem (1) after substitution (6) is reduced to solving a system of linear integral-differential equations

$$M_{ij}\ddot{y}_j(t) + K_{ij}y_j(t) - C_{ij}\int_{o}^{t}\Gamma_1(t-\tau)y_j(\tau)\,d\tau = F_i + Q_i f(t), \tag{8}$$

with initial conditions:

$$y_i(0) = y_{0i}, \quad \dot{y}_i(0) = \dot{y}_{0i}; \quad i,j,k,m = 1,2,\dots,N\,. \tag{9}$$

Here also the order of the system of equations (8) is equal to *N* - the number of retained in the expansion (6) eigenmodes of oscillations of elastic dam. The coefficients $f_{1i},\ f_{2i}, Q_i, F_i, M_{ij}, K_{ij}, C_{ij}$ of the system of integral-differential equations (7) and (8) are determined through eigenmodes of oscillations $\vec{u}_k^*(\vec{x})$ by integrating them over the volume of the dam in question. Here $f_{1i},\ f_{2i}, F_i, f(t)$ was a total external load from mass forces, hydrostatic pressure, and kinematic effect varying in time.

The system (8), under the initial conditions (9), is solved by the method of quadrature formulas set forth in [17, 19].

To verify the reliability of the developed algorithm and the computer program, a linear integral-differential equation of the following form is solved

$$\ddot{y}(t)+\omega^2\left[y(t)-\int_0^t \Gamma_1(t-\tau)y(\tau)d\tau\right]=f(t) \qquad (10)$$

with initial conditions

$$y(0)=1,\ \dot{y}(0)=-\beta \qquad (11)$$

and with basic data

$$\Gamma_1(t)=Ae^{-\beta t}\cdot t^{\alpha-1},$$
$$f(t)=\left[\beta^2+\omega^2-\frac{A\omega^2 t^\alpha}{\alpha}\right]e^{-\beta t}, \qquad (12)$$
$$A=0.01;\ \alpha=0.25;\ \omega=2\pi,$$

both numerically by the method of quadrature formulas [17, 19], and in exact form [17]. The results of the numerical solutions obtained and their comparison with the exact solution $y=e^{-\beta t}$ are given in Table 1.

Table 1. Solutions of linear integral-differential equations (10)

Time, *t*, s	0.4	1.2	2.0	4.0	8.0	12.0	16.0	20.0	24.0	28.0
Solution, obtained by the authors	0.973	0.927	0.887	0.801	0.654	0.536	0.439	0.361	0.297	0.245
Exact solution	0.980	0.942	0.905	0.819	0.670	0.549	0.449	0.368	0.301	0.247

Comparison of the results (Table 1) shows that with the developed algorithm based on quadrature formulas it is possible to obtain a solution of integral-differential equations with required accuracy.

3. Results and Discussion

Dynamic behavior and stress-strain state of the Nurek (296 m high), Gissarak (138.5 m high) and Sokh (87.3 m high) earth dams [27] were studied with account of their real geometry and heterogeneous structural features.

Various mechanical properties of soil were taken into account for various sections of the dam, and Rzhanitsyn's three-parameter relaxation kernels [26] were used to describe the viscoelastic properties of soil (with kernel parameters given in [8]).

To solve the above problems, first the eigenmodes of oscillations of these dams were determined with account of real features of the structures under consideration in elastic statement. The obtained natural frequencies of the Nurek dam were compared with the spectra of the oscillation frequencies of the Nurek dam [20], obtained during the earthquakes. The comparison also showed a sufficiently high accuracy of the results obtained,

3.1. Study of steady-state forced oscillations

Next, steady-state forced oscillations are studied with consideration of viscoelastic properties of soil under two-component periodic kinematic effects at the base of the structure:

$$\vec{x} \in \Sigma_u \quad : \begin{matrix} u_{10}(t) = B\exp(-i\Omega t) \\ u_{20}(t) = C\exp(-i\Omega t) \end{matrix}, \tag{13}$$

where *B, C* – are the amplitudes, and Ω – is a frequency of kinematic effect.

The result of calculation is a construction for a number of characteristic points of the dam of amplitude-frequency characteristics (AFC) of displacements (u_1, u_2) and stresses: normal – σ_{11}, σ_{22}, tangential σ_{12}, principal σ_1, σ_2, maximal tangent τ_{max} and intensity of stresses σ_i for various frequencies "Ω" of kinematic action (10) in the range from 1.0 to 20.0 rad/sec. In the vicinity of the proposed viscoelastic resonance, the step for the frequency "Ω" is 2–3 times less. The amplitude ratio was assumed to be *B/C* = 2.0 (*B* = 0.01 m).

As an example Figure 2a shows the AFC of horizontal – u_1 and vertical – u_2 displacements of the point (x_1=-301 m, x_2=92.5 m), and Figure 2b - AFC of the maximum tangential stress $\tau_{\max}$ at the point (x_1=-204m, x_2=104.8 m) of the Nurek dam, with consideration of viscoelastic properties of material and without consideration of mass forces.

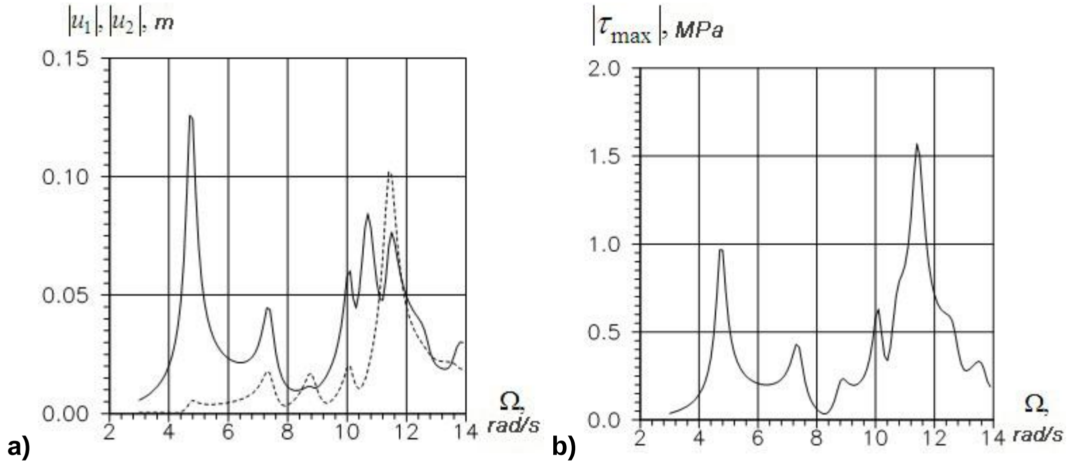


Figure 2. Amplitude-frequency characteristics of displacements $|u_1|,|u_2|$ of the point (x_1=-301 m , x_2=92.5 m) and maximum tangential stresses $|\tau_{max}|$ at the point (x_1= -204 m, x_2=104.8 m)of the Nurek dam, with consideration of viscoelastic properties of material: ___ horizontal displacements (u_1); --- vertical displacements (u_2).

The results obtained (Fig. 2a) indicate an excess of the amplitudes of horizontal displacements in comparison with vertical ones at the first resonant frequency. At the second resonance, on the contrary – the vertical displacements exceed the horizontal ones. This is due to the nature of the dam's eigenmodes of oscillation at the appropriate frequencies: during the first mode there occurs the shift of the central section, and during the second - the vertical strain of the dam, and so on.

Analysis of the amplitude-frequency characteristics of stresses (Fig. 2b) shows that the largest amplitudes of stresses at the points of the dam arise when the frequency of the effect Ω coincides with the first natural frequency and with the frequencies of the dense spectrum in the range between $\omega_4 \div \omega_6$ or ω_9, ω_{10}. This is explained by the interaction of eigenmodes of oscillations of a structure with close frequencies, which create a single peak with great amplitude. Therefore, for this dam it is dangerous to operate with a frequency of $\Omega = \omega_1$ and with a frequency in the range between the frequencies ω_4 and ω_6.

3.2. Investigation of unsteady forced oscillations

Unsteady forced oscillations were studied with account of real features and viscoelastic properties of soil of the above-mentioned dams; kinematic effect at the base of the structure Σ_u was taken as an external influence:

horizontal $$\{u_o(t)\} = \begin{cases} a\sin(pt), & 0 \prec t \le t^* \\ 0, & t^* \succ t \end{cases};\qquad (14)$$

vertical $$\{v_o(t)\} = \begin{cases} b\sin(pt), & 0 \prec t \le t^* \\ 0, & t^* \succ t \end{cases}.\qquad (15)$$

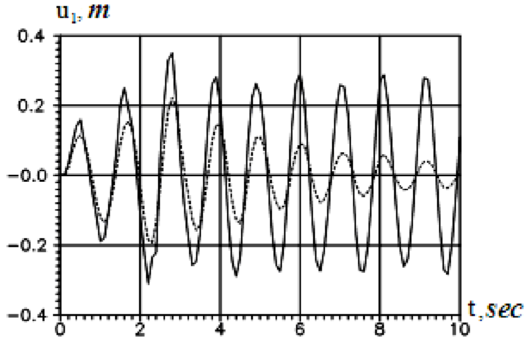
Here: p – is a frequency; a, b – the amplitudes; t^* – effect time; t – considered time of the process. Initial conditions of the problem are homogeneous.

In calculations, the parameters of kinematic effect (14)–(15) were taken as: a = 0.01 m, b = 0.01 m; t^*=3sec. The frequency of the effect was taken: for the Gissarak dam: p = 5.70 rad/sec (pre-resonant mode), p = 7.70 rad/sec (post-resonant mode); for Sokh: p = 16.30 rad/sec (pre-resonant mode), p = 22.00 rad/sec (post-resonant mode).

At each moment of the effect the motions of various points of the dam were determined in time.

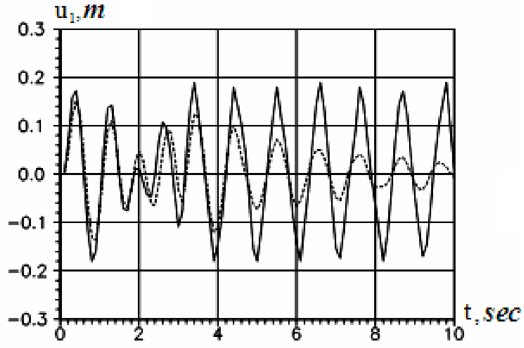
Figures 3–4 show the variation of horizontal displacements (u_1) in time of the points (x_1= 8.0m, x_2=138.5m) of the Gissarak dam and the point (x_1=5.0m, x_2=87.0m) of the Sokhdam at different frequencies "p" of the two-component kinematic effect (14)–(15).

Analysis of the results shows that vertical displacements are inferior in magnitude to horizontal ones u_1. The explanation for this is the character of the first waveform representing the shear of the cross section in the direction of x_1 axis.



a)

Fluctuations of the dam point in the resonant mode (ω1>p)



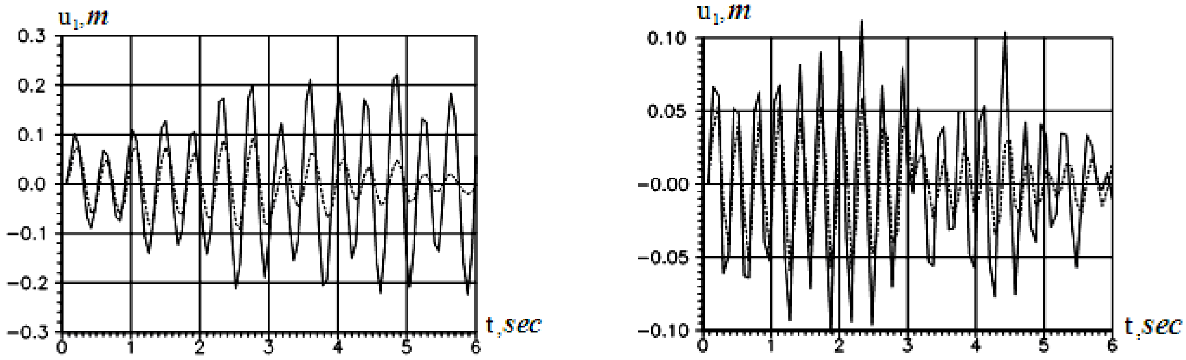
b)

Fluctuations of the dam point in the post-resonant mode (ω1<p)

Figure3. Change of horizontal displacements (u1) of the point (x1 = 8.0 m, x2 = 138.5 m) of the Gissarak dam under two-component effect (t^* =3 sec)

From the results (Figs. 3–4) it can be seen that the consideration of viscoelastic properties of soil leads to a significant attenuation of the oscillations even during the effect of the load both for structures with low-frequency spectrum (Fig. 3) and high-frequency spectrum (Fig. 4); that is explained by the use of viscoelastic model, in which the change in dissipative properties of material weakly depends on the frequency of oscillations.

Analysis of the displacements of dam points under multicomponent kinematic effects in the pre-resonant mode (at frequency $p<\omega_1$) shows that horizontal oscillations of different points of the dam occur with the greatest amplitude, almost twice exceeding the amplitude of vertical oscillations. In the post-resonant mode, the amplitudes of the oscillations of elastic structure have almost the same value for all the components of displacements.



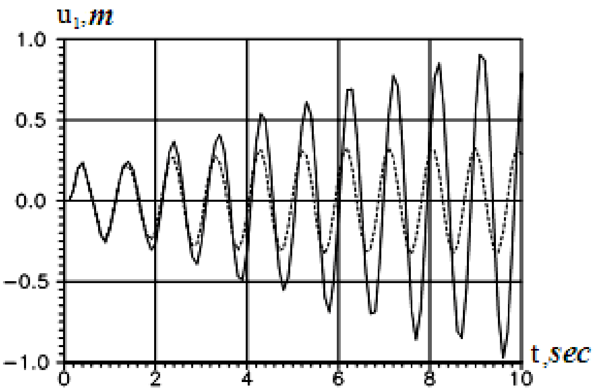
a) **Fluctuations of the dam point in the pre-resonant mode ($\omega_1>p$)**

b) **Fluctuations of the dam point in the post-resonant mode ($\omega_1<p$)**

Figure 4. Change of horizontal displacements (u_1) of the point (x_1=5 m, x_2=87 m) of the Sokh dam under two-component effect (t^* =3sec.)

The account of viscoelastic properties of soil strongly attenuates horizontal oscillations, both during the effect, and after it. In this case, the amplitude of horizontal viscoelastic oscillations (in the pre-resonant mode) is almost two times less than the amplitude of elastic oscillations. The damping of oscillations of other components of point displacements basically occurs after the end of the effect both in the pre-resonant and post-resonant modes. In the post-resonant mode, the amplitude of the oscillations of the point in all directions (in both elastic and viscous-elastic cases) is inferior to the amplitudes of horizontal oscillations in the pre-resonant mode. This type of oscillation is also observed for the Sokh dam, the oscillations of which are high-frequency ones.

The amplitude of oscillations of the dam point in the resonant mode in elastic soil is infinitely increasing in time (Fig. 5).



Fluctuations of the dam point in the resonant mode ($\omega_1=p$)

Figure 5. Horizontal displacements (u_1) of the point (x_1=8.0m, x_2=138,5m, x_3=330.0m) of the Gissarak dam under multicomponent kinematic effect (t^* =10.0сек.)

When taking into account the viscoelastic properties of soil, the amplitude of dam oscillations is limited and, with the passage of time, remains constant at the same level (Fig. 5).

4. Conclusions

The carried out researches on strength parameters evaluation of earth dams under various dynamic effects have allowed us to draw the following conclusions:

1. In solving the problem of forced oscillations of the structures of complex shapes, the use of eigenmodes of oscillations of the structures in question in elastic statement, taken as coordinate functions, makes it possible to accurately describe the real geometry and various structural features.

2. In the case of the existence of a dense spectrum of eigenfrequencies in considered structures, the oscillations in the resonant mode lead to oscillations with a larger amplitude than at the first resonance.

3. Consideration of viscoelastic properties of the dam's soil leads to a significant attenuation of the oscillations even during the effect of the load, both for the structures with low-frequency spectrum and high-frequency spectrum, although the dissipative properties of material weakly depend on the frequency of oscillations.

4. The magnitude of displacements and stresses arising at different points of the dam under forced oscillations exert a rather strong influence, not only on the amplitudes of the effect, but also on the ratio of natural frequency of the structure and the frequency of external effects.

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