Dynamics of an earth dam with account for rheological properties of soil under dynamic effect

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Abstract. The design, construction and operation of high earth dams in seismic regions of the republic require continuous improvement of the methods to calculate them on basic loads and special combinations of them, including seismic ones. The aim of this work is to improve the calculation methods for earth dams, taking into account the real physical and mechanical characteristics of structure and its foundation soil under various types of loads. Improved calculation methods make it possible to predict the stress-strain state of the most vulnerable points in the dam, which will lead to a reliable and safe operation of earth dams in seismic zones.

1. Introduction
Regulatory methods include the spectral method for calculating dams for seismic effects, which does not consider the mentioned factors. The statement, methods and algorithm for solving static and dynamic problems of an earth dam are given. The stress-strain state of a high earth dam of the Charvak hydroelectric power station, located near the capital of Uzbekistan - the Tashkent city, was studied taking into account elastic and inelastic soil characteristics of the structure under dynamic (seismic) impact. The soil is taken into account as an elastic medium, when water saturated - as viscoelastic one, and elastic one with dissipation in the form of dry friction (according to Sorokin's theory). The problem was solved in a plane statement by the finite element method, which allows us to consider nonlinear soil properties of structure, and its design features.

According to the developed methods, the solution of the dynamic problem is reduced to solving a system of nonlinear differential equations under the corresponding initial conditions, solved by the Newmark method. The calculation results are presented in the form of stress isolines in the body of the dam under basic loads (gravity, hydrostatics). When solving dynamic problems the results are given in the form of stresses and displacements dependences in time. This allows us to determine the vulnerable zones in earth dam, where the loss of structure stable operation is possible. An analysis of numerical results on behavior of vulnerable sections of earth structure under dynamic impact showed that an account for internal friction in soil reduces the amplitude of the forced vibrations.

Design and construction of high earth dams in seismic regions requires paying attention to long-term processes occurring in their body and affecting the quality of construction. Disasters are known during the destruction of the arch dam Malpas in France or during a landslide in the reservoir of the arch dam
Vaillont in Italy, the destruction of the earth dam Titon in the United States. Recently, in 2017 there has been a panic in California (USA); at a threat of destruction of the Oroville dam more than two hundred thousand residents were evacuated from the settlements near the dam. All this confirms the need to meet the safety requirements of dams (earth dams as well). Forecasting and identifying the basic laws of the stress-strain state and behavior of hydro-technical structures (dams) under dynamic (seismic) impacts taking into account real geometry, design features, piecewise inhomogeneous properties of soils that change under the influence of filtration flows, the nature of static, hydrostatic and dynamic effects, allows creating and carrying out effective anti-seismic measures that ensure trouble-free operation of existing earth dams and the dams under project [1-5].

A special contribution to the development of methods and algorithms for calculating earth dams on basic loads (gravity, hydrostatics, etc.) and special combinations of loads (seismic, hydrodynamic pressure, etc.) are made by researchers of the national school of engineers of Uzbekistan [6-16].

In these studies, on the basis of plane and spatial design schemes, the issues related to the seismic resistance of designed and operated in the republic hydro-technical structures subject to high seismic risk are considered. Various soil properties are taken into account - plasticity, degree of moisture content, non-linear properties and structural features of structures.

The spectral method of structure calculation for seismic impacts, stated in regulatory documents, is performed under conditional seismic loads determined using the assumption of elastic strain of a cantilever model with the masses concentrated in height [17,18]. This model is suitable only when calculating high structures, compact in plan, the modes of vibration of which have a bending nature. Oscillations of massive earth dams are more complex and include not only horizontal shear, but also vertical displacements, which cannot be determined using the cantilever model. In the cited works, calculations of static and dynamic behavior of earth hydro-technical structures (earth dams) were performed using:

1. - a plane-deformable model (Figure. 1 a), representing the cross section of the dam [7];
2. – a spatial model [8-9], representing the real body of the dam (Figure. 1 b);
3. - a model consisting of two intersecting planes, one of which is a transverse, and the other - a longitudinal section of the dam, coinciding with the dam location (Figure. 1 c).

![Figure 1. Calculation models of earth dam on a rigid foundation](image)

In the considered calculation models, the dam base is assumed to be absolutely rigid, but to account for non-uniform strain, subsidence, protrusion of part of soil or any other negative manifestation of weakened base, it is necessary to consider the structure models together with the base having sliding lateral faces (Figure 2), i.e. to consider only vertical displacement of an infinite strip of the base.

Design models of this type were considered in [10], where the effect of a weakened fractured section on the stress-strain state of a high earth dam \( T \) and the surrounding rock base with a weakened fractured section was studied. Soil characteristics were obtained by experimental drilling conducted by JSC Hydroproject. The studies performed had practical results in the form of recommendations on further increasing the height of the considered earth dam.

In studies of the stress-strain state (SSS) and dynamic behavior of earth dam with the indicated models under static, hydrostatic and dynamic effects, a numerical method is used - the finite element method, which allows us to take into account the real geometry, design features of objects and various ground
conditions manifested under loading and moistening [10,11] i.e. plasticity, fracturing, geometrical and physical nonlinearity. To account for the nonlinear properties of the material (soil), special calculation methods have been developed based on solving linear and nonlinear systems of high-order algebraic, differential and integro-differential equations.

![Figure 2. Dam models with a base: transverse - a; longitudinal (in the canyon) - b](image)

The study of the SSS of an earth dam is an extremely difficult task, since the strain properties of soil depend on many factors: the acting average stress; stress deviator component; applied load; moisture content; degree of fracturing, etc. Non-linear laws of soil strain in the structure, implemented in calculation programs, include an account for: structural damage during volume strain; moisture content; geometric (for high dams) and physical non-linearity under loading, and dry and viscous friction. The developed methods of static and dynamic calculation and the solution of complex problems of SSS and dynamic behavior of earth dams made it possible to analyze the effect of hydrostatic pressure, viscosity, nonlinear strain and soil moisture on the SSS of concrete earth dams of Uzbekistan [12-14].

GIS is successfully used to assess the seismic stability of earth dams. Since the earthquakes cause huge losses of human lives and damage to the infrastructure and economy, the risks caused by dam destruction built to provide the population with fresh and irrigation water, and electricity can be achieved by the decision making. GIS is used to create a digital relief model and visualizing the effects of dam destruction and a virtual seismic wave propagation. Using GIS technology and hydrological modeling software, the possible consequences and damage from flooding during dam destruction were investigated and modeled to show the significant impact of dam destruction on the safety of the region. The seismic wave propagation after dam destruction can be predicted using favorable technologies such as GIS. Such advanced model technologies become inevitable. The analysis of the zones of possible destruction arising in the dams under various static and dynamic impacts allows a sound and economical approach to the operation of the selected earth protective structures - this determines the relevance and practical value of research.

2. Materials and methods
A mathematical model is built using [19]:

1) - the variation principle of the minimum of total energy of the system:
\[ \delta\Pi - \delta'W = 0 \]  
\[ (1) \]
Where \( \delta\Pi \) is the increment of potential energy of the system, and \( \delta'W \) is the sum of work of external forces on virtual displacements;

2) - the equation of state expressing the relationship between the stress \( \sigma_{ij} \) and strain \( \varepsilon_{ij} \) components for an elastic medium
\[ \sigma_{ij} = \lambda \varepsilon_{kk} \delta_{ij} + 2\lambda \mu \]
\[ (2) \]

3) – Cauchy relations connecting strains to displacements
\[ \varepsilon_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \]
\[ (3) \]

4) - boundary conditions on a rigid base, meaning the absence of virtual displacements \( \delta \bar{u} = 0 \)
\[ (4) \]
5) - the external impact is represented by volume forces - \( \vec{p} \) (weight) applied over the entire volume of the structure, and surface forces \( \vec{f} \), acting on part of structure surface being in fact a hydrostatic pressure.

Here \( \vec{u} = \{u_i, u_j\} \) are the horizontal and vertical displacements of a body point with coordinates: \( \{x_i, x_j\} \); \( \sigma_{ij}, \varepsilon_{ij} \) - are the components of stress and strain tensor; \( \lambda, \mu \) are the Lame constants.

For the numerical solution of the problem posed, the finite element method [19-20] is used, characterized by the simplicity of account for the structure-external medium interaction, static and dynamic loads, and various types of boundary conditions.

Mathematically, the problem of unsteady forced vibrations is reduced to solving a system of inhomogeneous second-order differential equations with the right-hand side being a function of time

\[
[M] \ddot{q} + [C] \dot{q} + [K] q = \{P(t)\}
\]

where \( [M] \) is the mass matrix; \( [K] \) - stiffness matrix; \( \{P(t)\} = [M] \{\ddot{u}_0\} \); attenuation matrix \( [C] \) describes the internal friction due to the medium viscosity. The aspect of choosing the type of matrix \( [C] \) is considered below.

The solution of the system of equations (5) under the corresponding initial conditions can be obtained by the Newmark method [20]. The Newmark method is based on expansions \( q(t_i + \tau) \) and \( \dot{q}(t_i + \tau) \) in series in powers of \( \tau \) (the integration step):

\[
q(t_i + \tau) = q_i + \tau \dot{q}_i + \frac{\tau^2}{2} \ddot{q}_i + \alpha \tau^3 \dddot{q}_i
\]

\[
\dot{q}(t_i + \tau) = \dot{q}_i + \tau \ddot{q}_i + \beta \tau^3 \dddot{q}_i
\]

where \( \alpha \) and \( \beta \) are chosen such that unconditional convergence of the integration process is ensured: \( \beta \geq 0.5; \alpha \geq 0.25(\beta+0.5)^2 \).

The solution for nodal displacements \( q_{i+1} \) at the end of the \( i \)-th time step is determined from the algebraic system of equations [20]:

\[
[A] \{q_{i+1}\} = \{P_{i+1}\},
\]

solved by the Gauss method.

Here

\[
[A] = [K] + [C] \beta / (\alpha \tau) + [M] / \alpha \tau;
\]

\[
\{P_{i+1}\} = \{R_{i+1}\} + [M] \left[ \frac{q_i}{\alpha \tau^2} + \frac{\ddot{q}_i}{\alpha \tau} + \left( \frac{1}{2 \alpha} + 1 \right) \dddot{q}_i \right] + [C] \left[ \frac{\beta \dddot{q}_i}{\alpha \tau} + \frac{\beta (\dddot{q}_i - 1) \dddot{q}_i}{\alpha \tau} + \frac{\tau (\beta - 2)}{2} \dddot{q}_i \right].
\]

\( \{q_i\}, \{\dot{q}_i\}, \{\dddot{q}_i\} \) - are the displacements, velocities and accelerations of nodal points found on the previous time step.

The described algorithm of the Newmark method is applied to solving problems of unsteady forced vibrations of earth dams; dynamic impact for each structure is selected individually.

The studies were carried out numerically by the finite element method on the example of a plane model, an analog of the Charvak dam. Dam height is \( H = 168 \text{m} \); slope coefficients \( m_1 = m_2 = 2.2 \); slopes of the core \( m_1 = m_2 = 0.2 \). Physical-mechanical parameters of soil of retaining prisms are \( E = 60 \text{ MPa}; \rho = 1.8 \text{ t/m}^3 \); core \(- E = 30 \text{ MPa}; \rho = 1.7 \text{ t/m}^3, \nu = 0.3.\)

The following boundary conditions were accepted when calculating the dam:

- in the absence of hydrostatics, the surface of the side slopes and the crest of the dam are free of loads; \( \sigma_{ij} n_i = 0 \), \( n \) is the normal vector to the surface;
- when hydrostatics is taken into account, the pressure on the surface of the upper slope of the dam is a linear function of the depth \( z \): \( \rho g z \);
- the absence of displacements on the rigid boundary of the base: \( \frac{\delta u}{\nu} = 0; \frac{\delta v}{\nu} = 0 \).

The spectral method [17,18] included into the design standards involves the determination of the
conditional seismic load, determined by the formula

$$S_i = k_i \beta_i \eta_i Q$$

including the dynamic characteristics of the object: $\beta_i$ are the dynamic coefficients of the corresponding spectral curves and $\eta_i$ are the coefficients of the eigen modes.

To determine dynamic characteristics, the finite element discretization of a plane model is used. Then finding the eigen frequencies ($\omega$) and vibration modes $\{u\}$ is reduced to solving the problem by eigen values - [19-20]

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

3. Results and discussion

For the Charvak earth dam, the first two eigen frequencies obtained, corresponding to the horizontal shear (Figure 3a) and vertical displacement of the cross section (Figure 3b) of the dam, are: $\omega_1 = 1.69$ Hz (period $T_1 = 0.59$ s) and $\omega_2 = 2.4$ Hz ($T_2 = 0.41$ s), respectively.

![Figure 3. Natural modes of vibration a) the first mode; b) the second mode](image)

The first mode and period are used to determine the basic tensile ($\sigma_1$) stresses under the first mode of vibration – under horizontal shear.

To do this, the static problem is solved

$$[K] \cdot \{u\} = \{S\}$$

Based on the obtained displacements $\{u\}$ of nodal points of the model, the Cauchy equations determine the strains and the Hooke’s law – the stresses in the dam.

Dams are an integral part of the hydro-technical complex that holds a large volume of water in the reservoir, therefore, under seismic effect, in addition to its own weight, the effect of hydrostatic pressure must be taken into account. The propagation of basic stresses in the dam under horizontal shear (the first mode of vibration), obtained without account and with account for hydrostatics, is shown in Figure 4.

![Figure 4. Distribution of basic stresses in the dam: without hydrostatic pressure (a) and with account for hydrostatics (b) under horizontal vibrations, MPa: $\sigma_{1\text{max}} = 2.53$; $\sigma_{1\text{min}} = 0.032$; 0.032-0.71 (white zone); 0.71-1.42 (gray); 1.42-2.11 (black)](image)

As seen from the results obtained, under horizontal shear, additional account for hydrostatic pressure on the upstream slope increases tensile stresses at the base of the upstream slope. The dynamics of an earth dam is considered under the assumption that a two-component kinematic impact is applied at the base of the model:

$$\ddot{u}_0 = \begin{cases} A \sin(2\pi t) & 0 \leq t \leq 2 \text{ sec} \\ 0 & t > 2 \text{ sec} \end{cases}$$
The initial conditions are assumed to be homogeneous, and the amplitude of base acceleration corresponds to a 7-point earthquake (A=0.1m/s^2) along the horizontal and vertical axes. The duration of the impact is T=2 sec, the frequency of the impact is taken equal to the fundamental frequency of dam vibrations.

Dynamic calculations were performed for soils with various properties: elastic, when wetted, viscoelastic, and elastic with dissipation in the form of dry friction (according to Sorokin's theory).

With the indicated properties of soil: elastic, viscous and with dry friction, solutions were obtained for the dynamic behavior of an earth dam (displacements of points).

In the absence of energy dissipation ([C]=0), the system describes the motion of an elastic dam without damping. This case under short-term impact T = 2sec is shown in Figure 5a for horizontal displacements of two points of the dam - on the crest (solid line) and on the slope (line with asterisks). These results can be considered as test ones, confirming the reliability of calculations, namely, the occurrence of resonance when the impact frequency and the natural vibration frequency of the structure are equal. Under such an impact, horizontal vibrations of the dam prevail, while vertical ones are insignificant, and therefore are not given.

After the termination of the impact (>2sec), the vibrations go into the steady-state mode (Figure 5b) at an amplitude reached at the time of the impact termination.

Thus, under a frequency equal to the frequency of structure horizontal vibrations, the horizontal vibrations occur with an amplitude that increases linearly with time until the impact termination (up to T = 2sec).
To describe the absorbing properties of moistened soils and to obtain a resolving system of equations, the Kelvin-Voigt dynamic model of a visco-elastic medium is used in calculation of base and hydro-technical structures built of earth materials for seismic effects, since it allows us to take into account the absorption of vibration energy and the dependence of vibration damping on frequency

\[ \sigma_{ij} = \lambda \theta \delta_{ij} + 2G \varepsilon_{ij} + \lambda' \theta \delta_{ij} + 2G' \varepsilon_{ij} \]

Where \( \sigma_{ij}, \varepsilon_{ij} \) - are the components of the stress and strain tensor; \( \lambda, G \) - are the corresponding viscosity coefficients of the medium; \( \theta = \frac{1}{3} (\varepsilon_i + \varepsilon_2 + \varepsilon_3) \), \( \dot{\theta} = \frac{1}{3} (\dot{\varepsilon}_i + \dot{\varepsilon}_2 + \dot{\varepsilon}_3) \) - volume strain and its velocity; \( \delta_{ij} \) - the Kronecker symbol.

The use of complex modules \( \lambda(i\omega) = \lambda - i\omega \lambda' \) and \( G(i\omega) = G - i\omega G' \) allows us to represent the dynamic Kelvin-Voigt model similar to Hooke’s law:

\[ \sigma_{ij} = \lambda(i\omega)\theta \delta_{ij} + 2G(i\omega)\varepsilon_{ij} \]

Which makes it possible to generalize the problems of ideal theory of elasticity to the case of imperfectly elastic media, such as the soil medium of the dam. The use of this model in finite element discretization of a structure leads to a resolving system of differential equations

\[ [M][\ddot{q}] + [\eta][K][\dot{q}] + [K][q] = [P(t)] \]

with viscosity coefficient \( \eta = \lambda' + 2G' \). Given \( [M]^{-1}[K] = diag(\omega_i^2) \), a system of separate equations is obtained

\[ \{\ddot{q}\} + \eta diag(\omega_i^2)\{\dot{q}\} + diag(\omega_i^2)\{q\} = [M]^{-1}[P(t)] \]

To determine the value of \( \eta \), we use the well-known data /7/, according to which the values of the coefficient of soil internal absorption \( \psi = 0.2 \leq \psi \leq 0.35 \). Given the relationship of coefficient \( \psi \) with friction coefficients (coefficients of the displacement derivative) and frequencies (\( \omega_i \)) we get:

\[ \psi = \frac{2\eta_i \omega_i^2}{\omega_i}, \quad \eta_i = \frac{\psi}{2\pi \omega_i} \]

Taking into account the range of variation of \( \psi (0.2 \leq \psi \leq 0.35) \) and the spectrum of the fundamental frequencies (1±3 Hz), we obtain the following limits of variation of coefficient \( \eta \)

\[ 0.006 \leq \eta \leq 0.0175 \]

When we choose the average value of \( \eta = 0.01 \), used in calculations of dynamic behavior of earth dam on dynamic load.

The obtained horizontal displacements of the dam points, taking into account viscous friction under the indicated short-term impact, are shown in Figure 5b. Comparing the graphs in Figures 5a and 5b, it can be seen that an account for soil viscosity reduces the vibration amplitude by almost an order of

![Figure 5](image-url)
magnitude without causing a resonance in the structure. After the impact termination, the amplitude damps rapidly, avoiding the mode of free vibrations (compare Figures. 5a and 5b).

Finally, an account for dissipation in the form of dry friction is reduced to a system of differential equations –

\[ [M][\ddot{u}] + 2\varepsilon[M][\dot{u}] + [K][u] = \{f(t)\}, \]

where \( \varepsilon = \frac{\delta}{2\pi} \omega \) - is the doubled attenuation coefficient of vibrations; \( \delta \) - logarithmic decrement of vibrations; \( \omega \) - natural frequency of structure vibrations.

The results of horizontal movements of the same points of the dam, with account for dry friction in soil, are shown in Figure. 5c. The impact termination leads to gradually damping vibrations, in contrast to the viscoelastic case, when the vibrations cease immediately with the impact termination (compare Figures. 5c and 5b). Energy dissipation in a dam with dry friction in soil is manifested to a lesser extent than in a viscous soil, with a greater amplitude of vibrations during the impact.

The prevalence of the amplitude of horizontal vibrations over vertical ones for three types of structure soil is due to the occurrence of first mode vibrations of a dam under the indicated impact, in which the horizontal displacements of the dam cross-sections points prevail. The prevalence of vertical displacements of structure points is observed under the impact at a frequency of \( \omega_2 = 2.4 \) Hz, causing the second mode of structure vibrations.

Figure 5 (right) shows the displacements of the same points of the dam under a two-component impact at a frequency \( \omega = \omega_2 = 2.4 \) Hz, which causes vertical resonance during the impact and smooth or vibration-damping behavior when accounting for viscosity or dry friction in soil (Figure. 5 right).

4. Conclusion

Thus, on the basis of studies on earth dam dynamics with various soil properties under seismic influences that cause fundamental modes of vibrations, the following aspects were revealed:

- the appearance of a resonance in a dam with elastic soil and the transition of the structure to steady-state vibrations at the impact termination;
- a smooth return of the dam with saturated soil to a state of static equilibrium after the impact termination;
- gradual damping vibrations of the dam with dissipation in soil at dry friction after the impact termination;
- strengthening of the upstream slope stability during earth dam vibrations with a filled reservoir.

The statement of the problem of an earth dam forced vibrations under dynamic impact with and without account for internal friction in soils is given; an algorithm for solving non-stationary problems by the numerical finite element method using the Newmark method is presented; an analysis of numerical results — the dependences of displacements and stresses in vulnerable points of earth structure during dynamic impact, showed that an account for internal friction in soil reduces the amplitude of the forced vibrations.

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